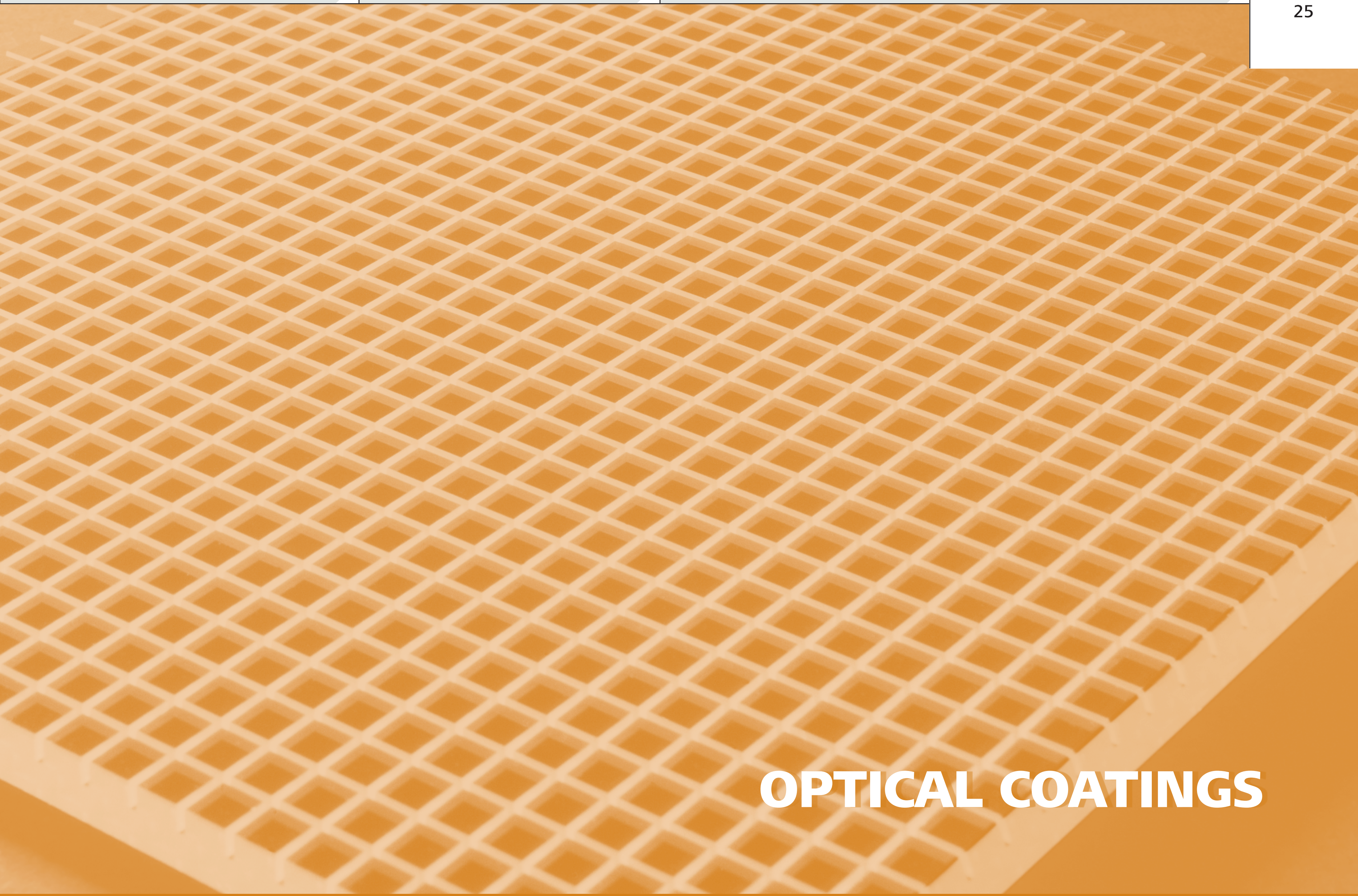


OPTICAL COATINGS

LAYERTEC®
OPTICAL COATINGS · OPTICS

CONTENTS

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)

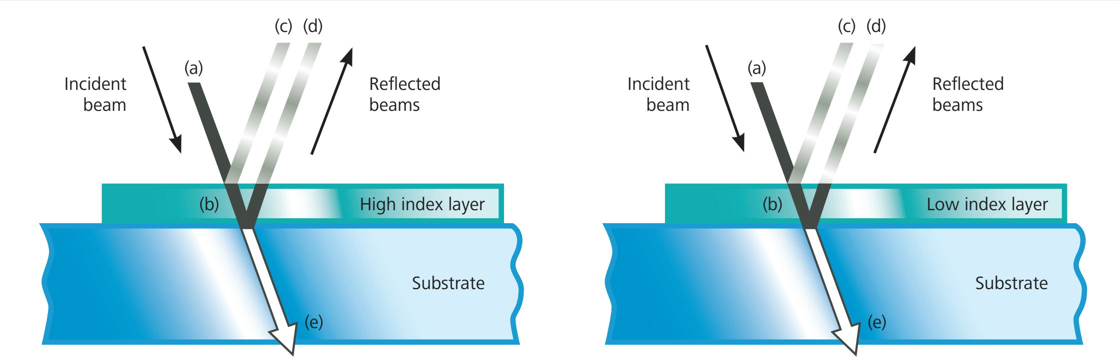


Figure 1: Schematic drawing to explain the interference effect of quarter-wave layers of a high index material and a low index material (after [1])

For normal incidence (α = 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.

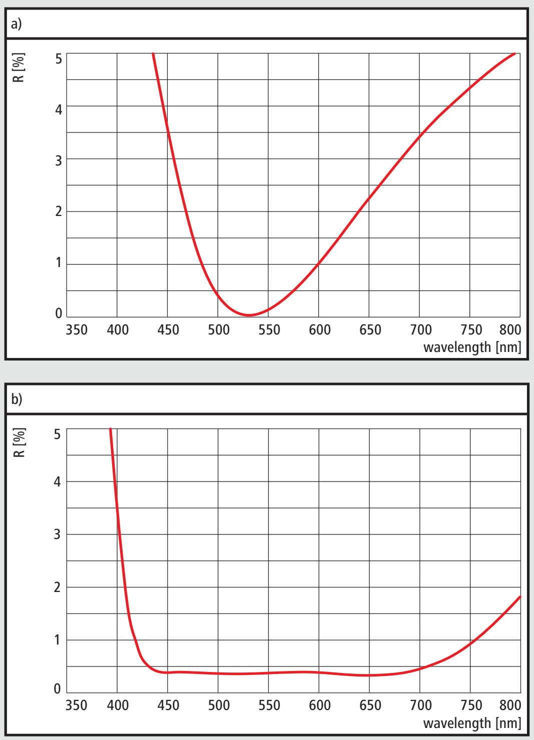


Figure 2: Schematic reflectance spectra:
a) Single wavelength AR coating ("V-coating")
b) Broadband AR coating

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.

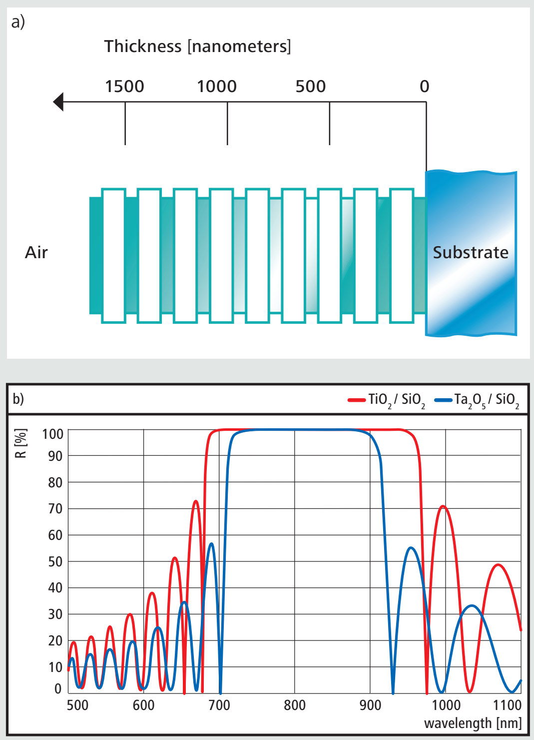


Figure 3: a) Schematic drawing of a quarter-wave stack consisting of layers with equal optical thickness of a high index material (shaded) and a low index material (no shading) (after [1])
b) Reflectance spectra of quarter-wave stacks consisting of 15 pairs of Ta_2O_5 / SiO_2 and TiO_2 / SiO_2

- 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.

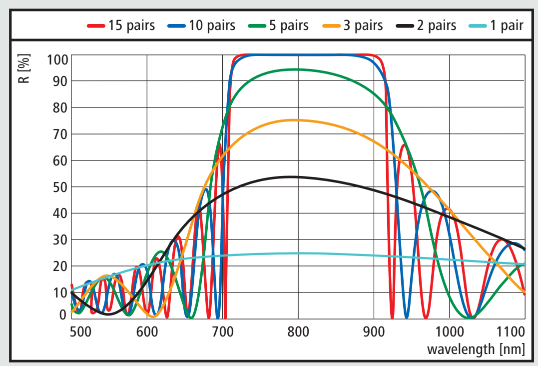


Figure 4: Calculated reflectance of quarter-wave stacks consisting of 1, 2, 3, 5, 10 and 15 layer pairs of Ta_2O_5 / SiO_2 for 800 nm

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 < λ, $S \sim 1/\lambda^4$). 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.

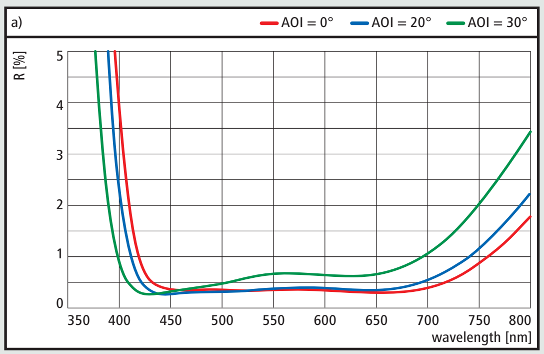
ANGLE SHIFT

- 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.



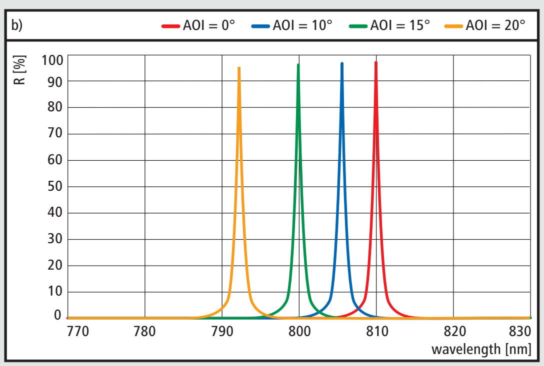
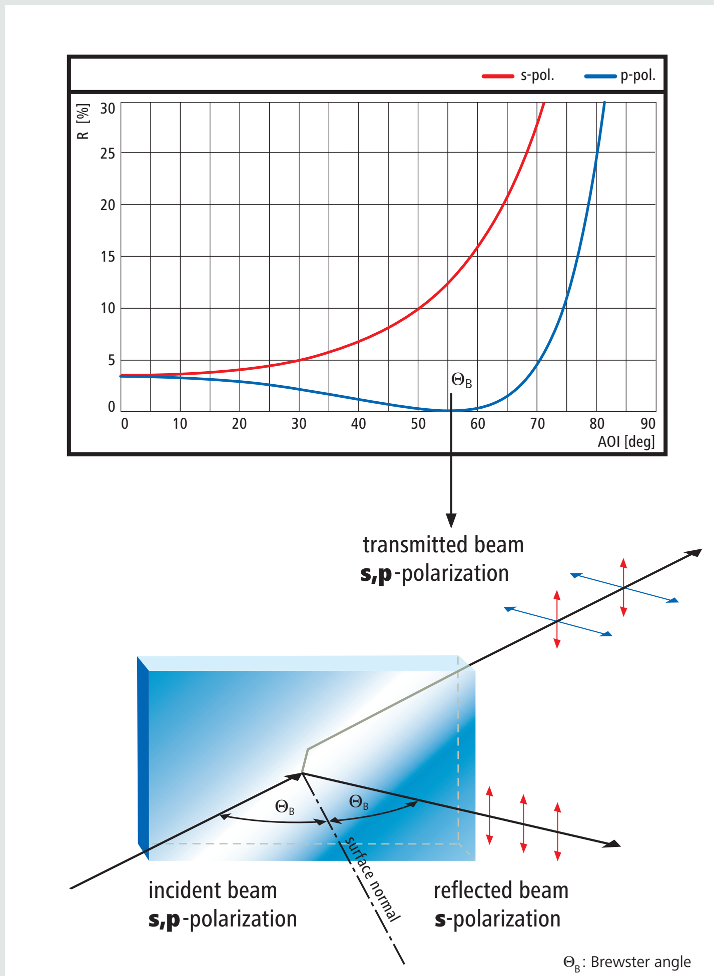


Figure 5: a) Angle shift and change of reflectance of a broadband AR coating (unpolarized light)
b) Angle tuning of a narrow band filter for 800 nm

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

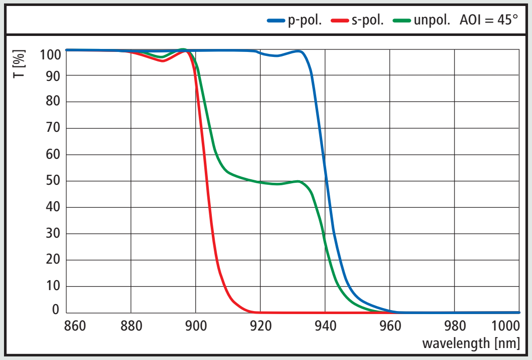


Figure 7: Polarization splitting of an edge filter. Please note that the edges of the reflectance bands are steep for s- as well as for p-polarization even at AOI = 45°, but they are located at different wavelengths. As a result, the edge of the reflectance band for unpolarized light is considerably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

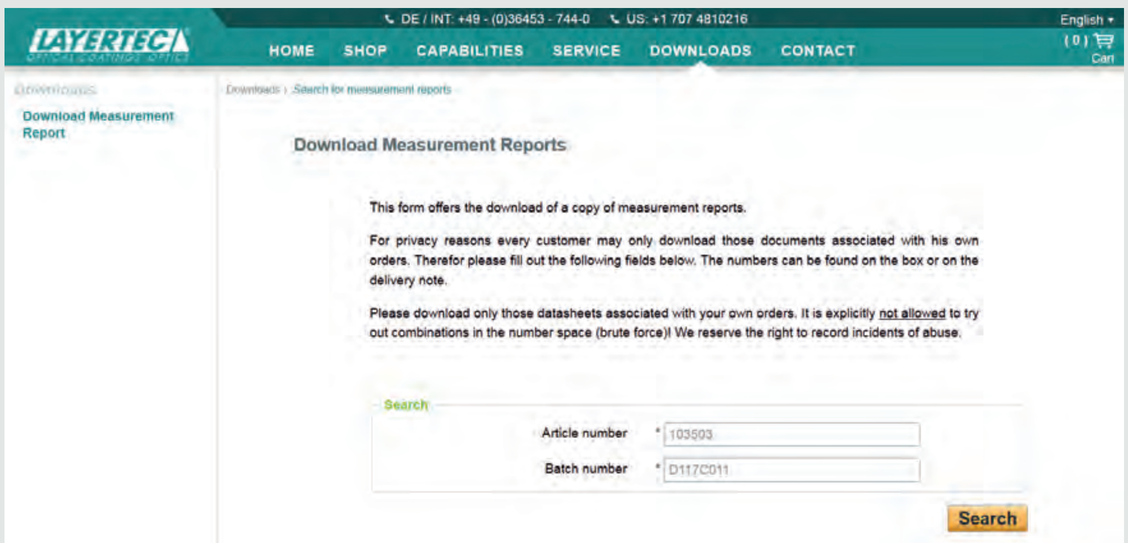


Figure 8: Download measurement report from the LAYERTEC website

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.

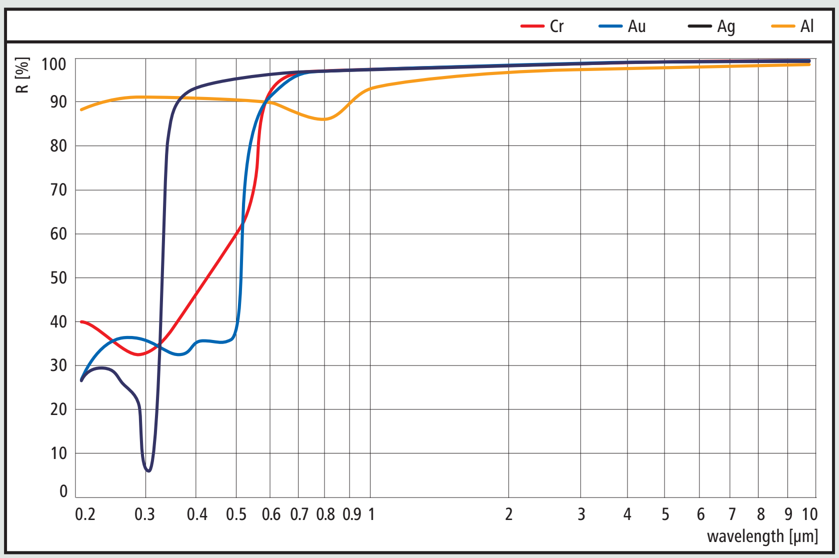


Figure 9: Reflectance of several metals versus wavelength (taken from [2])

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

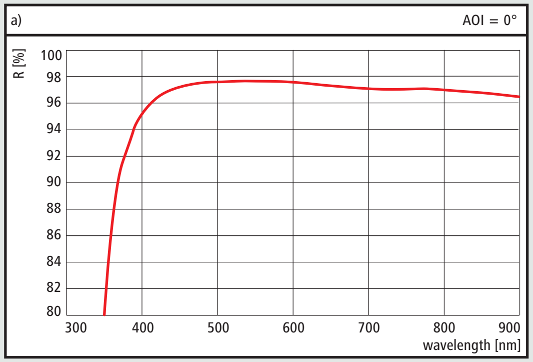
- Enable cleaning of optics and improve chemical stability.
- Influence the reflectance of the metal.
- Even very thin sputtered layers can be used for chemical protection of the metal because of the high atomic density of the layers. Such layers show minimal influence on the VIS and NIR reflectance 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.

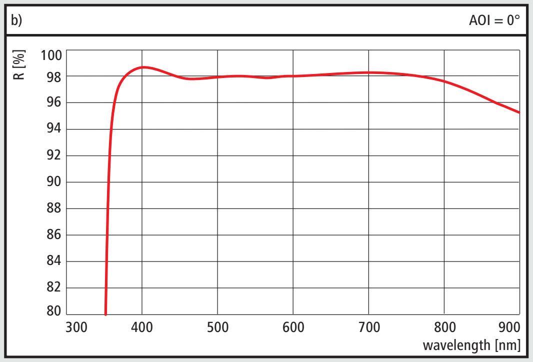
METAL-DIELECTRIC COATINGS

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.





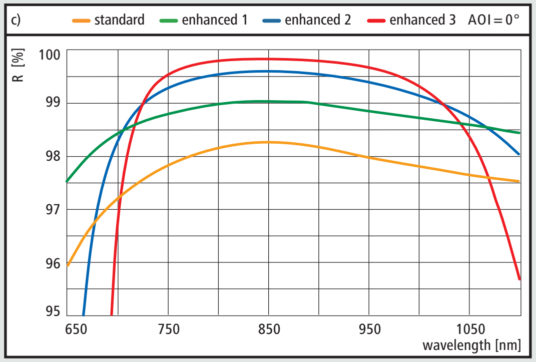


Figure 10: Reflectance spectra of silver mirrors with different top coatings
a) Protected silver mirror
b) Metal-dielectric mirror
Optimized for high reflectance in the VIS for use in astronomical applications
c) Different designs for enhanced reflectance around 850 nm (AOI = 0°) for use in fs lasers

Figure 11: Silver mirrors with D-cut geometry

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

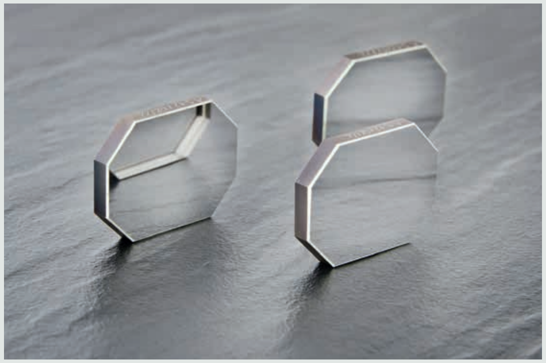


Figure 13: Scanning mirrors with customized shape coated with a metal-dielectric silver mirror

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

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.

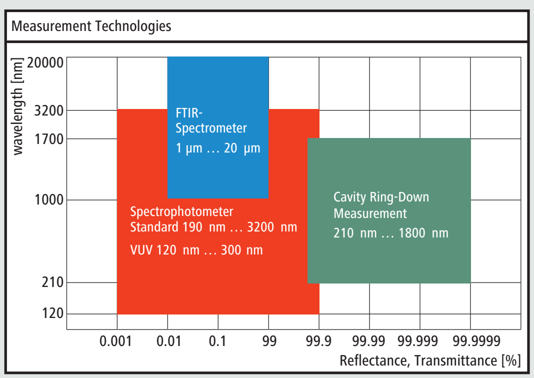


Figure 1: Measurement technologies and their range for reflectance and transmittance measurements at LAYERTEC

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.

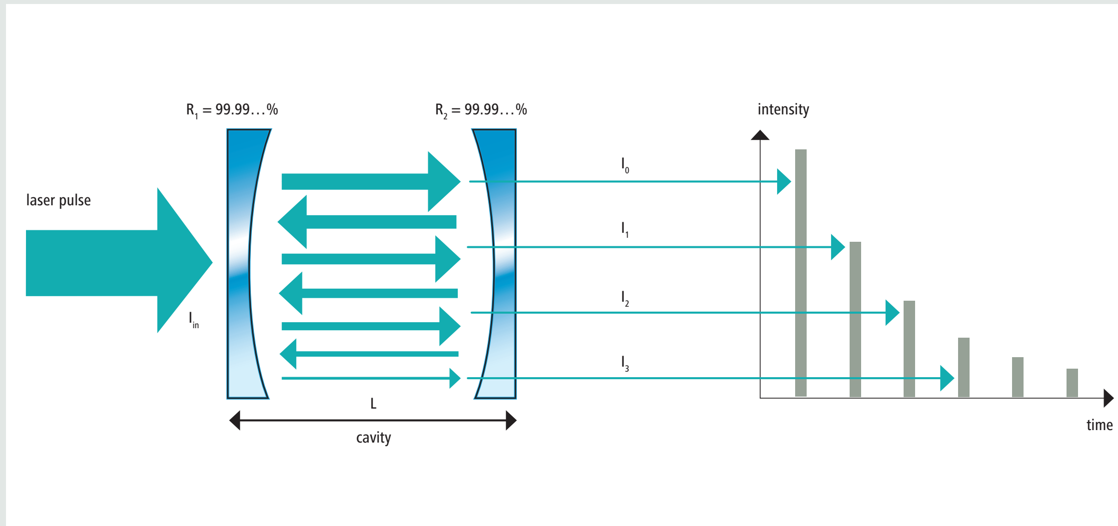


Figure 2: Schematic representation of the CRD method

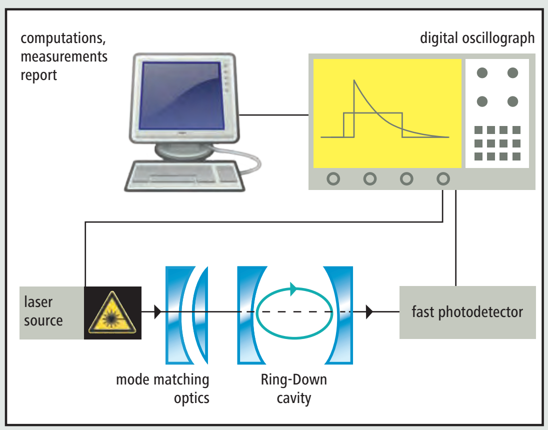


Figure 3: Schematic representation of a Cavity Ring-Down setup

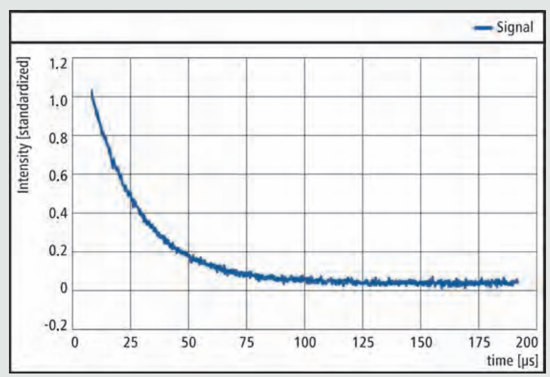


Figure 4: Exemplary mono-exponential CRD-curve of a highly reflecting mirror pair for 450 nm with R = 99.995 % measured using a resonator length L = 228 mm

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

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

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:

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

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

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

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.*.

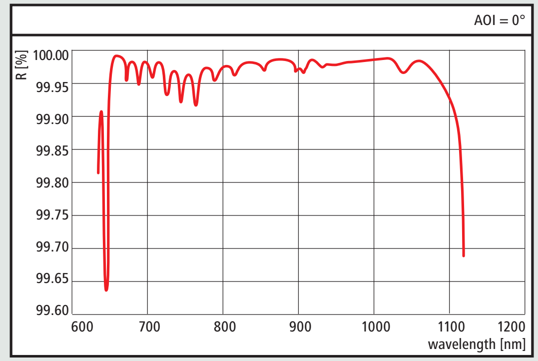


Figure 5: Reflectance spectrum of a negative dispersive broadband mirror for the wavelength region 650 – 1100 nm with R > 99.9 %. The measurement was performed by using an optical cavity consisting of 2 identical mirrors.

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.

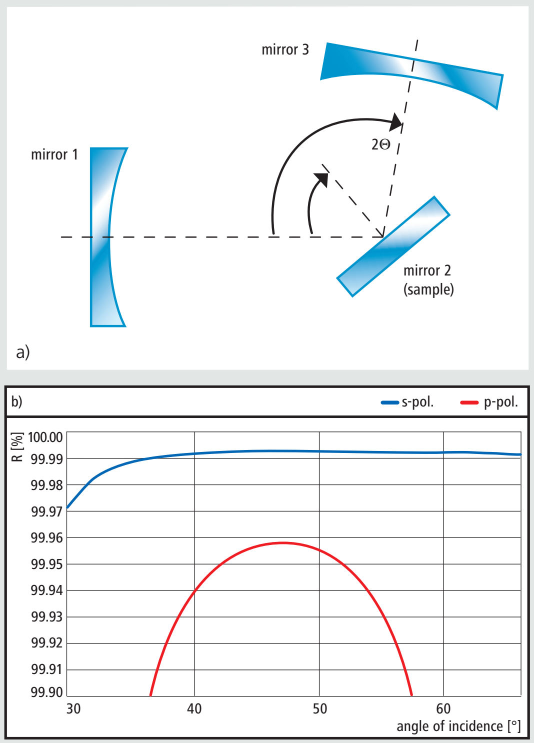


Figure 6: a) Schematic representation of a three mirror cavity ("V-cavity")
b) CRD reflectance measurement of a turning mirror for 1064 nm with variable angle of incidence, but with fixed wavelength of 1064 nm.
A V-shaped CRD cavity is used for the measurement. To analyze the polarization dependency 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).

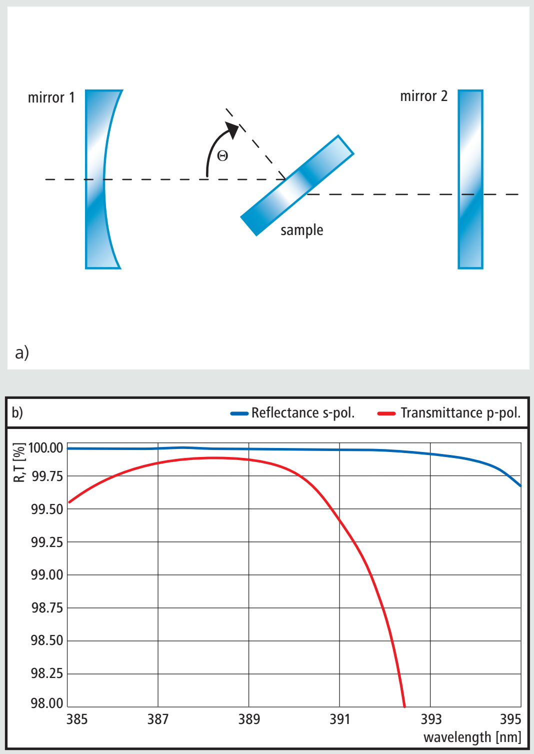


Figure 7: a) Schematic representation of a cavity for transmittance measurement
b) CRD measurement of a thin film polarizer for 390 nm: blue curve - Rs (V-cavity), red curve - Tp (two mirror cavity)

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.

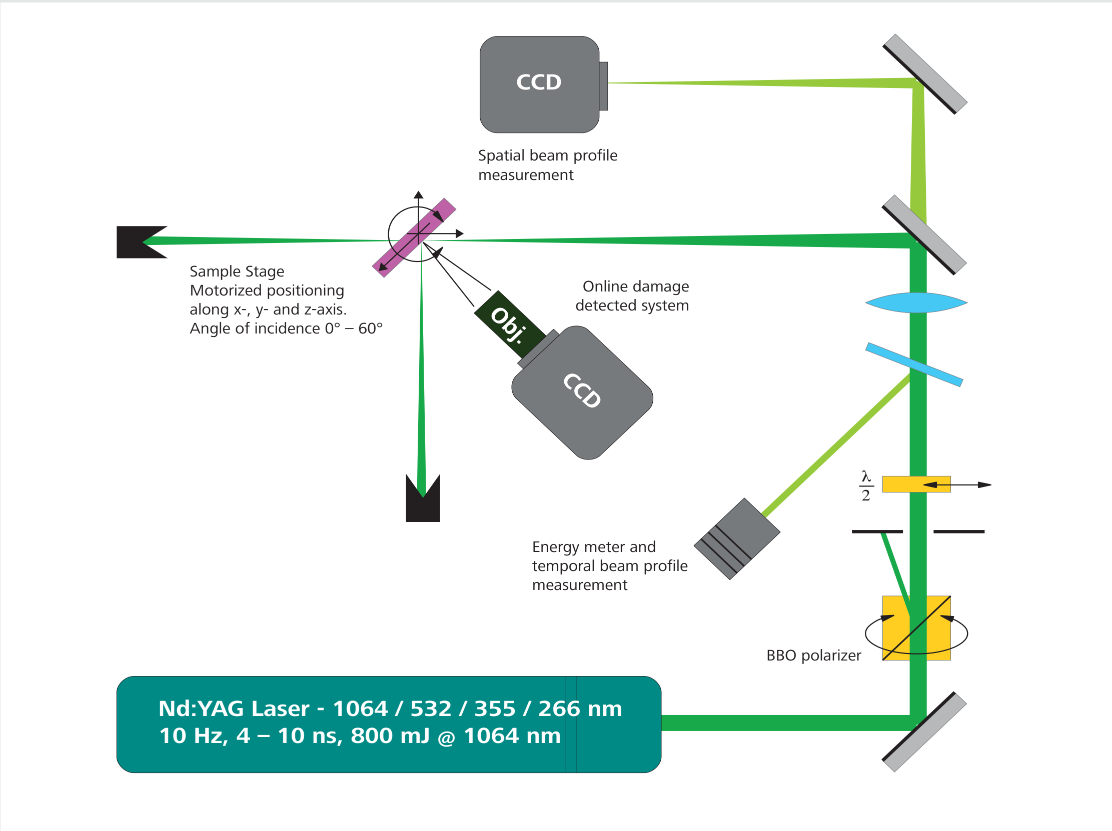


Figure 1: Nanosecond Nd:YAG Laser LIDT measurement setup at LAYERTEC.

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.

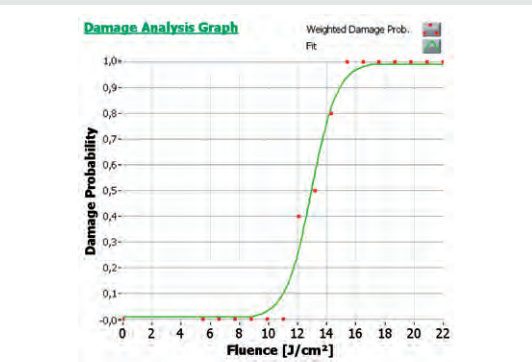


Figure 2: Damage probability of an antireflection coating for 355 nm after 1000 pulses (pulse duration 7 ns, 10 Hz repetition rate) according to ISO 11254-2.
This measurement was performed at LAYERTEC.

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.

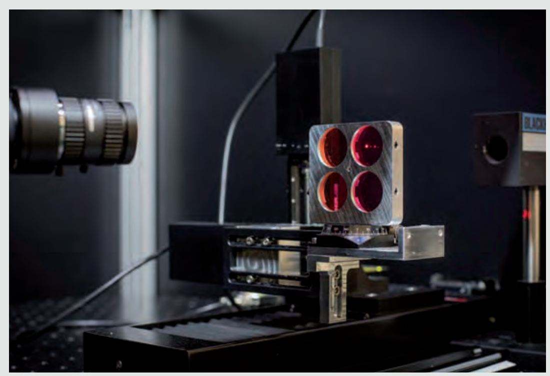


Figure 3: Sample stage of the LIDT measurement setup

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.

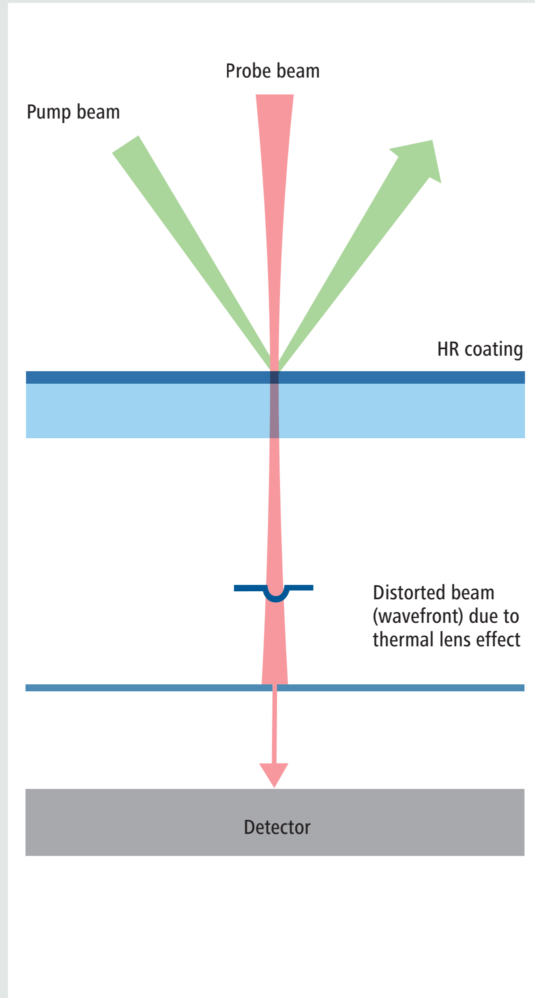


Figure 4: Schematic drawing of a common path interferometer (CPI)

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 ($1/e^2$) 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.

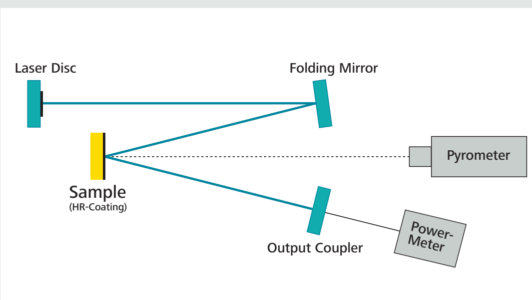


Figure 1: Intracavity heating measurement setup for HR-mirrors at 1030 nm

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 down to 6 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.

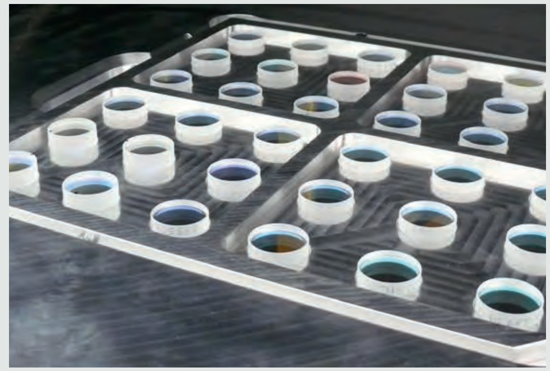


Figure 2: Laser mirrors are placed in a special magazine holder for automated defect inspection at LAYERTEC.

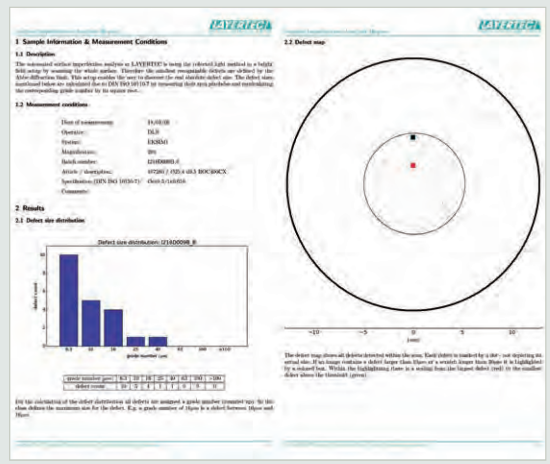


Figure 3: Simplified inspection report of a laser mirror. The report shows the sizes and the coordinates of large defects on the coated surface. Furthermore, all defects which were found are shown in a histogram plot.