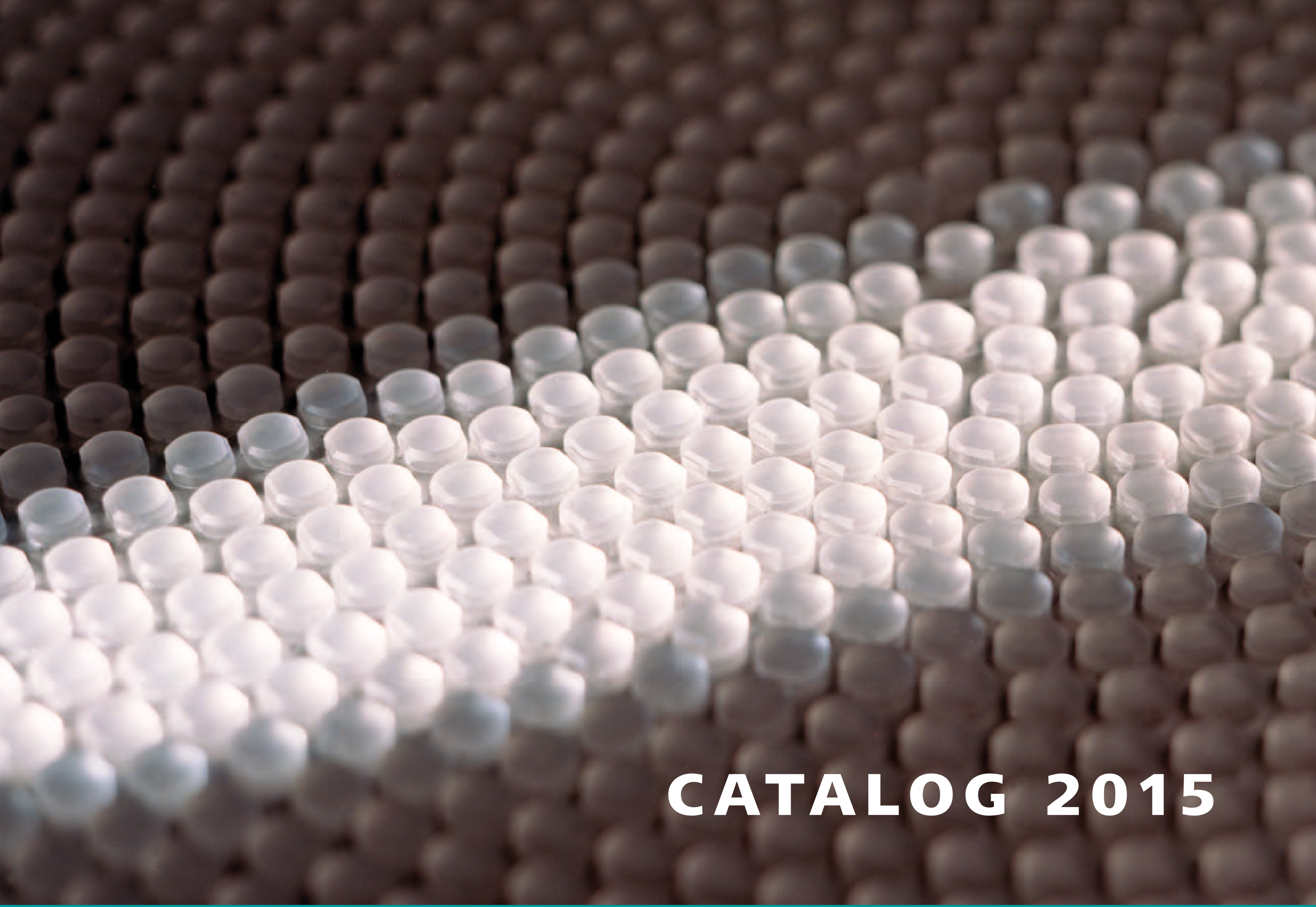

CATALOG 2015

LAYERTEC
OPTICAL COATINGS · OPTICS

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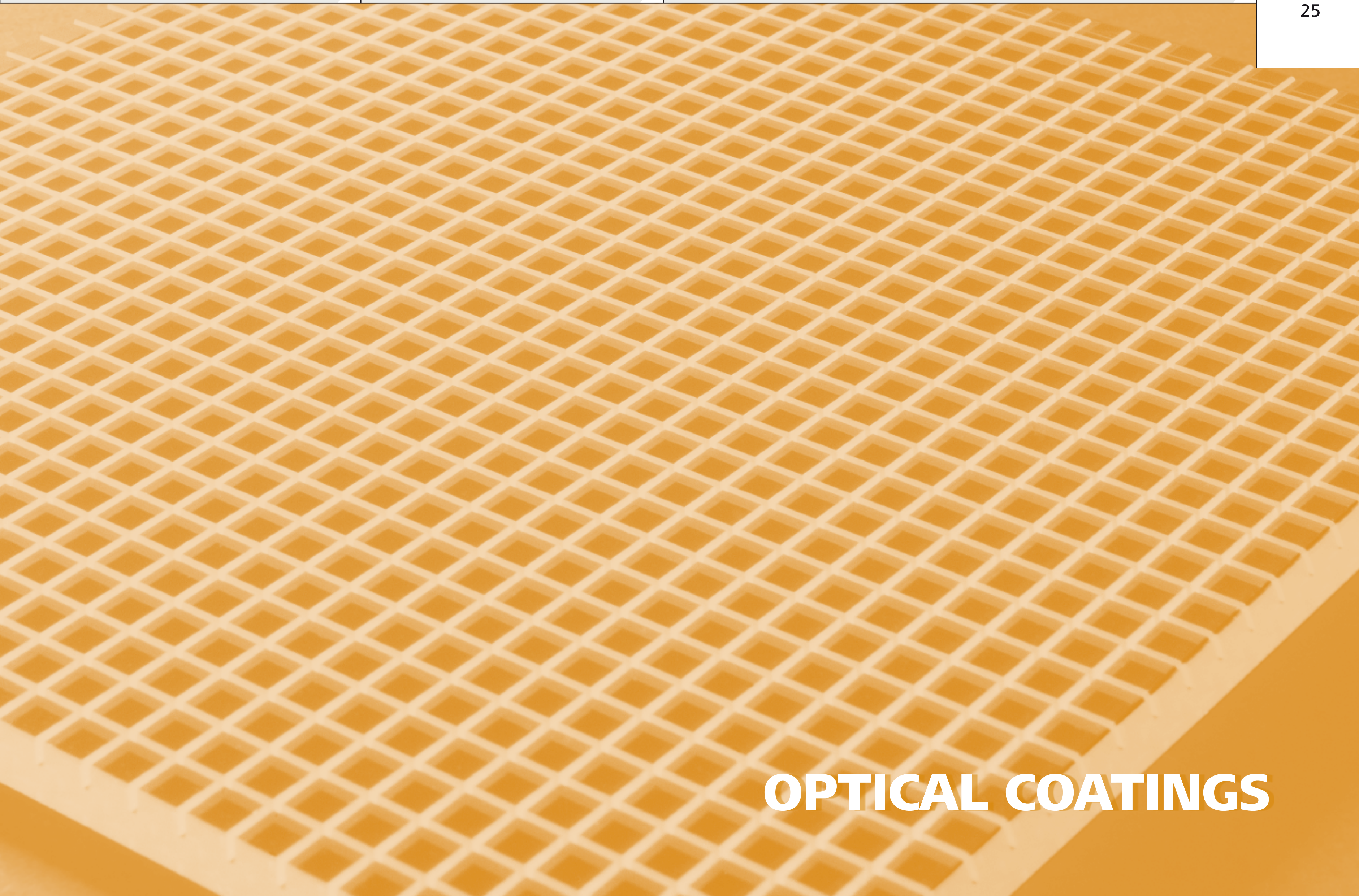


OPTICAL COATINGS

LAYERTEC®
OPTICAL COATINGS · OPTICS

OPTICAL INTERFERENCE COATINGS

The purpose of optical coatings is to change the reflectivity of optical surfaces. In principle, one can distinguish between metallic and dielectric coatings according to the materials used. Metallic coatings are used for reflectors and neutral density filters. The achievable reflectivity is given by the properties of the metal. Common metals used for optical applications are described on page 31.

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

BASICS

The influence of a single dielectric layer on the reflectivity 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 wave 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 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 ... reflectivity for s-polarization
R_p ... reflectivity 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)

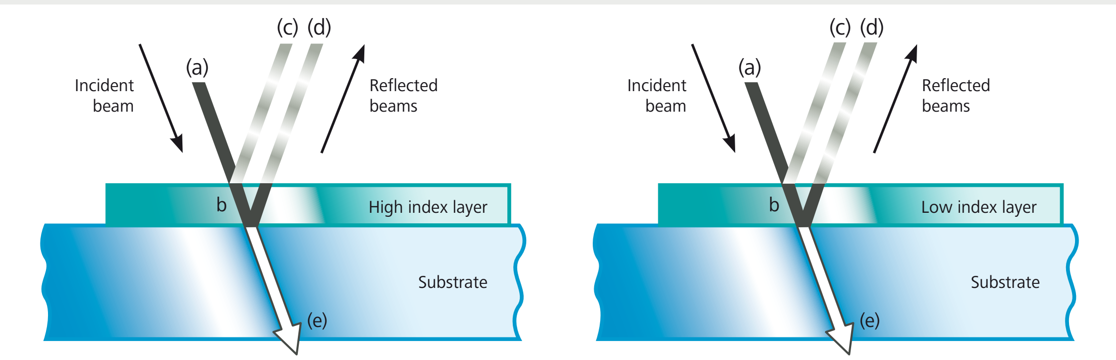


Figure 1: Schematic drawing to explain the interference effect of quarter-wave layers of a high index material and a low index material (after [1])

For normal incidence (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 $n \cdot t$ of the layer (the product of the refractive index n and the geometrical thickness t). One must take into account that a phase jump of π, i.e. one half-wave, occurs 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 our customers understand the optical properties of the coatings described in this catalog:

- High index layers always increase the reflectivity of the surface. The maximum reflectivity for a given wavelength λ is reached for $n \cdot t = \lambda / 4$. A layer with $n \cdot t = \lambda / 2$ does not change the reflectivity of the surface for this wavelength λ.
- Low index layers always decrease the reflectivity of the surface. The minimum reflectivity for a given wavelength λ is reached for $n \cdot t = \lambda / 4$. A layer with $n \cdot t = \lambda / 2$ does not change the reflectivity of the surface 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 reflectivity 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 reflectivity for the given wavelength to nearly zero. These coatings are specially used in laser physics. AR coatings for several wavelengths or for broad wavelength ranges are also possible and consist of 4 – 10 layers.

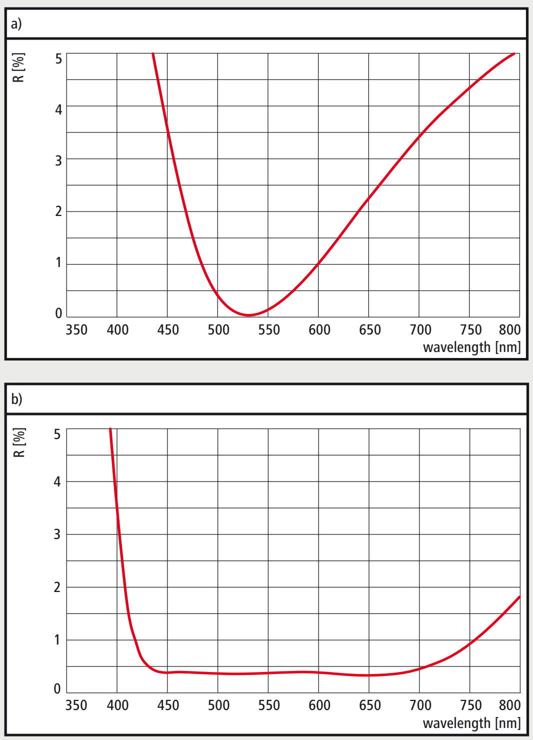


Figure 2: Schematic reflectivity spectra:
a) Single wavelength AR coating ("V-coating")
b) Broadband AR coating

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 an equal optical thickness of n · t = 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 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.

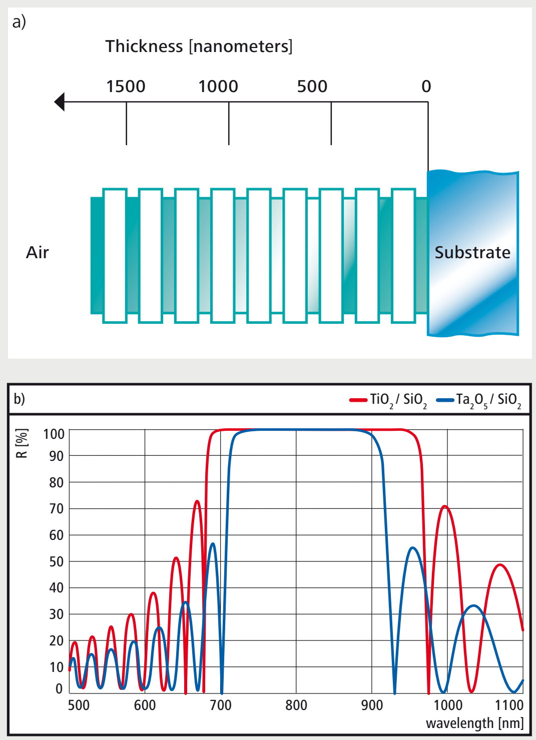


Figure 3: a) Schematic drawing of a quarter-wave stack consisting of layers with equal optical thickness of a high index material (shaded) and a low index material (no shading) (after [1])
b) Reflectivity spectra of quarter-wave stacks consisting of 15 pairs of Ta_2O_5/SiO_2 and TiO_2/SiO_2

- To visualize the effect of different refractive index ratios, figure 3b compares the reflectivity 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 reflectivity 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 reflectivity 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 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 low reflectivity side bands. Extremely steep edges require a large number of layer pairs which also results in a very high reflectivity. Extremely high reflectivity values require very low optical losses. This can be achieved by using sputtering techniques.

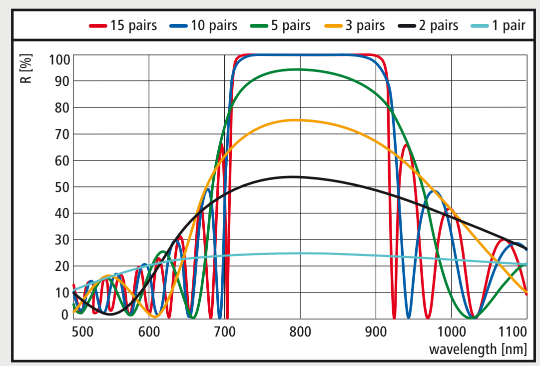


Figure 4: Calculated reflectivity of quarter-wave stacks consisting of 1, 2, 3, 5, 10 and 15 layer pairs of Ta_2O_5/ SiO_2 for 800 nm

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 … Reflectivity,
  T … Transmission,
  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 reflectivity which can be achieved depends on the absorption and scattering losses of the optics.

- Scattering losses increase drastically with decreasing wavelength, which can be described by the Mie theory (scattering by particles with diameters in the order of λ, $S \sim 1 / \lambda^2$) and Rayleigh theory (scattering by particles with diameters $< \lambda$, $S \sim 1 \lambda^4$). Depending on the surface and bulk structure, Mie and Rayleigh scattering occur simultaneously. Scattering losses are critically depending 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.

- 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	Reflectivity
~ 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: Reflectivity 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 reflectivity; however, in practice, it also increases the optical losses. There is an optimum number of layer pairs which generates the maximum reflectivity especially for evaporated coatings with relatively large 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.

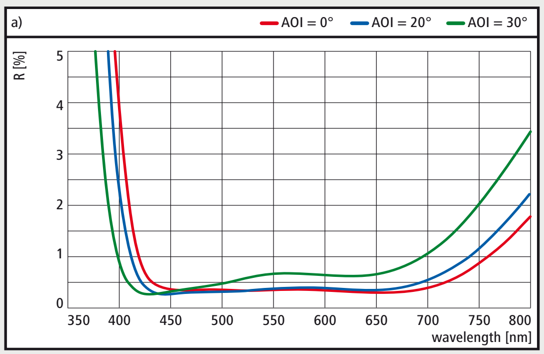
ANGLE SHIFT

- A special problem with 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 reflectivity at AOI ≥ 30° (see fig. 5a).

- The angle shift offers 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. It may decrease the output and increase the costs drastically if the specifications for wavelength and AOI are fixed. Angle tuning (see fig. 5b) is the best way to optimize the performance and to minimize the costs.



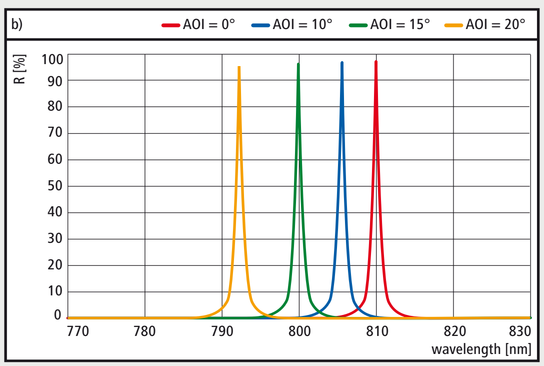


Figure 5: a) Angle shift and change of reflectivity of a broadband AR coating (unpolarized light)
b) Angle tuning of a narrow band filter for 800 nm

POLARIZATION EFFECTS

- Besides the 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 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 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 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. The reflectivity for p-polarized light decreases initially while R reaches zero percent at the "Brewster angle" and then increases again as the angle of incidence extends beyond the Brewster angle. In principle, the same applies 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 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, which results in a broadening of the edge if unpolarized light is used.

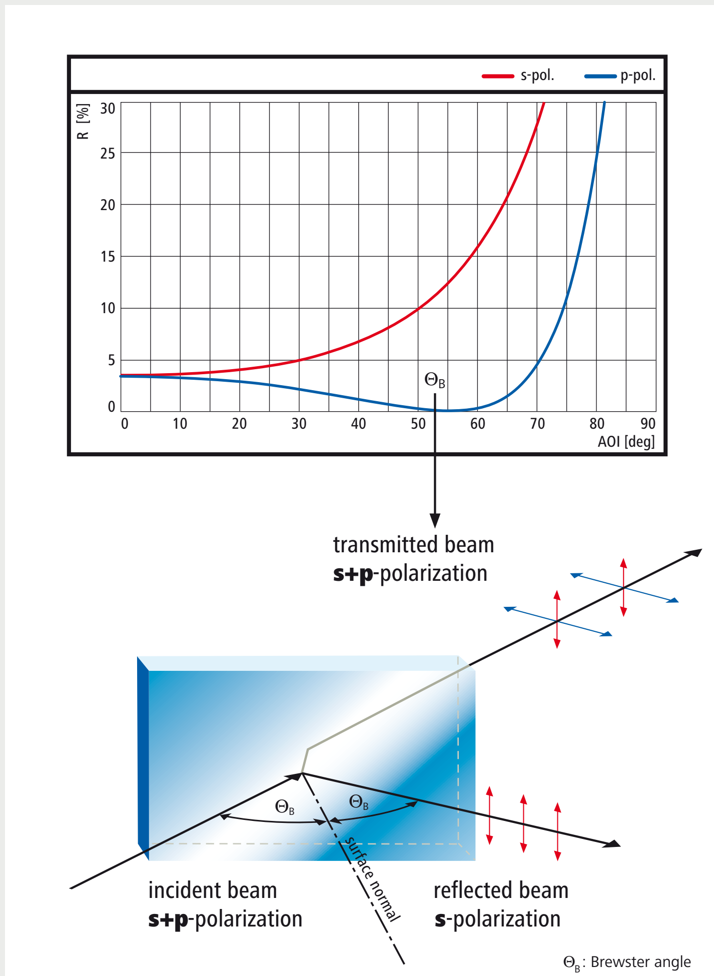


Figure 6: Definition of the terms "s-polarized light" and "p-polarized light" and reflectance of an uncoated glass surface vs. angle of incidence for s- and p-polarized light

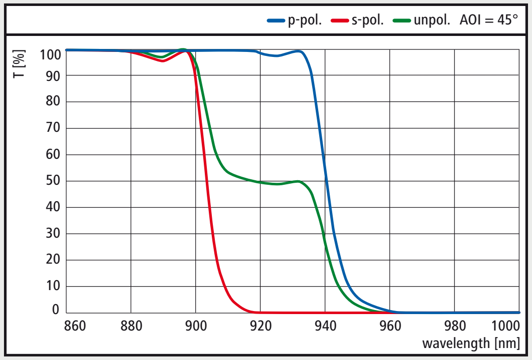


Figure 7: Polarization splitting of an edge filter. Please note that the edges of the reflectance bands are steep for s- as well as for p-polarization even at AOI = 45°, but they are located at different wavelengths. As a result, the edge of the reflectance band for unpolarized light is considerably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

DOCUMENTATION OF COATING PERFORMANCE AT LAYERTEC

LAYERTEC includes a data sheet of transmission and/or reflectivity for each delivered optical component. The standard procedure is to measure the transmission of the optics at AOI = 0°. A mathematical fit of the theoretical design to this measured spectrum is carried out and the reflectivity at the desired AOI is calculated from said measurement and fit.
Sputtered optical coatings for the VIS and NIR exhibit extremely low stray light and absorption losses (both in the order of some 10^{-5}). This has been confirmed in direct measurements of stray light and absorption as well as via highly accurate reflectivity measurements (e.g. by Cavity Ring-Down spectroscopy). The reflectivity of sputtered mirrors can be determined 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 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 %. Determining the reflectivity of sputtered coatings in the VIS and NIR via 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 are only about 1-3 x 10^{-3} and can be included into the reflectivity calculation.
In the deep UV range, the coatings usually show stray light losses on 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 reflectivity measurements. Direct reflectivity 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 reflectivity of metals is limited to 92 – 99 % (see the following paragraphs) but it can be increased by dielectric coatings. For such ultra-broadband metal-dielectric mirrors see page 109.

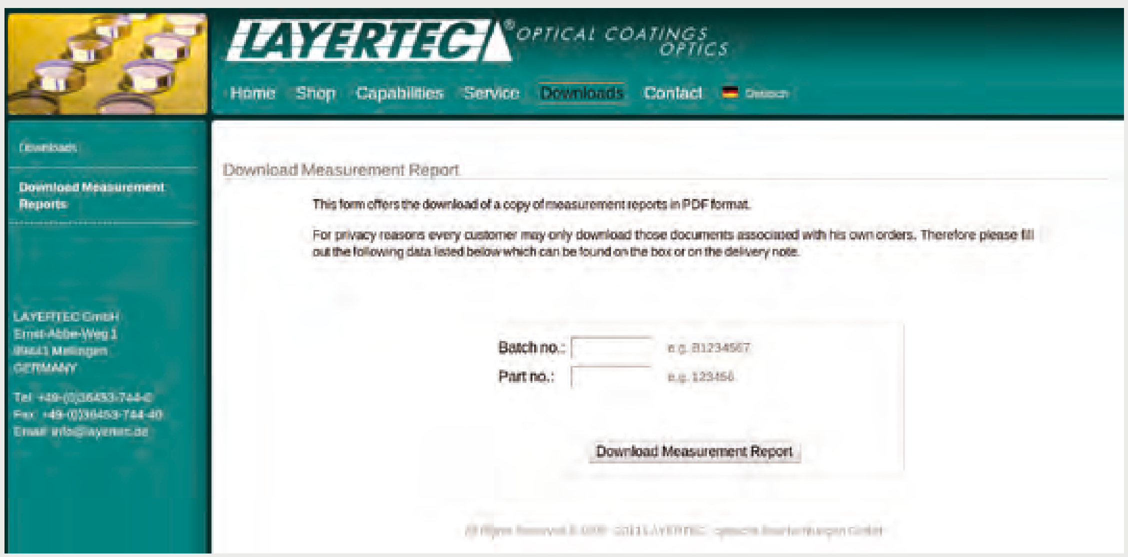


Figure 8: Download measurement report from the LAYERTEC website

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 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 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 stray light losses. 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 86 – 87 and 120 – 125.
Fig. 9 gives an overview about the reflectivity of the most common metals.

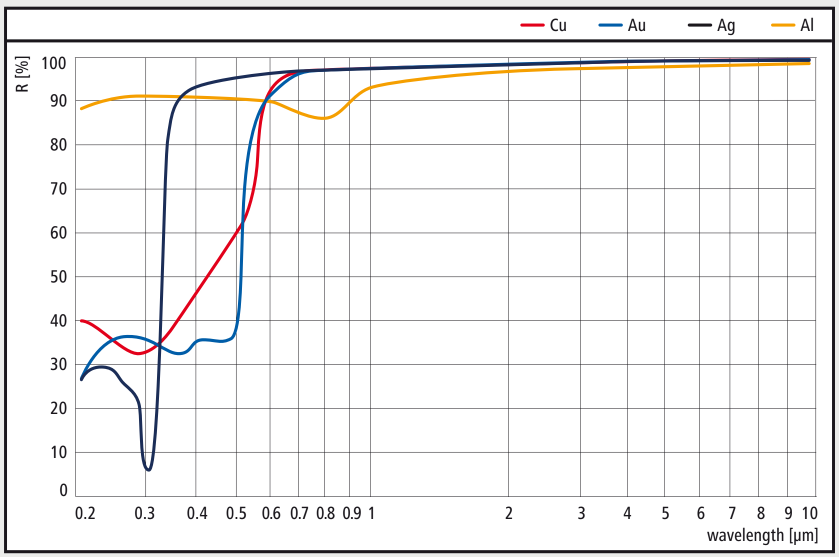


Figure 9: Reflectance of several metals versus wavelength (taken from [2])

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

SILVER

- Highest 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). 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.
- We recommend using protected silver mirrors instead of protected gold. The sputtered protective layers overcome the insufficiencies of silver. The broader wavelength range, the slightly higher reflectivity 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 reflectivity 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 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

- Enable cleaning of optics and improve chemical stability.
- Influence the reflectivity 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 to enable cleaning of optics can 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.

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 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 to metal-dielectric reflectors. Metals and metallic coatings show an extremely broadband natural reflectivity 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 reflectivity of the metals. Single dielectric layers of any thickness lower the reflectivity in most parts of the spectrum. Multilayer coatings on metals can increase the reflectivity of the metallic coating. The bandwidth of enhanced reflectivity can also be optimized for extremely broad spectral ranges as can be seen in fig. 10. For more examples please see pages 86 – 87, 108 – 109 and 120 – 123.

Literature:
[1] P. W. Baumeister "Optical coating technology", SPIE press monograph, PM 137, Washington 2004
[2] H. A. Macleod "Thin film optical filters", A. Hilger, Bristol, 1986
[3] A. J. Thelen "Design of optical interference coatings", Mc Graw Hill, New York 1989
[4] N. Kaiser, H.K.Pulker (eds.) "Optical interference coatings", Springer Verlag Berlin Heidelberg, 2003

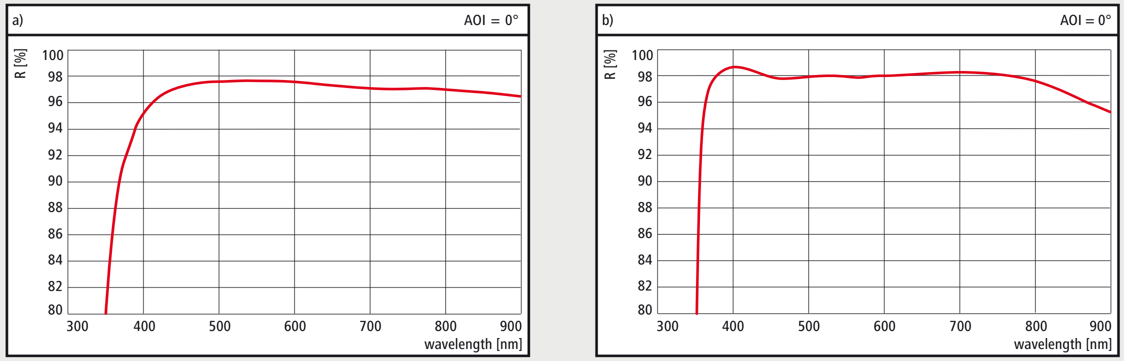
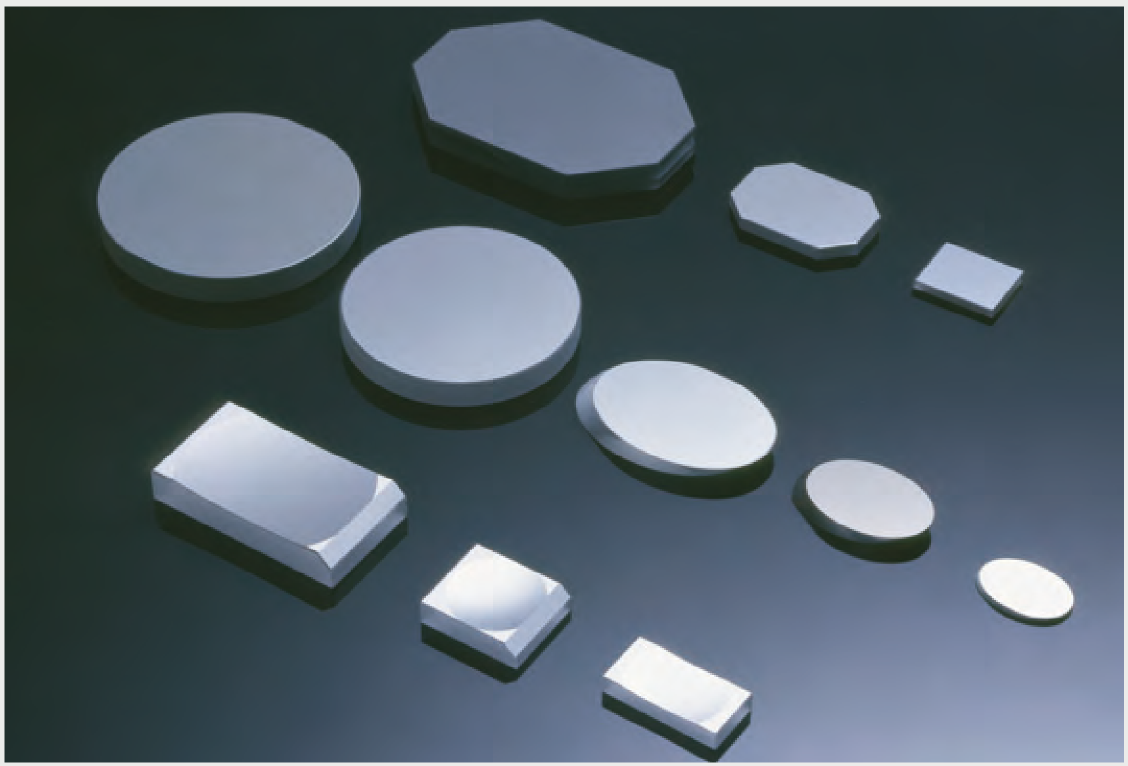


Figure 10: Reflectance spectra of silver mirrors with different top coatings optimized for high reflectivity in the VIS for use in astronomical applications a) Protected silver mirror
b) Metal dielectric silver mirror



MEASUREMENT TOOLS FOR COATINGS

SPECTROPHOTOMETRY

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

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

For measurements beyond this wavelength range, LAYERTEC is equipped with an FTIR spectrometer (λ = 1 µm – 20 µm) and a VUV spectrophoto-meter (λ = 120 nm – 240 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.

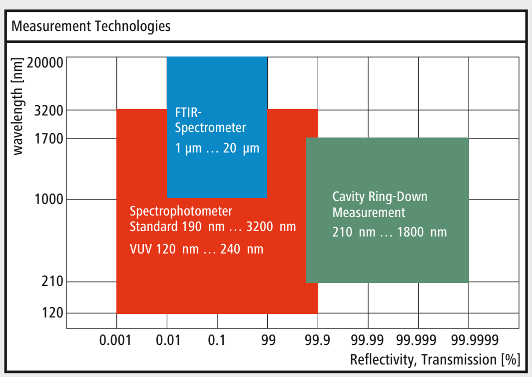


Figure 1: Measurement technologies and their range for reflectivity and transmission measurements at LAYERTEC

CAVITY RING-DOWN (CRD) MEASUREMENT

High reflectivity 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 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.

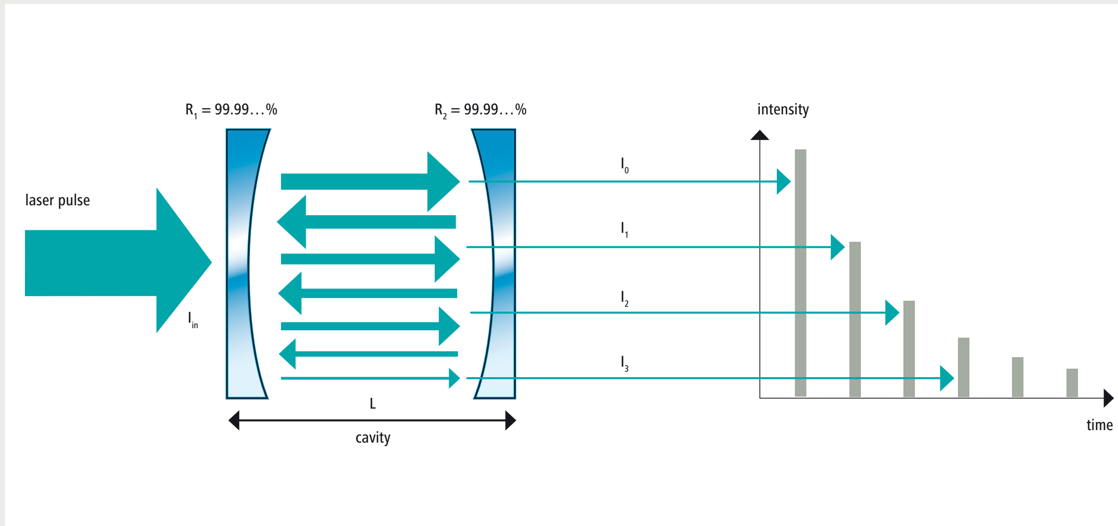


Figure 2: Schematic representation of the CRD method

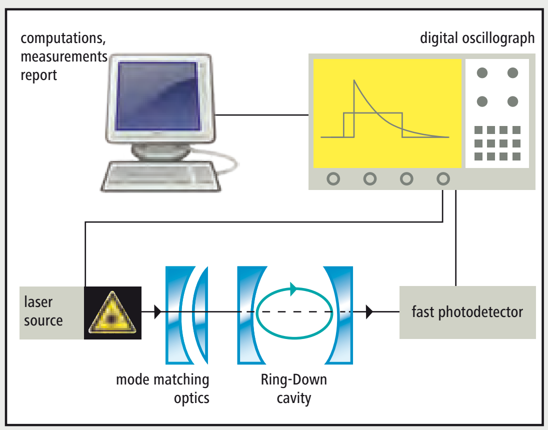


Figure 3: Schematic representation of a Cavity Ring-Down setup

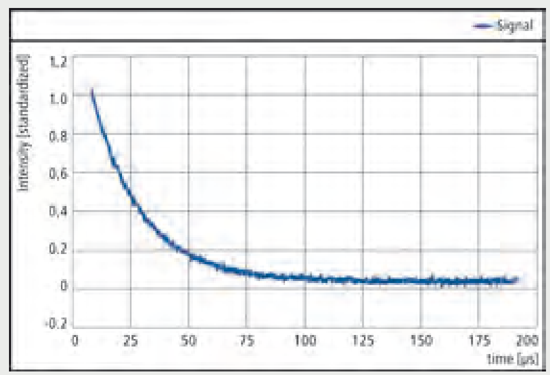


Figure 4: Exemplary mono-exponential CRD-curve of a highly reflecting mirror pair for 450 nm with R = 99.995 % measured using a resonator length L = 228 mm

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

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

with

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

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

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

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 reflectivity values. Compared to a reflectivity measurement in a spectrophotometer, CRD has two main advantages:

- It is applicable for very high reflectivity 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 pairs of measurements of a triplet of mirrors with R1, R2 and R3 being the reflectivity values of the mirrors 1, 2 and 3, respectively, and RM12, RM23 and RM13 being the measured geometric means of the reflectivity for the pair of mirrors with the corresponding numbers. Three measurements of mirror pairs provide:

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

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

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

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,

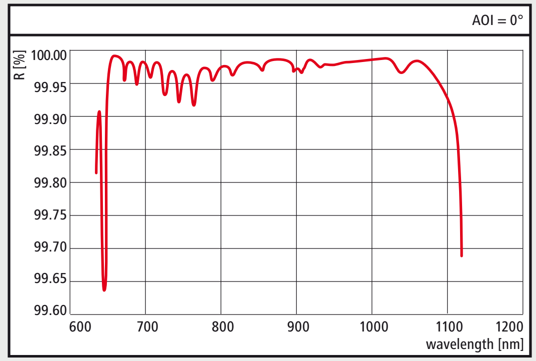


Figure 5: Reflectivity spectrum of a negative dispersive broadband mirror for the wavelength region 650 – 1100 nm with R > 99.9 %. The measurement was performed by using an optical cavity consisting of 2 identical mirrors.

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 reflectivity 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.*.

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 station 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 (Fig. 5 shows such a measurement).

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 reflectivity of two mirrors is known, the reflectivity 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.

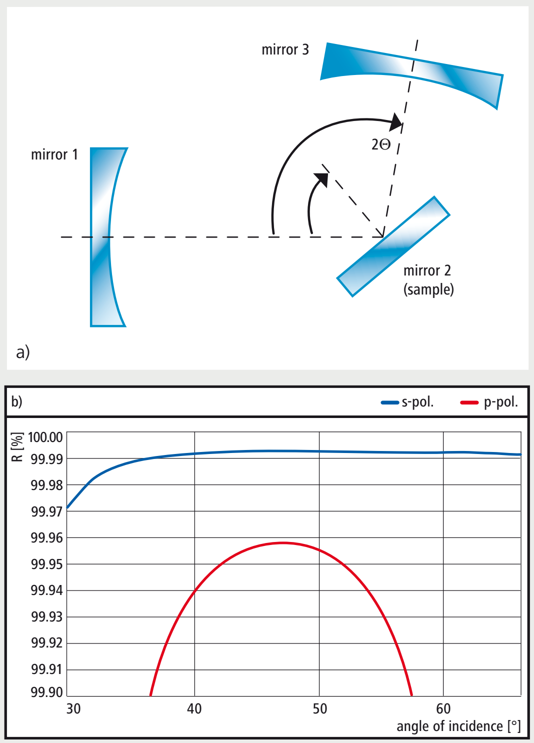


Figure 6: a) Schematic representation of a three mirror cavity ("V-cavity")
b) CRD reflectivity measurement of a turning mirror for 1064 nm with variable angle of incidence, but with fixed wavelength of 1064 nm.
A V-shaped CRD cavity is used for the measurement. To analyze the polarization dependency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

Furthermore, the system can be used for the measurement of high transmission values T > 99.5 %. Therefore, the transmission sample is placed between both cavity mirrors. Since the sample is an additional optical loss for the cavity, 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 (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).

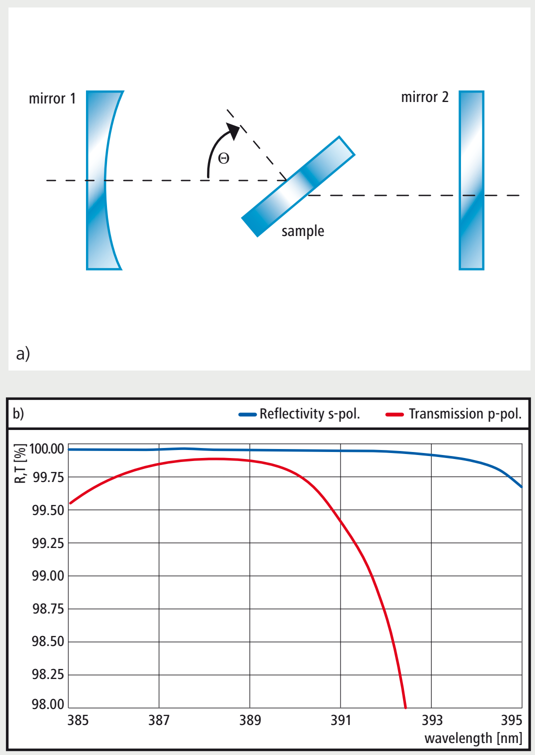


Figure 7: a) Schematic representation of a cavity for transmission measurement
b) CRD measurement of a thin film polarizer for 390nm: blue curve - Rs (V-cavity), red curve - Tp (two mirror cavity)

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. 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 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 accurate value depends on the wavelength and the focal length of the lens. The setup fulfills 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 schematically shown in fig. 1.

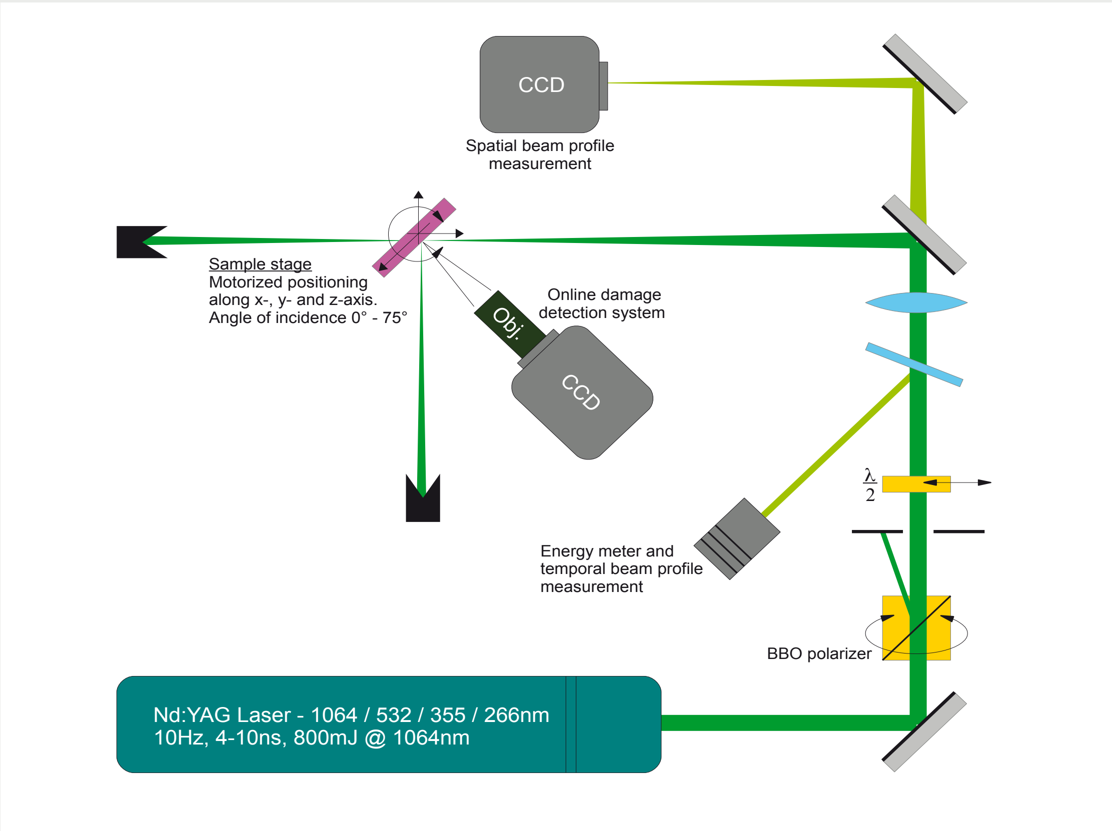


Figure 1: Nanosecond Nd:YAG Laser LIDT measurement setup at LAYERTEC.

LAYERTEC tests samples by using its own procedure (please see next paragraph "LAYERTEC LIDT Testing Procedure..."), because the ISO standards deliver wrong values for damage thresholds higher than 30 J / cm². If there is an explicit request for a measurement according to ISO 11254-2, we have the ability to do this. In this case, we apply only 100 or 1000 pulses at each measurement position to minimize the measurement time:

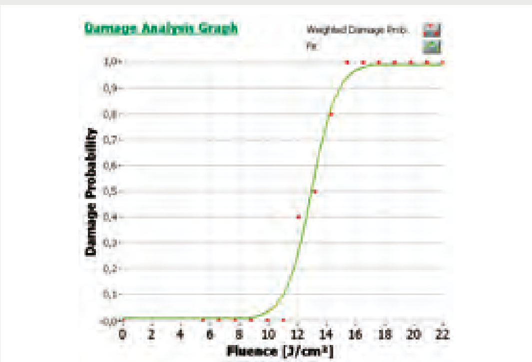


Figure 2: Damage probability of an antireflection coating for 355 nm after 1000 pulses (pulse duration 7 ns, 10 Hz repetition rate) according to ISO 11254-2.
This measurement was performed at LAYERTEC.

This is not a 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 intended 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).

LAYERTEC LIDT TESTING PROCEDURE FOR PULSED LASER SOURCES

During the last two years, LAYERTEC has gained a lot of experience in laser damage testing by utilizing the LIDT testing procedures according to ISO-11254 standards. It became clear that the measurements are both cost and time intensive but often only deliver 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, we use a relatively large Gaussian-shaped laser spot to measure the damage threshold of our coatings. 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 appropriate fluence which causes destruction of the testing position. 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 position 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. According to our experience, 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. We observe 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. The main reason for this phenomenon are imperfections in the coating and sometimes the surface quality itself, assuming that the influence of debris can be neglected. Contrary to ISO standards, significant low threshold values must 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 our coatings with high damage thresholds. We developed our own 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 values are subdivided into 50 energy classes. For the most part, 100 laser pulses are applied at each energy class 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.

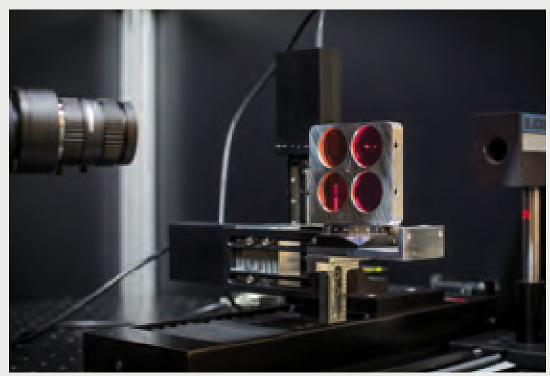
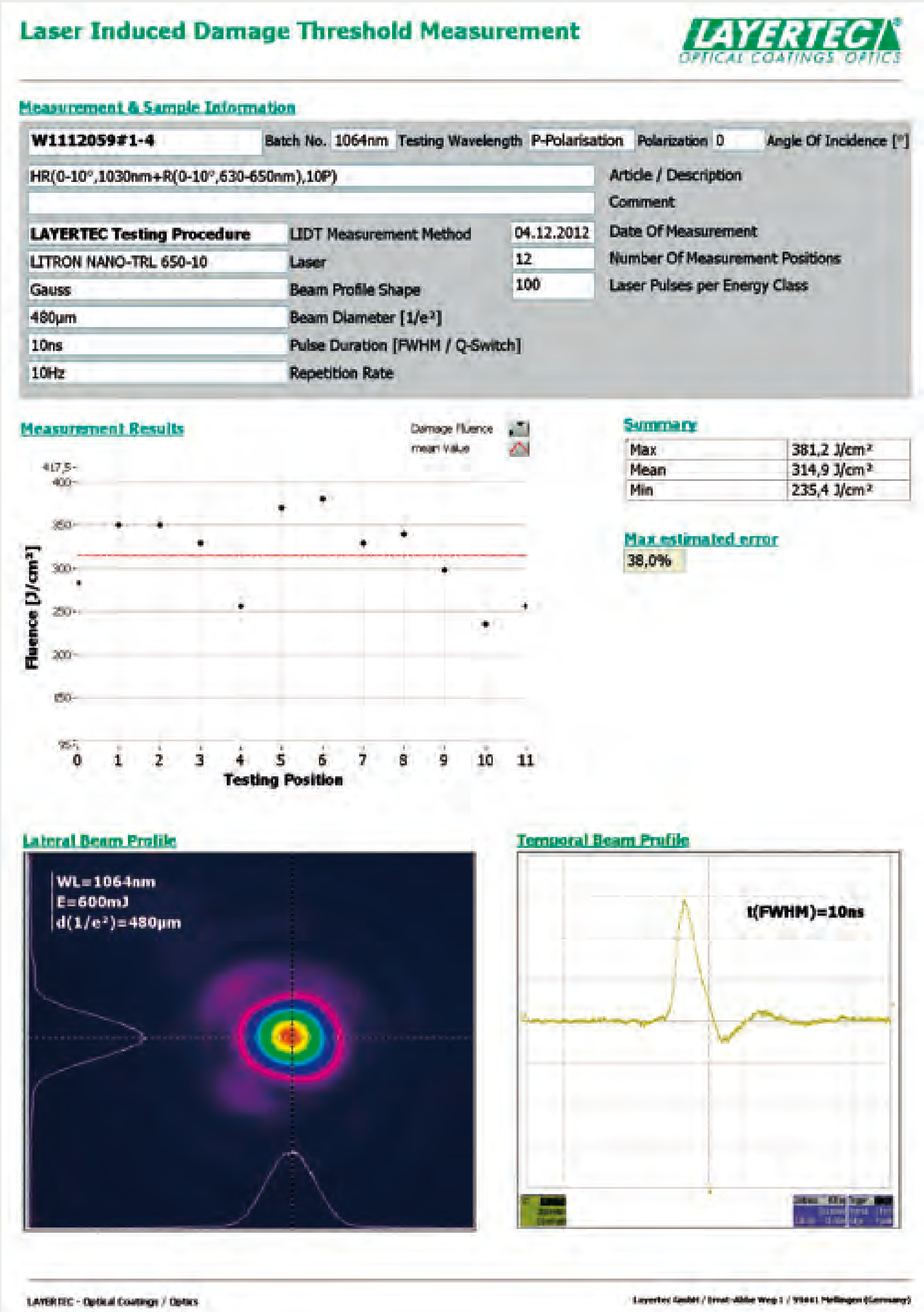


Figure 3: Sample stage of the LIDT measurement setup



In this way all positions on the sample are irradiated until every position exhibits damage. For the purpose of measurement analysis, the highest, the average and the lowest measured damage threshold are reported. A further statistical analysis is not carried out. An example of a LIDT measurement report is shown in fig.4. All damage threshold values measured at LAYERTEC GmbH, which are stated in this catalog, are determined according to the LAYERTEC LIDT testing procedure for pulsed laser sources.

The LIDT values given in this catalog are our own measurements but also measurements which were taken by our partners 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. Still, we think that information about parameters for long life time operation of our optics will certainly help to decide 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 the test pieces.

Figure 4: Exemplary of LIDT measurement report

INTRA CAVITY HEATING MEASUREMENT SETUP

Absorption losses in optical coatings lead to the heating of the coating and the substrate. At an average laser power of several kilowatts (cw) and higher, even low absorption losses in the range of some parts per million cause significant heating of the optical component. LAYERTEC has built a heating measurement setup for the purpose of quality assurance and technology development 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 and a second folding mirror, the output coupler, a laser power meter and a pyrometer for the temperature measurement on the sample. The beam spot size on the irradiated sample surface area is 1.5 mm (1 / e²) in diameter. A very high intracavity laser power of about 120 kW (cw) is achieved by choosing an output coupler with a relatively low transmission value. Under these conditions, the power density on the sample is approximately 15 MW / cm².

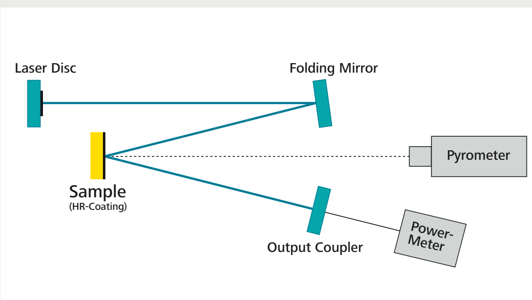


Figure 1: Intracavity heating measurement setup for HR-mirrors at 1030 nm

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.

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 accomplished 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 to count and classify defects in optical coatings. The system is able to inspect the whole surfaces. It detects defects down to 4 µm in size. Both, small and large optical components 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 to run in a single inspection (fig. 2).

Measuring small defects is very challenging because the necessary microscope objectives have a very short depth of focus and require a precise adjustment and positioning. Another important factor is the proper lighting. Depending on the geometry of the defect, it can only be seen when it is illuminated in a certain angle.

Finally, our wide range of different geometries demands a very flexible controller software, quick in adapting to new geometries to avoid collisions between the sample and the test system.

We constantly improve the system, enabling it for the inspection of cylindric and aspheric optics while reducing effort and measurement time.

When the inspection procedure is accomplished, the defects are classified by size according to DIN EN ISO 10110-7. Measurement reports of each inspected piece are generated. An exemplary inspection report is shown in fig. 3.

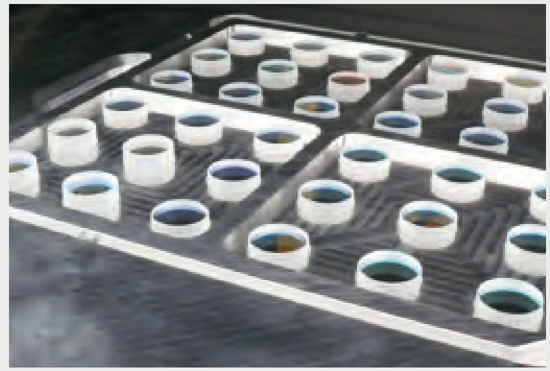


Figure 2: Laser mirrors are placed in a special magazine holder for automated defect inspection at LAYERTEC.

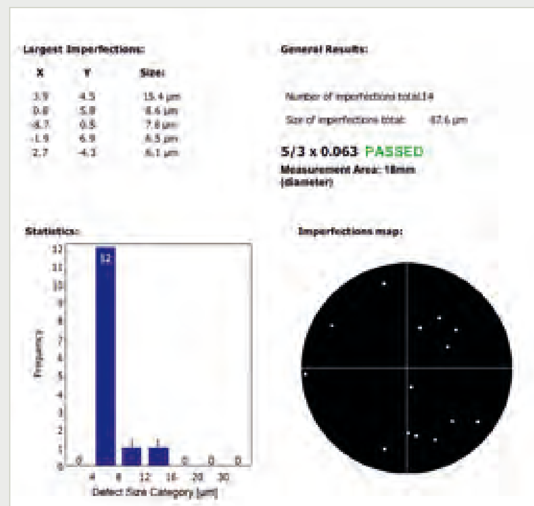


Figure 3: Simplified inspection report of a laser mirror. The report shows the sizes and the coordinates of large defects on the coated surface. Furthermore, all defects which were found are shown in a histogram plot.