# CATALOG 2011

LAYERTEC®
OPTICAL COATINGS · OPTICS

# CONTENTS

# 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 transmission. If no transmission 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. Basically all combinations of plane, convex and concave surfaces are possible. A special role plays the wedge. A wedge (e.g. 30 arcmin) can be applied on every 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 "+" and "-" to the light propagation. In this case "+" means "curvature with the direction of propagation", "-" means "curvature against the direction of propagation". To avoid confusion please specify concave or convex in words or by the acronyms CC or CX, respectively.

## Size

The main decision should be the edge length or diameter. Small diameters are more favourable for the production. The rising heights become lower and it is easier to achieve a good form tolerance.

Unless the impact on the optical design the thickness description means the maximum thickness of the substrate, i.e. the centre thickness for plano-convex substrates and the edge thickness for plano-concave substrates. Consequently, a wedged plate is measured on the thicker side.

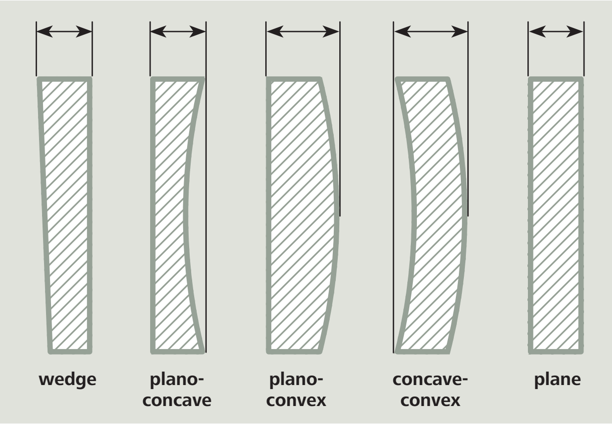


**Figure 1:** Conventions for the specification of the thickness of different types of substrates (schematic drawing)

In order to achieve a good form tolerance one should take care for the ratio of diameter and thickness. As a rule of thumb the thickness should be the fifth part of the diameter. Of course, other ratios are possible but the production expenditure increases.

## Tolerances

Beside size and material the tolerances are most important for the price. Of course, the optics must fit into the mount, so that the diameter should not be larger than specified. The most common specification is –0.1mm. Mostly, the thickness is free in both directions. LAYERTEC usually specifies it with a tolerance of ±0.1mm.

There is a lot of confusion about the specification of wedge, parallelism and centring. Please note that wedge and parallelism describe the angle between the optical surfaces while centring describes the angle between the optical surfaces and the side surfaces (see figure 2).

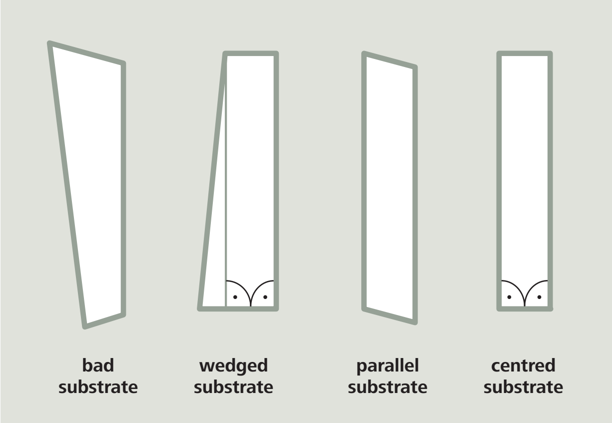


**Figure 2:** Different kinds of plane substrates with respect to wedge and centring (schematic drawing)

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.

Normally, the 90° angle to the side surface has a precision of 20 arcmin. Centring is an additional optics processing which improves this accuracy to a few arcmin.

Using the same nomenclature one can describe curved substrates. There should be distinguished between mirrors and lenses. The side surfaces of mirror substrates are just parallel. Nevertheless the direction of the optical axis can be inclined to the side surfaces. After centring the side surfaces are parallel to the optical axis. That way the mirror substrate becomes a lens.

## Surface form tolerance

The surface form tolerance is normally measured by interferometers and is specified in terms of lambda, which is the reference wavelength. Without further statements the reference wavelength is $\lambda = 546$ nm.

To avoid confusion, one must 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 figure 3). The distance between these planes is called the flatness. This flatness consists of two contributions. The first contribution is a spherical bent of the surface, which may be described by two best fitted spheres for the "peaks" and "valleys". The sagitta of this curvature with respect to an ideal plane is denoted as power. This spherical bent does not affect the quality of the reflected beam. It just causes a finite focal length. The second contribution is the deviation of the best fitted spheres, which is named irregularity. This is the most important value for the quality of the beam.

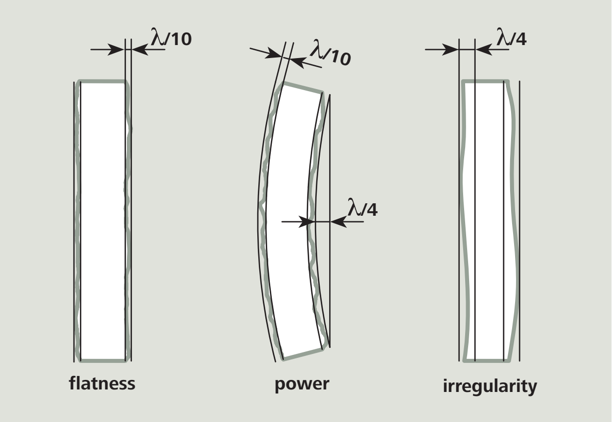


**Figure 3:** Schematic drawing for the explanation of substrate properties:
a) flatness of $\lambda/10$
b) spherical bending (power of $\lambda/4$)
c) irregularity of $\lambda/4$, but transmitted wavefront of $\lambda/10$

The standard ISO 10110 provides a sufficient opportunity for specifying the surface form tolerance. Having the best comparability with the measurement results all values are given as numbers of interference fringes. They should be read as 1 fringe = $\lambda/2$. In the drawings the surface form tolerance is allocated as item number three:

3/ power (irregularity)

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

3/ 0.5 (0.2)

Using the optics only for transmission (e.g. laser windows) the power as well as the irregularity do not matter. If the optics has the same thickness all over the free aperture the transmitted beam is not affected. The deviation from this equality is defined in a similar way as the flatness. It is also measured in parts of the reference wavelength and called "transmitted wavefront". For instance, the window in figure 3 has a flatness of $\lambda/4$ but a transmitted wavefront of $\lambda/10$.

## Coating stress

Often 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.

Taking the mentioned values seriously the flatness becomes poor. Nevertheless the quality of the beam is not affected.

## Defects

MIL-O-13830 and ISO 10110 are different standards for the description of optical elements. This often causes obscurities. Basically, one should distinguish between scratches and digs. The scratch number in MIL-O-13830 means 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 seriously. The MIL norm does not examine a direct 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 the dig number can be measured easily. The numerical value means the maximum dig diameter in hundredths of a millimeter. Maximum size digs can be one per 20 mm of diameter. According to ISO 10110 the defects are specified as item number 5. The grade number means the side length in millimeters of a quadratic area which is equivalent to the total fault area. So 5/1 x 0.025 means a surface fault area of 0.000625 mm². Additionally, scratches of any length are stated by 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 catalogue correspond to ISO 10110. The mentioned scratch-dig values are a rough analogy to MIL-O-13830.

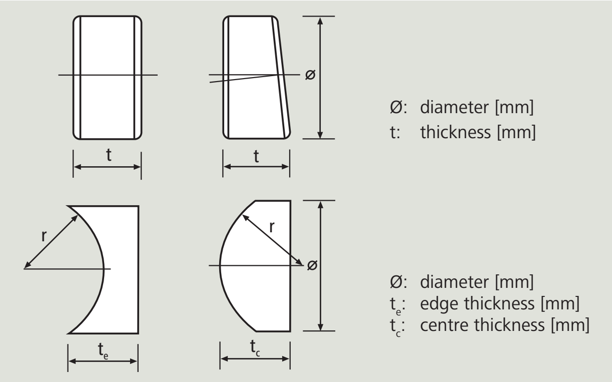
# STANDARD QUALITY SUBSTRATES

The precision optics facility of LAYERTEC produces plane and spherically curved mirror substrates, lenses and prisms of fused silica, optical glasses like 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.

## STANDARD SPECIFICATIONS

**Materials**

- Fused silica: Corning 7980®, Lithosil® Q2 (SCHOTT AG) or equivalent
- Fused silica for high power applications: Suprasil® 300 / 3001 / 3002 (Heraeus Quarzglas GmbH)
- UV fused silica (excimer grade) Lithosil® Q1 E-193 and E-248 (SCHOTT AG),
- IR fused silica: Infrasil 302® (Heraeus Quarzglas GmbH)
- ULE® (Corning Incorporated)
- Zerodur® (SCHOTT AG)
- BK7®: optical glass (SCHOTT AG)
- $CaF_2$: transparent from UV to IR, prices for excimer grade qualities (HELLMA Materials GmbH) on request
- Sapphire: random oriented, single crystal, special orientations on request
- YAG: undoped, random oriented, single crystal



**Dimensions**

- Fused silica, ULE®, Zerodur®, BK7®: diameter 6.35 mm … 508 mm (¼ inch … 20 inches)
- Calcium fluoride, YAG, sapphire: diameter 6.35 mm … 50.8 mm (¼ inch … 2 inches)
- Rectangular substrates and other diameters available on request

**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

**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: 633nm)**

| Material | | Standard Specification | On request |
|---|---|---|---|
| Fused silica | plane<br>spherical | λ/10<br>λ/4 reg. (typical λ/10 reg.) | λ/20<br>λ/20 reg. (Ø<51mm) |
| ULE and Zerodur | plane<br>spherical | λ/10<br>λ/4 (typical λ/10 reg.) | λ/20<br>λ/20 reg. (Ø<51mm) |
| BK7 | plane<br>spherical | λ/10<br>λ/4 reg. (typical λ/10 reg.) | λ/20<br>λ/20 reg. (Ø<51mm) |
| $CaF_2$ | plane Ø<26mm<br>plane Ø<51mm<br>spherical | λ/10<br>λ/4<br>λ/4 reg. | λ/10<br>λ/10<br>λ/10 reg. |
| Sapphire | | λ/2 | λ/10 |
| YAG | plane<br>spherical | λ/10<br>λ/4 reg. (typical λ/10 reg.) | λ/20<br>λ/20 reg. (Ø<51mm) |

**Sureface quality**

| Material | Standard Roughness | Standard Specification | On request |
|---|---|---|---|
| Fused silica | < 2 Å | 5/1 x 0.025 L1 x 0.001<br>Scratch-Dig 10-3 | 5/1 x 0.010 L1 x 0.0005<br>Scratch-Dig 5-1 |
| ULE | < 2 Å | 5/3 x 0.025 L1 x 0.001<br>Scratch-Dig 10-5 | 5/1 x 0.010 L1 x 0.0005<br>Scratch-Dig 5-1 |
| Zerodur | < 3 Å | 5/2 x 0.040 L1 x 0.001<br>Scratch-Dig 10-5 | 5/2 x 0.025 L1 x 0.0010<br>Scratch-Dig 10-3 |
| BK7 | < 3 Å | 5/2 x 0.040 L1 x 0.001<br>Scratch-Dig 10-5 | 5/2 x 0.025 L1 x 0.0010<br>Scratch-Dig 10-3 |
| $CaF_2$ | < 2 Å | 5/3 x 0.025 L1 x 0.0025<br>Scratch-Dig 20-3 | 5/3 x 0.016 L1 x 0.0010<br>Scratch-Dig 10-2 |
| Sapphire | < 5 Å | 5/3 x 0.025 L20 x 0.0025<br>Scratch-Dig 20-3 | 5/3 x 0.016 L1 x 0.0010<br>Scratch-Dig 10-2 |
| YAG | < 2 Å | 5/1 x 0.025 L2 x 0.0025<br>Scratch-Dig 20-3 | 5/1 x 0.010 L1 x 0.0005<br>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

# SPECIAL OPTICAL COMPONENTS

## ETALONS

In optics, the etalon as a kind of a Fabry-Pérot interferometer is typically made of a transparent plate with two reflecting surfaces. Its transmission spectrum as a function of wavelength exhibits peaks of large transmission corresponding to resonances of the etalon. Etalons are widely used in telecommunications, lasers and spectroscopy for controlling and measuring the wavelength of laser sources. LAYERTEC offers etalons of various materials and customized diameters depending on the wavelength range. Subject to the diameter thicknesses down to 50 µm and a parallelism < 1 arcsec are possible. Do not hesitate to contact us for the customized diameter and thickness you need.

| | Thickness | | Parallelism |
|---|---|---|---|
| | **Ø = 25 mm** | **Ø = 12.7 mm** | |
| **Fused Silica** | > = 200 µm | > = 50 µm | < 1 arcsec |
| **YAG** | > = 200 µm | > = 50 µm | < 1 arcsec |
| **$CaF_2$** | > = 300 µm | > = 100 µm | < 5 arcsec |

## CUSTOMIZED PRISMS AND SHAPES

In addition to the mentioned circular substrates LAYERTEC is able to produce a lot of different shapes. Besides rectangular substrates, wedges and prisms uncommon optics are possible. Typical issues are definite holes through the optics. So called D-cuts and notches can be produced. Currently LAYERTEC establishes a production line for aspheric and freeform surfaces.

## POLISHING OF CRYSTALS

Besides the high quality optical coatings on crystals (see pages 100 – 101) LAYERTEC supports the polishing of various types of crystals such as YAG, KGW, KYW, ZGP or LBO. Our polishing technology also allows us the careful handling and processing of small crystal sizes or extraordinary forms. Do not hesitate to contact us for your special problem.

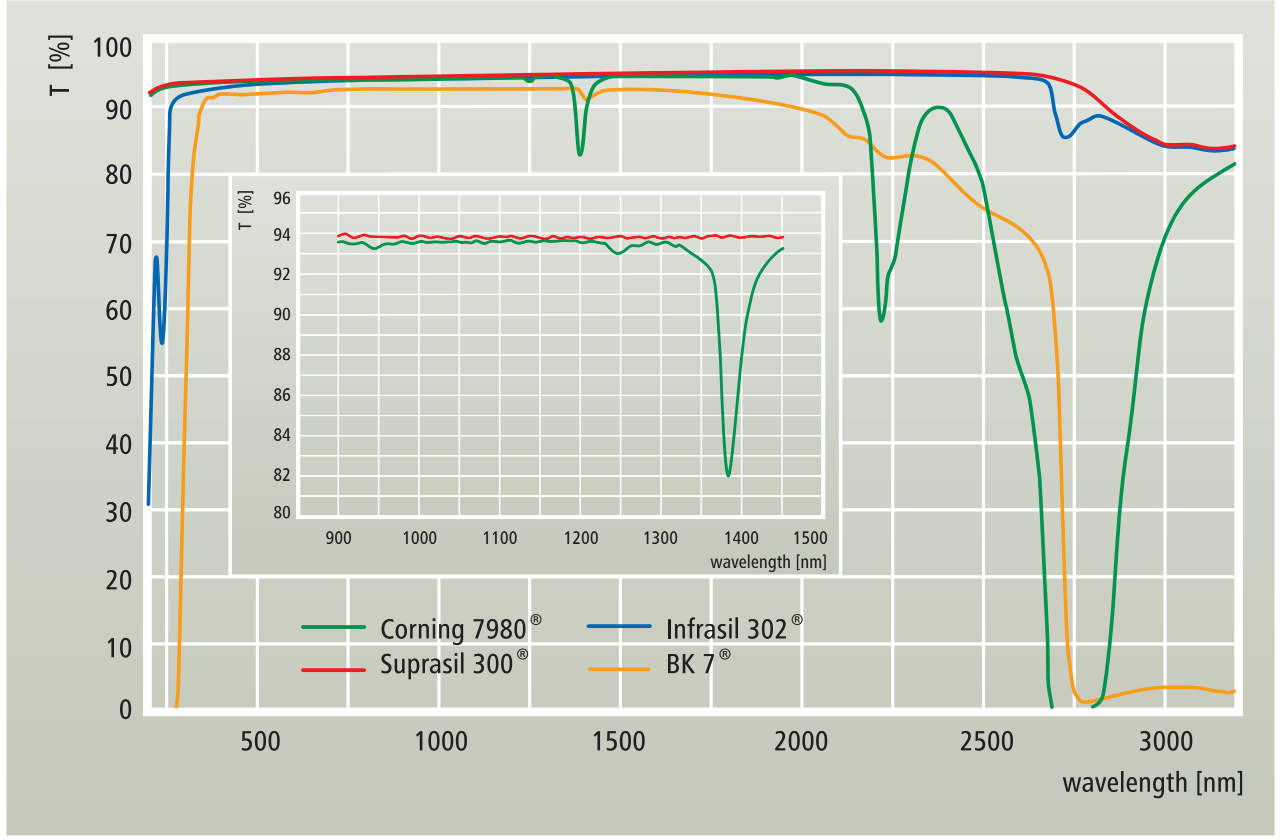
# SUBSTRATE MATERIALS FOR UV, VIS AND NIR/IR OPTICS

| | YAG (undoped) | Sapphire | BaF$_2$ | CaF$_2$ | Infrasil * | Fused silica (UV) | BK7 ** | SF10 ** |
|---|---|---|---|---|---|---|---|---|
| **Wavelength range free of absorption** | 400nm – 4µm | 400nm – 4µm | 400nm – 10µm | 130nm – 7µm | 300nm – 3µm | 190nm – 2.0µm*** | 400nm – 1.8µm | 400nm – 2.0µm |
| **Refractive index at** | | | | | | | | |
| 200nm | | | | 1.49516 | | 1.55051 | | |
| 300nm | | | | 1.45403 | | 1.48779 | | |
| 500nm | 1.8450 | 1.775 | 1.479 | 1.43648 | 1.46233 | 1.46243 | 1.5214 | 1.7432 |
| 1µm | 1.8197 | 1.756 | 1.468 | 1.42888 | 1.45042 | 1.45051 | 1.5075 | 1.7039 |
| 3µm | 1.7855 | 1.71 | 1.461 | 1.41785 | 1.41941 | | | |
| 5µm | | 1.624 | 1.451 | 1.39896 | | | | |
| 9µm | | | 1.408 | 1.32677 | | | | |
| **Absorbing in the 3µm region** | no | no | no | no | yes | yes | yes | yes |
| **Absorbing in the 940nm region** | For high power applications at 940nm we recommend the fused silica types SUPRASIL 300* and SUPRASIL 3001/3002* | | | | | | | |
| **Birefringence** | no | yes | no | no**** | no | no | no | no |
| **Thermal expansion coefficient [$10^{-6}$K] ******* | 7 | 5 | 19 | 18 | 0.5 | 0.5 | 7 | 8 |
| **Resistance against temperature gradients and thermal shock** | high | high | very low | low | high | high | high | medium |
| **LAYERTEC standard specifications for substrates with Δ 25mm** | | | | | | | | |
| Surface roughness (rms) | 0.2nm | 0.5nm | 1nm | 0.15nm | 0.15nm | 0.15nm | 0.3nm | 0.5nm |
| Flatness (plane surfaces) (546nm) | λ/10 | λ/2 | λ/2 | λ/10 | λ/10 | λ/10 | λ/10 | λ/10 |
| Surface figure (curved) (546nm) | λ/4 | λ/2 | | λ/4 | λ/4 | λ/4 | λ/4 | λ/4 |
| Surface quality (ISO 10110) | 5/1x0.025<br>L2x0.0025 | 5/3x0.025<br>L20x0.0025 | 5/2x0.4<br>L20x0.0063 | 5/3x0.025<br>L1x0.0025 | 5/1x0.025<br>L1x0.001 | 5/1x0.025<br>L1x0.001 | 5/2x0.04<br>L1x0.001 | 5/2x0.04<br>L1x0.01 |

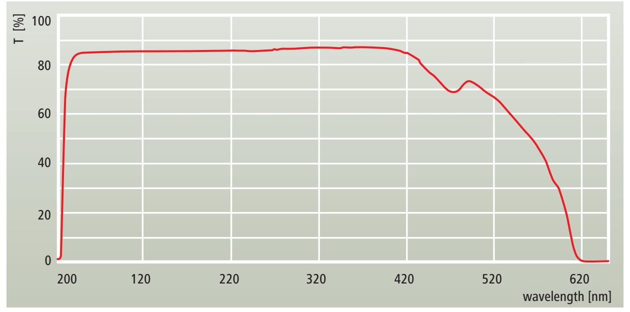
* Registred trademark of Heraeus Quarzglas GmbH & Co. KG
** Registred trademark of SCHOTT AG
*** Absorption band within this wavelength range, please see transmission curve
**** measurable effects only in the VUV wavelength range
***** The values given here are rounded, because the measurements of different authors in the literature are inconsistent. Please note that the thermal expansion coefficient of crystals depends also on the crystal orientation.

# TRANSMISSION CURVES

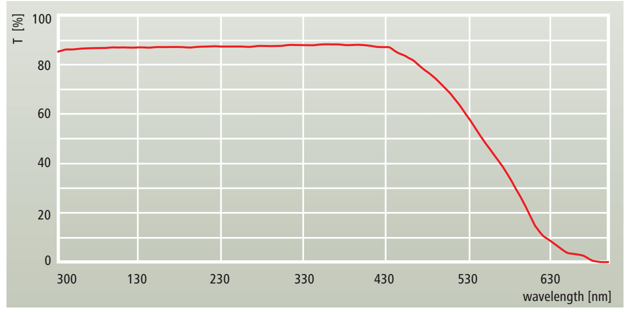
**Fused silica and BK7® (9.5 mm thick)**



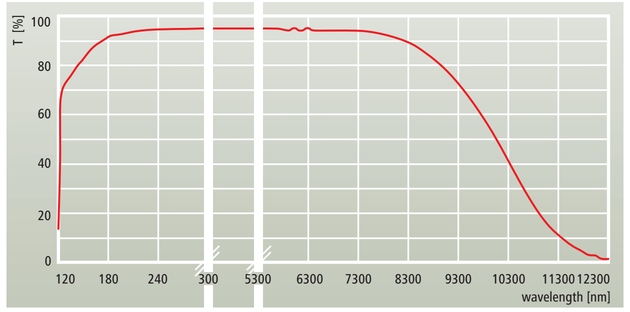
**YAG undoped (3 mm thick)**



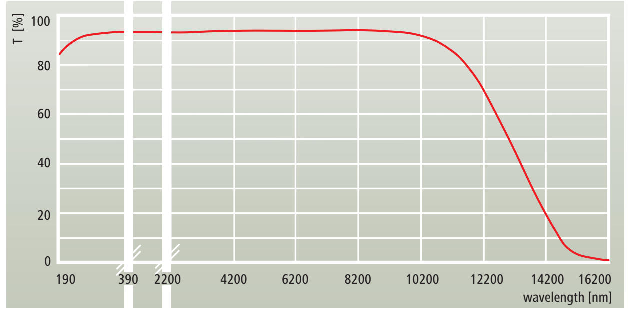
**Sapphire (3 mm thick)**



**Calcium fluoride (3 mm thick)**



**Barium fluoride (3 mm thick)**



# MEASUREMENT TOOLS FOR PRECISION OPTICS

## 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, spherically and parabolically curved surfaces. Additionally, a tactile measurement device (Taylor Hobson PGI 1240 Asphere) is available for general aspheric and grinded surfaces. Besides the purpose of quality control, surface form measurement is a key function for the zonal polishing technology which is established at LAYERTEC.

### Abbreviations

- **P-V:** The peak-to valley height difference
- **ROC:** Radius of curvature of a spherically curved surface.
- **λ**: measuring wavelength of the laser interferometer (e.g. 633 nm or 546 nm). The P-V value is stated in a fractional amount of λ. The concrete value of λ is stated in our protocols.

For detailed information about the standards concerning surface form measurement please refer to DIN EN ISO 10110-5.

### Accuracy of interferometric measurements

Without special calibration procedures, the accuracy with which the form of an optical surface can be measured with a laser interferometer, cannot be better than the accuracy of the reference surface. With calibration the accuracy can be increased by factor 2 or even more. Furthermore the precision is influenced by the size of the region (aperture) which is measured, and when it is about curved surfaces, by the radius of curvature itself. The accuracy values stated as "P-V better than …" in the following articles are worst-case guaranteed values. Very often accuracies in the region of λ/20 or better will be reached.

### 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 protocols 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 P-V = λ/8 over Ø ≤100 mm, but often 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 (thus disturbing air turbulences during the measurement are kept small too).

### Large aperture interferometry

Especially 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.

Figure 1 shows the height map of a flat surface with a diameter of Ø=520mm which was measured with the MiniFIZ 300 interferometer and the stitching configuration at LAYERTEC.

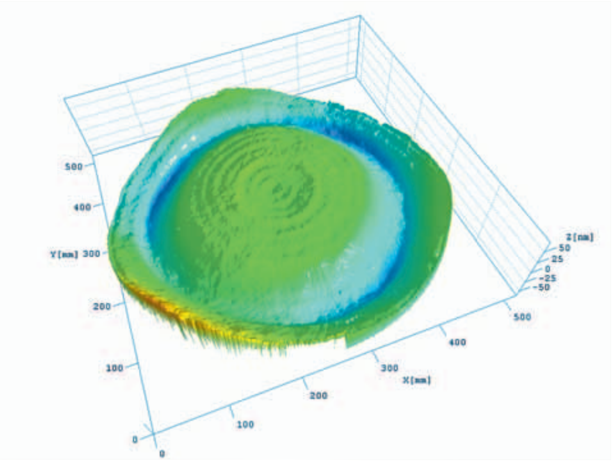


**Figure 1:** Height map of a flat surface with a diameter of Ø=520 mm polished and measured at LAYERTEC. The P-V value is λ/10 over the full aperture (Ø=500 mm inspection area) after zonal correction.

The measurements of spherically curved concave surfaces are carried out with a Twyman-Green interferometer (PhaseCam 5030® from 4D-Technology). This interferometer uses a special technology which allows measurement times in the region of a few milliseconds. Thus, the interferometer is insensitive to vibrational errors when measuring over long distances up to 20m 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 (concave surfaces only).

## SURFACE ROUGHNESS MEASUREMENT

The surface roughness value of an optical surface is stated as roughness parameter Rq or Sq. This parameter is also named "RMS roughness" because it is calculated as the root mean square of the surface height values. The letter „R" indicates that only a 2-dimensional roughness profile is basis of calculation according to ISO 4287/1. The letter „S" stands for a 3-dimensional measurement and calculation (3D-Reference ISO/DIS 25178-2).

For the aim of measuring and stating roughness parameters of optical surfaces, the corresponding measurement device and the spectral range within which the optical surface should be used, has to be taken into account. The spatial resolution of the roughness measurement device plays an important role with respect to the roughness value. A higher spatial resolution allows the detection of smaller surface structures and higher spatial frequencies, respectively. Otherwise, the amount of stray light losses on the surface depends on the spatial frequencies of the surface structures and the wavelength of the light itself. Figure 1 shows the spatial frequencies which influence the scattering losses in different spectral ranges and typical spatial resolutions of roughness measurement devices.

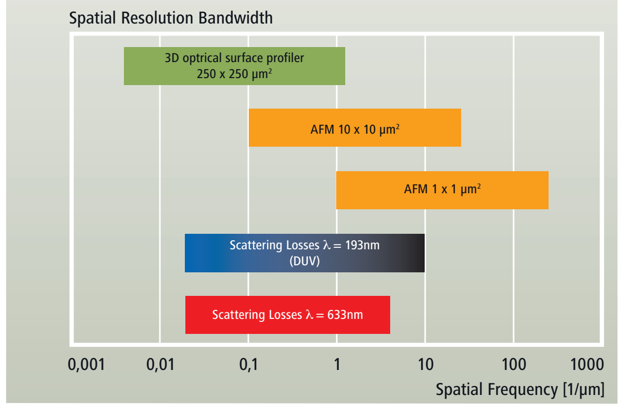


**Figure 1:** Spatial frequency resolution of AFM and 3D optical surface profiler at LAYERTEC for typical scan sizes. Additionally, the figure shows the spatial frequency ranges which influence the scattering losses in the VIS and DUV spectral range*.

Generally, for the characterization of optical surfaces which are appointed to be used in the NIR, VIS and UV spectral range, surface roughness measurements should be accomplished with spatial resolutions which are equal or better than 10/µm to obtain roughness information over the entire relevant spatial frequency range. Figure 2 clarifies the differences between an AFM measurement and an optical surface profiler measurement with respect to the calculated RMS roughness and the spatial resolution.

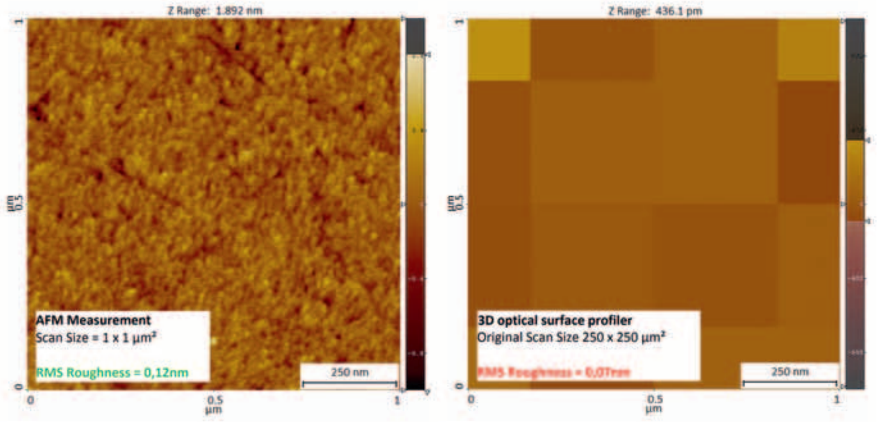


**Figure 2:** Surface roughness measurement of a super polished Low Loss substrate for an UV application made of fused silica. Both images show the same region on the surface, but they were recorded with different measurement devices (optical surface profiler and AFM). The color bar scaling is ±1nm for both images. At equivalent lateral pixel scaling, the AFM measurement with high spatial resolution shows fine structures which are relevant for stray light losses. The optical profiler measurement only shows a few pixels but no significant information about the surface roughness and structures. Moreover, the roughness value obtained from such undersampled measurements is too low, that means that the value seems to be too good.

LAYERTEC has available a phase shifting 3D optical surface profiler (Fa. Atos MICROMAP 3D) and a scanning probe microscope (AFM) DI Nanoscope 3100 for the purpose of measuring and analyzing the surface roughness of optical components. The optical profiler has a low spatial resolution <2/µm but the acquisition time of a measurement amounts only a few seconds. Thus, the device is used for the measurement of optics with lower surface roughness requirements and for the general inspection of the polishing processes. Surface defects and inhomogeneities can be characterized too. The AFM is used for the characterization of polished surfaces which have roughness values Sq<0,5nm. This device has a very high spatial as well as vertical resolution, but the acquisition time is approximately 10 – 30 minutes. Therefore it is primarily used for the further development of the polishing processes. Our premium polish and especially our optics for UV applications with Sq < 0,2nm are checked randomly for the reason of quality control in regular periods of time. The standard AFM measurement parameters at LAYERTEC are: Scan size of 10 x 10 µm² and a spatial resolution of 25/µm (see figure 1). Measurement reports are available on request.

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

# OPTICAL INTERFERENCE COATINGS

The purpose of optical coatings is to change the reflectivity of optical surfaces. According to the materials and physical phenomena which are used one can in principle distinguish metallic and dielectric coatings. Metallic coatings are used for reflectors and neutral density filters. The reflectivity which can be achieved is given by the properties of the metal. Some of the most common metals for optical applications are described on page 24.
Dielectric coatings use, however, optical interference to change the reflectivity of the coated surfaces. Another major difference is that the materials used for this kind of coatings show very low absorption. Using optical interference coatings the reflectivity of optical surfaces can be varied from nearly zero (anti reflection coatings) to nearly 100% (low loss mirrors with R>99.999%). However, these reflectivity values are achieved only for a certain wavelength or wavelength range.

## Basics

The influence of a single dielectric layer on the reflectivity of a surface is schematically shown in figure 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.

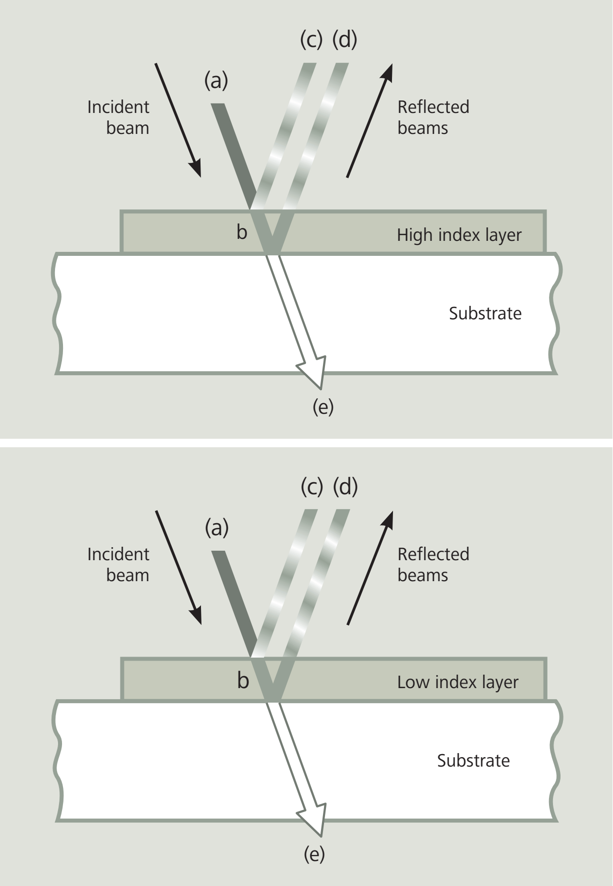


**Figure 1:** Schematic drawing to explain the interference effect of quarterwave layers of a high index material and a low index material (after [1])

In figure 1 the wavelength 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 reflectivity of the interface between 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.

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

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

$R_s$ ... reflectivity for s-polarization
$R_p$ … reflectivity for p-polarization
$n_1$ … refractive index of medium 1
$n_2$ … refractive index of medium 2
$\alpha$ … angle of incidence (AOI)
$\beta$ … angle of refraction (AOR)

For normal incidence (a = b = 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 n·t of the layer (the product of the refractive index n and the geometrical thickness t). Moreover, one must take into account that a phase jump of $\pi$, i.e. one half wave, occurs if light coming from a low index medium is reflected at the interface to a high index medium.

For a detailed explanation of the physics of optical interference coatings we refer to the literature cited on page 25. To help our customers understand the optical properties of the coatings described in this catalog, we only present some rules of thumb:

- High index layers always increase the reflectivity of the surface. The maximum reflectivity for a given wavelength $\lambda$ is reached for $n\cdot t = \lambda/4$. A layer with $n\cdot t = \lambda/2$ doesn´t change the reflectivity of the surface for this wavelength $\lambda$.
- Low index layers always decrease the reflectivity of the surface. The minimum reflectivity for a given wavelength $\lambda$ is reached for $n\cdot t = \lambda/4$. A layer with $n\cdot t = \lambda/2$ doesn´t change the reflectivity of the surface for this wavelength $\lambda$.

## Anti reflection 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 n=1.38 in the VIS an NIR. This material reduces the reflectivity per surface to R~1.8% for fused silica and to nearly zero for sapphire.

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

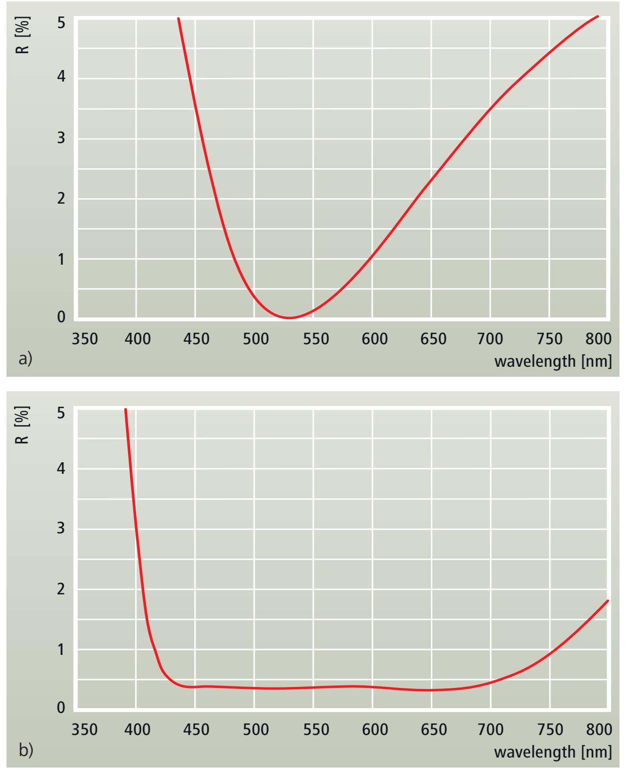


**Figure 2:** Schematic reflectivity spectrum of a single wavelength AR coating ("V-coating") (a) and of a broadband AR coating (b)

## Mirrors and partial reflectors

- The most common mirror design is the so called quarterwave stack, i.e. a stack of alternating high and low index layers with an equal optical thickness of $n\cdot t = \lambda/4$ for the desired wavelength. This results in constructive interference of the reflected beams arising at each interface between the layers. The spectral width of the reflection band and the achievable reflectivity for a given number of layer pairs depends 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.

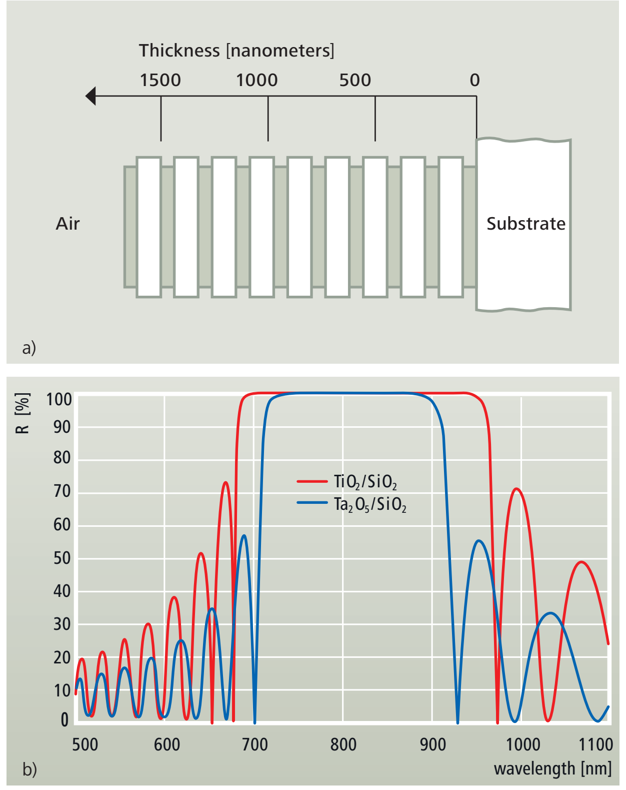


**Figure 3:** Schematic drawing of a quarterwave stack consisting of layers with equal optical thickness of a high index material (grey shading) and a low index material (no shading) (after [1]) (a), reflectivity spectra of quarterwave stacks consisting of 15 pairs of $Ta_2O_5/SiO_2$ and $TiO_2/SiO_2$ (b)

- To visualize the effect of different refractive index ratios figure 3b compares the reflectivity spectra of quarterwave 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).

- Assuming ideal coatings with zero absorption and scattering losses the theoretical reflectivity will approach R=100% with increasing number of layer pairs. Also partial reflectors with several discrete reflectivity values between R=0% and R=100% can be manufactured using only a small number of layer pairs (see figure 4). Adding some non-quarterwave layers to such a stack allows to optimize the reflectivity to any desired value.

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

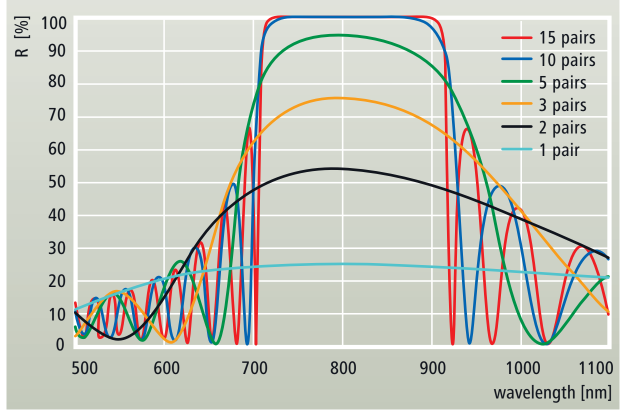


**Figure 4:** Calculated reflectivity of quarterwave stacks consisting of 1, 2, 3, 5, 10 and 15 layer pairs of $Ta_2O_5/SiO_2$ for 800 nm

## Optical losses

- Light which impinges 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 … reflectivity,
  T … transmission,
  A … absorption and
  S … scattering

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

- Scattering losses increase drastically with decreasing wavelength. The basic phenomena are described by the Mie-theory (scattering by particles with diameters in the order of λ, S~1/λ2) and by the Rayleigh-theory (scattering by particles with diameters <λ, S~1/λ4).). Depending on the surface and bulk structure scattering losses are a mixture of Mie-scattering and Rayleigh-scattering at the same time. 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. Scattering losses depend critically on the microstructure of the coatings. This causes a dependence on the coating technology used. Usually, coatings produced by evaporation techniques show significantly larger scattering losses than coatings produced by magnetron sputtering or ion beam sputtering.

- Absorption in optical coatings and substrates is mainly determined by the band structure of the materials. Common oxide materials show bandgaps of 3-7 eV which correspond to absorption edges in the NUV and DUV, while fluorides have bandgaps of 9-10 eV resulting in absorption edges in the VUV spectral range (for examples please see page 11). Some materials show also absorption bands apart from the basic absorption edge as for instance the absorption band of Si-O-H-bonds in fused silica around 2.7 µm. Another reason for absorption losses at wavelengths apart from the absorption edge are defects in the layers which form absorbing states in the band gap of the materials. These may result from contaminations or from the formation of substoichiometric compounds. That´s why optical coatings must be optimized with respect to low contamination levels and good stoichiometry. This kind of absorption losses also increases with decreasing wavelength.

- Of course, all kinds of losses depend on the thickness of the layer system. Each layer pair increases the theoretical reflectivity. However, in practice it also increases the optical losses. Thus, especially for evaporated coatings with relatively large scattering losses there´s an optimum number of layer pairs which generates the maximum reflectivity. In practice, evaporated mirrors for the UV show a typical reflectivity between R=96% at 200 nm and R=99.5% at 300 nm. Evaporated coatings for the VIS show R=99.7% while sputtered coating can be specified with R>99.9%. NIR coatings reach R>99.9% (evaporated) and R>99.98% (sputtered). Sputtered low loss mirrors (see pages 98 – 99) reach R>99.99% in the VIS and R>99.999% in the NIR. This shows that the main disadvantage of evaporated coatings is the layer structure which results in increased scattering losses.

## Stress

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

- 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 problem of interference coatings is the angle shift. This means that features shift to shorter wavelengths with increasing angle of incidence. Turning an optical component from AOI=0° to AOI=45° results, for instance, in a shift of the features by about 10%. That´s why the angle of incidence must always 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. AR coatings can be improved significantly, if these items are known. Besides the shift, broadband AR coatings often show an increased reflectivity at AOI≥30° (see figure 5a).

- The angle shift offers, however, also the possibility to angle tune 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 which may decrease the output and increase the costs drastically, if the specifications for wavelength and AOI are fixed. Angle tuning (see figure 5b) is in these cases the best way to optimize the performance and to minimize the costs.

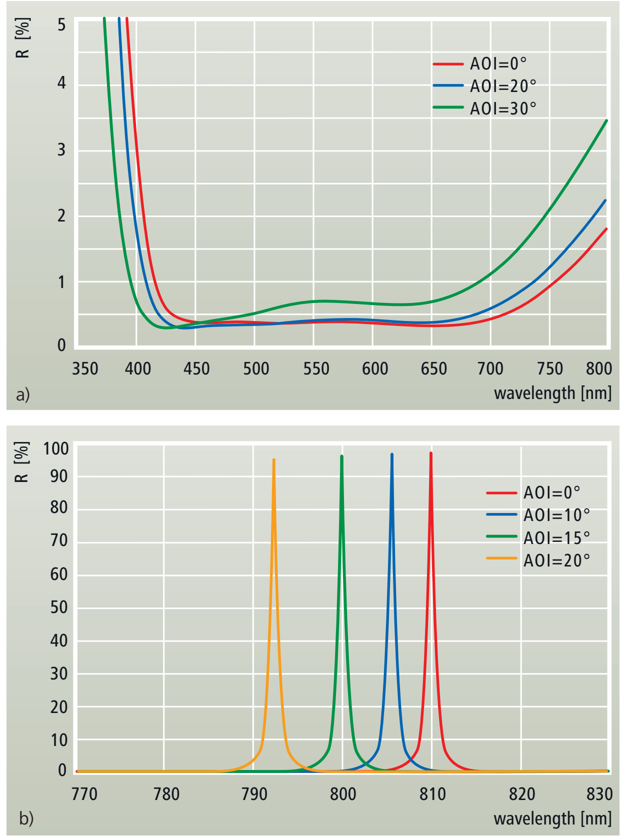


**Figure 5:** Angle shift and change of reflectivity of a broadband AR coating at AOI=0° (red), 20° (blue) and 30° (green) (a) and angle tuning of a narrow band filter for 800 nm (b)

## Polarization effects

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

- To explain the meaning of the terms “s-polarization” and “p-polarization” one must first determine a reference plane (see lower part of figure 6). This plane is spanned 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 whose plane of oscillation is inclined to these directions are splittet into a p-polarized and an s-polarized part.

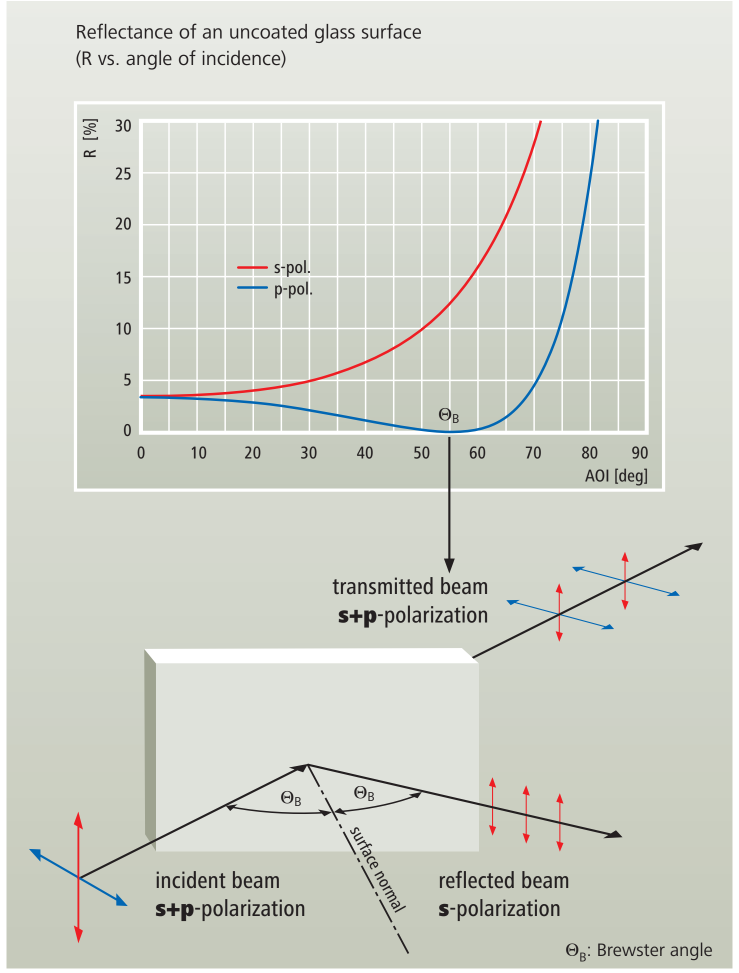


**Figure 6:** Definition of the terms "s-polarized light" and "p-polarized light" and reflectance of an uncoated glass surface vs. angle of incidence for s- and p-polarized light

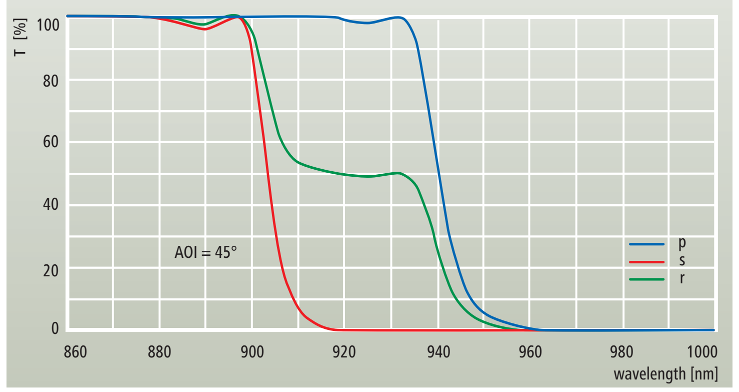


**Figure 7:** Polarization splitting of an edge filter. Please note that the edges of the reflectance bands are steep for s- as well as for p-polarization even at AOI=45°, but are located at different wavelengths. As a result, the edge of the reflectance band for unpolarized light is considerably broadened.

- The upper part of Figure 6 shows the reflectivity of a glass surface vs. AOI for s- and p-polarized light. The reflectivity for s-polarized light increases with increasing angle of incidence while the reflectivity for p-polarized light decreases first, reaches R=0% at the "Brewster angle" and increases again for angles of incidence beyond Brewster angle. In principle, the same is true for dielectric mirrors. For AOI≠0° the reflectivity for s-polarized light is higher and the reflection band is broader than for p-polarized light.

- In the case of edge filters, where one of the edges of the reflectance band is used to separate wavelength regions of high reflectivity and high transmission, tilting results in a polarization splitting of the edge. This means that the angle shift is different for s- and p-polarized light. This results in a broadening of the edge if unpolarized light is used.

**Documentation of coating performance at LAYERTEC**
LAYERTEC provides a data sheet for transmission and/or reflectivity with each delivered optical component. The standard procedure is to measure the transmission of the optics at AOI=0° and to calculate the reflectivity at the desired AOI from this measurement.
Sputtered optical coatings for the VIS and NIR exhibit extremely low straylight and absorption losses (both in the order of some $10^{-5}$). This has been confirmed by direct measurements of straylight and absorption as well as by highly accurate reflectivity measurements (e.g. by Cavity Ring-Down spectroscopy). With these very small optical losses, the reflectivity of sputtered mirrors can be determined by measuring the transmittance T and the simple calculation:

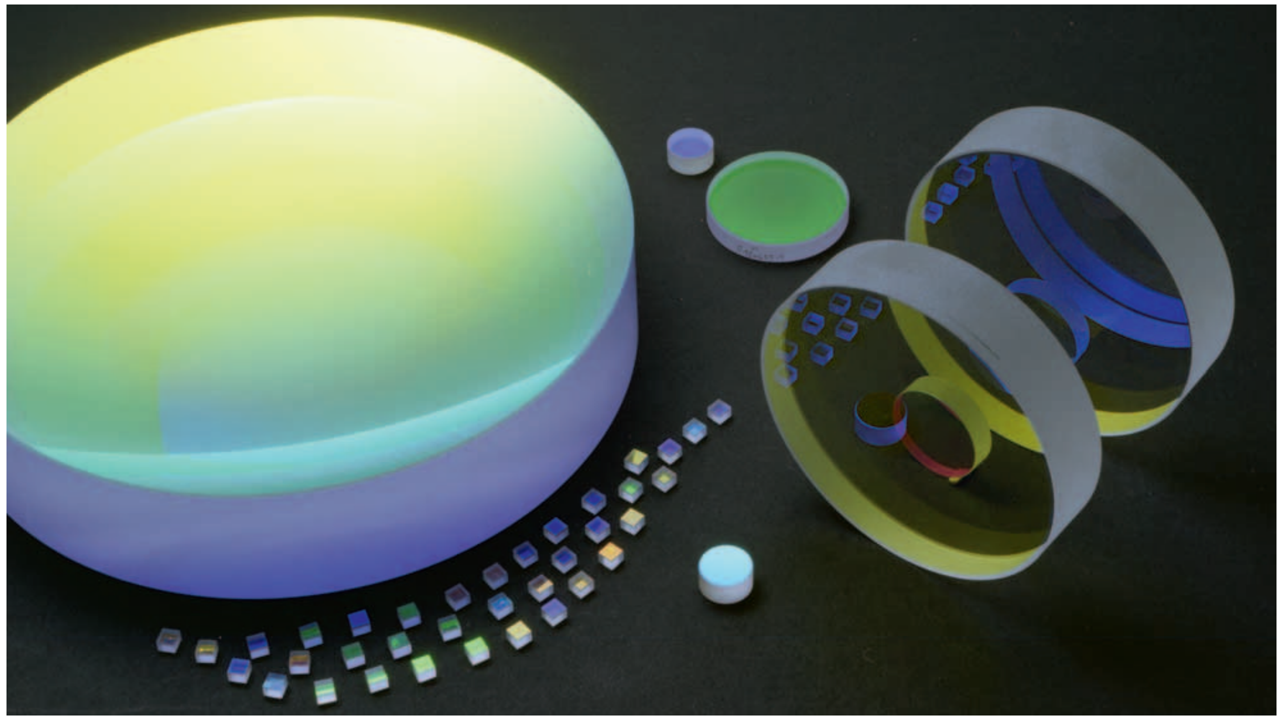
$$R = 100\% - T.$$

In a normal spectrophotometer, the transmission 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, the determination of the reflectivity of sputtered coatings in the VIS and NIR by transmission measurements is much more accurate than direct reflectivity 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 of only 1-3x$10^{-3}$ can be included into the reflectivity calculation.

In the deep UV range, the coatings usually show straylight losses in the order of some $10^{-3}$...$10^{-2}$, depending on the wavelength. That´s why, especially fluoride coatings for wavelengths < 220 nm are delivered with direct reflectivity measurements.
Direct reflectivity measurements are also necessary for low loss mirrors. LAYERTEC has Cavity Ring-Down measurement setups for a variety of wavelengths setups for the wavelength range between 210 – 1800 nm without gaps.

**Dielectric broadband coatings**

- The first step to broadband mirrors and output couplers is to use coating materials with a large refractive index ratio (see above). The bandwidth can be further increased by special coating designs which apply also non-quarterwave layers.
- The easiest way is to combine two or more quarterwave stacks with overlapping reflectance bands. However, this results in increased optical losses at the wavelengths where the bands overlap. Moreover, such multiple stack designs cannot be used for fs-lasers because they induce pulse distortion.
- LAYERTEC offers special all-dielectric broadband components for fs-lasers up to bandwidths of one octave, i.e. 550 nm – 1100 nm (see pages 66 – 69).
- Larger bandwidths can be achieved using metals. However, the natural reflectivity of metals is limited to 92 – 99% (see the following paragraphs). It can, however, be increased by dielectric overcoatings. For such ultra broadband metal-dielectric mirrors see page 93.



# METALLIC COATINGS

Metals are the most common materials for mirror fabrication. Polished metals, especially gold, copper and bronze, were used as mirrors already in the ancient world. In the middle ages, mirrors with relatively constant reflectivity 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 aldehyd.

Mirrors for applications in precision optics and laser physics are produced by evaporation or sputtering techniques. LAYERTEC uses magnetron sputtering for the fabrication of metallic coatings. This results in coatings with extremely low straylight losses. Moreover, also transparent, i.e. very thin metal coatings can be produced with high accuracy. For detailed information about our metallic mirrors and neutral density filters please see pages 72 – 73 and 102 – 107. Figure 8 gives an overview about the reflectivity of the most common metals.

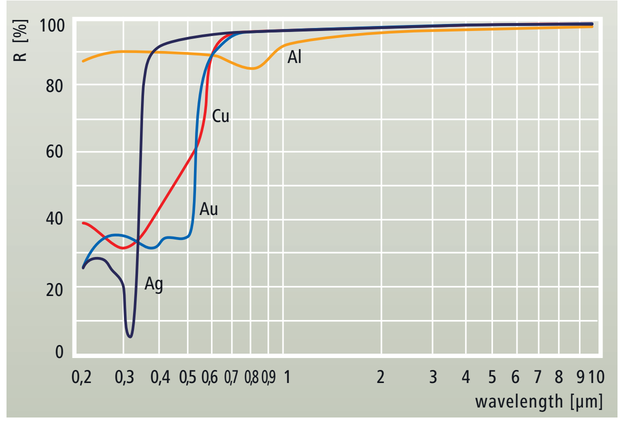


**Figure 8:** Reflectance of several metals versus wavelength (taken from [2])

In the following we give some hints for the use of these metals and about the role of protective coatings:

**Silver:**

- Highest reflectivity 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). Lifetimes of 10 years in normal atmosphere were demonstrated.
- The use of protective layers is mandatory, because unprotected silver is chemically unstable and soft
- See separate data sheets on pages 72 – 73 and 102 – 103

**Gold:**

- Similar reflectance as silver in the NIR
- Chemically stable, but soft
- Protective layers are necessary to make gold mirrors cleanable
- We recommend to use protected silver mirrors instead of protected gold, because the sputtered protective layers overcome the insufficiency of silver and make it a better choice because of the broader wavelength range, the slightly higher reflectivity and the more favourable price.
- See separate data sheet on page 107

**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
- See separate data sheet on pages 104 – 105

**Chromium:**

- Medium reflectivity 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:**

- Ensure cleanability and chemical stability
- Influence on the reflectance of the metal
- Even very thin sputtered layers can be used for chemical protection of the metal because of high atomic density of the layers. Such layers show minimal influence on the VIS and NIR reflectivity of the metal
- Mechanical protection and cleanability can, however, only be reached by relatively thick protective layer systems
- Optimization of the protective layer system for the wavelength of interest is particularly necessary in the UV

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# METAL-DIELECTRIC COATINGS

**Metal-dielectric coatings**

In general, all layer systems consisting of metals and dielectric layers 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 the reflectivity and absorption of the metallic layers. The spectral position of the transmission band is determined by the optical thickness of the dielectric spacer layer.

In this catalog we want to draw the attention of the reader, however, to metal-dielectric reflectors. Metals and metallic coatings show an extremely broadband natural reflectivity which is, however, restricted to about 90% in the UV spectral range (aluminum), 96% in the VIS (silver) and 99% in the NIR (gold and silver). Moreover, most of the metals must be protected by dielectric coatings to overcome limitations of chemical (silver) or mechanical stability (aluminum, silver, gold). More strictly speaking, almost all metallic mirrors are metal-dielectric coatings. The protective coatings always influence the reflectivity of the metals. Single dielectric layers of any thickness lower the reflectivity in most parts of the spectrum. However, multilayer coatings on metals can increase the reflectivity of the metallic coating. The bandwidtdh of enhanced reflectivity can also be optimized for extremely broad spectral ranges as can be seen in figure 9. For more examples please see pages 72–73, 92–93 and 102–107.

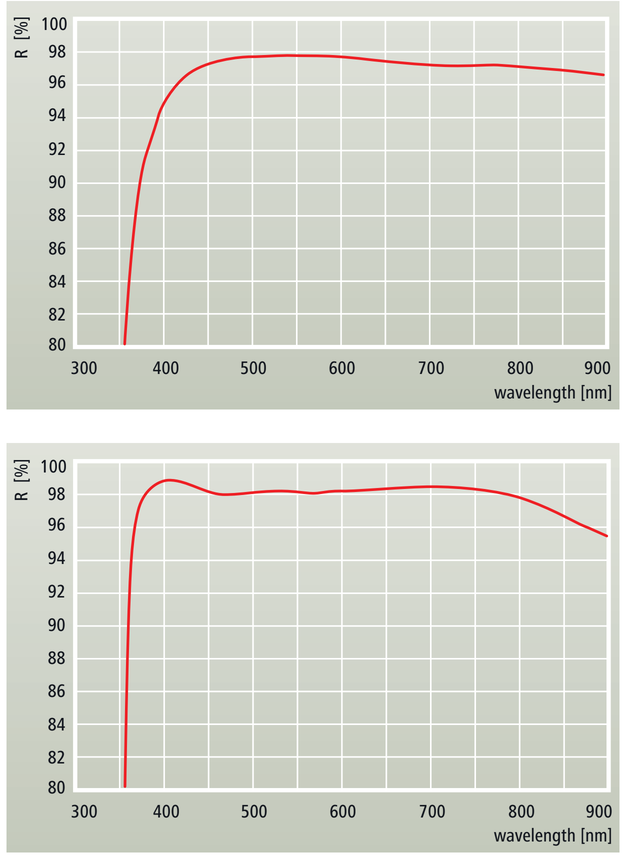
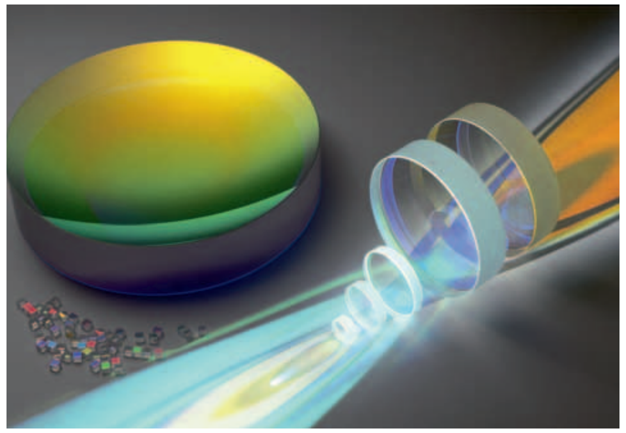


**Figure 9:** Reflectance spectra of a protected silver mirror and a metal dielectric silver mirror, both optimized for high reflectivity in the visible spectral range for use in astronomical telescopes.



**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“, McGraw Hill, New York 1989
[4] N. Kaiser, H.K.Pulker (eds.) „Optical interference coatings“, Springer Verlag Berlin Heidelberg, 2003

# MEASUREMENT TOOLS FOR COATINGS

## SPECTROPHOTOMETRY

**Spectrophotometric measurements**
Standard spectrophotometric measurements in the wavelentgh range λ = 190nm – 3200nm 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 a FTIR spectrometer (λ = 1µm – 20µm) and a VUV spectrophotometer (λ = 120nm – 240nm). Please note that the absolute accuracy of spectrophotometric measurement amounts 0,2...0,4% over the full scale measurement range R, T = 0...100%. A self-constructed setup for transmission measurements in the limited range T = 0,1 – 0,0001% but with higher accuracy will be available soon.

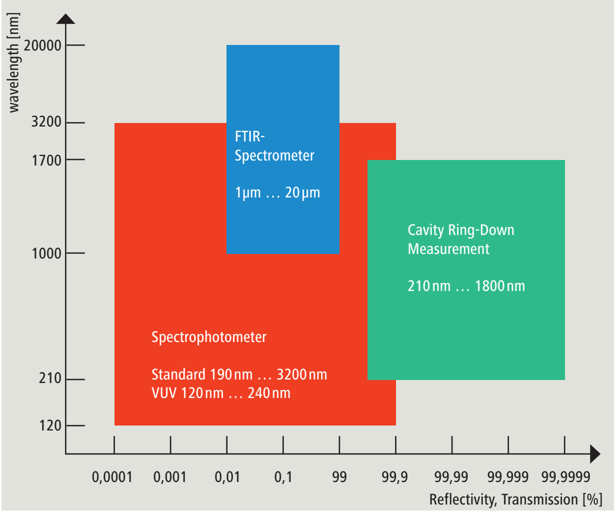


**Figure 1:** Measurement technologies and their range for reflectivity and transmission measurements at LAYERTEC

## CAVITY RING-DOWN (CRD) MEASUREMENT

High reflectivities and transmission values in the order of R, T = 99,5% ... 99,9999% are determined by Cavity Ring-Down Time measurements. This method has a high accuracy, e.g. R = (99,995 ± 0,001)%, and it is an absolute measurement procedure. LAYERTEC comes with various CRD systems which were developed in cooperation with research institutes and universities. A schematic representation of the CRD method is shown in figure 2.

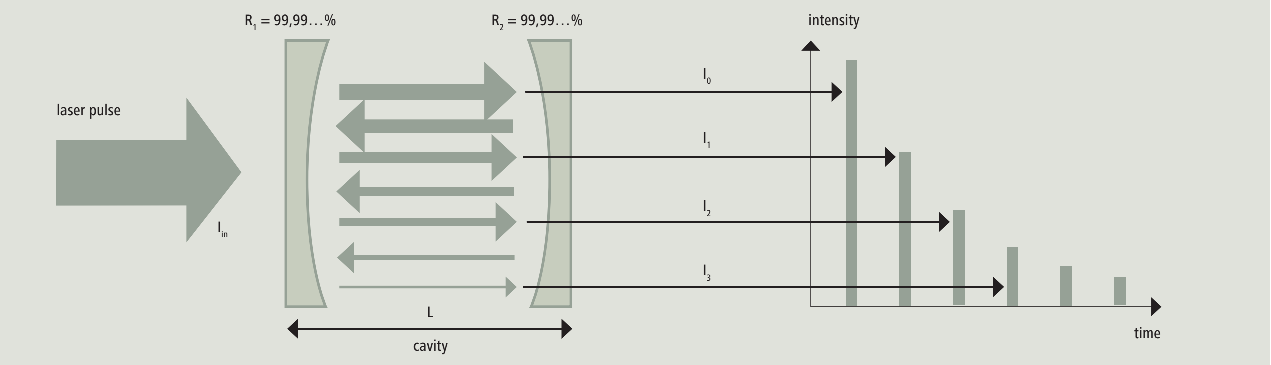


**Figure 2:** Schematic representation of the CRD method

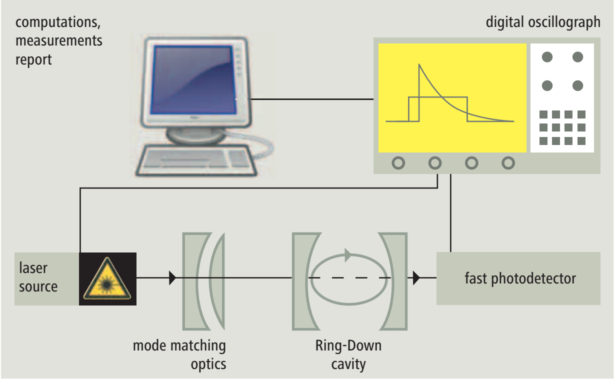


**Figure 3:** Schematic representation of a cavity Ring-Down setup

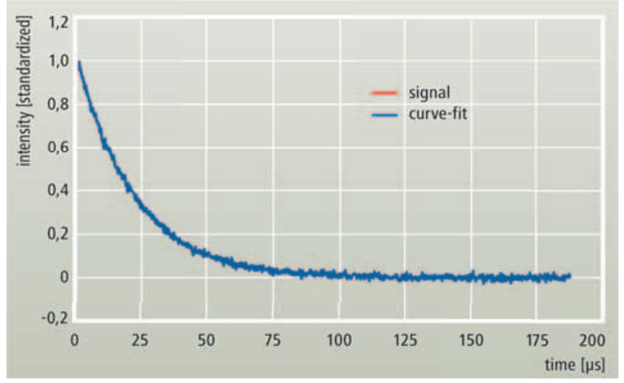


**Figure 4:** Exemplary mono-exponential CRD-curve of a highly reflecting mirror pair for 450nm with R = 99,995% measured using a resonator length L = 228mm

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

$$I_T = I_0 e^{-\left(\frac{1}{\tau}\right)t} \qquad (1)$$

with

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

where **c** is the velocity of light and ***L*** is the cavity length. **RM** is the geometric mean of the mirror reflectivities 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 mainly depends on the accuracy of the time measurement and the measuement of the cavity length. Please note that errors of beam adjustment will always lower the decay time and/or it will cause non mono-exponential Ring-Down curves. Thus, in the case of a mono-exponential decay (figure 4), stochastic errors cannot result in overstated reflectivity values. Compared to a reflectivity measurement in a spectrophotometer, CRD has two main advantages:

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

The reflectivity of single mirrors can be derived from the pairwise measurements of a triplet of mirrors. With $R_1$, $R_2$ and $R_3$ being the reflectivities of the mirrors 1, 2 and 3, respectively, and $RM_{12}$, $RM_{23}$ and $RM_{13}$ being the measured geometric means of the reflectivities for the pair of mirrors with the corresponding numbers, three measurements of mirror pairs provide

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

Solving this system of equations the mirror reflectivities can be calculated by

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

In practice this method is often used to determine the reflectivity of a set of reference mirrors. Knowing the reflectivity of a reference mirror, the reflectivity 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. Though there was the limitation that only discrete wavelengths, either generated by solid state lasers or diode lasers, were used. The increasing demands concerning the optical properties of spectrally broadband mirrors required a measurement system for a spectral range over several hundreds of nanometers with a very high accuracy for measuring high reflectivities. So LAYERTEC has developed a novel spectrally broadband Cavity Ring-Down Time measurement system in cooperation with the Institute for Physical High Technologies (IPHT) Jena e.V.*.
An optical parametric oscillator (OPO), which is pumped by the third harmonics of a Nd:YAG laser is used as light source. By the use of an additional wavelength range extension towards the ultraviolet region, a spectral measurement range from 210 – 1800nm is covered without gaps. 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 reflectivity measurements at 0° angle of incidence (Figure 5 shows such a measurement).

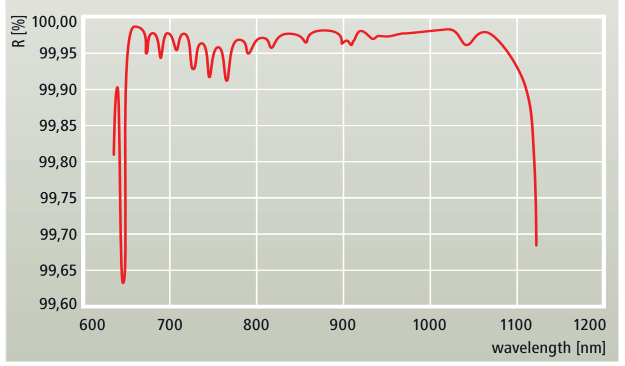


**Figure 5:** Reflectivity spectrum of a negative dispersive broadband mirror for the wavelength region 650 – 1100nm with R > 99,9%. The measurement was performed by using a simple 2-mirror optical cavity consisting of 2 identical mirrors

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* 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

The mirrors are mounted on precision rotary stages. So the setup can be used for wavelength scans at constant angle or for angle resolved measurements with a constant wavelength (see figure 6). If the reflectivity of two mirrors is known, the reflectivity of the third mirror can be calculated. When 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.

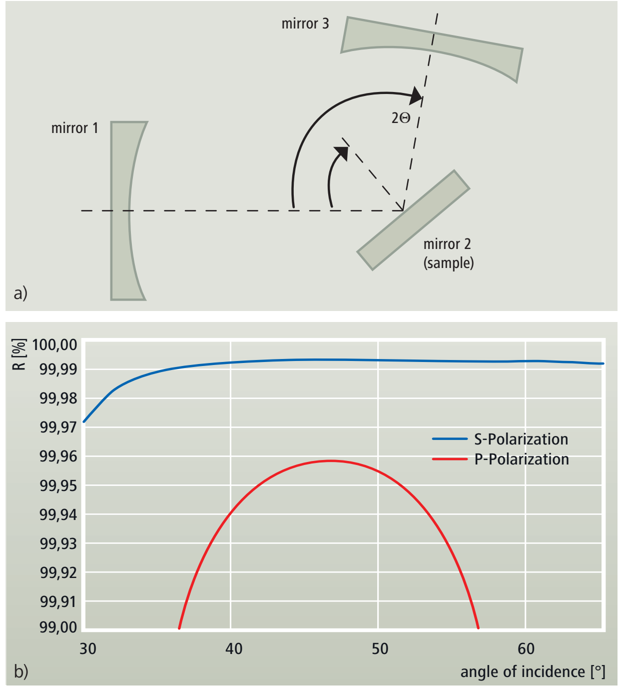


**Figure 6:** Schematic representation of a V-cavity (a) CRD reflectivity measurement with variable angle of incidence, but with fixed wavelength 1064 nm on a special separator for intra cavity frequency doubling. A V-shaped CRD cavity is used for the measurement. For the reason of analyzing the polarization dependency of the separator exactly, the measurement was performed at parallel (p-polarization) and perpendicular (s-polarization) polarization with respect to the sample (mirror 2) (b)

Furthermore the system can be used for the measurement of high transmission values T > 99,5%. For this purpose, the transmission sample is placed between both cavity mirrors. Since the sample is an additional optical loss between the cavity mirrors, the transmission value can be calculated if the reflectivity of the 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 (Figure 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 (TFP).

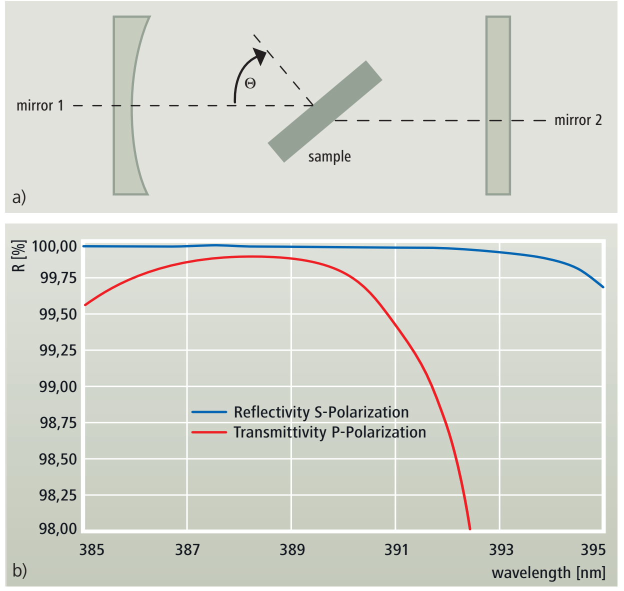


**Figure 7:** Schematic representation of a cavity for T-measurement (a), CRD measurement of TFP for 390 nm: blue curve – Rs (V-cavity), red curve – Tp (two mirror cavity) (b)

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

# LASER INDUCED DAMAGE THRESHOLD (LIDT)

Damage in cw and ns laser optics is mainly related to thermal effects such as increased absorption – either intrinsic absorption in the coating materials or absorption by defects – or poor thermal conductivity and low melting temperatures of the coatings. High power coatings require both the controlling 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. High power coatings for these lasers require very special coating designs.

The determination of the laser induced damage threshold (LIDT) according to the standards ISO 11254-1 (cw-LIDT and 1 on 1–LIDT, 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 the reason, why only a limited number of measurement systems with only a few types of lasers is available (e.g. for 193 nm, 266 nm, 355 nm, 532 nm and 1064 nm at Laserzentrum Hannover). For some of the most prominent laser wavelengths such as e.g. Argon ion lasers (488 nm or 514 nm), there is no measurement system available and no certified LIDT data can 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 comparison of different coatings and for optimization procedures. Moreover, 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) and can be interpreted as 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.

LAYERTEC has now developed its own LIDT measurement setup for in-house measurements. The aim is to optimize the coatings concerning their stability against laser damage. The light source is a q-switched Nd:YAG laser which can emit the wavelengths 1064, 532, 355 and 266 nm. The pulse duration is about 7ns and the repetition rate is 10 Hz at all 4 possible wavelengths. A gaussian shaped beam profile is generated by focusing the laser beam with a lens. The spot size is in the region of 200 µm ...700 µm (1/e² radius). The accurate value depends on the wavelength and the focal length of the lens. The setup fulfils the requirements of ISO 11254. It has an online detection system based on a digital camera with image processing to inspect the sample with respect to damage after every laser pulse. Beam profile measurements and the determination of the energy density are carried out with a CCD camera beam profiler in combination with calibrated energy measuring heads with single pulse resolution. A motorized 3-axis stage and a holder for multiple samples allow automated measurements at angles of incidence in the range of 0°...60°.

The linear polarization of the laser beam is set up to p- or s-polarization with the help of a quarter wave plate for the desired wavelength.

Generally we test our samples according to ISO 11254-2 (S-on-1). To reduce the expenditure of time, we apply only 100 or 1000 pulses at each measurement position (for a measurement example see figure 1). This is no test for longtime stability but the LIDT result after 100 or 1000 pulses is more realistic in comparison with a 1-on-1 LIDT result. Our measurements are primarily attended to compare LAYERTEC coatings among themselves for the purpose of coating and technology development. We provide 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).

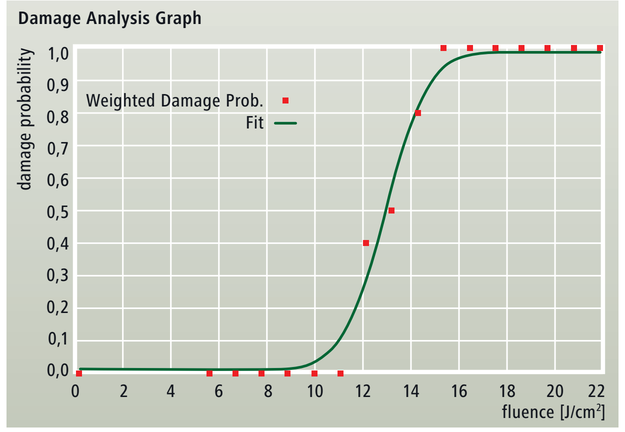


**Figure 1:** Damage probability of an anti reflection coating for 355 nm after 1000 pulses (pulse duration 7 ns, 10 Hz repetition rate) according to ISO 11254-2. This measurement was accomplished at LAYERTEC.

The LIDT values given in this catalog are own measurements but also measurements which were taken by our partners Laser Zentrum Hannover, Laser Labor Göttingen and Friedrich-Schiller-Universität Jena.

The limited number of measurement facilities and the need for lifetime tests for practical applications make it necessary to include also measurements, lifetime tests or 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 there are those without damage. Moreover, there is always an uncertainty of these values, especially with respect to the determination of the spot size. Errors in the order of about 30% must be taken into account. Nevertheless, we think that information on parameters of successful operation of our optics will certainly help to decide to use LAYERTEC optics. Sometimes, however, tests at the customers laser system will be necessary. LAYERTEC supports such tests at the customers facility by a considerable discount for the test pieces.

## GROUP DELAY AND GROUP DELAY DISPERSION

The coating design of phase optimized optical components is complex and the coatings are very sensitive with respect to fluctuations during the coating process. Thus, the verification of the phase properties is important. LAYERTEC has the ability to measure the phase properties of laser mirrors within the spectral range from 250 nm to 1700 nm. For this purpose, several measurement devices are available. These devices are working on the principle which is described by A. P. Kovács in OPTICS LETTERS / Vol. 20, No. 7 / April 1, 1995, K. Osvay, and Zs. Bor. A spectrally resolving Michelson interferometer is illuminated by a white light source (Figure 1). A mirror with negligible dispersion is placed in the reference arm. The sample mirror is placed in the other arm.

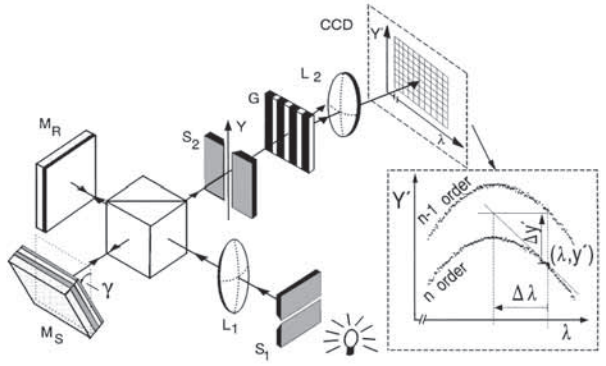


**Figure 1:** Spectrally resolved white-light interferometer for group-delay measurement of dielectric mirrors. L1, L2,achromatic lenses; S1, S2, slits; MS, sample mirror; MR, reference mirror; G, transmission grating.

Interference patterns occur on the CCD chip of a camera when the sample mirrors gets tilted (Figure 2). The interference patterns corresponding to different wavelengths are linearly dispersed in the perpendicular direction of the mirror tilt. The frequency-dependent group delay (dispersion) of the sample mirror is calculated by analyzing the intensity values of the image column by column. Figure 3 shows a GDD measurement curve of a laser mirror pair with negative dispersion over 500 nm spectral range.

**Figure 2:** Interference patterns occur on the CCD chip of a camera

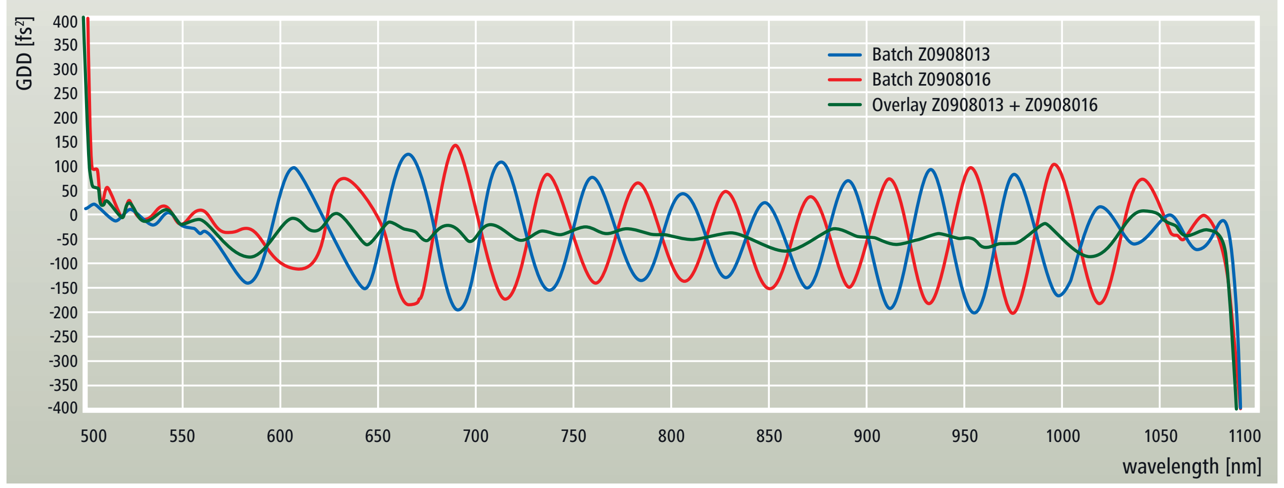


**Figure 3:** Group Delay Dispersion (GDD) measurement of a laser mirror pair for femtosecond lasers (Article 106800, Batch Z0908013-16). This mirrors have a reflectivity R > 99,7% and a GDD = -40 ± 20 fs² over the entire spectral octave in the range of 540 – 1040 nm

In comparison with common scanning measurement methods (so called Fourier Transform methods), our measurement devices have these main advantages:

- Spectral resolution in the range of 0,1 – 1nm (depending on device and wavelength)
- Short acquisition time of a few seconds for a spectral measurement range of several hundreds of nanometers

The phase sensitivity can be increased by multiple reflections on the sample mirror when folding the measurement arm of the interferometer by the use of 2 additional mirrors with negligible dispersion. This causes an angle of incidence in range of 4° – 12° (depending on device) which introduces a systematic spectral shift of the measurement. This shift is not relevant with respect to the phase properties of the sample mirror.

## DEFECT INSPECTION SYSTEM FOR COATINGS

LAYERTEC is equipped with a measurement system which counts and analyzes defects in optical coatings. The system is able to inspect coated surfaces completely and it detects defects in the dimension down to 4 µm.
Small optical components as well as large optics with a diameter up to Ø ≤ 600 mm can be analyzed. Small and 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 batch (figure 1).

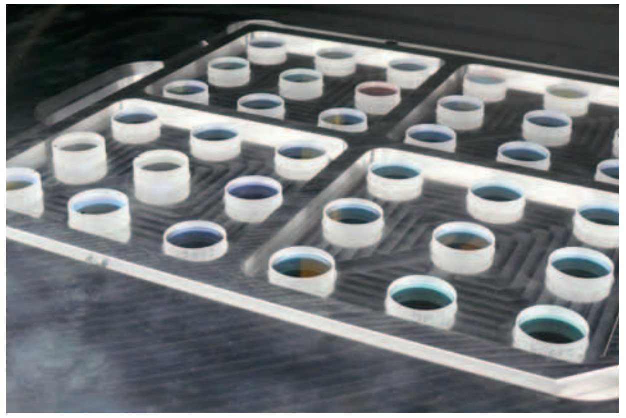
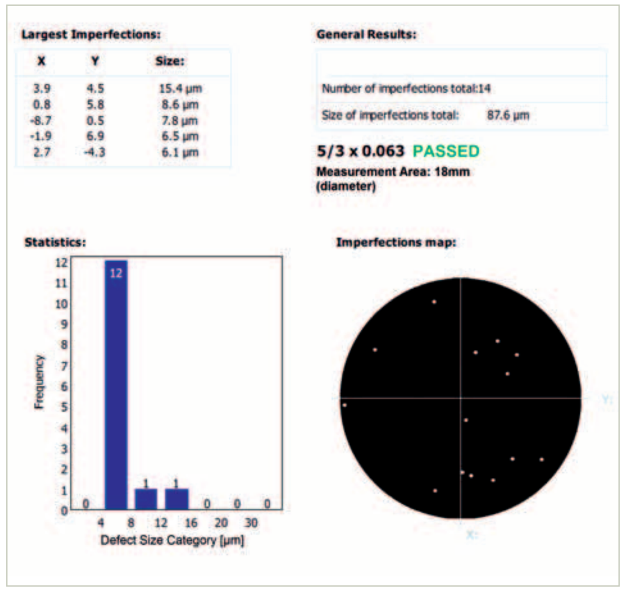


**Figure 1:** Laser mirrors are placed in a special holder magazine for automated defect inspection at LAYERTEC.

When the inspection procedure is accomplished, the defects are sized and classified according to DIN EN ISO 10110-7. Measurement reports of each inspected piece are generated. An exemplary inspection report is shown figure 2.



**Largest Imperfections:**

| X | Y | Size: |
|---|---|---|
| 3.9 | 4.5 | 15.4 µm |
| 0.8 | 5.8 | 8.6 µm |
| -8.7 | 0.5 | 7.8 µm |
| -1.9 | 6.9 | 6.5 µm |
| 2.7 | -4.3 | 6.1 µm |

**General Results:**

Number of imperfections total:14
Size of imperfections total: 87.6 µm

**5/3 x 0.063 PASSED**

**Measurement Area: 18mm (diameter)**

**Statistics:**

**Imperfections map:**

**Figure 2:** 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.

Our Defect Inspection System for coatings is able to measure optical components with standard geometries but no parts with special or infrequently appearing dimensions. For uncommon part geometries we use several microscopy inspection stations (figure 3). Besides the purpose of quality control, these microscopes can be used for the characterization of laser induced damage threshold (LIDT) samples and general inspection tasks.

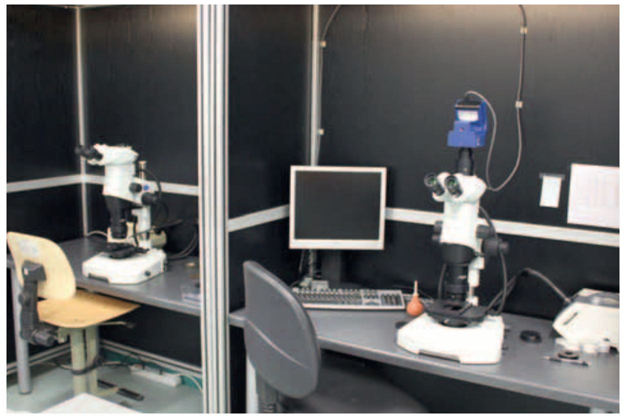
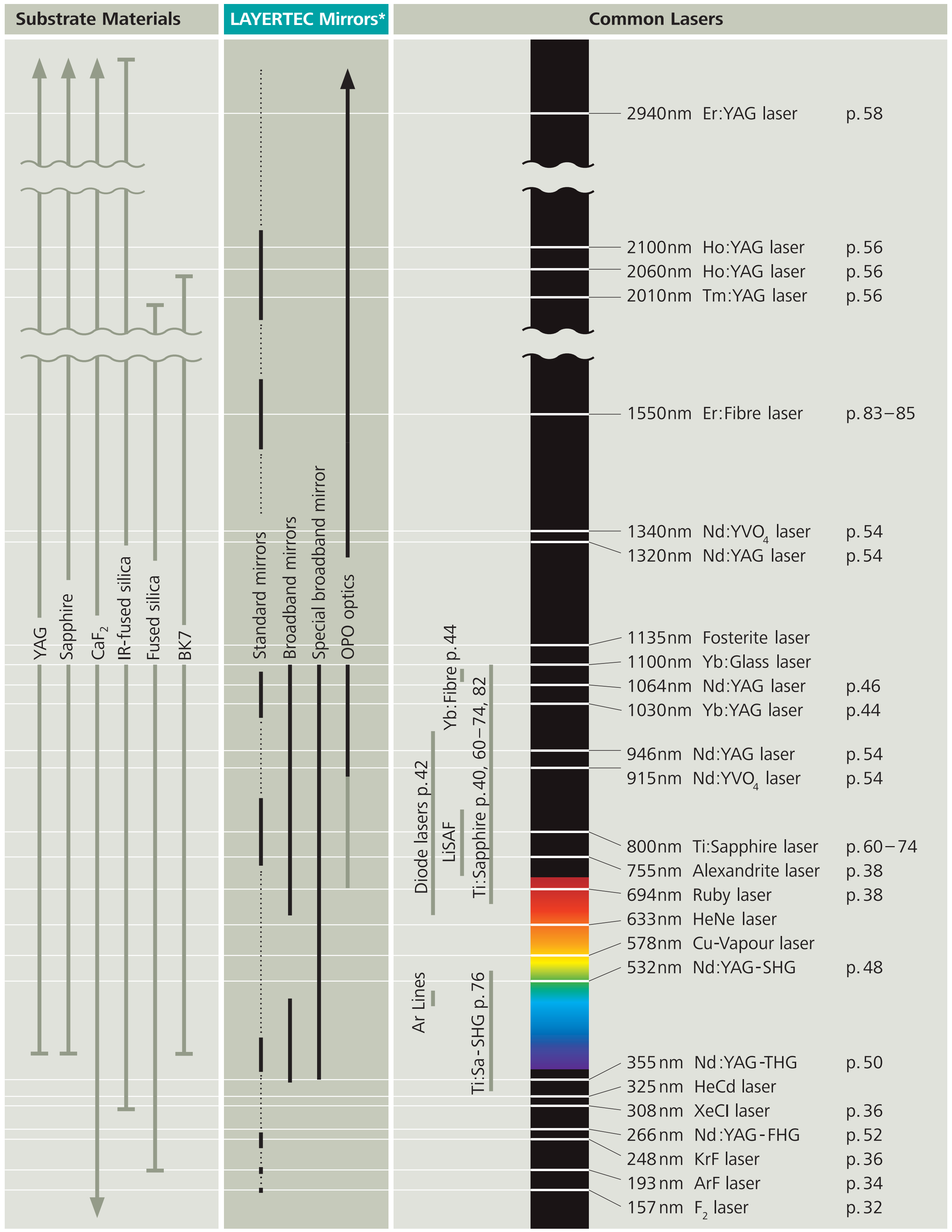


**Figure 3:** One of several microscopy inspection stations at LAYERTEC.

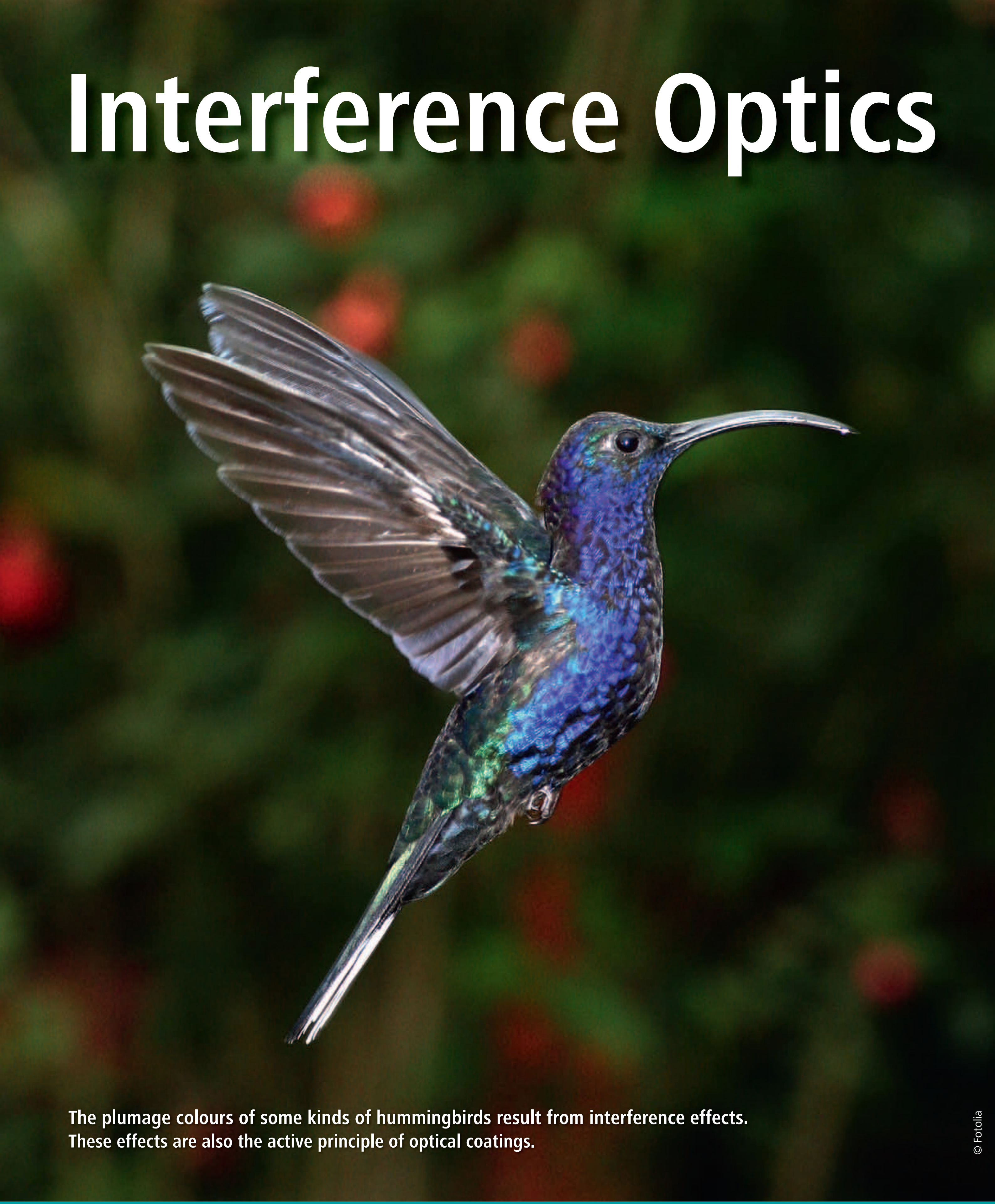
# REGISTER

# LAYERTEC MIRRORS



*Bandwidths of selected LAYERTEC mirrors

# Interference Optics



The plumage colours of some kinds of hummingbirds result from interference effects.
These effects are also the active principle of optical coatings.

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phone: +49(0)3 64 53/744-0, fax: +49(0)3 64 53/744-40
Ernst-Abbe-Weg 1, 99441 MELLINGEN, GERMANY
e-mail: info@layertec.de, internet: www.layertec.de

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