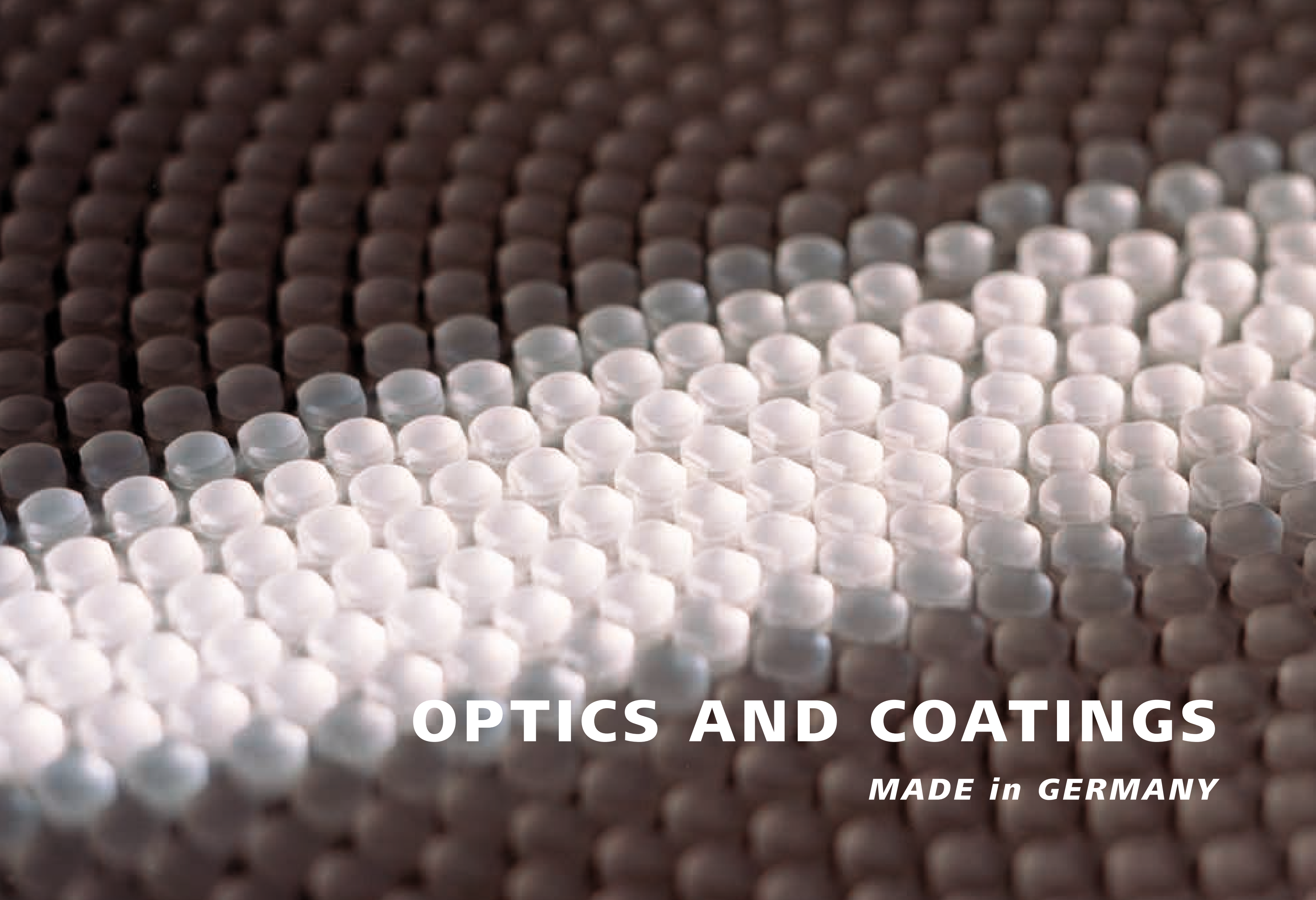


OPTICS AND COATINGS

MADE in GERMANY

LAYERTEC®
OPTICAL COATINGS · OPTICS

CONTENTS

ABOUT LAYERTEC

LAYERTEC, established in 1990 as a spin-off of the Friedrich-Schiller-University Jena, produces high quality optical components for laser applications in the wavelength range from the VUV (157 nm) to the NIR (~ 6 µm).

Since the beginning LAYERTEC has worked for universities and research institutes worldwide and many important developments in laser technology of the past years have been supported by LAYERTEC products.

Today, more than 200 employees are working in the precision optics facility and coating laboratories of LAYERTEC. More than 30 coating machines are available to cover the wavelength range from the VUV to the NIR using sputtered and evaporated coatings made of fluorides and oxides, metallic and metal-dielectric coatings.

LAYERTEC offers the full spectrum of design and manufacturing options for a high flexibility to customize optical components for special applications with an optimum of coating performance and cost efficiency. The variety in size and technology of our coating equipment allows a high-volume fabrication of serial products as well as a flexible prototype manufacturing for R&D groups in the industry and for research institutes.

This catalog gives an overview about our production program and shows some highlights which represent innovative solutions of outstanding quality and which are intended to point out the capabilities of LAYERTEC for further developments.

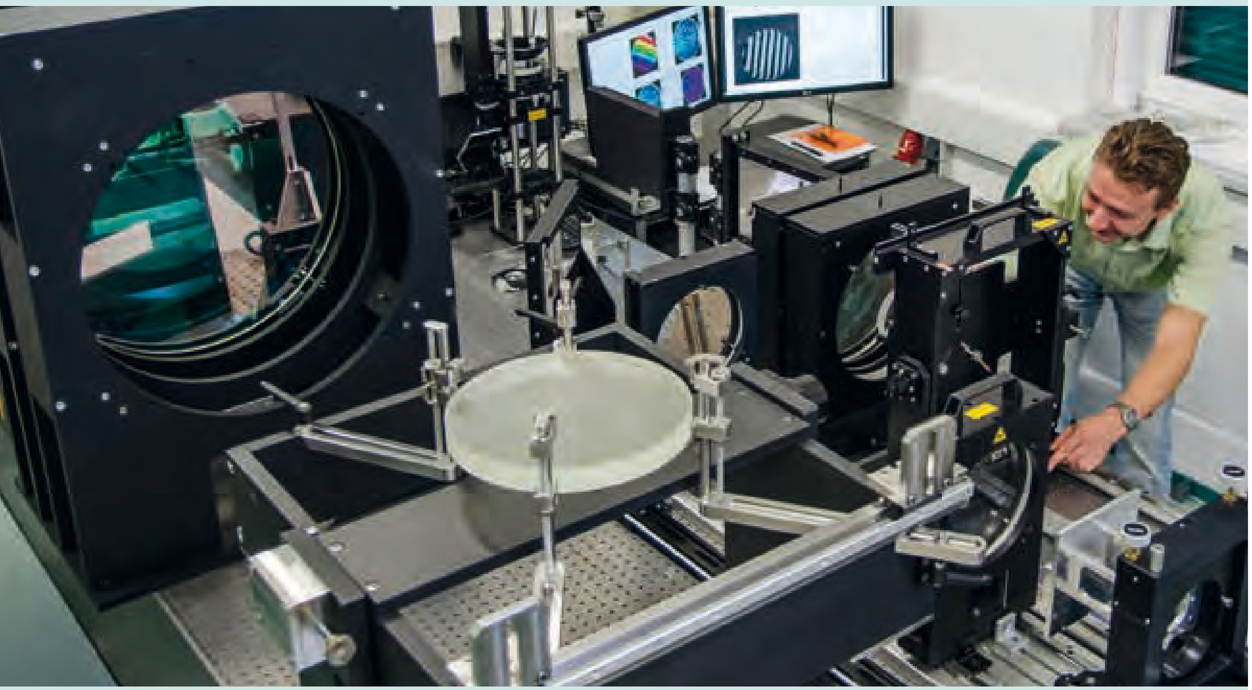
Please do not hesitate to contact LAYERTEC for an offer or for a discussion of your special project even if your type of laser or your special field of interest is not explicitly mentioned in this catalog.

Our company combines a precision optics facility and a variety of coating techniques (magnetron and ion-beam sputtering, thermal evaporation, ion assisted e-beam evaporation) which enables LAYERTEC to control the quality of the optical components over the whole production process from grinding, polishing and cleaning of the substrates to the final coating process.

PRECISION OPTICS

The precision optics facility of LAYERTEC produces **mirror substrates, etalons**, retarders, lenses and prisms of fused silica, optical glasses like BK7® and SF10® and some crystalline materials, e.g. calcium fluoride.

The polishing of fused silica and YAG has been optimized over the recent years. We are able to offer fused silica substrates with a surface **rms-roughness of 1.5 Å**.



LAYERTEC produces precision optics in a wide range of sizes. Typical diameters for the laser optics are between 6.35 mm and 100 mm, but sizes down to 2 mm for a serial production of the smallest laser devices as well as **diameters up to 600 mm** for high-energy lasers or astronomical telescopes are possible.

High quality substrates for laser mirrors are characterized by:

- Geometry and shape (diameter, thickness, wedge and radius of curvature)
- Surface roughness
- Surface form tolerance
- Surface defects

LAYERTEC offers substrates which are optimized for all of these parameters. The specifications of premium quality fused silica substrates with diameters up to 50 mm are:

- Surface rms-roughness as low as 1.5 Å
- Surface form tolerance of $\lambda / 30$ (546 nm)
- Defect density as low as 5 / 1 x 0.025 (ISO 10110)

These parameters are not limited to a standard geometry but can also be achieved on substrates with uncommon sizes, shapes or radii of curvature. LAYERTEC substrates meet the demands for the production of components for Cavity Ring-Down Spectroscopy and EUV mirrors.

SPUTTERING

PRINCIPLE

In general, the term "sputtering" refers to the extraction of particles (atoms, ions or molecules) from a solid by ion bombardment. Ions are accelerated towards a target and collide with the target atoms. The original ions as well as recoiled particles, move through the material, collide with other atoms and so on. Most of the ions and recoiled atoms remain within the material, but a certain fraction of the recoiled atoms is scattered towards the surface by this multiple collision process. These particles leave the target and may then move to the substrates and build up a thin film.

PROPERTIES OF SPUTTERED COATINGS

Because of the high kinetic energy (~10 eV), i.e. high mobility of the film forming particles, sputtered layers exhibit

- An amorphous microstructure
- A high packing density (which is close to that of bulk materials)

These structural characteristics result in very advantageous optical properties such as:

- Low losses due to scattered light
- High stability of the optical parameters under various environmental conditions due to the blocking of water diffusion
- High laser-induced damage thresholds
- High mechanical stability

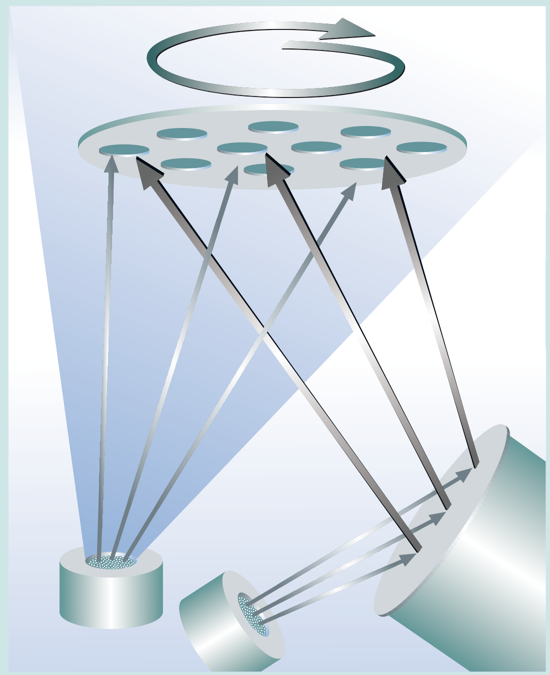
MAGNETRON SPUTTERING

Ions are delivered by a gas discharge which burns in front of the target. It may be excited either by a direct voltage (DC-sputtering) or by an alternating voltage (RF-sputtering). In the case of DC-sputtering the target is a disk of a high purity metal (e.g. titanium). For RF-sputtering, dielectric compounds (e.g. titanium dioxide) can also be used as targets. Adding a reactive gas to the gas discharge (e.g. oxygen) results in the formation of the corresponding compounds (e.g. oxides).

Developments at LAYERTEC have taken magnetron sputtering from a laboratory technique to a very efficient industrial process, which yields coatings with outstanding properties especially in the VIS and NIR spectral range. The largest magnetron sputtering machine can coat substrates up to a diameter of 600 mm.

ION BEAM SPUTTERING (IBS)

This technique uses a separate ion source to generate the ions. To avoid contaminations, RF-sources are used in modern IBS machines. The reactive gas (oxygen) is in most cases also provided by an ion source. This results in a better reactivity of the particles and in more compact layers.



The main difference between magnetron sputtering and ion beam sputtering is that ion generation, target and substrates are completely separated in the IBS process while they are very close to each other in the magnetron sputter process.

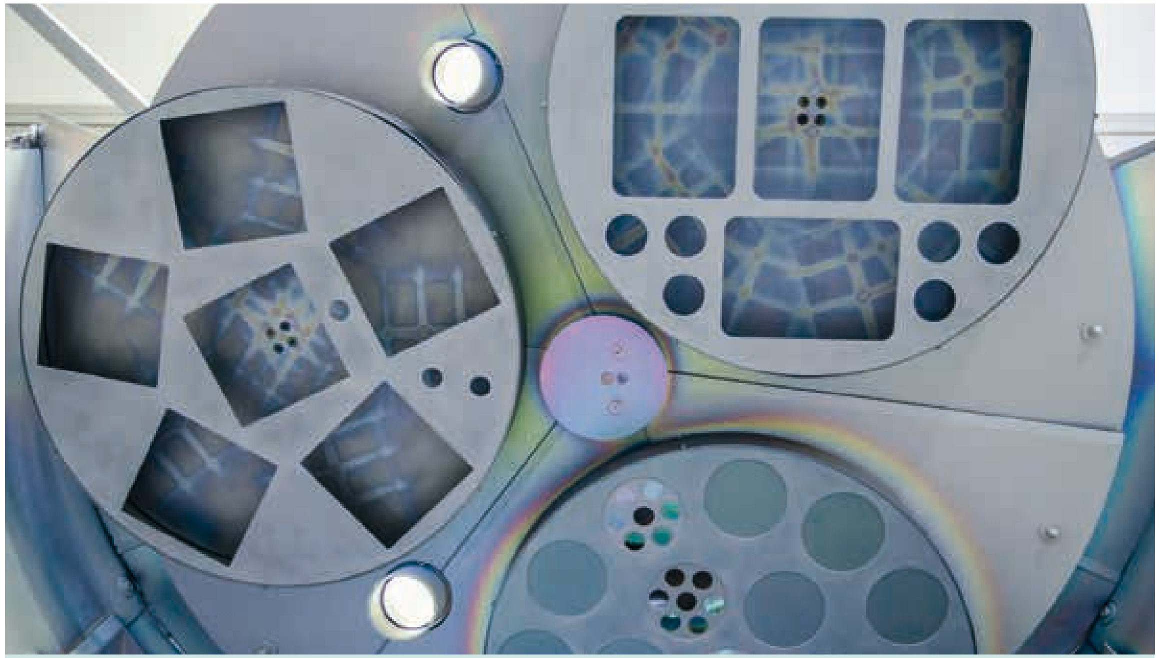
THERMAL AND E-BEAM EVAPORATION

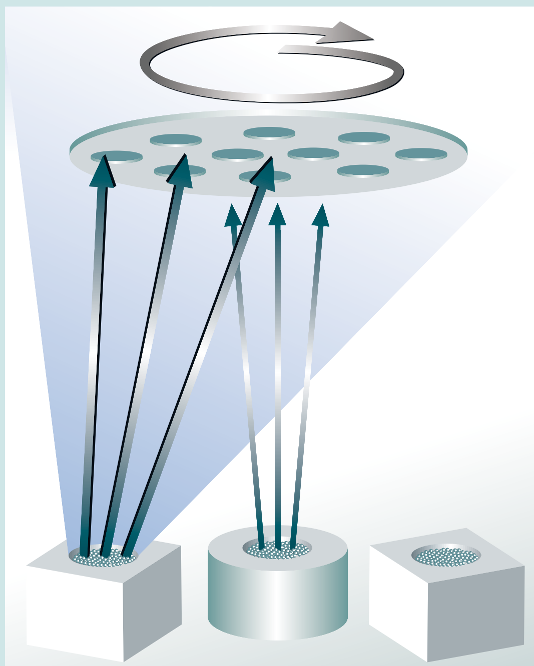
WORKING PRINCIPLE

Thermal and electron beam evaporation are the most common techniques for the production of optical coatings. LAYERTEC uses these techniques mainly for UV-coatings. The evaporation sources are mounted at the bottom of the evaporation chamber. They contain the coating material which is heated by an electron gun (e-beam evaporation) or by resistive heating (thermal evaporation). The method of heating depends on the material properties (e.g. the melting point) and the optical specifications.
The substrates are mounted on a rotating substrate holder at the top of the evaporation chamber. Rotation of the substrates is necessary to ensure coating homogeneity. The substrates must be heated to a temperature of 150 – 400°C, depending on the substrate and coating materials. This provides low absorption losses and good adhesion of the coating to the substrates. Ion guns are used to get more compact layers.

LAYERTEC is equipped with several evaporation machines covering the whole bandwidth of the above mentioned techniques from simple thermal evaporation to ion assisted deposition (IAD) using the APS pro® and LION® ion sources.

APS pro® and LION® are a trademarks of Bühler Alzenau GmbH





PROPERTIES OF EVAPORATION COATINGS

The energy of the film forming particles is very low (~1eV). That is why the mobility of the particles must be enhanced by heating the substrates.
The packing density of standard evaporated coatings is relatively low and the layers often contain micro crystallites. This results in relatively high scattering losses (some tenth of a percent to some percent, depending on the wavelength). Moreover, atmospheric water vapor can diffuse in and out of the coating depending on temperature and humidity resulting in a shift of the reflectance bands by ~1.5 % of the wavelength.

Shift-free, i.e. dense, evaporated coatings can be produced by IAD using the APS pro® and LION® ion sources which provide very high ion current densities.

Nevertheless, evaporated coatings have also high laser damage thresholds and low absorption. They are widely used in lasers and other optical devices.

MEASUREMENT TOOLS FOR PRECISION OPTICS

SURFACE FORM MEASUREMENT

The precision optics facility of LAYERTEC is equipped with laser interferometers and special interferometer setups for plane, spherical and parabolic surfaces. For aspheric surfaces, LAYERTEC uses tactile and contactless metrology systems. In general, the form tolerance of spherical and plane optics with diameters up to 100 mm can be measured with an accuracy of λ / 10 (633 nm). However, in many cases, a higher accuracy up to λ / 30 is possible. Measurement reports can be provided on request.

LARGE APERTURE METROLOGY

Especially for laser optics with large dimensions, LAYERTEC uses a high performance Fizeau interferometer and a Twyman-Green interferometer within the following measurement ranges:

- Plane surfaces: Ø ≤ 300 mm with an accuracy up to λ / 50 (633 nm) and Ø ≤ 600 mm better than λ / 10
- Spherical surfaces: Ø ≤ 600 mm with an accuracy better than λ / 10 (633 nm)
- Parabolic surfaces: Ø ≤ 300 mm full aperture measurement with an accuracy up to λ / 10 (633 nm)

Interferometry of large surfaces

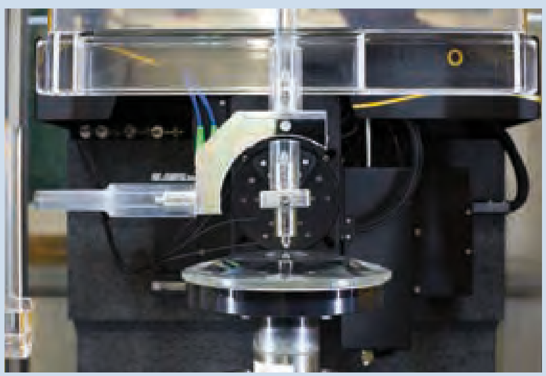
CONTACTLESS METROLOGY

The metrology system LuphoScan, developed by Luphos GmbH, allows an ultra-high precision measurement of distance and surface form. The unique system combines many advantages of other distance measurement systems without their disadvantages of necessary contact, small working distance or tiny working range. This technology allows the determination of the topology of different objects down to the nanometer range.

Highly reflective objects as mirrors or metal coated substrates can be measured as well as transparent objects providing only weak reflectance (glass lenses, substrates).

Due to its absolute measurement range, it is possible to resolve structures of up to 1 mm height with a precision of ± 5 nm.

Especially, topological errors of aspheric surfaces can be exactly determined and used for a correction of the form parameters during the polishing process.



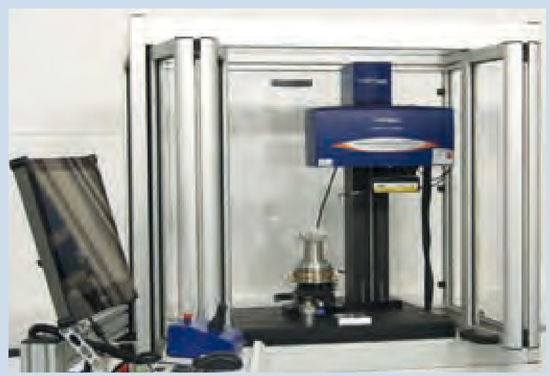
LuphoScan metrology system

TACTILE SURFACE PROFILER

The Talysurf PGI 1240 is a tactile surface profile measuring tool used to characterize strongly curved surfaces. A small tip is in contact with the surface and moves along a line while its displacement is measured.

The measurement principle is independent from surface topology or optical properties such as coatings or thin contaminations, which often prevent direct interferometry. The vertical accuracy depends on the gradient of the surface and can reach values of 200 nm, which corresponds to ≈ λ / 2 (633 nm).

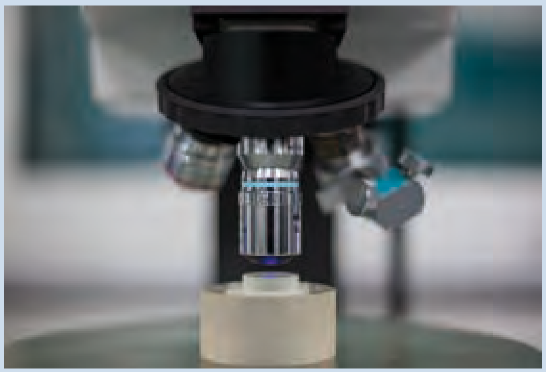
LAYERTEC uses this tool for measurements of small to mid-size non-spherical surfaces up to a diameter of 200 mm.



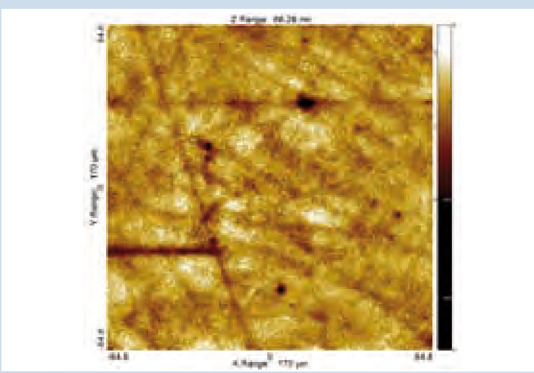
Taylor Hobson Talysurf PGI 1240

OPTICAL PROFILOMETRY

A 3D optical surface profiler based on a white light interferometer is used to visualize the surface form and roughness of our substrates. The profiler is furthermore applied for the characterization of surface defects and other structures in the range of sizes from 0.5 µm up to 100 µm.



Optical profiler Sensofar

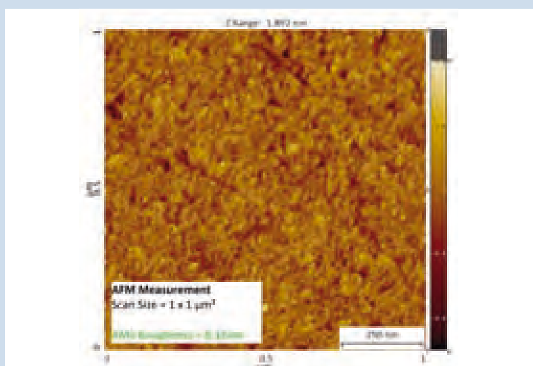


Surface defects visualized by the optical profiler

SCANNING PROBE MICROSCOPY

LAYERTEC utilizes a scanning probe microscope (atomic force microscope, AFM) with a measurement range between 10 nm and 1 µm. It is used to control the special polishing processes for surface roughness values below Sq ≤ 5 Å as well as to provide inspection reports on request.

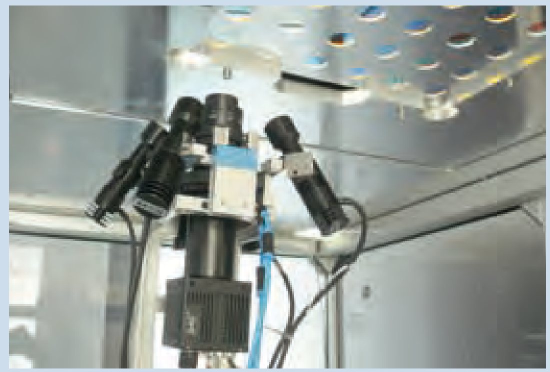
DI Nanoscope 3100 AFM



AFM scan of an optical surface

DEFECT ANALYSIS

LAYERTEC has developed an automated measurement system for the detection and analysis of defects and scratches on optical surfaces. This system enables LAYERTEC to classify defect sizes according to ISO 10110-7. Thus, quality control procedures, such as final inspection, are facilitated, especially for high-quality optics with defects specified below 25 µm.



Defect inspection system for optical components

Automatic handling unit

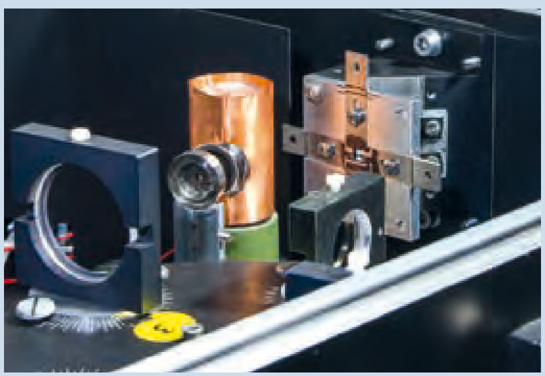
MEASUREMENT TOOLS FOR COATINGS

Quality control is most important for production as well as for research and development. The standard inspection routines at LAYERTEC include interferometric measurements of the substrates and spectrophotometric measurements of the coated optics in the wavelength range between 120 nm and 20 µm.

SPECTROPHOTOMETER

Standard spectrophotometric measurements in the wavelength range $\lambda = 120$ nm – 20 µm are carried out with UV-VIS-NIR spectrophotometers, VUV- and FTIR-spectrophotometers.

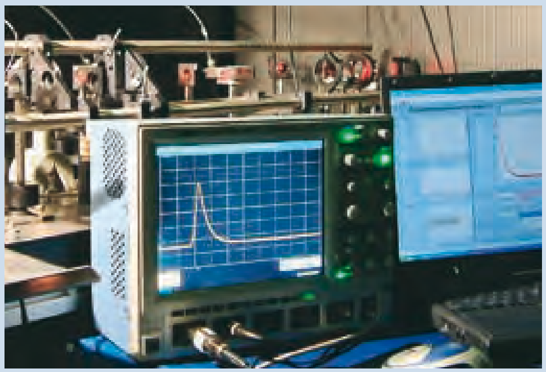
Spectrophotometer Perkin Elmer Lambda 950



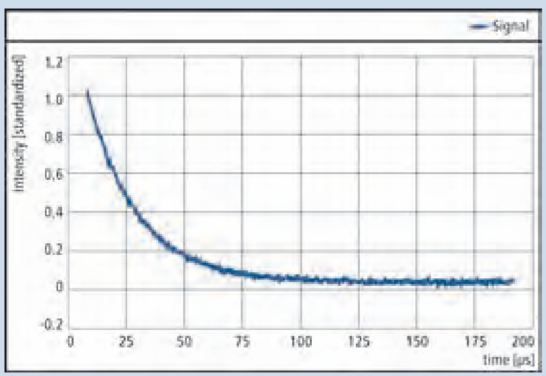
Measurement chamber of the Vacuum-UV spectrophotometer

CAVITY RING-DOWN (CRD)

High reflectance and transmittance values in the range of R, T = 99.5 % … 99.9999 % are determined by Cavity Ring-Down time measurements. This method is an absolute measurement procedure of high accuracy. LAYERTEC employs various CRD setups to cover the whole spectral range from 220 to 1800 nm without any gaps. A CRD setup for the wavelength range from 2500 to 4700 nm is under construction.



CRD measurement setup

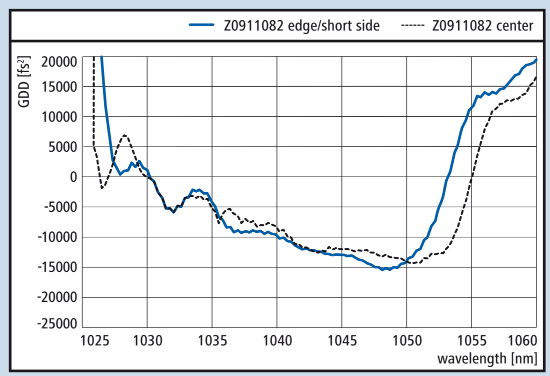


Exemplary mono-exponential CRD-curve of a highly reflecting mirror pair for 450 nm with R = 99,995 % measured using a resonator length L = 228 mm

GROUP DELAY (GD) & GROUP DELAY DISPERSION (GDD)

Besides transmittance and reflectance, LAYERTEC is able to measure the phase properties of mirrors in the wavelength range between 250 and 1700 nm with several white light interferometers. These setups can be used for the characterization of broadband femtosecond laser mirrors with positive or negative GDD as well as for measuring the GDD of GTI mirrors down to -10000 fs² in a narrow spectral range.

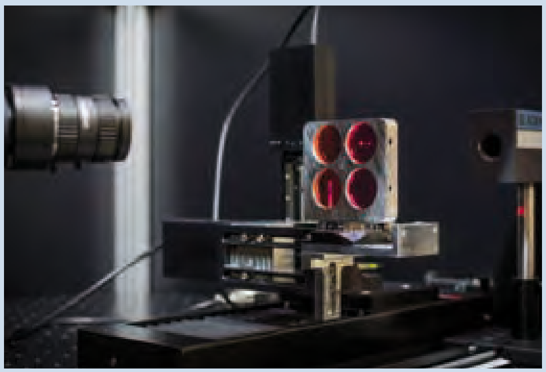
GDD measurement setup



GDD spectra of GTI mirrors, see also pages 96, 97

LASER INDUCED DAMAGE THRESHOLD (LIDT)

LIDT measurements according to ISO standards and to our own procedures can be carried out (see pages 37, 38) with a measurement setup at LAYERTEC. The following wavelengths are available: 266 nm, 355 nm, 532 nm and 1064 nm. The pulse duration is 4 – 10 ns. Measurements with other LIDT test conditions are carried out in cooperation with the Laser Zentrum Hannover (LZH), for example.

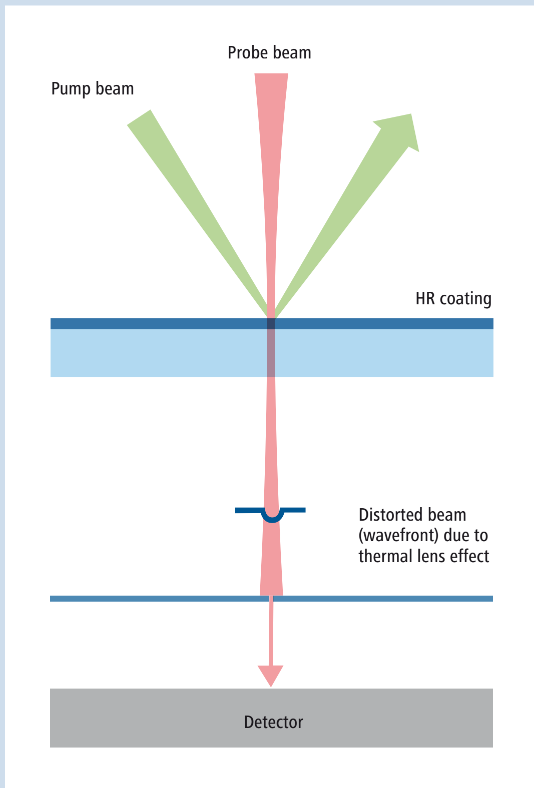


LIDT measurement setup for pulsed laser sources

LIDT beamline

ABSORPTION LOSSES

Absorption of optical thin films and bulk materials can also be measured in-house. Measurements are available for 355 nm, 532 nm or 1030 nm and angles of incidence between 10° and 70° for s- and p-polarized light. Due to the measurement setup, a transmittance above 1% for 635 nm is required. Apart from that, any HR, PR or AR coating (including single layers) on most common substrates may be measured. Substrates have to be plane with a thickness of 1 – 12 mm. Calibration reports are available on request.

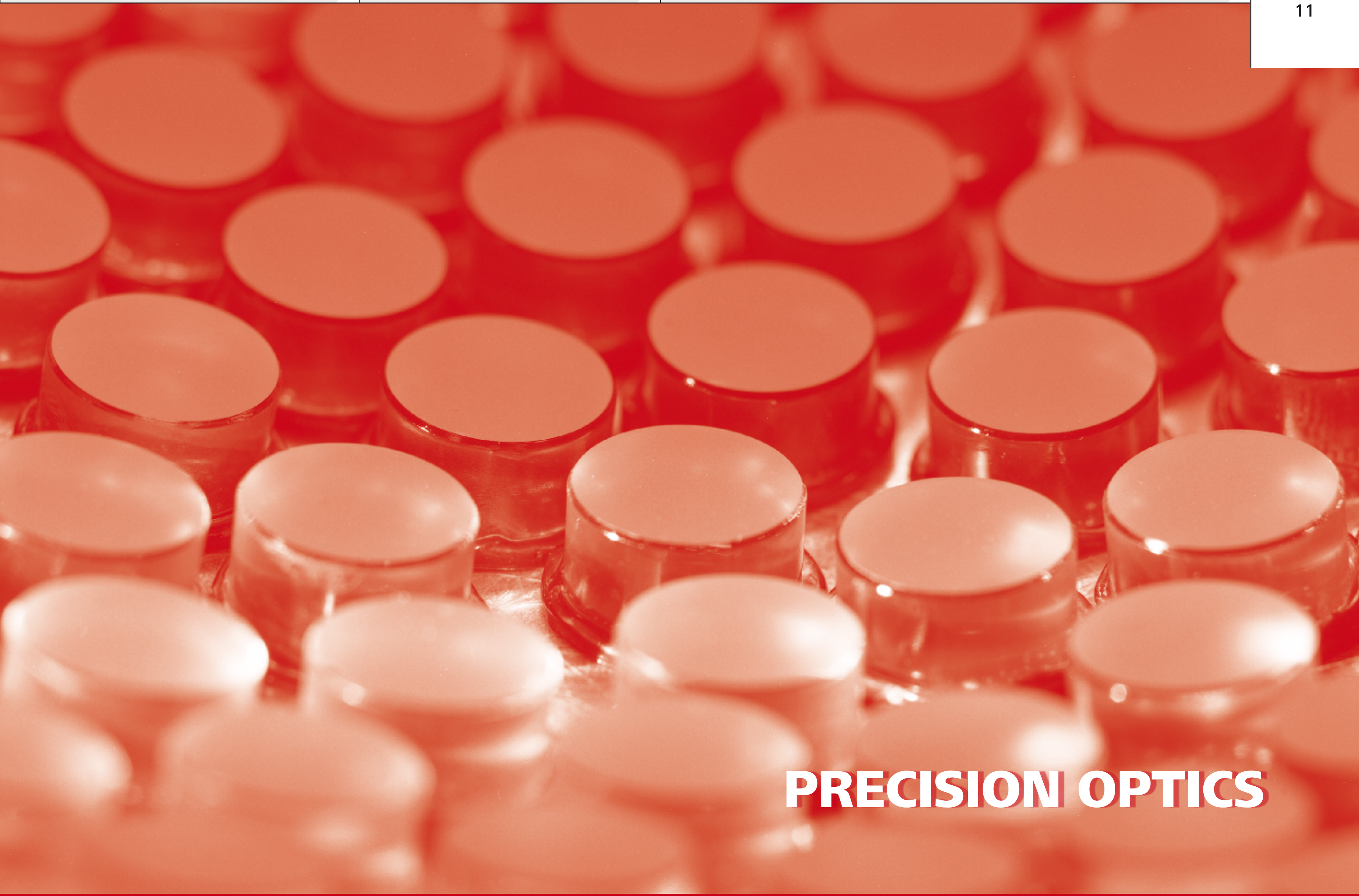


Schematic drawing of the CPI measurement setup

INTRA-CAVITY HEATING

Absorption losses in optical coatings lead to the heating of coating and substrate. For average laser power levels above several kilowatts (cw), even low absorption losses in the range of some parts per million cause significant heating of the optical component. LAYERTEC has built a heating measurement setup for the purpose of quality assurance and technology development of high-power optical components for the wavelength 1030 nm.

Absorption measurement using a high power cw laser



PRECISION OPTICS

LAYERTEC®
OPTICAL COATINGS · OPTICS

HOW TO SPECIFY SUBSTRATES

Price and quality of substrates are determined by material, shape, size, tolerances and polishing quality.

MATERIAL

The first decision is the material of the substrate. It should be free of absorption for all wavelengths of high transmittance. If no transmittance occurs, a low cost material can be used, e.g. Borofloat® (SCHOTT AG), for metallic mirrors.
With respect to the surface form tolerance, a low thermal expansion is beneficial.

SHAPE

The shape must be specified for both sides separately. All combinations of plane, convex and concave surfaces are possible. This is also the case for wedges, e.g. 30 arcmin, which can be appied to any kind of surface, plane as well as convex or concave.
For curved substrates there are different conventions for the sign of the radius. Sometimes "+" means convex and "-" means concave. Other users refer to the direction of light propagation. In this case, "+" means "curvature in the direction of propagation" and "-" means "curvature against the direction of propagation". Please specify concave or convex in words or using the acronyms CC or CX to avoid confusion.

SIZE

The main decision should be about the size of the substrate, i.e. edge length or diameter. Small diameters are more favorable for production. The sagitta heights become lower and it is easier to achieve a good form tolerance.

Although often denoted otherwise in optical designs, LAYERTEC specifies the thickness as the maximum thickness of the substrate, i.e. the center thickness for plano-convex substrates and the edge thickness for plano-concave substrates. Consequently, the thickness of a wedged plate is measured on the thicker side.

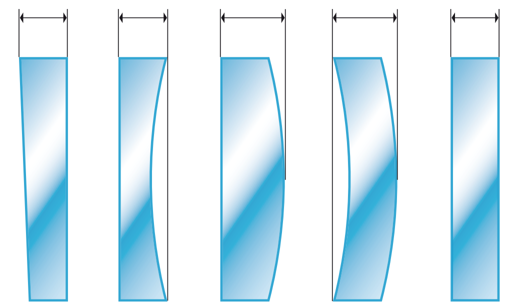


Figure 1: Conventions for the specification of the thickness of different types of substrates (schematic drawing)

In order to achieve a good form tolerance, the ratio of diameter and thicknes should be considered. As a rule of thumb the thickness should be one fifth of the diameter. Of course, other ratios are possible but production costs and therefore prices increase as well.

TOLERANCES

Besides size and material, the tolerances are most important for manufacturing costs and therefore also for prices. Of course, the optics must fit into the mount, so the diameter should not be larger than specified. Thus, the most common specification is + 0 - 0.1 mm. In contrast, the thickness is generally free in both directions. LAYERTEC usually specifies it with a tolerance of ± 0.1 mm.
There is a lot of confusion about the specification of wedge, parallelism and centering. Please note that wedge and parallelism describe the angle between the optical surfaces while centering describes the angle between the optical surfaces and the side surfaces (see fig. 2).

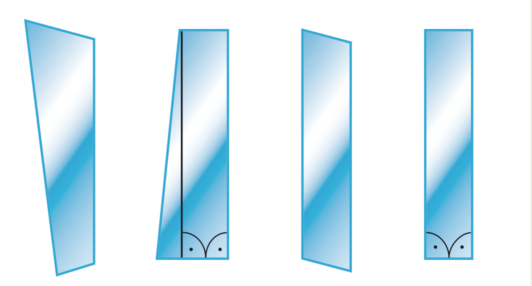


Figure 2: Different kinds of plane substrates with respect to wedge and centering (schematic drawing)

LAYERTEC standard substrates have a parallelism better than 5 arcmin. Specially made parallels may have a parallelism as low as 10 arcsec. Standard wedged substrates have wedges of 0.5° or 1°. Larger wedge angles are possible depending on the substrate size.
In general, the 90° angle between optical and side surface has a precision of 20 arcmin. Centering is an additional optics processing step which improves this accuracy to a few arcmin.
Curved substrates can be described using the same nomenclature. It should be distinguished between mirrors and lenses. The side surfaces of mirror substrates are parallel. Nevertheless, the direction of the optical axis can be inclined with respect to the side surfaces. After centering, the side surfaces are parallel to the optical axis.

SURFACE FORM TOLERANCE

The surface form tolerance is usually measured by interferometers and specified in terms of lambda, which is the reference wavelength (λ = 546 nm if not otherwise stated). In order to avoid confusion, it is necessary to clearly distinguish between flatness, power and irregularity. In the following, flatness and irregularity shall be explained for a plane surface. Generally speaking, every real surface is more or less curved. Imagine that the "peaks" and "valleys" of a real surface are covered by parallel planes (see fig. 3). The distance between these planes is called the flatness. This flatness consists of two contributions. The first contribution is a spherical bend of the surface, which may be described by a best fitted sphere to the surface. With respect to an ideal plane, the sagitta of this curvature is denoted as power. This spherical bend does not affect the quality of the reflected beam. It just causes a finite focal length. The second contribution is the deviation from the best fitted sphere, which is named irregularity. This is the most important value for the quality of the beam.

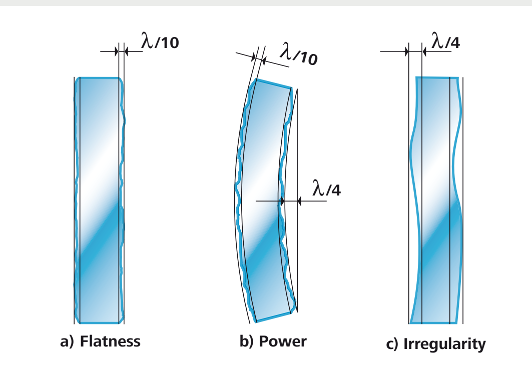


Figure 3: Schematic drawing for the explanation of substrate properties:
a) Flatness of λ/10
b) Spherical bending (power of λ/4)
c) Irregularity of λ/4, but transmitted wavefront of λ/10

The standard ISO 10110 provides a sufficient method for specifying the surface form tolerance. Having the best comparability with the measurement results, all values are specified as numbers of interference fringes, with 1 fringe = λ / 2. In technical drawings according to ISO 10110, the surface form tolerance is allocated as item number three:

3 / power (irregularity)

Example: A slightly bent (λ / 4) optics which is regular (λ / 10) would be specified as follows:

3 / 0.5 (0.2)

Using the optics only for transmittance (e.g. laser windows), power as well as irregularity do not matter. A transmitted beam is not affected if the optics has the same thickness all over the free aperture. The influence of thickness deviations on the transmitted beam is defined in a similar way as the flatness. It is also measured in parts of the reference wavelength and called "transmitted wave front". For instance, the window in fig. 3c has a flatness of λ / 4 but a transmitted wave front of λ / 10.

COATING STRESS

Thin substrates cannot withstand the coating stress. The coating will cause a spherical deformation. This means that a finite sagitta or power occurs. In case of circular substrates, the irregularity is not affected by this issue.
Even if power deviation is considered, the quality of a beam under normal incidence is not affected.

DEFECTS

MIL-O-13830 and ISO 10110 are different standards for the description of optical elements. This often causes obscurities. Basically, scratches and digs have to be distinguished. The scratch number in MIL-O-13830 refers to the visibility of the biggest scratch compared to the corresponding one on a norm template. Actually "10" is the smallest scratch on this template. Thus, better qualities cannot be specified legitimately. Moreover, the MIL norm does not specify a directly measured scratch width. Sometimes the number is interpreted as tenths of a micron, sometimes as microns. Actually, a direct measurement never corresponds to the MIL norm.

In contrast to the scratch, the dig number can be measured easily. The numerical value is equal to the maximum dig diameter in hundredths of a millimeter. One maximum-size dig per 20 mm diameter is allowed. According to ISO 10110, defects are specified as item number 5. The grade number is the side length in millimeters of a square area which is equivalent to the total defect area. So, 5 / 1 x 0.025 describes a surface defect area of 625 µm². Additionally, scratches of any length are denoted with a leading L. A long scratch with a width of 4 microns would be specified as L 1 x 0.004.
All these explanations are very simplified. For a detailed specification please read the complete text of the relevant standard.

PLEASE NOTE:

There is no direct conversion between MIL-O-13830 and ISO 10110. All specifications in this catalog are according to ISO 10110. The mentioned scratch/dig values are rough approximations to MIL-O-13830.

STANDARD QUALITY SUBSTRATES

The precision optics facility of LAYERTEC produces plane and spherically curved mirror substrates, lenses and prisms of fused silica, optical glasses like N-BK7® and SF14® and some crystalline materials, e.g. calcium fluoride and YAG. In the following you can find information on the specifications of our standard substrates.
Please do not hesitate to contact us also for other sizes, shapes, radii and materials or for special components. For cylindrical, aspherical and free form optics see page 16.

STANDARD SPECIFICATIONS

Materials

- Fused silica:
  Corning 7980® or equivalent
- Fused silica for high power applications:
  Suprasil® 300 / 3001 / 3002 or equivalent
- UV fused silica (excimer grade):
  SQ1 E-193® and SQ1 E-248®
- IR fused silica:
  Infrasil 302® or equivalent
- ULE®
- Zerodur®
- N-BK7® or equivalent
- CaF_2:
  single crystal, randomly oriented, special orientations on request, excimer grade (248 nm and 193 nm) on request
- Sapphire:
  single crystal, C-cut
- YAG:
  undoped, single crystal, randomly oriented

All trademarks mentioned are the property of the respective owners.

Plane substrates, parallels and wedges

- Standard plane substrates:
  wedge < 5 arcmin
- Standard parallels:
  wedge < 1 arcmin or wedge < 10 arcsec
- Standard wedges:
  wedge = 30 arcmin or wedge = 1 deg

Plano-concave and plano-convex substrates

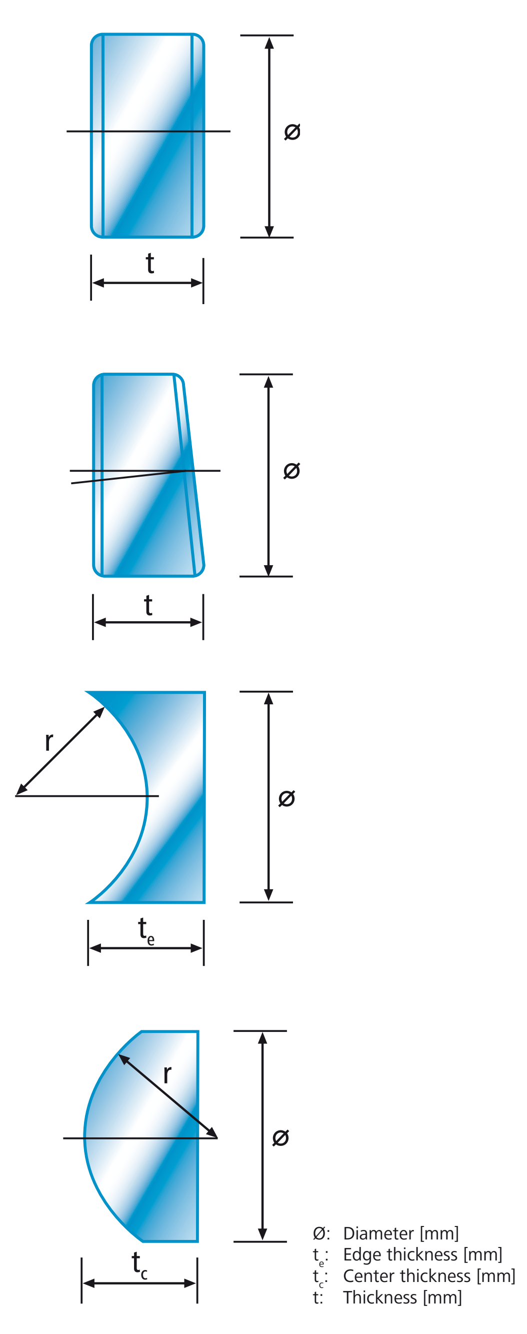
- Standard radii:
  25, 30, 38, 50, 75, 100, 150, 200, 250, 300, 400, 500, 600, 750, 1000, 2000, 3000, 4000, 5000 mm

Dimensions

- Fused silica, ULE®, Zerodur®:
  diameter 3 mm … 600 mm
- Calcium fluoride, YAG, sapphire:
  diameter 3 mm … 50.8 mm
- Rectangular substrates and other diameters available on request

Tolerances

- Diameter:
  + 0 mm, - 0.1 mm
- Thickness:
  ± 0.1 mm
- Clear aperture:
  central 85 % of dimension
- Chamfer:
  0.2 … 0.4 mm at 45°



Surface form tolerance (reference wavelength: 546 nm)

Material		Standard Specification	On request
Fused silica	plane spherical	λ / 10 λ / 10 reg.	λ / 30 λ / 30 reg. (Ø < 51 mm)
ULE® and Zerodur®	plane spherical	λ / 10 λ / 10 reg.	λ / 30 λ / 30 reg. (Ø < 51 mm)
N-BK7®	plane spherical	λ / 10 λ / 10 reg.	λ / 30 λ / 30 reg. (Ø < 51 mm)
CaF_2	plane Ø < 26 mm plane Ø < 51 mm spherical	λ / 10 λ / 4 λ / 4 reg.	λ / 20 λ / 20 λ / 20 reg.
Sapphire		λ / 10	λ / 30
YAG	plane spherical	λ / 10 λ / 8 reg. (typical λ / 10 reg.)	λ / 30 λ / 30 reg. (Ø < 51 mm)
Si	plane spherical	λ / 10 λ / 8 reg. (typical λ / 10 reg.)	λ / 20 λ / 20 reg. (Ø < 51 mm)

Surface quality

Material	Standard Roughness*	Standard Specification	On request	
Fused silica	< 2 Å	5 / 1 x 0.025 L1 x 0.001 Scratch-Dig 10-3	< 1.5 Å	5 / 1 x 0.010 L1 x 0.0005 Scratch-Dig 5-1
ULE®	< 2 Å	5 / 3 x 0.025 L1 x 0.001 Scratch-Dig 10-5	< 2 Å	5 / 1 x 0.010 L1 x 0.0005 Scratch-Dig 5-1
Zerodur®	< 4 Å	5 / 2 x 0.040 L1 x 0.001 Scratch-Dig 10-5	< 3 Å	5 / 2 x 0.025 L1 x 0.0010 Scratch-Dig 10-3
N-BK7®	< 3 Å	5 / 2 x 0.040 L1 x 0.001 Scratch-Dig 10-5	< 2 Å	5 / 2 x 0.025 L1 x 0.0010 Scratch-Dig 10-3
CaF_2	< 3 Å	5 / 3 x 0.025 L1 x 0.0025 Scratch-Dig 20-3	< 1.5 Å	5 / 3 x 0.016 L1 x 0.0010 Scratch-Dig 10-2
Sapphire	< 3 Å	5 / 1 x 0.025 L20 x 0.0025 Scratch-Dig 20-3	< 2 Å	5 / 1 x 0.016 L1 x 0.0010 Scratch-Dig 10-2
YAG	< 2 Å	5 / 1 x 0.025 L2 x 0.0025 Scratch-Dig 20-3	< 2 Å	5 / 1 x 0.010 L1 x 0.0005 Scratch-Dig 5-1
Si	< 10 Å	5 / 3 x 0.025 L1 x 0.001 Scratch-Dig 10-5	< 6 Å	5 / 3 x 0.016 L3 x 0.0005 Scratch-Dig 5-1

All specifications according to ISO 10110 (Ø 25 mm). The mentioned Scratch-Dig values are approximately equivalent to MIL-O-13830.
* Valid for measurements with optical profilometer taking into account spatial structures in the 0.663 – 42.5 µm range.

ASPHERES, OFF-AXIS AND FREE FORM OPTICS

BASICS

Plane and spherical optics can be efficiently manufactured by using traditional techniques of area grinding and polishing. The tool always works on a significant fraction of the substrate area at once. However, it is hardly possible to manufacture surface geometries that differ from regular forms like planes, spheres or cylinders.

Using ultra precision CNC machinery, surfaces can be processed zonally, i.e. the tool works on one point at a time. The possible surface forms and tolerances are only limited by the precision of the machine and the measurement equipment. In contrast to the areal techniques, zonal processing usually works with one single piece per run only.

Non-spherical optics can be divided into three categories: rotationally symmetric, off-axis and free form optics.

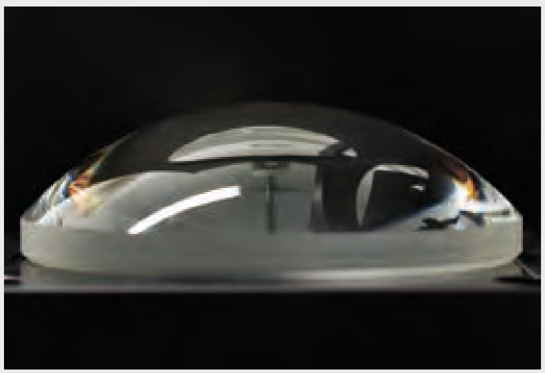


Figure 1: Aspheric lens

ROTATIONALLY SYMMETRIC NON-SPHERICAL OPTICS (ASPHERES)

Although the term "asphere" may stand for any non-spherical optics, it is often restricted to rotationally symmetric optics. They are described by the following equation (ISO 10110):

$$z\,(r) = \frac{r^2}{R\left[1 + \sqrt{1 - (1 + k)\frac{r^2}{R^2}}\right]} + A_3 r^3 + A_4 r^4 + \ldots$$

- z = sagitta
- k = conic constant
- r = distance from axis, $r = \sqrt{x^2 + y^2}$
- R = radius of curvature
- A_i = aspheric coefficients

Neglecting the aspheric coefficients leads to a profile of conic sections:

- Sphere: $k = 0$
- Ellipse: $-1 < k < \infty$
- Parabola: $k = -1$
- Hyperbola: $k < -1$

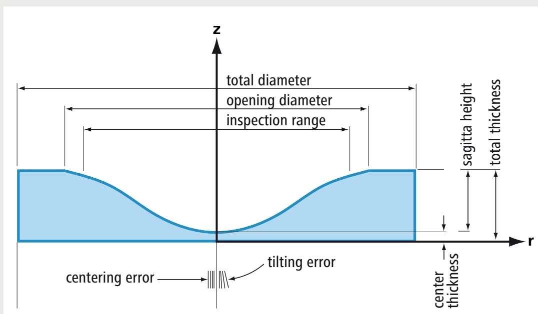


Figure 2: Profile of an aspheric mirror

	Dimension	Tolerances
Total diameter	25 – 560 mm	< 0.1 mm
Inspection range	< 550 mm	
Total thickness	< 100 mm	< 0.1 mm
Sagitta	< 50 mm	
Centering error		< 50 µm
Tilting error		< 30 ''
Surface form tolerance (PV)		< λ / 4 (< λ / 10 on request)
Roughness*		< 4 Å (< 2 Å on request)

Table 1: Production dimensions and tolerances

* Valid for measurements with optical profilometer taking into account spatial structures in the 0.65 - 55 µm range.

OFF-AXIS SURFACES

An off-axis surface can be seen as a section of a bigger on-axis surface. The focal point still is on the original optical axis but not the center of the section. It is located off axis.

Off-axis surfaces derived from aspheres are described by the mentioned equation, the off-axis distance a and / or the off-axis angle α.

Example: Off-Axis Parabola (OAP)

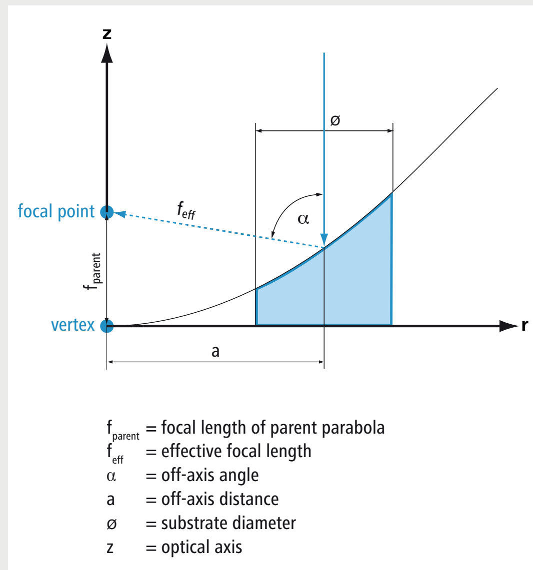


Figure 3: Schematic drawing of an off-axis parabola

The focal length of the parent parabola f_{parent} is measured from the vertex on the optical axis. For the off-axis parabola, an effective focal length f_{eff} is introduced.
The off-axis distance is measured from the optical axis to the middle of the OAP. The radius R denotes the radius of curvature in the vertex of the parent parabola. The conic constant k is -1.

In principle an off-axis substrate can always be mechanically cut from an on-axis substrate. The alternative way is a direct manufacturing. Depending on the size and tolerances, both ways are possible. Fig. 4 shows the common process of manufacturing a number of smaller OAPs from a parent parabola.

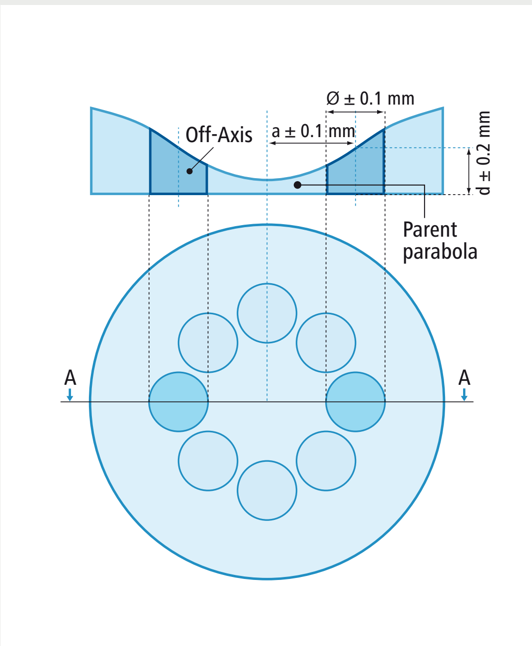


Figure 4: Manufacturing off-axis parabolas as pieces of one "parent parabola"

FREE FORM SURFACES

In general, free form surfaces do not exhibit any symmetries. They are always customer specific and can be defined by an equation. Additional specification of tabulated sagitta values is highly recommend. Free form surfaces are manufactured as single pieces. With respect to machining, the production of an off-axis asphere from a single piece represents a free form as well. Table 2 shows LAYERTEC's production dimensions and tolerances for free form surfaces.

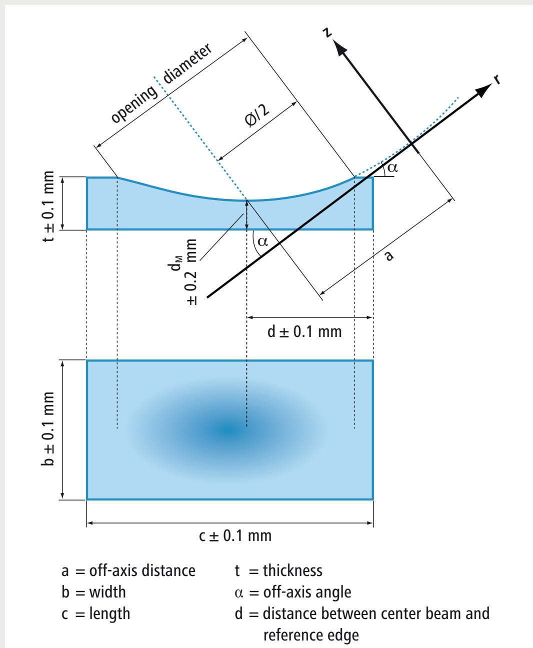


Figure 5: Basic dimensional parameters of a free form substrate

	Dimension	Tolerances
Ø	< 300 mm	0.2 mm
b	< 300 mm	0.1 mm
c	< 450 mm	0.1 mm
α	< 45°	
t	< 80 mm	0.1 mm
d		0.1 mm
Surface form tolerance (PV)		< λ / 10 on request (λ /10 on request)
Roughness*		< 4 Å (< 2 Å on request)

Table 2: Dimensions and tolerances of free form substrates

* Valid for measurements with optical profilometer taking into account spatial structures in the 0.65 - 55 µm range.

MATERIALS

The surface quality and the final tolerances strongly depend on the material of the substrate. LAYERTEC uses a process optimized for fused silica. Materials like Zerodur®, ULE® or N-BK7® may be used in special cases.

MEASUREMENT

Measuring aspheric surfaces requires sophisticated devices. LAYERTEC applies 4 different measurement principles.

- **Tactile measuring**
  A tip has mechanical contact to the surface and its excursion is recorded. One line is measured at a time. Precision < 200 nm on a 200 mm line.
- **Single point interferometer**
  Contactless measurement of the surface, measuring the surface point by point. Precision < 50 nm on ≤ Ø 420 mm.
- **Interferometer with reference surface**
  The surface is compared to a well-known reference surface. Precision < 50 nm, on Ø ≤ 300 mm. Concave surfaces preferred.
- **Interferometer with hologram**
  The surface is compared to the wave front provided by a computer generated hologram (CGH).

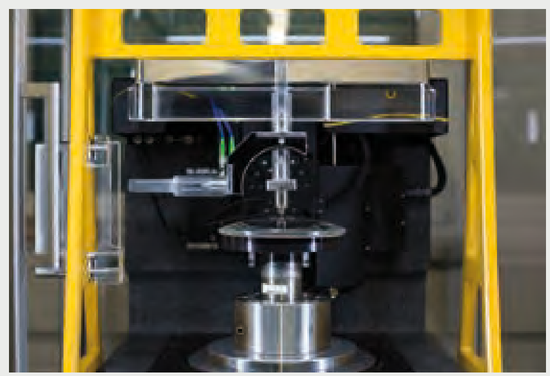


Figure 6: LuphoScan single point interferometer

SPECIAL OPTICAL COMPONENTS

ETALONS

As a kind of a Fabry-Pérot interferometer, the etalon is typically made of a transparent plate with two reflective surfaces. Its transmittance spectrum, as a function of wavelength, exhibits peaks of high transmittance corresponding to resonances of the etalon. Etalons are widely used in telecommunication, lasers and spectroscopy for controlling and measuring the wavelength of laser sources.

LAYERTEC offers etalons of customized diameters and various materials depending on the wavelength range. Thicknesses down to 50 µm and a parallelism < 1 arcsec are possible subject to the diameter. Do not hesitate to contact us for the customized diameter and thickness you need.

	Thickness			Parallelism
	Ø = 50 mm	Ø = 25 mm	Ø = 12.7 mm	
Fused Silica	≥ 200 µm	≥ 130 µm	≥ 50 µm	< 1 arcsec
YAG	≥ 200 µm	≥ 130 µm	≥ 50 µm	< 1 arcsec
CaF_2	——	≥ 300 µm	≥ 100 µm	< 5 arcsec

WAVEPLATES

LAYERTEC offers customer specific retardation plates made of crystalline quartz. Due to requirements for mechanical stability, a minimum thickness is required depending on diameter. Thus, there is a constraint with respect to the shortest available wavelength for a given wave-plate order. For two frequently requested diameters, examples are given below. Other diameters are available on request.

Order	Ø = 25 mm	Ø = 18 mm	Precision	Parallelism
λ / 2	**Available wavelengths**			
K = 0	——	λ > 1530 nm	± 1 µm	< 1 arcsec
K = 1	λ > 720 nm	λ > 560 nm	± 1 µm	< 1 arcsec
K = 2	λ > 450 nm	λ > 350 nm	± 1 µm	< 1 arcsec
λ / 4	**Available wavelengths**			
K = 1	λ > 860 nm	λ > 660 nm	± 1 µm	< 1 arcsec
K = 2	λ > 500 nm	λ > 380 nm	± 1 µm	< 1 arcsec

CUSTOMIZED PRISMS AND SHAPES

In addition to the mentioned circular substrates, LAYERTEC is able to produce a lot of different shapes. Customized optics are possible besides rectangular substrates, wedges and prisms. Typical examples feature defined holes through the optics. So-called D-cuts and notches can be produced as well.

POLISHING OF CRYSTALS

Besides the high quality optical coatings on crystals (see pages 116, 117), LAYERTEC supports the polishing of various types of crystals such as YAG, KGW, KYW, KTP, LBO or BBO. This polishing technology also enables the careful handling and processing of small crystal sizes or extraordinary forms. Do not hesitate to contact LAYERTEC for your special project.

ULTRASONIC DRILLING

Using ultrasonic drilling, LAYERTEC is able to manufacture holes and other structures in a variety of forms and sizes in glass, ceramics or crystals in a low-tension way. Coated as well as uncoated optics may be processed.

LARGE SCALE OPTICS

LAYERTEC is able to produce plane, spherical and aspherical optics up to a diameter of 600 mm. This also includes interferometers. Measurements for large optics are described on page 22. These optics can be coated using magnetron sputtering and IAD. The main products are large scale laser mirrors. A coating homogeneity of ± 0.5 % was demonstrated which also enables the production of large scale thin film polarizers and other complex coating designs.

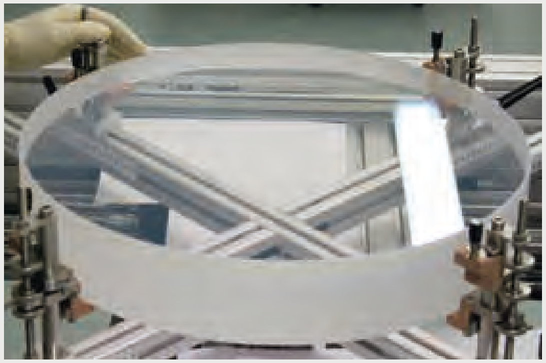


Figure 1: Mirror substrate with a diameter of 500 mm

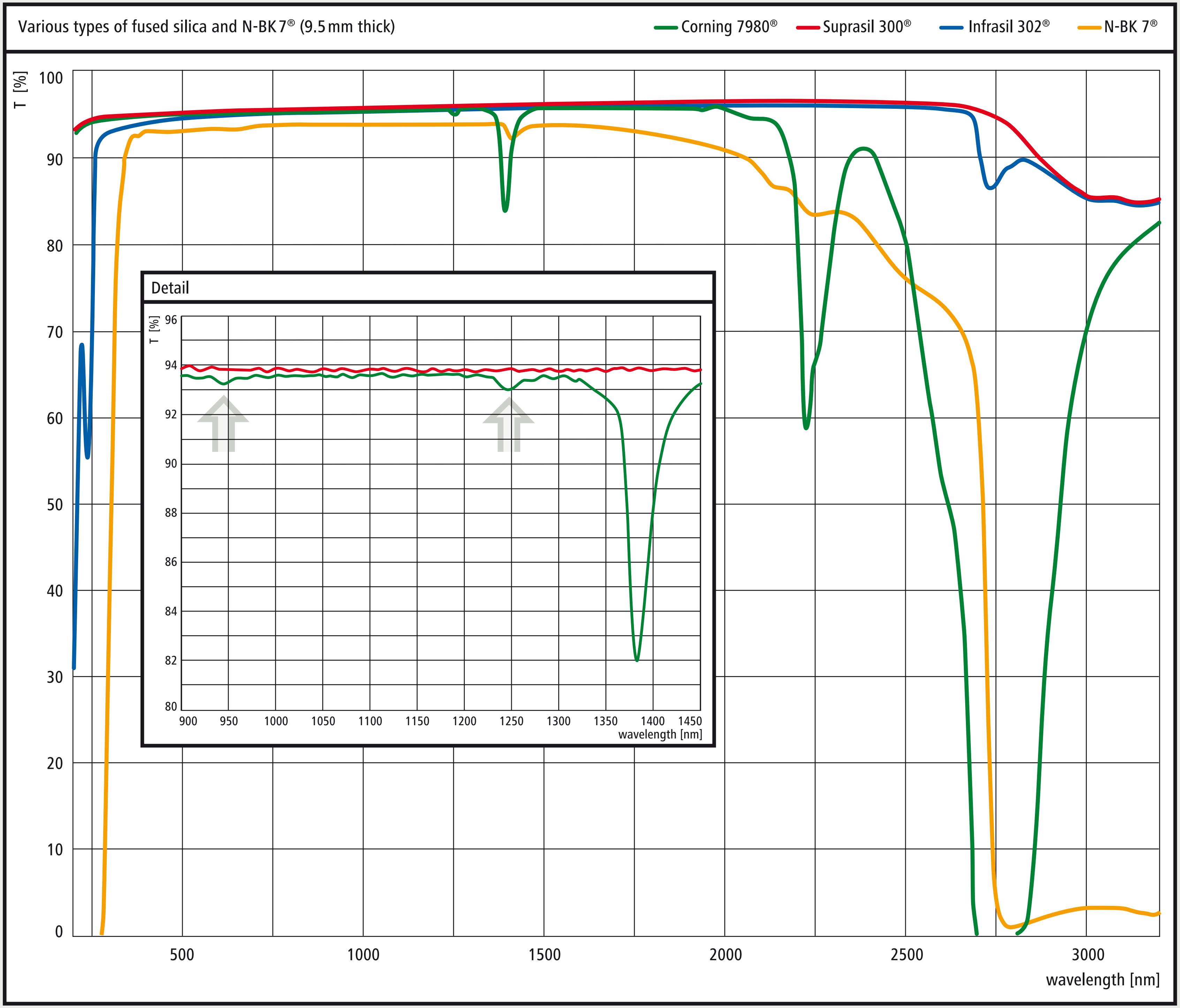
SUBSTRATE MATERIALS FOR UV, VIS AND NIR/IR OPTICS

	YAG (undoped)	Sapphire (C-cut)	BaF_2	CaF_2	Infrasil®1)	Fused silica (UV)	N-BK7®2)	SF10®2)
Wavelength range free of absorption	400 nm – 4 µm	400 nm – 4 µm	400 nm – 10 µm	130 nm – 7 µm	300 nm – 3 µm	190 nm – 2.0 µm3)	400 nm – 1.8 µm	400 nm – 2.0 µm
Refractive index at								
200 nm				1.49516		1.55051		
300 nm				1.45403		1.48779		
500 nm	1.8450	1.775	1.479	1.43648	1.48799	1.46243	1.5214	1.7432
1 µm	1.8197	1.756	1.468	1.42888	1.45042	1.45051	1.5075	1.7039
3 µm	1.7855	1.71	1.461	1.41785	1.41941			
5 µm		1.624	1.451	1.39896				
9 µm			1.408	1.32677				
Absorbing in the 3 µm region	no	no	no	no	yes	yes	yes	yes
Absorbing in the 940 nm region	For high power applications at 940 nm the fused silica types SUPRASIL 300®1) and SUPRASIL 3001/3002®1) are recommend.							
Birefringence	no	yes	no	no4)	no	no	no	no
Thermal expansion coefficient [10^{-6}K] 5)	7	5	19	18	0.5	0.5	7	8
Resistance against temperature gradients and thermal shock	high	high	very low	low	high	high	medium	medium
GDD fs² per mm								
400 nm	240	150	90	68	98	98	120	640
800 nm	97	58	38	28	36	36	45	160
1064 nm	61	29	26	17	16	16	22	100
1500 nm	13	-25	13	1.9	-22	-22	-19	38
2000 nm	-59	-120	-2.4	-21	-100	-100	-99	-36
TOD fs³ per mm								
400 nm	75	47	27	19	30	30	41	500
800 nm	57	42	20	16	27	27	32	100
1064 nm	71	65	22	21	44	44	49	100
1500 nm	140	180	34	46	130	130	140	140
2000 nm	360	530	72	120	450	450	460	350

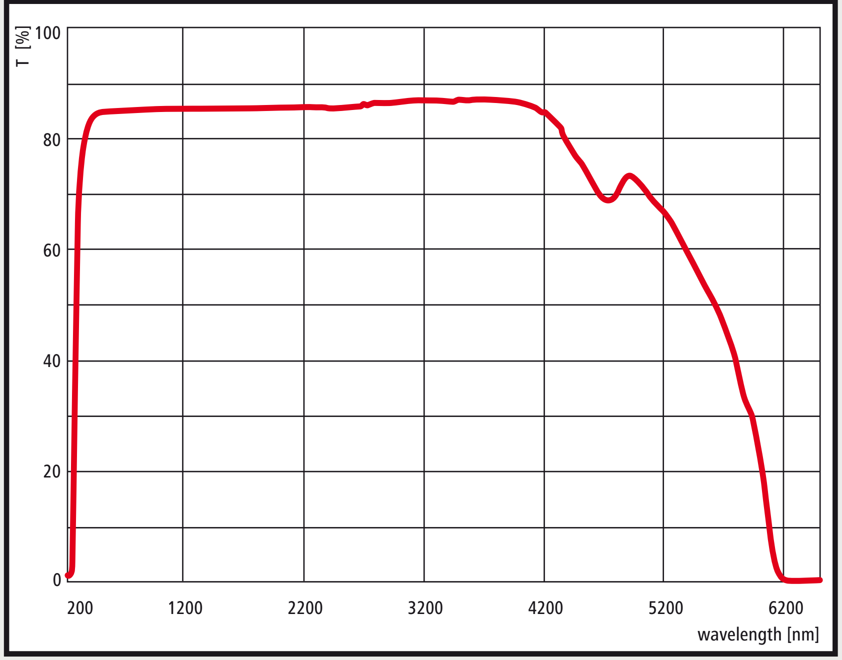
1) Registered trademark of Heraeus Quarzglas GmbH & Co. KG
2) Registered trademark of SCHOTT AG
3) Absorption band within this wavelength range, please see transmittance curve
4) Measurable effects only in the VUV wavelength range
5) The values given here are rounded, because the measurements of different authors in the literature are inconsistent.
Please note that the thermal expansion coefficient of crystals depends also on the crystal orientation.

All values are for informational purposes only. LAYERTEC cannot guarantee the correctness of the values given.

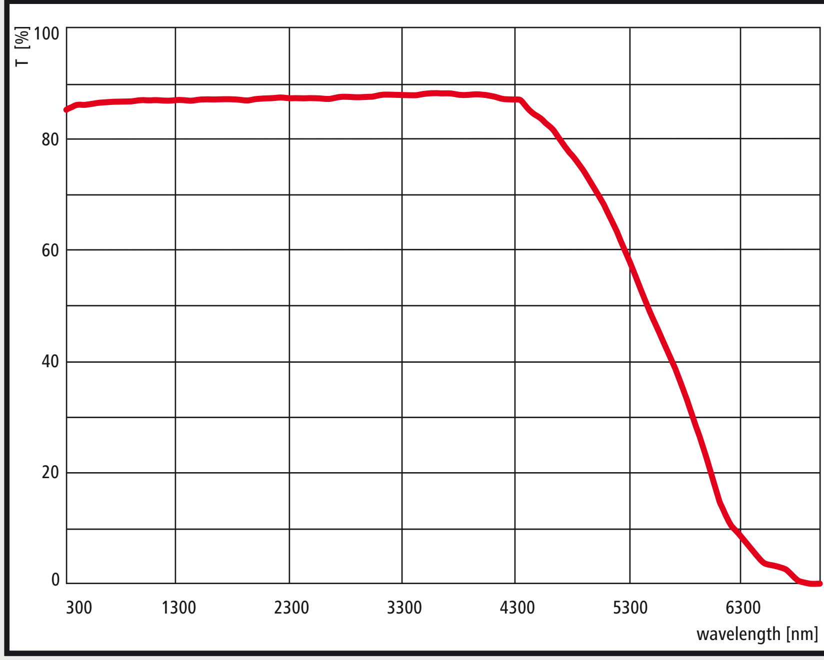
TRANSMITTANCE CURVES



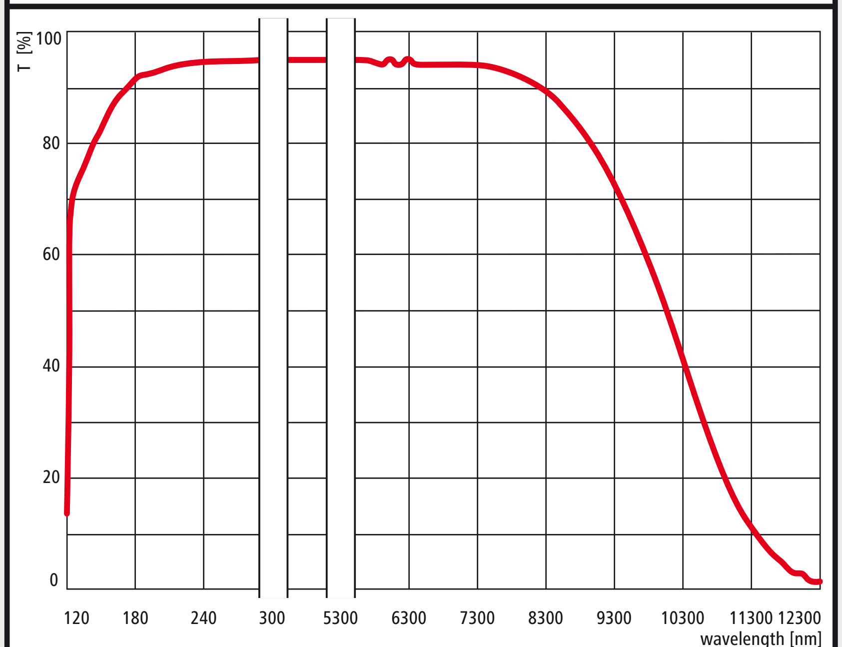
YAG undoped (3 mm thick)



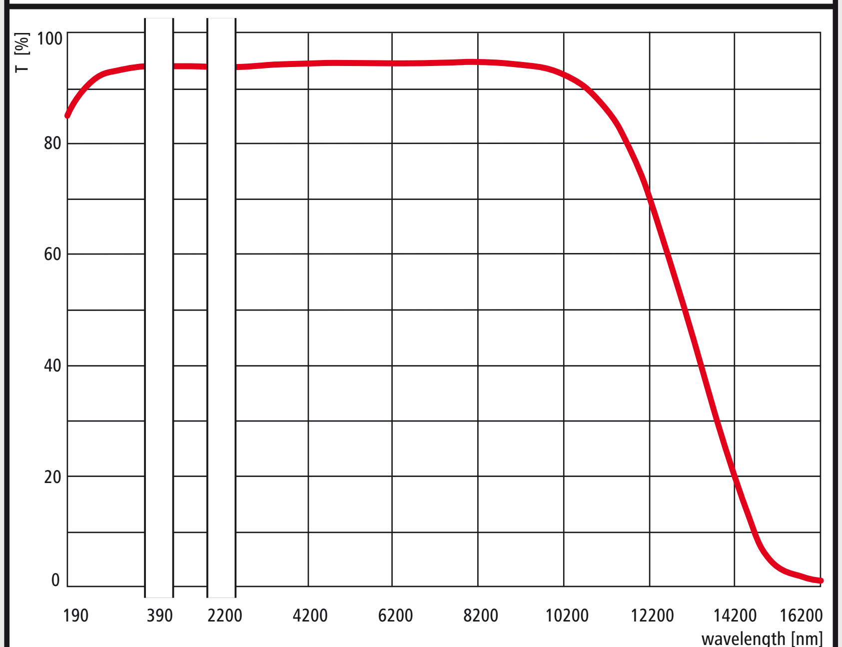
Sapphire (3 mm thick)



Calcium fluoride (3 mm thick)



Barium fluoride (3 mm thick)



MEASUREMENT TOOLS FOR PRECISION OPTICS

DEVIATIONS FROM THE IDEAL SURFACE

Any machined substrate exhibits deviations from its theoretical design. The effect of these deviations on the optical funcionality of the optics can be categorized with respect to the spatial dimension of the deviations.

The inverse length of this spatial dimension – the spatial frequency – is used to mathematically describe the different kinds of deviations. A rough classification of deviations distinguishes between Form (low spatial frequencies), Waviness (mid-spatial frequencies) and Roughness (high spatial frequencies).

Form deviations affect the wavefront of the passing light while leaving the direction of propagation nearly unchanged. They lead to a distortion of the image or a significant alteration of the focal intensity distribution near the optical axis.

Waviness deviations also conserve the total energy of the propagating beam but mainly affect focal regions away from the optical axis. For example, periodical deviations in this frequency band can give rise to the formation of parasitic secondary foci.

Finally, Roughness affects the propagating wavefront on spatially small regions. These disturbances lead to an effective scattering of energy off the direction of the main beam. Thus, there is a widespread intensity background resulting in a reduction of image contrast.

A quantitative distinction of Form, Waviness and Roughness involves different optical and geometrical parameters, mainly the operating wavelength as well as numerical aperture and focal length. Thus, the same surface deviation may lead to a significantly different optical behavior when used in different applications.

SURFACE FORM MEASUREMENT

For the measurement of surface form and regularity, the precision optics facility of LAYERTEC is equipped with laser interferometers and special interferometer setups for plane, spherical and parabolic surfaces. Additionally, a tactile measurement device (Taylor Hobson PGI 1240 Asphere) is available for general aspheric and ground surfaces. Besides the purpose of quality control, surface form measurement is a key function for the zonal polishing technology established at LAYERTEC.

Abbreviations

- **P-V:** The peak-to valley height difference
- **ROC:** Radius of curvature of a spherically curved surface.
- **λ**: measurement wavelength of the laser interferometer (e.g. 546 nm). The P-V value is stated in a fractional amount of λ. The actual value of λ is stated in measurement reports.

For detailed information about the standards concerning surface form measurement please see ISO 10110-5.

Accuracy of interferometric measurements

Without special calibration procedures, the accuracy of an interferometric measurement is only as accurate as the reference surface. Calibration can increase the accuracy by a factor of 2 or more. Furthermore, the precision is influenced by the size of the measured area and in case of a curved surface by the radius of curvature itself. The accuracy values stated as "P-V better than …" in the following articles are guaranteed values. Very often accuracies of λ / 20 or better will be achieved.

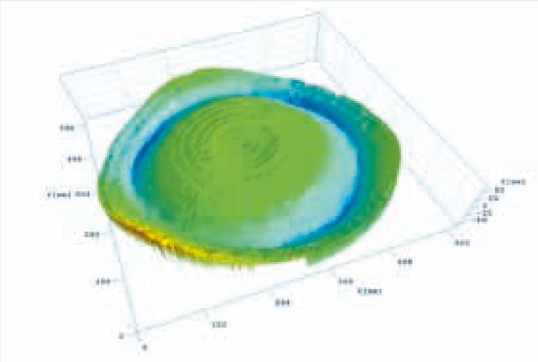


Figure 1: Height map of a flat surface with a diameter of Ø = 520 mm polished and measured at LAYERTEC. The P-V value is λ / 10 over the full aperture (Ø = 500 mm inspection area) after zonal correction.

Standard measurements

In general, the form tolerance of spherical and plane optics with diameters Ø ≤ 100 mm can be measured with an accuracy of P-V better than λ / 10 by using ZYGO Fizeau interferometers. To cover a measurement range of ROC = ± 1200 mm over an aperture of Ø = 100 mm, LAYERTEC uses high precision JenFIZAR Fizeau objectives. In many cases, a higher accuracy up to P-V = λ / 30 is possible. Measurement reports can be provided on request.

Large Radius Test (LRT)

Surfaces with radii of curvature beyond ± 1200 mm are tested with a special Fizeau zoom lens setup called Large Radius Test (LRT). This setup was developed by DIOPTIC GmbH in cooperation with LAYERTEC.
Its operating range is ROC = ± 1000 mm … ± 20.000 mm at working distances lower than 500 mm. The accuracy is guaranteed as P-V = λ / 8 over Ø ≤ 100 mm, but typically it is better than P-V = λ / 15. LRT has the advantages that only one Fizeau-objective is needed to cover a wide range of radii of curvature and that the working distance is kept small. This reduces the influence of disturbing air turbulences during the measurement.

Large aperture interferometry

For laser optics with large dimensions, LAYERTEC uses high performance interferometers. A wavelength-shifting Fizeau interferometer (ADE Phaseshift MiniFIZ

300®) is used for flat surfaces. LAYERTEC has enlarged the measurement aperture of the system with a special stitching setup. The measurement range of the system is:

- P-V up to λ / 50 (633 nm) at Ø ≤ 300 mm with a full aperture measurement
- P-V better than λ / 10 (633 nm) at Ø ≤ 600 mm with a special stitching measurement setup. See Figure 1 for an exemplary measurement on Ø 520 mm.

The interferometric measurements of spherical concave surfaces are carried out using a Twyman-Green interferometer (PhaseCam 5030®; 4D-Technology). This interferometer uses a special technology which allows measurement times in the region of a few milliseconds. Therefore, the interferometer is insensitive to vibrational errors when measuring over long distances up to 20 m between the device and the specimen. The measurement accuracy of the system is P-V better than λ / 10 at Ø ≤ 600 mm with a full aperture measurement (in case of concave surfaces).

SURFACE ROUGHNESS MEASUREMENT

In many applications, scattered light represents a crucial restriction to the proper operation of an optical device. For one thing, scattered light reduces the intensity of the light propagating through the system, leading to optical losses. It also leads to a noise background of light reducing the overall contrast of imaging optics.
The amount of scattered light produced by an optic is mainly determined by its surface roughness. Thus, requirements to the surface roughness are often necessary to guarantee the proper operation of a device.
For a quantitative comparison, the RMS roughness is a widely-used measure to specify optical surfaces. It is defined as the root mean square of the surface height profile z:

$$Rq = \sqrt{\frac{1}{L}\int z^2(x)\,dx}, \quad Sq = \sqrt{\frac{1}{A}\iint z^2(x,y)\,dxdy}$$

Here the letter 'R' indicates line scans according to ISO 4287-1 while the letter 'S' refers to a scan on a two-dimensional base area as described in ISO 25178-2. The scan field size (maximum spatial frequency) as well as the resolution of the measurement setup (minimum spatial frequency) affect the numerical value of Rq and Sq. For that reason, the specification of an RMS roughness value requires the specification of the underlying band of spatial frequencies as well. Often, technical drawings are lacking information on the frequency band and thus become meaningless.

By using the power spectral density (PSD) of a surface, the distribution of the surface roughness with respect to the spatial frequencies becomes obvious. The RMS value of a surface simply follows from integration of the PSD over the given spatial frequency band. Generally, the scattered light of optical surfaces produced for the NIR, VIS and UV spectral range is dominated by spatial frequencies ranging from 0.01 to 10 μm^{-1}.

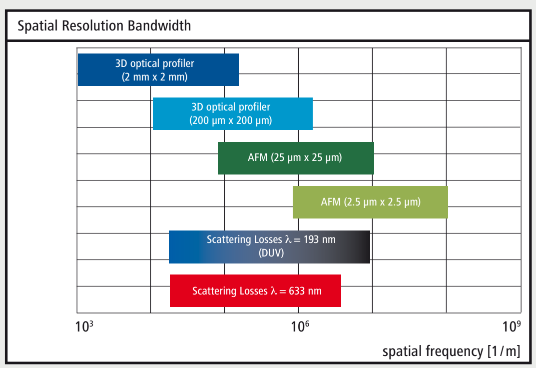


Figure 2: Spatial frequency resolution of AFM and 3D optical surface profiler at LAYERTEC for typical scan sizes. Additionally, the figure shows the spatial frequency ranges which influence the scattering losses in the VIS and DUV spectral range.

At LAYERTEC, a phase shifting optical surface profiler (Sensofar) and a scanning probe microscope (AFM) DI Nanoscope 3100 are used to cover the given frequency band (see fig. 2). The optical profiler covers low spatial frequencies and has an aquisition time of a few seconds. It is used for the general inspection of the polishing process and is able to identify surface defects and inhomogeneities. The AFM addresses high spatial frequencies using scan field sizes of 2.5 x 2.5 µm² and 25 x 25 µm² and has an aquisition time of 10 to 30 minutes. Therefore, it is used primarily for the development of polishing processes. It further serves to monitor the LAYERTEC premium-polishing process and especially optics for UV applications with Sq < 2 Å (spatial bandwidth: 7 - 1200 nm) with respect to quality control. Measurement reports are available on request.

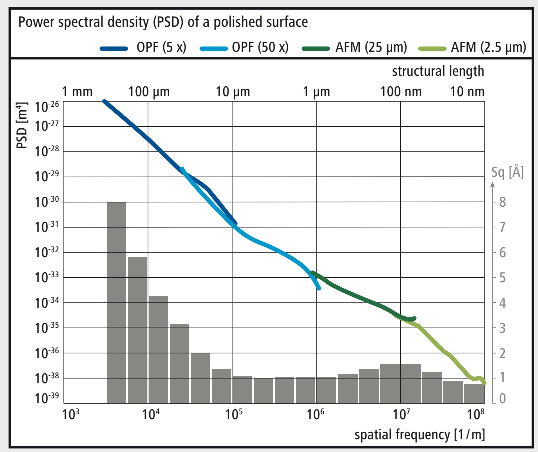
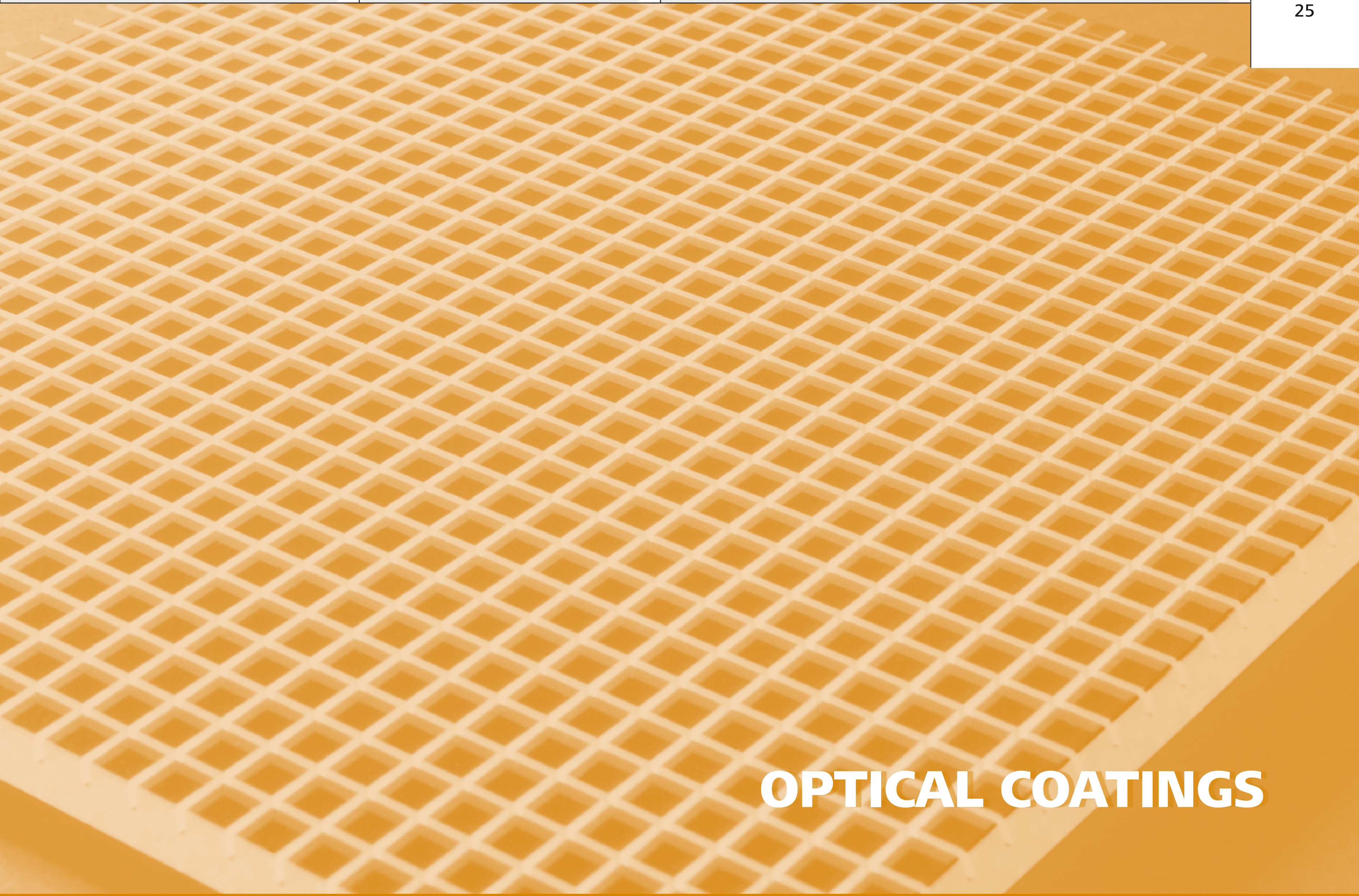


Figure 3: PSD of a LAYERTEC standard polish obtained by combining measurements using AFM and optical profiler. The right axis shows Sq values on a logarithmic grid over spatial frequencies. To obtain the total roughness Sq_{tot} over multiple bars Sq_i, square values have to be added $Sq_{tot}^2 = Sq_1^2 + Sq_2^2 + \dots$

For more information on scattering losses please see: A. Duparré, "Light scattering on thin dielectric films" in "Thin films for optical coatings", eds. R. Hummel and K. Günther, p. 273 – 303, CRC Press, Boca Raton, 1995.



OPTICAL COATINGS

LAYERTEC®
OPTICAL COATINGS · OPTICS

OPTICAL INTERFERENCE COATINGS

The purpose of optical coatings is to change the reflectance of optical surfaces. According to the materials used, metallic and dielectric coatings can be distinguished.

Metallic coatings are used for reflectors and neutral density filters. The achievable reflectance is given by the properties of the metal. Common metals used for optical applications are described on page 31.

Dielectric coatings use optical interference to change the reflectance of the coated surfaces. Another advantage is that the materials used in these coatings show very low absorption. The reflectance of optical surfaces can be varied from approximately zero (antireflection coatings) to nearly 100 % (low loss mirrors with R > 99.999 %) with optical interference coatings. These reflectance values are achieved only for a certain wavelength or a wavelength range.

BASICS

The influence of a single dielectric layer on the reflectance of a surface is schematically shown in fig. 1. An incident beam (a) is split into a transmitted beam (b) and a reflected beam (c) at the air-layer interface. The transmitted beam (b) is again split into a reflected beam (d) and a transmitted beam (e). The reflected beams (c) and (d) can interfere.

In fig. 1 the phase is represented by the shading of the reflected beams. The distance from "light-to-light" or "dark-to-dark" is the wavelength. Depending on the phase difference between the reflected beams, constructive or destructive interference may occur. The reflectance of the interface between the two media depends on the refractive indices of the media, the angle of incidence and the polarization of the light. In general, it is described by the Fresnel equations.

$$R_s = \left(\frac{n_1 \cos\alpha - n_2 \cos\beta}{n_1 \cos\alpha + n_2 \cos\beta}\right)^2$$

$$R_p = \left(\frac{n_2 \cos\alpha - n_1 \cos\beta}{n_2 \cos\alpha + n_1 \cos\beta}\right)^2$$

R_s ... reflectance for s-polarization
R_p ... reflectance for p-polarization
n_1 ... refractive index of medium 1
n_2 ... refractive index of medium 2
α ... angle of incidence (AOI)
β ... angle of refraction (AOR)

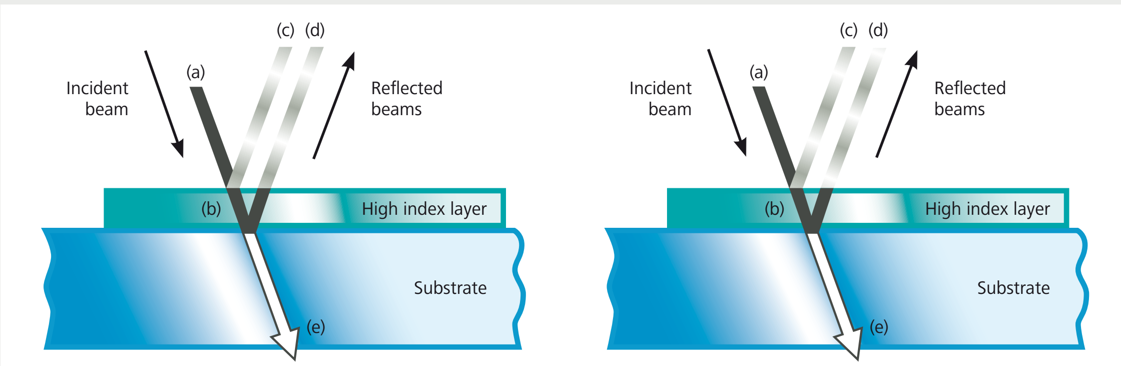


Figure 1: Schematic drawing to explain the interference effect of quarter-wave layers of a high index material and a low index material (after [1])

For normal incidence ($\alpha = ß = 0°$) the formulae can be reduced to the simple term:

$$R = \left(\frac{n_2 - n_1}{n_2 + n_1}\right)^2$$

The phase difference between the beams (c) and (d) is given by the optical thickness nt of the layer (the product of the refractive index n and the geometrical thickness t). Furthermore, a phase jump of π, i.e. one half-wave, has to be taken into account, if light coming from a low index medium is reflected at the interface to a high index medium.

Please refer to the literature cited on page 32 for a detailed explanation of the physics of optical interference coatings. Below are a few unwritten rules to help customers understand the optical properties of the coatings described in this catalog:

- High index layers increase the reflectance of the surface. The maximum reflectance for a given wavelength λ is reached for $nt = \lambda / 4$.
  Only in the case of an optical thickness $nt = \lambda / 2$, the reflectance of the surface does not change for this wavelength λ.
- Low index layers always decrease the reflectance of the surface. The minimum reflectance for a given wavelength λ is reached for $nt = \lambda / 4$.
  Only in the case of an optical thickness $nt = \lambda / 2$, the reflectance of the surface does not change for this wavelength λ.

ANTIREFLECTION COATINGS

- A single low index layer can be used as a simple AR coating. The most common material for this purpose is magnesium fluoride with a refractive index of n = 1.38 in the VIS and NIR. This material reduces the reflectance per surface to R ~ 1.8 % for fused silica and nearly zero for sapphire.

- Single wavelength AR coatings consisting of 2 – 3 layers can be designed for all substrate materials to reduce the reflectance for the given wavelength to nearly zero. These coatings are used especially in laser physics. AR coatings for several wavelengths or for broad wavelength ranges are also possible and consist of 4 – 10 layers.

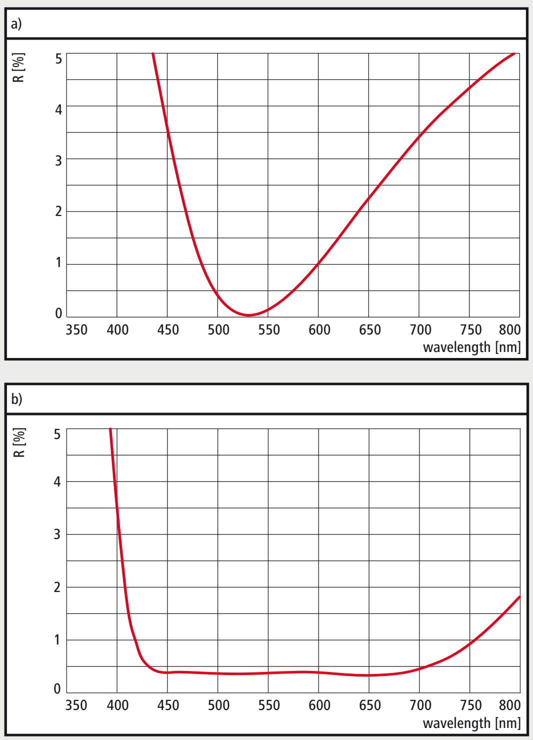


Figure 2: Schematic reflectance spectra:
a) Single wavelength AR coating ("V-coating")
b) Broadband AR coating

MIRRORS AND PARTIAL REFLECTORS

- The most common mirror design is the so-called quarter-wave stack, i.e. a stack of alternating high and low index layers with equal optical thickness of nt = λ / 4 for the desired wavelength. This arrangement results in constructive interference of the reflected beams arising at each interface between the layers. The spectral width of the reflection band and the maximum reflectance for a given number of layer pairs depend on the ratio of the refractive indices of the layer materials. A large refractive index ratio results in a broad reflection band while a narrow reflection band can be produced using materials with a low refractive index ratio.

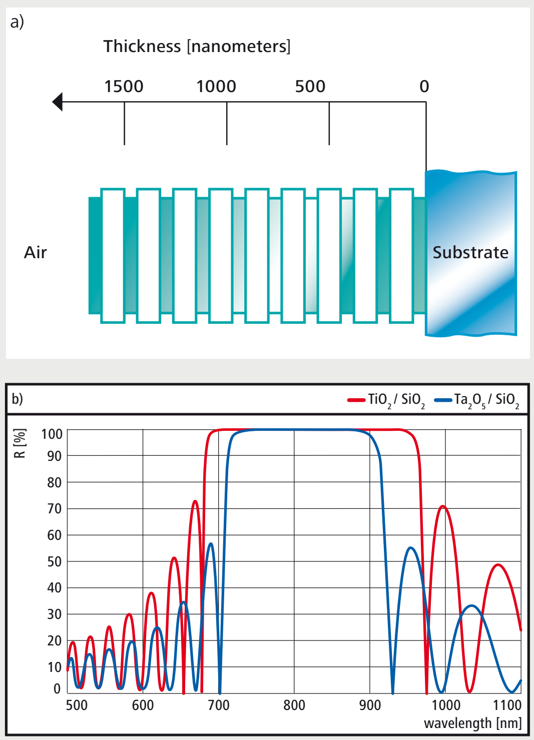


Figure 3: a) Schematic drawing of a quarter-wave stack consisting of layers with equal optical thickness of a high index material (shaded) and a low index material (no shading) (after [1])
b) Reflectance spectra of quarter-wave stacks consisting of 15 pairs of Ta_2O_5 / SiO_2 and TiO_2 / SiO_2

- To visualize the effect of different refractive index ratios, figure 3b compares the reflectance spectra of quarter-wave stacks consisting of 15 pairs of Ta_2O_5 / SiO_2 and TiO_2 / SiO_2 for 800 nm (n1 / n2 = 2.1 / 1.46 and 2.35 / 1.46, respectively).

- The theoretical reflectance will approach R = 100 % with an increasing number of layer pairs, assuming that ideal coatings have zero absorption and scattering losses. Partial reflectors with several discrete reflectance values between R = 0 % and R = 100 % can be manufactured using only a small number of layer pairs (see fig. 4). Adding non-quarter-wave layers to a stack optimizes the reflectance to any desired value.

- Figure 4 also shows that an increasing number of layer pairs results in steeper edges of the reflectance band. This is especially important for edge filters, i.e. mirrors with low reflectance side bands. Extremely steep edges require a large number of layer pairs which also results in a very high reflectance. Extremely high reflectance values require very low optical losses. This can be achieved by using sputtering techniques.

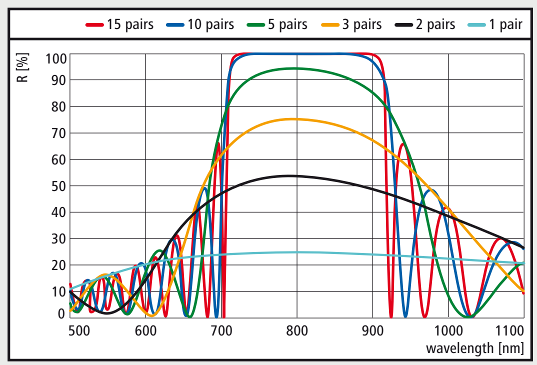


Figure 4: Calculated reflectance of quarter-wave stacks consisting of 1, 2, 3, 5, 10 and 15 layer pairs of Ta_2O_5 / SiO_2 for 800 nm

OPTICAL LOSSES

- Light, which impinges on an optical component, is either reflected, transmitted, absorbed or scattered. From this basic point of view, the energy balance can be written in the simple equation
  $R + T + A + S = 1$
  with R … Reflectance,
  T … Transmittance,
  A … Absorption and
  S … Scattering

- In laser physics and precision optics absorption and scattering are summarized as optical losses because the absorbed and scattered part of the incoming light can no longer be used as a carrier of information or as an optical tool. In practice, the reflectance which can be achieved depends on the absorption and scattering losses of the optics.

- Scattering losses increase drastically with decreasing wavelength, which can be described by the Mie theory (scattering by particles with diameters in the order of λ, $S \sim 1/\lambda^2$) and Rayleigh theory (scattering by particles with diameters $< \lambda$, $S \sim 1/\lambda^4$). Depending on the surface and bulk structure, Mie and Rayleigh scattering occur simultaneously. Scattering losses depend critically on the microstructure of the coatings and as such on the coating technology used. Usually, coatings produced by evaporation techniques show significantly higher scattering losses than coatings produced by magnetron sputtering or ion beam sputtering. The strong dependence of the scattering losses on the wavelength is the reason why scattering losses are a huge problem in the UV range while they are less important in the NIR and beyond.

- Absorption in optical coatings and substrates is mainly determined by the band structure of the materials. Common oxide materials show band gaps of 3 – 7 eV which correspond to absorption edges in the NUV and DUV. Fluorides have band gaps of 9 – 10 eV resulting in absorption edges in the VUV spectral range (for more information please see page 20 and following). Some materials also show absorption bands in addition to the basic absorption edge as seen in the absorption band of Si-O-H bonds in fused silica around 2.7 µm.
  Defects in the layers form absorbing states in the band gap of the materials. These defects may result from contaminations or from the formation of non-stoichiometric compounds. Optical coatings must be optimized with respect to low contamination levels and good stoichiometry. This kind of absorption losses also increases with decreasing wavelength.

Wavelength range	Materials	Coating technology	Reflectance
~ 200 nm	fluorides	evaporation	> 96.00 %
~ 250 nm	oxides	IAD	> 99.00 %
		sputtering	> 99.70 %
~ 300 nm	oxides	IAD	> 99.50 %
		sputtering	> 99.90 %
~ 350 nm	oxides	IAD	> 99.80 %
		sputtering	> 99.95 %
VIS	oxides	IAD	> 99.90 %
		sputtering	> 99.95 %
Low loss mirrors VIS	oxides	sputtering	> 99.99 %
NIR	oxides	IAD	> 99.90 %
		sputtering	> 99.98 %
Low loss mirrors NIR	oxides	sputtering	> 99.998 %

Table 1: Reflectance of HR mirrors in different spectral regions (for AOI = 0°)

- The amount of all kinds of losses depends on the thickness of the layer system. Each layer pair increases the theoretical reflectance; however, in practice, it also increases the optical losses. There is an optimum number of layer pairs which generates the maximum reflectance, especially for evaporated coatings with relatively large scattering losses.

STRESS

- Another effect which limits the number of layers is the stress in the coating. This stress results from the structure of the layers but also from different thermal expansion coefficients of substrate and coating. Mechanical stress may deform the substrate but it may also result in cracks in the coating or in a reduced adherence of the coating.

- Stress can be limited by material selection and the optimization of process temperature, deposition rate and, in case of ion assisted and sputtering processes, ion energy and ion flux.

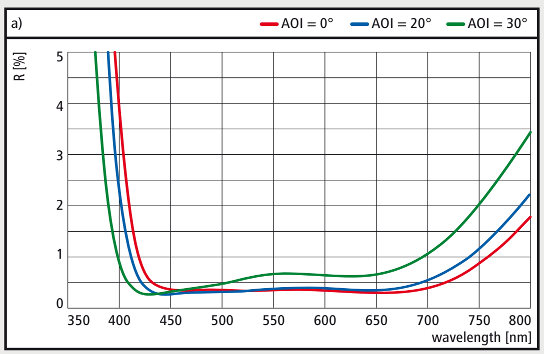
ANGLE SHIFT

- A special feature of interference coatings is the angle shift. It means that features shift to shorter wavelengths with increasing angle of incidence. Turning an optical component from AOI = 0° to AOI = 45° results in a shift of the features by about 10 %. The angle of incidence must be known to design any optical coating.

- Moreover, polarization effects must be taken into account at non-normal incidence (see below).

- Please note that the angle of incidence varies naturally if curved surfaces are used. Lenses in an optical system always have a range of acceptance angles which is determined by the shape of the lens and by the convergence or divergence of the beam. If these features are known, AR coatings can be improved significantly. Besides the shift, broadband AR coatings often show an increased reflectance at AOI ≥ 30° (see fig. 5a).

- The angle shift offers the possibility of angle adjustment of an interference coating. This is especially useful in the case of filters and thin film polarizers. These optics show extremely narrow spectral ranges of optimum performance. It may decrease the output and increase the costs drastically if the specifications for wavelength and AOI are fixed. Angle adjustment (see fig. 5b) is the best way to optimize performance and to minimize costs.



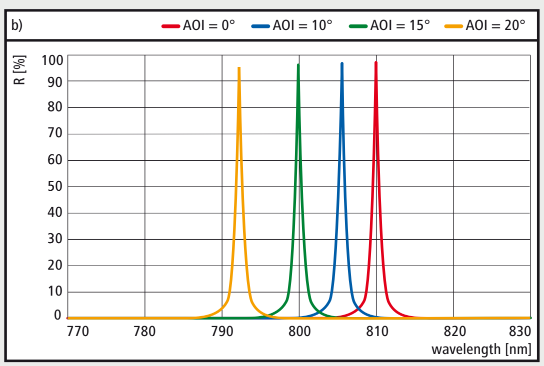


Figure 5: a) Angle shift and change of reflectance of a broadband AR coating (unpolarized light)
b) Angle tuning of a narrow band filter for 800 nm

POLARIZATION EFFECTS

- Besides angle shift, polarization effects appear at non-normal incidence. For optical interference coatings, it is sufficient to calculate the reflection coefficients for s- and p-polarized light. The reflectance of unpolarized light is calculated as the average of Rs and Rp.

- To explain the meaning of the terms "s-polarization" and "p-polarization", a reference plane must be determined (see lower part of fig. 6). This plane is defined by the incident beam and by the surface normal of the optic. "S-polarized light" is that part of the light which oscillates perpendicularly to this reference plane ("s" comes from the German word "senkrecht" = perpendicular). "P-polarized light" is the part which oscillates parallel to the reference plane. Light waves with a plane of oscillation inclined to these directions, are split into p-polarized and s-polarized parts.

- The upper part of fig. 6 shows the reflectance of a glass surface vs. AOI for s- and p-polarized light. The reflectance for s-polarized light increases with increasing angle of incidence. The reflectance for p-polarized light decreases initially, with R reaching zero percent at the "Brewster angle" and then increasing again as the angle of incidence extends beyond the Brewster angle. In principle, the same applies for dielectric mirrors. For AOI ≠ 0°, the reflectance for s-polarized light is higher and the reflection band is broader than for p-polarized light.

- In case of edge filters, where one of the edges of the reflectance band is used to separate wavelength regions of high reflectance and high transmittance, non-normal incidence results in a separation of the edges for s- and p-polarized light as the polarizations experience different angle shifts. Thus, for unpolarized light the edge is broadened considerably.

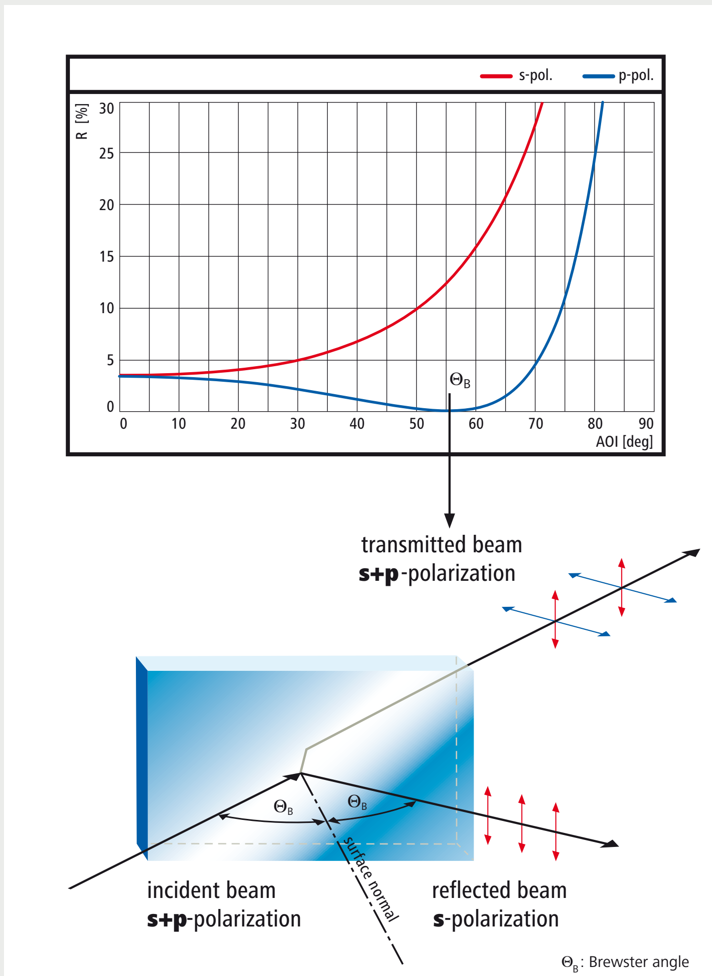


Figure 6: Definition of the terms "s-polarized light" and "p-polarized light" and reflectance of an uncoated glass surface vs. angle of incidence for s- and p-polarized light

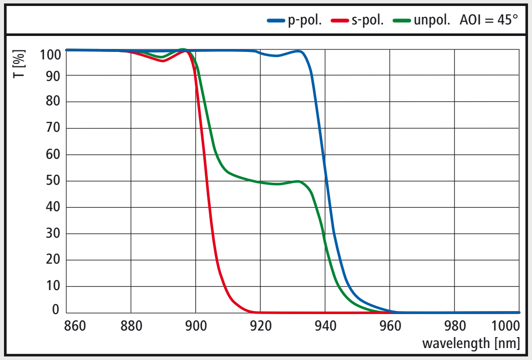


Figure 7: Polarization splitting of an edge filter. Please note that the edges of the reflectance bands are steep for s- as well as for p-polarization even at AOI = 45°, but they are located at different wavelengths. As a result, the edge of the reflectance band for unpolarized light is considerably broadened

DOCUMENTATION OF COATING PERFORMANCE AT LAYERTEC

LAYERTEC includes a data sheet of transmittance and /or reflectance for each delivered optical component. The standard procedure is to measure the transmittance of the optics at AOI = 0°. A mathematical fit of the theoretical design to this measured spectrum is carried out and the reflectance at the desired AOI is calculated from said fit.

Sputtered optical coatings for the VIS and NIR exhibit extremely low scattering and absorption losses (both in the order of some 10^{-5}). This has been confirmed in direct measurements of scattering and absorption as well as via highly accurate reflectance measurements (e.g. by Cavity Ring-Down spectroscopy). The reflectance of sputtered mirrors can be approximated by measuring the transmittance T and using the simple formula

$$R = 100\ \% - T.$$

due to very small the optical losses. In a normal spectrophotometer, the transmittance can be measured with an accuracy of about 0.1 ... 0.2 % (depending on the absolute value); whereas reflectance measurements in spectrophotometers mostly have errors of about 0.5 %. Thus, determining the reflectance of sputtered coatings in the VIS and NIR via transmittance measurements is much more accurate than direct reflectance measurements. Please note that this method can only be applied because the optical losses are very small (which is one of the advantages of sputtered coatings). The method is also used for evaporated coatings in the NIR, VIS and near UV spectral range where the optical losses are only about 1-3 x 10^{-3} and can be included into the reflectance calculation.

In the deep UV range, the coatings usually show scattering losses in the order of 10^{-3}...10^{-2}, depending on the wavelength. That is why, for example, fluoride coatings for wavelengths < 220 nm are delivered with direct reflectance measurements. Direct reflectance measurements are also necessary for low-loss mirrors. LAYERTEC has a Cavity Ring-Down setup for spectrally resolved measurements in the wavelength range between 210 – 1800 nm. The data sheets are available and can also be downloaded from the LAYERTEC website. Fig. 8 shows the download window for data sheets. To avoid mistakes, registration is required for batch# and part#.

DIELECTRIC BROADBAND COATINGS

- The first step to broadband mirrors and output couplers is to use coating materials with a large refractive index ratio. The bandwidth can be further increased by using special coating designs i.e. by using non-quarter-wave layers.
- The easiest way is to combine two or more quarter-wave stacks with overlapping reflectance bands. However, this results in an increase of optical losses at the wavelengths where the bands overlap. Moreover, multiple stack designs cannot be used for femtosecond lasers because they induce pulse distortion.
- LAYERTEC offers special all-dielectric broadband components for femtosecond-lasers up to a bandwidth of one octave, i.e. 550 nm – 1100 nm (see pages 84 – 85).
- An even larger bandwidth can be achieved using metals. However, the natural reflectance of metals is limited to 92 – 99 % (see the following sections) but it can be increased by dielectric coatings. For such ultra-broadband metal-dielectric mirrors see page 109 and 120 – 125.

Figure 8: Download measurement report from the LAYERTEC website

METALLIC COATINGS

Metals are the most common materials for mirror fabrication. Polished metals, especially gold, copper and bronze, were used as mirrors in the ancient world. In the middle ages, mirrors with relatively constant reflectance in the visible spectral range were fabricated using tin foils and mercury which were put on glass. The era of thin film metal coatings on glass began in the 19th century when Justus von Liebig discovered that thin films of silver can be manufactured using silver nitrate and aldehyde.

For applications in precision optics and laser physics, mirrors are produced by using the evaporation or the sputtering technique. LAYERTEC uses magnetron sputtering for manufacturing metallic coatings with extremely low scattering losses. Transparent, i.e. very thin, metal coatings can be produced with high accuracy. For detailed information about metallic mirrors and neutral density filters please see pages 86 – 87 and 120 – 125.
Fig. 9 gives an overview about the reflectance of the most common metals.

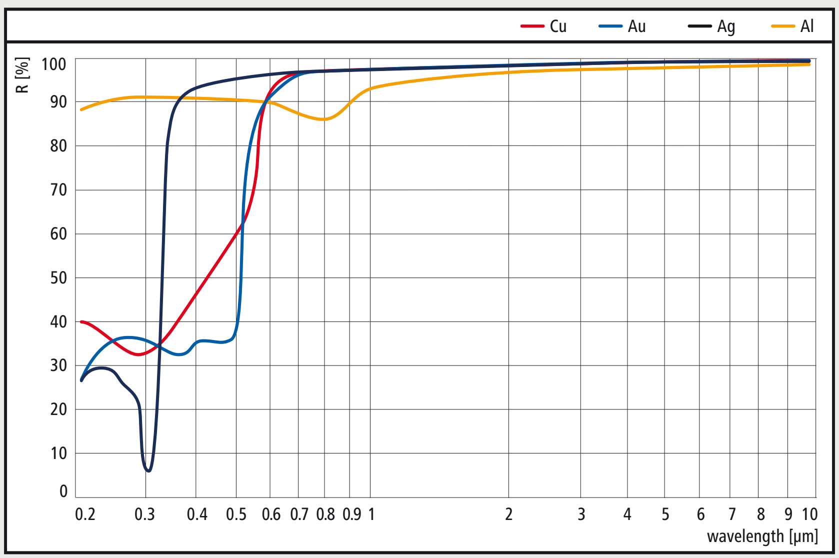


Figure 9: Reflectance of several metals versus wavelength (taken from [2])

In the following, we give some advice about the use of these metals and the role of protective coatings.

SILVER

- Highest reflectance in the VIS and NIR.
- LAYERTEC produces protective layers by magnetron sputtering. These layers with very high packing density make silver mirrors as stable as mirrors of other metals (e.g. aluminum). In normal atmosphere lifetimes of 10 years were demonstrated.
- The use of protective layers is mandatory. Unprotected silver is chemically unstable and soft.
- Please see separate data sheets on pages 86 – 87 and 120 – 121.

GOLD

- Similar reflectance as silver in the NIR.
- Chemically stable, but soft.
- Protective layers are necessary to allow cleaning of gold mirrors.
- LAYERTEC recommends using protected silver mirrors instead of protected gold. The sputtered protective layers overcome the insufficiencies of silver. The broader wavelength range, the slightly higher reflectance and the favorable price also make silver the better option.
- See separate data sheet on page 125.

ALUMINUM

- Relatively high and constant reflectance in the VIS and NIR.
- Highest reflectance in the UV.
- Surface oxide layer absorbs in the deep UV.
- A protective layer is recommended because aluminum is soft.
- Please see separate data sheet on pages 122 – 123.

CHROMIUM

- Medium reflectance in the VIS and NIR (R ~ 40 % – 80 % depending on the coating process).
- Hard, can be used without protective layer.
- Good adhesive layer for gold and other metals on glass substrates.

PROTECTIVE LAYERS

- Enable cleaning of optics and improve chemical stability.
- Influence the reflectance of the metal.
- Even very thin sputtered layers can be used for chemical protection of the metal because of the high atomic density of the layers. Such layers show minimal influence on the VIS and NIR reflectance of the metal.
- Mechanical protection to enable cleaning of optics can only be achieved by relatively thick protective layer systems.
- Optimization of the protective layer system for the wavelength of interest is particularly necessary in the UV.

METAL-DIELECTRIC COATINGS

METAL-DIELECTRIC COATINGS

In general, all layer systems consisting of metals and dielectric materials can be called “metal dielectric coatings”. The most familiar ones are metal-dielectric filters consisting of transparent metal layers which are separated by a dielectric layer. These filters are characterized by extremely broad blocking ranges which result from reflectance and absorption of the metallic layers. The spectral position of the transmittance band is determined by the optical thickness of the dielectric spacer layer.

Moreover, metal-dielectric reflectors can be used for a variety of applications in optics and laser physics. Metals and metallic coatings show an extremely broadband natural reflectance which is restricted to about 90 % in the UV spectral range (aluminum), 96 % in the VIS (silver) and 99 % in the NIR (gold and silver). Most of the metals must be protected by dielectric coatings to overcome limitations of chemical (silver) or mechanical stability (aluminum, silver, gold). Almost all metallic mirrors are metal-dielectric coatings. The protective coatings always influence the reflectance of the metals. Single dielectric layers of any thickness lower the reflectance in most parts of the spectrum. Multilayer coatings on metals can increase the reflectance of the metallic coating. The bandwidth of enhanced reflectance can also be optimized for extremely broad spectral ranges as can be seen in fig. 10. For more examples please see pages 86 – 87, 108 – 109 and 120 – 123.

Literature:

[1] P. W. Baumeister "Optical coating technology", SPIE press monograph, PM 137, Washington 2004

[2] H. A. Macleod "Thin film optical filters", A. Hilger, Bristol, 1986

[3] A. J. Thelen "Design of optical interference coatings", Mc Graw Hill, New York 1989

[4] N. Kaiser, H.K.Pulker (eds.) "Optical interference coatings", Springer Verlag Berlin Heidelberg, 2003

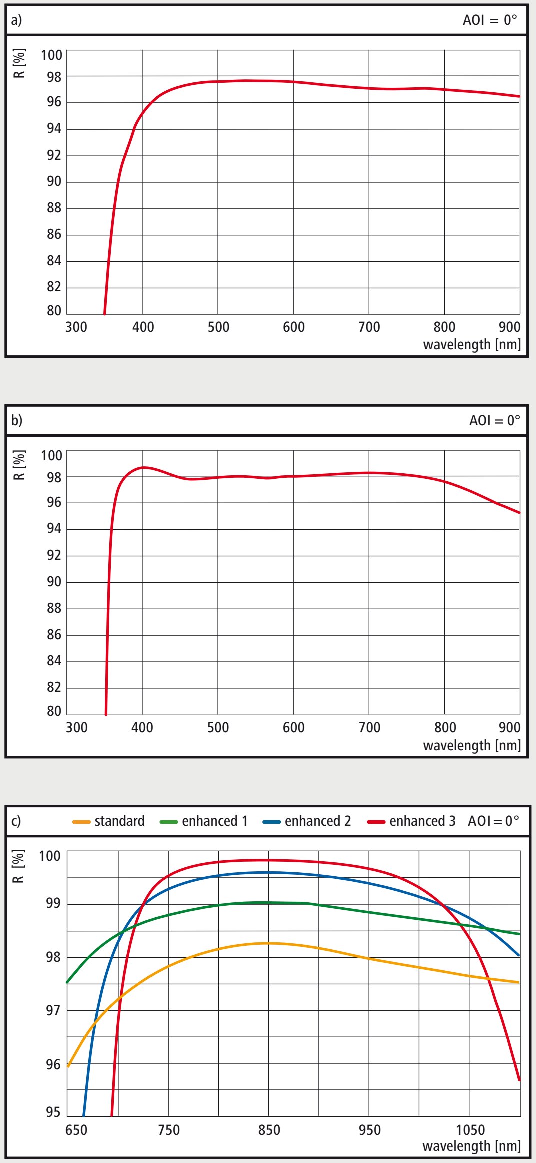


Figure 10: Reflectance spectra of silver mirrors with different top coatings
a) Protected silver mirror
b) Metal-dielectric mirror
Optimized for high reflectance in the VIS for use in astronomical applications
c) Different designs for enhanced reflectance around 850 nm (AOI = 0°) for use in fs lasers

Figure 11: Silver mirrors with D-cut geometry

Figure12:Off-axis parabola coated with a metal-dielectric silver mirror

Figure 13: Scanning mirrors with customized shape coated with a metal-dielectric silver mirror

MEASUREMENT TOOLS FOR COATINGS

SPECTROPHOTOMETRY

Standard spectrophotometric measurements in the wavelength range λ = 190 nm – 3200 nm are carried out with commercial spectrophotometers

- PERKIN ELMER Lambda 1050®
- PERKIN ELMER Lambda 950®
- PERKIN ELMER Lambda 750®
- PERKIN ELMER Lambda 19®
- ANALYTIK JENA specord 250 plus®.

For measurements beyond this wavelength range, LAYERTEC is equipped with an FTIR spectrometer (λ = 1 µm – 20 µm) and a VUV spectrophotometer (λ = 120 nm – 300 nm). Please note that the absolute accuracy of spectrophotometric measurement amounts to 0.2 % ... 0.4 % over the full scale measurement range R, T = 0 % ... 100 %. For measurements with higher precision, a self-constructed setup in the limited range T = 0.1 % ... 0.0001 % with an accuracy up to 0.2 ppm is available.

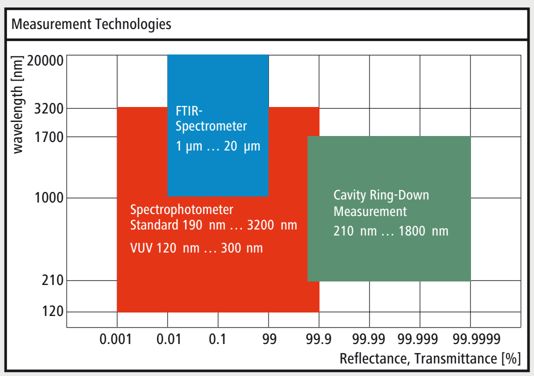


Figure 1: Measurement technologies and their range for reflectance and transmittance measurements at LAYERTEC

CAVITY RING-DOWN (CRD) MEASUREMENT

High reflectance and transmittance values in the order of R, T = 99.5 % ... 99.9999 % are determined by Cavity Ring-Down Time measurements. This method is an absolute measurement procedure with high accuracy, e.g. R = 99.995 % ± 0.001 %.

LAYERTEC operates various CRD systems which were developed in cooperation with research institutes and universities. A schematic representation of the CRD method is shown in fig. 2.

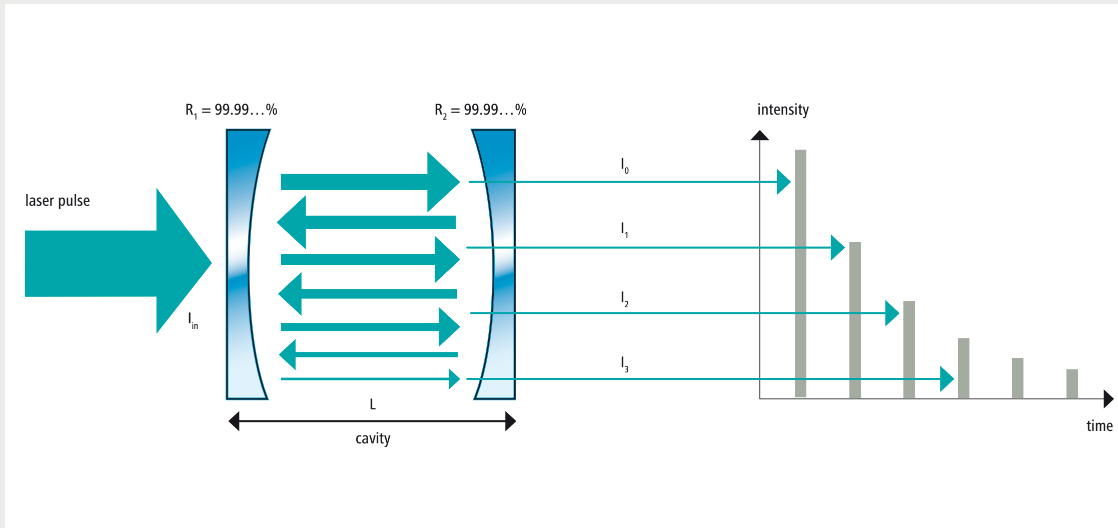


Figure 2: Schematic representation of the CRD method

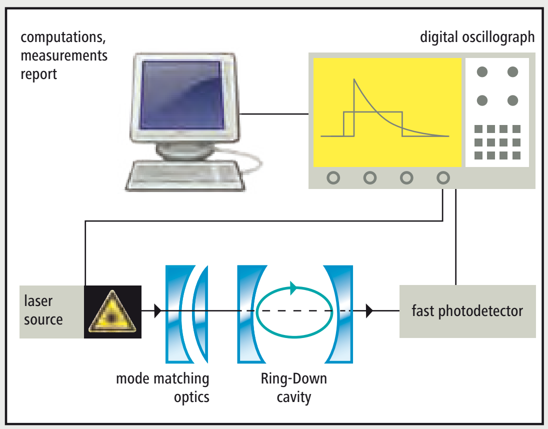


Figure 3: Schematic representation of a Cavity Ring-Down setup

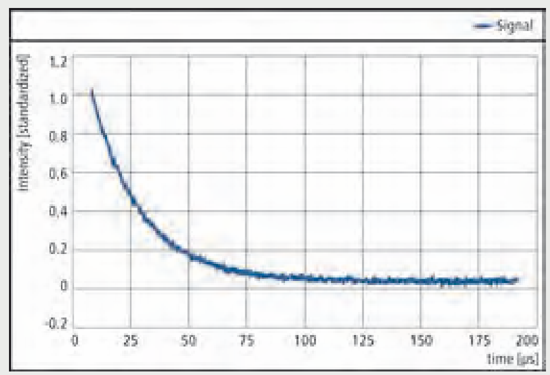


Figure 4: Exemplary mono-exponential CRD-curve of a highly reflecting mirror pair for 450 nm with R = 99.995 % measured using a resonator length L = 228 mm

WORKING PRINCIPLE

A laser pulse is coupled into an optical cavity consisting of two highly reflecting mirrors. The intensity of the light is measured behind the cavity. At the beginning, the intensity increases during the pulse duration. Then it decreases exponentially with the time constant τ according to

$$I_\tau = I_0 \exp\left(-\frac{t}{\tau}\right) \qquad (1)$$

with

$$\tau = \frac{L}{c\,(1-RM)} \qquad (2)$$

where **c** is the speed of light and **L** is the cavity length. **RM** is the geometric mean of the mirror reflectance and can be derived from the measurement of the time constant by

$$RM = \sqrt{R_1 R_2} = 1 - \frac{L}{c\tau} \qquad (3)$$

The accuracy of the measurement depends on the accuracy of the time measurement and the measurement of the cavity length. Please note that errors of beam adjustment will always lower the decay time and/or will cause multi-exponential Ring-Down curves. In case of a single-exponential decay (fig. 4), stochastic errors cannot result in overstated reflectance values. Compared to a reflectance measurement in a spectrophotometer, CRD has two main advantages:

- It is applicable for very high reflectance and transmittance values when using an enhanced measurement setup.
- It is impossible to get measurement values which are higher than the real ones.

The reflectance of single mirrors can be derived from pairs of measurements of a triplet of mirrors with R1, R2 and R3 being the reflectance values of the mirrors 1, 2 and 3, respectively, and RM12, RM23 and RM13 being the measured geometric means of the reflectance for the pairs of mirrors with the corresponding numbers. Three measurements of mirror pairs provide:

$$RM_{12} = \sqrt{R_1 R_2} \qquad RM_{23} = \sqrt{R_2 R_3} \qquad RM_{13} = \sqrt{R_1 R_3} \qquad (4)$$

Solving this system of equations the mirror reflectance can be calculated by:

$$R_1 = \frac{RM_{12}\, RM_{13}}{RM_{23}} \qquad R_2 = \frac{RM_{23}\, RM_{12}}{RM_{13}} \qquad R_3 = \frac{RM_{13}\, RM_{23}}{RM_{12}} \qquad (5)$$

In practice, this method is often used to determine the reflectance of a set of reference mirrors. Knowing the reflectance of a reference mirror, the reflectance of a specimen mirror can directly be derived using equation (3).

BROADBAND CAVITY RING-DOWN SETUP AND APPLICATIONS

LAYERTEC has used CRD for the qualification of low loss mirrors for some years. Initially, there was the limitation that only discrete wavelengths, either generated by solid state lasers or diode lasers, could be used. The increasing demands concerning the optical properties of broadband mirrors required a measurement system for a spectral range over several hundreds of nanometers with a very high accuracy for measuring high reflectance values. So LAYERTEC has developed a novel spectrally broadband Cavity Ring-Down Time measurement system in cooperation with the Leibniz-Institute of Photonic Technology (IPHT) Jena e.V.*.

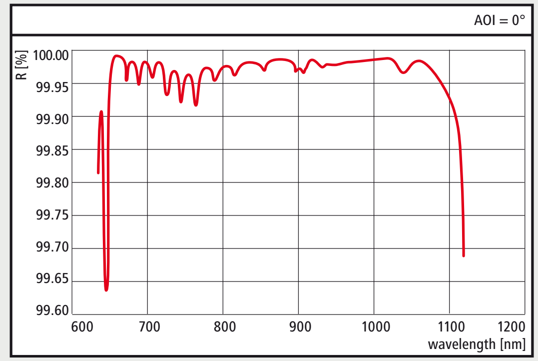


Figure 5: Reflectance spectrum of a negative dispersive broadband mirror for the wavelength region 650 – 1100 nm with R > 99.9 %. The measurement was performed by using an optical cavity consisting of 2 identical mirrors.

An optical parametric oscillator (OPO), which is pumped by the third harmonic of a Nd:YAG laser, is used as a light source. The use of harmonic conversion extends the tuning range towards the ultraviolet region and provides a measurement range from 220 – 1800 nm without gaps. In this measurement setup, photomultipliers and avalanche diodes are used as detectors. The Ring-Down cavity can consist of two or three cavity mirrors. A two mirror cavity is used for reflectance measurements at 0° angle of incidence (Fig. 5 shows such a measurement).

In contrast, a three mirror cavity setup is used for non-zero angle of incidence measurements with two mirrors mounted on precision rotary stages. This setup can be used for wavelength scans at a constant angle or for angle resolved measurements at a constant wavelength (see fig. 6). If the reflectance of two mirrors is known, the reflectance of the third mirror can be calculated. If the incidence of light is not perpendicular to the sample, the linear polarization of the OPO output beam can be rotated to set up perpendicular (s-) or parallel (p-) polarized light with respect to the sample over the entire spectral measurement range.

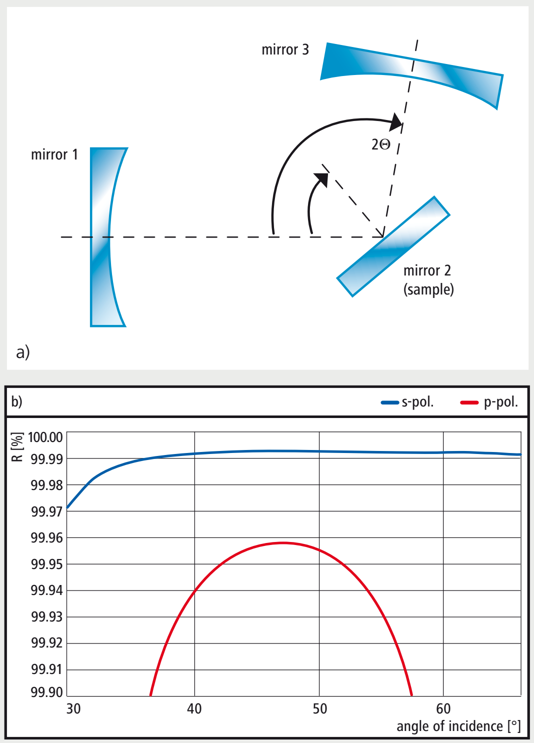


Figure 6: a) Schematic representation of a three mirror cavity ("V-cavity")
b) CRD reflectance measurement of a turning mirror for 1064 nm with variable angle of incidence, but with fixed wavelength of 1064 nm.
A V-shaped CRD cavity is used for the measurement. To analyze the polarization dependency of the mirror reflectance exactly, the measurement was performed at parallel (p-pol.) and perpendicular (s-pol.) polarization with respect to the sample (mirror 2).

Furthermore, the system can be used for the measurement of high transmittance values T > 99.5 %. Therefore, the transmittance sample is placed between both cavity mirrors. As the sample is an additional optical loss for the cavity, the transmittance value can be calculated if the reflectance of the cavity mirrors is known. For measurements at a defined angle of incidence, the sample can be tilted in the range of 0° – 75° with respect to the optical axis of the cavity (fig. 7). Wavelength resolved measurements as well as angle resolved measurements are possible. The latter is very useful for the determination of the optimum angle for thin film polarizers (TFPs).

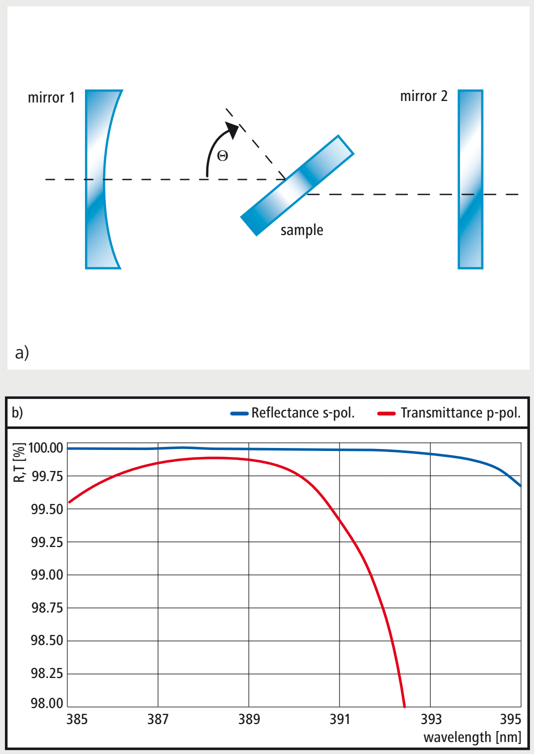


Figure 7: a) Schematic representation of a cavity for transmittance measurement
b) CRD measurement of a thin film polarizer for 390 nm: blue curve - Rs (V-cavity), red curve - Tp (two mirror cavity)

Measurements and reports can be provided on request. The broadband setup permanently undergoes further development. The measurement capabilities and the performance increase steadily.

* S. Schippel, P. Schmitz, P. Zimmermann, T. Bachmann, R. Eschner, C.Hülsen, B. Rudolph und H. Heyer: Optische Beschichtungen mit geringsten Verlusten im UV-VIS-NIR-Bereich, Tagungsband Thüringer Grenz- und Oberflächentage und Thüringer Kolloquium "Dünne Schichten in der Optik" 7.– 9. September 2010, Gera; S. 268 – 282

LASER INDUCED DAMAGE THRESHOLD (LIDT)

Damage in cw and ns laser optics is mainly related to thermal effects such as increased absorption – either due to the intrinsic absorption of the coating materials or absorption by defects – or poor thermal conductivity and low melting temperatures of the coatings. High power coatings require control of the intrinsic properties of the coating materials and the reduction of defects in the layers. Laser damage of picosecond and femtosecond laser optics is mainly caused by field strength effects. Thus, high-power coatings for these lasers require materials with large band gap and very special coating designs.

The determination of the laser-induced damage threshold (LIDT), according to the standards ISO 11254-1 (cw and 1-on-1, i.e. single pulse LIDT), ISO 11254-2 (S-on-1, i.e. multiple pulse LIDT) and ISO 11254-3 (LIDT for a certain number of pulses) requires laser systems operating under very stable conditions, precise beam diagnostics as well as online and offline damage detection systems. This is why a limited number of measurement systems with only a few types of lasers is available (e.g. for 1064 nm at Laser Zentrum Hannover). For some of the most prominent laser wavelengths, for example Argon ion lasers (488 nm or 514 nm), there is no measurement system available and certified LIDT data cannot be provided.

The 1-on-1 LIDT (i.e. 1 pulse on 1 site of the sample) is not representative for the normal operation conditions. However, these values can be used for comparing different coatings and for optimization procedures. The 1-on-1 values are directly related to the more practical S-on-1 LIDT (LIDT for a given number "S" of pulses on the same site of the sample). They can be interpreted as the upper limit of the LIDT. Laser systems with high repetition rates (some kHz) require lifetime tests expressed by LIDT values for high numbers of pulses.

LIDT MEASUREMENT SETUP AT LAYERTEC

LAYERTEC has developed its own LIDT measurement setup for in-house measurements with the aim to optimize the coatings concerning their stability against laser damage. The light source is a Q-switched Nd:YAG laser which can emit wavelengths of 1064, 532, 355 and 266 nm. The pulse duration is about 4 – 10 ns and the repetition rate is 10 Hz at all four possible wavelengths. A close-to-Gaussian shaped beam profile is generated by focusing the laser beam with a lens. The spot size is in the region of 200 µm ... 1000 µm (1 / e² radius). The actual value depends on the wavelength and the focal length of the lens. The setup satisfies the requirements of ISO 11254. It has an online detection system based on a digital camera with fast image processing to inspect the sample for damage after every laser pulse. Online beam profile measurements and the determination of the energy density are done with a CCD camera beam profiler in combination with calibrated energy measuring heads with single pulse resolution. A motorized 3-axis stage and a sample holder for multiple pieces allow automated measurements at angles of incidence in the range of 0° – 60° either on reflecting or transmitting samples. The linear polarization of the laser beam can be oriented for either p- or s-polarization with the help of wave plates and a broadband polarizer for the desired wavelength. The measurement setup is shown schematically in fig. 1.

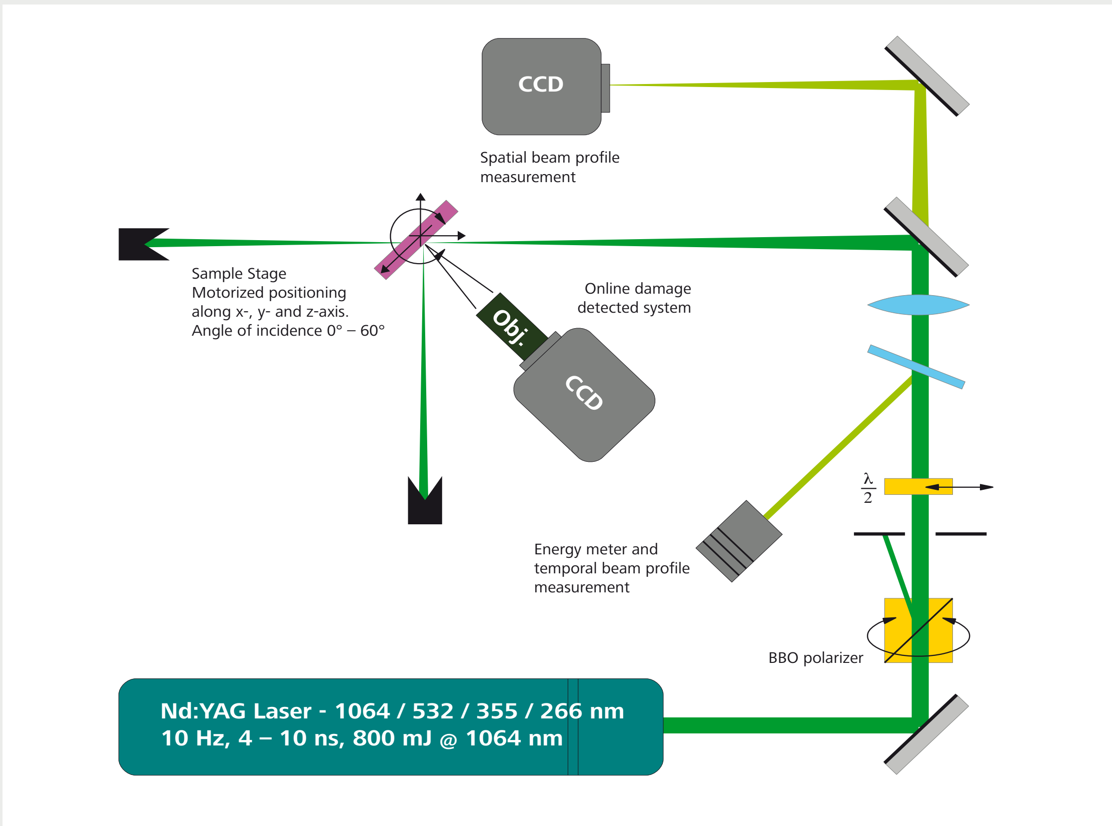


Figure 1: Nanosecond Nd:YAG Laser LIDT measurement setup at LAYERTEC.

LAYERTEC tests samples by using its own procedure (please see next section), because the ISO standards deliver unreliable values for damage thresholds above 30 J / cm². However, if a measurement according to ISO 11254-2 is explicitly requested, the ISO procedure will be used. In this case, 100 or 1000 pulses will be used at each measurement position in order to minimize measurement time. This is not a test for longtime stability. However, LIDT results for 100 or 1000 pulses are more realistic in comparison to 1-on-1 LIDT results. Figure 2 shows the result of an LIDT measurement according to ISO 11254-2.

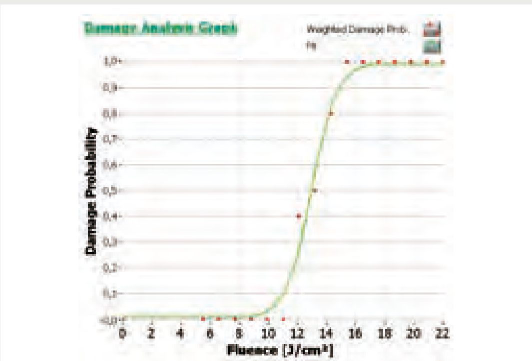


Figure 2: Damage probability of an antireflection coating for 355 nm after 1000 pulses (pulse duration 7 ns, 10 Hz repetition rate) according to ISO 11254-2.
This measurement was performed at LAYERTEC.

The in-house LIDT measurements are mainly intented to compare LAYERTEC coatings among themselves for the purpose of coating and technology development. LAYERTEC provides LIDT results on request, but please note that these results are only valid for the specific measurement conditions (pulse duration, wavelength, number of pulses, beam shape, repetition rate).

LAYERTEC LIDT TESTING PROCEDURE FOR PULSED LASER SOURCES

LAYERTEC has gained a lot of experience in laser damage testing by utilizing the LIDT testing procedures according to ISO 11254. However, it became clear that the measurements are both cost and time intensive but often deliver only questionable results. Significantly lower damage thresholds and strongly distorted damage probability distributions were observed in many cases. Troubleshooting the measurement setup did not reveal any issues leaving only other reasons to explain the measurement errors.

As mentioned above, LAYERTEC uses a relatively large Gaussian-shaped laser spot to measure the damage threshold. The typical spot size is about 1 mm (1 / e^2 diameter). Large spot sizes require a high laser energy and peak power to reach the fluence necessary to cause destruction at the testing site. Coatings with damage thresholds above 50 J / cm² require several hundreds of millijoules laser pulse energy to show damage. In this case, large amounts of debris are generated and deposited within a circle of several millimeters in diameter around the damaged position. If an adjacent test site is located within this zone its damage threshold is significantly reduced due to the debris. This systematic error can be avoided by choosing a larger separation between the measurement positions while providing enough test sites. Very high damage thresholds above 100 J / cm² require a separation between adjacent positions of more than 10 millimeters.

The ISO standard assumes a symmetric distribution for the damage probability. LAYERTEC observes this behavior only at average damage thresholds below 30 J / cm². Threshold probability distributions with average damage values above 30 J / cm² are significantly distorted towards lower values. Assuming that the influence of debris can be neglected, the main reason for this phenomenon are imperfections in the coating and sometimes the surface quality itself. Contrary to ISO standards, significantly low threshold values should not be treated as statistical outliers. Strictly speaking, they have to be taken into account. Otherwise, damage threshold measurements would provide wrong values.

As discussed above, LIDT tests based on ISO standards are not viable for coatings with high damage thresholds. LAYERTEC developed an LIDT measurement method, which is well suited to measure the minimal damage threshold of optical coatings for high power or high-energy laser applications. This procedure requires 4 – 7 testing positions with a separation of approximately 10 mm to each other on the sample. Wherever applicable, four identical samples with 25 mm in diameter are used to get 16 – 28 measuring positions per testing procedure. Every position is irradiated with stepwise increasing energy densities. The energy range of the test laser is subdivided into 50 levels. For the most part, 100 laser pulses are applied at each energy level to watch for cumulative effects in the coating. The starting energy has to be low enough to prevent any laser-induced damage. Then, the energy is increased until laser-induced damage occurs at the testing position.

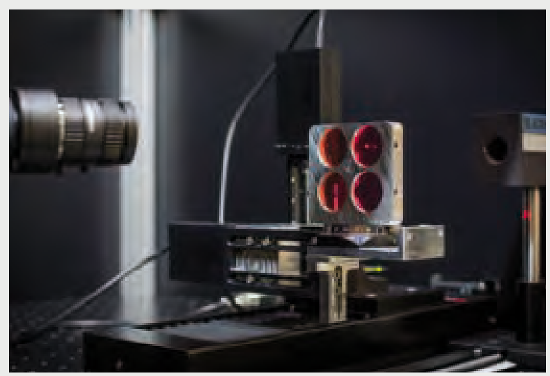


Figure 3: Sample stage of the LIDT measurement setup

All positions on the sample are irradiated in this way, until each position exhibits damage. For the purpose of measurement analysis, the highest, the average and the lowest measured damage threshold are reported. Further statistical analysis is not carried out. An example of an LIDT measurement report is shown in fig.4. All damage threshold values measured at LAYERTEC, which are stated in this catalog, were determined according to the LAYERTEC LIDT testing procedure for pulsed laser sources. Additional measurements were performed by several partners, e.g. Laser Zentrum Hannover, Laser Labor Göttingen and Friedrich-Schiller-University Jena.

Due to the limited number of measurement facilities and the need for lifetime tests in practical applications, it is also necessary to include the measurements and lifetime tests (cumulative irradiation tests) of several customers into this catalog. Please take into account that these values cannot be compared with a standardized LIDT measurement because the laser parameters given are those without damage. Besides, these values always come with a measurement error, especially with respect to the determination of the spot size. Errors in the order of about 30 % must be taken into account. Information about parameters for long-time operation will certainly convince the customer to use LAYERTEC optics. Sometimes, however, these tests will be required in the customer's laser system. LAYERTEC supports such tests at the customer's facility with a considerable discount for test samples.

CPI ABSORPTION MEASUREMENTS

A common path interferometer (CPI) allows LAYERTEC to determine the absorption of optical thin films and bulk materials. In this setup, an optical surface is irradiated by a pump laser, resulting in the absorption of part of the infalling radiation, see figure 4. Due to thermal conduction, the absorbed energy is dispersed as heat within the optics, leading to the formation of a thermal lens.

A second laser, the probe beam, irradiates the thermal lens which deforms the wavefront of said probe beam. This deformation leads to interference effects within the probe beam and can be measured as intensity variations with a photo detector. The magnitude of the wavefront deformation is proportional to the amount of energy absorbed by the optics. The pump beam is switched on and off periodically, with a modulation frequency of several 100 Hz. Thus, the intensity of the probe interference-pattern is temporally modulated as well.

Pump beams at 355 nm, 532 nm or 1030 nm are available for s- and p-polarized light, measurement may be conducted for angles of incidence between 10° and 70°. However, a transmittance above 1% for the wavelength of the probe beam, 635 nm, is required. Apart from that, any HR, PR or AR coating (including single layers) on most common substrates may be measured. Substrates have to be plane with a thickness of 1 – 12 mm. Calibration reports are available on request.

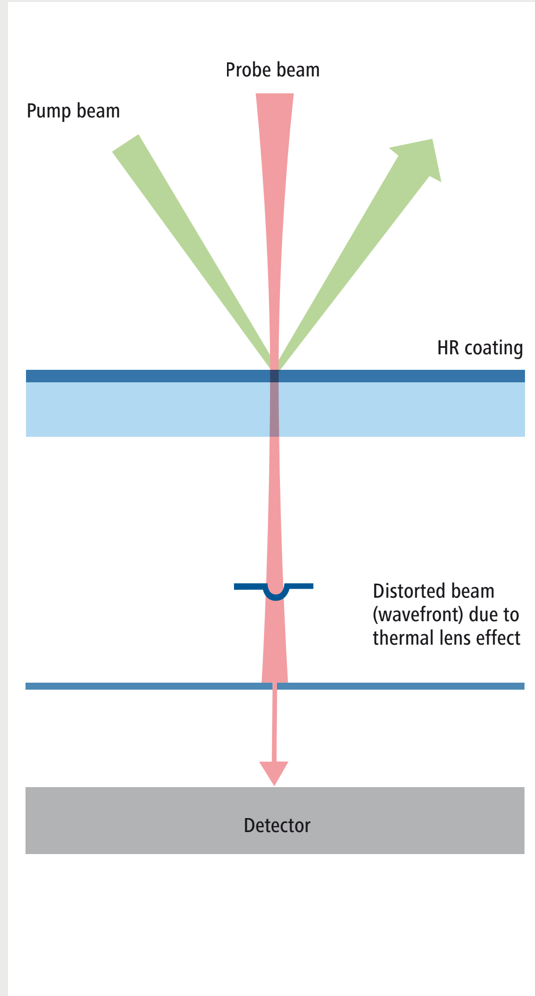


Figure 4: Schematic drawing of a common path interferometer (CPI)

INTRA-CAVITY HEATING MEASUREMENT

Absorption losses in optical coatings result in heating of coating and substrate. For average laser power levels above several kilowatts (cw), even low absorption losses in the range of some parts per million cause significant heating of the optical component. For example, the irradiated zone (1.5 mm in diameter) of a HR-coating with an absorption loss of 5ppm at 1030 nm is heated to a temperature of about 80 °C when exposed to a power of 80 kW.

LAYERTEC has built a heating measurement setup for the purpose of quality assurance and technology development on high power optical components at a wavelength of 1030 nm. An Yb:YAG thin disc laser is used to generate a high power laser beam (fig. 1). The setup consists of a laser disc, a pump chamber, a sample (e.g. a highly reflective mirror) which works as a folding mirror, a second folding mirror, an output coupler, a laser power meter and a pyrometer for the temperature measurement. The beam spot size on the irradiated sample surface area is 1.5 mm (1 / e²) in diameter. A very high intra-cavity laser power of about 120 kW (cw) is achieved by choosing an output coupler with a relatively low transmittance value. Under these conditions, the power density on the sample is approximately 15 MW / cm².

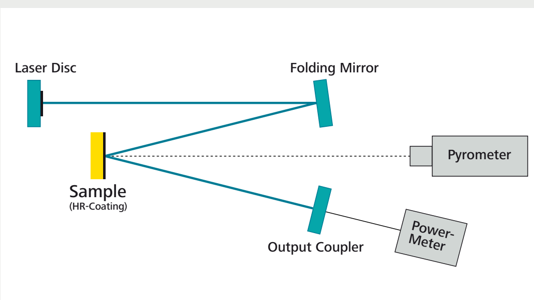


Figure 1: Intracavity heating measurement setup for HR-mirrors at 1030 nm

Generally, coatings with a setup-specific operating temperature lower than 100 °C can be used for high power applications. Please note that the average temperature of the optical component which is measured is clearly lower than the temperature within the small irradiated zone on the coating.

For the purpose of achieving absolute absorption measurements, it is possible to calibrate the setup with a set of samples with well-known absorption. The absorption measurement of the calibration samples was performed by using the LID (laser induced deflection) measurement setup at the Leibniz-Institute of Photonic Technology (IPHT) Jena.

DEFECT INSPECTION SYSTEM FOR COATINGS

LAYERTEC is equipped with a measurement system capable of counting and classifying defects in optical coatings and on uncoated optical surfaces. The system detects defects down to 4 µm in size. It is able to inspect the complete surface of small as well as large optical components. Diameters Ø ≤ 600 mm and surface slopes up to 25° can be analyzed. Small to medium sized pieces are placed in a special sample holder magazine which enables the automated measurement of a large number of pieces in a single inspection run (fig. 2).

Measuring small defects is very challenging because the necessary microscope lenses have a very short depth of focus and require precise adjustment and positioning. Another important factor is proper lighting. Finally, the wide range of available geometries demands a very flexible controller software, quickly adapting to new geometries in order to avoid collisions between the sample and the test system.

LAYERTEC constantly improves the system, enabling it to inspect cylindrical and aspherical optics while reducing effort and measurement time.

Defects are classified by size according to ISO 10110-7 and their position on the optical surface is recorded. Thus, the complete set of microscopic imperfections on the optical surface can be visualized in a macroscopic defect map. Individual measurement reports, including defect maps and defect distributions, can be generated on request. An exemplary inspection report is shown in fig. 3.

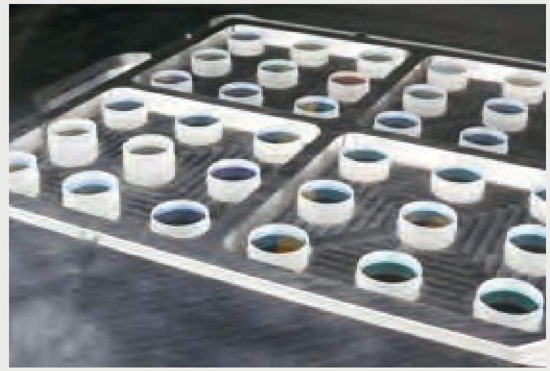


Figure 2: Laser mirrors are placed in a special magazine holder for automated defect inspection at LAYERTEC.

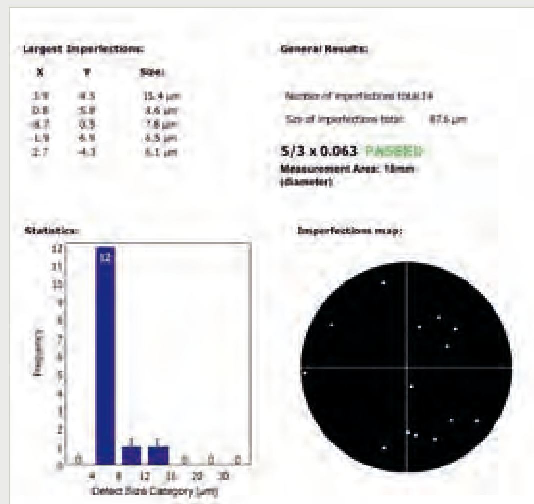
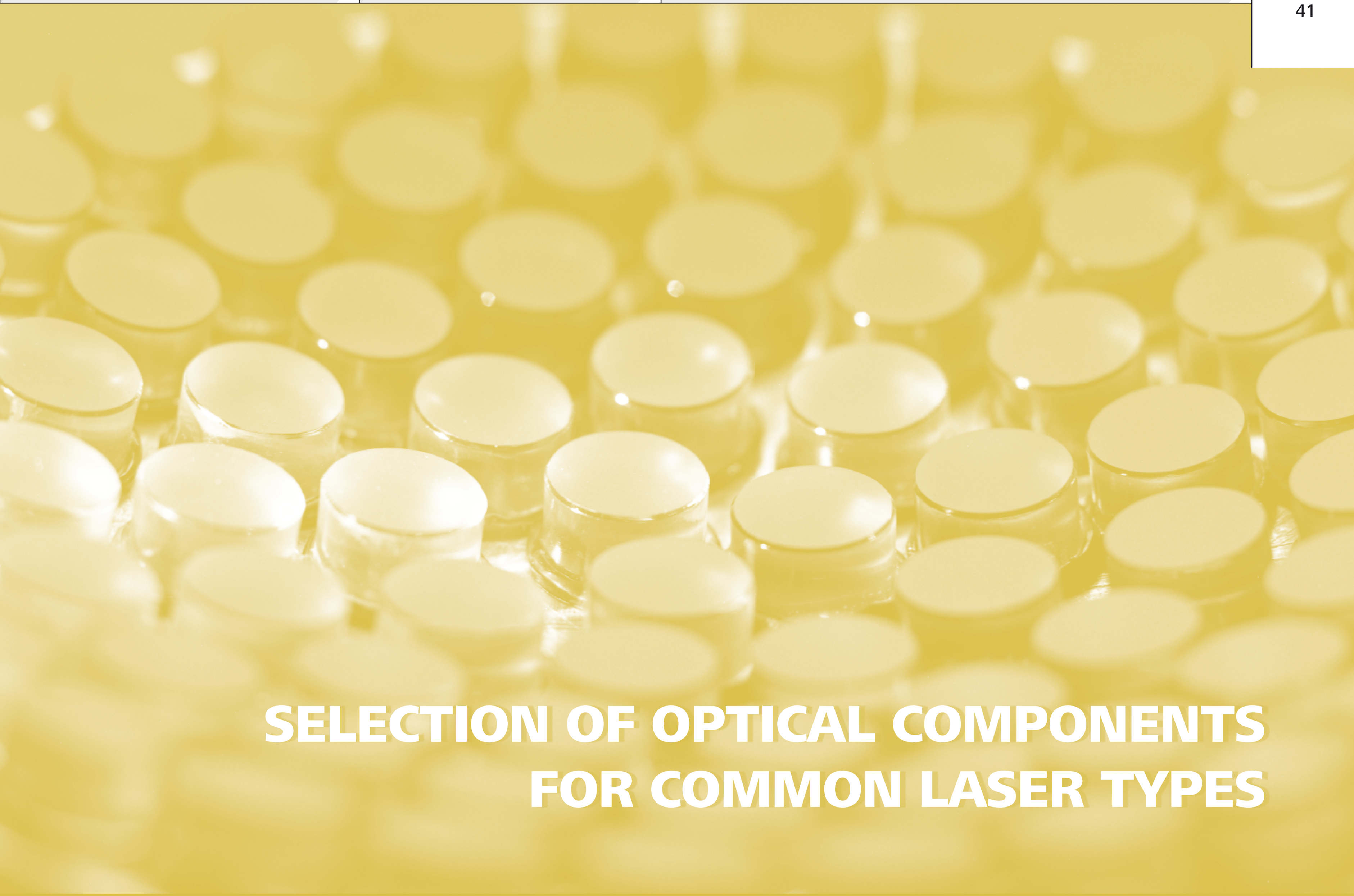


Figure 3: Simplified inspection report of a laser mirror. The report shows the sizes and the coordinates of large defects on the coated surface. Furthermore, all defects which were found are shown in a histogram plot.



SELECTION OF OPTICAL COMPONENTS FOR COMMON LASER TYPES

LAYERTEC®
OPTICAL COATINGS · OPTICS

COMPONENTS FOR F_2 LASERS

MIRRORS

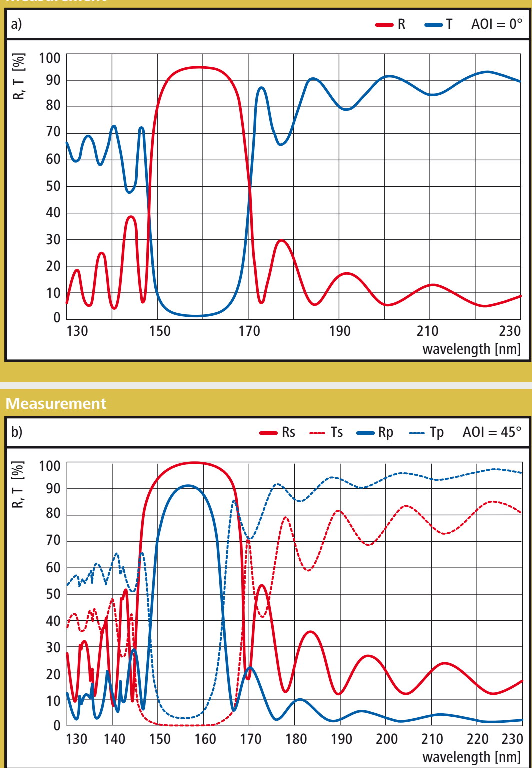


Figure 1: Measured reflectance and transmittance spectra of mirrors for 157 nm
a) Laser mirror (AOI = 0°)
b) Turning mirror (AOI = 45°)

- Laser mirrors: R = 92 % … 95 % at AOI = 0°.
- Turning mirrors (AOI = 45°): Rs > 95 %
  Rp > 90 %
  Ru > 92 %.

OUTPUT COUPLERS AND LENSES

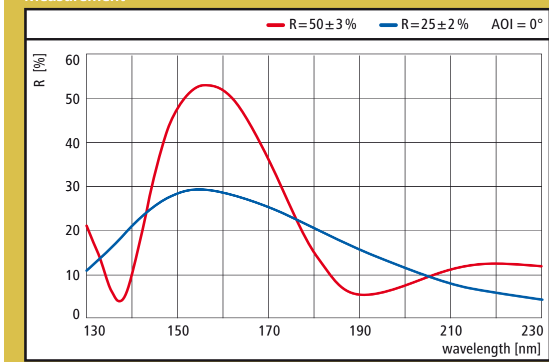


Figure 2: Measured reflectance spectra of standard output couplers with R = 50 % ± 3 % and R = 25 % ± 2 % (back side uncoated)

- High quality mirror substrates, windows and lenses of CaF_2 (193 nm excimer grade quality, HELLMA Materials GmbH).
- Please note that the 157 nm excimer grade CaF_2 can no longer be offered. The market for this kind of material is too small compared to the huge effort necessary for the crystal manufacturers to test the material according to this quality standard. Thus, all optics for F_2 lasers will be manufactured using 193 nm excimer grade material in the future.
- PR coatings with tolerances of
  ± 2 % for R = 10 % ... 30 %
  ± 3 % for R = 30 % ... 75 %
  and ± 2 % for R = 75 % … 90 %.
- Development and production of customer specific components like beam splitters and variable attenuators on request.

VARIABLE ATTENUATORS

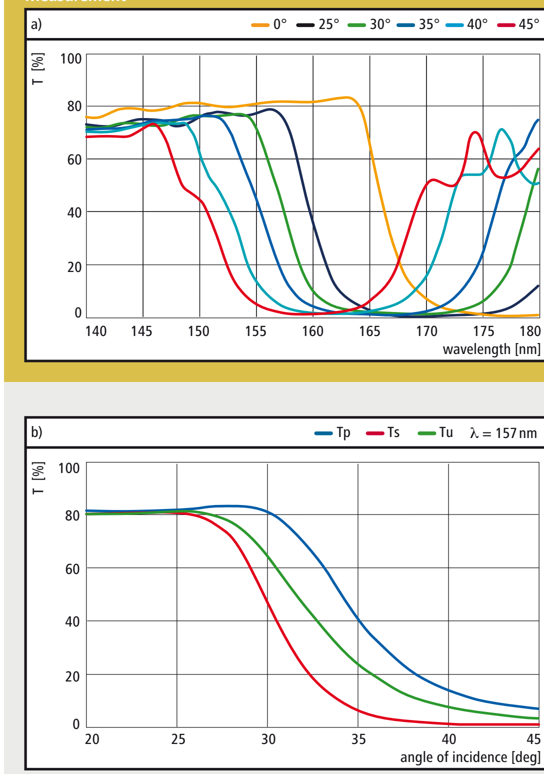


Figure 3: Measured transmittance spectra of a variable attenuator for 157 nm
a) Transmittance vs. wavelength at different AOI
b) Transmittance at 157 nm vs. AOI for different polarizations
The transmittance varies from
T > 75 % at AOI = 0° to T < 5 % at AOI = 45°

157 nm

ALUMINUM MIRRORS FOR F_2 LASERS

Measurement

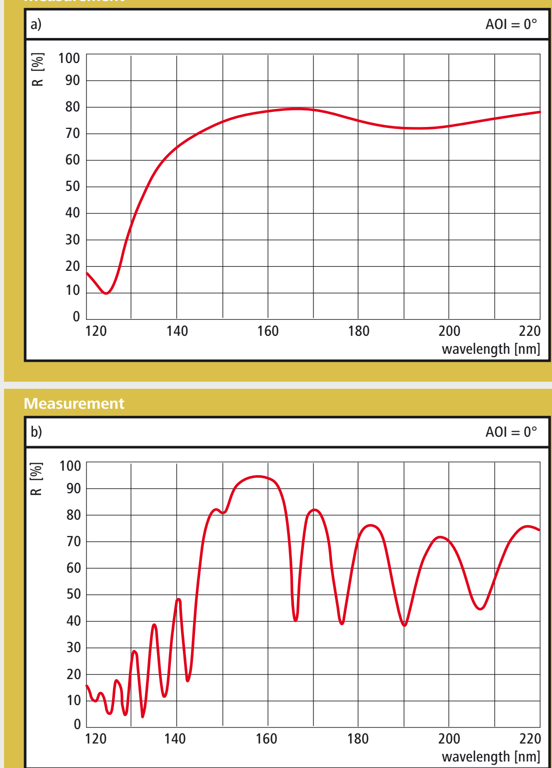


Figure 4: Reflectance spectra of aluminum mirrors
a) Protected aluminum mirror
b) Enhanced aluminum mirror for 157 nm

- Protected aluminum mirrors (optimized for 157 nm): R = 74 % … 78 %.
- Dielectrically enhanced aluminum mirrors: up to R = 94 % at AOI = 0°.
- For more information on aluminum mirrors see pages 122 – 123.

TECHNICAL DATA OF STANDARD F_2 LASER COMPONENTS

LIDT - INFO

Coating	Spectral performance	Lifetime tests
HR(0°, 157 nm)	R = 92 % ... 95 %	2 x 10^8 – 1 x 10^9 pulses*
HR(45°, 157 nm)	R = 90 % ... 94 % (unpol. light)	
PR(0°, 157 nm)	R = 50 % ± 3 %	2 x 10^8 – 1 x 10^9 pulses*
PR(0°, 157 nm)	R = 25 % ± 2 %	2 x 10^8 – 1 x 10^9 pulses*
Attenuator	T = 67 % ± 3 %	5 x 10^7 pulses**, no damage
Attenuator	T = 33 % ± 3 %	1 x 10^8 pulses***, no damage
Beam splitter	T = 20 % ± 3 %	1 x 10^8 pulses***, no damage
AR(0°, 157 nm)	R = 0.3 % ... 0.7 %	

* Energy density: 25 mJ / cm², repetition rate: 800 Hz, pulse duration: 15 ns; tested at COHERENT AG, München
** Energy density: 15 mJ / cm², repetition rate: 200 Hz, pulse duration: 20 ns; tested at Institut für Photonische Technologien (IPHT) Jena
*** Energy density: 20 mJ / cm², repetition rate: 50 Hz, pulse duration: 20 ns; tested at Institut für Photonische Technologien (IPHT) Jena

COMPONENTS FOR THE FIFTH AND SIXTH HARMONIC OF Ti:SAPPHIRE LASERS

Measurement

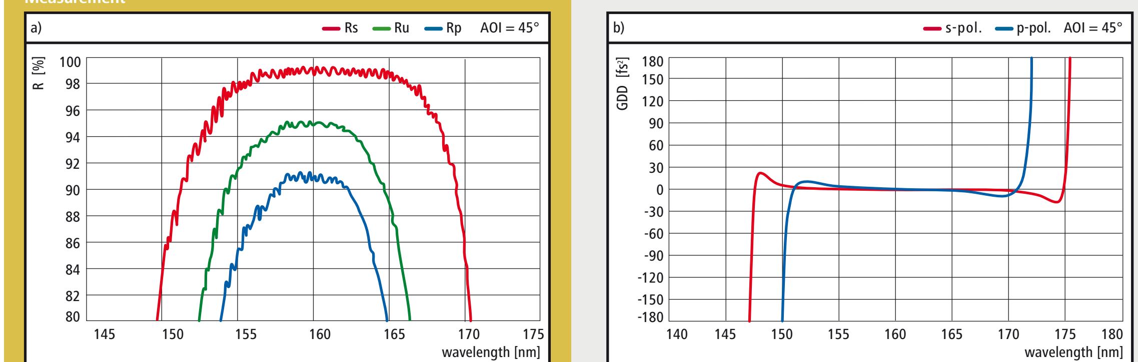


Figure 5: Reflectance and GDD - spectra of a turning mirror for 160 nm (AOI = 45°)
a) Reflectance vs. wavelength (measured)
b) GDD vs. wavelength (calculated)

Mirrors and separators for the 133 nm and 160 nm range are produced by coating techniques which were developed for F_2 laser coatings. For more information please see pages 94 – 95.

COMPONENTS FOR ArF LASERS

MIRRORS

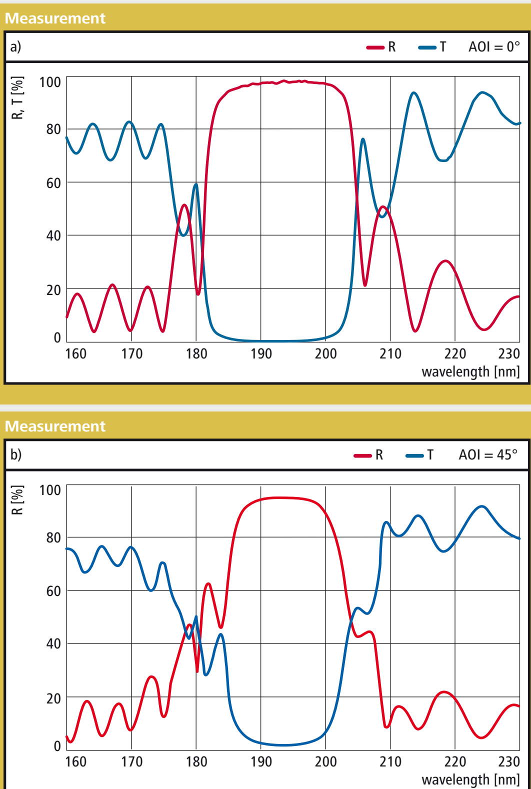


Figure 1: Measured reflectance and transmittance spectra of mirrors for 193 nm
a) Laser mirror (AOI = 0°)
b) Turning mirror (AOI = 45°, unpolarized light)

- All fluoride systems guarantee high reflectance and high damage thresholds.
- High quality mirror substrates, windows and lenses of CaF_2 (193 nm excimer grade, HELLMA Materials GmbH) and fused silica.
- Development and production of customer specific components such as beam splitters and variable attenuators on request.

OUTPUT COUPLERS AND LENSES

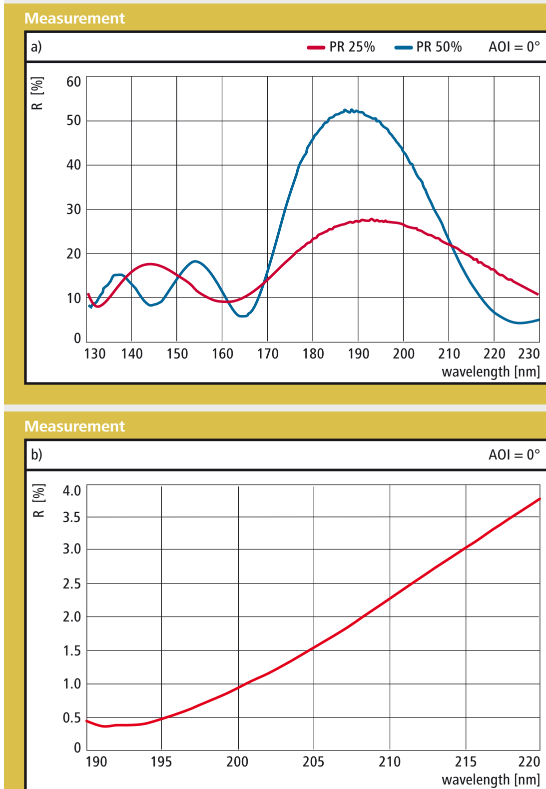


Figure 2: Measured reflectance spectra of output couplers and windows
a) Output couplers with R (0°, 193 nm) = 50 % ± 3 % and R (0°, 193 nm) = 25 % ± 2 % (back side uncoated)
b) CaF_2 window coated on both sides with a fluoride AR coating for 193 nm

- PR coatings with tolerances of
  ± 2 % for R = 10 % ... 30 %
  ± 3 % for R = 30 % ... 75 %
  ± 2 % for R = 75 % ... 90 %
  and ± 1 % for R > 90 %.
- Single wavelength AR coating with residual reflectance values of
  R < 0.25 % at AOI = 0° and
  R < 0.6 % at AOI = 45° (unpolarized light).
- Broadband and multiple wavelength AR coatings.

VARIABLE ATTENUATORS

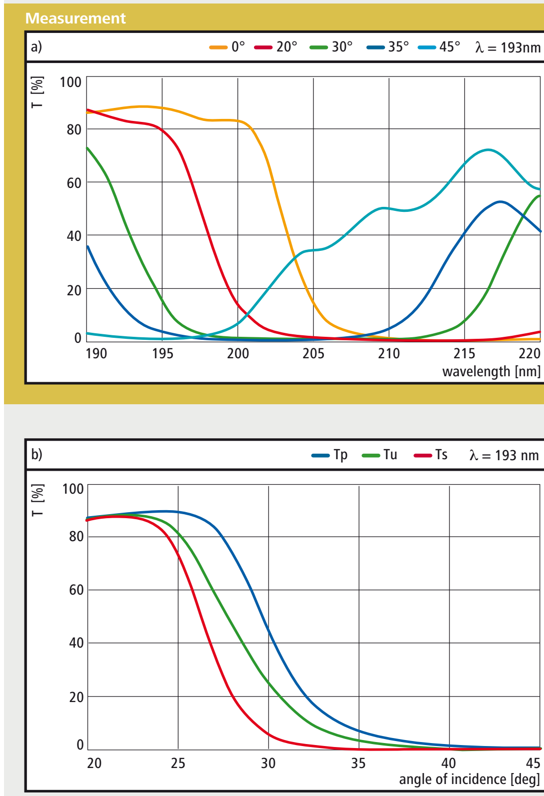


Figure 3: Measured transmittance spectra of a variable attenuator for 193 nm
a) Transmittance vs. wavelength at different AOI
b) Transmittance at 193 nm vs. AOI for different polarizations
The transmittance varies from T > 88 % at AOI = 0° to T < 2 % at AOI = 45°

- Attenuators with custom transmittance ranges on request.
- Attenuators can be delivered with AR coated compensation plates of CaF_2 or fused silica.

193 nm

ALUMINUM MIRRORS

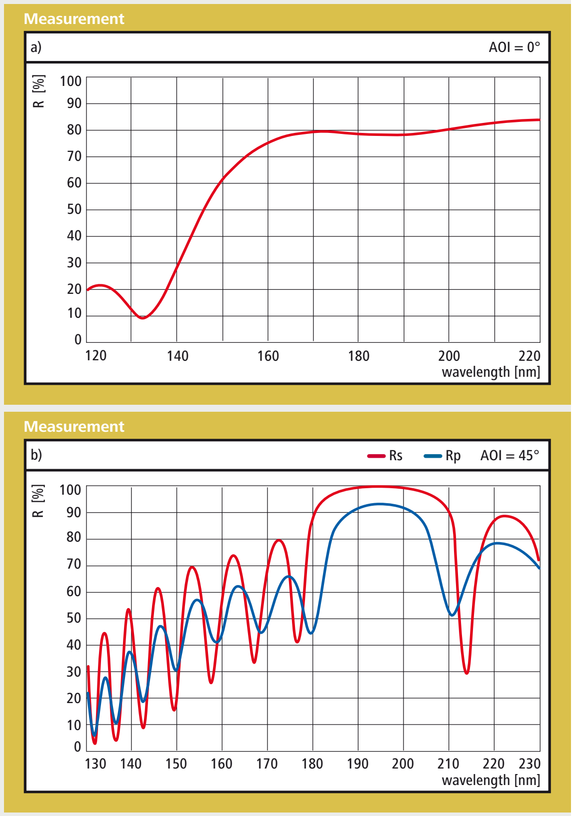


Figure 4: Reflectance spectra of aluminum mirrors
a) Protected aluminum mirror optimized for 193 nm
b) Enhanced aluminum mirror for 193 nm, AOI = 45°

Enhanced aluminum mirrors: Rp > 93 %
Rs > 98 %
Ru > 96 %.

For more information on aluminum mirrors see pages 122 – 123.

TECHNICAL DATA OF STANDARD ArF LASER COMPONENTS

LIDT - INFO

Coating/reflectance Fluoride coatings	Substrate	Damage threshold*	Lifetime test
AR (0°, 193 nm) R < 0.25 %	CaF_2	4 – 5 J/cm^2	10^8 pulses, no damage**
AR (0°, 193 nm) R < 0.25 %	fused silica	2 – 3 J/cm^2	
PR (0°, 193 nm) R = 25 %	CaF_2	3 – 4 J/cm^2	10^{10} pulses, no damage**
PR (0°, 193 nm) R = 50 %	CaF_2	2 – 3 J/cm^2	10^{10} pulses**
HR (0°, 193nm) R > 96 %	CaF_2	2 – 3 J/cm^2	10^{10} pulses **, no damage 4 x 10^9 pulses ***, no damage
HR (45°, 193 nm) R > 95 % (unpolarized light)	CaF_2	2 – 3 J/cm^2	

* 1000-on-1, 14 ns; measurements were performed at Laser Labor Göttingen, Laser Zentrum Hannover and at Friedrich-Schiller-University Jena
** Energy density: 55 mJ/cm^2, repetition rate: 1 kHZ, pulse duration: 15 ns; tested at COHERENT AG, München
*** Energy density: 80 mJ/cm^2, repetition rate: 1 kHz, pulse duration: 12 ns; tested at COHERENT AG, München

COMPONENTS FOR THE 200 nm RANGE

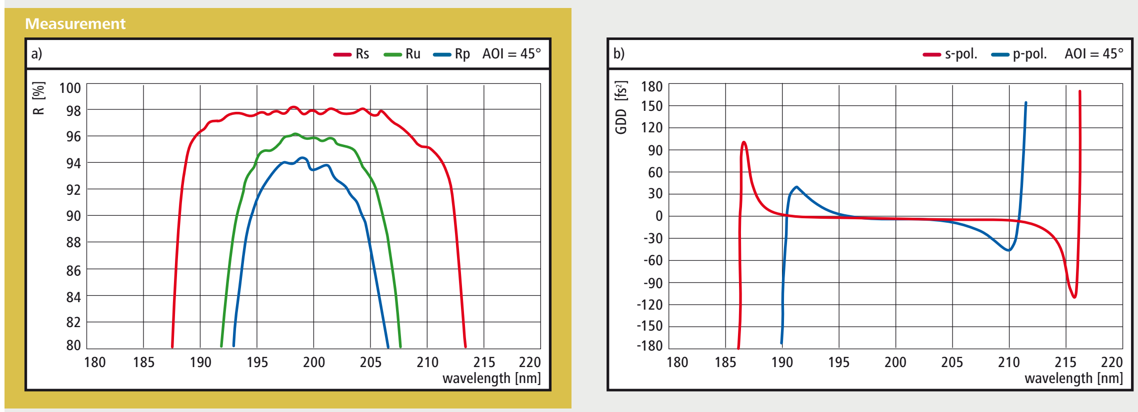


Figure 5: Reflectance and GDD - spectra of a turning mirror for 200 nm (AOI = 45°)
a) Reflectance vs. wavelength (measured)
b) GDD vs. wavelength (calculated)

Mirrors and separators for the 200 nm range are produced by coating techniques which were developed for ArF laser coatings. For more information please see pages 94 – 95.

COMPONENTS FOR KrF, XeCl and XeF LASERS

CAVITY MIRRORS

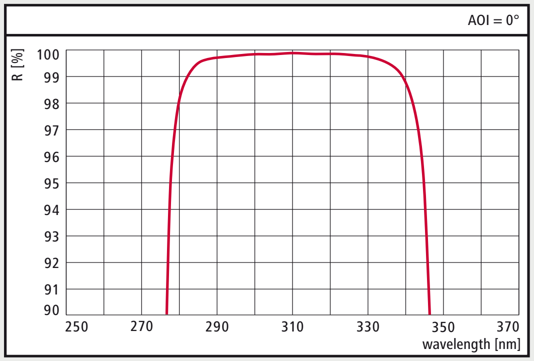


Figure 1: Reflectance spectrum of a 308 nm cavity mirror

- Oxide coatings for high mechanical stability.
- Coatings can be produced by IAD, magnetron sputtering or IBS.

OUTPUT COUPLERS

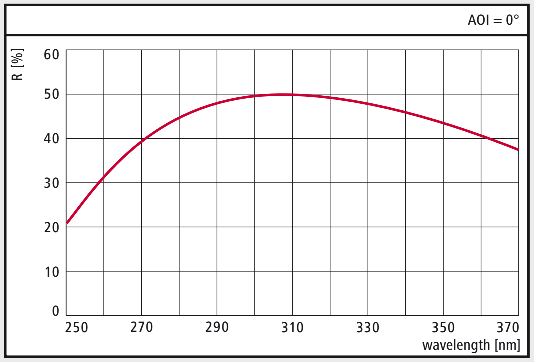


Figure 3: Reflectance spectrum of an output coupler for 308 nm R (0°, 308 nm) = 50 % ± 3 %

- PR coatings with tolerances of
  - ± 2 % for R = 10 % ... 30 %
  - ± 3 % for R = 30 % ... 75 %
  - ± 2 % for R = 75 % ... 90 %
  - and ± 1 % for R > 90 %.

WINDOWS AND LENSES

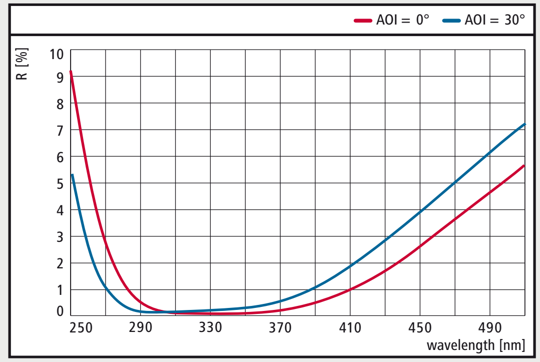


Figure 5: Reflectance spectra of an AR coating for 308 nm and AOI = 0° – 30°

- High quality mirror substrates, windows and lenses of fused silica.

FLUORINE RESISTANT CAVITY MIRRORS

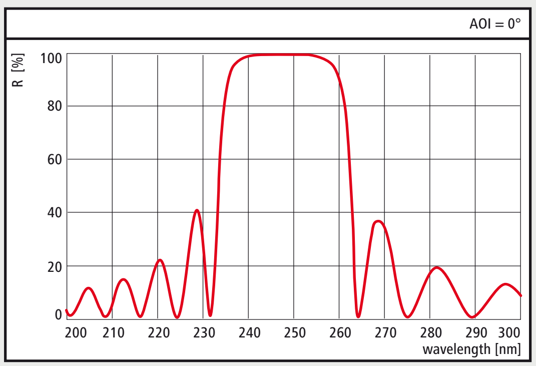


Figure 2: Reflectance spectrum of a fluoride KrF cavity mirror

- Fluoride coatings and CaF_2 substrates for high stability against fluorine and chlorine.
- Laser mirrors (R > 98 % at 248 nm, 308 nm and 351 nm).

FLUORINE RESISTANT OUTPUT COUPLERS

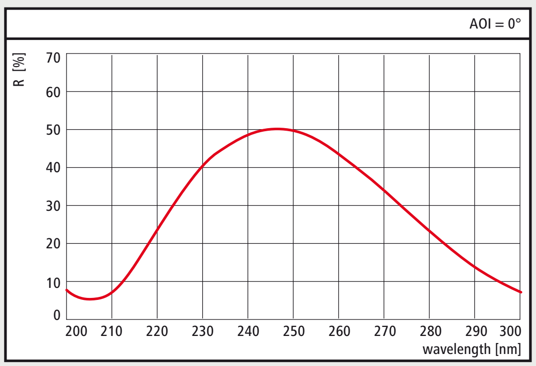


Figure 4: Reflectance spectrum of a fluoride output coupler with R (0°, 248 nm) = 50 % ± 3 %

- PR coatings with tolerances of
  - ± 2 % for R = 10 % ... 30 %
  - ± 3 % for R = 30 % ... 75 %
  - and ± 2 % for R = 75 % ... > 90 %.

FLUORINE RESISTANT WINDOWS

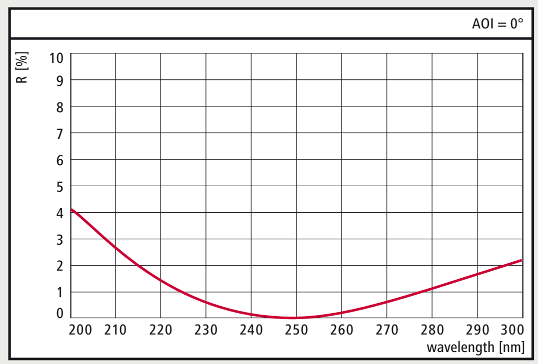


Figure 6: Reflectance spectrum of a fluoride AR coating for 248 nm

- High quality mirror substrates, windows and lenses of CaF_2 (248 nm excimer grade or UV quality, HELLMA Materials GmbH).
- Extended lifetimes at high energy densities at 248 nm.

248 nm, 308 nm, 351 nm

TURNING MIRRORS

Measurement

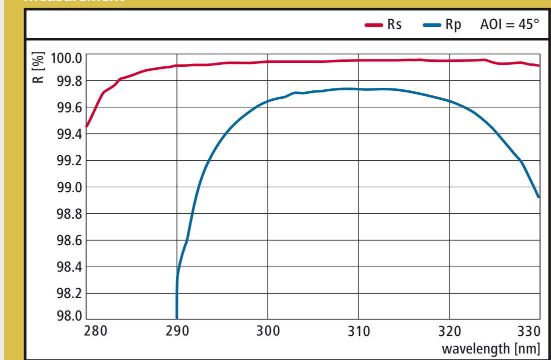


Figure 7: Reflectance spectra of a turning mirror for 308 nm produced by IBS
Reflectance measurement in s- and p-polarization by CRDS

Reflectance of turning mirrors (AOI = 45°):

Coating	Rs	Rp
248 nm IAD	> 99.5 %	> 99.0 %
248 nm sputtering	> 99.8 %	> 99.6 %
308 nm IAD	> 99.8 %	> 99.5 %
308 nm sputtering	> 99.9 %	> 99.7 %
351 nm IAD	> 99.9 %	> 99.7 %
351 nm sputtering	> 99.95 %	> 99.9 %

Reflectance of laser mirrors (AOI = 0°):

Coating	R
248 nm IAD	> 99.0 %
248 nm sputtering	> 99.7 %
308 nm IAD	> 99.7 %
308 nm sputtering	> 99.9 %
351 nm IAD	> 99.9 %
351 nm sputtering	> 99.95 %

ATTENUATORS

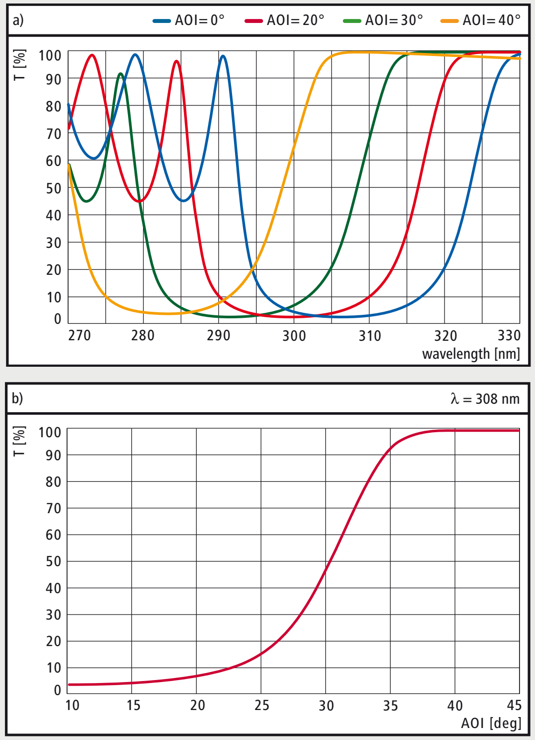


Figure 8: Measured transmittance spectra of a variable attenuator for 308 nm
a) Transmittance vs. wavelength at different AOI
b) Transmittance at 308 nm vs. AOI for unpolarized light
The transmittance varies from T < 10 % at AOI = 0° to T > 90 % at AOI = 40°

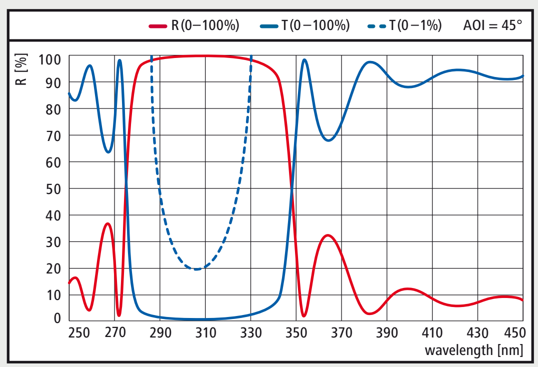


Figure 9: Transmittance spectrum of a sputtered attenuator for 308 nm with exactly adjusted and thermally stable transmittance of T = 0.2 % at AOI = 45° (unpolarized light)

LIDT AND LIFETIME DATA

LIDT of oxide coatings:

Coating	LIDT* [J / cm^2]
HR (0°, 248 nm) IAD	10 J / cm^2 (1-on-1) 5 J / cm^2 (1000-on-1)
HR (45°, 248 nm) IAD	10 J / cm^2 (1-on-1)

Lifetime of fluoride coatings:

Coating	Lifetime
HR (0°, 248 nm)	2 x 10^8 pulses**
PR (0°, 248 nm) = 50 %	2 x 10^8 pulses**
AR (0°, 248 nm)	2 x 10^8 pulses***
HR (0°, 308 nm)	2 x 10^8 pulses***
HR (0°, 351 nm)	2 x 10^8 pulses***
PR (0°, 351 nm) = 25 %	2 x 10^8 pulses***

* Measurements were performed at Laser Labor Göttingen and at Friedrich-Schiller-University Jena
** Energy density: 100 mJ / cm^2, repetition rate: 100 Hz, pulse duration: 15 ns; tested at COHERENT AG, München
*** Energy density: 55 mJ / cm^2, repetition rate: 100 Hz, pulse duration: 15 ns; tested at COHERENT AG, München

COMPONENTS FOR RUBY AND ALEXANDRITE LASERS

Ruby and Alexandrite Lasers are especially used for medical laser applications and work at 694 nm and 755 nm, respectively. LAYERTEC offers a wide range of laser optics for both wavelengths with high laser-induced damage thresholds and long lifetimes. Besides typical combinations with wavelengths for the alignment of the optical system (e.g. 694 nm + 633 nm), a special feature of LAYERTEC products is the variety of combinations with other common wavelengths used for medical applications in the same device, but from different laser sources (e.g. 532 nm + 694 nm).

CAVITY MIRRORS

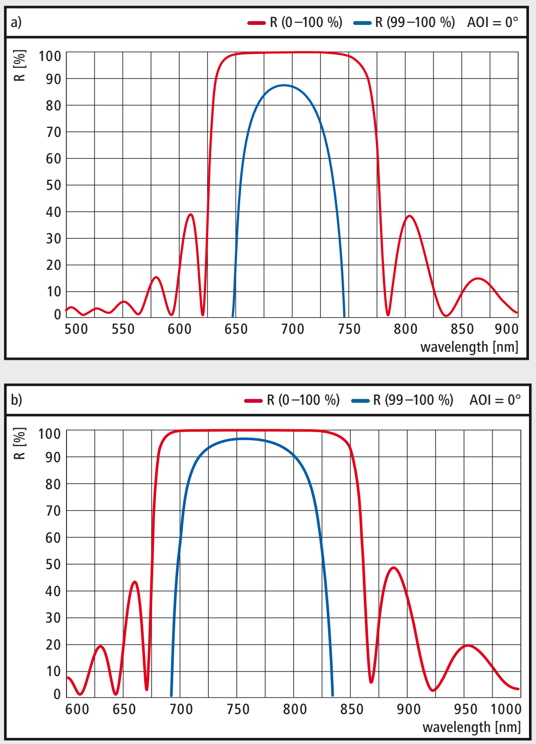


Figure 1: Reflectance spectra of cavity mirrors for
a) 694 nm
b) 755 nm

- Reflectance: R > 99.8 ... R > 99.9 % at AOI = 0°.

LIDT - INFO

800 MW / cm², 694 nm, 35 ns

TURNING MIRRORS

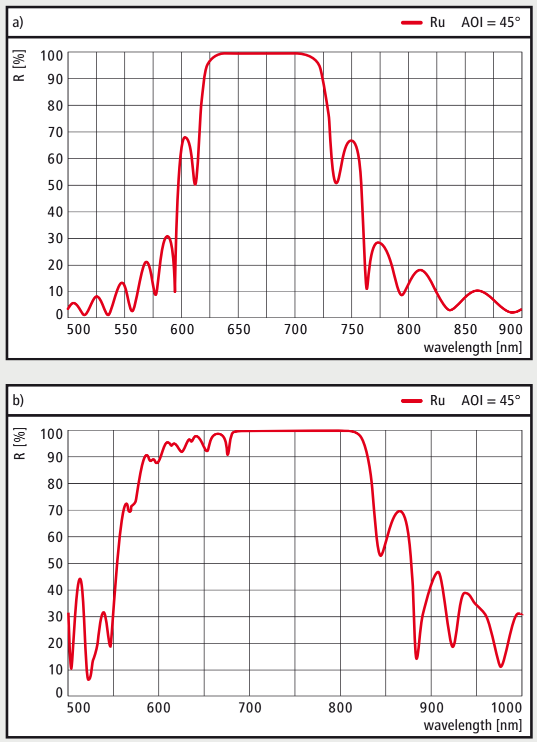


Figure 2: Reflectance spectra of turning mirrors for
a) 694 nm
b) 755 nm

- Reflectance: R > 99.5 % at AOI = 45° for unpolarized light.
- Easy combination with alignment beam (e.g. at 630 – 650 nm).

LIDT - INFO

800 MW / cm², 694 nm, 35 ns

BEAM COMBINERS

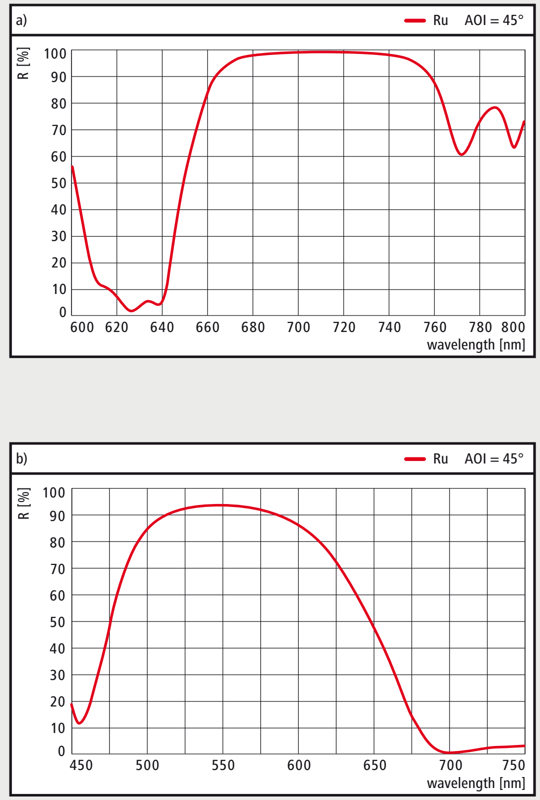


Figure 3: Reflectance spectra of special beam combiners for 694 nm and 633 nm:
a) PRu (45°, 694 nm) = 99.0 % ± 0.3 %
+ Ru (45°, 633nm) < 35 %
b) Ru (45°, 630 - 640 nm) > 35 %
+ Rp (45°, 694 nm) < 0.3 %

- Precisely adjusted degree of reflectance by using sputtering technology.
- Easy combination with alignment beam (e.g. at 635 nm).
- High performance and cost-optimized solutions with special designs.

694 nm, 755 nm

OUTPUT COUPLERS

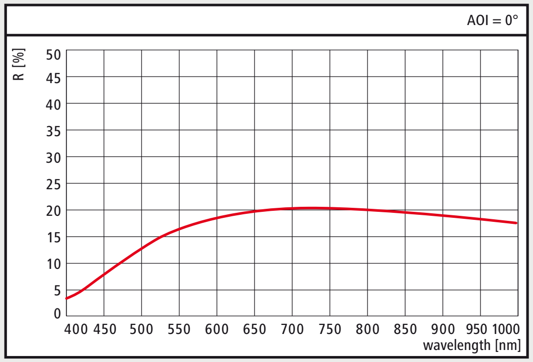


Figure 4: Reflectance spectrum of an output coupler for the ruby laser: PR (0°, 694 nm) = 20 % ± 2 %

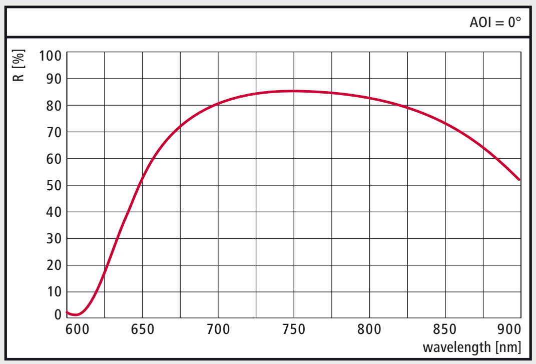


Figure 5: Reflectance spectrum of an output coupler for the alexandrite laser: PR (0°, 755 nm) = 85 % ± 2 %

- Output couplers with precisely adjusted degree of reflectance.

WINDOWS AND LENSES

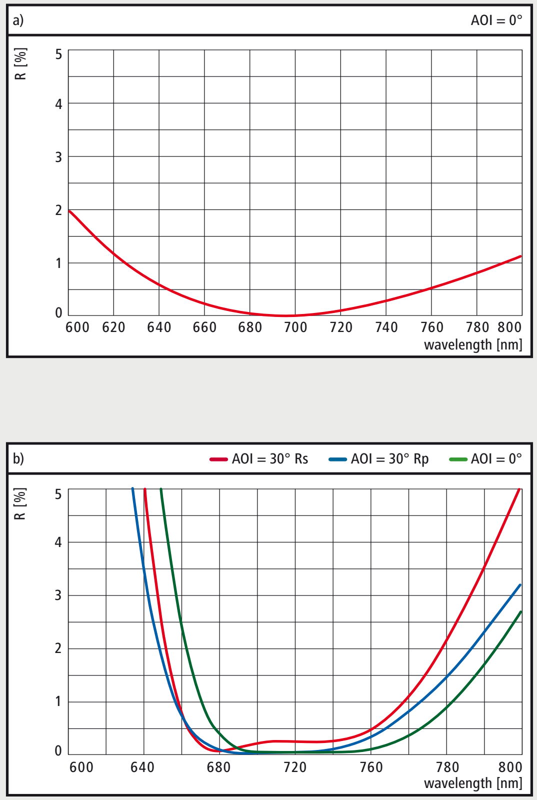


Figure 6: Reflectance spectra of AR coatings for 694 nm and 755 nm:
a) AR (0°, 694 nm) < 0.2 %,
b) AR (0° – 30°, 694 + 755 nm) < 0.5 %

- AR coatings for a single wavelength with a residual reflectance of R < 0.2 % on the back side of output couplers as well as on both sides of lenses and windows made of fused silica.

COMPONENTS FOR COMBINING RUBY LASERS WITH OTHER HIGH POWER LASERS

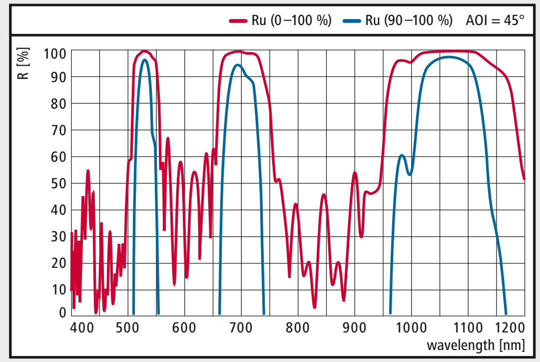


Figure 7: Reflectance spectrum of a triple wavelength turning mirror for 532 nm, 694 nm and 1064 nm (for unpolarized light)

- R > 99 % at all three wavelengths (AOI = 45°, unpolarized light).
- High laser damage thresholds.

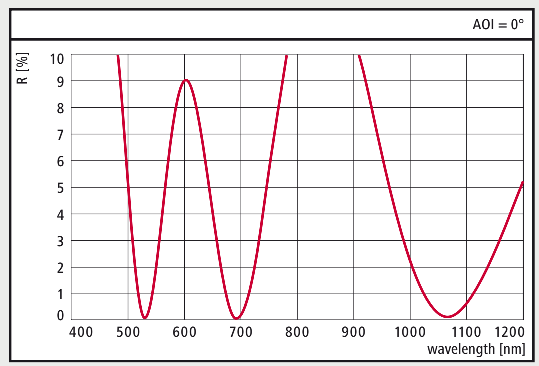


Figure 8: Reflectance spectrum of a triple wavelength AR coating for 532 nm, 694 nm and 1064 nm

COMPONENTS FOR Ti:SAPPHIRE LASERS IN THE ns REGIME

LAYERTEC offers a wide range of optical components for Ti:Sapphire lasers which operate with ns-pulses. Please note that all of these components are optimized for smooth group delay (GD) spectra in order to achieve wide tuning ranges. However, these components are not optimized for group delay dispersion (GDD). Such optics are necessary for fs-pulses and they will be introduced on pages 74 and following.

CAVITY MIRRORS

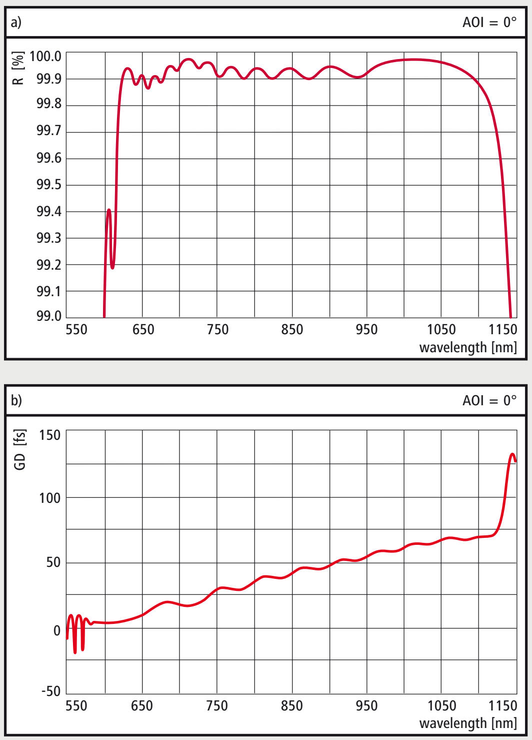


Figure1: Reflectance and GD - spectra of a broadband laser mirror
a) Reflectance vs. wavelength
b) GD vs. wavelength

PUMP MIRRORS

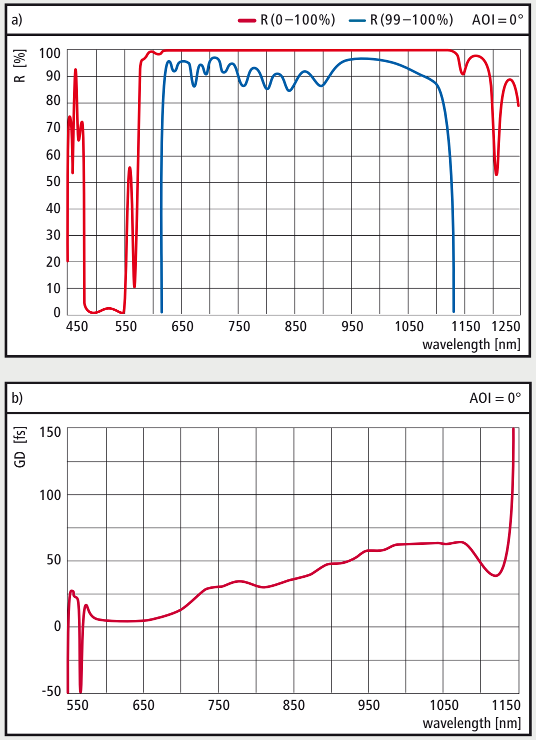


Figure 2: Reflectance spectra of a broadband pump mirror
a) Reflectance vs. wavelength
b) GD vs. wavelength

Special features:

- Very high reflectance of the mirrors: R > 99.9 %, depending on bandwidth R > 99.98 % may also be achieved.
- Spectral tolerance: ±1% of center wavelength.
- Center wavelength, bandwidth and reflectance of partial reflectors according to customer specification.

TURNING MIRRORS

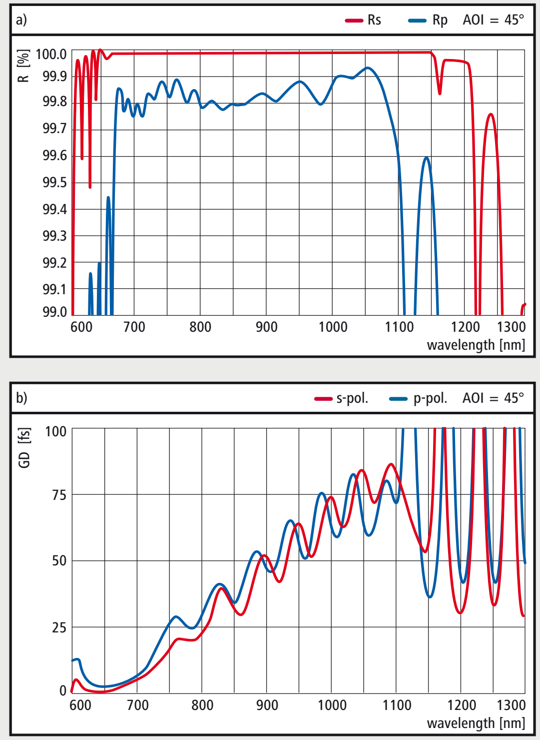


Figure 3: Reflectance and GD spectra of a broadband turning mirror
a) Reflectance vs. wavelength
b) GD vs. wavelength

550 – 1100 nm

OUTPUT COUPLERS AND BEAM SPLITTERS

Tolerances:

- Standard output couplers (bandwidth: 120 – 150 nm):
  - ± 2.5 % for R = 10 % … 70 %
  - ± 1.5 % for R = 70 % … 90 %
  - ± 0.75 % for R = 90 % … 95 %
  - ± 0.5 % for R = 95 % … 98 %
  - ± 0.25 % for R > 98 %.

Tolerances:

- Broadband output couplers (bandwidth: 200 – 600 nm):
  - ± 3 % for R = 10 % … 70 %
  - ± 2 % for R = 70 % … 90 %
  - ± 1 % for R = 90 % … 95 %
  - ± 0.5 % for R = 95 % … 98 %.

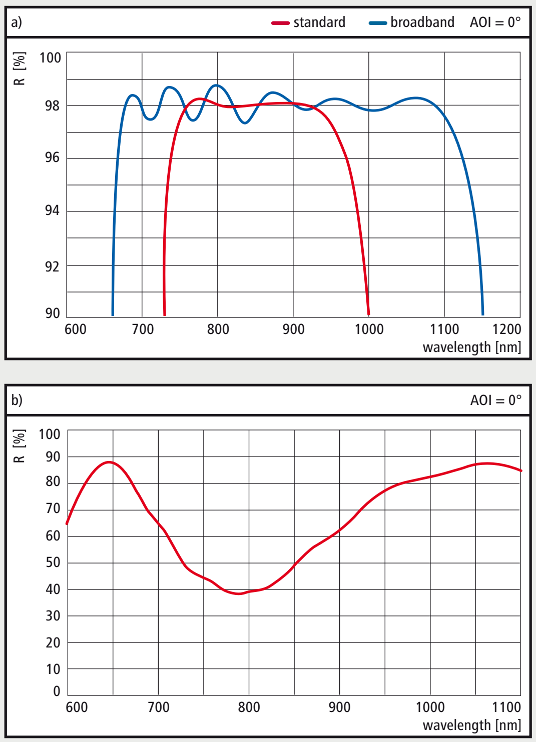


Figure 4: Reflectance spectra of several types of output couplers
a) Standard and broadband output coupler
b) Output coupler with a special reflectance profile which enables the compensation of the amplification characteristics of the laser; see also B. Jungbluth, J. Wueppen, J. Geiger, D. Hoffmann, R. Poprawe: "High Performance, Widely Tunable Ti:Sapphire Laser with Nanosecond Pulses" in: Solid State Lasers XV: Technology and Devices, Proc. of SPIE Vol. 6100, 6100 - 20, San Jose 2006

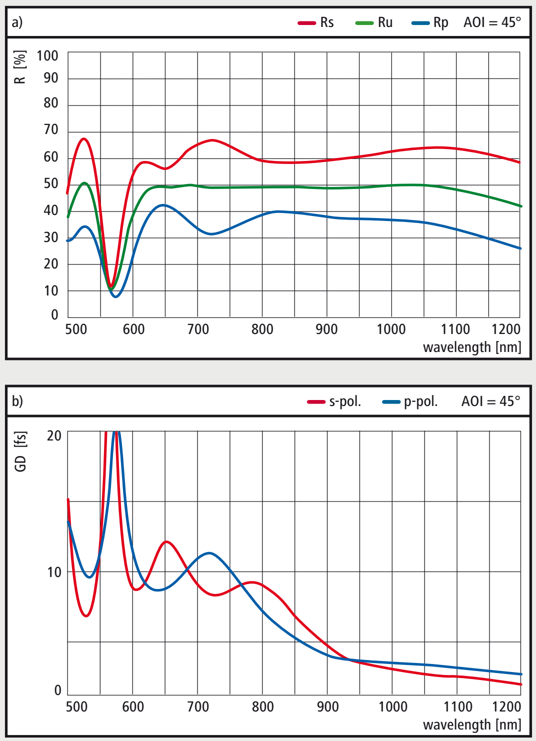


Figure 5: Reflectance and GD spectra of a broadband beamsplitter PRu (45°, 650 - 1050 nm) = 50 % ± 3 %
a) Reflectance vs. wavelength
b) GD vs. wavelength

SPECIAL COMPONENTS

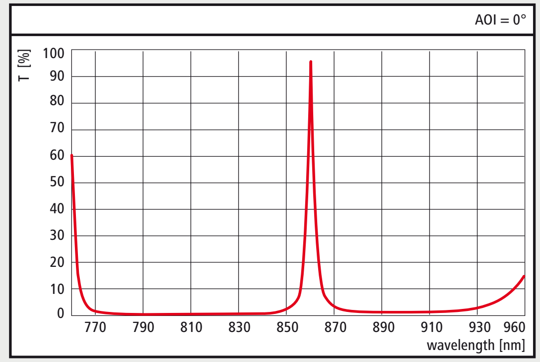


Figure 6: Transmittance spectrum of a narrow band intracavity filter for 860 nm which is used to select one wavelength from the Ti:Sapphire spectrum

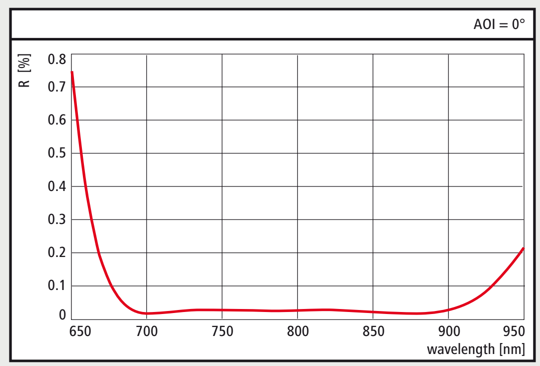


Figure 7: Reflectance spectrum of a broadband antireflection coating with extremely low residual reflectance:
AR (0°, 700 – 900 nm) < 0.05 %

COMPONENTS FOR DIODE LASERS

Diode lasers are widely used for measurement applications, as alignment lasers, for pumping of solid-state lasers and for direct materials processing. Diode lasers do not require external resonator optics and are mostly coupled to fibers. Many applications require high quality beam steering optics such as beam combiners or scanning mirrors which are shown on the following pages. For more information on pump mirrors for solid-state lasers and combiners for diode lasers please see also pages 54 – 57 and 110 – 111.

TURNING MIRRORS

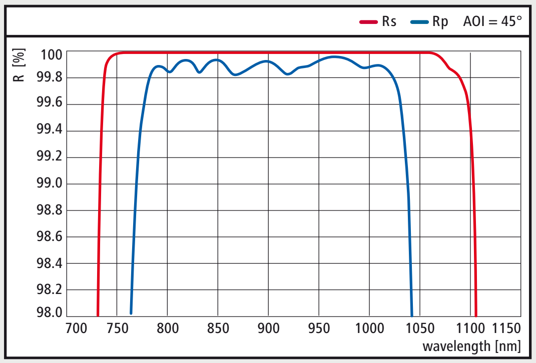


Figure 1: Reflectance spectra of a broadband turning mirror which can be used for all diode lasers between 808 nm and 980 nm (AOI = 45°, s- and p-polarization)

SCANNING MIRRORS

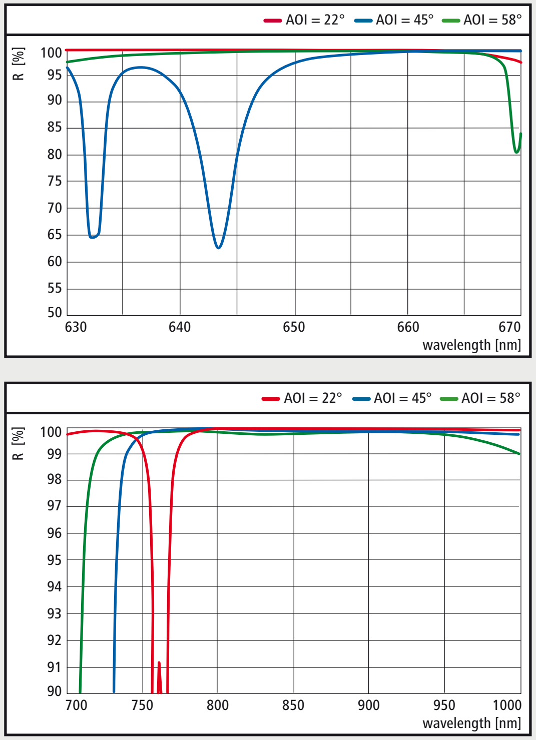


Figure 2: Reflectance spectra of a scanning mirror for diode lasers between 805 and 940 nm combined with R > 50 % between 630 and 670 nm (alignment laser):
HRu (22°– 58°, 805 – 940 nm) > 99.3 %
+ Ru (22°– 58°, 630 – 670 nm) > 50 %

- Scanning mirrors with other specifications on request.
- For more information and examples about scanning mirrors please see pages 108 – 109 and 120 – 121.

THIN FILM POLARIZERS

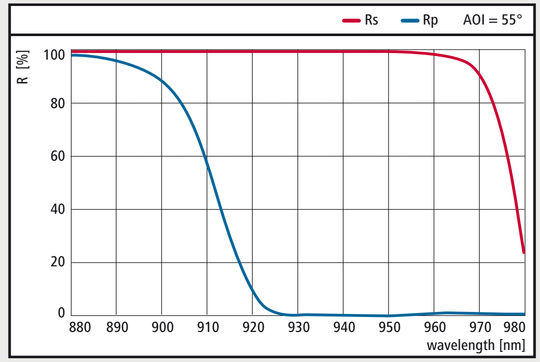


Figure 3: Reflectance spectra of a thin film polarizer for 940 nm, AOI = 55°

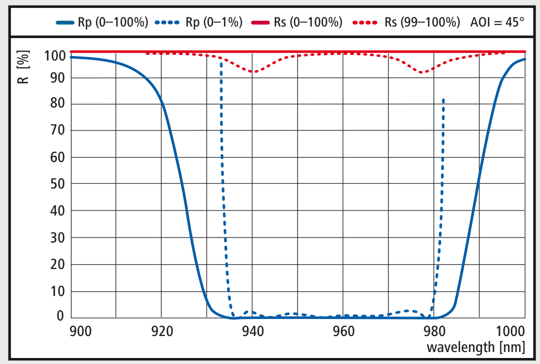


Figure 4: Reflectance spectra of a broadband thin film polarizer for 940 – 970 nm: HRs (45°, 940 – 970 nm) > 99.9 %
+ Rp (45°, 940 – 970 nm) < 1%

- Thin film polarizers are especially useful for polarization coupling of high power laser diodes.
- For high power 940 nm radiation we recommend to use SUPRASIL 300® or SUPRASIL 3001/3002® as substrate material because standard fused silica shows an absorption band around this wavelength (see page 20).

620 – 680 nm , 808 – 990 nm

CONVENTIONAL STEEP EDGE COMBINERS FOR DIODE LASERS

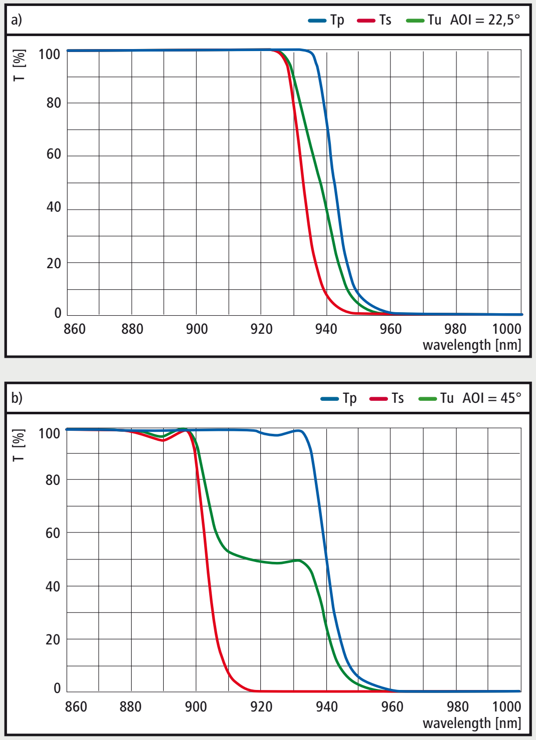


Figure 5: Transmittance spectra of conventional steep edge filters HR (980 nm) > 99.9 % + R (915 nm) < 5 % which are used as combiners for pump laser diodes at 915 nm and 980 nm;
a) HRs,p (22.5°, 980 nm) > 99.9 % + Rs,p (22.5°, 915 nm) < 2 %
b) HRs,p (45°, 980 nm) > 99.9 % + Rp (45°, 915 nm) < 2 %

- At AOI = 22.5° the conventional steep edge filter separates 915 nm and 980 nm for p- and s-polarized and unpolarized light.
- To preserve the steep edge at AOI = 45° the radiation must be polarized and only one polarization can be used. Unpolarized light changes the slope of the edge significantly.

SPECIAL STEEP EDGE COMBINERS FOR UNPOLARIZED LIGHT

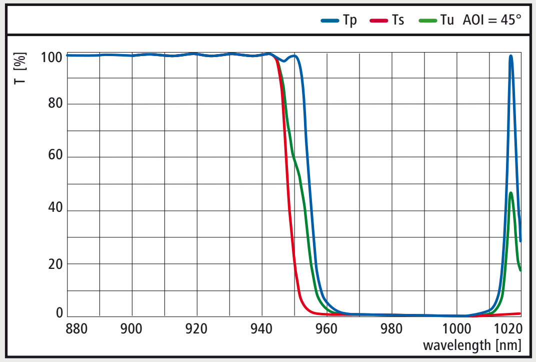


Figure 6: Transmittance spectra of a special steep edge filter HRu (45°, 980 nm) > 99.8 % + Ru (45°, 940 nm) < 3 %

- Filters of this type can be used as separators or combiners for s- and p-polarized light even at 45° incidence.
- The cut-on / cut-off edges for the two polarizations only show a spectral separation of about 10nm.
- Consequently, these filters can be applied as combiners for unpolarized light of 940 nm and 980 nm diodes at AOI = 45°.

WINDOWS AND LENSES

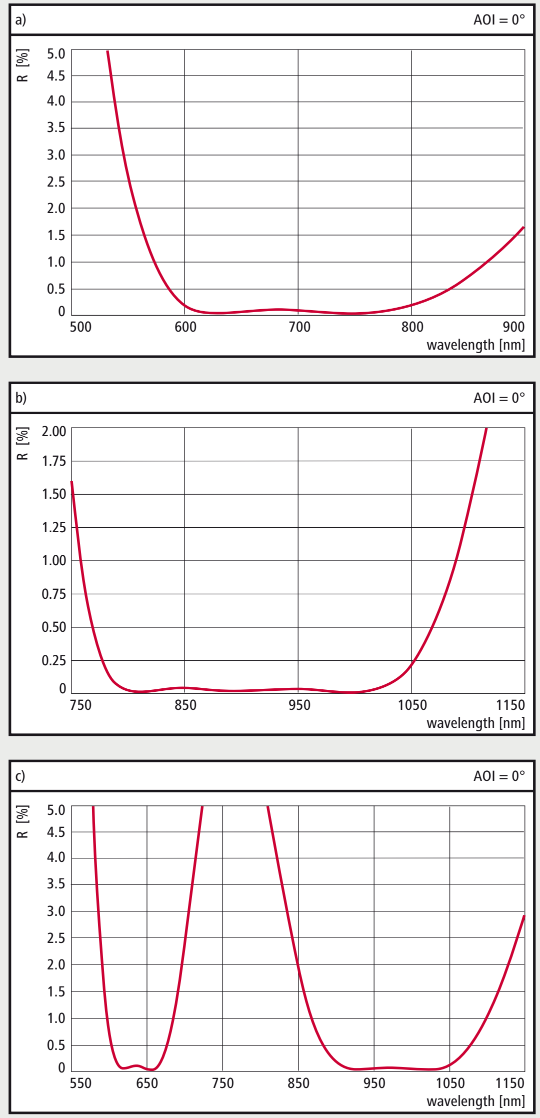


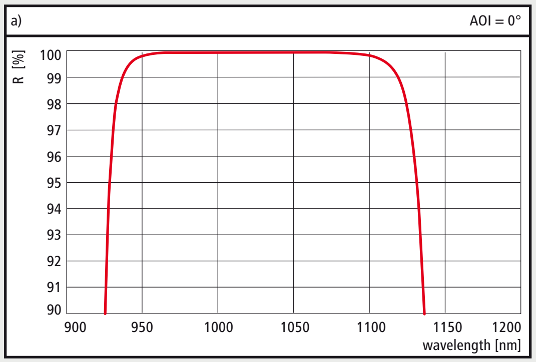
Figure 7: Reflectance spectra of broadband AR coatings for several types of laser diodes:
a) AR (0°, 600 – 800 nm) < 0.5 %
b) AR (0°, 790 – 1050 nm) < 0.5 %
c) Broadband AR coating which is combined with an AR coating for an alignment laser:
AR (0°, 633 + 900 – 1000 nm) < 0.5 %

- High quality substrates and lenses of fused silica.
- SUPRASIL 300® or SUPRASIL 3001/3002® substrates on request.
- Broadband and multiple wavelength AR coatings according to customer specifications.

COMPONENTS FOR Yb:YAG, Yb:KGW AND Yb-DOPED FIBER LASERS

In recent years, lasers using Yb-doped crystals or fibers have seen an increase in importance. Yb:YAG thin disk lasers as well as Yb-doped fiber lasers were developed to achieve high cw output power of about 10 kW and excellent beam quality. Yb:YAG and Yb:KGW lasers can also be operated as high-power lasers in the ns to fs range.

MIRRORS



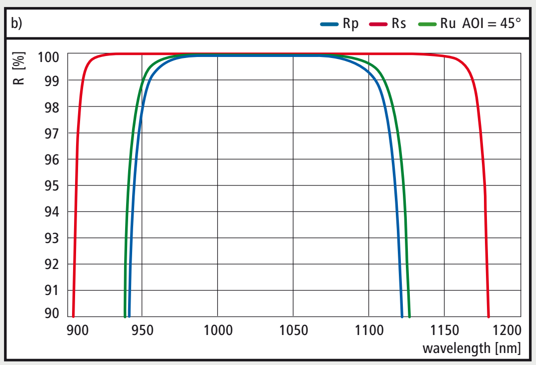


Figure 1: Reflectance spectra of HR mirrors for 1030 nm
a) Cavity mirror b) Turning mirror

Lasers with **extremely high output power** (e.g. >10 kW cw) are often based on Yb:YAG. LAYERTEC has developed different coating designs for handling extraordinarily high fluences. The designs **are optimized either for cw radiation, ns pulses or ps pulses.**

EDGE FILTERS AND PUMP MIRRORS

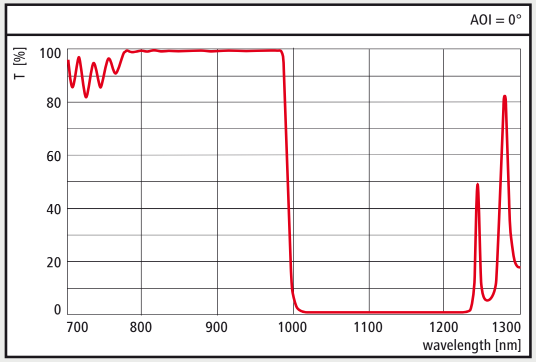


Figure 2: Transmittance spectrum of a steep edge short-wavelength pass filter
HR (0°, 1030 nm) > 99.9 % + R (0°, 808 – 980 nm) < 0.5 % (back side AR coated)

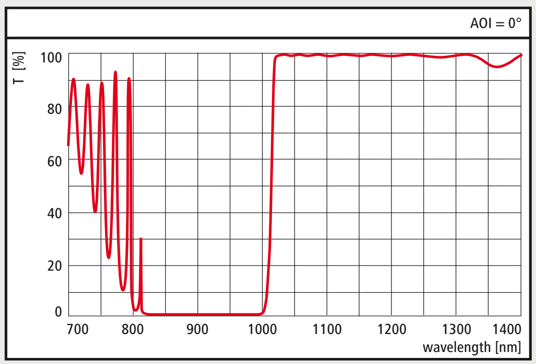


Figure 3: Transmittance spectrum of a steep edge long-wavelength pass filter
HR (0°, 915 – 980 nm) > 99.8 %
+ R (0°,1030 – 1200 nm) < 3 %
for use as output mirror of a fiber laser (back side AR coated)

Special features:

- Short-wavelength pass filters with a very steep edge which are utilized as a pump mirror for solid-state lasers based on Yb-doped materials (e.g. Yb:YAG, Yb:KGW, Yb-doped fiber).
- Also useful for Nd-doped and Yb-Nd-co-doped materials.

SPECIAL OUTPUT COUPLERS

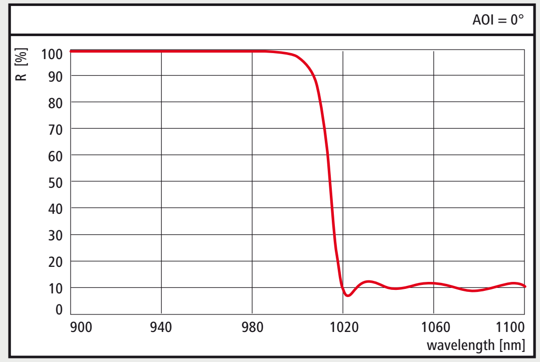


Figure 4: Reflectance spectrum of an output mirror for a fiber laser
HR (0°, 976 – 980 nm) > 99.9 %
+ PR (0°, 1030 – 1100 nm) = 10 % ± 2 %
which blocks the diode radiation at 980 nm and has partial reflectance for 1030 – 1100 nm (back side AR coated)

Special features:

- Transmittance T > 99 % at 808 nm – 990 nm, reflectance R > 99.9 % at 1030 nm, i.e. transition from the high transmittance range to the high reflectance range within 4 % of the laser wavelength.
- Environmentally stable.

LIDT - INFO

100 MW / cm², 1064 nm, cw

Measured with a high power fiber laser at Institut für Angewandte Physik, Friedrich-Schiller-Universität Jena

1020 – 1080 nm

THIN FILM POLARIZERS

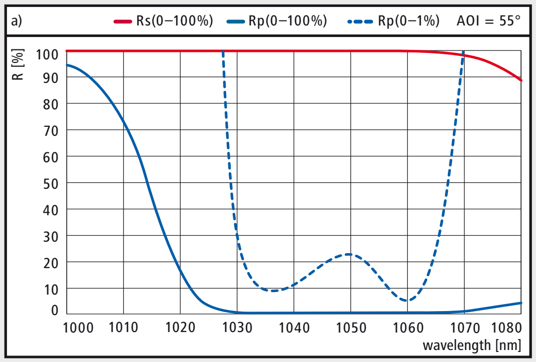


Figure 5a: Reflectance spectra for s- and p-polarized light of a broadband thin film polarizer showing a bandwidth of 25 nm with Rp < 0.2 % (AOI = 55°)

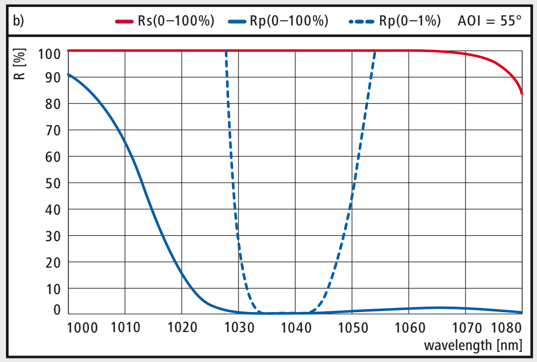


Figure 5b: Reflectance spectra for s- and p-polarized light of a narrow band thin film polarizer which is optimized for very low Rp values and easy angle adjustment for the optimization of the polarizer performance (AOI = 55°)

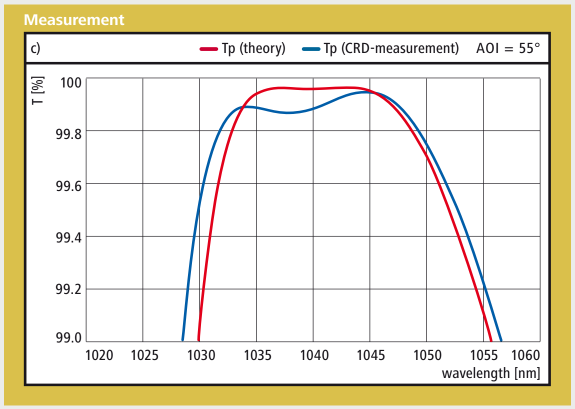


Figure 5c: Calculated and measured transmittance spectra for p-polarized light of a narrow band thin film polarizer according to the design shown in fig. 5b (AOI = 55°). Tp > 99.8 % is reached with a bandwidth of 15 nm and Tp > 99.9 % can be achieved within a bandwidth of 5 nm. The spectral position of this transmittance maximum can be adjusted to any wavelength between 1035 nm and 1045 nm by angle adjustment.

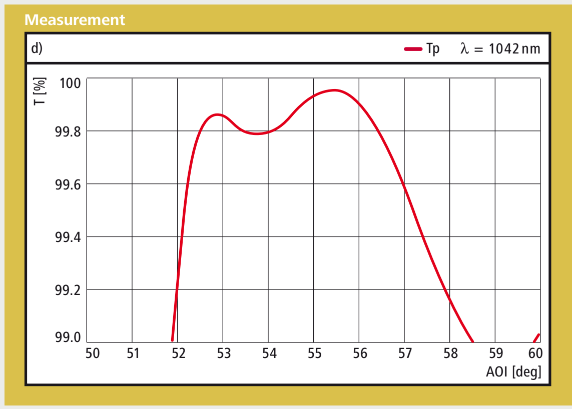


Figure 5d: Transmittance spectrum Tp vs. AOI at 1042 nm **measured** at the polarizer shown in fig.5c

Thin film polarizers are key elements for regenerative amplifiers in ns- and ps-lasers. LAYERTEC optimizes its polarizer designs for high laser- induced damage thresholds. Figure 5 shows examples of a broadband polarizer with Rp (55°) < 0.2 % within a bandwidth of 25 nm in the wavelength range of Yb-doped fiber lasers (fig.5a) and a narrow band polarizer which is optimized for very low Rp values at a single wavelength (fig.5b). Figure 5c shows a comparison of the calculated transmittance spectrum for p-polarized light and a measurement in a CRD setup. Figure 5d shows Tp vs. AOI for the same polarizer (measured at 1042 nm). These measurements prove that **Tp > 99.9 %** can be reached by **angle adjustment**. This is important especially for intra-cavity applications.

PICOSECOND LASERS ON THE BASIS OF Yb-DOPED MATERIALS

Picosecond lasers, i.e. lasers with pulse lengths of some hundred fs to 10 ps, can be built based on Yb:YAG, Yb:KGW and Yb:KYW. These lasers enable materials to be processed without unwanted thermal effects such as melting, which results in unprecedented accuracy of the processes. Moreover, ps lasers do not require chirped pulse amplification which reduces the cost compared to fs lasers. Laser systems with an average power in the kW range are available.

Picosecond laser optics require specially designed optics to achieve high laser damage thresholds. For detailed information please see pages 88 – 89. For GTI mirrors which are often used for pulse compression from the ps range down to a few hundred fs please see pages 96 – 97.

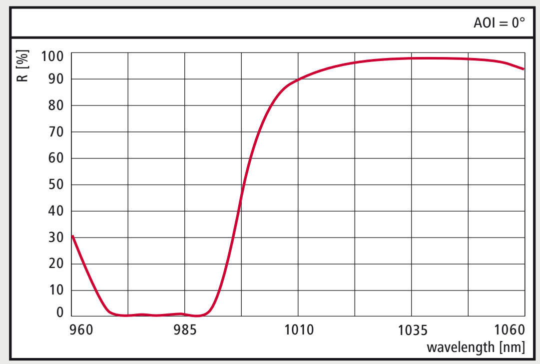


Figure 6: Reflectance spectrum of a special output coupler with high transmittance for the pump radiation:
PR (0°, 1040 nm) = 98 % + R (0°, 975 – 985 nm) < 2 %.
Moreover, this output coupler exhibits |GDD| < 20 fs² around 1040 nm

LIDT - INFO

4 - 6 J / cm² depending on design,
1030 nm, 10 ps, 1 kHz, Ø 50 µm

Measurements were performed by Lidaris Ltd., Lithuania.

COMPONENTS FOR Nd:YAG/Nd:YVO$_4$ LASERS

CAVITY MIRRORS

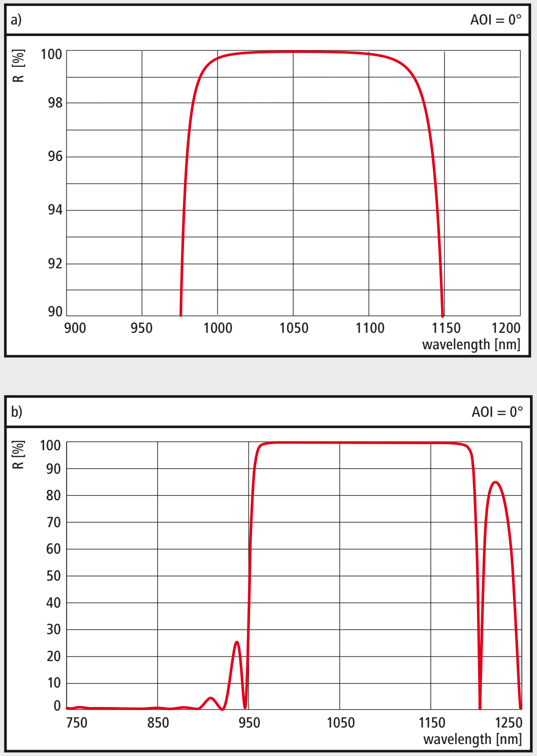


Figure 1: Reflectance spectra of HR mirrors for 1064 nm
a) High power cavity mirror
b) Pump mirror
HR (0°, 1064 nm) > 99.9 % + R (0°, 808 nm) < 2 %

- HR cavity mirrors with R > 99.9 %.
- Typical reflectance: R > 99.95 %.
- On request, LAYERTEC guarantees R > 99.99 % (delivery with Cavity Ring-Down measurement report).
- Spectral bandwidth of about 70 nm
- Pump mirrors
  HR (0°,1064 nm) > 99.9 % + R (0°, 808 nm) < 2 %.

LIDT - INFO

> 50 MW / cm², 1064 nm, cw, 1-on-1
> 50 J / cm², 1064 nm, 10 ns, 1-on-1
> 100 J / cm² on request for 10 ns pulses

TURNING MIRRORS, SEPARATORS AND COMBINERS

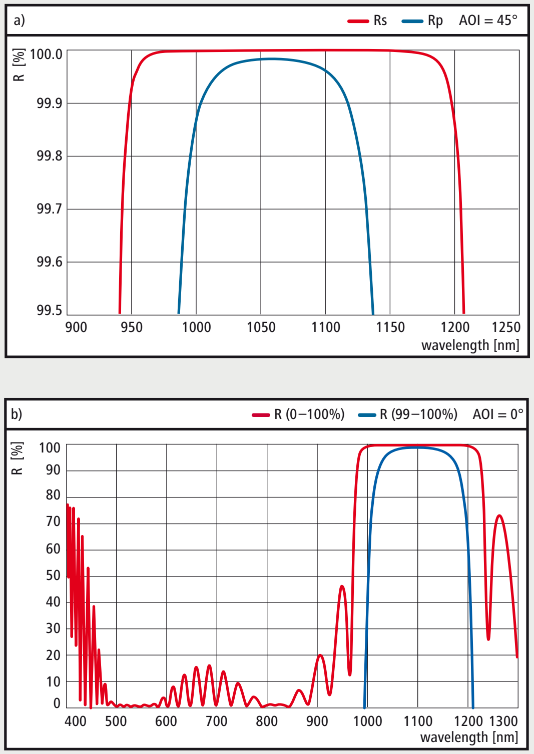


Figure 2: Reflectance spectra of special mirrors for 1064 nm
a) High power turning mirror
b) Separator for the second harmonic from the fundamental
HR (0°, 1064 nm) > 99.9 % + R (0°, 532 + 808 nm) < 3 %

- HR turning mirrors with R > 99.9 % for s- and p-polarization.
- Optics for the harmonics of the Nd:YAG /Nd:YVO$_4$ laser are presented on pages 58 – 63.

ALIGNMENT AND PROCESS MONITORING

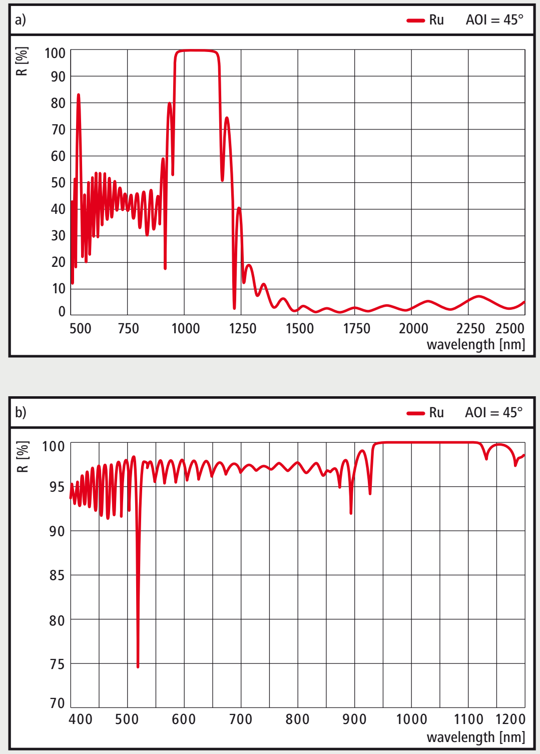


Figure 3: Reflectance spectra of turning mirrors with special features for alignment and process monitoring
a) Turning mirror for the laser beam with a partial reflector for the alignment laser and high IR transmittance for process monitoring
b) Silver based turning mirror with Ru (45°, 1064 nm) > 99.8 % and with Ru > 80 % for an alignment laser in the red spectral range

1064 nm

THIN FILM POLARIZERS

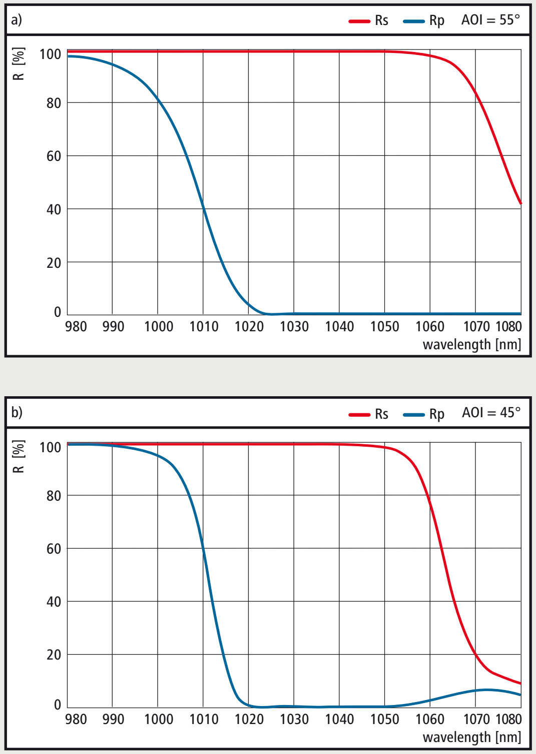


Figure 4: Reflectance spectra of thin film polarizers for 1040 nm
a) Standard TFP (AOI = 55°)
b) Special TFP (AOI = 45°)

Thin film polarizers working at the Brewster angle exhibit a considerably broader bandwidth than those working at AOI = 45°:
Bandwidth for Tp/Ts > 1000

- Standard: AOI = 55° → 40 – 60 nm
- Special: AOI = 45° → 15 – 25 nm

depending on design.

BEAM SPLITTERS AND OUTPUT COUPLERS

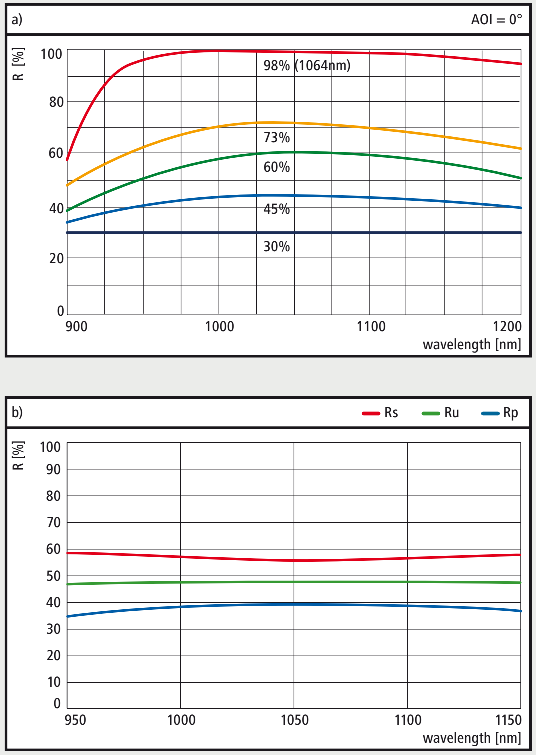


Figure 5: Reflectance spectra of output couplers and beam splitters
a) Output couplers with different degrees of reflectance
b) Common 50 : 50 beam splitter for unpolarized light

Beam splitters and output couplers can be produced with a precisely adjusted degree of reflectance:

Reflectance	Tolerance
R > 95 %	± 0.5 %
R = 80 % ... 95 %	± 1 %
R = 10 % ... 80 %	± 2 %

NON-POLARIZING BEAM SPLITTERS

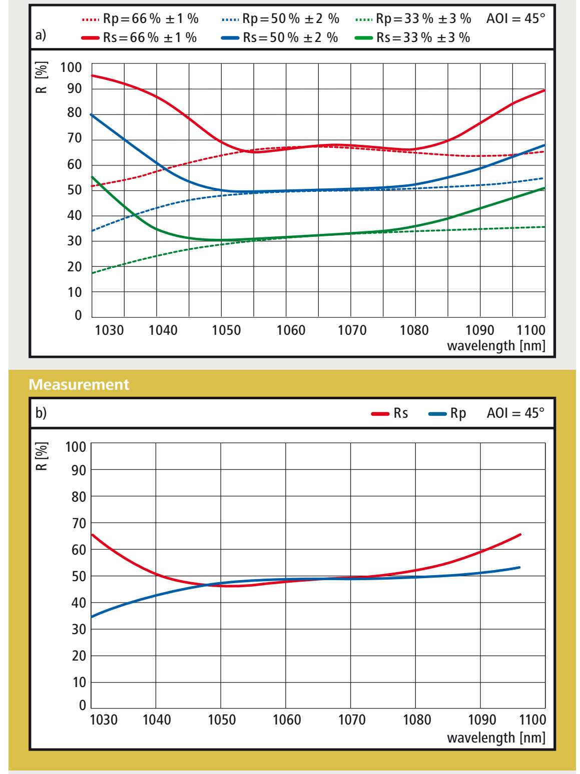


Figure 6: Non-polarizing beam splitters
a) Calculated reflectance spectra of 3 types of non-polarizing beam splitters for AOI = 45°
b) Measured reflectance spectra of the 50 % beam splitter

- Beam splitters with Rs ≈ Rp (|Rs - Rp| < 1.5 %) for AOI = 45° and different degrees of reflectance.
- Common types: Rs,p = 66 % ± 1 %
  Rs,p = 50 % ± 2 %
  Rs,p = 33 % ± 3 %.
- All non-polarizing beam splitters with rear side AR (Rs ≈ Rp ≤ 0.6 %).

COMPONENTS FOR THE SECOND HARMONIC OF Nd:YAG, Nd:YVO_4 AND Yb:YAG LASERS

The harmonics of Nd:YAG, Nd:YVO_4 and Yb:YAG lasers are widely used for materials processing as well as for measurement applications. Moreover, the second harmonic of these lasers is often used as a pump source for Ti:Sapphire lasers. LAYERTEC offers a variety of optics for 532 nm: dual wavelength mirrors, separators, thin film polarizers and non-polarizing beam splitters, but also cavity optics for compact diode pumped lasers of different configurations. Coatings for 515 nm are available as well. All designs are calculated according to customer specification.

DUAL WAVELENGTH TURNING MIRRORS

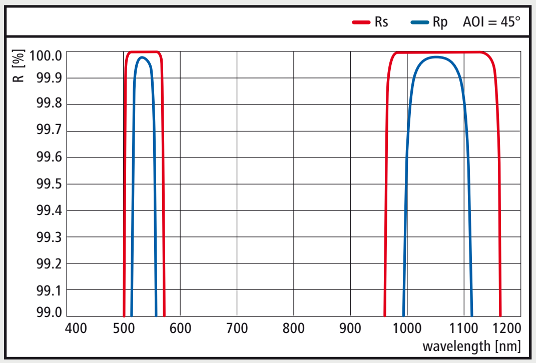


Figure 1: Reflectance spectra of a dual wavelength turning mirror HRs,p (45°, 532 + 1064 nm) > 99.9 %

DUAL WAVELENGTH CAVITY MIRRORS

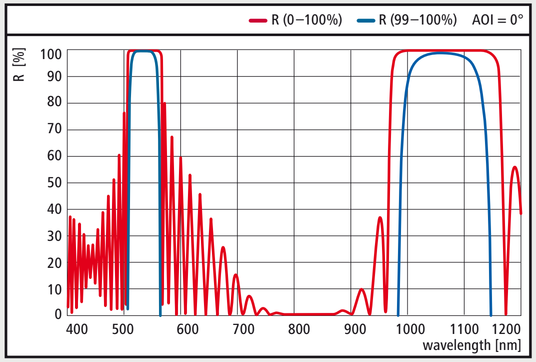


Figure 2: Reflectance spectra of a dual wavelength cavity mirror with high transmittance for the pump wavelength (808 nm)

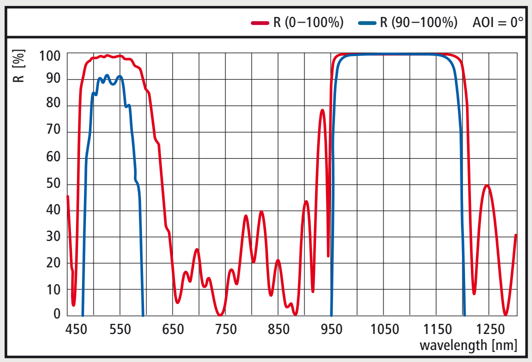


Figure 3: Reflectance spectra of a HR mirror for 1064 nm with additional output coupler for 532 nm:
HR (0°, 1064 nm) > 99.9 %
+ R (0°, 532 nm) = 99 % ± 0.3 %

SEPARATORS FOR THE SECOND HARMONIC AND THE FUNDAMENTAL WAVE

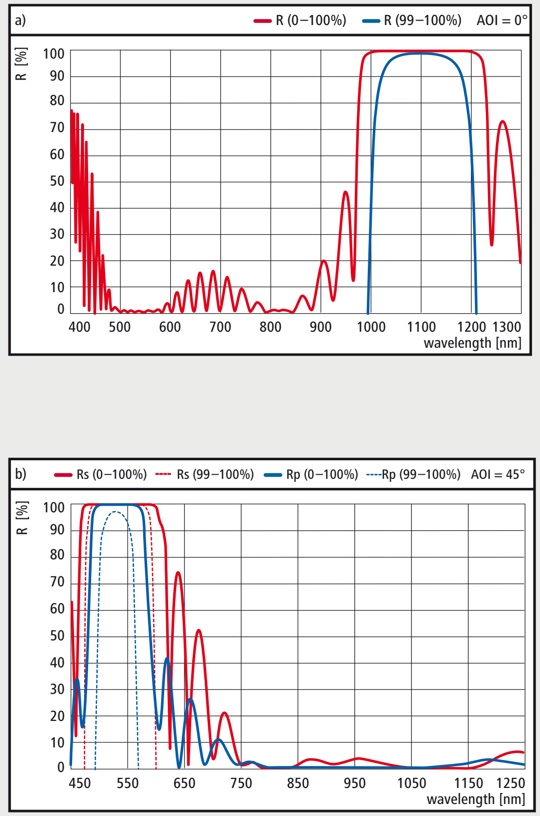


Figure 4: Reflectance spectra of separators for the second harmonic and the fundamental wavelength:
a) HR(0°,1064 nm) > 99.9 % + R (0°, 532 + 808 nm) < 3 %
b) HRs,p (45°, 532 nm) > 99.9 %
+ Rs,p (45°, 808 + 1064 nm) < 2 %

Separators with different features are available according to customer specifications.

515 nm, 532 nm

THIN FILM POLARIZERS

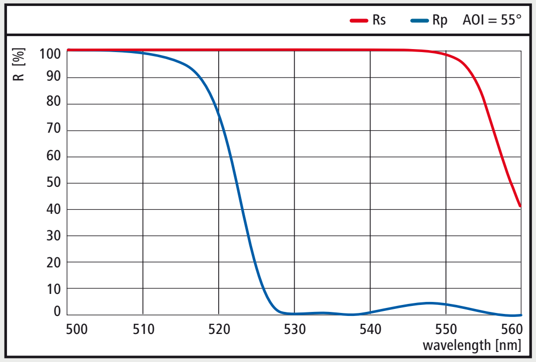


Figure 5: Reflectance spectra of a thin film polarizer for 532 nm

The transmittance of thin film polarizers for p-polarized light can be measured in-house with high accuracy using a modified Cavity Ring-Down setup.

NON-POLARIZING BEAM SPLITTERS

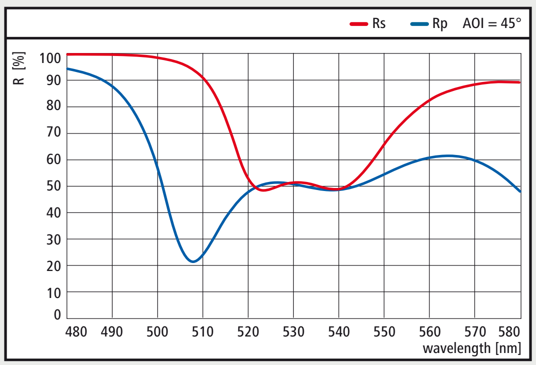


Figure 6: Reflectance spectra of a non-polarizing beam splitter for 532 nm with Rs = Rp = 50 ± 2 % (|Rs - Rp| < 3 %)

COMPONENTS FOR THE SECOND AND THIRD HARMONIC

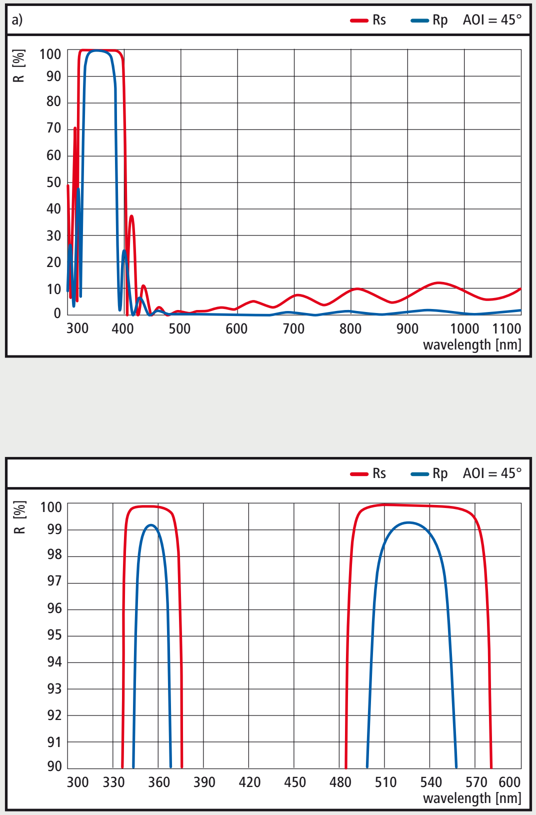


Figure 7: Reflectance spectra of mirrors and separators
a) Separator for the third harmonic and the second harmonic and the fundamental wave
b) Dual wavelength turning mirror for 355 nm and 532 nm

For common specifications of separators for the harmonics in the UV spectral range please see table on page 63. Please do not hesitate to contact us for separators or mirrors with other angles of incidence.

COATINGS ON NONLINEAR OPTICAL CRYSTALS

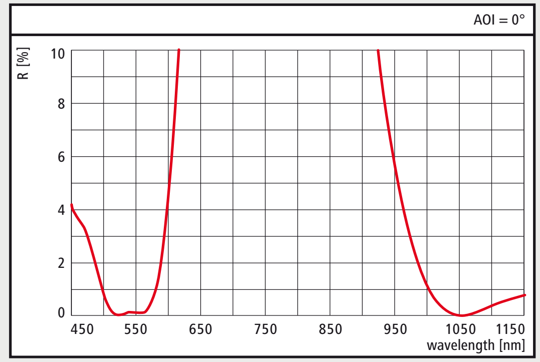


Figure 8: Reflectance spectrum of a dual wavelength antireflection coating on KTP for 532 nm and 1064 nm

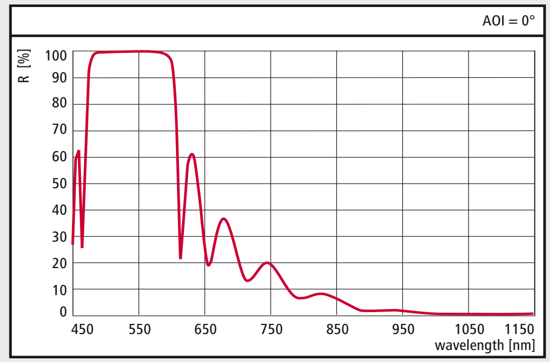


Figure 9: Reflectance spectrum of a dichroic mirror on KTP:
HR (0°, 532 nm) > 99.98 % + R (0°, 1064 nm) < 0.2 %
optimized for very high transmittance at 1064 nm

Nonlinear optical crystals are the key elements for frequency conversion. LAYERTEC offers a variety of coatings on crystals like KTP and lithium niobate. For more information about coatings on crystals see pages 116 – 117.

COMPONENTS FOR THE THIRD HARMONIC OF Nd:YAG, Nd:YVO_4 AND Yb:YAG LASERS

STANDARD COMPONENTS

The third harmonic of Nd:YAG, Nd:YVO_4 and Yb:YAG lasers has gained importance in the field of materials processing, for measurement applications and as pump source for optical parametric oscillators. LAYERTEC manufactures a wide range of optics for 355 nm: single and multiple wavelength mirrors, separators, thin film polarizers and antireflection coatings. The coating designs shown here are calculated for 355 nm, but designs for 343 nm are available as well. In general, the designs are calculated according to customer specifications.

TURNING MIRRORS

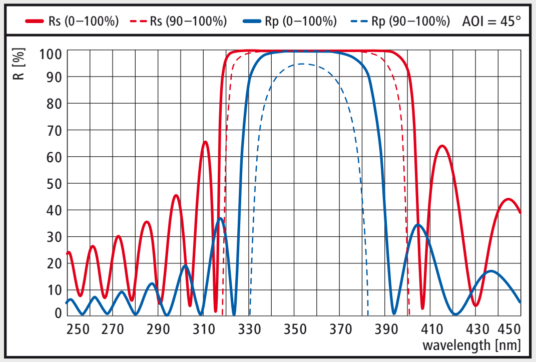


Figure 1: Reflectance spectra of a turning mirror
HRs (45°, 355 nm) > 99.9 %
+ HRp (45°, 355 nm) > 99.5 %

STANDARD SEPARATORS

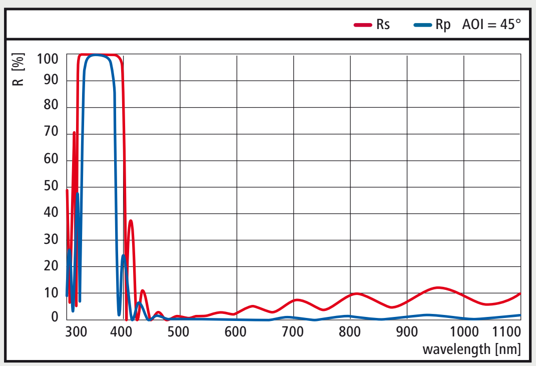


Figure 2: Reflectance spectra of a standard separator reflecting the third harmonic and transmitting the second harmonic and the fundamental wave:
HRs (45°, 355 nm) > 99.9 % + HRp (45°, 355 nm) > 99.5 %
+ Rp (45°, 532 + 1064 nm) < 2 % + Rs (45°, 532 nm) < 5 %
+ Rs (45°, 1064 nm) < 10 %

SPECIAL SEPARATORS

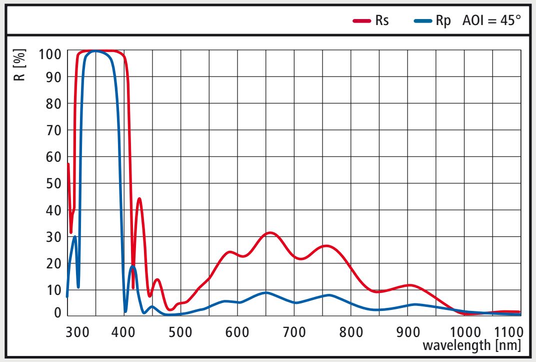


Figure 3: Reflectance spectra of a special separator optimized for low reflectance at 1064 nm:
HRs (45°, 355 nm) > 99.9 % + HRp (45°, 355 nm) > 99.5 %
+ Rp (45°, 532 + 1064 nm) < 2 % + Rs (45°, 532 nm) < 5 %
+ Rs (45°, 1064 nm) < 2 %

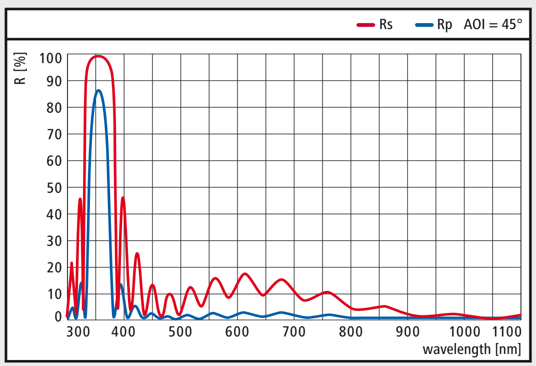


Figure 4: Reflectance spectra of a special separator reflecting the third harmonic and transmitting the second harmonic and the fundamental wavelength:
HRs (45°, 355 nm) > 95 % + Rp (45°, 532 nm) < 2 %
+ Rs,p (45°, 1064 nm) < 2 %; substrate and coatings consist of fluoride materials

Separators based on fluorides show an extended lifetime at high power densities.

WINDOWS AND LENSES

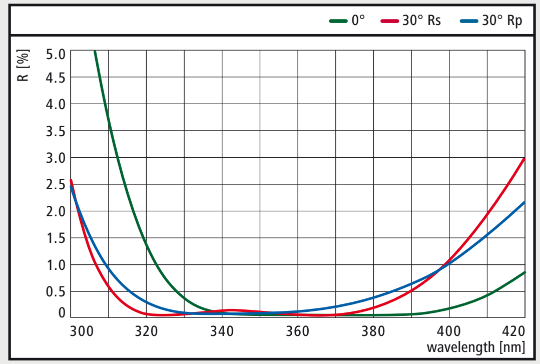


Figure 5: Reflectance spectra of a single wavelength AR coating for 355 nm optimized for AOI = 0°– 30°

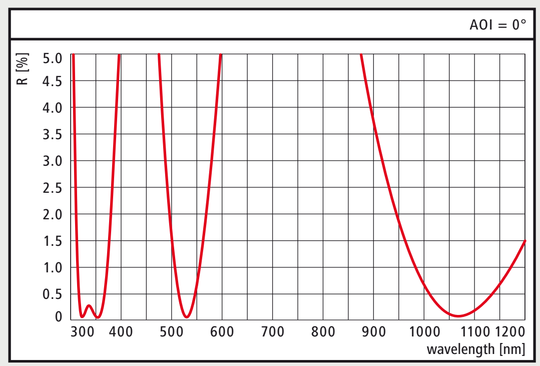


Figure 6: Reflectance spectrum of a triple wavelength antireflection coating on fused silica for 355 nm, 532 nm and 1064 nm

343 nm, 355 nm

SPUTTERED COMPONENTS

MULTIPLE WAVELENGTH MIRRORS

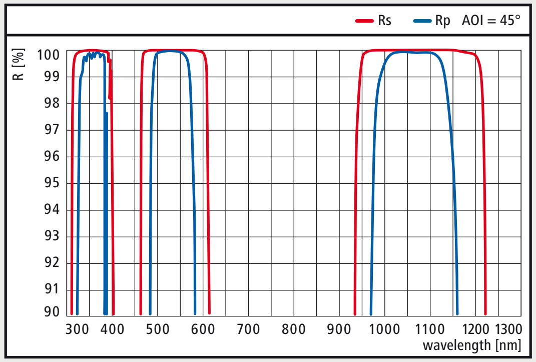


Figure 7: Reflectance spectra of a triple wavelength turning mirror for 355 nm, 532 nm and 1064 nm

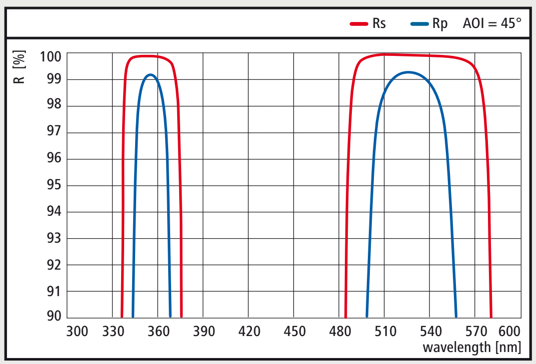


Figure 8: Reflectance spectra of a dual wavelength turning mirror for 355 nm and 532 nm

SEPARATORS WITH HIGH TRANSMITTANCE IN THE UV RANGE

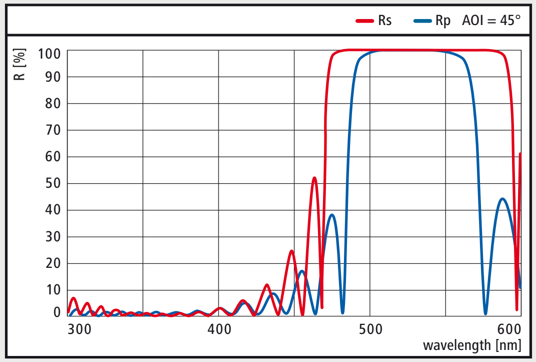


Figure 9: Reflectance spectra of a special separator for the third harmonic and the second harmonic:
HRs,p (45°, 532 nm) > 99.8 % + Rs,p (45°, 355 nm) < 2 %

Due to the low scattering losses of sputtered components a transmittance of T > 98 % is achieved for this type of separators.

THIN FILM POLARIZERS

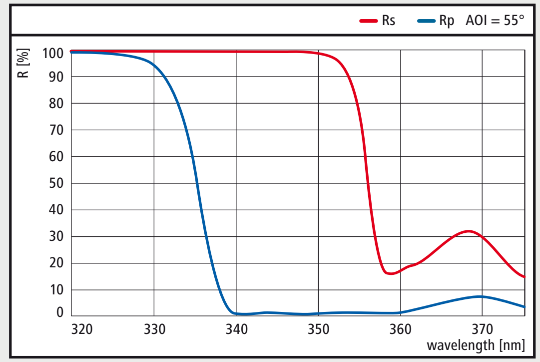


Figure 10: Reflectance spectra of a thin film polarizer for 343 nm:
HRs (55°, 343 nm) > 99.5 % + Rp (55°, 343 nm) < 2 %

The transmittance of p-polarized light can be optimized by angle adjustment. Tilting the polarizer by ± 2° shifts the minimum of Rp to longer or shorter wavelengths which can improve the polarization ratio significantly.

TECHNICAL DATA OF MIRRORS AND SEPARATORS

Type of coating	Standard	Sputtered
Mirror for AOI = 0°	R > 99.7 %	R > 99.9 %
Turning mirror	Rs > 99.9 %, Rp > 99 %	Rs > 99.95 %, Rp > 99.8 %
Separator AOI = 45°	Rs (355 nm) > 99.9 % Rp (355 nm) > 99 % Rs (532 nm) < 5 % Rp (532 nm) < 2 % Rs (1064 nm) < 10 %, Rp (1064 nm) < 2 %	Rs (355 nm) > 99.9 % Rp (355 nm) > 99.7 % Rs (532 nm) < 2 % Rp (532 nm) < 1 % Rs (1064 nm) < 2 %, Rp (1064 nm) < 1 %

COMPONENTS FOR THE HIGHER HARMONICS OF Nd:YAG AND Nd:YVO$_4$ LASERS

The harmonics of Nd:YAG and Nd:YVO$_4$ lasers are widely used for materials processing as well as for measurement applications. LAYERTEC offers a variety of optics utilizing the fourth (266 nm) and fifth (213 nm) harmonic. All designs are calculated according to customer specifications.

MULTIPLE WAVELENGTH MIRRORS

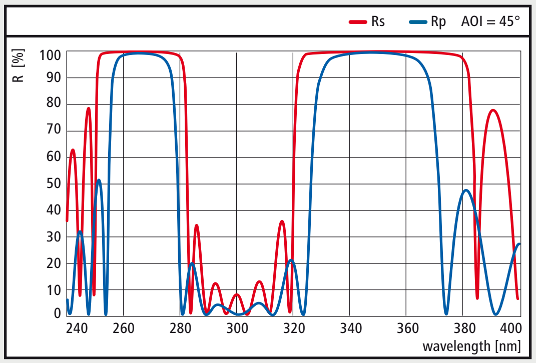


Figure 1: Reflectance spectra of a dual wavelength turning mirror for 266 nm and 355 nm

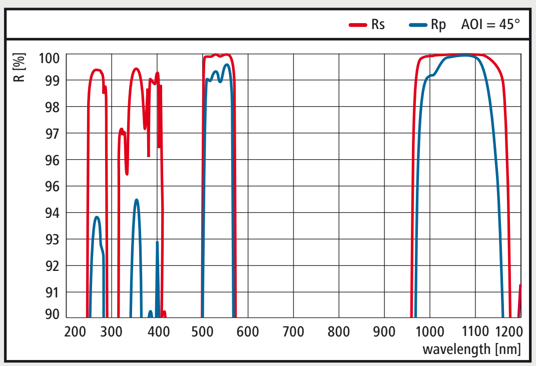


Figure 2: Reflectance spectra of a four wavelength turning mirror:
HRs (45°, 266 nm + 355 nm) > 99 %
+ HRs (45°, 532 nm + 1064 nm) > 99.9 %

SEPARATORS FOR THE FOURTH HARMONIC

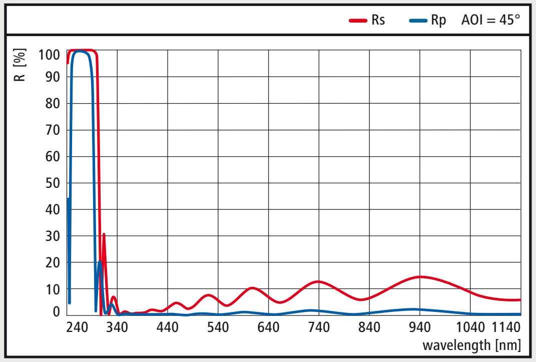


Figure 3: Reflectance spectra of a separator reflecting the fourth harmonic and transmitting the lower harmonics and the fundamental

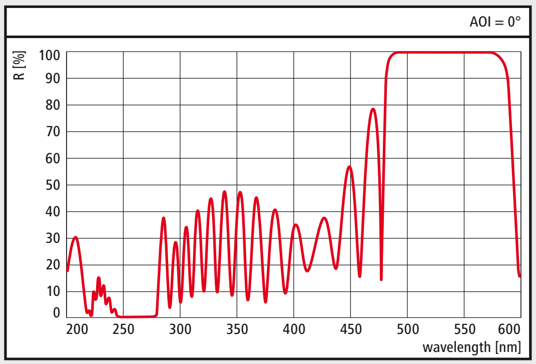


Figure 4: Reflectance spectrum of a special separator for the second harmonic and the fourth harmonic:
HR (0°, 532 nm) > 99.95 % + R (0°, 266 nm) < 5 %

SEPARATORS FOR THE FIFTH HARMONIC

Measurement

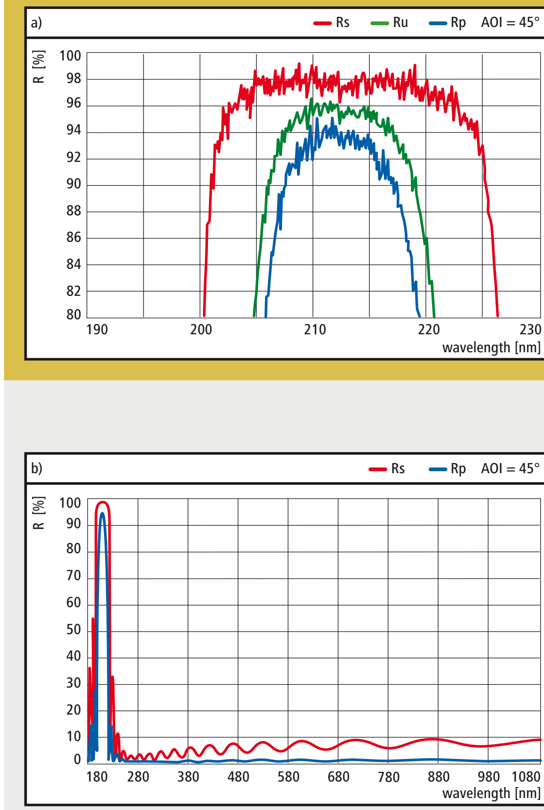


Figure 5: Reflectance spectra of fluoride coatings on CaF_2:
a) Turning mirror for the fifth harmonic (measured spectra)
b) Separator reflecting the fifth harmonic and transmitting the lower harmonics and the fundamental

For high power applications LAYERTEC recommends fluoride coatings on calcium fluoride which are manufactured according to the technology for ArF-excimer laser mirrors.

213 nm, 266 nm

SPECIAL SEPARATORS

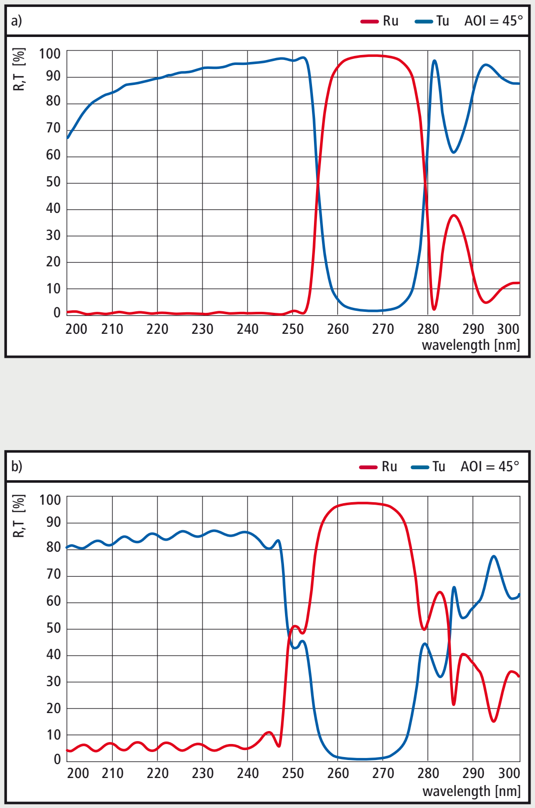


Figure 6: Reflectance spectra of separators for the fourth and fifth harmonics:
HRu (45°, 266 nm) > 98 % + Ru (45°, 213 nm) < 10 % for unpolarized light
a) Oxide coatings optimized for low scattering losses
b) Fluoride coatings for high laser induced damage thresholds

The fifth harmonic at 213 nm is a critical wavelength for oxide coatings because the absorption edge of aluminum oxide begins in this wavelength range. However, aluminum oxide is the only high index oxide material which can be used for 213 nm.

Compared to fluorides, oxide coatings are hard and show low scattering losses. Fluorides exhibit higher LIDT values and extended lifetime for medium and high power applications.

THIN FILM POLARIZERS

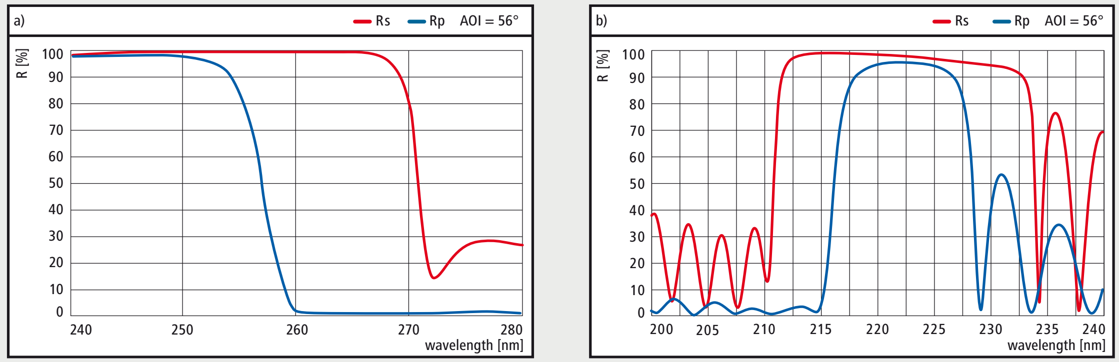


Figure 7: Reflectance spectra of thin film polarizers for 266 nm and 213 nm:
a) HRs (56°, 266 nm) > 98 % + Rp (56°, 266 nm) < 5 %, Tp (56°, 266 nm) ≈ 95 %
b) HRs (56°, 213 nm) > 97 % + Rp (56°, 213 nm) < 5 %, Tp (56°, 213 nm) ≈ 75 %

Sputtering techniques enable LAYERTEC to offer thin film polarizers also for the fourth and fifth harmonic of the Nd:YAG laser.

Common specifications of separators for the harmonics in the UV spectral range:

Separator type	Type	Reflectance at center wavelength [%]		Reflectance at the corresponding longer Nd:YAG wavelengths [%]							
				266 nm		355 nm		532 nm		1064 nm	
		Rs	Rp	Rs	Rp	Rs	Rp	Rs	Rp	Rs	Rp
3rd harmonic, 355 nm	IAD	> 99.9	> 99.5					< 5	< 2	< 10	< 2
	sputtered	> 99.9	> 99.8					< 2	< 1	< 2	< 1
4th harmonic, 266 nm	IAD	> 99.7	> 99.4			< 5	< 2	< 10	< 2	< 10	< 2
	sputtered	> 99.8	> 99.5			< 5	< 1	< 2	< 1	< 2	< 1
5th harmonic, 213 nm*	evaporated	> 97	> 93	< 5	< 2	< 10	< 2	< 10	< 2	< 10	< 2

Table 1: Common specifications of separators for the harmonics in the UV
*Fluoride coating on CaF_2

COMPONENTS FOR WEAK Nd:YAG OR Nd:YVO_4 LASER LINES

Neodymium doped crystals exhibit laser transitions at different wavelengths. Tables 1 and 2 give an overview about the laser wavelengths of the most common Nd-doped materials Nd:YAG and Nd:YVO_4.

Nd:YAG	
Laser lines	**Second harmonic**
946 nm	473 nm
1064 nm	532 nm
1123 nm	561 nm
1319 nm	659 nm

Table 1: Laser lines and corresponding wavelengths of the second harmonic of Nd:YAG

Nd:YVO_4	
Laser lines	**Second harmonic**
915 nm	457 nm
1064 nm	532 nm
1340 nm	670 nm

Table 2: Laser lines and corresponding wavelengths of the second harmonic of Nd:YVO_4

A variety of laser lines in the VIS and NIR can be obtained from these crystals. This process is utilized to build compact diode pumped solid state lasers with a variety of wavelengths which are used for measurement applications as well as for projection systems (RGB lasers).

The strongest laser transition in both materials is the 1064 nm line. Efficient laser radiation at other wavelengths is only possible by suppressing this line. LAYERTEC offers a variety of laser mirrors for this application.

Compact laser designs also include the pump diode (808 nm) and a unit for the second harmonic generation. This is the reason why coatings for Nd:YAG or Nd:YVO_4 wavelengths apart from 1064 nm mostly show several spectral regions of high transmittance as well as high reflection. All coatings are designed according to customer specifications, because the specifications depend on the laser design. All examples on these pages are for Nd:YAG wavelengths. Coatings for Nd:YVO_4 can be designed and produced as well.

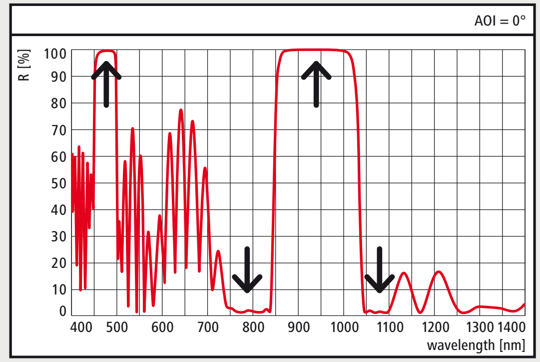


Figure 1: Reflectance spectrum of a dual wavelength mirror for a weak laser line and its second harmonic with high transmittance for the pump wavelength and the strongest laser line: HR (0°, 473 nm) > 99.85 %
+ HR (0°, 946 nm) > 99.95 %
+ R (0°, 808 nm) < 2 %
+ R (0°, 1064 nm) < 5 %

Feature	Reflectance
Suppression of the strongest laser line	R (0°, 1064 nm) < 5 %
HR mirror for the weak laser line	R (0°, 946 nm) > 99.95 %
High transmittance for the pump wavelength	R (0°, 808 nm) < 2 %
HR mirror for the second harmonic of the weak laser line	HR (0°, 473 nm) > 99.85 %

915 nm, 946 nm, 1123 nm, 1340 nm

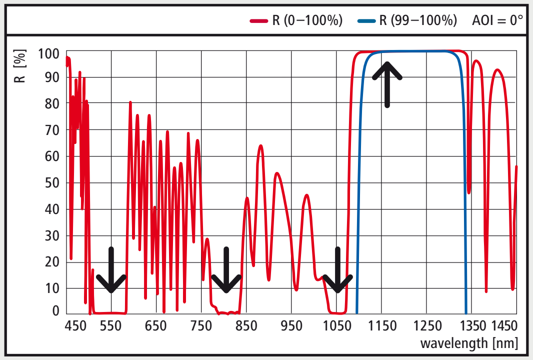


Figure 2: Reflectance spectrum of a dichroic mirror with high transmittance for the pump wavelength which also suppresses the 1064 nm line:
HR (0°, 1123 nm) > 99.9 %
+ R (0°, 561 nm) < 2 %
+ R (0°, 808 nm) < 10 %
+ R (0°, 1064 nm) < 50 %

Feature	Reflectance
HR mirror for the weak laser line	HR (0°, 1123 nm) > 99.9 %
Suppression of the strongest laser line	R (0°, 1064 nm) < 50 %
High transmittance for the pump wavelength	R (0°, 808 nm) < 10 %
High transmittance for the second harmonic of the weak laser line	R (0°, 561 nm) < 2 %

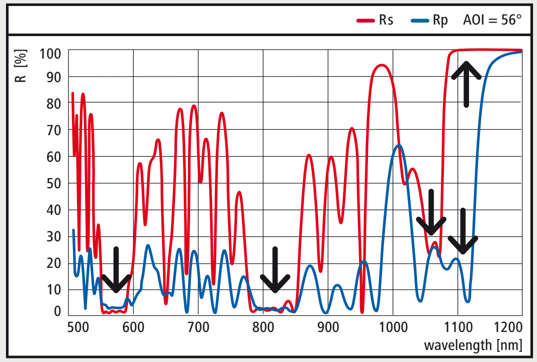


Figure 3: Reflectance spectra of a thin film polarizer with high transmittance for the pump wavelength and the second harmonic which also suppresses the 1064 nm line:
HRs (56°, 1123 nm) > 99.9 %
+ Rp (56°, 1123 nm) < 50 %
+ Rs,p (56°, 561 nm + 808 nm) < 10 %
+ Rs,p (56°, 1064 nm) < 50 %

Feature	Reflectance
HR for s-polarized light of the weak laser line	HRs (56°, 1123 nm) > 99.9 %
Suppression of p-polarized light of the weak laser line	Rp (56°, 1123 nm) < 50 %
Suppression of the strongest laser line	Rs,p (56°,1064 nm) < 50 %
High transmittance for the pump wavelength	Rs,p (56°, 808 nm) < 10 %
High transmittance for the second harmonic of the weak laser line	Rs,p (56°, 561 nm) < 10 %

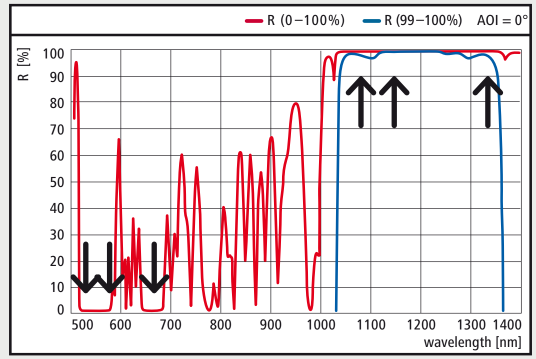


Figure 4: Reflectance spectrum of a dichroic mirror with high reflectance for the NIR wavelengths and high transmittance for the corresponding second harmonic wavelengths:
HR (0°, 1064 nm + 1123 nm + 1319 nm) > 99.9 %
+ R (0°, 532 - 561 nm + 659 nm) < 2 %

Feature	Reflectance
Broadband HR mirror for several laser lines	HR (0°, 1064 nm + 1123 nm + 1319 nm) > 99.9 %
High transmittance for the second harmonics of these laser lines	R (0°, 532 - 561 nm + 659 nm) < 2 %

COMPONENTS FOR Ho:YAG AND Tm:YAG LASERS

Ho:YAG and Tm:YAG lasers emitting at wavelengths of 2010 nm and 2100 nm are widely used for medical applications. LAYERTEC offers optical coatings for this wavelength range with high laser-induced damage thresholds and long lifetimes.

CAVITY MIRRORS

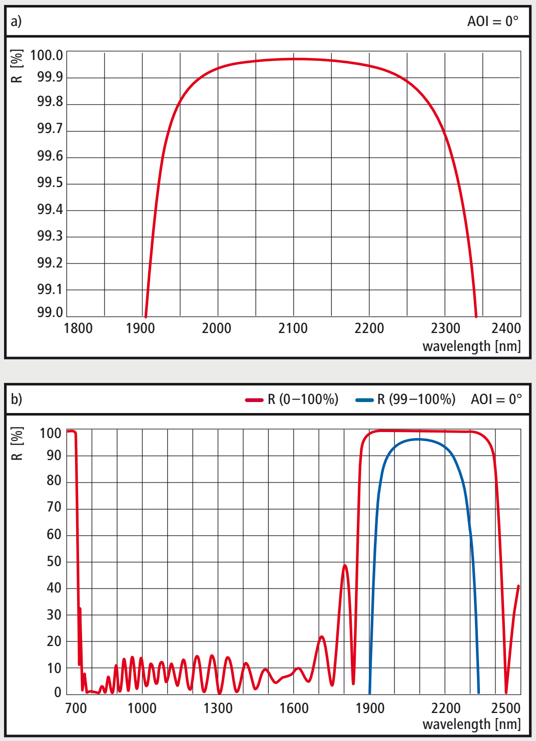


Figure 1: Reflectance spectra of cavity mirrors
a) HR cavity mirror
b) Pump mirror with high transmittance around 808 nm.

- HR cavity and pump mirrors with R > 99.9 %.
- High laser-induced damage thresholds.

TURNING MIRRORS

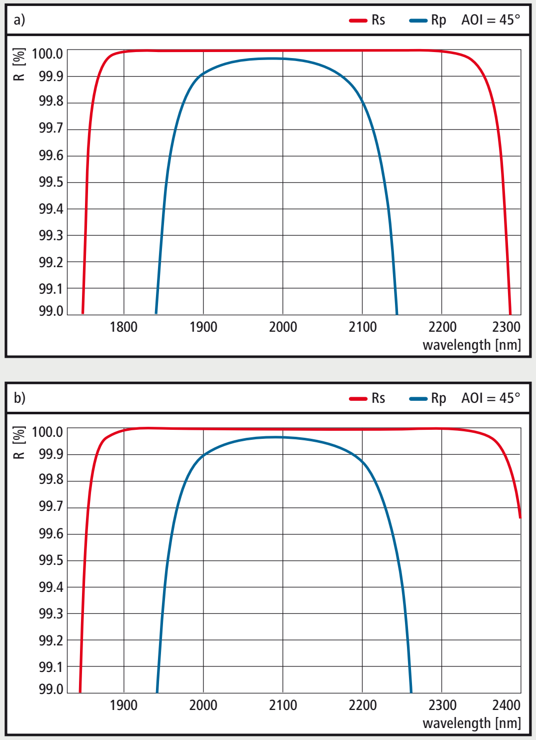


Figure 2: Reflectance spectra of turning mirrors for
a) 2010 nm
b) 2100 nm

The coating materials are chosen to guarantee high laser-induced damage thresholds. To achieve the maximum reflectance for p-polarization, mirrors should be specified for either 2010 nm or 2100 nm.

- Turning mirrors with R > 99.9 % for s-polarized light and R > 99.8 % for p-polarized light at AOI = 45°.
- High laser-induced damage thresholds.

OUTPUT COUPLERS

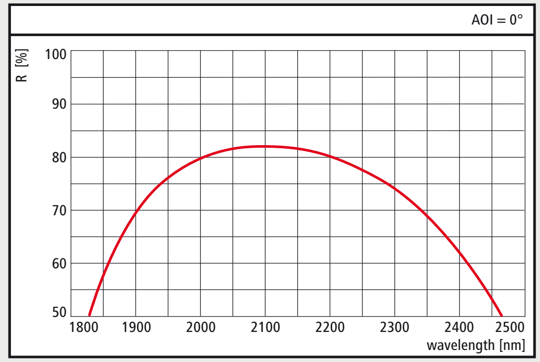
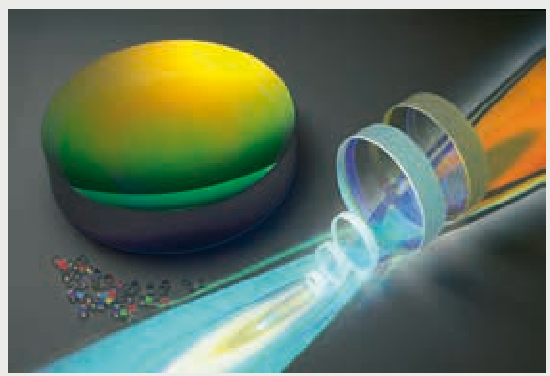


Figure 3: Reflectance spectrum of an output coupler with R = 82 % ± 1 % at 2100 nm

Output couplers with precisely adjusted degrees of reflectance:

Reflectance	Tolerance
R > 95 %	± 0.5 %
R = 80 ... 95 %	± 1 %
R = 10 % ... 80 %	± 2 %



2010 nm, 2100 nm

EDGE FILTERS

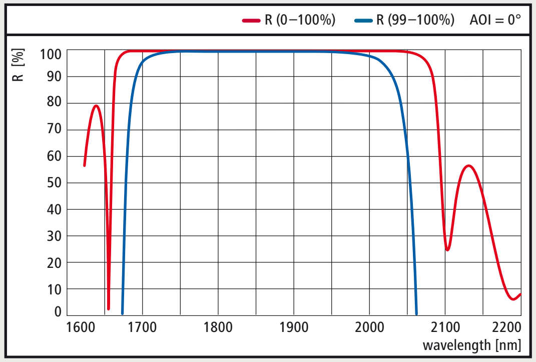


Figure 4: Reflectance spectra of a cavity mirror for 2010 nm suppressing the 2100 nm line

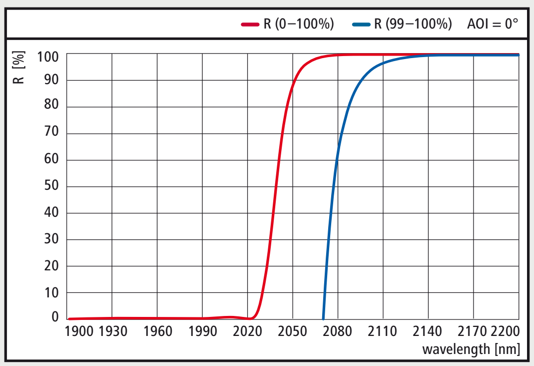


Figure 5 Reflectance spectra of a steep edge filter for the separation of the 2010 nm and 2100 nm lines

THIN FILM POLARIZERS

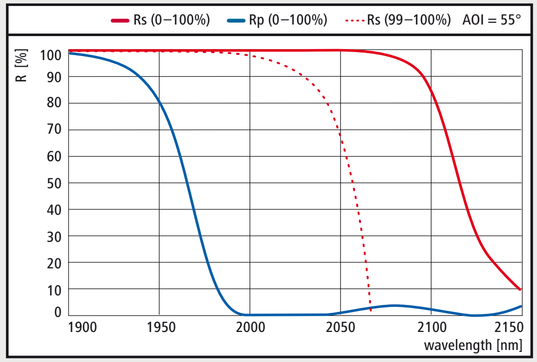


Figure 6: Reflectance spectra of a thin film polarizer for 2010 nm (Rs > 99.8 %, Rp < 2 %, AOI = 55°)

- Separation of the s- and p-polarized component of the light (s-polarized light is reflected and p-polarized light is transmitted).
- Thin film polarizers designed at Brewster angle (≈ 55°) exhibit a higher Tp / Ts ratio and a considerably broader bandwidth than those at AOI = 45°.

WINDOWS AND LENSES

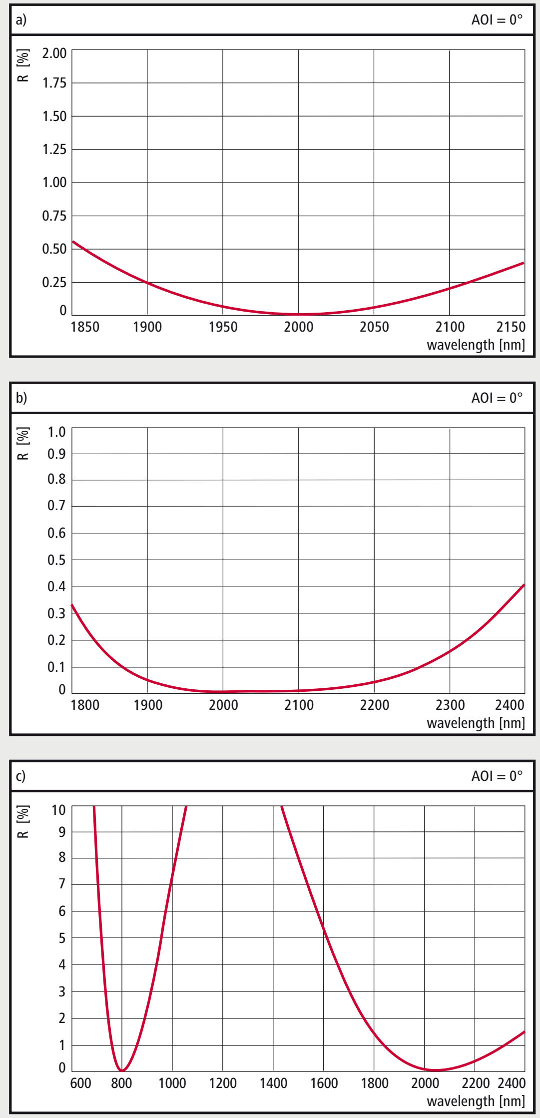


Figure 7: Reflectance spectra of typical antireflection coatings:
a) Single wavelength AR coating for 2010 nm
b) Broadband AR coating 2010 nm - 2100 nm
c) Dual wavelength AR coating for the pump and laser wavelength (808 nm + 2010 nm)

- Lens materials according to customer specifications.
- Infrasil®, sapphire and undoped YAG can be used.
- Special AR coatings for high index materials such as GGG on request.

COMPONENTS FOR Er:YAG LASERS AND THE 3 µm REGION

Er:YAG lasers are widely used in medical applications, especially in dermatology, due to the high absorption coefficient of water for 2940 nm radiation. This makes surgical applications easier but is also a challenge for the optical coatings which must be completely free of water. Coatings produced by magnetron sputtering have proved to be ideal for this kind of application.

CAVITY MIRRORS

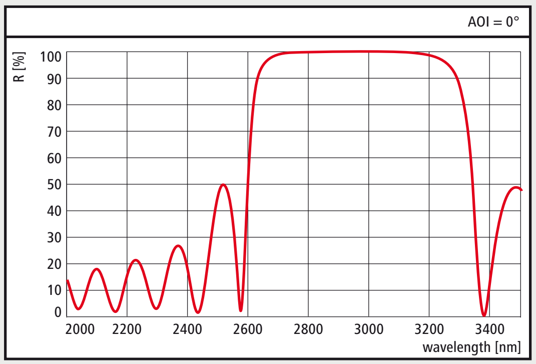


Figure 1: Reflectance spectrum of a HR cavity mirror HR (0°, 2940 nm) > 99.8 %

PUMP MIRRORS

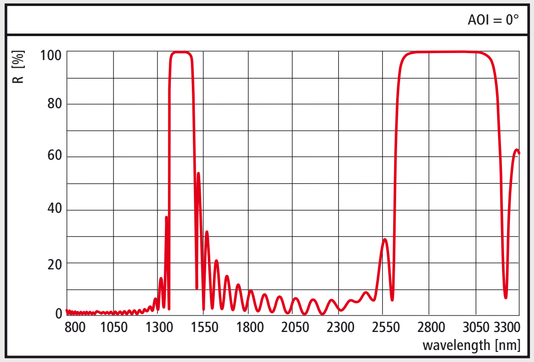


Figure 2: Reflectance spectrum of a HR cavity mirror with a HT region between 800 nm and 1100 nm

- Reflectance of cavity mirrors and pump mirrors: R > 99.9 % at AOI = 0°.
- Pump mirrors with high transmittance between 800 nm and 1100 nm for pumping with a Nd:YAG laser or a diode laser.

TURNING MIRRORS

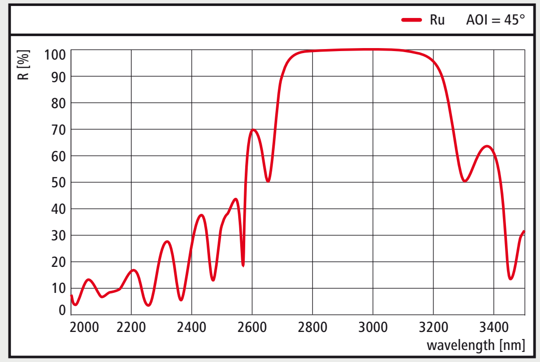
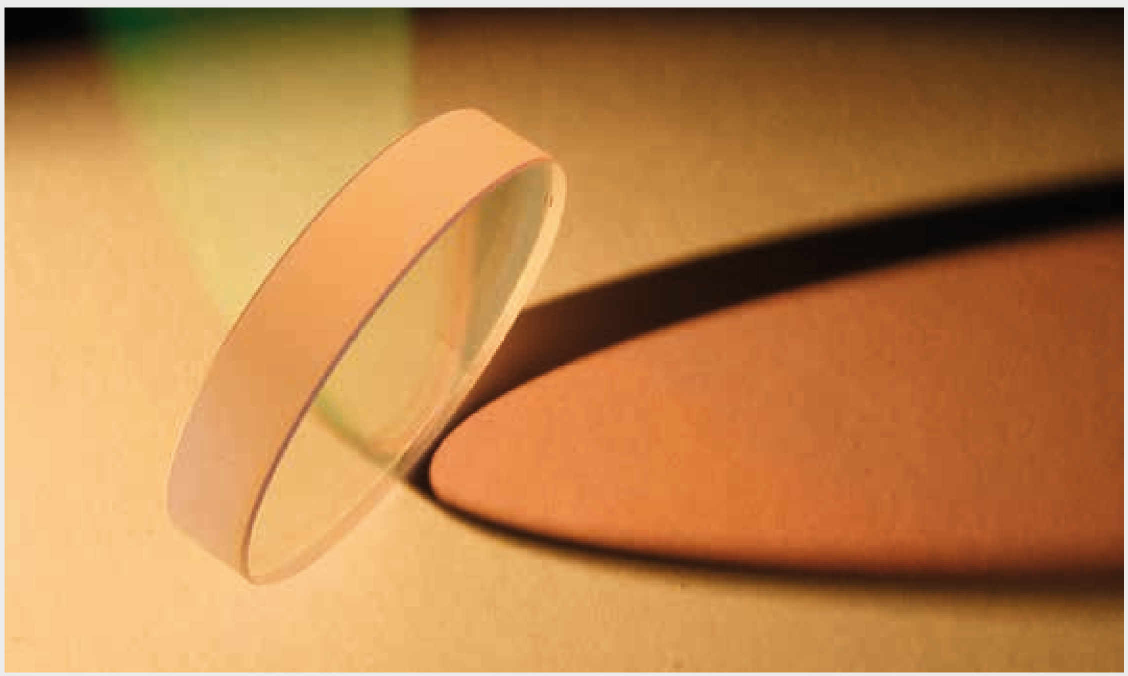


Figure 3: Reflectance spectrum of a turning mirror for unpolarized light

- Reflectance of turning mirrors: R > 99.8 % at AOI = 45° for unpolarized light.

LIDT - INFO

400 J / cm², 2940 nm, 400 µs



2940 nm

BEAM COMBINERS AND ALIGNMENT LASER MIRRORS

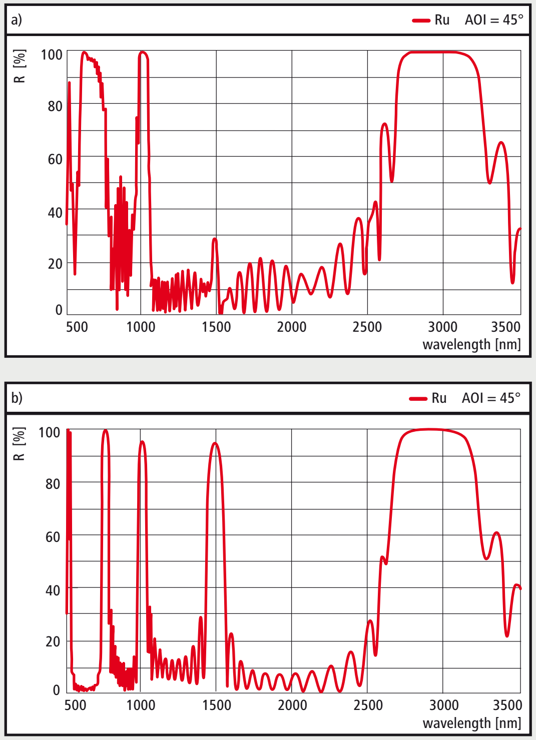


Figure 4: Reflectance spectra of beam steering mirrors
a) Dual wavelength turning mirror
b) Separator/combiner
for 2940 nm and an alignment laser between 630 nm and 655 nm

- Designs for beam splitters and alignment laser mirrors are calculated according to customer specifications.

OUTPUT COUPLERS AND LENSES

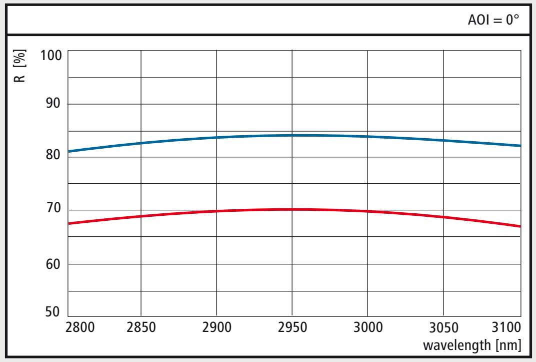


Figure 5: Reflectance spectra of output couplers with R = 70 % ± 1 % and R = 84 % ± 1%

- Output couplers with precisely adjusted degrees of reflectance (tolerances of ± 1% at reflectance values between 70 % and 90 %).

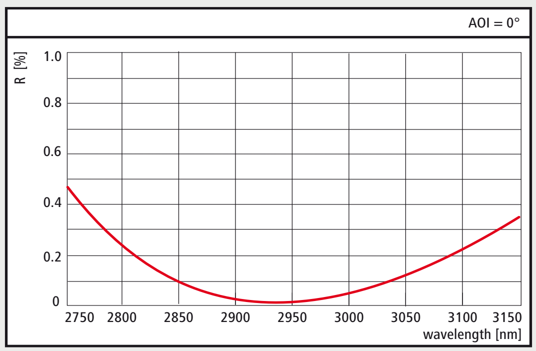


Figure 6: Reflectance spectrum of an antireflection coating for 2.94 µm on sapphire

- AR coatings with residual reflectance of R < 0.2 % on the back side of output couplers as well as on lenses and windows.
- Infrasil®, sapphire and undoped YAG can be used (for substrate materials see pages 20 – 21).

COMPONENTS FOR OTHER LASERS AROUND 3µm

The strong absorption of water in the wavelength range of 2.6 – 3.4 µm is the fundamental effect which is commonly used for medical laser applications. Between 2.6 µm and 2.8 µm the absorption of water is even stronger than at 2.94 µm (Er:YAG laser) making lasers that work in this wavelength range (e.g. the Er:Cr:YSGG laser) promising candidates for future applications.
However, the strong absorption of water is also the most serious problem with respect to laser damage. Therefore, it is essential to keep the layer system free of water. LAYERTEC uses magnetron sputtering for the production of coatings for the 3 µm region. The high atomic density of sputtered layers, which is close to that of bulk material, suppresses the diffusion of water into the layer systems.

This enables LAYERTEC to offer coatings for the critical 2.6 – 2.8 µm region. As an example, figure 7 shows a dielectric HR mirror centered at 2.8 µm with reflectance R > 99.7 %.

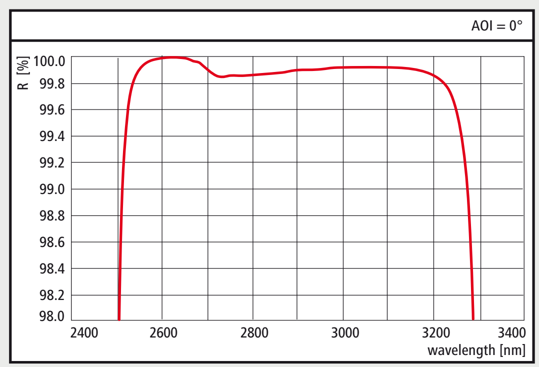
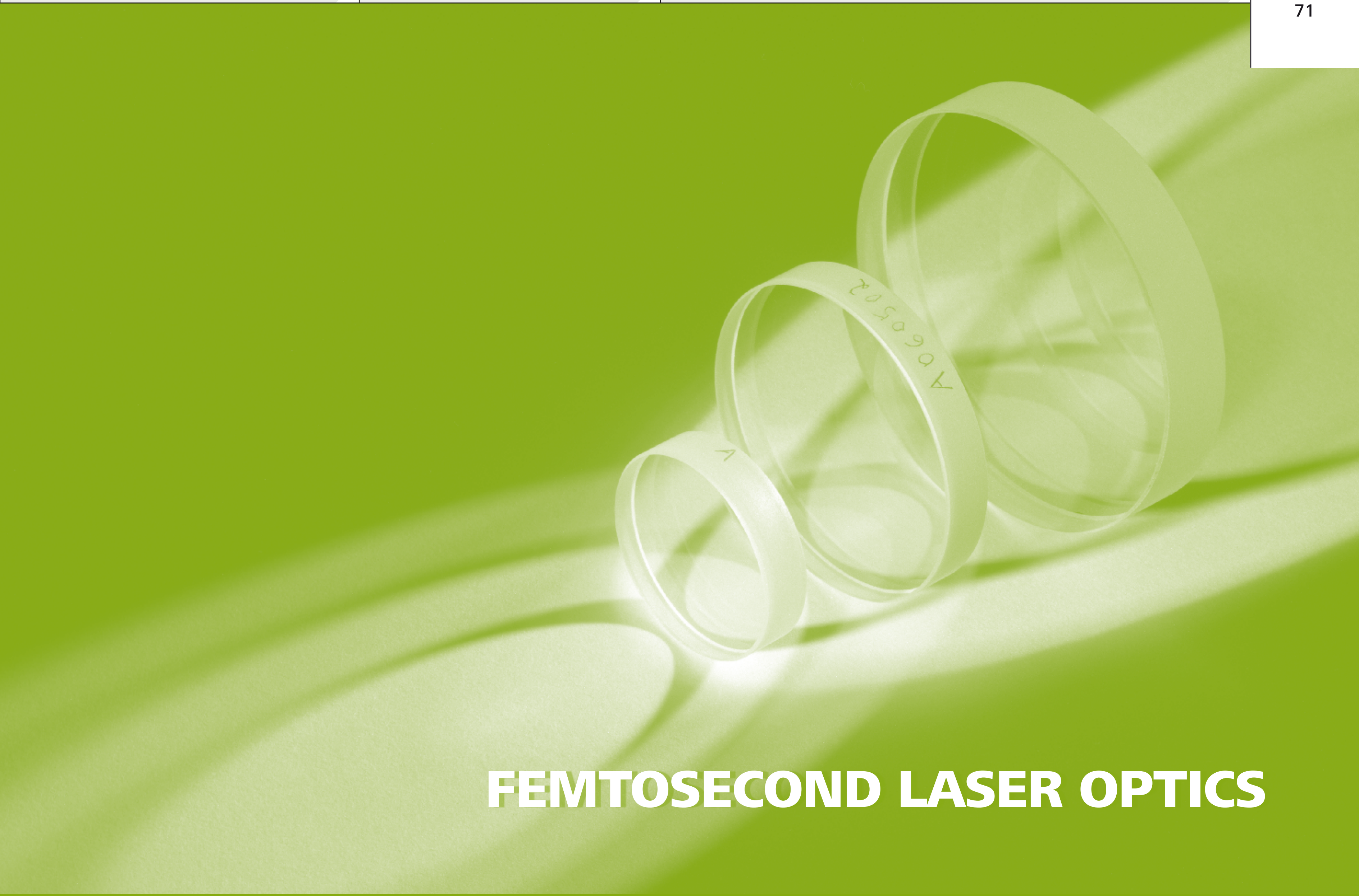


Figure 7: Reflectance spectrum of a HR mirror for 2.8 µm with R > 99.7 %



FEMTOSECOND LASER OPTICS

LAYERTEC®
OPTICAL COATINGS · OPTICS

INTRODUCTION TO FEMTOSECOND LASER OPTICS

Short pulse lasers are used in numerous applications such as time resolved spectroscopy, precision material processing and non-linear optics. Driven by these applications, recent developments in this field are directed to lasers generating higher output power and shorter pulses. Currently, most short pulse physics is done with Ti:Sapphire lasers. Solid-state lasers based on other transition metal or rare earth metal doped crystals (Yb:KGW) are also used for the generation of femtosecond pulses. The reproducible generation of sub-100 fs-pulses is closely connected to the development of broadband low loss dispersive delay lines consisting of prism or grating pairs or of dispersive multilayer reflectors.

The spectral bandwidth of a pulse is related to the pulse duration by a well-known theorem of Fourier analysis. For instance, the bandwidth (FWHM) of a 100 fs Gaussian pulse at 800 nm is 11 nm. For shorter pulses, the wavelength spectrum becomes significantly broader. A 10 fs pulse has a bandwidth of 107 nm.

If such a broad pulse passes through an optical medium, the spectral components of this pulse propagate with different speeds. Dispersive media, like glass, impose a so-called “positive chirp” on the pulse, meaning that the short wavelength ("blue") components are delayed with respect to the long wavelength ("red") components (see schematic drawing in fig. 1).

A similar broadening can be observed if a pulse is reflected by a dielectric mirror and the bandwidth of the pulse is larger or equal to the width of the reflection band of the mirror. Consequently, broadband mirrors consisting of a double stack system cause pulse broadening because the path lengths of the spectral components of the pulse are extremely different in these coatings.

In the sub-100 fs-regime it is essential to control the phase properties of each optical element over the extremely wide bandwidth of the fs-laser. This holds not only for the stretcher and compressor units, but also for the cavity mirrors, output couplers and the beam propagation system. In addition to the power spectrum, i.e. reflectance or transmittance, the phase relationship among the Fourier components of the pulse must be preserved in order to avoid broadening or distortion of the pulse.

Mathematical analysis of the phase shift, which is applied to a pulse passing through a medium or being reflected by a mirror (see insert on page 73), shows that the main physical properties which describe this phenomenon are the group delay dispersion (GDD) and the third order dispersion (TOD). These properties are defined as the second and third derivative of the phase with respect to the frequency.

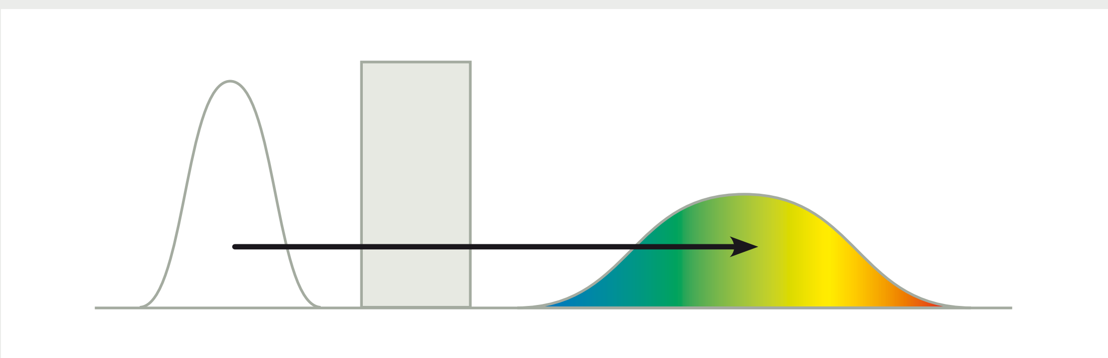


Figure 1: Broadening of a pulse by propagation through an optical medium (schematic drawing)

Especially designed dielectric mirrors offer the possibility to impose a “negative chirp” on a pulse. Thus, the positive chirp which results from crystals, windows, etc. can be compensated. The schematic drawing in fig. 2 explains this effect in terms of different optical path lengths of blue, green and red light in a negative dispersion mirror.

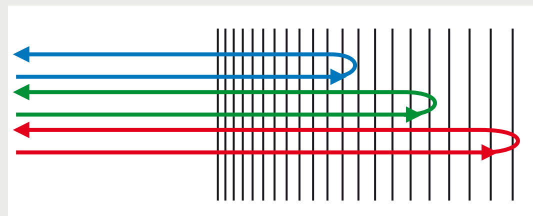


Figure 2: Optical path lengths of blue, green and red light in a negative dispersion mirror (schematic drawing)

LAYERTEC offers femtosecond laser optics with different bandwidths. This catalog shows optics for the wavelengths range of the Ti:Sapphire laser in three chapters, each representing a characteristic bandwidth of the optics: standard components with a bandwidth of about 120 nm, broadband components (bandwidth about 300 nm) and octave spanning components.

Each of these chapters shows low dispersion laser and turning mirrors, negative dispersion mirrors or mirror pairs, output couplers and beam splitters of corresponding bandwidth. Moreover, silver mirrors for fs applications are presented which offer the broadest low-GDD bandwidth available.

Please note that the GDD spectrum of a dielectric negative dispersion mirror is not a flat graph. All types of negative dispersion mirrors exhibit oscillations in the GDD spectrum. These oscillations are small for standard bandwidths. However, broadband and ultra-broadband negative dispersion mirrors exhibit strong GDD oscillations. Considerable reduction of these oscillations can be achieved by using mirror pairs consisting of mirrors with carefully shifted GDD oscillations. Fig. 3 shows a schematic drawing of said mirror pair and the corresponding GDD spectra.

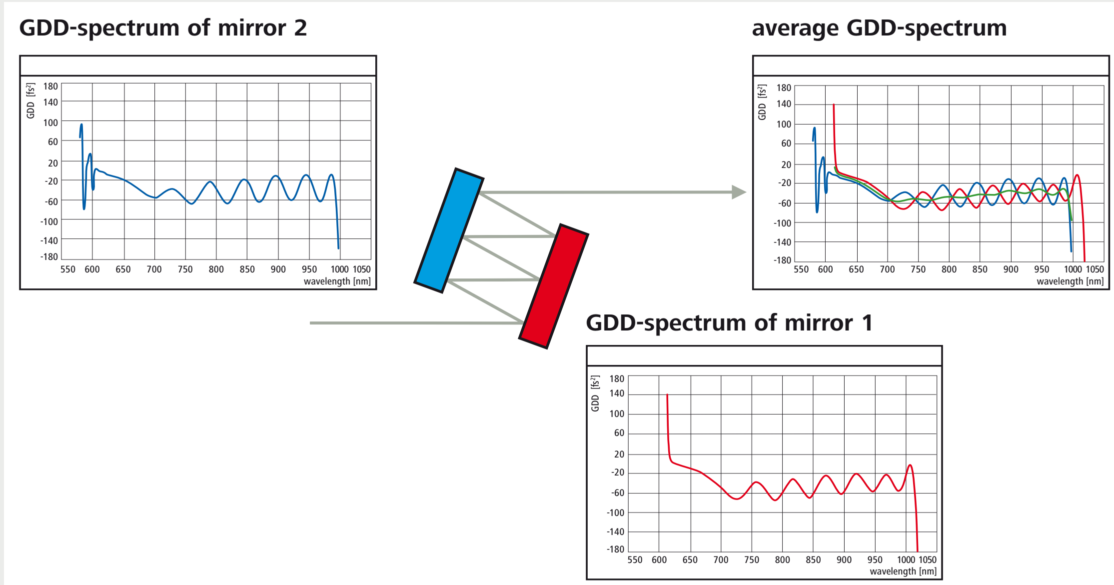


Figure 3: Schematic drawing of a negative dispersion mirror pair

GDD and TOD

If a pulse is reflected by a dielectric mirror, i. e. a stack of alternating high and low refractive index layers, there will be a phase shift between the original and the reflected pulse resulting from the time which it takes the different Fourier components of the pulse to pass through the layer system of the mirror. In general, the phase shift $\Phi(\omega)$ near the center frequency ω_0 may be expanded in a Taylor series for frequencies near ω_0:

$$\Phi(\omega) = \Phi(\omega_0) + \Phi'(\omega_0)(\omega-\omega_0) + \Phi''(\omega_0)(\omega-\omega_0)^2/2 + \Phi'''(\omega_0)(\omega-\omega_0)^3/6 + \ldots$$

The derivatives are, respectively, the **G**roup **D**elay (GD) $\Phi'(\omega_0)$, the **G**roup **D**elay **D**ispersion (GDD) $\Phi''(\omega_0)$ and the **T**hird **O**rder **D**ispersion (TOD) $\Phi'''(\omega_0)$. More strictly speaking, this expansion is only useful in an exactly soluble model, for the propagation of a transform limited Gaussian pulse and for pure phase dispersion. For extremely short pulses and combinations of amplitude and phase dispersion numerical calculations may be necessary. Nevertheless, this expansion clearly shows the physical meaning of the single terms:

Assuming the phase shift is linear in frequency (i.e. GD $\neq 0$, GDD = 0 and TOD = 0 over the pulse bandwidth), the reflected pulse is delayed in time by the constant group delay and, of course, scaled by the amplitude of reflectance R. The pulse spectrum will remain undistorted.

If GDD $\neq 0$, two important effect are observed:

- The reflected pulse is temporally broadened. This broadening effect depends only on the absolute value of the GDD. LAYERTEC offers "low GDD mirrors", i. e. mirrors with $|GDD| < 20\ fs^2$ over a given wavelength range, which guarantee the preservation of the pulse shape when the pulse is reflected by these mirrors.

- Moreover, the pulse becomes "chirped", i. e. it changes its momentary frequency during pulse time. This effect depends on the sign of the GDD, so that the momentary frequency may become higher (up-chirp, GDD > 0) or lower (down-chirp, GDD < 0). This allows to compensate positive GDD effects of nonlinear optical elements by using negative GDD mirrors.

The TOD determines also pulse length and pulse shape (distortion of the pulse) and becomes a very important factor at pulse lengths of 20 fs and below.

It is also possible to use negative dispersion mirrors with high values of negative GDD for pulse compression. These so-called Gires-Tournois-Interferometer (GTI) mirrors (see pages 96 – 97) are successfully used in Ti:Sapphire lasers, Yb:YAG and Yb:KGW oscillators and Er:Fiber lasers. Pulse compression in Yb:YAG and Yb:KGW oscillators provides pulses of some hundred femtoseconds pulse length. For each wavelength, components with different amounts of negative GDD are presented on the following pages.
Besides these optics for the spectral range of the Ti:Sapphire fundamental and for the very promising Yb:YAG and Yb:KGW lasers, LAYERTEC also offers optics for the harmonics of this radiation down to the VUV wavelength range, optics for femtosecond lasers in the 1500 nm-range and especially designed optics for high power ultra-short pulse lasers.
LAYERTEC has its own capabilities for design calculation and also for GDD-measurements in the wavelength range from 250 – 1700 nm.

References:

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- G. Tempea, V. Yakovlev and F. Krausz; "Interference coatings for Ultrafast Optics" in N. Kaiser, H.K. Pulker (eds.) "Optical Interference Coatings ", Springer-Verlag Berlin Heidelberg 2003, p. 393 – 422 and the references therein

STANDARD FEMTOSECOND LASER OPTICS

- The coatings shown here are calculated for a bandwidth of 120 – 150 nm in the wavelength range between 600 nm and 1000 nm.
- Very high reflectance of the mirrors (R > 99.99 %).
- Spectral tolerance 1 % of center wavelength.
- In-house design calculation and GDD measurement capabilities.
- Center wavelength, GDD and TOD according to customer specifications.
- Measured GDD spectra available on request.

LIDT - INFO

0.4 J / cm², 800 nm, 42 fs, 1 kHz, Ø 80 µm *
2 J / cm², 800 nm, 70 fs, 10 Hz, Ø 700 µm **
For high power mirrors see page 88.

* Measurements were performed at Wigner Research Centre for Physics, Budapest
** Measurements were performed at Helmholtz-Zentrum Dresden-Roessendorf

STANDARD MIRRORS AOI = 0°

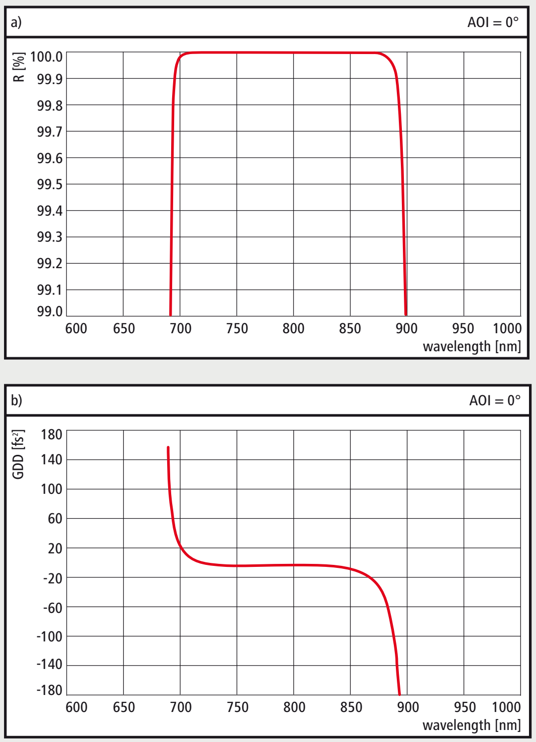


Figure 1: Reflectance and GDD spectra of a standard low dispersion femtosecond laser mirror
a) Reflectance vs. wavelength
b) GDD vs. wavelength

All types of mirrors are also available with negative GDD (e.g. - 40 fs²).
For high dispersion mirrors see page 76.

PUMP MIRRORS AOI = 0°

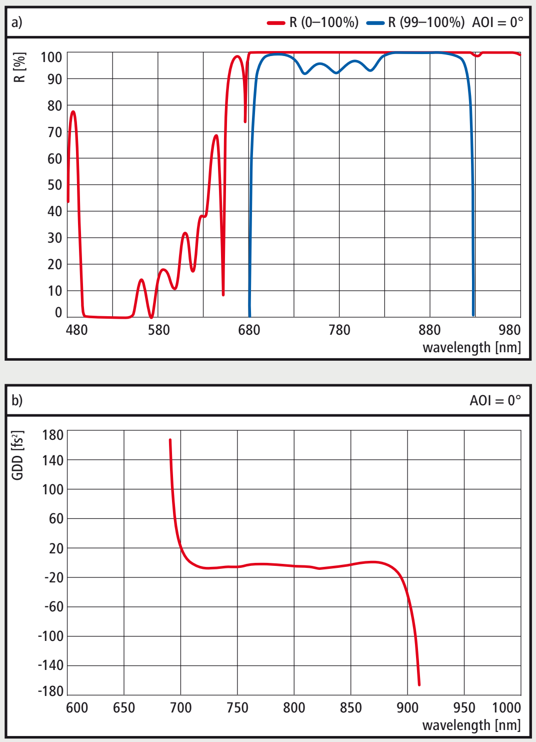


Figure 2: Reflectance and GDD spectra of a standard low dispersion pump laser mirror
a) Reflectance vs. wavelength
b) GDD vs. wavelength

TURNING MIRRORS AOI = 45°

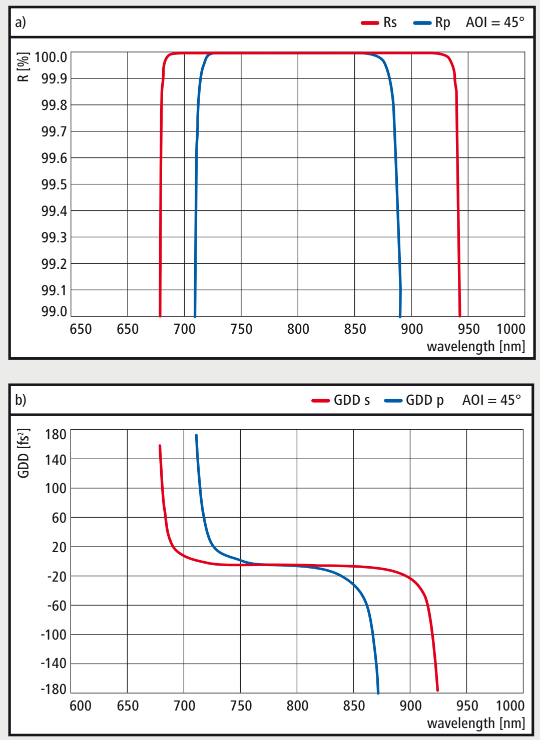


Figure 3: Reflectance and GDD spectra for a standard low dispersion turning mirror (bandwidth Ru (45°) > 99.9 % ~ 160 nm)
a) Reflectance vs. wavelength
b) GDD vs. wavelength

120 – 150 nm BANDWIDTH

- Reflectance and transmittance of output couplers and beam splitters can be adjusted according to customer specifications.

- Tolerances for output couplers:
  - R = 10 % … 70 % ± 2.5 %
  - R = 70 % … 90 % ± 1.5 %
  - R = 90 % … 95 % ± 0.75 %
  - R = 95 % … 98 % ± 0.5 %
  - R > 98 % ± 0.25 %.

- Standard AR coatings:
  - AOI = 0°: R < 0.2 %
  - AOI = 45°: Rs or Rp < 0.2 %
  - In case of p-polarization, uncoated back side possible, Rp (fused silica, 45°) ≈ 0.6 %.

OUTPUT COUPLERS AOI = 0°

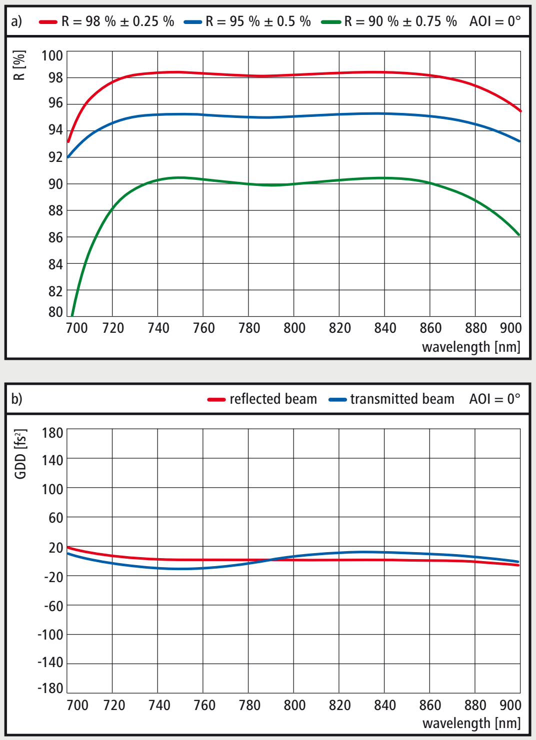


Figure 4: a) Reflectance spectra of several standard output couplers
b) GDD spectra of the output coupler with R = 98 %; the GDD spectra are similar for all levels of reflectance

BEAM SPLITTERS FOR P-POLARIZED LIGHT AT AOI = 45°

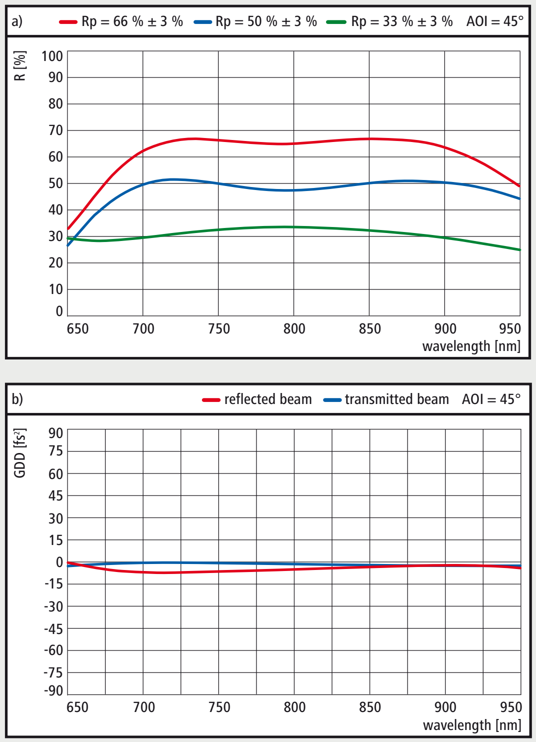


Figure 5: a) Reflectance spectra of several standard beam splitters for AOI = 45° and p-polarized light
b) GDD spectra of the beam splitter with R = 50 %; the GDD spectra are similar for all levels of reflectance

BEAM SPLITTERS FOR S-POLARIZED LIGHT AT AOI = 45°

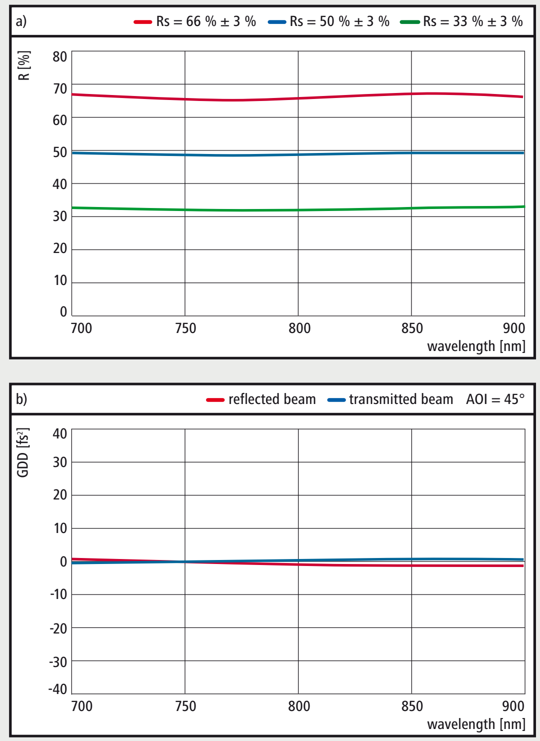


Figure 6: a) Reflectance spectra of several standard beam splitters for AOI = 45° and s-polarized light
b) GDD spectra of the beam splitter with R = 50 %; the GDD spectra are similar for all levels of reflectance

STANDARD FEMTOSECOND LASER OPTICS

Recent advances in design calculation and process control enable LAYERTEC to offer high dispersion mirrors for pulse compression in advanced Ti:Sapphire lasers. These mirrors and mirror pairs show spectral bandwidths of 100 nm – 300 nm and negative GDD values of some hundred fs². These mirrors can be used for pulse compression. Compared to prism compressors, high dispersion mirrors reduce the intracavity losses resulting in higher output power of the laser.

NEGATIVE DISPERSION MIRRORS AOI = 0°

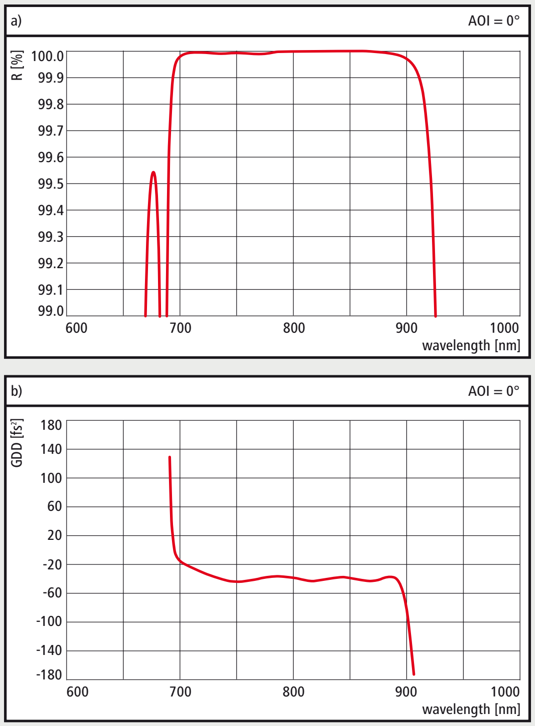


Figure 1: Reflectance and GDD spectra of a standard negative dispersion mirror with GDD = −40 ± 10 fs²
a) Reflectance vs. wavelength
b) GDD vs. wavelength

Matching measured and calculated GDD-spectra prove the reliability of the coating process.

HIGH DISPERSION MIRRORS AOI = 0°

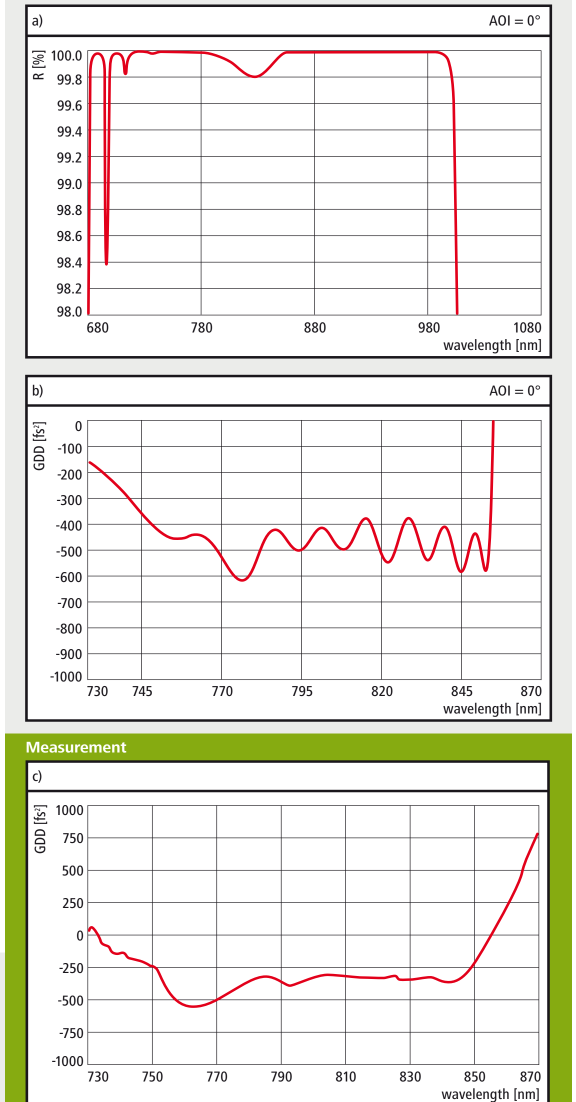


Figure 2: Reflectance and GDD spectra of a high dispersion mirror with a bandwidth of 120 nm and a GDD of -450 ± 100 fs² in the 800 nm range
a) Reflectance vs. wavelength
b) Calculated GDD vs. wavelength
c) Measured GDD vs. wavelength

HIGH DISPERSION MIRROR PAIRS AOI = 0°

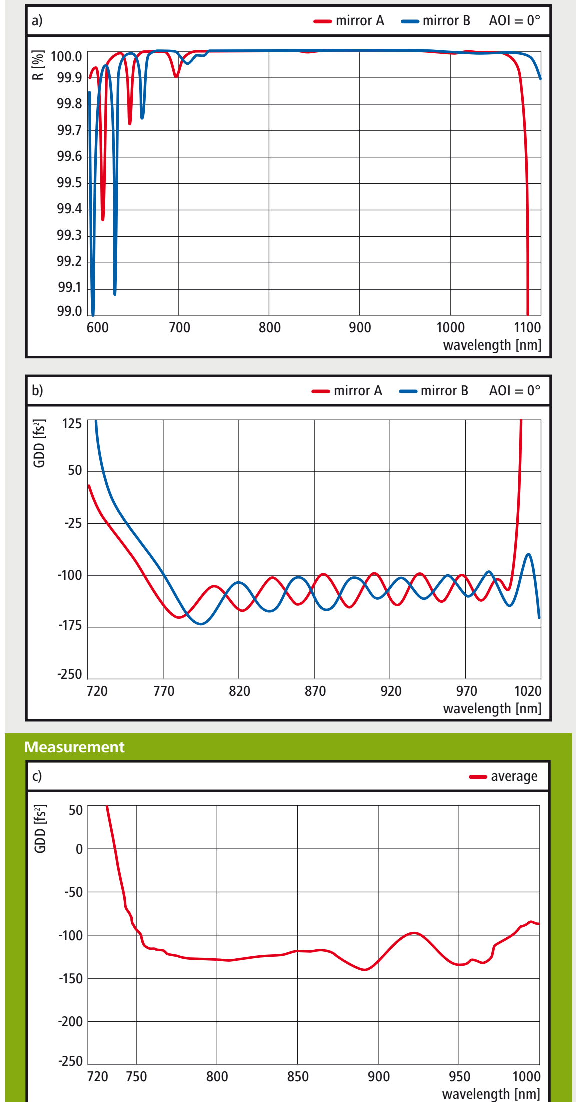


Figure 3: Reflectance and GDD spectra of a high dispersion mirror pair with a bandwidth of 200 nm and an average GDD of -120 ± 40 fs² per bounce in the 800 nm range
a) Reflectance vs. wavelength
b) Calculated GDD vs. wavelength
c) Measured GDD vs. wavelength

120 – 150 nm BANDWIDTH

This very special type of optical coatings can be used to compensate the third order dispersion which results from laser crystals, substrates or dispersive elements like prisms or gratings. Positive as well as negative TOD can be achieved with this type of coatings. All coatings are optimized for nearly constant TOD which means TOD oscillations in the order of some hundreds of fs^3. Please note that without TOD optimization these oscillations are on the order of some thousands of fs^3.

MIRRORS WITH NEGATIVE THIRD ORDER DISPERSION

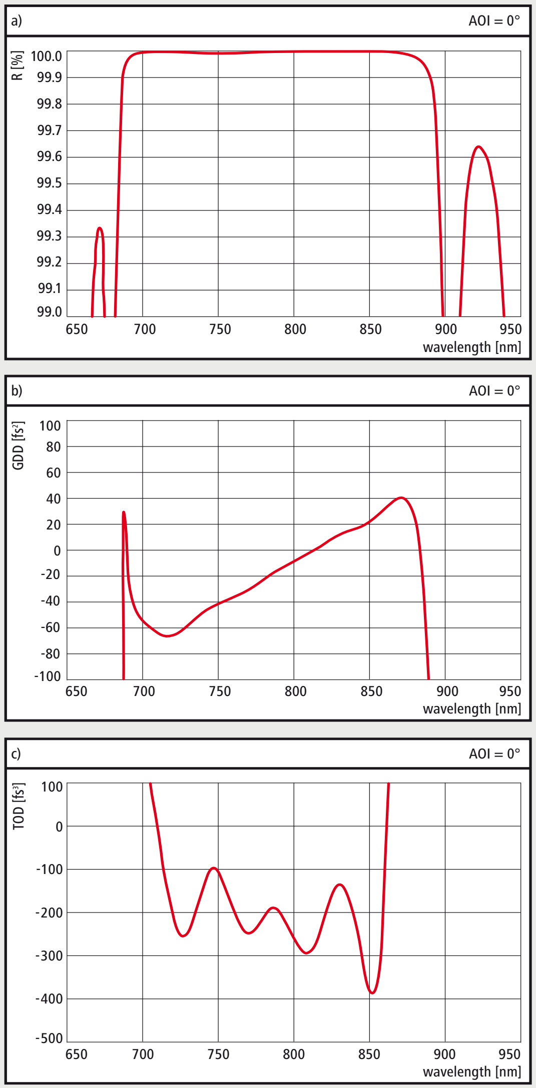


Figure 4: Reflectance, GDD and TOD spectra of a mirror optimized for nearly constant negative third order dispersion
a) Reflectance vs. wavelength
b) GDD vs. wavelength
c) TOD vs. wavelength

MIRRORS WITH POSITIVE THIRD ORDER DISPERSION

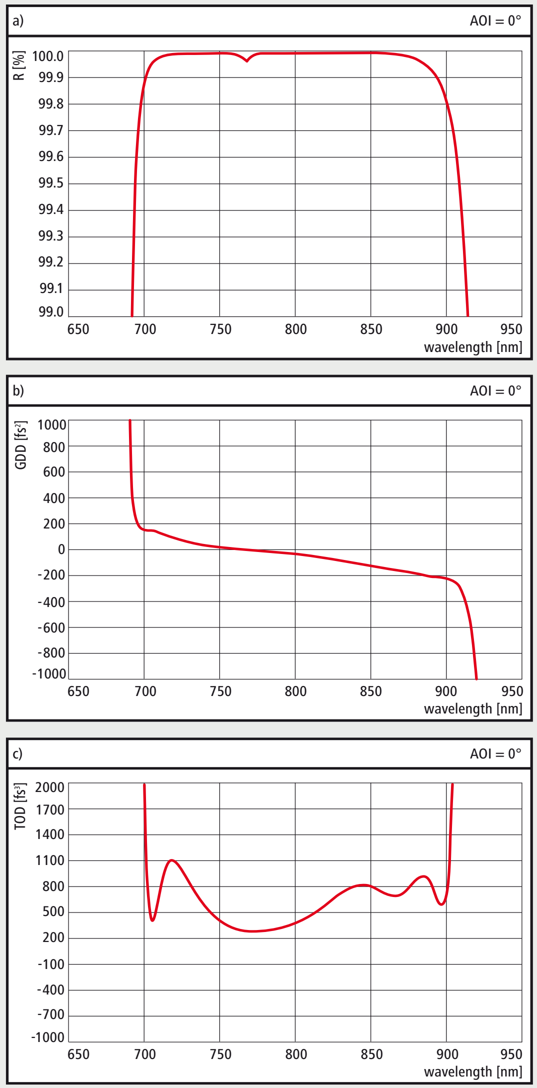


Figure 5: Reflectance, GDD and TOD spectra of a mirror optimized for nearly constant positive third order dispersion
a) Reflectance vs. wavelength
b) GDD vs. wavelength
c) TOD vs. wavelength

MIRROR PAIRS WITH OPTIMIZED THIRD ORDER DISPERSION

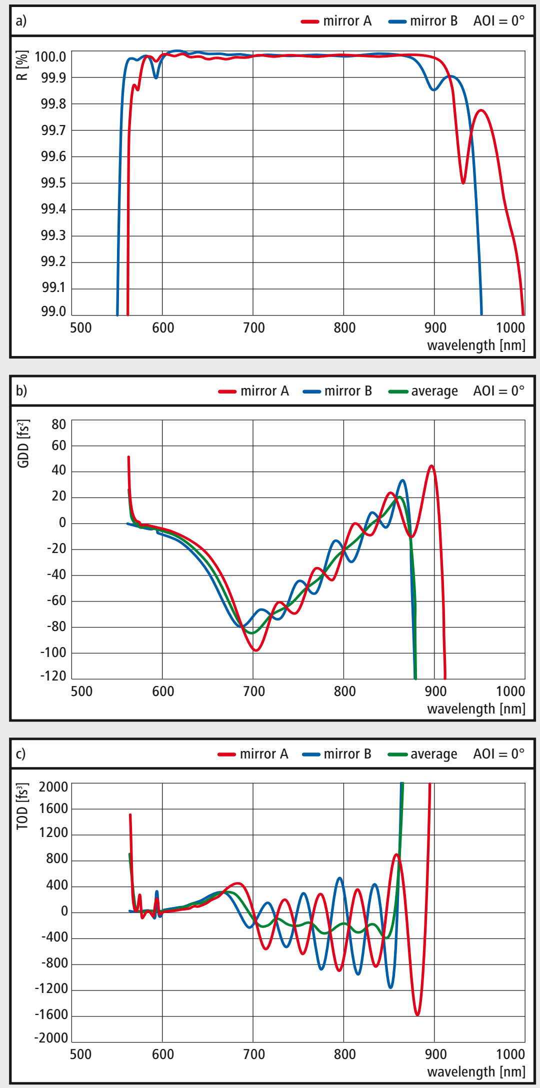


Figure 6: Reflectance, GDD and TOD spectra of a mirror pair optimized for nearly constant negative third order dispersion
a) Reflectance vs. wavelength
b) GDD vs. wavelength
c) TOD vs. wavelength

STANDARD FEMTOSECOND LASER OPTICS

MIRRORS WITH DIFFERENT TOD VALUES

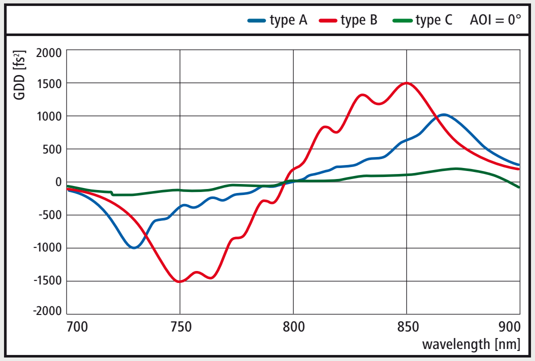


Figure 1: GDD spectra of three negative dispersive mirrors with different TOD values, i.e. different slope of the GDD curves

Increasing the GDD slope, i.e. increasing the absolute TOD results in a lower bandwidth and stronger GDD and TOD oscillations.

- Center wavelength and amount of TOD according to customer specifications.
- In the wavelength range of the Ti:Sapphire laser the bandwidth of single mirrors with optimized TOD is limited to about 150 nm.

THIN FILM POLARIZERS FOR AOI = 55°

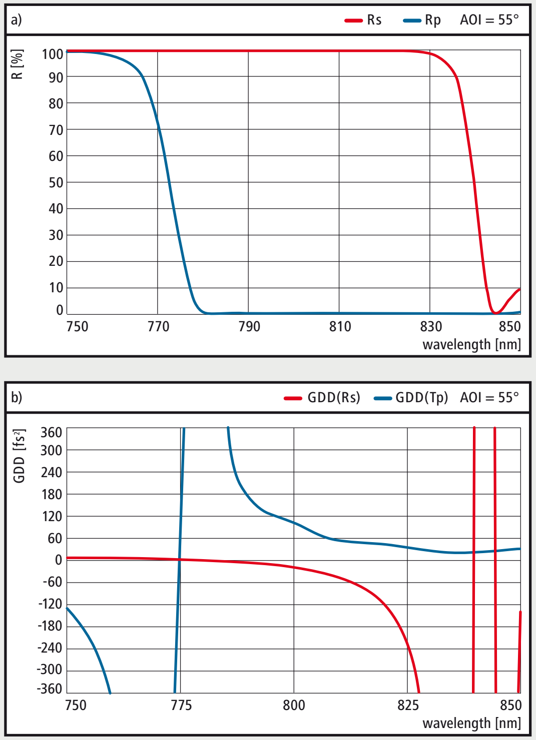


Figure 2: Reflectance and GDD spectra of a standard TFP (AOI = 55° to use the Brewster angle for the transmitted p-polarized light)
a) Reflectance vs. wavelength
b) GDD vs. wavelength

The bandwidth of thin film polarizers can be extended if large angles of incidence are used. As shown in fig. 4 a polarizer bandwidth as large as 100 nm can be achieved. However, this is combined with a reduced reflectance for the s-polarized light.

THIN FILM POLARIZERS FOR AOI = 65°

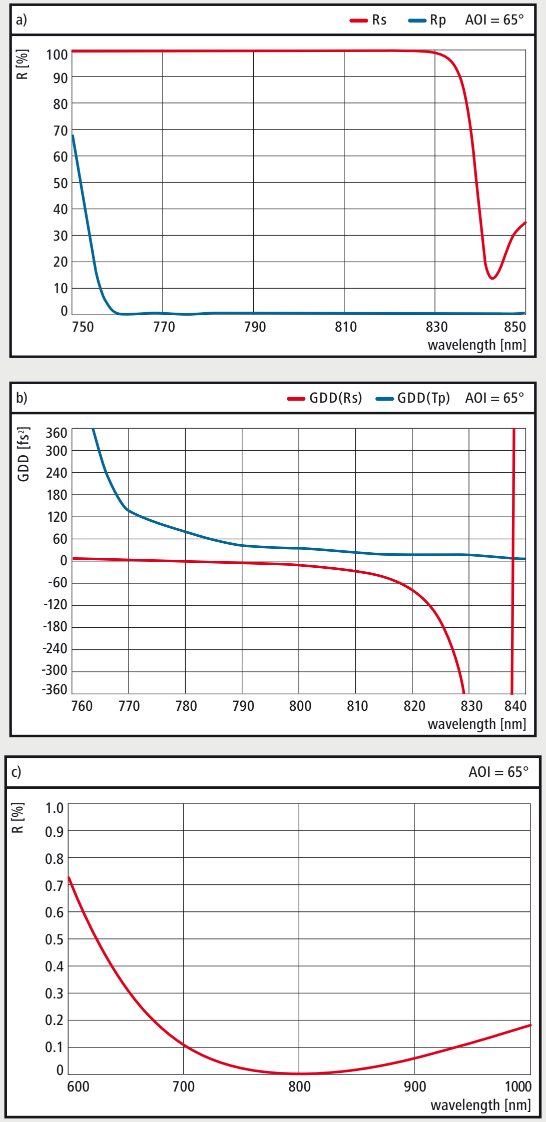


Figure 3: Reflectance and GDD spectra of a TFP (AOI = 65° to achieve a low GDD for Rs and Tp, bandwidth ~ 40 nm)
a) Reflectance vs. wavelength
b) GDD vs. wavelength
c) Back side ARp (65°, 750 – 850 nm)

120 – 150 nm BANDWIDTH

THIN FILM POLARIZERS FOR AOI = 80°

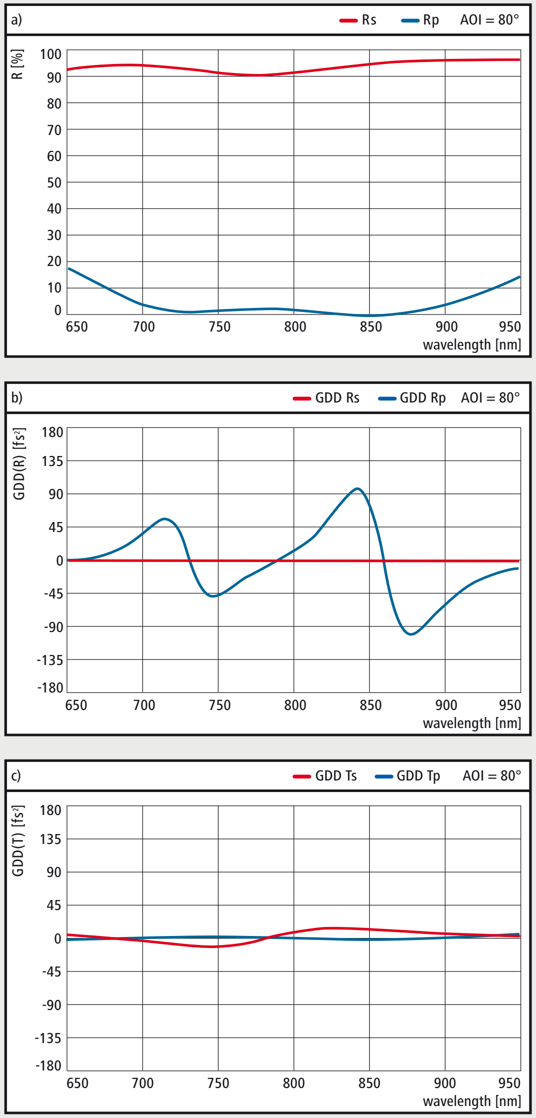


Figure 4: Reflectance and GDD spectra of a TFP (AOI = 80°, lower Rs-value to achieve a low GDD for Rs and Tp, bandwidth ~ 150 nm)
a) Reflectance vs. wavelength
b) GDD of the reflected light vs. wavelength
c) GDD of the transmitted light vs. wavelength

NON-POLARIZING BEAM SPLITTERS FOR AOI = 45°

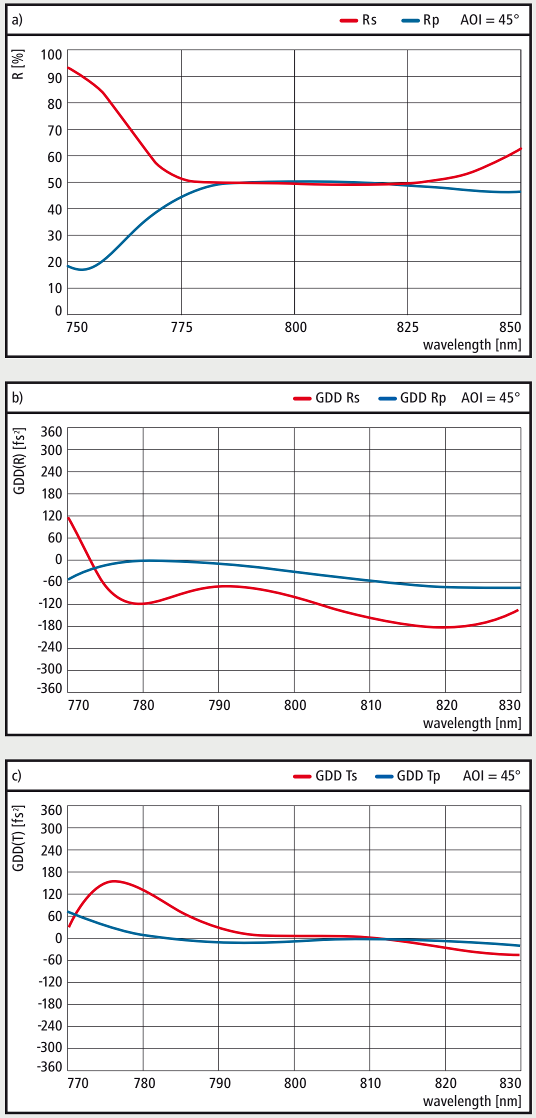


Figure 5: Reflectance and GDD spectra of a non-polarizing beam splitter
a) Reflectance vs. wavelength
b) GDD of the reflected light vs. wavelength
c) GDD of the transmitted light vs. wavelength

ANTIREFLECTION COATINGS

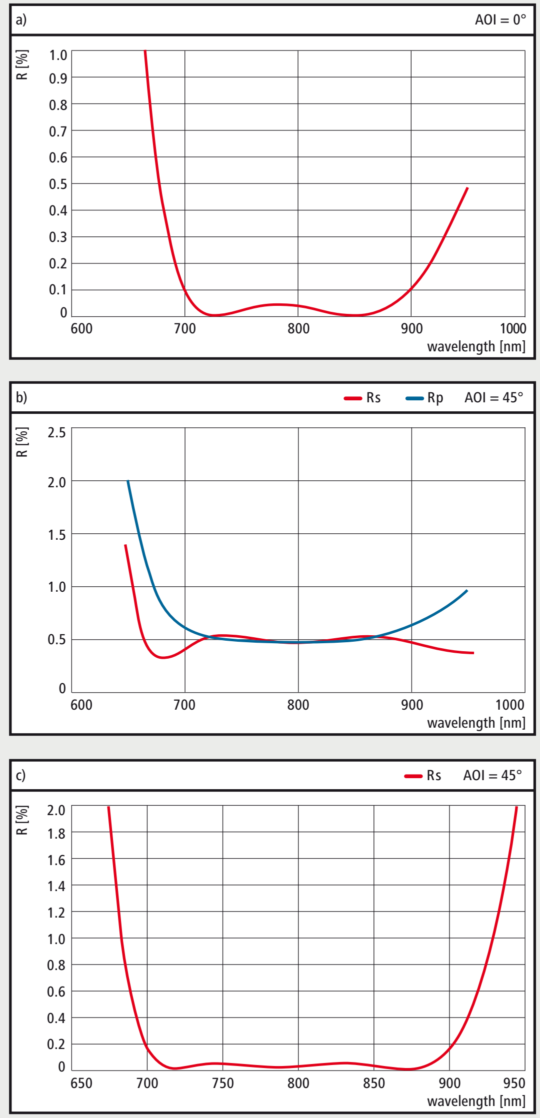


Figure 6: Reflectance of different antireflection coatings
a) AOI = 0°
b) AOI = 45° Rs = Rp ~ 0.5 %
c) AOI = 45° Rs < 0.2 % (only possible for s- or p-polarized light)

Broadband antireflection coatings for AOI = 0° or a single polarization at AOI > 0° with R < 0.1 % on request.

BROADBAND FEMTOSECOND LASER OPTICS

- The coatings shown here are calculated for the wavelength range 700 – 1000 nm. Similar coatings are available for 600 – 900 nm or 650 – 950 nm.
- Very high reflectance of the mirrors (R > 99.8 % … R > 99.95 % depending on the design).
- Center wavelength, bandwidth, GDD and TOD according to customer specifications.
- Spectral tolerance ±1 % of center wavelength.
- In-house design calculation and GDD measurement capabilities.
- GDD measurement reports are included in the delivery.

LIDT - INFO

≈ 0.1 J / cm², 800 nm, 150 fs,

Measurements were performed at Laser Zentrum Hannover

MIRROR PAIRS FOR AOI = 0°

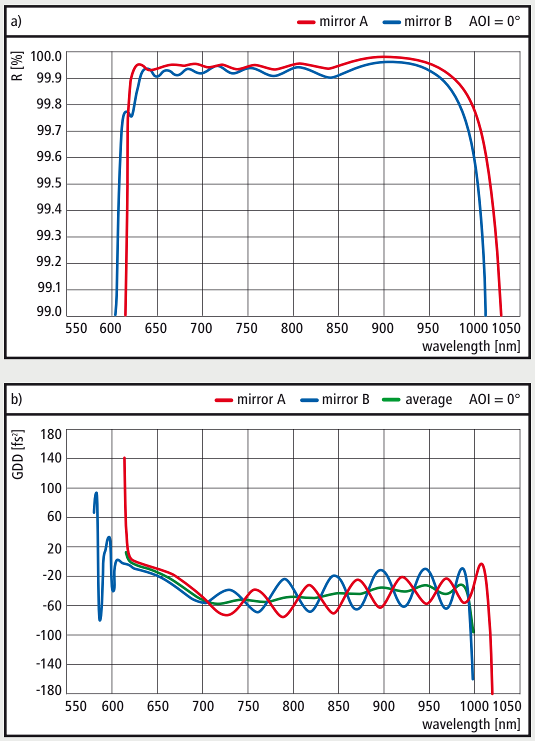


Figure 1: Reflectance and GDD spectra of a negative dispersion laser mirror pair
a) Reflectance vs. wavelength
b) GDD versus wavelength

Mirror pairs show a very smooth average GDD spectrum, although the single broadband mirrors exhibit strong GDD oscillations. Pump mirror pairs, i.e. mirror pairs with at least one mirror showing high transmittance between 514 – 532 nm, are also available. (See page 82)

TURNING MIRRORS FOR S-POLARIZED LIGHT AT AOI = 45°

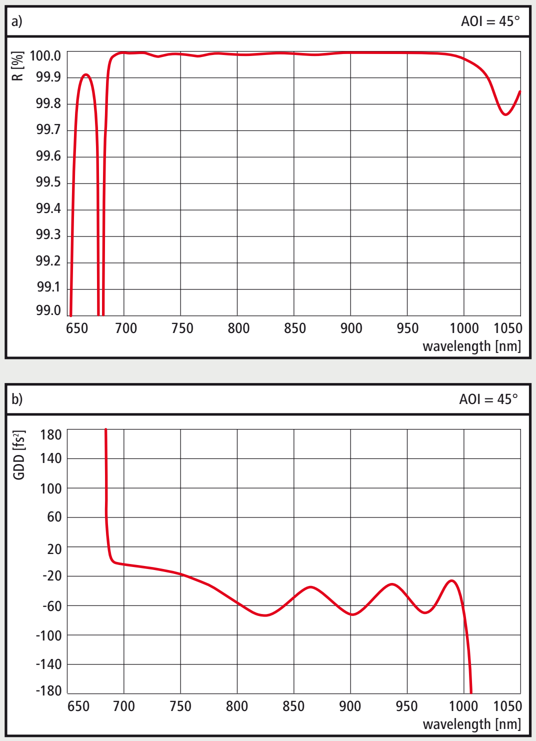


Figure 2: Reflectance and GDD spectra of a broadband turning mirror for s-polarized light
a) Reflectance vs. wavelength
b) GDD vs. wavelength

TURNING MIRRORS FOR P-POLARIZED LIGHT AT AOI = 45°

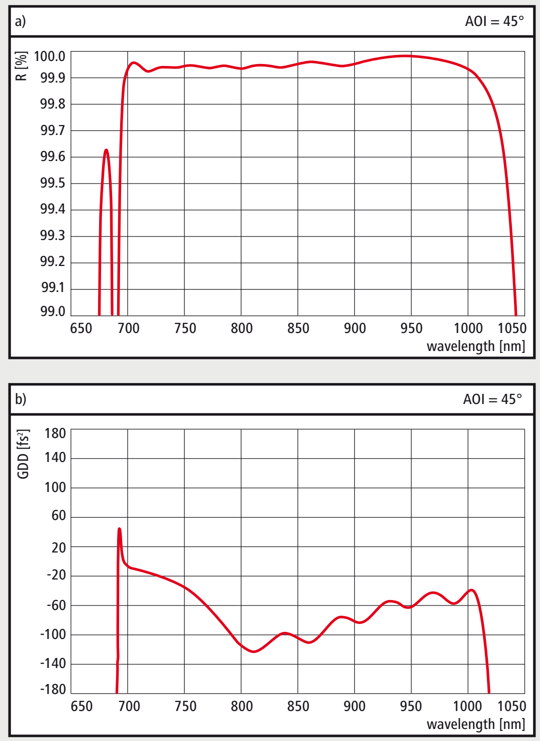


Figure 3: Reflectance and GDD spectra of a broadband turning mirror for p-polarized light
a) Reflectance vs. wavelength
b) GDD vs. wavelength

200 – 300 nm BANDWIDTH

OUTPUT COUPLERS FOR AOI = 0°

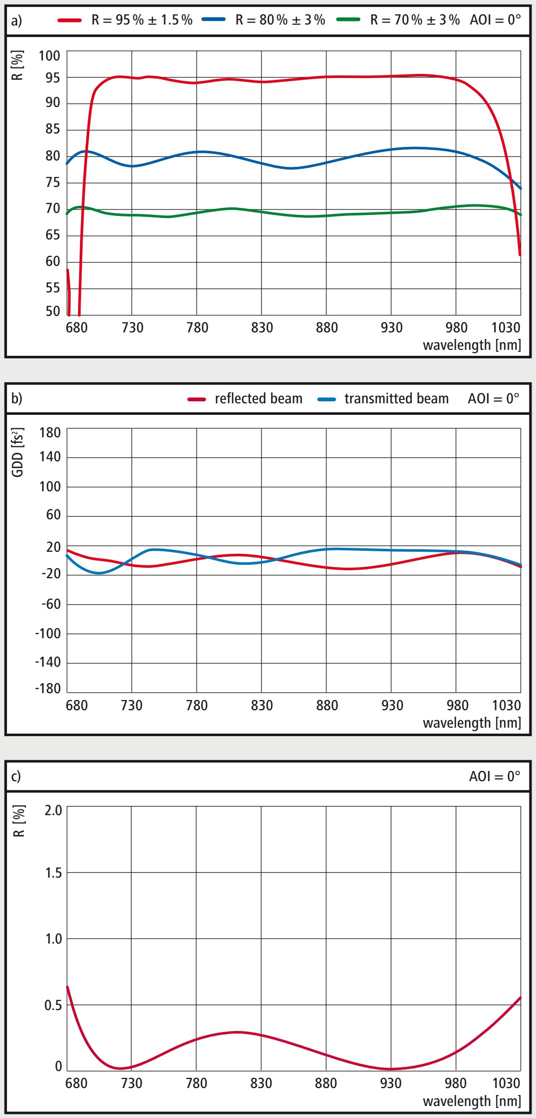


Figure 4: a) Reflectance spectra of several broadband output couplers
b) GDD spectra of the output coupler with R = 80 %; the GDD spectra are similar for all levels of reflectance
c) Reflectance spectrum of a broadband AR coating AR (0°, 680 - 1030 nm) < 0.5 %

BEAM SPLITTERS FOR P-POLARIZED LIGHT AT AOI = 45°

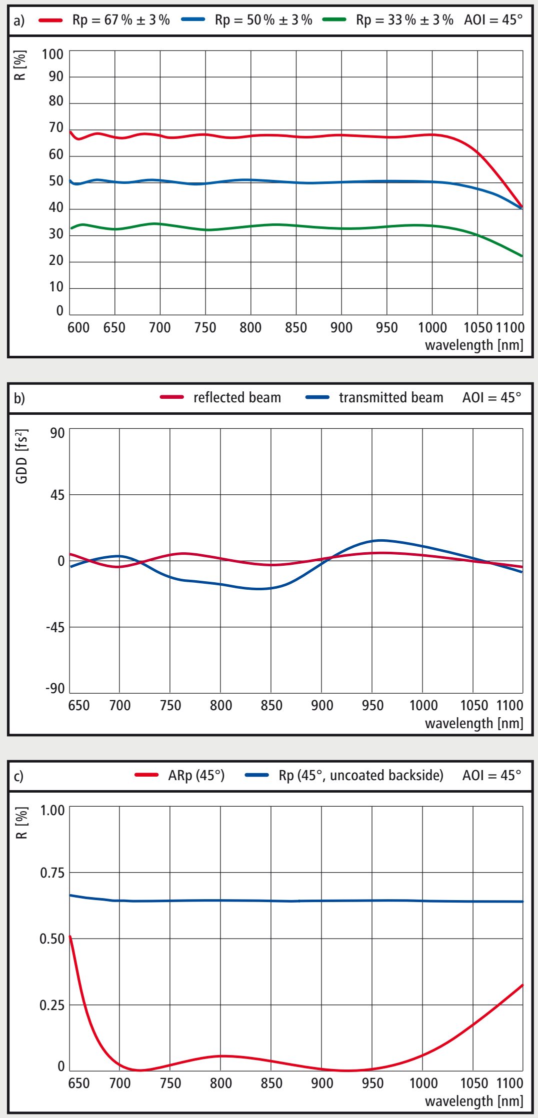


Figure 5: a) Reflectance of several broadband beam splitters for p-polarization
b) GDD spectra for the 50 % beam splitter
c) Reflectance spectrum of a broadband AR coating for p-polarized light

BEAM SPLITTERS FOR S-POLARIZED LIGHT AT AOI = 45°

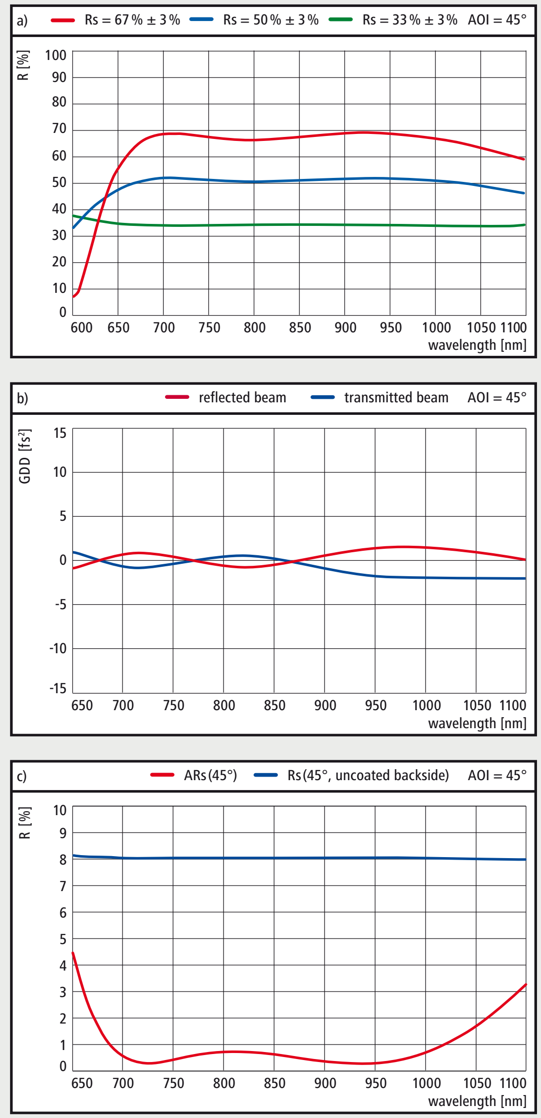


Figure 6: a) Reflectance of several broadband beam splitters for s-polarization
b) GDD spectra for the 50 % beam splitter
c) Reflectance spectrum of a broadband AR coating for s-polarized light

BROADBAND FEMTOSECOND LASER OPTICS

NEGATIVE DISPERSION PUMP MIRROR PAIRS FOR AOI = 0°

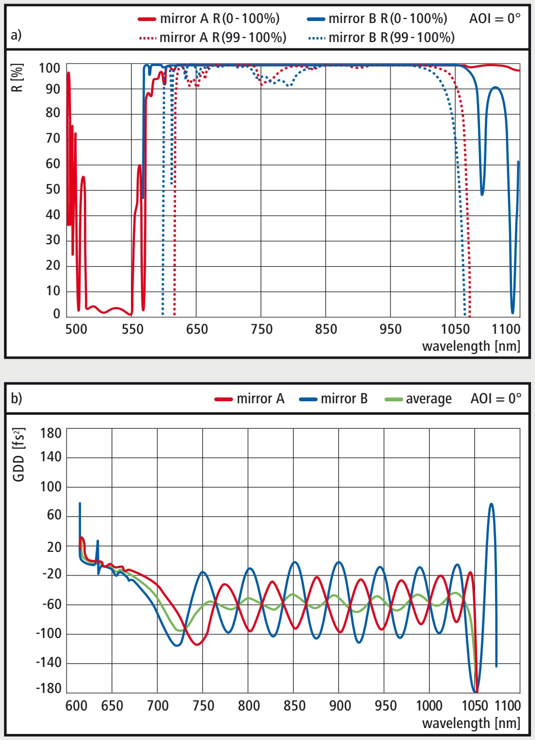


Figure 1: Reflectance and GDD spectra of a negative dispersion pump mirror pair (mirror 2 without HT- option)
a) Reflectance vs. wavelength
b) GDD vs. wavelength

MIRROR PAIRS WITH POSITIVE AVERAGE GDD

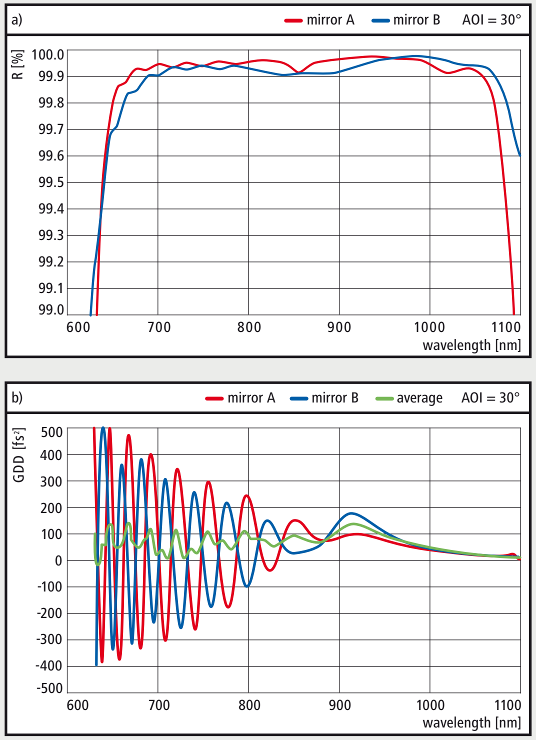


Figure 2: Reflectance and GDD spectra of a broadband mirror pair with positive average GDD for s-polarized light at AOI = 30°
a) Reflectance vs. wavelength
b) GDD vs. wavelength

THIN FILM POLARIZERS FOR AOI = 70°

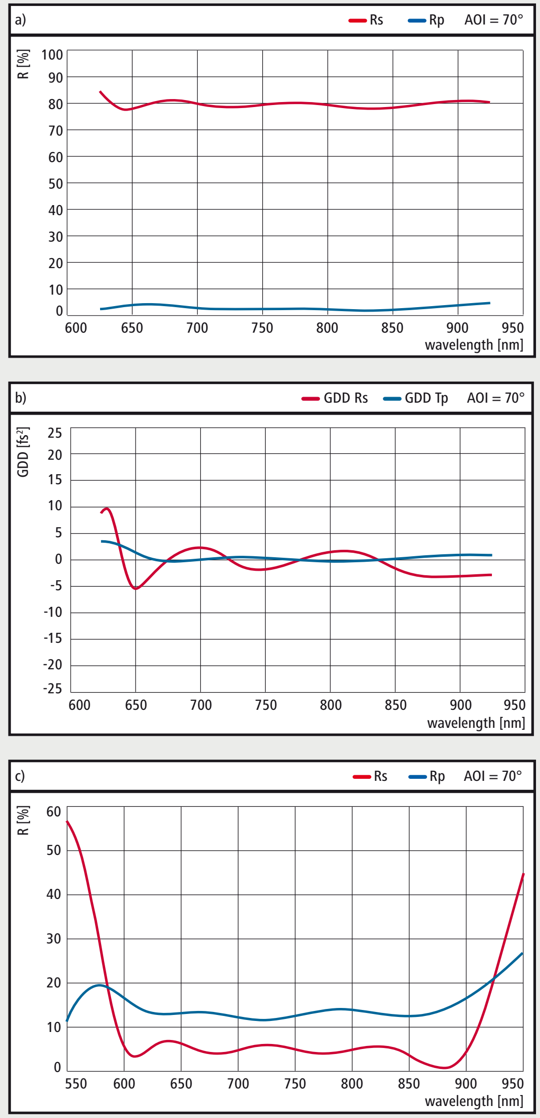


Figure 3: Reflectance and GDD spectra of a TFP (AOI = 70°), lower Rs to achieve "zero" GDD for Rs and Tp, bandwidth ≈ 300 nm
a) Reflectance vs. wavelength
b) GDD vs. wavelength
c) Back side AR coating for s-polarized light. Please note that this coating results in R ~ 15 % for the p-polarized component. As an AR coating for the p-polarization LAYERTEC suggests the use of the design from fig. 3a.

200 – 300 nm BANDWIDTH

HIGH NEGATIVE DISPERSION MIRROR PAIRS FOR AOI = 0°

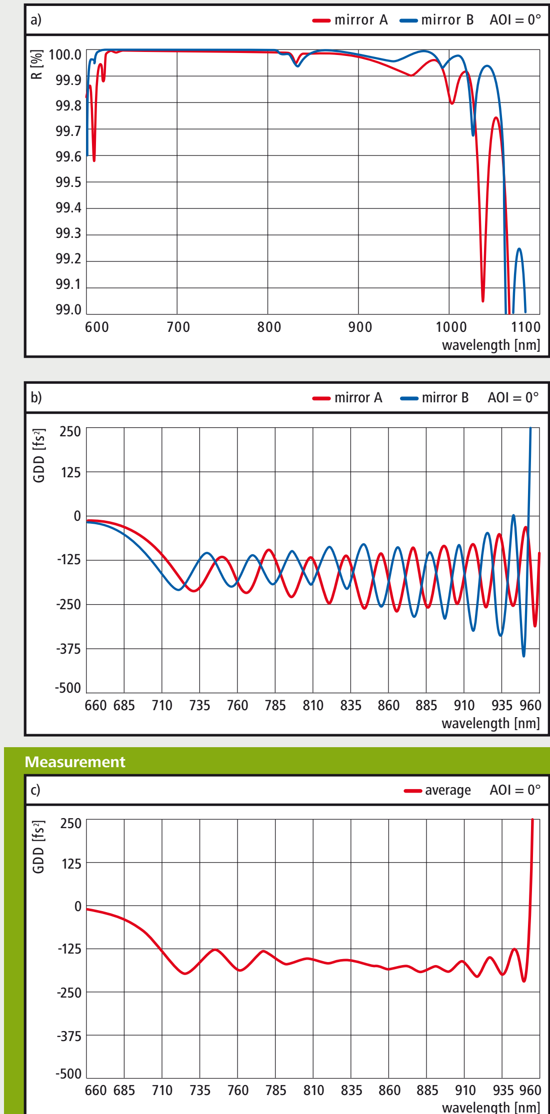


Figure 4: Reflectance and GDD spectra of a high dispersion mirror pair with a bandwidth of 250 nm and an average GDD of -180 fs² ± 40 fs² per bounce in the 800 nm range
a) Reflectance vs. wavelength
b) Calculated GDD vs. wavelength
c) Measured average GDD vs. wavelength

MIRROR PAIRS WITH OPTIMIZED THIRD ORDER DISPERSION FOR AOI = 0°

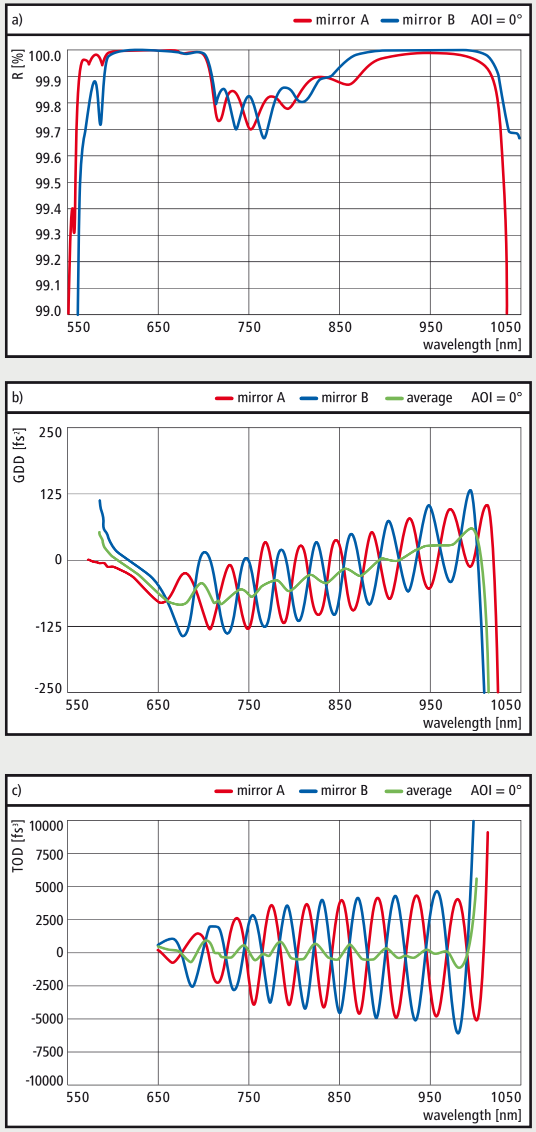


Figure 5: Reflectance, GDD and TOD spectra of a mirror pair optimized for broadband low third order dispersion
a) Reflectance vs. wavelength
b) GDD vs. wavelength
c) TOD vs. wavelength

Special features:

- GDD of high dispersive mirrors between -50 fs² and -500 fs².
- Very high reflectance.
- Center wavelength, bandwidth and GDD according to customer specifications.
- Please note that bandwidth and GDD are closely connected. High values of negative GDD result in a very narrow bandwidth.
- Spectral tolerance ± 1 % of center wavelength.
- In-house design calculation and measurement capabilities (GDD 250 – 1700 nm, reflectance measurement by CRD 220 – 1800 nm).

LIDT - INFO

≈ 0.1 J / cm², 800 nm, 150 fs,

Measurements were performed at Laser Zentrum Hannover

The mirror pair shows very smooth GDD and TOD spectra, although the single mirrors exhibit considerable GDD and TOD oscillations.

OCTAVE SPANNING FEMTOSECOND LASER OPTICS

- The coatings shown here are calculated for the wavelength range of one octave (e.g. 550 – 1100 nm). Similar coatings are possible for other wavelength ranges.
- Center wavelength, bandwidth, GDD and reflectance of output couplers and beam splitters according to customer specifications.
- Spectral tolerance ± 1 % of center wavelength.
- In-house design calculation and GDD measurement capabilities.
- GDD measurement reports are included in the delivery.

LIDT - INFO

≈ 0.1 J / cm², 800 nm, 150 fs,

Measurements were performed at Laser Zentrum Hannover

NEGATIVE DISPERSION LASER MIRROR PAIRS FOR AOI = 0°

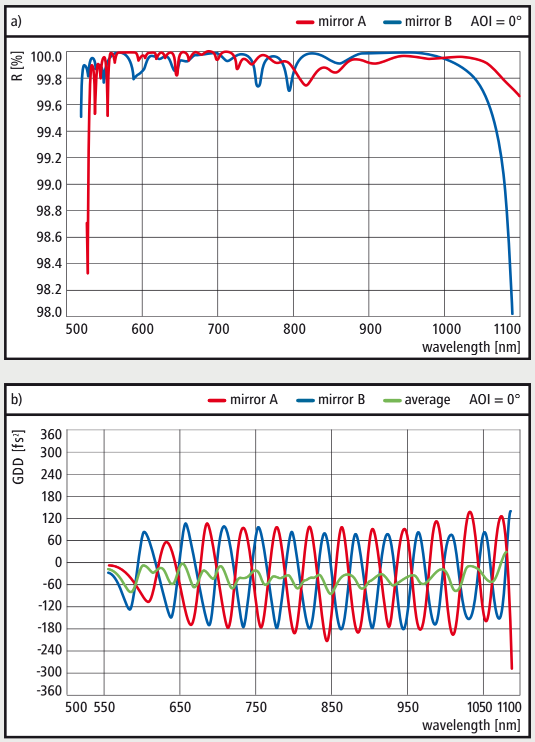


Figure 1: Reflectance and GDD spectra of an ultra broadband negative dispersion laser mirror pair
a) Reflectance vs. wavelength
b) GDD vs. wavelength

Mirror pairs designed by LAYERTEC show a very smooth average GDD spectrum even though the single broadband mirrors exhibit strong GDD oscillations.

NEGATIVE DISPERSION PUMP MIRROR PAIRS FOR AOI = 0°

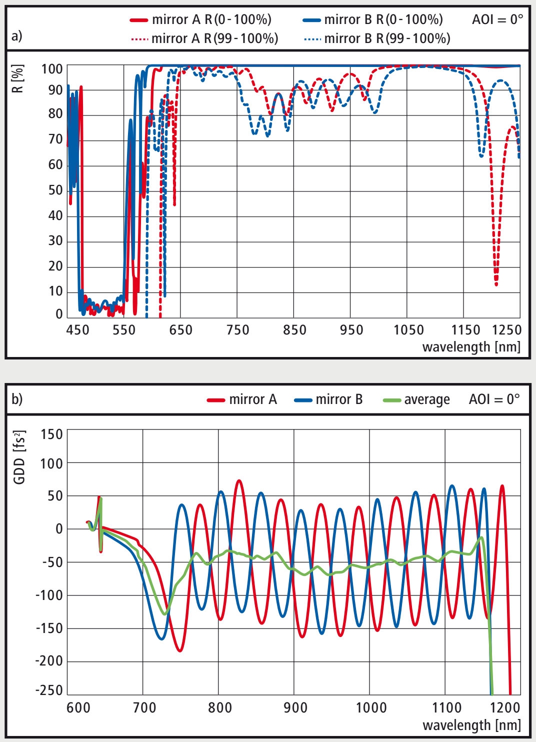


Figure 2: Reflectance and GDD spectra of an ultra broadband negative dispersion pump mirror pair
a) Reflectance vs. wavelength
b) GDD vs. wavelength

The pump mirror pair consists of two mirrors which both show a region of high transmittance around 500 nm.

NEGATIVE DISPERSION TURNING MIRROR PAIRS FOR P-POLARIZED LIGHT AOI = 45°

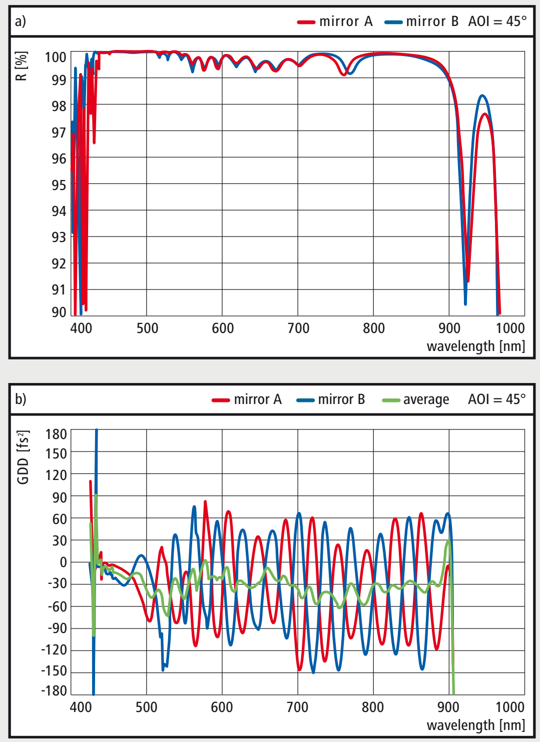


Figure 3: Reflectance and GDD spectra of an ultra broadband turning mirror pair for p-polarized light
a) Reflectance vs. wavelength
b) GDD vs. wavelength

400 – 500 nm BANDWIDTH

OUTPUT COUPLERS FOR AOI = 0°

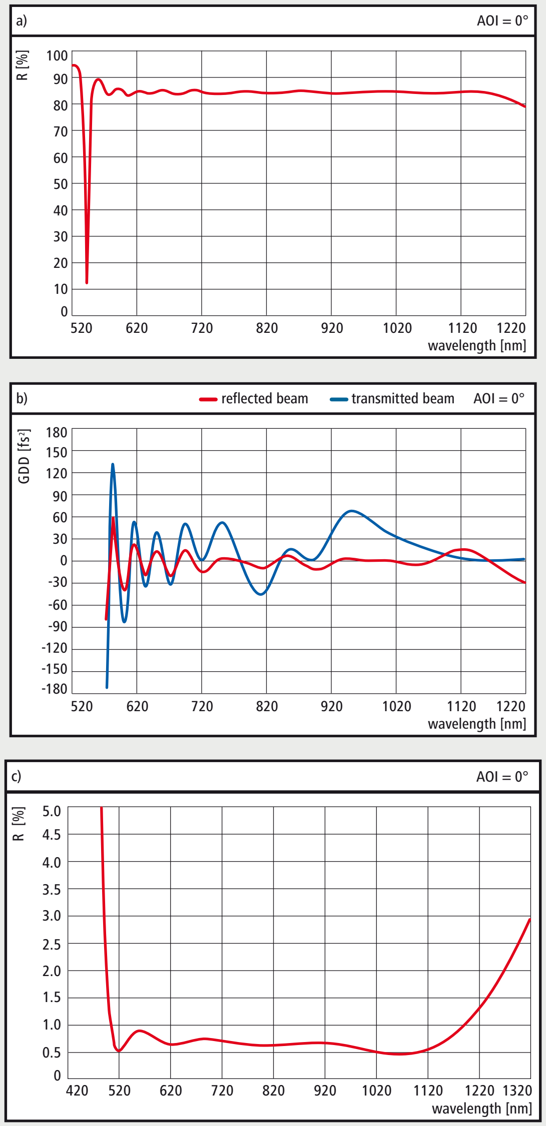


Figure 4: Reflectance and GDD spectra of an ultra broadband output coupler with R = 85 % ± 3 %
a) Reflectance vs. wavelength
b) GDD vs. wavelength
c) Back side octave spanning AR coating

BEAM SPLITTERS FOR P-POLARIZED LIGHT AT AOI = 45°

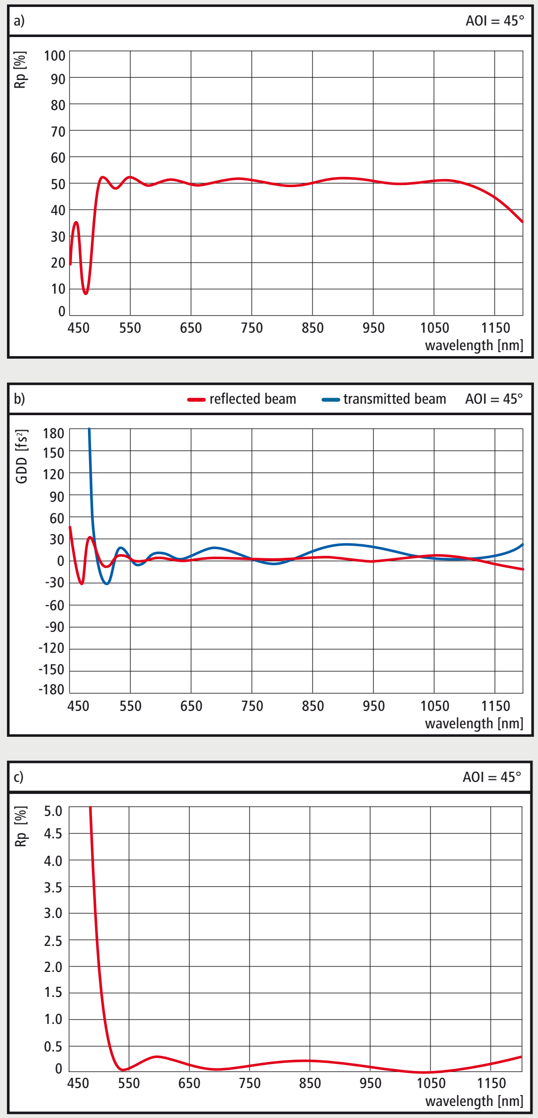


Figure 5: Reflectance and GDD spectra of an ultra broadband beam splitter for p-polarized light with Rp = 50 % ± 4 %
a) Reflectance vs. wavelength
b) GDD vs. wavelength
c) Back side octave spanning AR coating for p-polarized light

BEAM SPLITTERS FOR S-POLARIZED LIGHT AT AOI = 45°

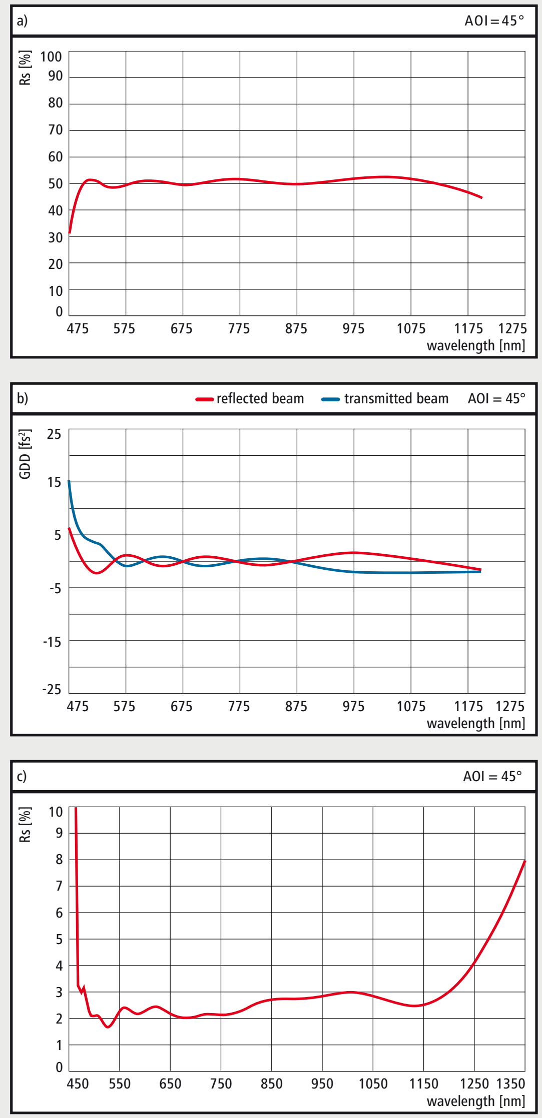


Figure 6: Reflectance and GDD spectra of an ultra broadband beam splitter for s-polarized light with Rs = 50 % ± 5 %
a) Reflectance vs. wavelength
b) GDD vs. wavelength
c) Back side octave spanning AR coating for s-polarized light

SILVER MIRRORS FOR FEMTOSECOND LASERS

SILVER MIRRORS OPTIMIZED FOR FEMTOSECOND LASER APPLICATIONS

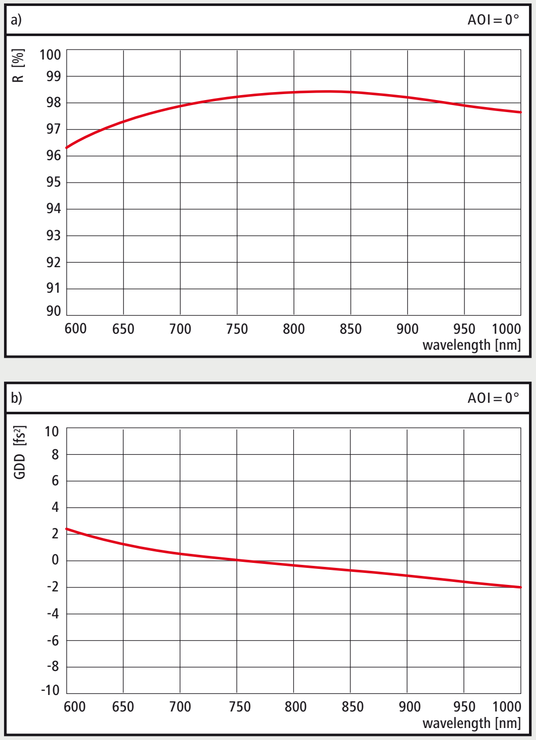


Figure 1: Reflectance and GDD-spectrum of a silver mirror optimized for use with fs-lasers in the wavelength range 600 – 1000 nm (AOI = 0°)
a) Reflectance vs. wavelength
b) GDD vs. wavelength

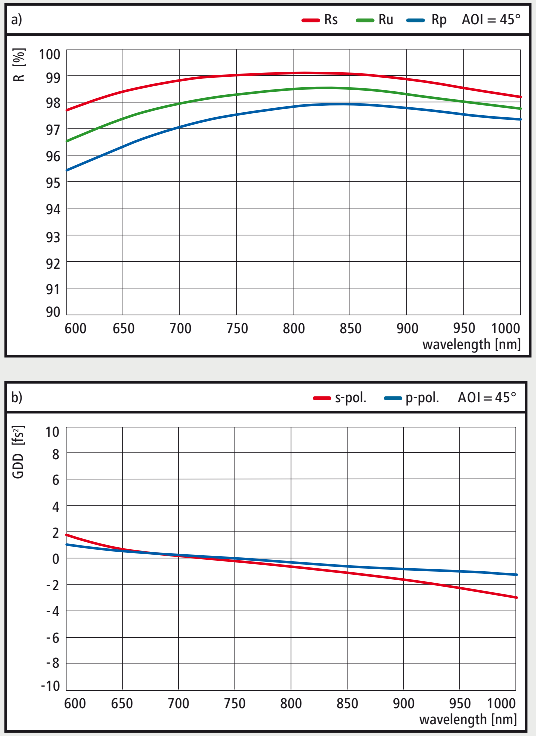


Figure 2: Reflectance and GDD-spectra of a silver mirror optimized for use with fs-lasers in the wavelength range 600 – 1000 nm (AOI = 45°)
a) Reflectance vs. wavelength
b) GDD vs. wavelength

Special features:

- High reflectance in the VIS and NIR.
- Very broad reflectance band with GDD ≈ 0 fs^2.
- Silver mirrors with defined transmittance (e.g. 0.01 %) exhibit high LIDT (see table) and the same reflectance and GDD values as shown in fig. 1 and 2.
- Extremely low scattering losses (total scattering TS ≈ 30 ppm in the VIS and NIR).
- Lifetimes of more than 10 years have been demonstrated in normal atmosphere.
- Highly stable optical parameters due to sputtered protective layers.
- Easy to clean (tested according to MIL-M-13508C § 4.4.5).

Stock of standard components:

- Standard and fs-optimized protected silver on substrates with Ø =12.7 mm, Ø = 25 mm and Ø = 50 mm:
  - Plane,
  - Plano/concave and plano/convex with a variety of radii between 10 mm and 10000 mm.
- Other sizes, shapes, radii and coatings for other wavelength ranges on request.

LIDT - INFO

Coating	Reflectance*	Wavelength range	LIDT [J / cm²] **
fs- optimized protected silver	R = 96.5 % ... 98.5 %	600 – 1000 nm	0.38
Enhanced silver 800 nm	R > 99 %	700 – 900 nm	0.37
Broadband enhanced silver	R = 98 % … 98.5 %	600 – 1200 nm	0.24
Partially transparent silver	R = 96.5 % … 98.5 %	600 – 1000 nm	0.22

* For unpolarized light at AOI = 45°
** Measurements were performed at Laser Zentrum Hannover according to ISO 11254
measurement conditions: pulse duration: 150 fs, 30000 pulses, repetition rate: 1 kHz, λ = 800 nm

550 – 1100 nm

SILVER MIRRORS WITH ENHANCED REFLECTANCE

The reflectance of silver mirrors can be enhanced by an additional dielectric coating. The bandwidth of the enhanced reflectance must be exactly specified. Outside this band, the reflectance of the mirror may be lower than that of a standard silver mirror.

For the use with fs-lasers, the additional dielectric coating must be optimized for high reflectance and low GDD. The following figures show examples for silver mirrors with enhanced reflectance at a specified wavelength (fig. 3 and 4) and over the wavelength range of the Ti:Sapphire laser (fig. 5). Enhanced silver mirrors can also be designed for a defined transmittance (e.g. T = 0.01 %).

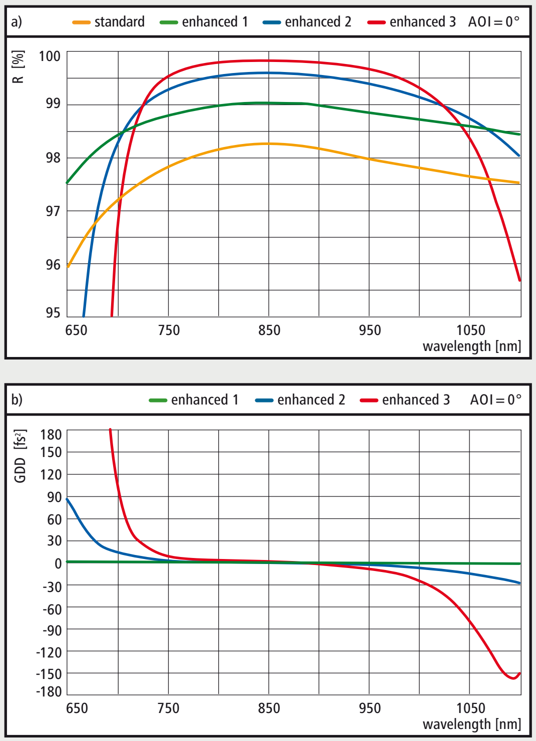


Figure 3: Reflectance and GDD spectra of silver mirrors with different designs for enhanced reflectance around 850 nm (AOI = 0°)
a) Reflectance vs. wavelength
b) GDD vs. wavelength

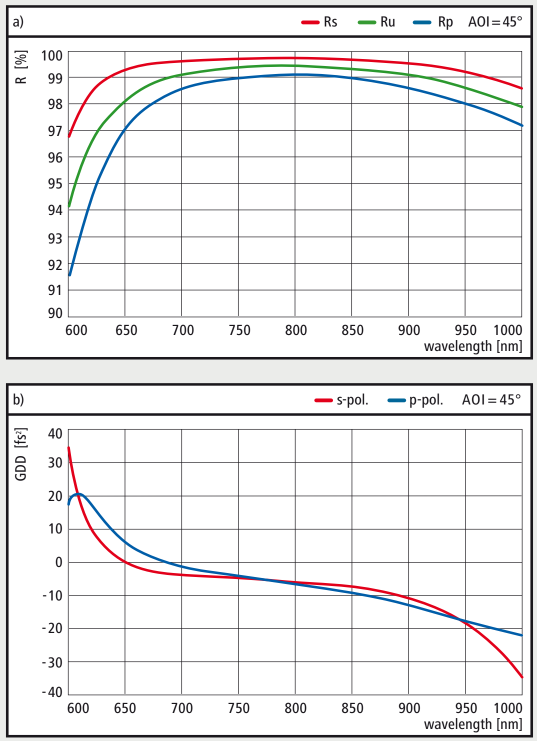


Figure 4: Reflectance and GDD spectra of silver mirrors with enhanced reflectance around 800 nm (AOI = 45°)
a) Reflectance vs. wavelength
b) GDD vs. wavelength

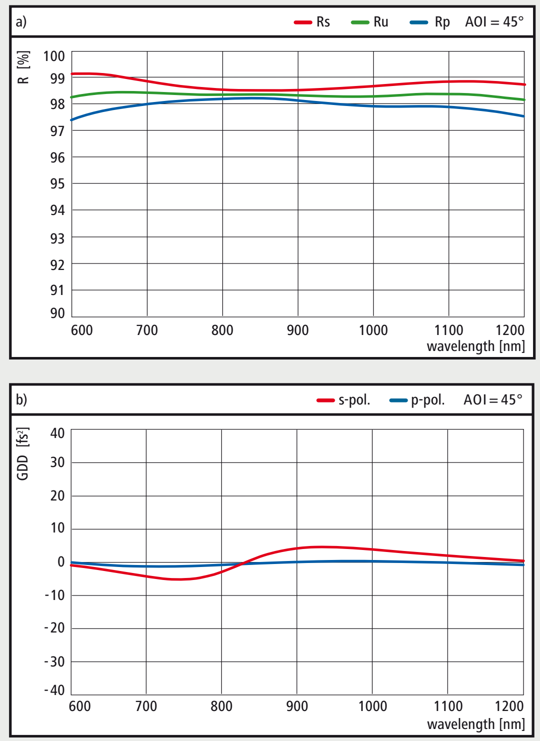


Figure 5: Reflectance and GDD spectra of silver mirrors with enhanced reflectance in the wavelength range 600 – 1200 nm (AOI = 45°)
a) Reflectance vs. wavelength
b) GDD vs. wavelength

HIGH POWER FEMTOSECOND LASER OPTICS

Femtosecond lasers are widely used in measurement applications and materials science. Ultrafast lasers enable the machining of metals as well as of dielectric materials by cold, i.e. non-thermal, processes. The most important feature of these treatment steps is the avoidance of melt. That is why pieces machined with ultrafast lasers are of high accuracy and do not require mechanical postprocessing. The demands for efficient production processes drive the development of high-power fs lasers. In most cases, these lasers show pulse lengths between 100 fs and 1ps (for high power ps lasers see page 55).

Moreover, high-power ultrafast lasers with power levels in the terawatt and petawatt range become more and more important in basic research on light-material-interaction, particle physics and even for medical applications. The pulse duration of these lasers is considerably shorter than that of lasers for material processing. Typical pulse durations range from 20 fs to 50 fs.

The laser types mentioned above require optics with high laser-induced damage thresholds (LIDT). High-power coatings for ultrafast lasers were the topic of a number of scientific investigations in the last years [1, 2]. Research institutes as well as optics manufacturers have spent much effort on the improvement of the LIDT of fs laser optics. LAYERTEC has dealt with this issue for nearly 20 years (please see LAYERTEC's catalogs of 2001 – 2015).

The main result of the investigations mentioned above was that the LIDT of optical coatings in the fs regime is strongly related to the band gap of the coating materials as well as the coating designs. Materials with larger band gaps exhibit larger LIDT. However, there is a trade-off between damage threshold and bandwidth, as large band gaps also translate into a smaller difference of the refractive indices. Thus, turning mirrors made of these materials only have a bandwidth of about 100 nm for p-polarized light at AOI = 45°. This bandwidth is sufficient for pulse lengths as low as 25 fs. Please note that all LAYERTEC high-power designs are optimized for GDD < 50 fs².

In contrast, materials with a large difference of the refractive indices may be used in order to achieve large bandwidths. Designs for standard low-GDD components exhibit medium LIDT values, whereas broadband designs result in low damage thresholds. This is also the case when considering mirrors with dispersion control, such as chirped mirror pairs or GTI mirrors. Here, bandwidth and phase requirements outweigh LIDT. However, depending on the complexity of the overall constraints, some optimization of damage thresholds may be possible.

The investigations have also shown that LAYERTEC's optimized silver mirrors possess significant LIDT values in the fs range. Another advantage of silver mirrors is their extremely broad zero-GDD reflectance band with reflectance up to 98.5 % at normal incidence. Even silver mirrors with a defined transmission of 0.01 % exhibit considerable damage thresholds, especially with respect to dielectric ultra-broadband components. For more information on silver mirrors see pages 86 – 87.

1) Femtosecond laser damage resistance of oxide and mixture oxide optical coatings
Author(s): B. Mangote, L. Gallais, M. Commandré, M. Mende, L. O. Jensen, H. Ehlers, M. Jupé, D. Ristau, A. Melninkaitis, J. Mirauskas, V. Sirutkaitis, S. Kicas, T. Tolenis, R. Drazdys
Optics Letters 9 (37), 1478/u20131480 (2012)

2) 40-fs broadband low dispersion mirror thin film damage competition
Author(s): Raluca A. Negres; Christopher J. Stolz; Kyle R. P. Kafka; Enam A. Chowdhury; Matt Kirchner; Kevin Shea; Meaghan Daly
Proc. SPIE 10014, Laser-Induced Damage in Optical Materials 2016, 100140E (6 December 2016); doi: 10.1117/12.2244758

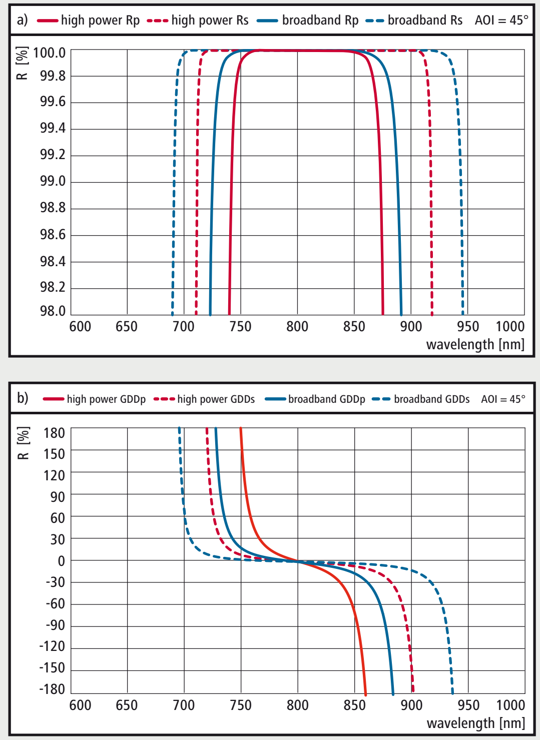
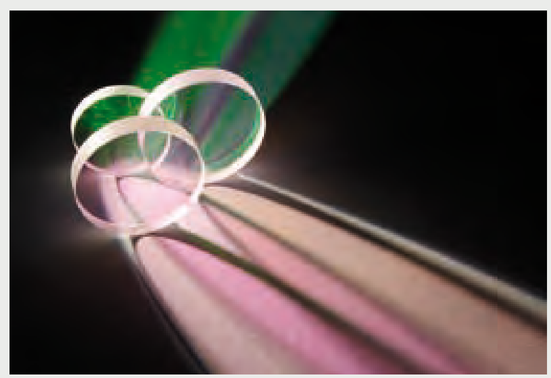


Figure 1: Reflectance (a) and GDD (b) spectra of a high power fs laser turning mirror (red) and a broadband fs laser turning mirror (blue)



550 – 1100 nm BANDWIDTH

OVERVIEW ABOUT LASER INDUCED DAMAGE THRESHOLDS OF FEMTOSECOND LASER OPTICS

LIDT - INFO

Coating	Reflectance [%] at 800 nm	LIDT [J / cm²] at 800 nm	Pulse duration Repetition rate
Unprotected gold	97.5	0.33 [1] 0.33 [2]	50 fs, 1 kHz 150 fs, 1 kHz
fs-optimized silver	**98.5**	**0.38 [1]** **0.38 [2]**	**50 fs, 1 kHz** **150 fs, 1 kHz**
Enhanced silver (800 nm)	99.7	0.37 [2]	150 fs, 1 kHz
Enhanced silver (600 – 1200 nm)	98.5	0.24 [2]	150 fs, 1 kHz
Partially transparent silver (T = 0.01 % @ 800 nm)	98.5	0.22 [2]	150 fs, 1 kHz
Negative-dispersion mirrors *	> 99.9	0.10 [2]	150 fs, 1 kHz
Broadband low-GDD mirrors *	> 99.9	0.15 [1] 0.10 [2]	6 fs, 1 kHz 150 fs, 4 kHz
Standard low-GDD mirrors	> 99.9	0.50 [3] 2.40 [4] 0.30 [2] 0.55 [2]	42 fs, 1 kHz 70 fs, 10 kHz 150 fs, 1 kHz 1 ps, 1 kHz
High-power mirror for ps pulses	**> 99.9**	**0.35 [1]** **0.44 [2]** **0.65 [2]**	**50 fs, 1 kHz** **150 fs, 1 kHz** **1 ps, 1 kHz**
High-power mirror for fs pulses	**> 99.5**	**0.90 [3]** **3.60 [4]**	**42 fs, 1 kHz** **70 fs, 1 kHz**
Single-wavelength AR coating **	< 0.2	1.10 [3] 1.20 [2]	42 fs, 1 kHz 1 ps, 1 kHz
Broadband AR coating **	< 0.5	1.20 [2]	1 ps, 1 kHz

1) Measurements were performed at Friedrich-Schiller Universität Jena
2) Measurements were performed at Laser Zentrum Hannover
3) Measurements were performed at Wigner Research Centre for Physics, Budapest
4) Measurements were performed at Helmholtz-Zentrum Dresden-Rossendorf
* A significant number of designs were tested. The LIDT values stated here are typical for the corresponding test conditions.
** Self-focusing effects may destroy the substrate while the AR coating is still intact.

METALLIC HIGH POWER MIRRORS

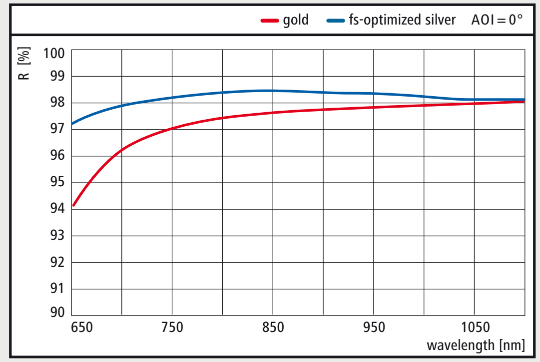


Figure 2: Reflectance spectra of unprotected gold and fs-optimized silver (optimized for high reflectance at 800 nm)

GDD OF HIGH POWER FEMTOSECOND LASER MIRRORS

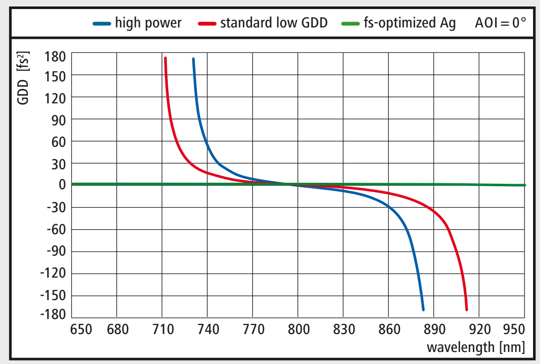


Figure 3: Group delay dispersion (GDD) of standard and high-power dielectric mirrors and fs-optimized silver mirrors

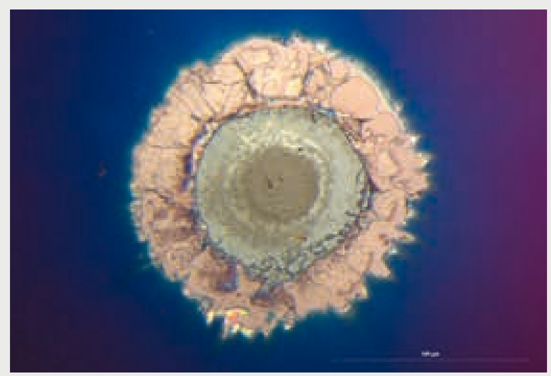


Figure 4: Laser-induced damage of a coated surface

COMPONENTS FOR THE SECOND HARMONIC OF THE Ti:SAPPHIRE LASER

DUAL WAVELENGTH MIRRORS

The second harmonic of the Ti:Sapphire laser provides fs-pulses in the NUV and VIS spectral range. This aspect offers a variety of applications in spectroscopy and materials science. Optics for these special applications must be optimized for both high reflectance and low dispersion. Also, negative dispersion mirrors for pulse compression are of interest.

Special features:

- Very high reflectance (R > 99.9 %).
- Center wavelength and bandwidth according to customer specifications.
- Spectral tolerance ± 1 % of center wavelength.

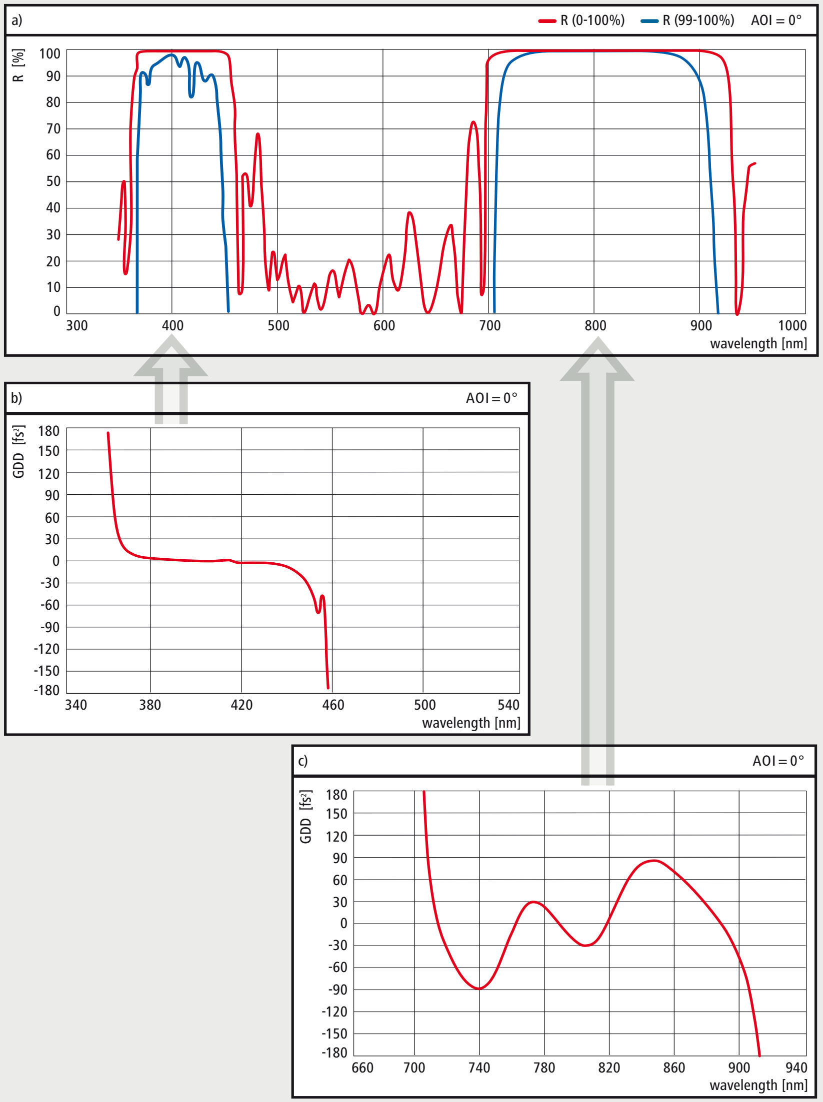


Figure 1: Reflectance and GDD spectra of a fs-optimized dual wavelength mirror for 400 nm + 800 nm at AOI = 0°
a) Reflectance vs. wavelength   b, c) GDD vs. wavelength

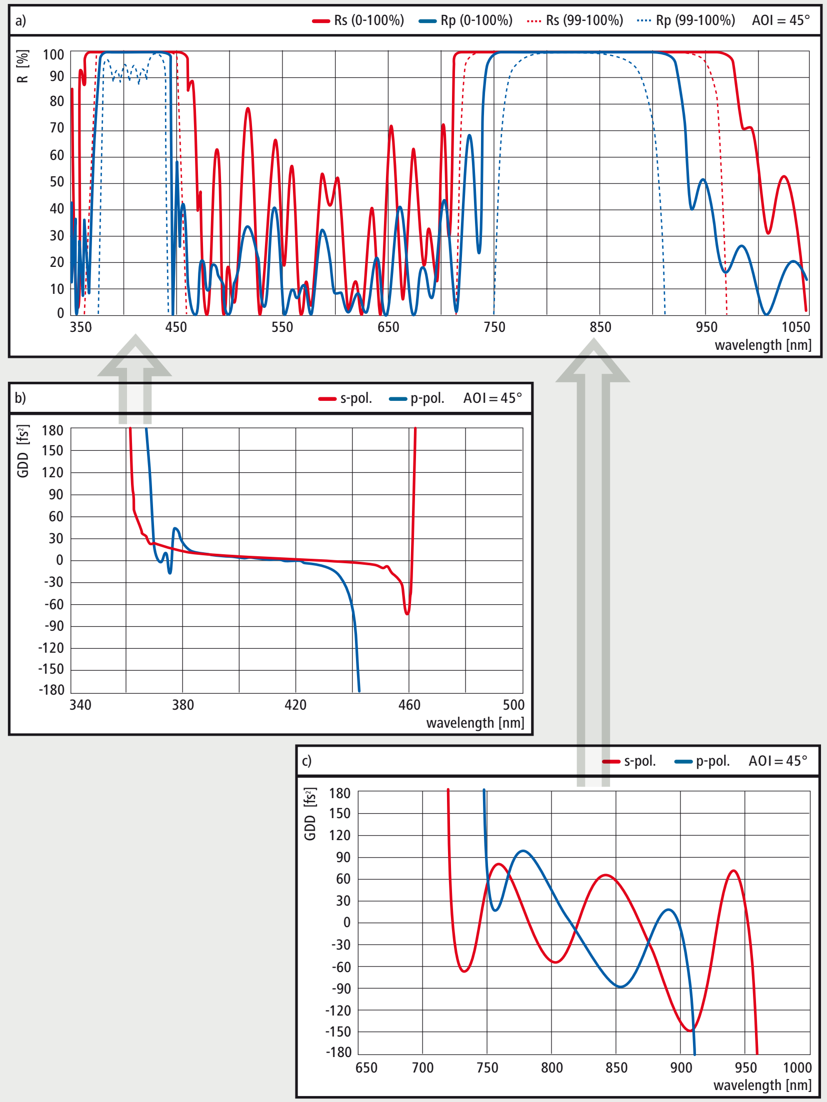


Figure 2: Reflectance and GDD spectra of a fs-optimized dual wavelength turning mirror for 400 nm + 800 nm at AOI = 45°
a) Reflectance vs. wavelength   b, c) GDD vs. wavelength

300 – 600 nm

SEPARATORS FOR THE SECOND HARMONIC FROM THE FUNDAMENTAL FOR AOI = 45°

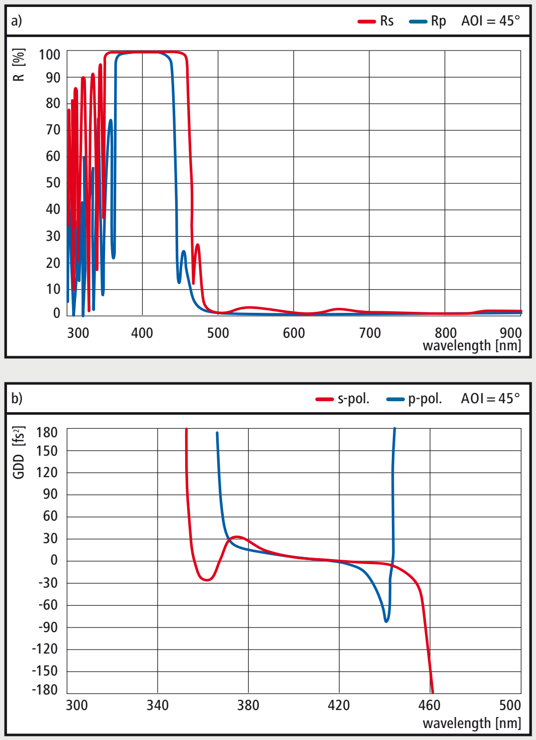


Figure 3: Reflectance and GDD spectra of a separator HRs,p (45°, 400 nm) > 99.9 % + Rs,p (45°, 800 nm) < 2 %
a) Reflectance vs. wavelength
b) GDD vs. wavelength

- Reflectance R > 99.9 % for s- and p-polarization in the reflectance band.
- Transmittance T > 95 % for s- and p-polarization in the transmittance band.
- These components work for p- and s- polarization, but performance can be optimized if the polarization is clearly specified.

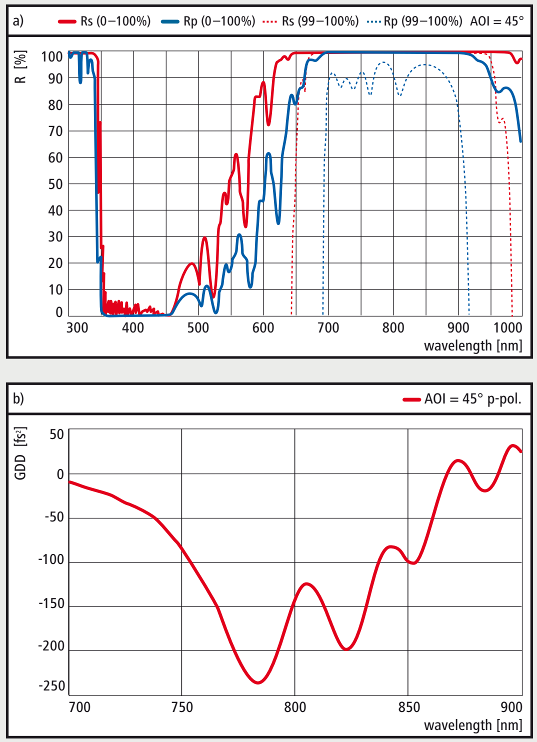


Figure 4: Reflectance and GDD spectra of a separator HRp (45°, 800 nm) > 99.9 % + Rp (45°, 400 nm) < 2 % + Rs (45°, 400 nm) < 10 %
a) Reflectance vs. wavelength
b) GDD vs. wavelength

- Bandwidth of the 800 nm reflectance band > 200 nm for p-polarization.
- All separators exhibit |GDD| < 20 fs² in the transmittance band.

NEGATIVE DISPERSION MIRROR PAIR FOR THE 400 nm SPECTRAL RANGE AT AOI = 0°

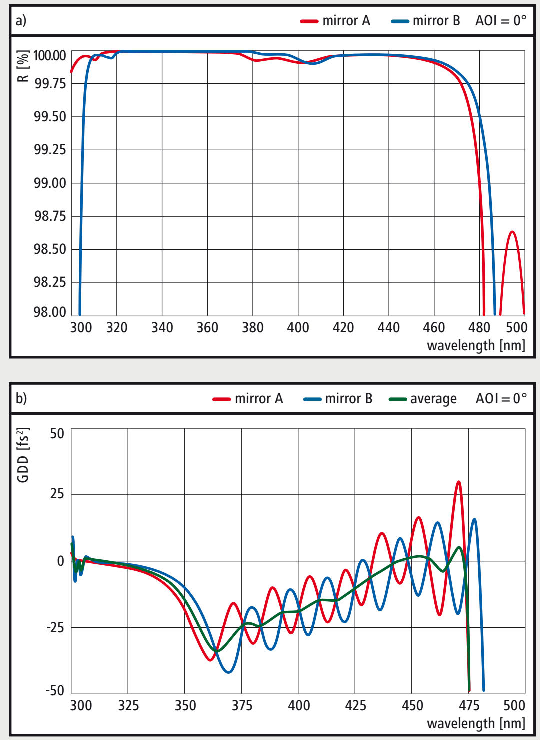


Figure 5: Reflectance and GDD spectra of a negative dispersion mirror pair for 350 – 480 nm with an average GDD varying from -30 fs² at 350 nm to 0 fs² at 480 nm (TOD optimized)
a) Reflectance vs. wavelength
b) GDD vs. wavelength

- Prototype production according to customer specifications.
- In-house design calculation and measurement capabilities.

COMPONENTS FOR THE THIRD HARMONIC OF THE Ti:SAPPHIRE LASER

DUAL WAVELENTGH TURNING MIRRORS FOR AOI = 45°

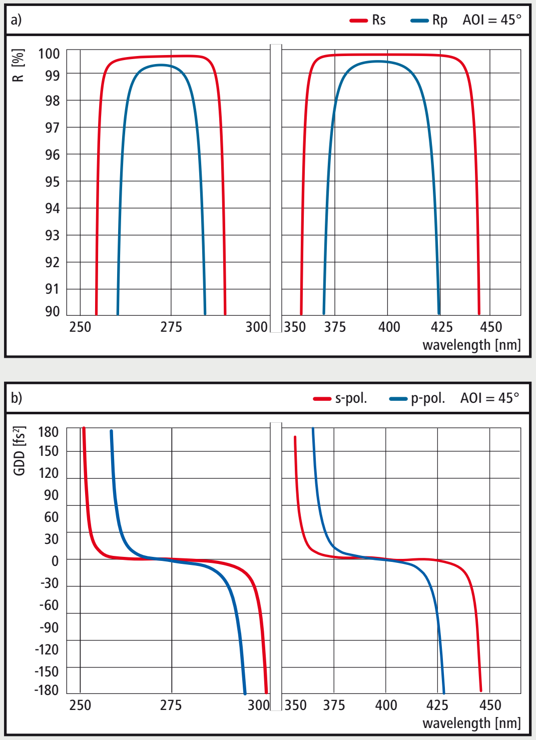


Figure 1: Reflectance and GDD spectra of a fs-optimized dual wavelength turning mirror for 270 nm and 405 nm
a) Reflectance vs. wavelength
b) GDD vs. wavelength

TRIPLE WAVELENTGH TURNING MIRRORS FOR AOI = 45°

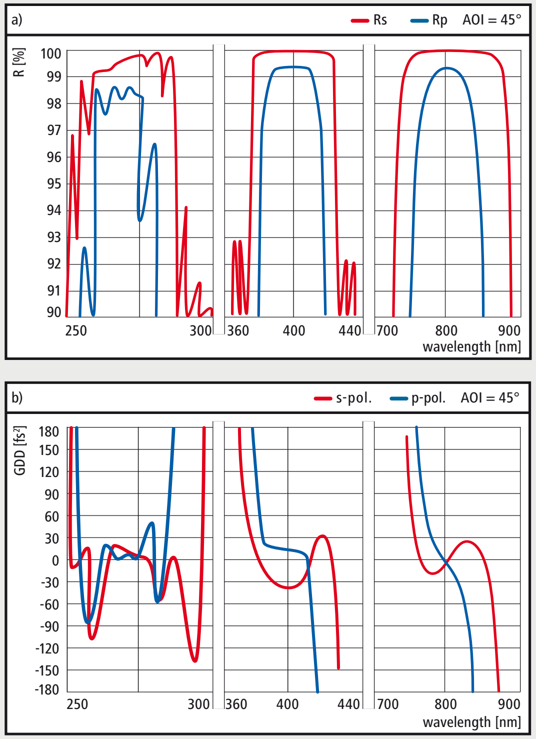


Figure 2: Reflectance and GDD spectra of a fs-optimized turning mirror for the 266 nm, 400 nm and 800 nm wavelength regions
a) Reflectance vs. wavelength
b) GDD vs. wavelength

Please note that this triple wavelength turning mirror exhibits |GDD| < 50 fs² in all three wavelength regions of interest.

BROADBAND LOW DISPERSION MIRRORS FOR AOI = 45°

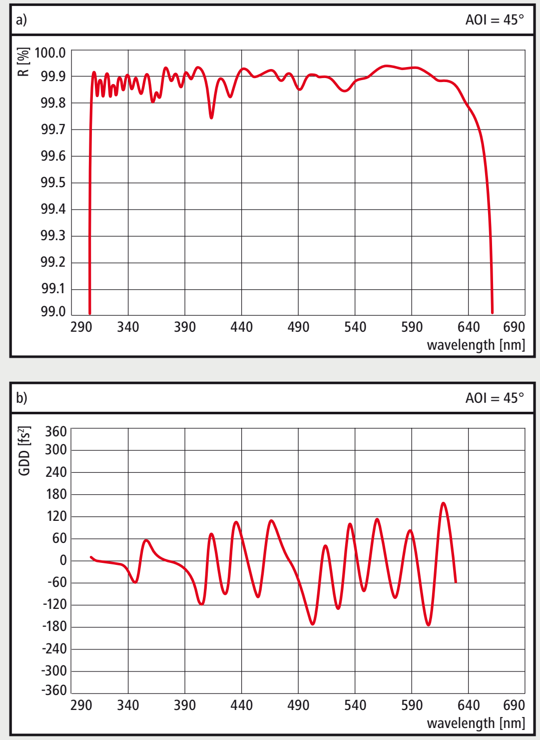


Figure 3: Reflectance and GDD spectra of a broadband negative dispersion mirror HRs (45°, 325 – 600 nm) > 99.7 % with low GDD
a) Reflectance vs. wavelength
b) GDD vs. wavelength

250 – 400 nm

SEPARATORS FOR THE THIRD HARMONIC FROM THE SECOND HARMONIC AND THE FUNDAMENTAL WAVE FOR AOI = 45°

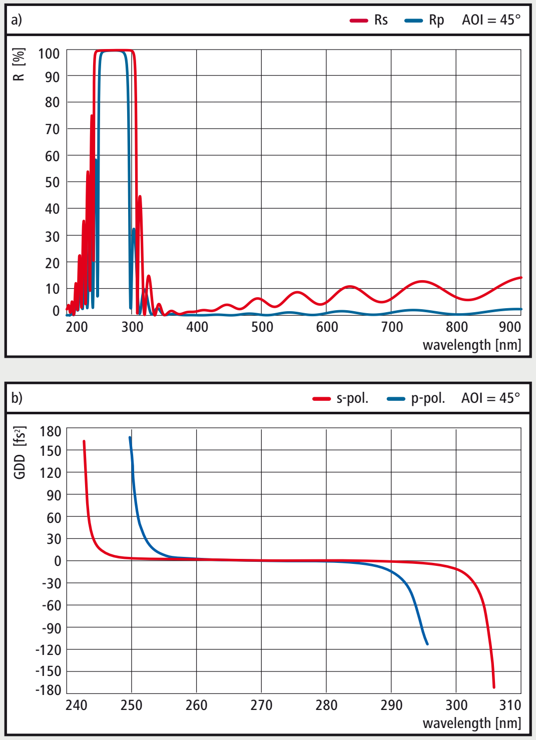


Figure 4: Reflectance and GDD spectra of a standard separator reflecting the third harmonic and transmitting the second harmonic and the fundamental
a) Reflectance vs. wavelength
b) GDD vs. wavelength

For the bandwidth of the reflectance and low-GDD ranges, please see table on page 95.

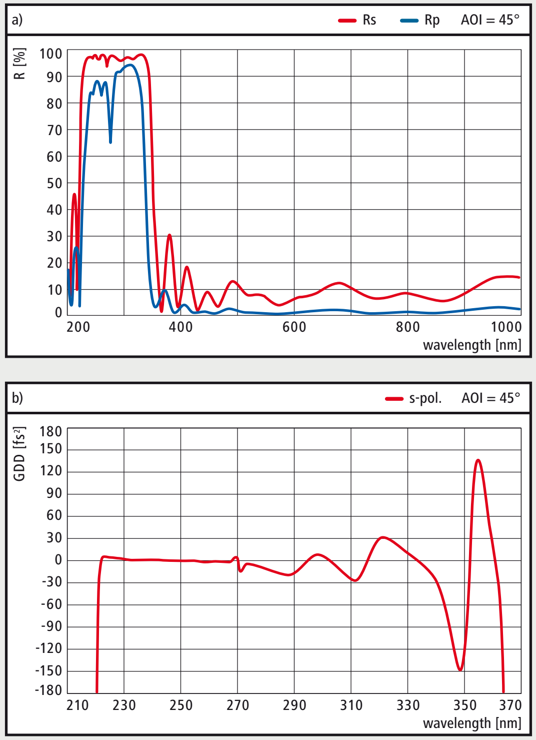


Figure 5: Reflectance and GDD spectra of a broadband separator with high reflectance for s-polarized light throughout the wavelength range of the third harmonic of the Ti:Sapphire laser and high transmittance for p-polarized light in the VIS and NIR:
HRs (45°, 250 – 330 nm) > 95 %
+ Rp (45°, 440 – 1000 nm) < 3 %
a) Reflectance vs. wavelength
b) GDD vs. wavelength

NEGATIVE DISPERSION MIRROR PAIR FOR AOI = 0°

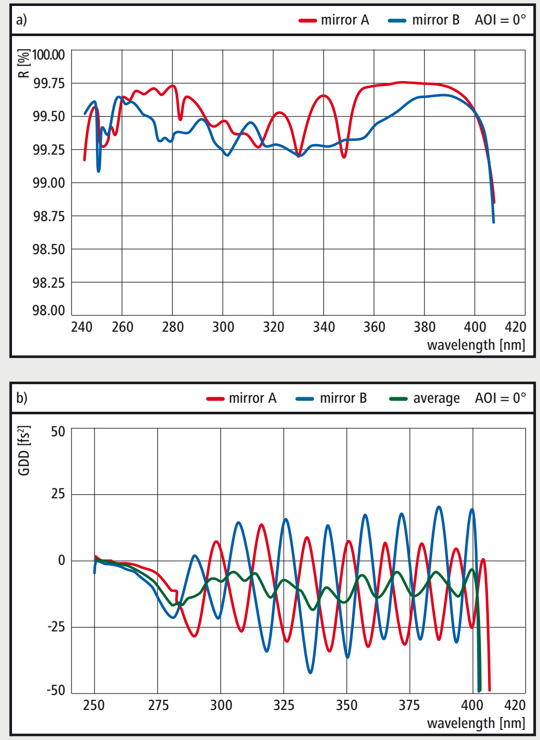


Figure 6: Reflectance and GDD spectra of a broadband negative dispersion mirror pair HR (0°, 275 – 400 nm) > 99 % with an average GDD of ≈ -10 fs^2 per bounce
a) Reflectance vs. wavelength
b) GDD vs. wavelength

COMPONENTS FOR THE HIGHER HARMONICS OF THE Ti:SAPPHIRE LASER

The fourth, fifth and sixth harmonics of the Ti:Sapphire laser provide fs-pulses in the DUV / VUV range. These harmonics offer a variety of applications in spectroscopy as well as in materials science. Optics for these very special applications must be optimized for high reflectance and low dispersion.

Mirrors and separators for the wavelength range 125 – 215 nm consist of fluoride layer systems on CaF_2 substrates while components for longer wavelengths can be made of oxides.

For mirrors, LAYERTEC recommends substrates with a thickness of 3 mm or 6.35 mm to achieve good flatness values. For special separators, LAYERTEC offers substrates of fused silica or calcium fluoride as thin as 1 mm or 0.5 mm.

TURNING MIRRORS AND SEPARATORS FOR THE FOURTH HARMONIC AT AOI = 45°

Measurement

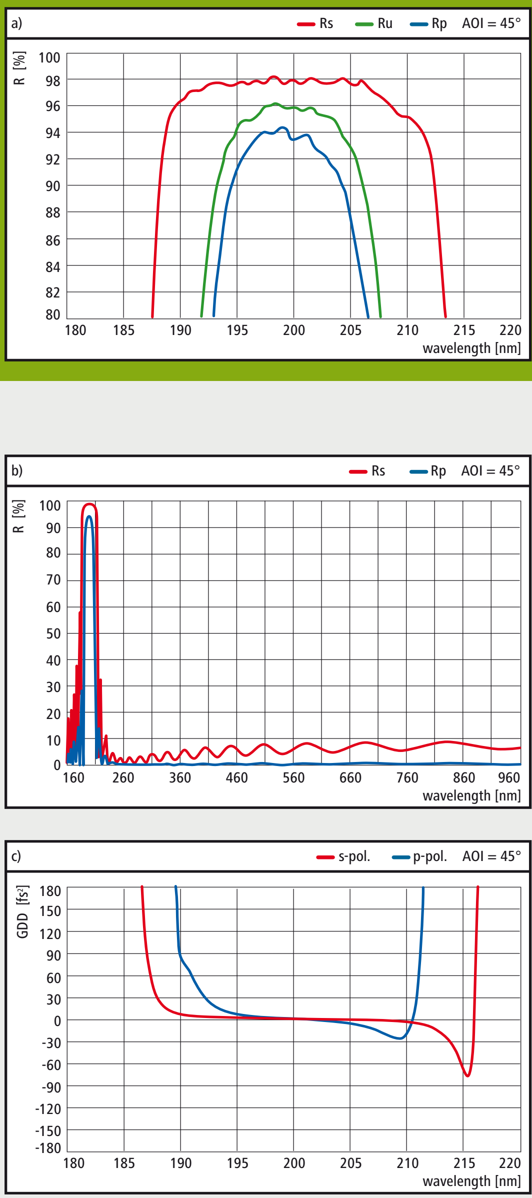


Figure 1: Reflectance and GDD spectra of a separator for the fourth harmonic from the longer wavelength harmonics and the fundamental wave (AOI = 45°)
a) Reflectance vs. wavelength (measured)
b) Reflectance vs. wavelength (calculated)
c) GDD vs. wavelength (calculated)

COMPONENTS FOR THE FIFTH HARMONIC AT AOI = 45°

Measurement

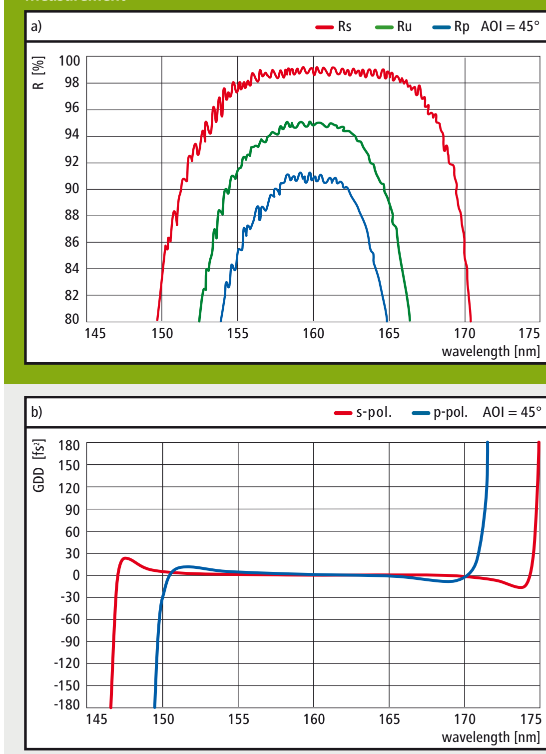


Figure 2: Reflectance and GDD spectra of a turning mirror for 160 nm (AOI = 45°)
a) Reflectance vs. wavelength (measured)
b) GDD vs. wavelength (calculated)

COMPONENTS FOR THE SIXTH HARMONIC AT AOI = 45°

Measurement

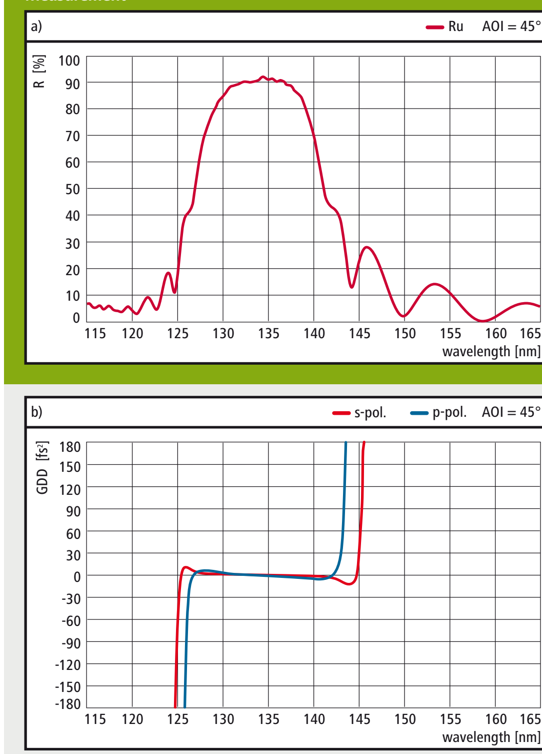


Figure 3: Reflectance and GDD spectra of a turning mirror for 133 nm (AOI = 45°)
a) Reflectance vs. wavelength (measured for unpolarized light)
b) GDD vs. wavelength (calculated)

140 – 250 nm

BANDWIDTH OF THE REFLECTANCE AND LOW-GDD RANGE OF STANDARD COMPONENTS

- The coatings described in the data sheets on pages 92 – 95 can be used to achieve center wavelengths as given in the following table. Different coating materials are used for different wavelength ranges.
- All coatings are optimized for broad reflection bands, high reflectance and low GDD.

Component	Wavelength range	P-polarization	S-polarization
		|GDD| < 20 fs²	|GDD| < 20 fs²
Turning mirror or separator 3rd harmonic	250 nm – 330 nm	30 nm (R > 99 %)	50 nm (R > 99 %)
Dual wavelength turning mirror	250 nm – 330 nm	15 nm (R > 99 %)	26 nm (R > 99 %)
	370 nm – 500 nm	34 nm (R > 99 %)	72 nm (R > 99 %)
Turning mirror or separator 4th harmonic	180 nm – 250 nm	5 nm (R > 93 %)	15 nm (R > 97 %)
Turning mirror or separator 5th harmonic	140 nm – 180 nm	4 nm (R > 90 %)	12 nm (R > 97 %)
Turning mirror or separator 6th harmonic	125 nm – 140 nm	8 nm (R > 85 % unpolarized)	

BROADBAND REFLECTORS FOR THE 200 – 250 nm WAVELENGTH RANGE

Advanced sputtering techniques enable LAYERTEC to produce broadband mirrors and separators for the wavelength range of the fourth harmonic of the Ti:Sapphire laser. These components consist of oxide coatings on fused silica substrates. Please note that oxide coatings show considerable absorption losses between 200 nm and 215 nm. That is why LAYERTEC only specifies R > 80 – 90 % in this wavelength range. Nevertheless, this is the only way to produce broadband low dispersion components for the UV with high transmittance in the VIS and NIR.

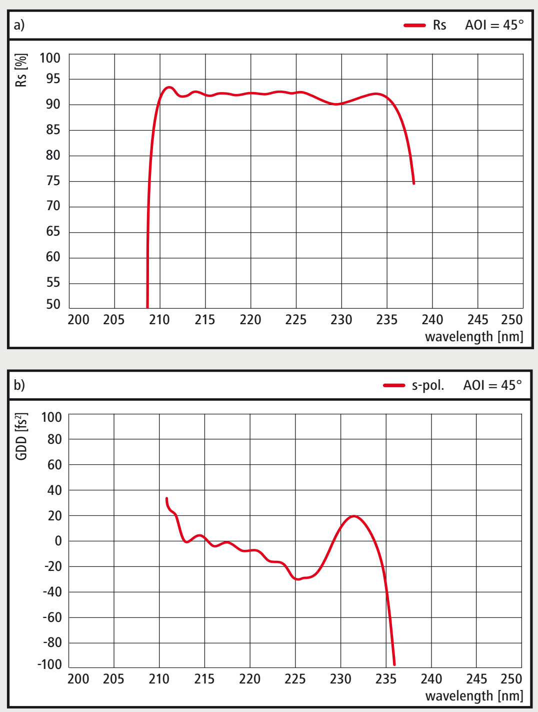


Figure 4: Reflectance and GDD spectra of a broadband mirror HRs (45°, 210 – 235 nm) > 90 %
a) Reflectance vs. wavelength
b) GDD vs. wavelength

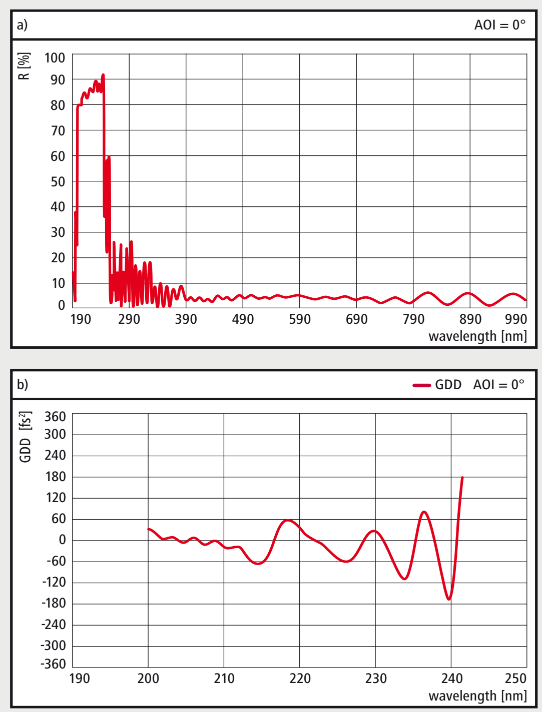


Figure 5: Reflectance and GDD spectra of a broadband separator HR (0°, 200 – 245 nm) > 80 % + R (0°, 300 – 1000 nm) < 10 %
a) Reflectance vs. wavelength
b) GDD vs. wavelength

GIRES-TOURNOIS-INTERFEROMETER (GTI) MIRRORS

Gires-Tournois- Interferometer (GTI) mirrors are used for pulse compression in short pulse lasers such as Yb:YAG- or Yb:KGW-lasers. LAYERTEC also offers GTI mirrors for the Ti:Sapphire wavelength range and for other femtosecond lasers in the NIR spectral range. Compared to prism compressors, GTI mirrors reduce the intra-cavity losses resulting in higher output power of the laser.

Special features:

- Very high reflectance.
- Center wavelength, bandwidth and GDD according to customer specifications.
- Please note that bandwidth and GDD are closely connected. A high value of negative GDD results in a very narrow bandwidth.
- Spectral tolerance ± 1 % of center wavelength.
- In-house design calculation and measurement capabilities (GDD 250 – 1700 nm, reflectance measurement by CRD 210 – 1800 nm).

LIDT - INFO

≈ 0.1 J / cm², 800 nm, 150 fs,
Measurements were performed at Laser Zentrum Hannover

GTI - MIRRORS FOR Yb:YAG- AND Yb:KGW-LASERS

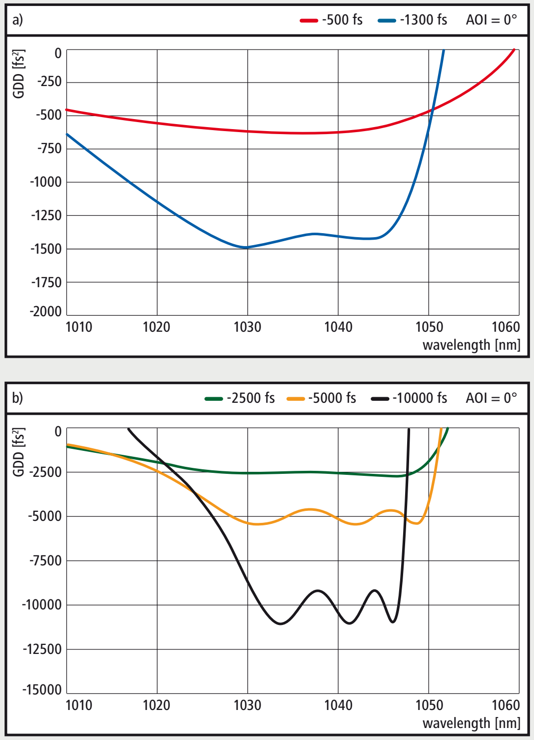


Figure 1: GDD spectra of GTI-mirrors for 1040 nm with different GDD Values

GDD [fs²]	Reflectance [%] measured by CRD
-500	99.99
-1300	99.98
-2500	99.97
-5000	99.95
-10000	99.95

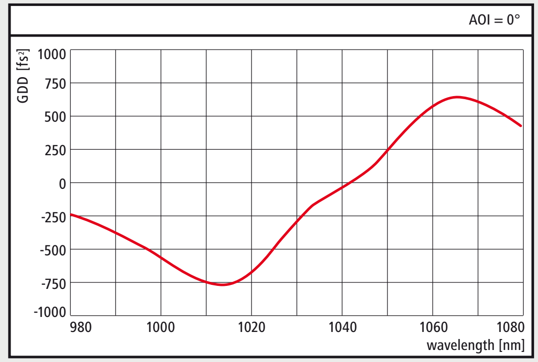


Figure 2: GTI mirror with nearly constant TOD

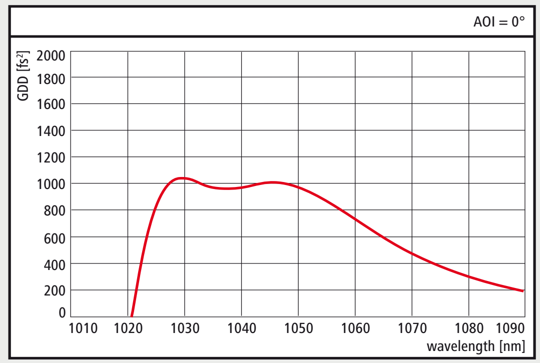


Figure 3: GTI mirror with positive GDD

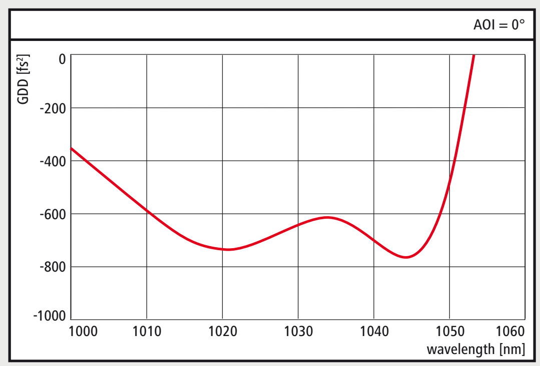


Figure 4: GDD spectrum of a rear side GTI mirror with GDD (0°- 10°, 1030 nm) ~ -700 fs². The mirror is irradiated through the substrate which has an AR coating on the front side. Back side GTI mirrors are insensitive against surface contaminations which sometimes distort the GDD spectrum of common front side GTI mirrors

600 – 1600 nm

OPTICAL LOSSES OF GTI MIRRORS

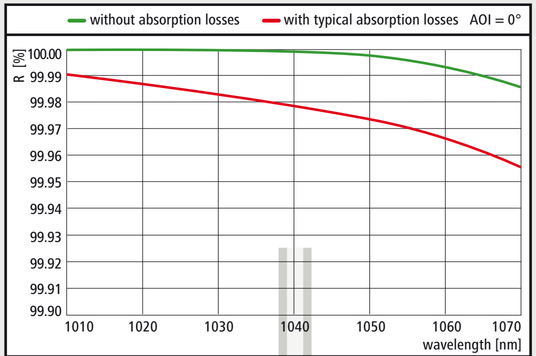


Figure 5: Calculated reflectance spectra of a GTI mirror without absorption losses (green) and with typical absorption losses (red)

Measurement

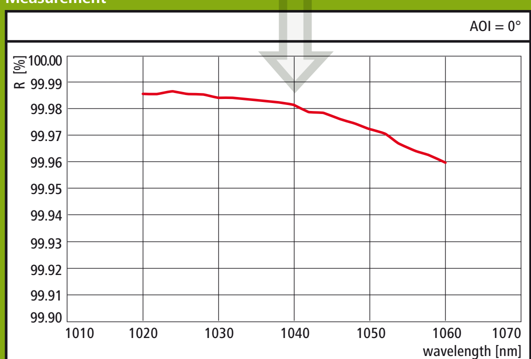


Figure 6: Measured reflectance spectrum of a GTI mirror (design as calculated in fig. 5)

GTI mirrors of LAYERTEC show high reflectance values (e.g. R > 99.98 % at 1030 nm). The reflectance can be measured exactly by CRD. The high reflectance proves that the absorption losses in the GTI mirrors are very small. This also results in very small thermal lensing inside these GTI mirrors if they are used in high power lasers.

COATING HOMOGENITY AND REPRODUCIBILITY OF GTI MIRRORS

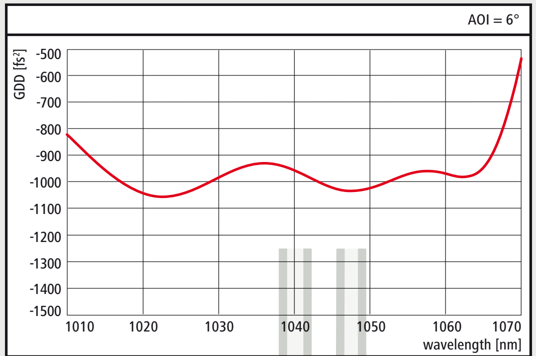


Figure 7: Calculated GDD spectrum of a GTI mirror: GDDr (6°, 1020 – 1060 nm) ~ -1000 ± 200 fs^2

Fig. 8 and 9 show that all GTI mirrors which were produced in these batches meet the specifications given in fig. 7. Comparing mirrors from two batches the variation within a batch and between batches are much smaller than what is allowed by the specifications. The excellent reproduction of complex coating designs is the basis for the use of GTI mirrors in industrial short pulse lasers.

Measurement

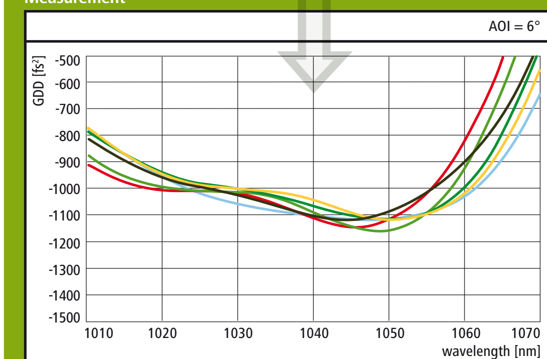


Figure 8: Measured GDD spectra of 6 GTI mirrors which were coated in the same batch according to the design of fig. 7

Measurement

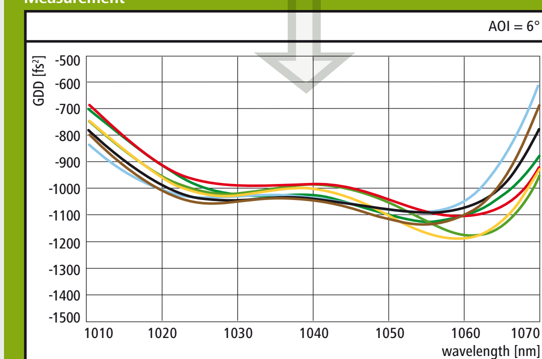


Figure 9: Measured GDD spectra of 6 GTI mirrors which were coated in a second batch according to the design of fig. 7

OPTICS FOR FEMTOSECOND LASERS IN THE 1100 – 1600 nm WAVELENGTH RANGE

Although Ti:Sapphire lasers are currently the most important femtosecond lasers, many applications require femtosecond pulses at considerably longer wavelengths. Several lasers emitting light between 1100 nm and 1600 nm have been developed in recent years, such as the Cr:Forsterite laser (1150 – 1350 nm) or the Er:Fiber laser (1550 nm).
Some examples of coatings such as negative dispersion mirrors and mirror pairs for these wavelength ranges are presented.

Special features:

- Very high reflectance of the mirrors (R > 99.8 % … R > 99.99 % depending on the design).
- Center wavelength, bandwidth, GDD and TOD according to customer specifications.
- Spectral tolerance 1 % of center wavelength.
- In-house design calculation and measurement capabilities (GDD 250 – 1700 nm, reflectance 210 – 1800 nm).

LIDT - INFO

≈ 0.1 J / cm² (estimated)

NEGATIVE DISPERSION LASER AND PUMP MIRRORS FOR AOI = 0°

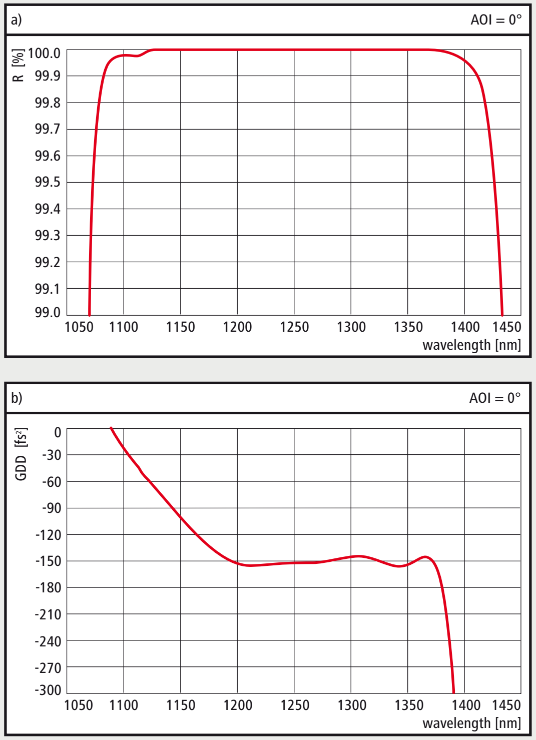


Figure 1: Reflectance and GDD spectra of a negative dispersion laser mirror (GDD ≈ -150 fs² for 1200 – 1370 nm)
a) Reflectance vs. wavelength
b) GDD vs. wavelength

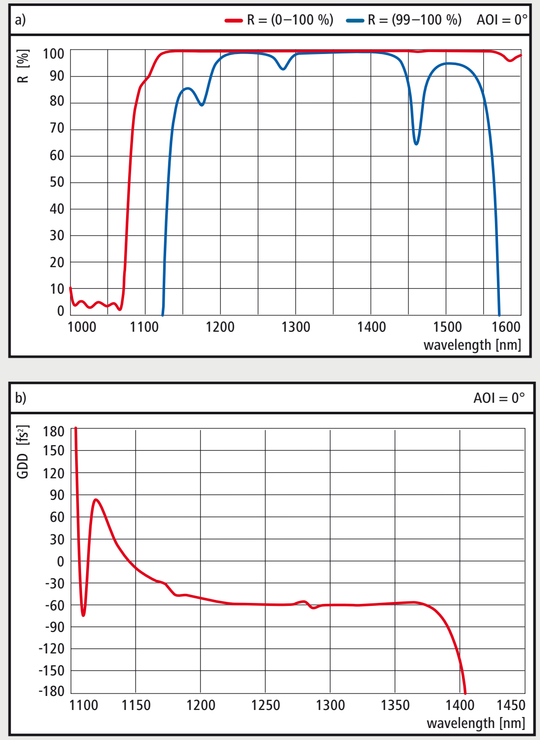


Figure 2: Reflectance and GDD spectra of a negative dispersion pump mirror:
HR (0°, 1180 – 1380 nm) > 99.8 %
+ R (0°, 1020 – 1070 nm) < 5 %,
GDD-R (0°, 1180 – 1380 nm) ≈ - 60 fs²
a) Reflectance vs. wavelength
b) GDD vs. wavelength

GTI MIRRORS FOR AOI = 0°

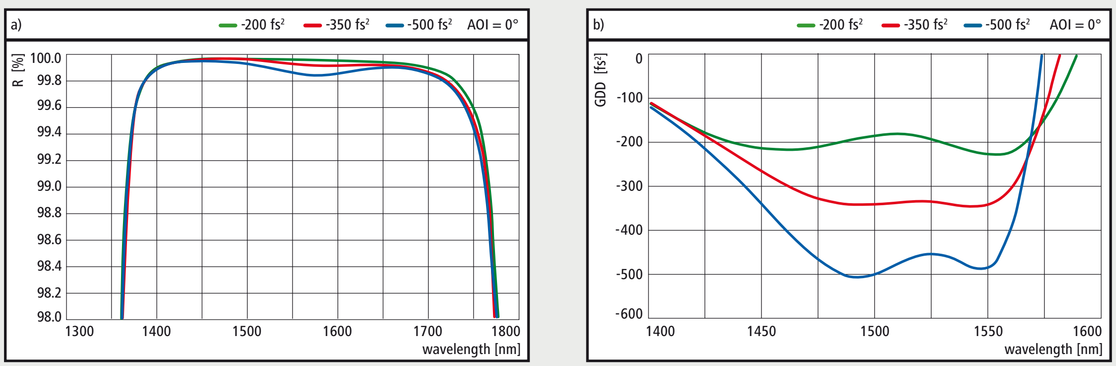


Figure 3: Reflectance and GDD spectra of GTI mirrors for 1500 nm with different GDD values
a) Reflectance vs. wavelength b) GDD vs. wavelength

1100 – 1600 nm

BROADBAND NEGATIVE DISPERSION MIRROR PAIRS FOR AOI = 0°

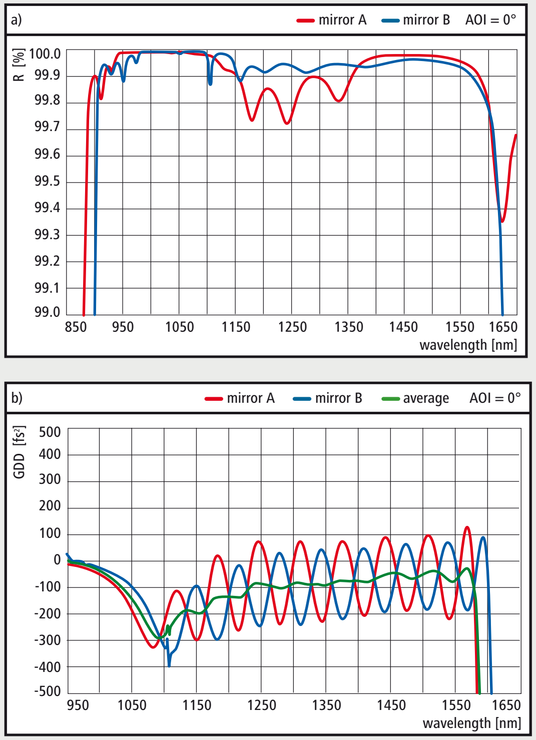


Figure 4: Reflectance and GDD spectra of a broadband negative dispersion mirror pair; single mirrors with R > 99.7 % (mirror A) and R > 99.85 % (mirror B)
a) Reflectance vs. wavelength
b) GDD vs. wavelength

Specially designed mirror pairs show a very smooth average GDD spectrum, although the single broadband mirrors exhibit strong GDD oscillations. Pump mirror pairs (i.e. mirror pairs with one mirror showing high transmittance at the pump wavelength of the respective laser type) are also available.

BROADBAND NEGATIVE DISPERSION TURNING MIRRORS FOR AOI = 45°

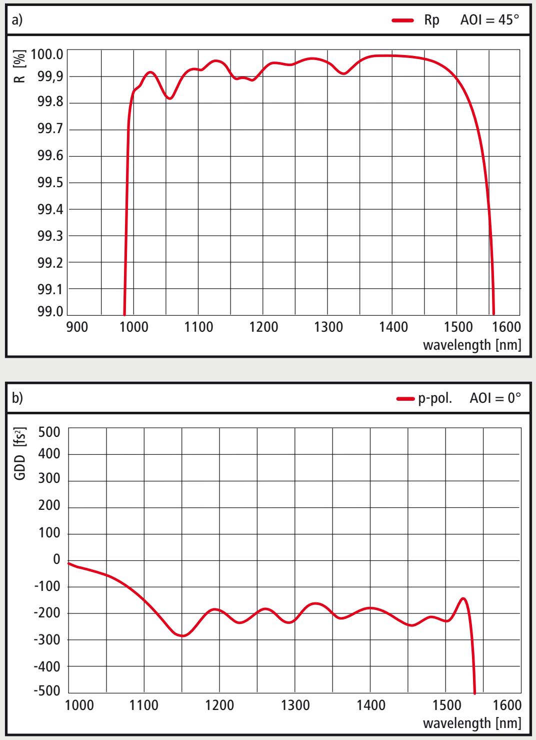


Figure 5: Reflectance and GDD spectra of a broadband negative dispersion turning mirror for p-polarized light
a) Reflectance vs. wavelength
b) GDD vs. wavelength

Please note the large bandwidth of this mirror. Low dispersion turning mirrors are available with bandwidths of about 200 nm for p-polarization and about 400 nm for s-polarization in this wavelength range.

SEPARATORS/COMBINERS WITH NEGATIVE GDD FOR AOI = 45°

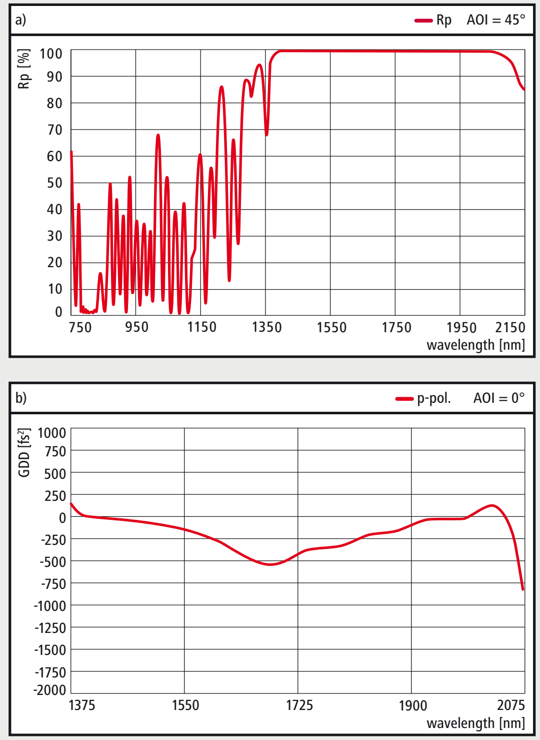
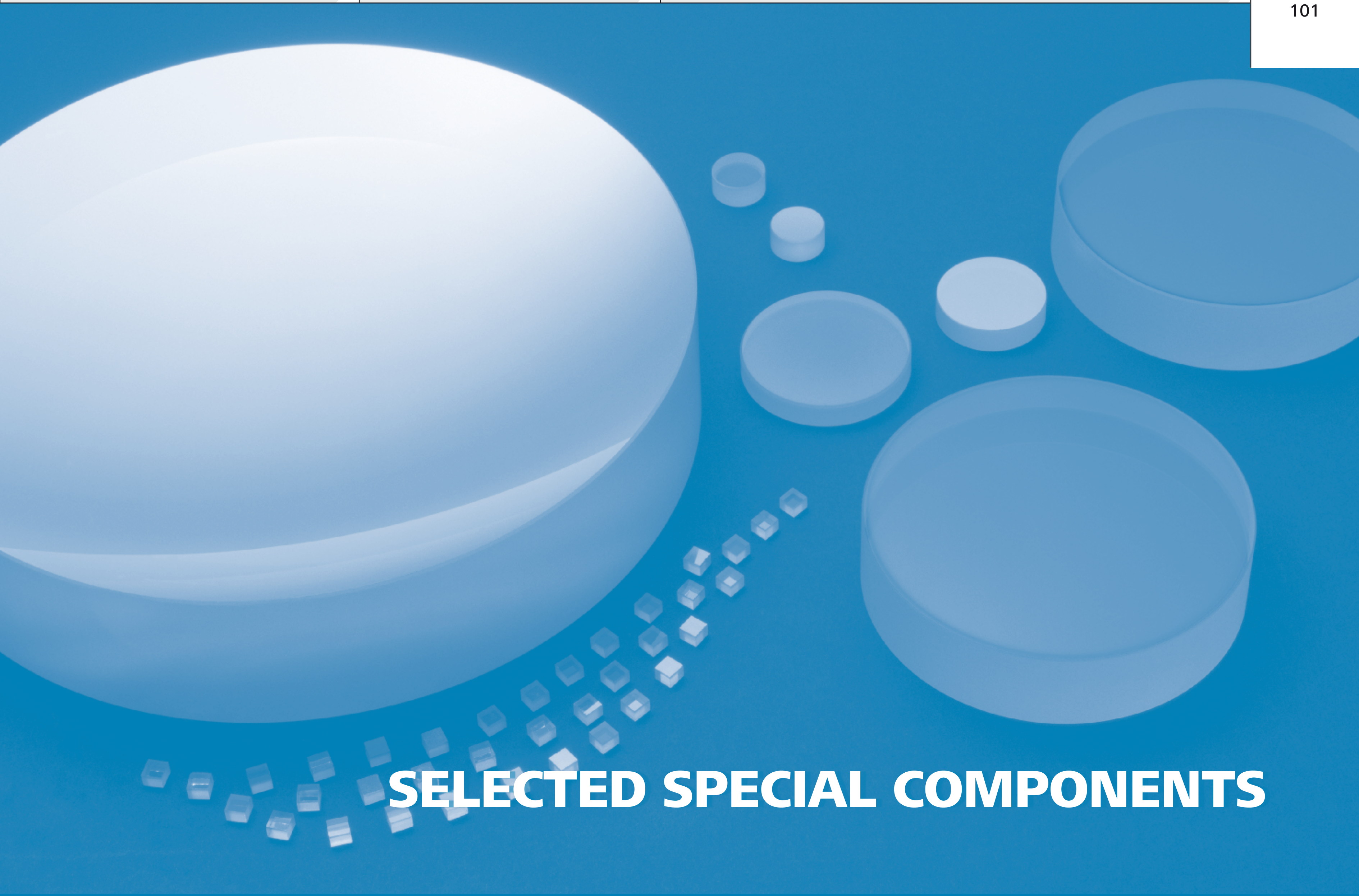


Figure 6: Reflectance and GDD spectra of a beam combiner HRp (45°, 1500 – 2000 nm) + Rp (45°, 800 nm) with negative GDD in the reflection band
a) Reflectance vs. wavelength
b) GDD vs. wavelength



SELECTED SPECIAL COMPONENTS

LAYERTEC®
OPTICAL COATINGS · OPTICS

COMPONENTS FOR OPTICAL PARAMETRIC OSCILLATORS (OPO)

Mirrors for OPOs are optimized for separation of the pump laser, signal and idler wavelengths. This application requires a broad reflectance band for the signal wavelength and a wide range of high transmittance for the idler and pump wavelengths. Moreover, most of the optics show smooth group delay (GD) and group delay dispersion (GDD) spectra. Thus, wide tuning ranges for the signal and the idler wavelengths can be achieved. This enables the operation of OPOs with fs-pulses. Broadband output couplers are also available. Center wavelength and tuning range can be adjusted according to customer specifications.

All OPO coatings are produced by magnetron sputtering. This process guarantees that the optical parameters are environmentally stable, because the coatings are dense, free of water and adhere strongly to the substrate in spite of the extreme coating thickness of 20 – 30 µm. This makes sputtered OPO coatings ideal for application in harsh environments.

CAVITY MIRRORS FOR AOI = 0°

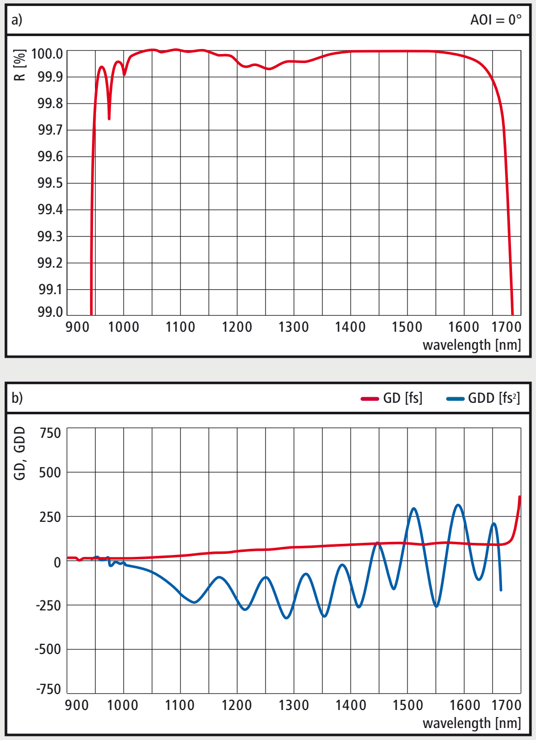


Figure 1: Reflectance, GD and GDD spectra of a broadband HR mirror for the signal wavelength:
HR (0°, 1000 – 1600 nm) > 99.9 %
a) Reflectance vs. wavelength
b) GD and GDD vs. wavelength

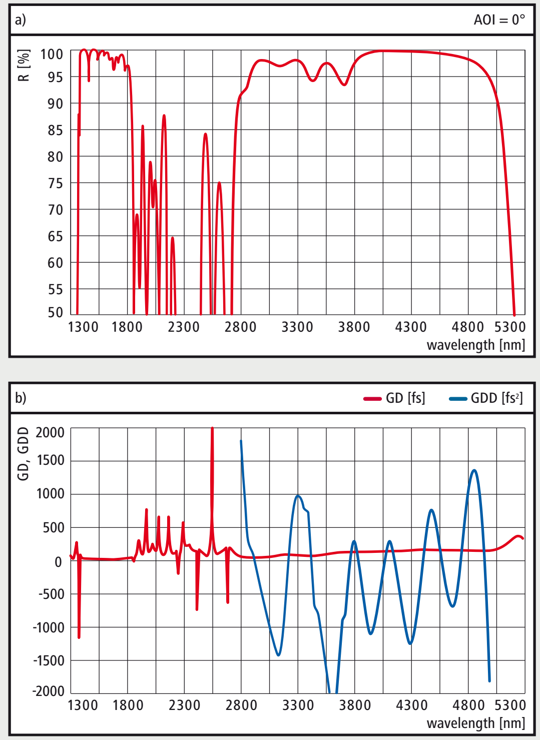
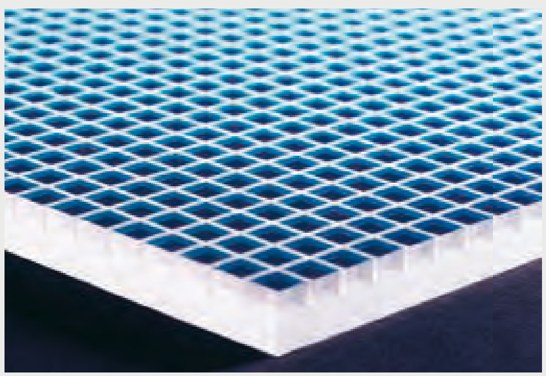


Figure 2: Reflectance, GD and GDD spectra of a dual HR mirror for the signal and idler wavelengths:
HR (0°, 1400 – 1800 nm) > 96 %
+ HR (0°, 2900 – 4900 nm) > 93 %
a) Reflectance vs. wavelength
b) GD and GDD vs. wavelength



This dual wavelength mirror posseses smooth GD spectra for signal and idler, but only the broadband mirror for the idler is GDD optimized.

PUMP MIRRORS AND SEPARATORS AOI = 0°

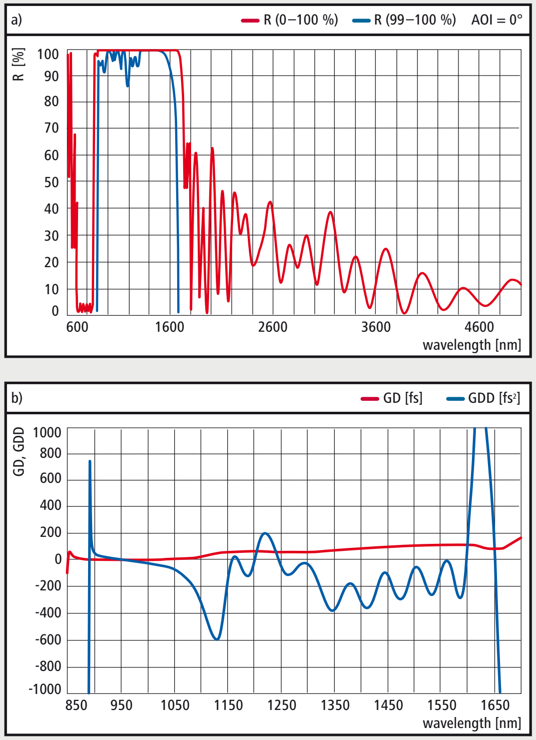


Figure 3: Reflectance, GD and GDD spectra of an OPO pump mirror
a) Reflectance vs. wavelength
b) GD and GDD vs. wavelength

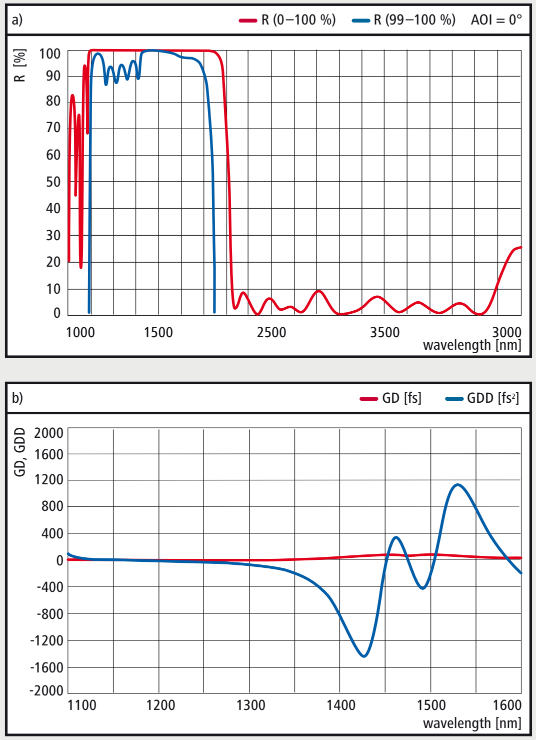


Figure 4: Reflectance, GD and GDD spectra of a separator for the signal and idler wavelengths
a) Reflectance vs. wavelength
b) GD and GDD vs. wavelength

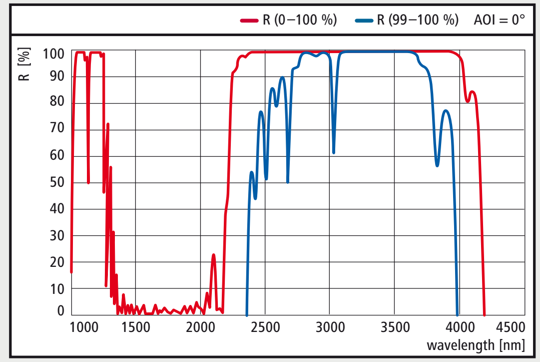


Figure 5: Reflectance spectrum of a broadband mirror for the NIR:
HR (0°, 2300 – 4000 nm) > 99 %

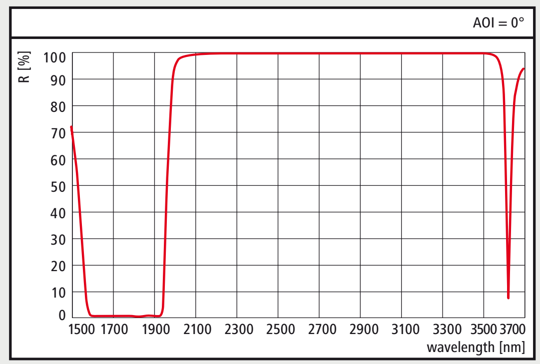


Figure 6: Reflectance spectrum of a separator for the signal and idler wavelengths:
HR (0°, 2050 – 3500 nm) > 99 %
+ R (0°, 1600 – 1930 nm) < 5 %

This type of mirror separates the pump and signal wavelengths while suppressing the idler wavelength:
R (0°, 700 – 850 nm) < 10 %
+ HR (0°, 900 – 1600 nm) > 99.8 %
+ R (0°, 1800 – 5000 nm) < 60 %.

- Edge filters separating signal and idler wavelengths can be used as broadband outcoupling mirrors for the idler:
  HR (0°, 1100 – 1600 nm) > 99.8 %
  + R (0°, 1730 – 2900 nm) < 10 %.
- These filters can also be provided with a band of high reflectance or high transmittance for the pump wavelengths or for the second harmonic of the signal wavelengths.
- LAYERTEC recommends undoped YAG or sapphire as substrate material if high transmittance for the idler wavelengths is required.
  (see also page 21 for transmittance curves)

COMPONENTS FOR OPTICAL PARAMETRIC OSCILLATORS (OPO)

OUTPUT COUPLERS FOR AOI = 0°

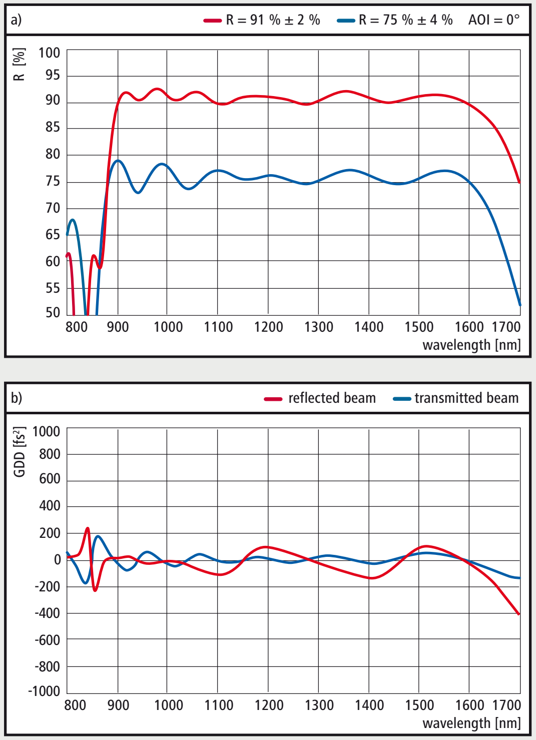


Figure 1: Reflectance and GDD spectra of different broadband output couplers for the signal wavelength range.
a) Reflectance vs. wavelength
b) GDD vs. wavelength
Please note the smooth GDD spectra. The GDD spectra shown are calculated for the 75 % output coupler, but the spectra for other reflectance values are very similar.

The reflectance of output couplers and beam splitters can be adjusted according to customer specifications.

BEAM SPLITTERS FOR AOI = 45°

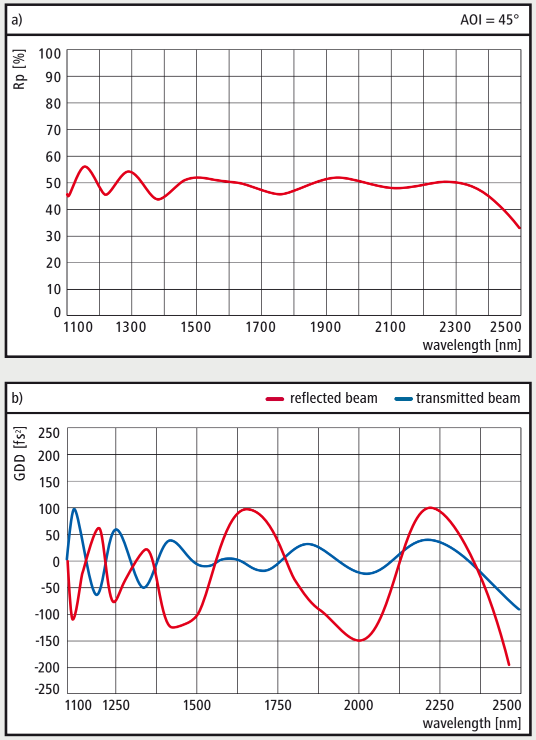


Figure 2: Reflectance and GDD spectra of a broadband beam splitter for p-polarized signal and idler radiation:
Rp (45°, 1100 – 2400 nm) = 50 % ± 5 %
a) Reflectance vs. wavelength
b) GDD vs. wavelength

SPECIAL OUTPUT COUPLERS FOR AOI = 0°

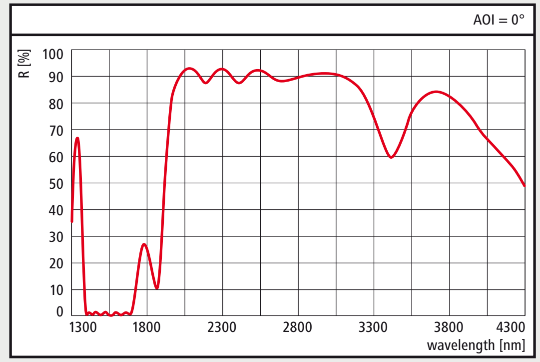


Figure 3: Reflectance spectrum of a special output coupler:
R (0°, 1400 – 1700 nm) < 3 %
+ PR (0°, 2000 – 3150 nm) = 90 ± 3 %

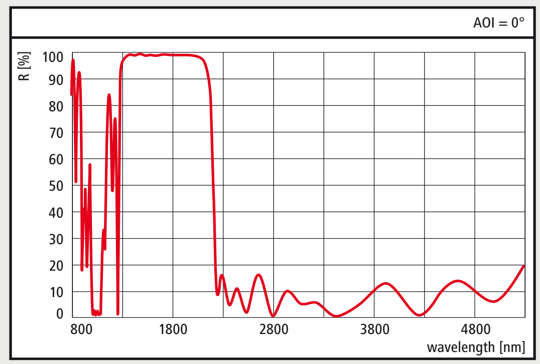


Figure 4: Reflectance spectrum of a special output coupler:
R (0°, 1000 – 1100 nm) < 3 %
+ PR (0°, 1350 – 2000 nm) = 98 % ± 0.5 %
+ R (0°, 2200 – 5000 nm) < 20 %

The output couplers for the signal wavelengths (fig. 3) can suppress the idler and vice versa (fig. 4). These output couplers may also have a pump window.

TURNING MIRRORS AND SEPARATORS FOR AOI = 45°

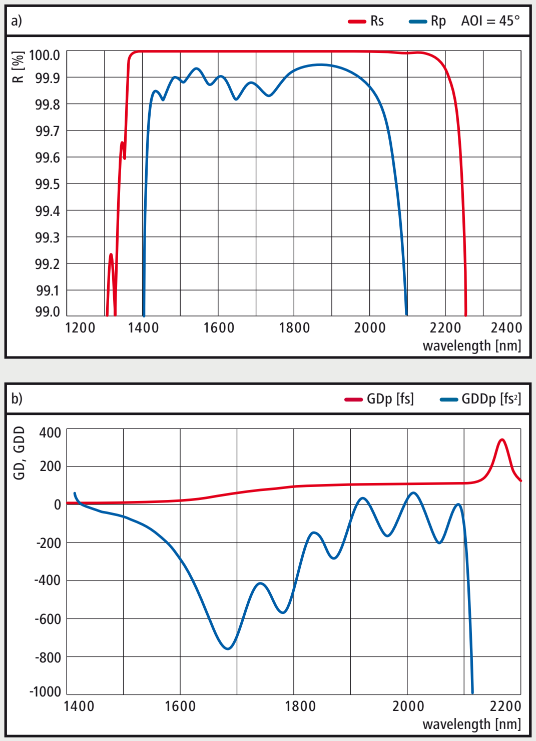


Figure 5: Reflectance, GD and GDD spectra of a turning mirror HRp (45°, 1450 – 2000 nm) > 99.8 %
a) Reflectance vs. wavelength
b) GD and GDD vs. wavelength

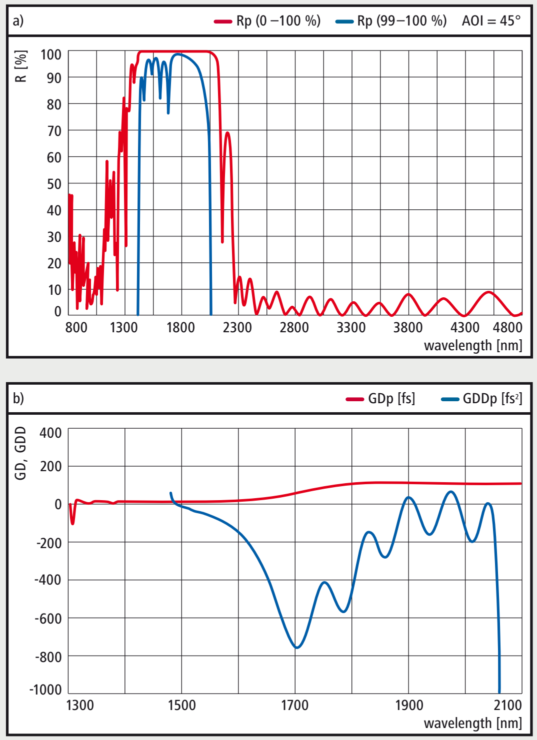


Figure 6: Reflectance, GD and GDD spectra of a separator for signal and idler
a) Reflectance vs. wavelength
b) GD and GDD vs. wavelength

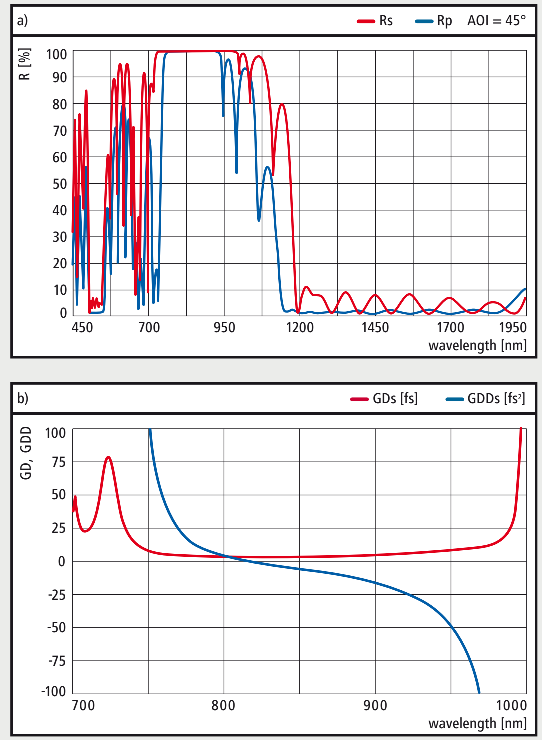


Figure 7: Reflectance, GD and GDD spectra of a separator for the signal and idler with high transmittance for the pump radiation
a) Reflectance vs. wavelength
b) GD and GDD vs. wavelength

Turning mirrors and separators for pump, signal and idler are key components of OPOs. The spectral position of the reflectance and transmittance bands can be adjusted according to customer specifications. Please note that GD and GDD can only be optimized for s- or p-polarization while the reflectance is usually very high for both polarizations.

A broad reflectance band for the signal is combined with a broad transmittance band for the idler:
HRp (45°, 1450 – 2000 nm) > 99.8 %
+ Rp (45°, 2350 – 4000 nm) < 10 %.

This separator can be used to couple the pump radiation into the resonator:
HRs (45°, 770 – 930 nm) > 99.8 %
+ Rp (45°, 510 – 550 nm) < 1 %
+ Rp (45°, 1160 – 1900 nm) < 10 %.

COMPONENTS FOR OPTICAL PARAMETRIC OSCILLATORS (OPO)

ULTRA BROADBAND COMPONENTS FOR AOI = 45°

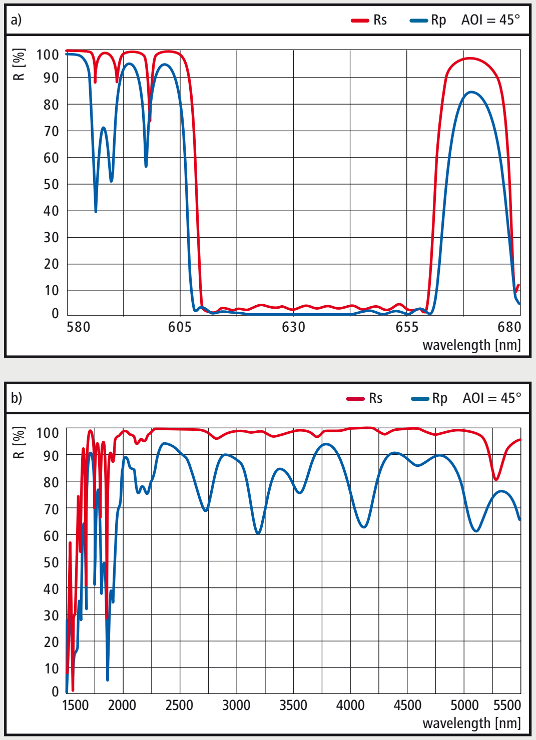


Figure 1: Reflectance spectrum of an ultra broadband beam combiner
HRs (45°, 2000 – 5000 nm) > 98 %
+ Rp (45°, 633 nm) < 2 %

This beam combiner can be used to couple an alignment laser into the beam line. Please note the very low reflectance at 620 – 650 nm.

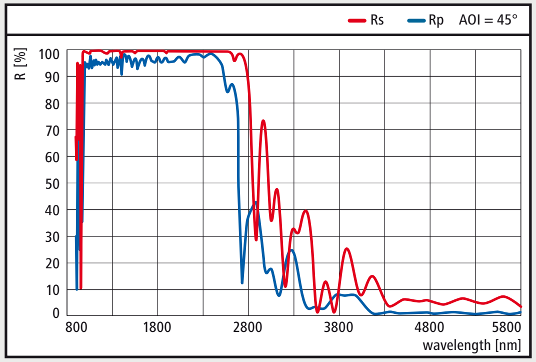


Figure 2: Reflectance spectrum of an ultra broadband separator for signal and idler wavelengths
HRu (45°, 1000 – 2500 nm) > 98 %
+ Ru (45°, 4400 – 5000 nm) < 5 %

EDGE FILTERS FOR AOI = 45°

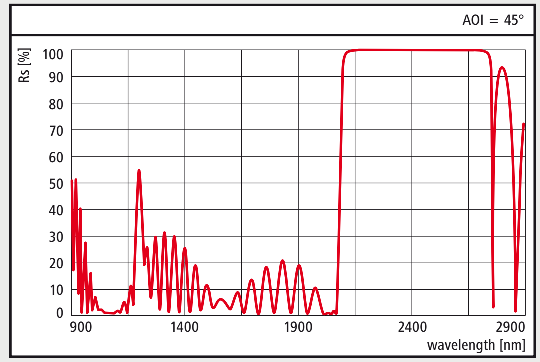


Figure 3: Reflectance spectrum of an edge filter for the idler and signal wavelength range with high transmittance for the pump wavelength:
HRs (45°, 2150 – 2700 nm) > 99.9 %
+ Rs (45°, 2000 – 2070 nm) < 10 % + Rs (45°, 1064 nm) < 1 %

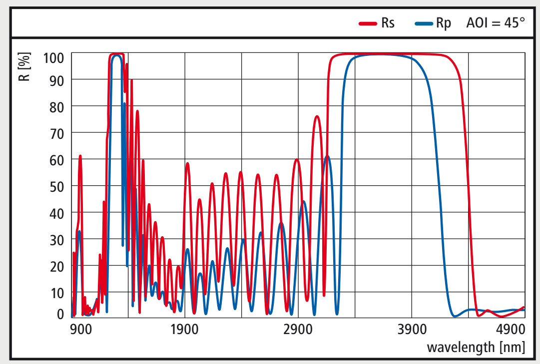


Figure 4: Reflectance spectrum of a broadband edge filter for the idler wavelength range with high transmittance for the pump wavelength:
HRs (45°, 3300 – 4200 nm) > 99.9 %
+ Rs (45°, 4500 – 4900 nm) < 6 % + Rs,p (45°, 1064 nm) < 5 %

SPECIAL MIRRORS AOI = 0°

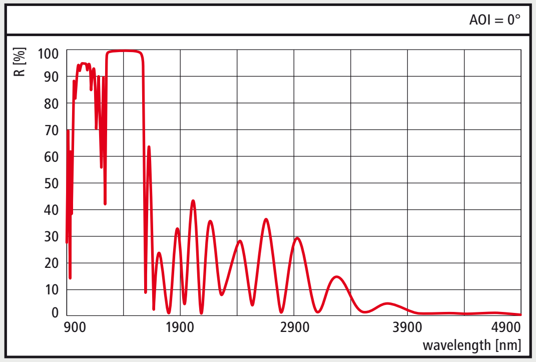


Figure 5: Reflectance spectrum of a special pump mirror:
PR (0°, 1064 nm) = 94 % ± 2 %
+ HR (0°, 1360 – 1460 nm) > 99.9 %
+ R (0°, 4000 – 4900 nm) < 3 %

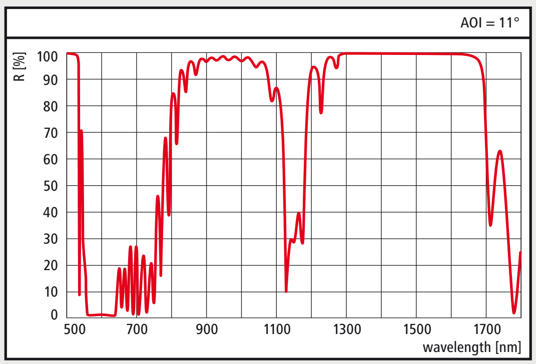


Figure 6: Reflectance spectrum of a special mirror:
R (11°, 565 – 620 nm) < 1 %
+ PR (11°, 900 – 1000 nm) = 98 % ± 0.5 %
+ HR (11°, 1280 – 1600 nm) > 99.9 %

COATINGS ON NONLINEAR OPTICAL CRYSTALS AOI = 0°

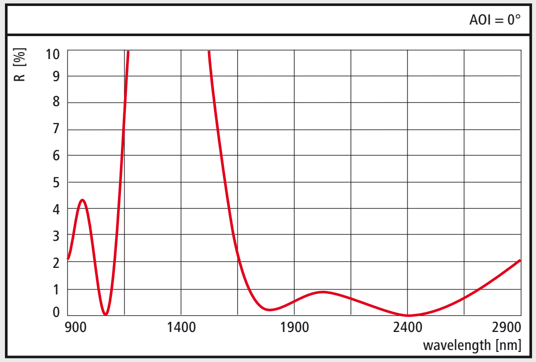


Figure 7: Reflectance spectrum of an AR coating on lithium niobate:
R (0°, 1064 nm) < 0.5 % + R (0°, 1750 – 2750 nm) < 1 %

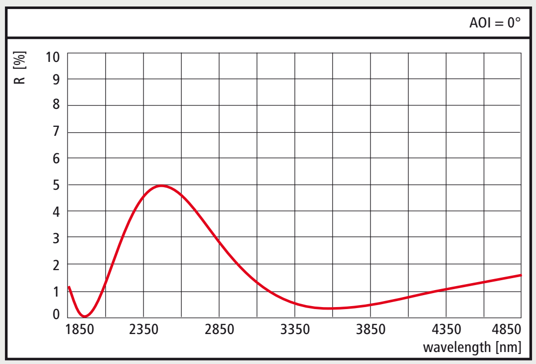


Figure 8: Reflectance spectrum of an AR coating on lithium niobate:
R (0°, 1910 – 2030 nm) < 0.5 %
+ R (0°, 3200 – 4200 nm) < 1 %

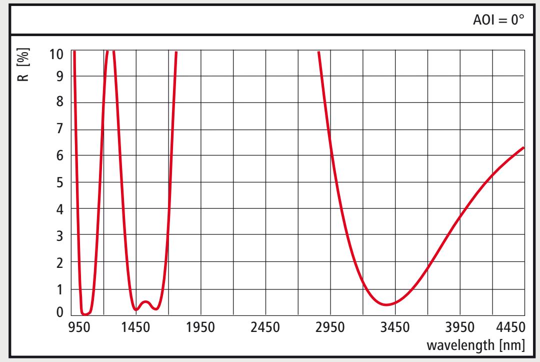


Figure 9: Reflectance spectrum of an AR coating on lithium niobate:
R (0°, 1064 nm) < 0.5 % + R (0°, 1420 – 1640 nm) < 0.5 %
+ R (0°, 3150 – 3700 nm) < 2 %

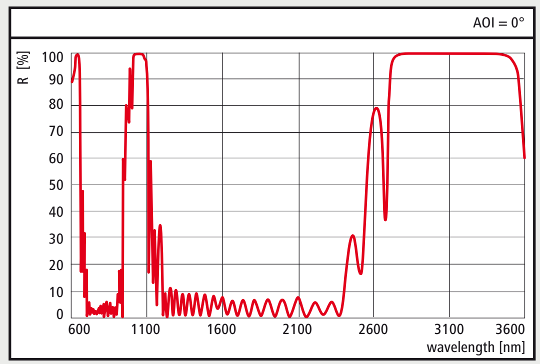


Figure 10: Reflectance spectrum of a double reflector with two regions of high transmittance on lithium niobate
HR (0°, 1010 – 1075 + 2750 – 3450 nm) > 99.8 %
+ R (0°, 700 – 900 + 1200 – 2400 nm) < 10 %

All coatings according to customer specifications.

BROADBAND AND SCANNING MIRRORS

LAYERTEC produces broadband and scanning mirrors according to customer specifications. Full dielectric and metal-dielectric coating designs are available. In the following, examples designed for broad wavelength regions or extremely large ranges of incidence angles are presented.

Broadband mirrors are widely used to reflect light from lasers that emit in a broad wavelength range like for example Ti:Sapphire lasers, dye lasers, or a combination of different diode lasers.
Special mirrors are also available to cover the whole visible spectrum, the near ultraviolet and considerable parts of the near infrared spectral regions. LAYERTEC recommends such mirrors as universal turning mirrors for nearly all types of laser diodes.

Broadband mirrors for the NIR range are especially useful for reflecting idler wavelengths of optical parametric oscillators or for special fs-applications. In combination with fused silica as a substrate material, a large blocking range from 2300 – 6000 nm can be achieved. Other NIR materials such as sapphire and YAG are possible alternatives. These materials can be used for high power applications to improve the cooling of the optics by the thermal conductivity of the substrate. This may be necessary if the absorption of water (around 2.8 µm) or of the coating material itself leads to an increase in temperature.

BROADBAND MIRRORS

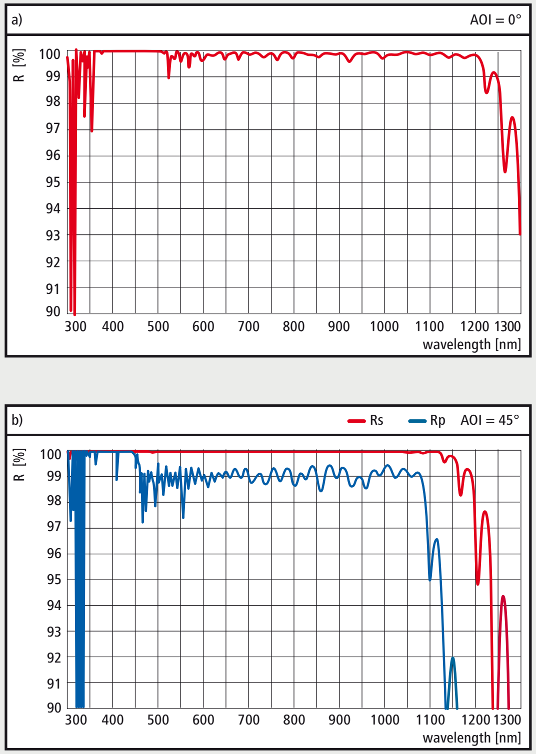


Figure 1: Reflectance spectra of an ultra broadband mirror for the NUV, VIS and NIR
a) R (0°, 360 – 1200 nm) > 99 %
b) Rs (45°, 350 – 1150 nm) > 99 %
+ Rp (45°, 350 – 1050 nm) > 97 %

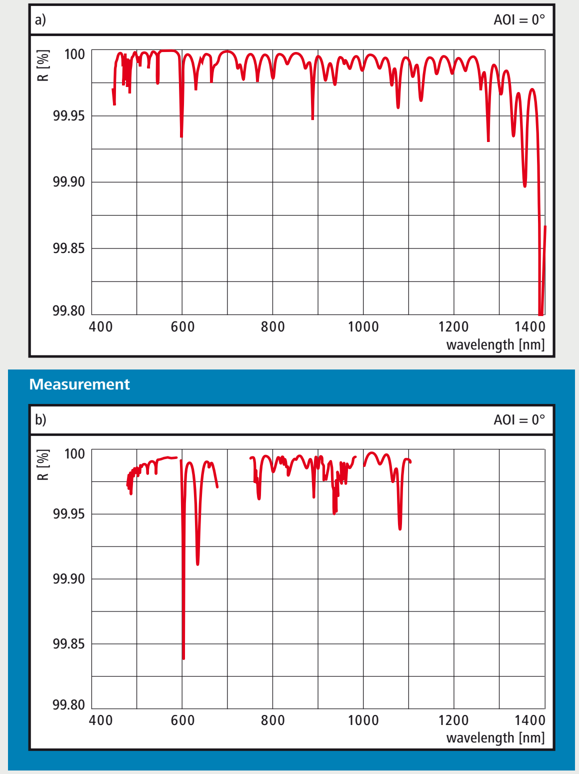


Figure 2: Reflectance spectra of a broadband mirror
HR (0°, 400 – 1400 nm) > 99.9 %
a) Calculated design
b) Broadband CRD measurement

Please note the good agreement between calculation and measurement. The CRD measurements are limited by the water absorption in the 750 – 780 nm and 1200 – 1400 nm regions. For these regions, measurements in vacuum are required.

400 – 1800 nm

SCANNING MIRRORS

LAYERTEC offers scanning mirrors for high power laser applications and for special demands with respect to wavelength and AOI range. Scanning mirrors are optimized for high reflectance for one wavelength or a certain wavelength region at a wide range of angles of incidence. LAYERTEC coating technology provides industrial solutions for light-weight scanning mirrors and special mirrors with uncommon sizes up to 600 mm for research with cw and pulsed high power lasers.

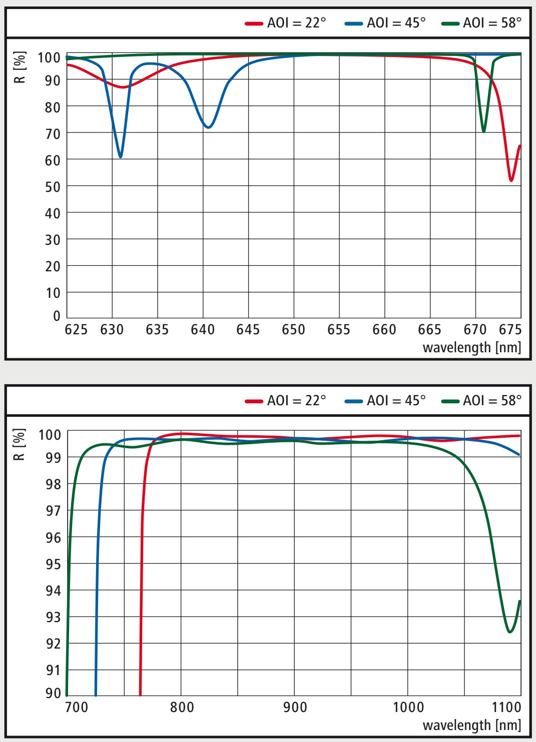


Figure 3: Reflectance spectra of a silver based scanning mirror with enhanced wavelength range for laser diodes in the NIR:
HRu (22° – 58°, 800 – 1000 nm) > 99 %
+ Ru (22° – 58°, 630 – 670 nm) > 50 %

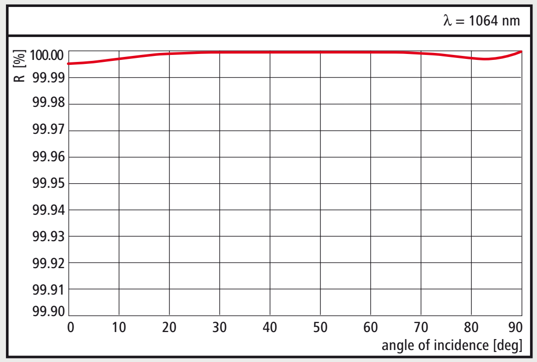
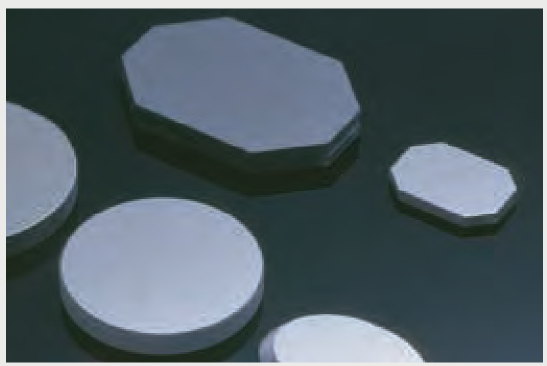


Figure 4: Reflectance vs. AOI of a wide angle scanning mirror for polarized Nd:YAG laser radiation:
HRs (0° – 90°, 1064 nm) > 99.9 %

These mirrors are ideal as scanning mirrors for s-polarized light or to facilitate the production of optical gratings.



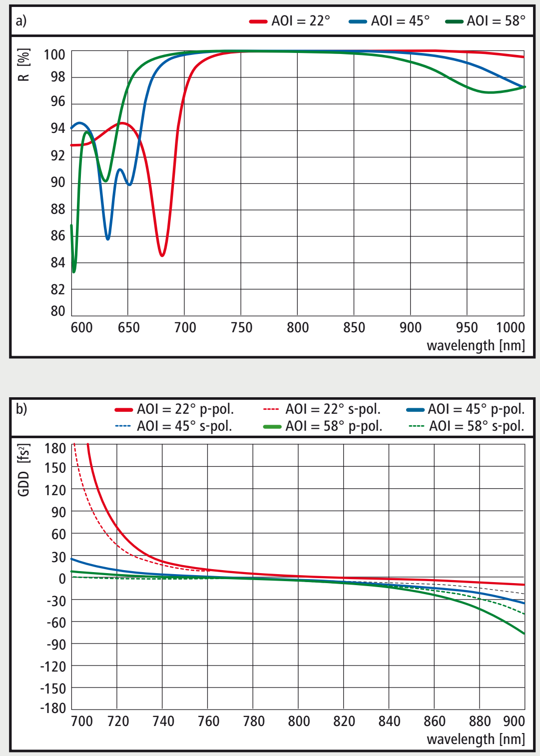


Figure 5: Reflectance and GDD spectra of a scanning mirror for femtosecond laser pulses from a Ti:Sapphire laser:
HRu (22° – 58°, 750 – 850 nm) > 99.5 %,
|GDD-Ru (22° - 58°, 750 - 850 nm)| < 20 fs²
a) Reflectance vs. wavelength
b) GDD vs. wavelength

The broad low-GDD wavelength range of these mirrors makes it possible to use them in femtosecond laser applications.
For more information or more examples on broadband and scanning mirrors please see pages 50 – 53 (optics for Ti:Sapphire and diode lasers), pages 74 and following (femtosecond laser optics) and, especially for scanning mirrors, page 120 – 121 (silver mirrors).

FILTERS FOR LASER APPLICATIONS

ANGLE ADJUSTMENT OF NARROW BAND FILTERS

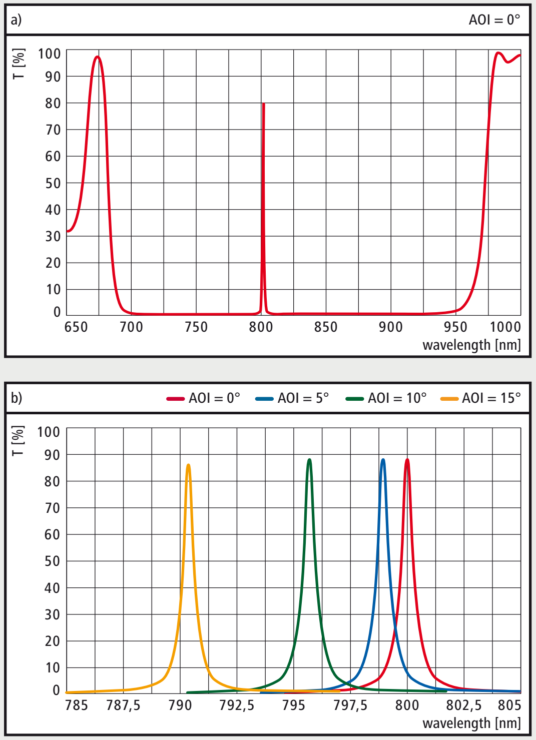


Figure 1: Transmittance spectra of a narrow band filter for ≈ 800 nm
a) Transmittance vs. wavelength, spectral overview
b) Transmittance vs. wavelength at AOI = 0°, 5°, 10° and 15°

- Narrow band filters with FWHM of 1 nm and maximum transmittance of T > 80 %.
- An FWHM of 50 pm with maximum transmittance of T = 50 % has been demonstrated.
- Blocking: T < 0.1 %, block band: ≈ 200 nm in the Ti:Sapphire range.
- These filters are useful to select one wavelength from the spectrum of the Ti:Sapphire laser.

VARIABLE FILTERS FOR LASER APPLICATIONS

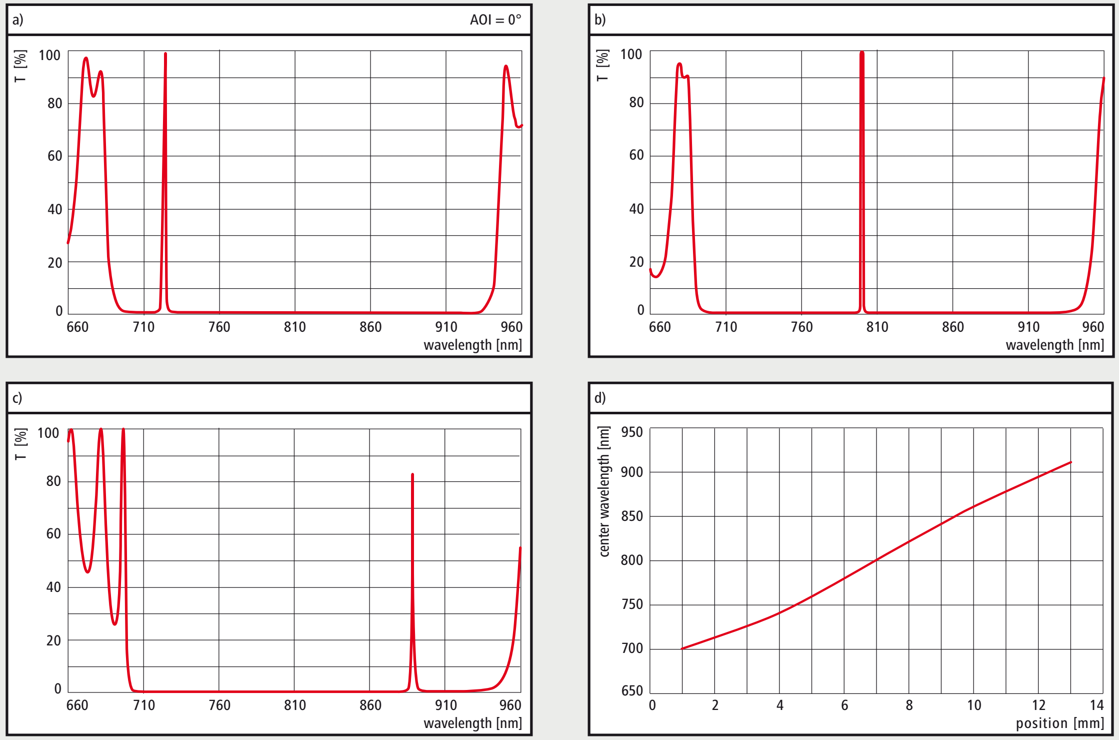


Figure 2: Transmittance spectra of a laterally variable filter for the wavelength range of the Ti:Sapphire laser taken
a) on the short wavelength side
b) in the center
c) on the long wavelength side of the filter
d) Center wavelength vs. position on the filter

Special features:

- Linear variation of the filter wavelength with respect to the lateral position on the filter.
- Similar designs for the VIS range (400 – 700 nm) and for the NIR range (up to 1800 nm).
- Blocking: T < 0.1 %; block band: ≈ 200 nm in the Ti:Sapphire range.
- Maximum transmittance: 90 %; FWHM: 1 nm.
- Shape: rectangular; size: 10 – 20 mm long, 5 – 10 mm wide.
- Spectral tolerance ± 1 % of center wavelength. The spectral position of the transmittance band may vary by ± 1 % between coating runs while the bandwidth remains unchanged. The spectral performance of the filter can be optimized by tilting the filter. Tilting results in a shift of the transmittance band towards shorter wavelengths. Thus, the spectral position of a filter, with the transmittance band at longer wavelengths than required, can be tuned to its best performance by angle adjustment.
- If angle adjustment is possible, the specifications for the filter can be less stringent which increases output and reduces price.

260 – 2500 nm

STEEP EDGE FILTERS

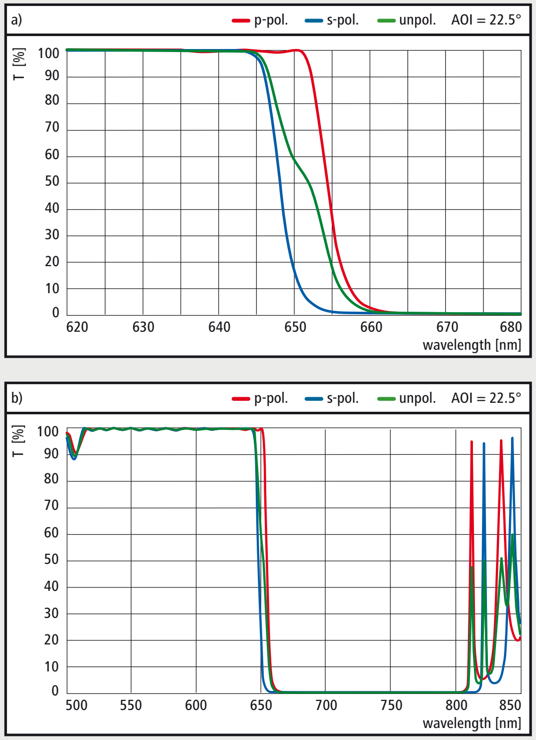


Figure 3: Transmittance spectra of a steep edge short-wavelength pass filter for use as a combiner for laser diodes at 635 nm and 670 nm
HRu (22.5°, 670 nm) > 99.9 %
+ Ru (22.5°, 635 nm) < 2 %, back side AR coated)
a) Section around the edge of the blocking band
b) Spectral overview

For more information on **combiners for diode lasers** see page 53.
For steep edge filters used as **pump mirrors** for solid-state lasers based on Yb-doped materials (e.g. Yb:YAG, Yb:KGW, Yb-doped fibers) see page 54.

NARROW BAND REFLECTANCE FILTERS

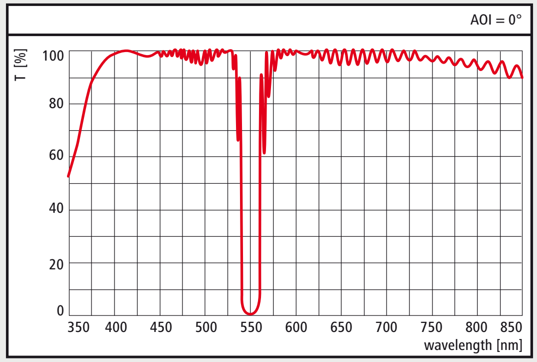


Figure 4: Transmittance spectrum of a narrowband reflectance filter for 550 nm

Filters of this type are ideal for the blocking of a single laser line while preserving a high and relatively constant transmittance over the whole visible range.

Special features:

- Spectral width of the reflectance band: 3 % (e.g. T < 1 % from 543 – 559 nm).
- T < 0.1 % at the center wavelength.
- T > 90 % throughout the visible spectral range.
- Filters for laser applications require excellent spectral quality and high damage thresholds.
- Spectral position of cut-on/cut-off wavelengths or reflectance bands according to customer specification.
- Sizes and shapes:
  Edge filters can be produced on round or rectangular substrates up to diameters of 38.1 mm (1.5 inch). The production of miniature size filters (e.g. 3 x 3 mm^2) is possible. Narrow band reflectance filters are limited to diameters of 25.4 mm (1 inch).
- Optical parameters are environmentally stable.

DUAL WAVELENGTH FILTER WITH BROAD BLOCKING RANGE

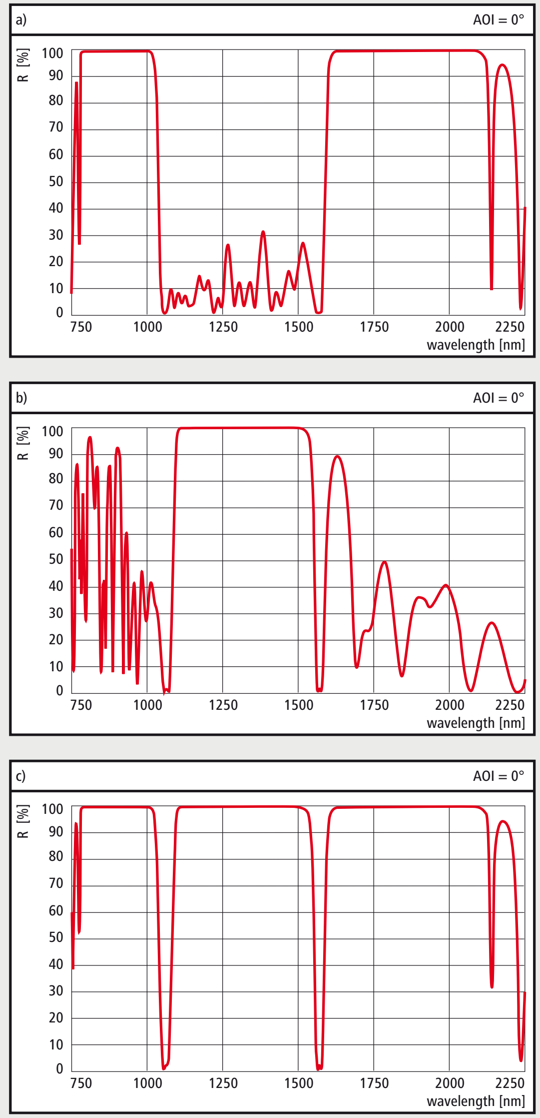


Figure 5: Reflectance spectra of a dual wavelength filter for 1064 nm and 1570 nm with a broadband blocking range from the UV to 2100 nm:
a) Front side coating
b) Back side coating
c) Sum
Double side coating reduces the mechanical stress. Blocking in the UV/VIS is done by a color glass.

THIN FILM POLARIZERS

TECHNICAL TERMS

In order to answer frequently asked questions and to help LAYERTEC customers to specify thin film polarizers, definitions of the most important technical terms are given here.
Light is a transversal wave; the vector of the electric field oscillates perpendicular with respect to the propagation direction of the light. Natural light (from the sun or from a lamp) is mostly “unpolarized”. This means that the oscillation planes of the electric field vectors of the single light waves are randomly distributed, but always transversal with respect to the direction of propagation. In contrast, the term “linearly polarized light” signifies that there is only one plane of oscillation.
There are different optics which can polarize light. An example of this would be crystal polarizers which split light into an unpolarized "ordinary beam" and a polarized "extraordinary beam" or thin film polarizers.

To explain the meaning of the terms “s-polarization” and “p-polarization”, first a reference plane must be determined (see fig.1). This plane is spanned by the incident beam and by the surface normal of the mirror (or polarizer). “**S-polarized light**” is the part of the light which oscillates perpendicularly to this reference plane (“**s**” comes from the German word “senkrecht” = perpendicular). “**P-polarized light**” is the part which oscillates **p**arallel to the reference plane. Light waves with a plane of oscillation inclined to these directions can be described as having a p-polarized and an s-polarized part.
The upper part of fig. 1 shows the reflectance of an uncoated glass surface vs. AOI for s- and p-polarized light. The reflectance for s-polarized light increases with rising angle of incidence. In contrast, the reflectance of p-polarized light decreases until reaching R = 0 at the “Brewster angle”, then increases for angles of incidence beyond the Brewster angle. In principle, the same is true for dielectric mirrors. Thin film polarizers separate the s-polarized component of the light from the p-polarized component using the effect that s-polarized light posseses a higher reflectance and broader reflection band than p-polarized light. There always is a wavelength range, where Rs is close to 100 % while Rp is close to zero. Special coating designs are used to make this wavelength range as broad as possible and to maximize the polarization ratio Tp/Ts. Very high values of Tp (> 99.5 %) can be measured very precisely using a special Cavity Ring-Down setup. The TFP is inserted into a cavity thus introducing additional losses equal to 100%-Tp. Utilizing this method, the most beneficial AOI for each TFP can be determined.
Thin film polarizers (TFPs) are key components in a wide variety of applications, e.g. in regenerative amplifiers. LAYERTEC produces thin film polarizers on plane substrates (dimensions according to customer specifications) for wavelengths between 260 nm and 2500 nm. All TFPs are optimized for high laser-induced damage thresholds. Although there are no certified measurements available, LAYERTEC has learned from several customers that the LIDT of a TFP is approximately one third of the LIDT of a highly reflecting mirror for the same wavelength coated using the same technology.

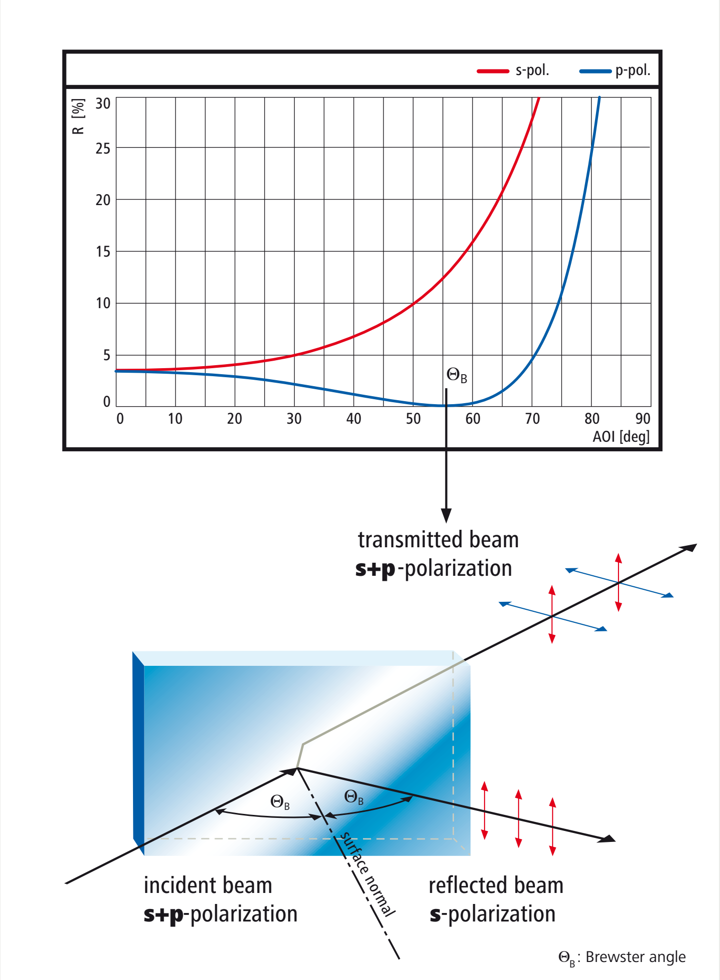


Figure 1: Explanation of the terms "s-polarized light" and "p-polarized light" and reflectance of an uncoated glass surface vs. angle of incidence for s- and p-polarized light

STANDARD THIN FILM POLARIZERS

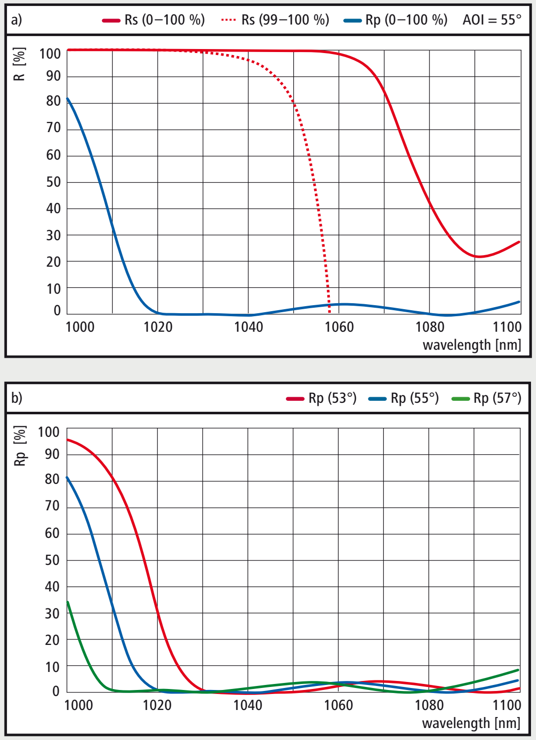
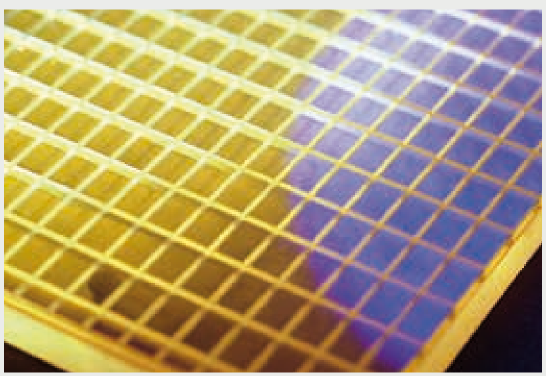


Figure 2: a) Reflectance spectra of a standard TFP for 1030 nm at AOI = 55° (Brewster angle) for s- and p-polarized light
b) Reflectance spectra of the same TFP design for AOI = 53°, 55° and 57° for p-polarized light (angle adjustment decreases Rp at 1030 nm from 0.25 % to < 0.1 % thus giving the option to optimize the polarization ratio)

- TFPs can be produced for AOI > 40°. Please note that thin film polarizers working at the Brewster angle exhibit a considerably broader bandwidth and a higher Tp / Ts ratio than those working at AOI = 45°.
- Typical polarization ratios Tp / Ts: standard: > 500 (AOI = 45° or 55°).
- An extended wavelength range with a limited polarization ratio can be obtained by choosing AOI beyond the Brewster angle.
- Special designs with a polarization ratio of Tp / Ts up to 10000 are possible.
- High laser-induced damage thresholds (useful for intracavity applications).
- It is beneficial to design the laser in a way that the polarizers can be tilted by ± 2° to adjust the polarizer to its best performance.
- The standard design can be used for wavelengths between 260 nm and 2500 nm.



SPECIAL THIN FILM POLARIZERS

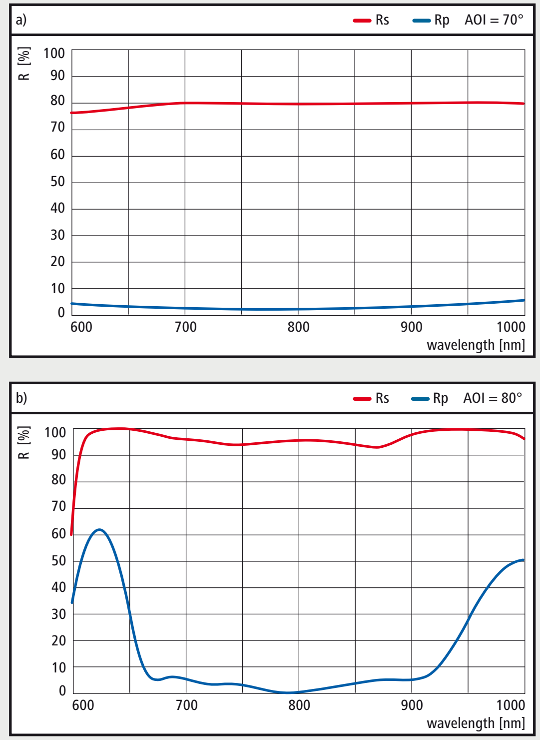


Figure 3: Broadband TFPs for the wavelength range of the Ti:Sapphire laser with different bandwidths and different polarization ratios, working at AOI = 70° and AOI = 80°
a) Rp and Rs vs. wavelength, TFP designed for AOI = 70°
b) Rp and Rs vs. wavelength, TFP designed for AOI = 80°

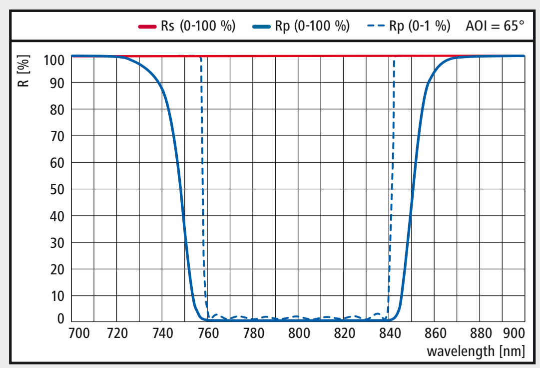


Figure 4: Broadband TFP for the 800 nm region

This special design provides an extremely broad polarizing wavelength range (≈ 10 % of the center wavelength) with Tp / Ts = 300 … 1000.

LOW LOSS OPTICAL COMPONENTS

HR MIRRORS

- **R > 99.99 %** in the VIS and NIR spectral range
- **R > 99.999 %** was demonstrated at several wavelengths between 1000 – 1600 nm.
- Mirrors with defined transmittance (e.g. T = 0.002 %).
- For Cavity Ring-Down time spectroscopy, it is favorable to adjust the transmittance to the value of the scattering and absorption losses (T = S + A), see fig.1.
- All mirrors for CRD experiments are delivered with back side AR coating. Wedged substrates on request.
- Plane and spherically curved fused silica substrates).
- Premium polish, rms-roughness: ≤ 1.5 Å (see page 15).
- Surface quality: 5 / 1 x 0.010 (ISO 10110) for Ø 25 mm.
- Coating technique: magnetron sputtering, ion beam sputtering.
- Optical parameters are stable against changes in temperature and humidity.
- Attractive prices for small and medium numbers of substrates per coating run.
- Very high reflectance values for complex coating designs, e.g. GTI laser mirrors with R > 99.95 %. (see pages 96 – 97)
- Vacuum packaging or packaging under nitrogen cover gas in dust free boxes.

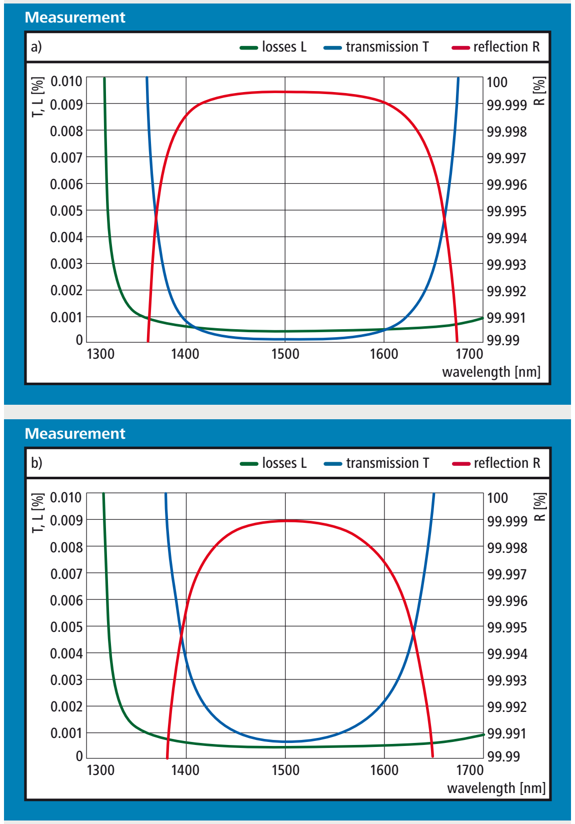


Figure 1: Reflectance, transmittance and loss spectra of low loss mirrors for 1550 nm
a) Optimized for highest reflectance (transmittance ~ 0)
b) Designed for T ≈ S + A

Please note that the reflectance of the mirrors in fig.1a and 1b is nearly the same. However, the extremely low transmittance of the mirror in figure 1a makes CRD measurements very difficult.

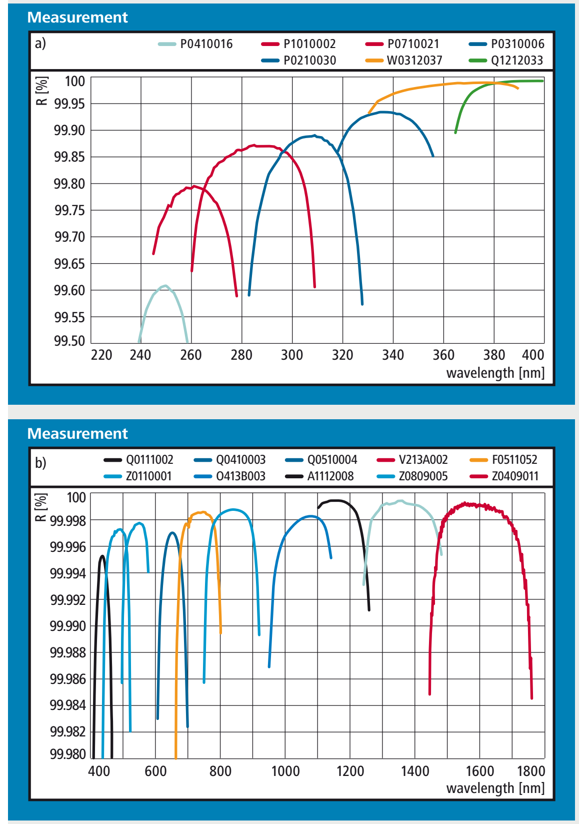


Figure 2: a) Reflectance spectra of a variety of low loss mirrors for the UV
b) Reflectance spectra of a variety of low loss mirrors for the VIS-NIR spectral range
All measurements were performed at the CRD setup which is described on pages 33 – 35. Please note that these mirrors are specially designed for relatively high transmittance.

340 – 3000 nm

DIRECT MEASUREMENTS OF OPTICAL LOSSES

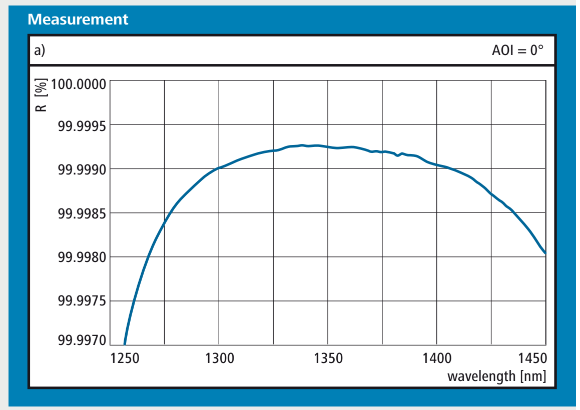
Type of losses	VIS	NIR
Scattering	Typical: 20 – 30 ppm Measured: 15 ppm @ 633 nm*, 20 – 30 ppm @ 532 nm**	< 10 ppm
Absorption	10 – 20 ppm***	< 10 ppm***
Total	< 50 ppm	< 20 ppm

* Measurement performed at Jenoptik L.O.S. GmbH, Jena
** Measurement performed at Fraunhofer Institute IOF Jena
*** Measurement performed at Leibniz-Institute of Photonic Technology (IPHT) e.V. Jena

CAVITY RING-DOWN TIME MEASUREMENTS AND REFERENCE DATA

Wavelength	R_{max} [%]	T [%]	Loss [ppm] L = 1 - R - T	Measured at
248 nm	99.87	0.00024	1300	LAYERTEC GmbH
266 nm	99.941	0.0031	560	LAYERTEC GmbH
355 nm	99.988	0.0004	116	LAYERTEC GmbH
400 nm	99.9954	—	—	LAYERTEC GmbH
550 nm	99.9977	0.00039	19	LAYERTEC GmbH
633 nm	99.992	0.006	20	Westsächsische Technische Hochschule Zwickau, Germany
660 nm	99.992	0.006	20	Universität Heidelberg, Germany
798 nm	99.995	0.003	10	LAYERTEC GmbH
840 nm	99.9988	0.0002	10	LAYERTEC GmbH
1030 nm	99.9980	0.0012	8	LAYERTEC GmbH
1150 nm	99.9994	0.00035	2.5	LAYERTEC GmbH
1392 nm	99.9985	0.0007	8	TIGER OPTICS, USA (R measurement) LAYERTEC GmbH (T measurement)
1550 nm	99.999	0.0002	8	IPHT Jena, Germany
2350 nm	99.995	0.002	30	University of Grenoble, France
3250 nm	99.928	0.012	600	University of Grenoble, France
4000 nm	99.9	—	—	Universität Bielefeld, Germany

Table 1: Reflectance and transmittance values of LAYERTEC low loss mirrors; Reflectance measured by Cavity Ring-Down spectroscopy, AOI = 0°



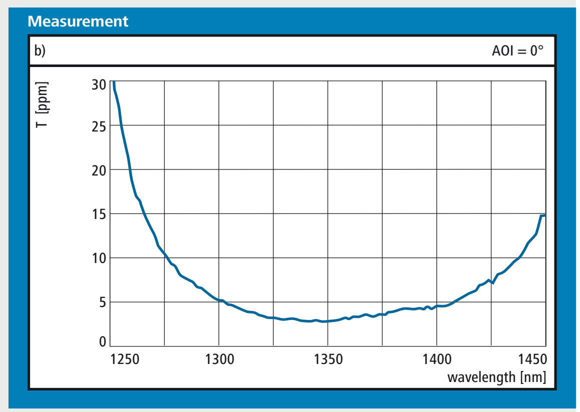


Figure 3: Measured reflectance and transmittance spectrum of a low loss mirror for the wavelength range 1250 – 1450 nm
a) Reflectance vs. wavelength
b) Transmittance vs. wavelength

COATINGS ON CRYSTAL OPTICS

Laser applications using crystal optics have reached a high standard in industry and research. Optical coatings on crystals are an essential part of modern laser designs. They cover a wide range from single wavelength AR coatings on laser and nonlinear optical crystals up to complex multilayer coatings providing several high-reflectance and high-transmittance wavelength ranges and thus, replacing external laser mirrors.

LAYERTEC has a lot of experience in coating laser crystals. LAYERTEC coatings are used in industrial high power Q-switched and cw lasers of several laser manufacturers. The quality of coatings on crystals depends on the coating technique as well as on the surface quality of the crystal. All coatings are produced using sputtering techniques which guarantee very low scattering losses and high environmental stability of the optical parameters.

The rapid progress in crystal growth techniques resulted in a wide variety of new crystals for laser applications, e.g. laser crystals like tungstanates and vanadates or nonlinear optical crystals like RTP. Each crystal type requires optimized polishing procedures and coating techniques. The coating design is determined by the optical properties of the crystal. However, the thermal expansion coefficients and the surface quality after storage and transport influence the coating quality as well. Especially, hygroscopic crystals like LBO or BBO require special pretreatments to achieve high damage thresholds and long lifetime for the coatings. Thus, coatings on new crystals always require experimental investigations to find the best coating procedures. Different dimensions and uncommon sizes and shapes are possible using the special LAYERTEC coating technology.

The following table gives an overview about the crystals which have already been coated at LAYERTEC and the types of layer systems which have been applied successfully.

EXAMPLES OF AVAILABLE COATINGS ON CRYSTALS

Crystal Type	AR/BBAR	Single HR optional with HT	Double HR/BBHR optional with HT
α-SiO_2 (Quartz)	x	x	x
BBO	x	-	-
BiBO	x	x	
$CaCO_3$	x		
CTA	x		
Nd:$GdVO_4$	x	x	x
Nd:GGG	x	x	
Nd:Cr:GSGG	x	x	
KTA	x	x	
KTP	x	x	x
Yb:KGW, Yb:KYW	x	x	x
LBO	x	-	-
$LiNbO_3$	x	x	
LMA	x		
Nd:LSB	x	x	x
RDP	x		
Ruby	x	x	x
Ti:Sapphire	x	x	x
Spinell	x	x	x
Cr:YAG	x	x	x
Er:YAG	x	x	x
Ho:YAG	x	x	x
Nd:YAG, Yb:YAG	x	x	x
Nd:YALO (YAP)	x		
YLF	x		
Nd:YVO_4	x	x	x
ZGP	x		
ZnSe	x	x	

x established coating process
- not possible due to technical reasons
empty box not requested yet

Detailed measurement reports are available for each batch. Do not hesitate to contact LAYERTEC for a discussion or a quotation regarding your special coating project.

340 – 3000 nm

COATINGS ON DOPED LASER CRYSTALS

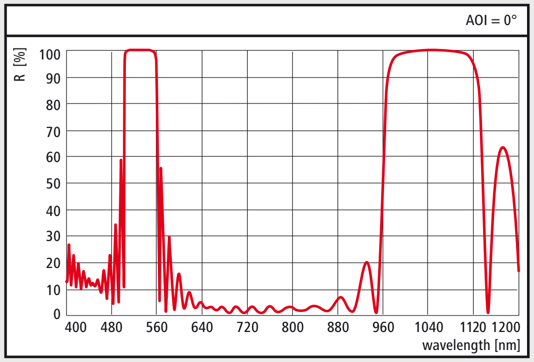


Figure 1: Reflectance spectrum of a dual HR mirror with a HT region for pumping with a laser diode (on Nd:YAG):
HR (0°, 532 nm + 1064 nm) > 99.9 % + R (0°, 808 nm) < 5 %

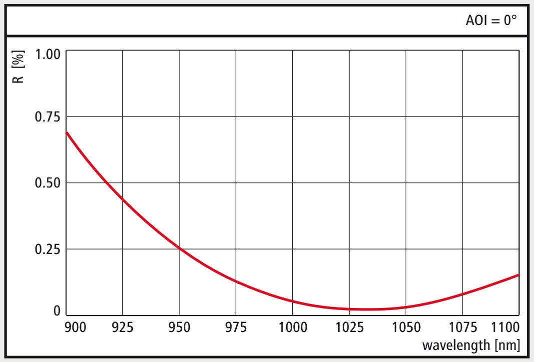


Figure 2: Reflectance spectrum of an AR coating for an Yb:KYW crystal:
AR (0°, 1030 nm) < 0.2 % + AR (0° - 30°, 980 nm) < 0.2 %.
Please note the large acceptance angle for the pump radiation

Sputtered coatings on laser rods, discs and slabs with:

- High laser-induced damage thresholds for critical industrial applications of Q-switched and cw lasers.
- Low residual reflectance.
- Broadband and multiple wavelength AR coatings.
- Complex HR and HR / HT-coatings for compact laser designs, e.g.
  HR (0°, 532 nm + 1064 nm) > 99.9 %
  + R (0°, 808 nm) < 5 %,
  on Nd:YVO_4 for diode-pumped and frequency-doubled "green" lasers).

COATINGS ON NONLINEAR OPTICAL CRYSTALS

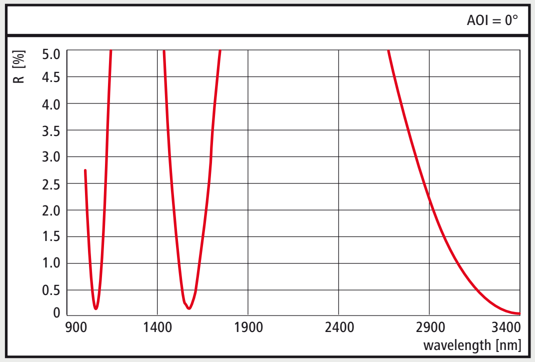


Figure 3: Reflectance spectrum of a triple wavelength AR coating on KTP:
AR (0°, 1064 nm + 1575 nm + 3400 nm) < 0.5 %

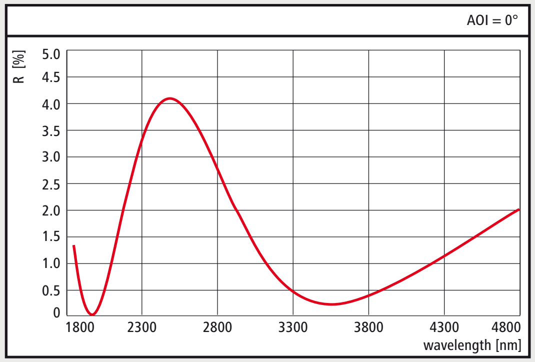


Figure 4: Reflectance spectrum of an AR coating for PPSLT:
AR (0°, 2000 nm) < 0.2 % + AR (0°, 3400 – 4400 nm) < 1.5 %

- Coating of crystals with variable or special sizes and shapes.
- Coating of the full aperture of small crystals.

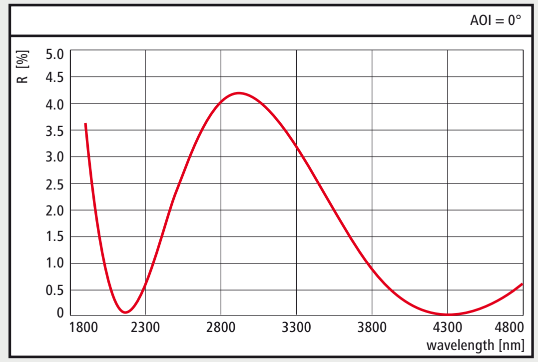


Figure 5: Reflectance spectrum of a dual wavelength AR coating on ZGP:
AR (0°, 2050 nm) < 1 % + AR (0°, 4300 nm) < 0.2 %

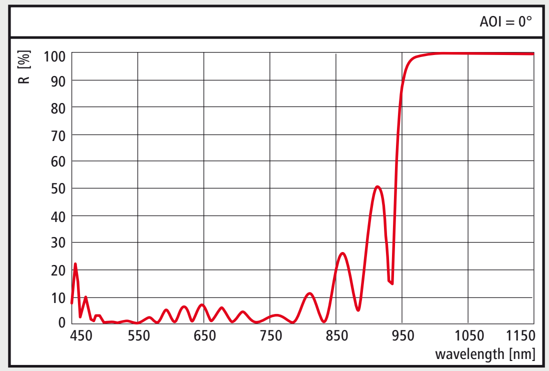
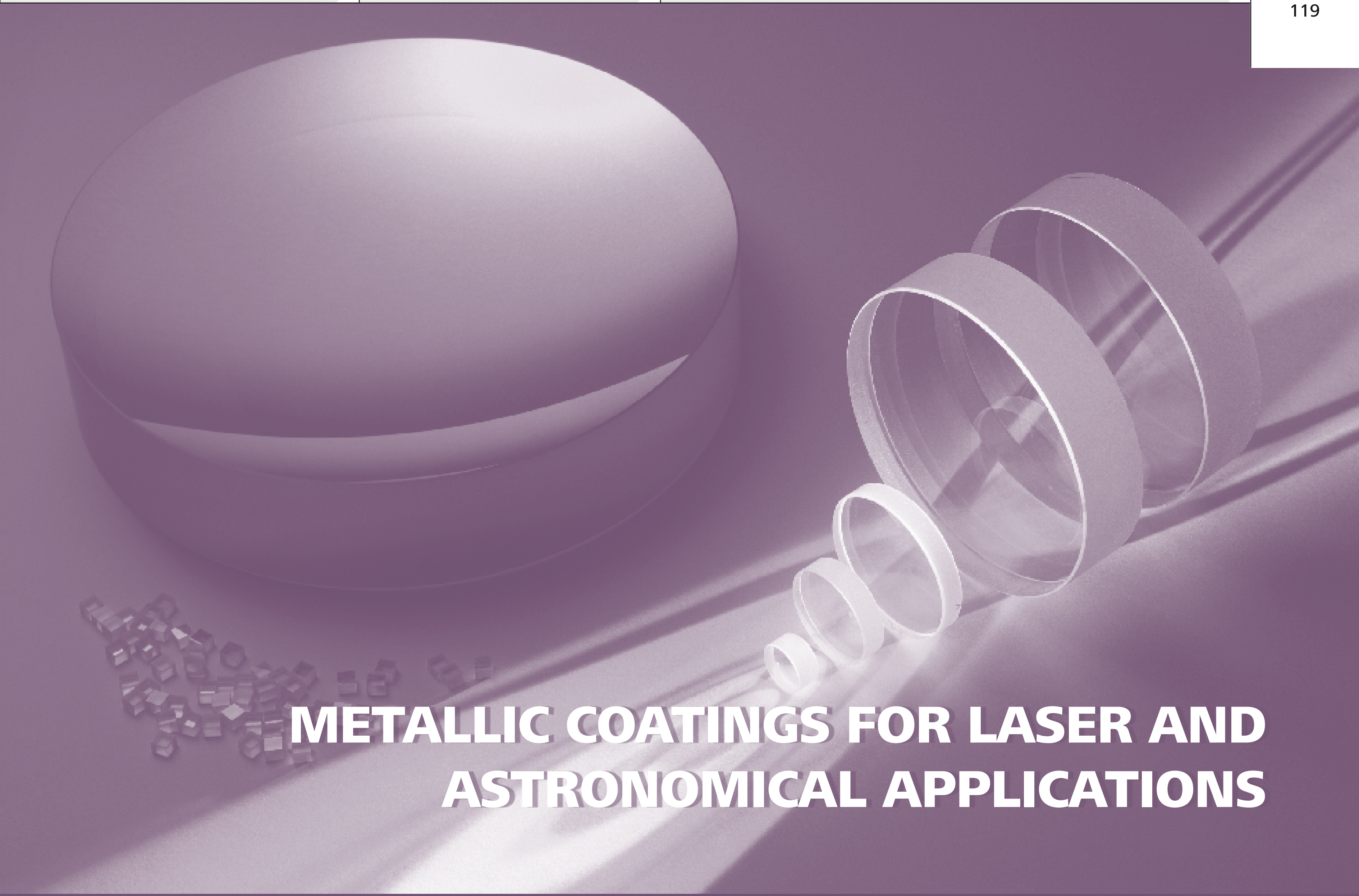


Figure 6: Reflectance spectrum of a dichroic mirror on KTP:
R (0°, 532 nm) < 1 % + HR (0°, 1064 nm) > 99.95 %

- Broadband and multiple wavelength AR coatings.
- Complex HR and HR / HT-coatings for compact laser designs, e.g.
  HR (0°, 1064 nm) > 99.9 % + R (0°, 532 nm) < 5 %, on KTP for frequency-doubled Nd:YAG or Nd:YVO_4 lasers.
- Coating for crystals with variable or special sizes and shapes.
- Coating of the full aperture for small crystals.



METALLIC COATINGS FOR LASER AND ASTRONOMICAL APPLICATIONS

LAYERTEC®
OPTICAL COATINGS · OPTICS

FRONT SURFACE SILVER MIRRORS

BROADBAND SILVER MIRRORS FOR THE VIS AND NIR

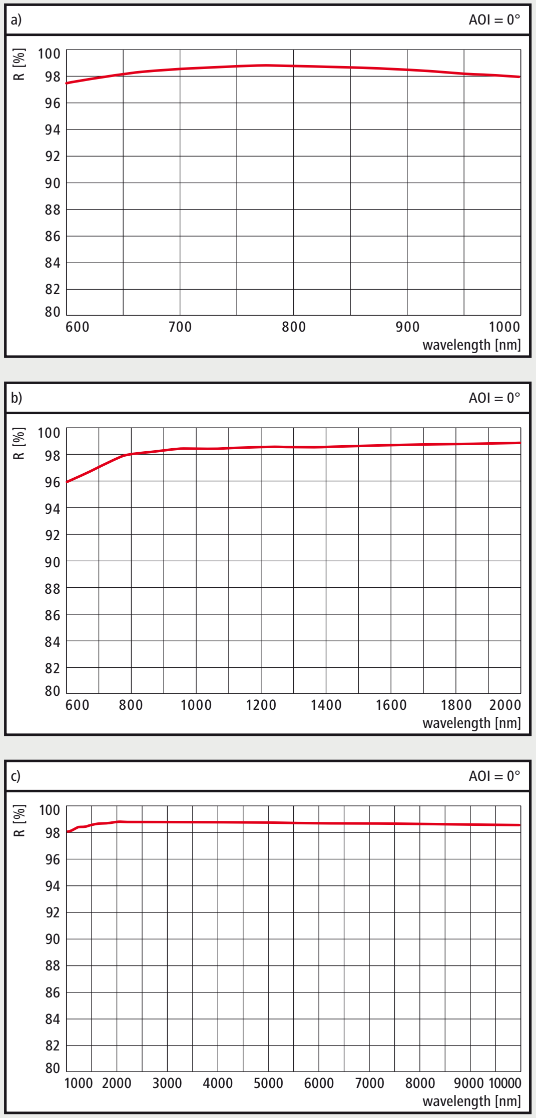


Figure 1: Reflectance spectra of three standard types of protected silver mirrors:
a) Optimized for 600 – 1000 nm with R > 98 %
b) Optimized for 600 – 2000 nm, 600 – 750 nm with R > 96 %, 750 – 2000 nm with R > 98 %
c) Optimized for 1000 – 10000 nm with R > 98 %

Optical properties:

- R > 98 % throughout the specified wavelength range (except type b).
- R = 94 %… 97 % in the VIS outside the specified wavelength range.
- R > 97 % in the NIR outside the specified wavelength range.

Special features:

- Silver has the highest reflectance of all metals in the VIS and NIR.
- Sputtered protective layers yield very stable optical parameters.
- Lifetime of more than 10 years in normal atmosphere has been demonstrated although unprotected silver is chemically unstable.
- The high atomic density of sputtered coatings guarantees that even very thin protective layers (≈ 20 nm) provide a good protection against the atmosphere.
- The thickness of the protective layer can be used to optimize the reflectance of the mirrors for different wavelength ranges (see fig. 1).
- Sputtered silver mirrors show extremely low scattering losses. (total scattering TS ≈ 30 ppm in the VIS and NIR).
- Silver mirrors with defined transmittance (e.g. T = 0.01 %) on request. (see page 86)
- Mechanical stability of protected silver mirrors is tested according to MIL-M-13508C § 4.4.5.
- Maximum diameter: 600 mm, especially for astronomical applications.

SILVER MIRRORS FOR USE IN FEMTOSECOND LASERS

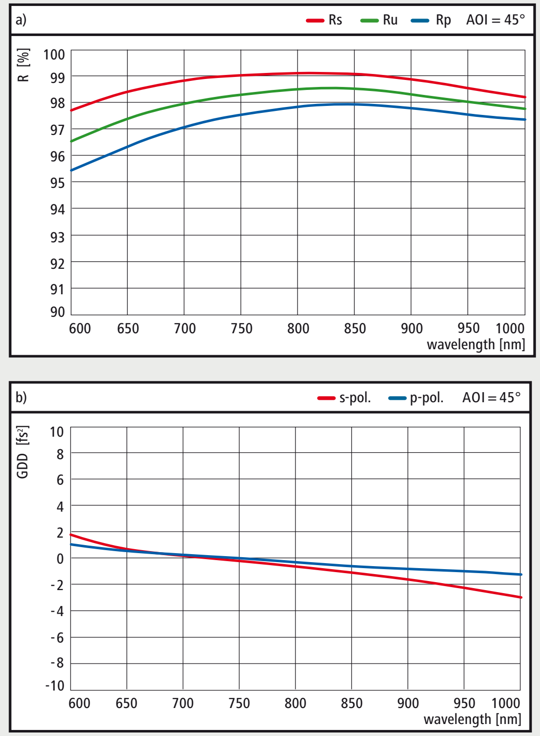


Figure 2: Reflectance and GDD spectra of a silver mirror optimized for use with fs-lasers in the wavelength range 600 – 1000 nm (AOI = 45°)
a) Reflectance vs. wavelength
b) GDD vs. wavelength

Silver mirrors are ideal in femtosecond laser systems because of their extremely broad low-GDD reflectance band.
For more examples see pages 86 – 87.

400 – 4000 nm

SILVER MIRRORS WITH ENHANCED REFLECTANCE

The reflectance of silver mirrors can be enhanced for selected wavelengths or wavelength regions by a dielectric protective coating. Figures 3 – 6 show examples for silver mirrors with enhanced reflectance. Such mirrors combine very high reflectance at the wavelengths of interest with a relatively high reflectance throughout the VIS which makes them ideal for use in conjunction with alignment lasers.

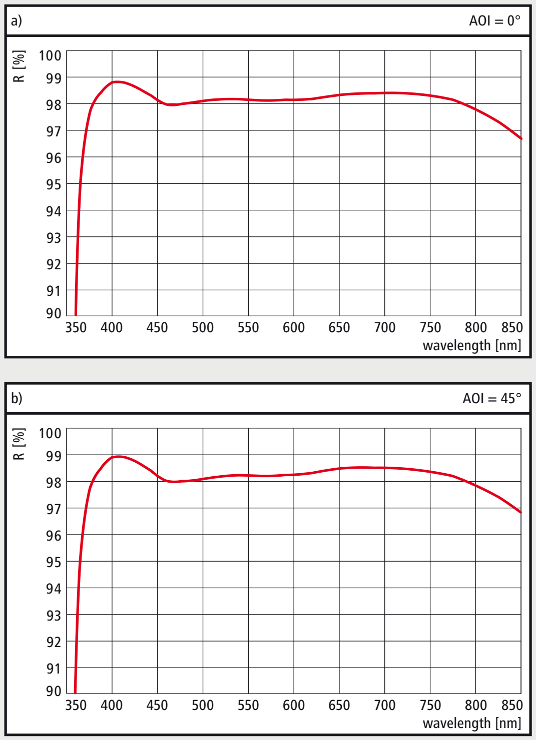


Figure 3: Reflectance spectra of an enhanced silver mirror which shows R ≥ 98 % throughout the visible spectral range:
a) AOI = 0°
b) AOI = 45°, unpolarized light

Enhanced silver mirrors of this type are useful for applications in astronomical devices.

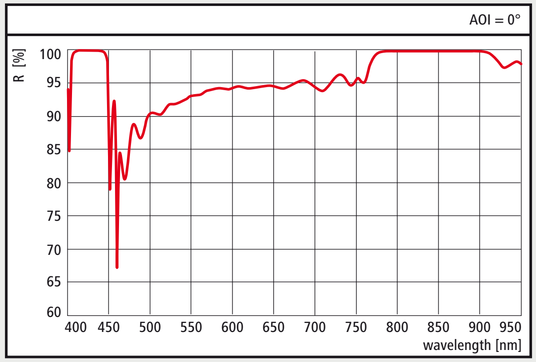


Figure 4: Silver mirror with enhanced reflectance at 425 and 850 nm (R > 99.5 %)

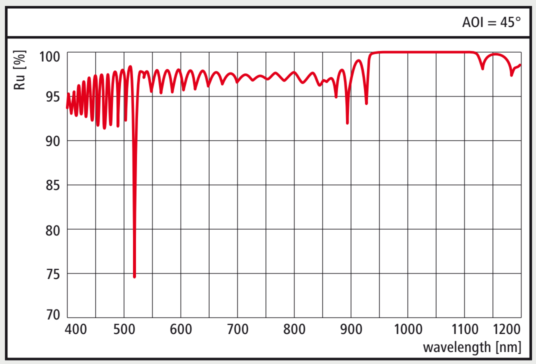


Figure 5: Silver based turning mirror for 1030 nm with R > 80 % for any alignment laser in the red spectral range

The mirror in figure 5 is a cost effective alternative for all dielectric mirrors for high power Yb:YAG- or Nd:YAG- lasers.

LIDT - INFO

tested without destruction:
50 kW / cm², wavelength: 1030 nm, cw

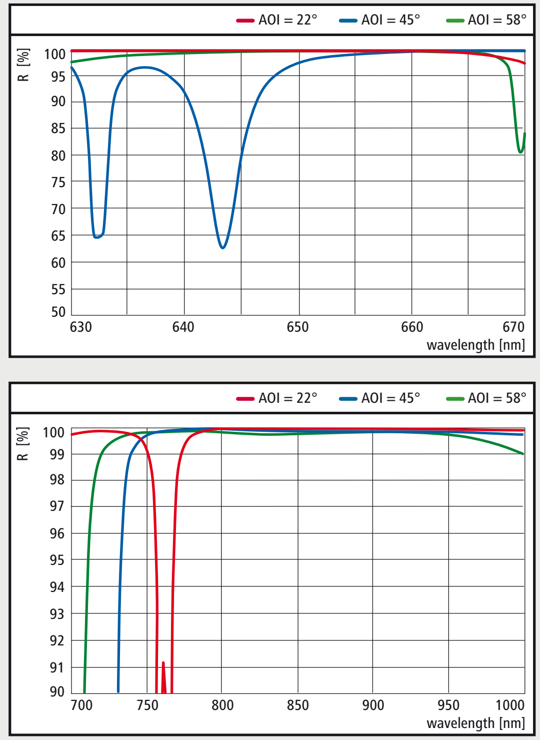


Figure 6: Reflectance spectra of a silver based scanning mirror for laser diodes in the NIR:
HRu (22° – 58°, 805 – 940 nm) > 99.3 %
+ Ru (22° - 58°, 630 – 670 nm) > 50 %

For more information on enhanced silver mirrors see pages 56, 86 – 87 and 108 – 109.

FRONT SURFACE ALUMINUM MIRRORS

BROADBAND MIRRORS FOR THE UV, VIS AND NIR

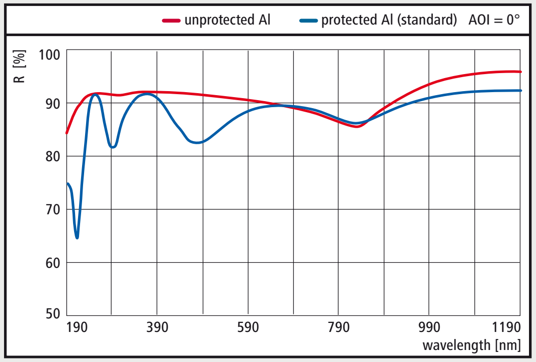


Figure 1: Reflectance spectra of unprotected aluminum and of a standard protected aluminum mirror

Optical properties:

Unprotected aluminum:

R > 80 % at 193 nm
R = 92 % at 248 nm
R > 85 % from 200 nm to 950 nm
(R > 90 % from 230 nm to 600 nm)
R > 90 % for λ > 1 µm.

Standard mirror:

R = 82 % … 92 % from 240 nm to 550 nm
R = 85 % … 92 % from 550 nm to 950 nm
R > 92 % for λ > 1 µm.

Aluminum is the metal with the highest reflectance in the UV spectral range. Besides this, aluminum has a high and relatively constant reflectance in the VIS and NIR. The minimum in the reflectance curve around 800 nm is due to a phonon resonance and can only be overcome by a dielectric protective coating. The reflectance in the VIS and UV spectral range can be influenced by the coating technologies. In case of protected aluminum mirrors, the positions of the minima and maxima of the reflectance depend on the design of the protective layer system and on the angle of incidence (AOI). Please specify AOI and the wavelengths of interest so that reflectance may be optimized as much as possible.

ALUMINUM MIRRORS FOR MULTIPLE WAVELENGTH AND FEMTOSECOND APPLICATIONS

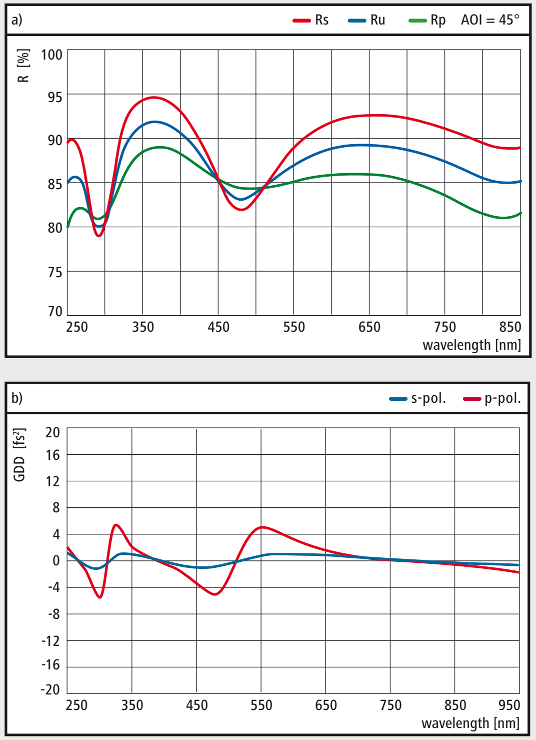


Figure 2: Reflectance and GDD spectra of an aluminum mirror optimized for R > 85 % at 266 nm, 400 nm and 800 nm (AOI = 45°)
a) Reflectance vs. wavelength
b) GDD vs. wavelength

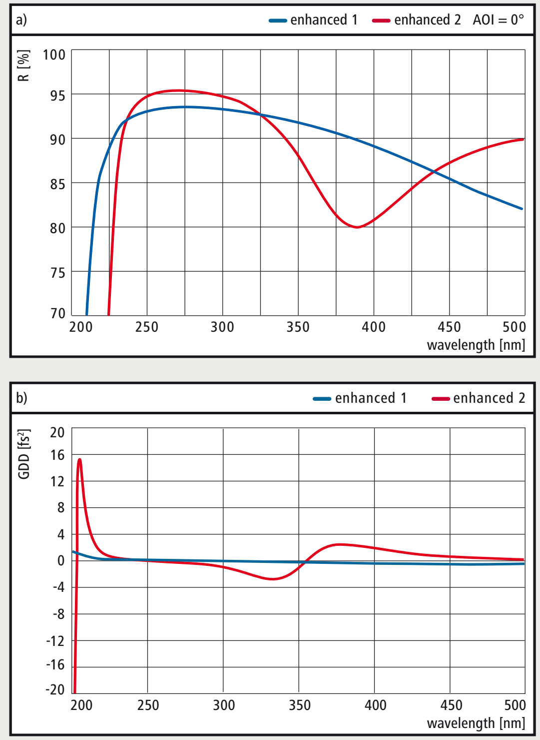


Figure 3: Reflectance and GDD spectra of aluminum mirrors with different designs for enhanced reflectance for the third harmonic of the Ti:Sapphire laser (AOI = 0°)
a) Reflectance vs. wavelength
b) GDD vs. wavelength

Fig. 2 shows the reflectance spectra of a mirror optimized for high reflectance at 266 nm, 400 nm and 800 nm at AOI = 45°.
Maximum diameter: 600 mm, especially for astronomical applications.

Special features:

- High reflectance in the wavelength range specified
- Extremely low scattering losses of protected aluminum mirrors (total scattering TS < 100 ppm at 633 nm, TS < 1000 ppm at 248 nm, TS < 5000 ppm at 193 nm).
- Standard mirrors can be cleaned using ethanol or acetone and are resistant to moderate abrasion (tested according to MIL-M-48497A § 4.5.4.2 and § 4.5.3.3).
- All mirrors are resistant to humidity (tested according to MIL-M-13508C §4.4.7).
- Highly stable optical parameters because of sputtered SiO_2 protective layer.

150 – 900 nm

PROTECTED AND ENHANCED ALUMINUM MIRRORS FOR THE DUV AND VUV

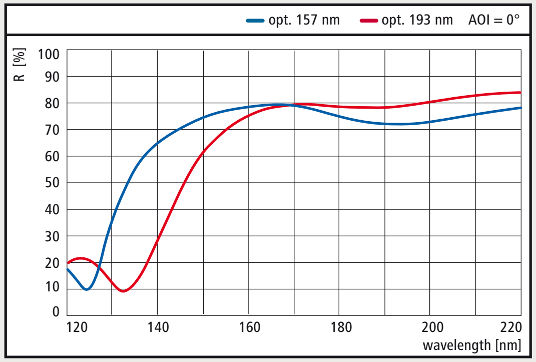


Figure 4: UV optimized aluminum: reflectance spectra of aluminum mirrors optimized for 157 nm and 193 nm (AOI = 0°)

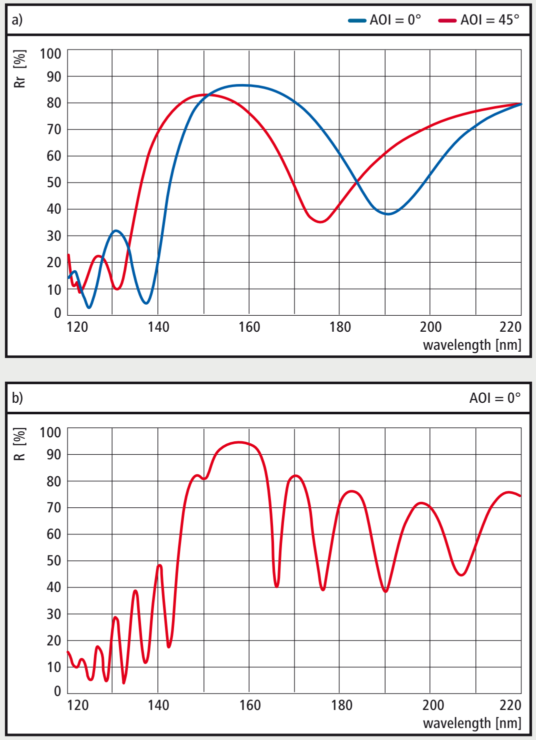


Figure 5: Reflectance spectra of two types of enhanced aluminum mirrors for 157 nm:
a) R > 80 % for AOI = 0° … 45°
b) R > 94 % at AOI = 0°

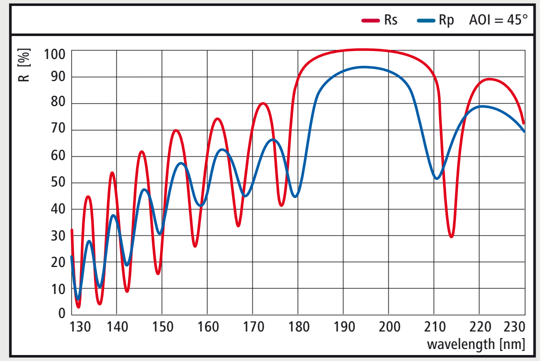


Figure 6: Reflectance spectra of an aluminum mirror with enhanced reflectance for 193 nm (AOI = 45°, Ru > 95 %)

- Reflectance at 193 nm can be improved up to Ru > 95 %.
- This kind of mirrors can also be used as scanning mirror for AOI = 45° – 50° with Ru > 93 %.
- Reflectance in the VIS: R = 60 … 80 %. This can be used for an alignment laser.
- VUV optimized mirrors should be treated with extreme care.

Optical properties:

Special coating design depending on the wavelengths of interest.

Optimized for 157 nm: R = 74 % … 78 % for 157 nm (R > 70 % from 150 to 200 nm).
Optimized for 193 nm: R = 75 % … 80% for 193 nm.
Optimized for 248 nm: R > 90 % for 248 nm.

- Reflectance at 157 nm can be further improved by dielectric protective coatings (up to R > 94 %).
- Reflectance in the VIS: R = 60 … 80 %. This can be used for an alignment laser.
- Especially mirrors with R = 85 … 90 % can be used at a wider range of AOI than all dielectric mirrors of this reflectance.

SPECIAL METALLIC COATINGS

CHROMIUM COATINGS FOR OPTICAL APPLICATIONS

Chromium coatings are used for lithographic processes and other special optical applications. LAYERTEC offers chromium coatings with extremely low pinhole density on mask blanks and silicon wafers. Typical substrates sizes are 6 inch x 6 inch, but uncommon sizes up to diameter 600 mm are also possible.

LAYERTEC uses specialized sputtering processes for very efficient industrial production. These processes are optimized for:

- Low pinhole density
- High optical density
- Low mechanical stress
- High electrical conductivity.

Besides high volume coating manufacturing, LAYERTEC still maintains its capabilities for flexible production of small volumes such as OEM components or components for research and development. Do not hesitate to contact LAYERTEC regarding your special request.

BROADBAND NEUTRAL DENSITY FILTERS FOR THE NIR

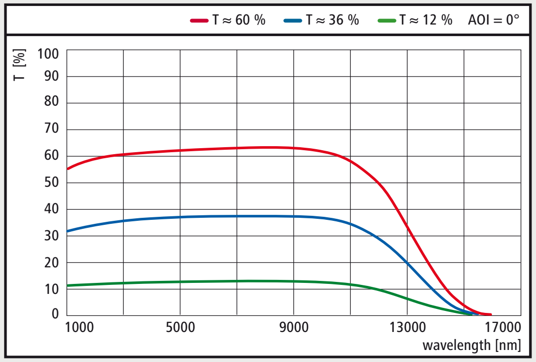


Figure 1: Transmittance spectra of broadband neutral density filters with different transmittance values

- Nearly constant transmittance for broad wavelength range from 1 µm to 10 µm.
- Substrate: BaF_2.
- Other transmittance values on request.

400 – 10000 nm

SOLDERABLE COATINGS

Soldering is one of the most important mounting techniques for optics which require excellent thermal contact to a heat sink.
LAYERTEC has developed several coating designs containing gold and other metals which can be used for soldering of the optics.

A very special problem is solder coatings on components for high power applications. As an example figure 2a and 2b show a pump mirror which is coated with a solder layer system on the top side and with dielectric coatings on the front and rear surfaces. Extreme care must be taken to avoid metallic contaminations on the optical surfaces. Nevertheless, the solder coating has to cover the whole top surface of the substrate.

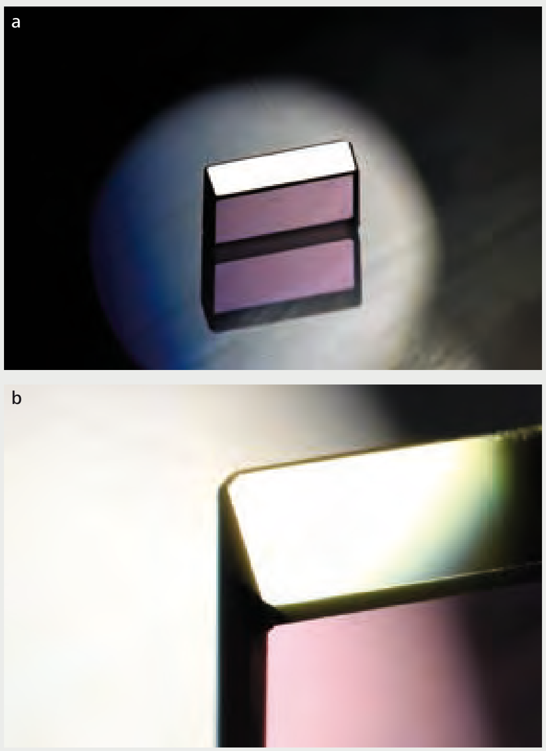


Figure 2: Pump mirror which is coated with a solder layer system on the top side

GOLD MIRRORS FOR THE NIR SPECTRAL RANGE

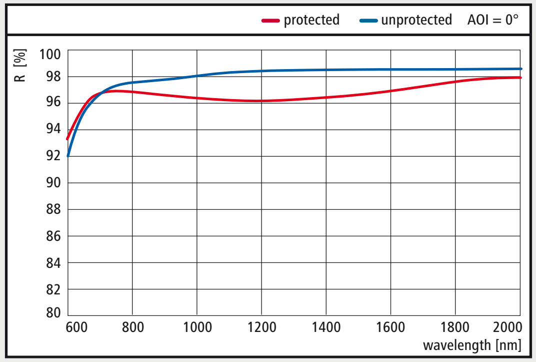


Figure 3: Reflectance spectra of protected and unprotected gold mirrors

Optical properties:

Unprotected gold:	R > 97 % from 700 nm to 1 µm
	R > 98 % for λ > 1 µm.
Protected:	R > 96 % from 700 nm to 2 µm
	R > 98 % for λ > 2 µm.

Special features:

- Extremely low scattering losses (total scattering TS < 100 ppm at 633 nm).
- Gold mirrors are chemically stable and can be used without protective layer.
- Unprotected gold is soft and scratches easily.
- Protected mirrors can be cleaned (tested according to MIL-M-13508C § 4.4.5).

Figure 4: Gold mirror on plano-concave substrate

PARTIALLY TRANSMISSIVE GOLD LAYERS FOR OPTICAL AND NON-OPTICAL APPLICATIONS

Gold coatings with a thickness of 10 nm to 50 nm can be used as partial reflectors or attenuators in the NIR spectral range. Fig. 5 shows transmittance spectra of gold layers with different thickness.
Moreover, thin gold layers are also useful for non-optical applications. An example of such an application is the generation of single electron pulses. Thin metallic layers are irradiated with femtosecond laser pulses. This results in the release of electrons. These electron pulses are generated with the repetition rate of the femtosecond laser. Recent investigations have shown that the pulse length of these electron pulses can be compressed to the attosecond range using a microwave cavity [1), 2)].
Magnetron sputtering allows the manufacture of partially transmissive gold layers in the mentioned thickness range. The optical parameters of these coatings are very stable because gold is chemically inert. Please note that gold layers are soft and can be easily damaged mechanically.

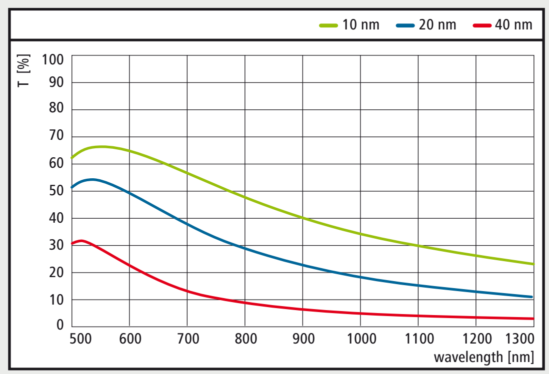


Figure 5: Transmittance of partially transparent gold coatings on sapphire

Literature:

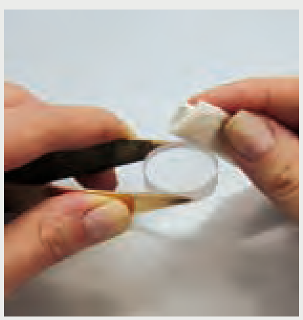
1) A. Gliserin, A. Apolonski, F. Krausz, P. Baum; "Compression of single electron pulses with a microwave cavity", New Journal of Physics 14(2012) 073055 (18 pp)
2) M. Aichelsburger, F.O. Kirchner, F. Krausz and P. Baum; PNAS vol.107 no.46 19714-19719

CLEANING OF OPTICAL SURFACES

1

2

3



4

Prerequisites:

- An air blower
- Optical cleaning tissue (e.g. Whatman®)
- Nonslip tweezers (e.g. with cork)
- Spectroscopy grade acetone*

Pre-cleaning:

- Clean hands with soap or use clean gloves (latex, nitrile)
- Blow off dust from all sides of the sample (2)
- Moisten tissue with acetone (3)
- Remove coarse dirt from the edge and the chamfer (4)

* Compared to alcohol acetone is the better solvent as it significantly reduces the formation of streaks

5

6

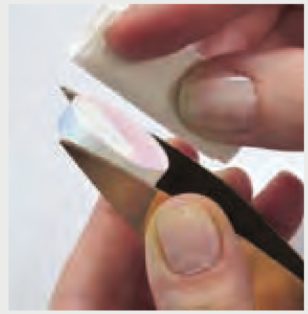
7

8

Preparation of the cleaning tissue:

- Fold a new tissue along the long side several times (5, 6)
- Fold across until you have a round edge (7)
- Grab the tissue as shown in (8)

9



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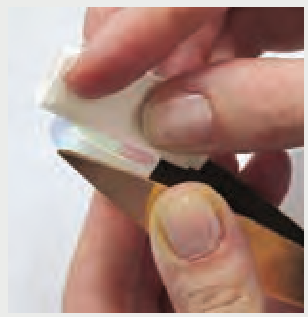

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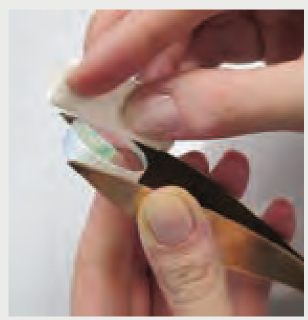


12

Cleaning of the optical surface:

- Moisten the tissue with acetone (9)
- A wet tissue will result in streaks
- Hold the sample with tweezers (10)
- Slide the curved tissue from one edge of the sample to the other **once** (10 … 12)
- The tissue may be turned inside out and used again once
- Repeat steps 9 … 12 with a new tissue until the sample is clean

HINTS


13

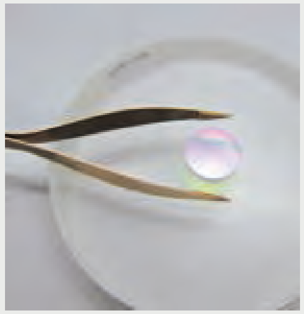
Small samples:

- Put sample onto a concave polished glass support to pick it up easily (13)
- Use special tweezers


14

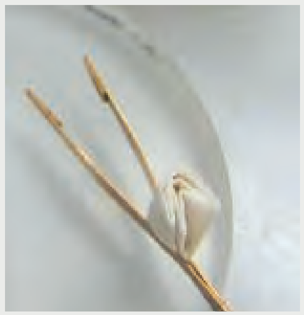
Fingerprints on sputtered coatings (14):

- Moisten the surface by breathing upon it
- Slide (acetone) moistened tissue over the surface as long as the water film is visible
- Exception: Never do this with hygroscopic materials (CaF_2 …)


15

Storage:

- It works best to store the samples on a polished curved glass support (15)
- Clean the support like an optical surface before use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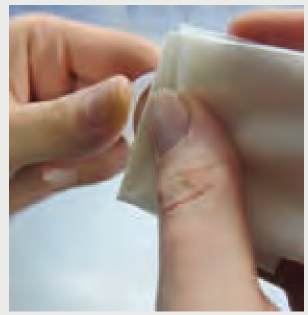
Holding the tissue:

- Use the tweezers to hold the moistened tissue (16)


17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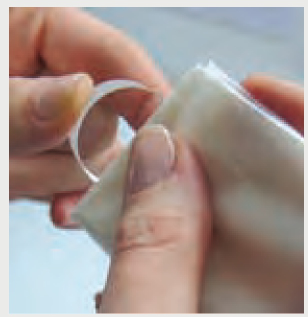
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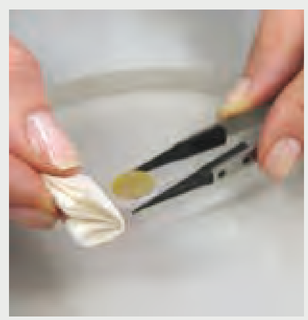
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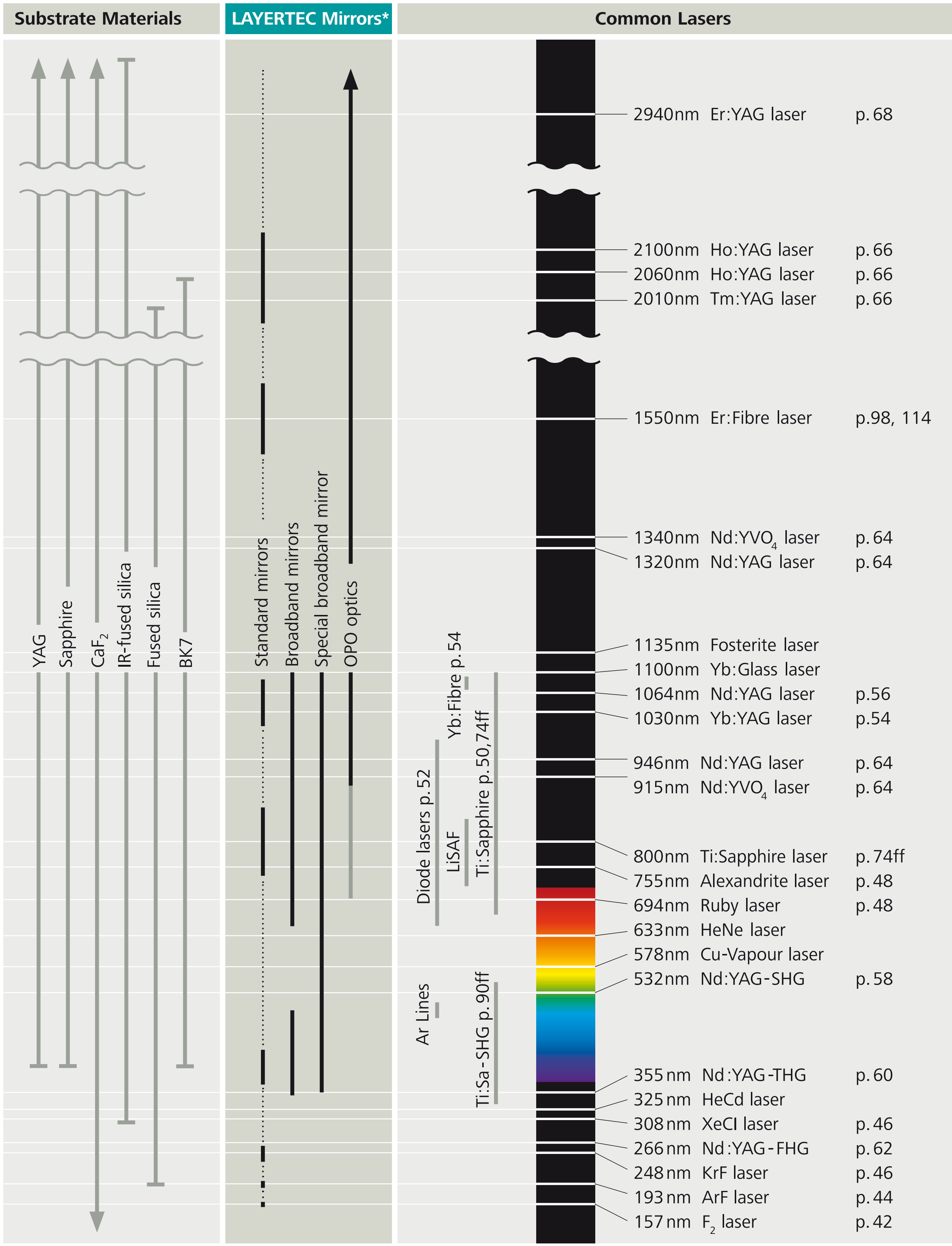
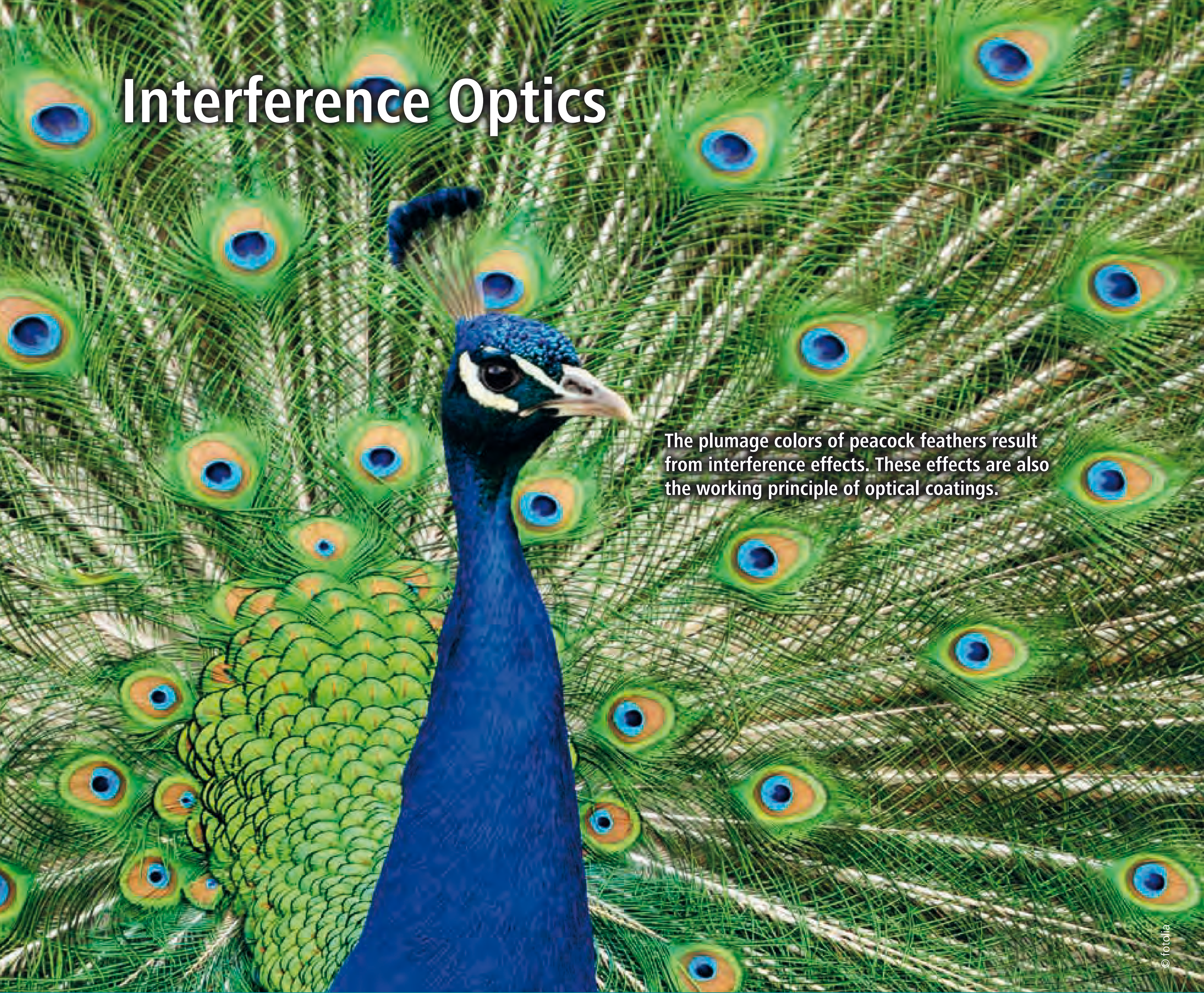
Cleaning of concave surfaces:

- Use a less often folded tissue that can be slidely bent (17)
- Clean analog to (9) … (12)
- Use your thumb to gently press the tissue onto the curved surface (18, 19)
- Use tissue only one time
- A concave support helps holding the sample (20)

REGISTER



*Bandwidths of selected LAYERTEC mirrors


Interference Optics
The plumage colors of peacock feathers result from interference effects. These effects are also the working principle of optical coatings.
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