7.2 Thin-film technology

D. Ristau

7.2.1 Introduction

Thin-film technology plays a key role in the development and application of modern lasers. Optical components with advanced thin-film systems are employed in each functional section of a laser, starting at the optical pumping scheme and the generation of laser radiation, over the manipulation and steering of the beam until shaping and focusing for its final application. As a consequence, the quality of optical coatings is often recognized as a limiting factor for the reliability and economic efficiency of many laser applications. Therefore, optical coatings and their specifications should be carefully considered during the design and implementation of laser systems. In this chapter, a brief review will be given on the state of the art of optical thin-film technology and on the characterization of optical coatings. Selected quality parameters of optical laser components will be presented and discussed with respect to typical applications in laser technology and modern optics.

7.2.2 Basic principle of optical thin-film systems

The fundamental structure of a dielectric layer system is illustrated in Fig. 7.2.1a. Thin transparent layers with a thickness in the range of the wavelength, at which the system is applied, are deposited on the surface of the optical component (refractive index n_{T}). In order to adapt the optical function

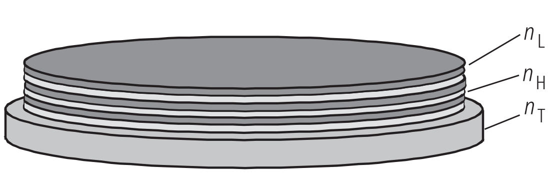

Fig. 7.2.1a. Basic structure of a thin-film system: Transparent layers of at least two different materials (n_{H}, n_{L}) are deposited on a substrate (n_{T}).

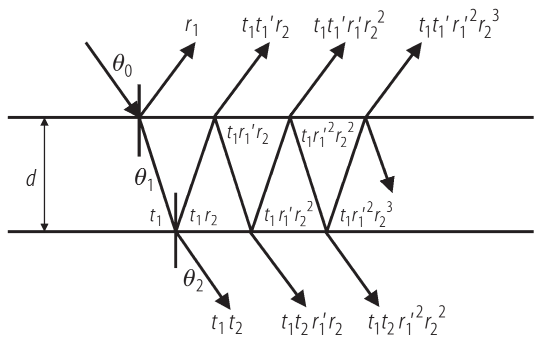

Fig. 7.2.1b. Path of the incident beam in a single layer. The reflection and transmission coefficients at the interfaces x are denoted by r_x and t_x, respectively.

of the coated surface to the required specifications, at least two layer materials with a high refractive index n_H and a low index n_L have to be selected. Besides the contrast in the indices of refraction, the choice of the thin-film materials is dependent on the application wavelength and the expected environmental influences on the coating system. The optical function of the layer structure is based on the interference of partial waves reflected and transmitted at the numerous interfaces between the layers. Thus, the spectral behavior of the coating can be described by tracing the incoming wave through the layer system and accumulating all contributions of the induced partial waves. This calculation method is quite comprehensible for a single-layer system (see Fig. 7.2.1b), where the interfering partial waves can be calculated with the Fresnel equations taking into account the phase shift acquired by the waves passing through the bulk of the layer. But, considering the enormously increasing number of partial beams, the resulting equations become extremely complicated for multilayer structures. Nowadays, the matrix formalism, which can be deduced from the boundary conditions of the electric and magnetic field at the interfaces [64Bor], is usually employed for the calculation of thin-film systems. In this approach, each layer is represented by a matrix M, which contains all specific parameters of the film [88The]. The matrix M_m of a thin film at the position m within the layer system relates the electric (E) and magnetic (H) field strength at the interface between the $(m-1)$th and mth layers:

$$\begin{pmatrix} E_{m-1} \\ H_{m-1} \end{pmatrix} = \mathsf{M}_m \begin{pmatrix} E_m \\ H_m \end{pmatrix} = \begin{pmatrix} \cos\varphi_m & \frac{1}{n_m} \cdot \mathrm{i} \cdot \sin\varphi_m \\ n_m \cdot \mathrm{i} \cdot \sin\varphi_m & \cos\varphi_m \end{pmatrix} \begin{pmatrix} E_m \\ H_m \end{pmatrix} . \tag{7.2.1}$$

The phase shift φ_m in (7.2.1) is dependent on the index of refraction n_m, the thickness d_m, and the angle of propagation θ_m within the mth layer:

$$\varphi_m = \frac{2\pi\, n_m d_m \cos\theta_m}{\lambda} . \tag{7.2.2}$$

The wavelength of the incoming electric wave is denoted by λ. As the outstanding advantage of the matrix method, the calculation of a layer structure can be simply accomplished by a multiplication of the matrices $\mathsf{M_m}$ for the constituent single layers:

$$\mathsf{M} = \mathsf{M}_1 \times \mathsf{M}_2 \times \mathsf{M}_3 \times \cdots \times \mathsf{M}_k , \tag{7.2.3}$$

where M denotes the transfer matrix of the entire stack with a number of k layers, and the multiplication is performed according to the rule for 2×2-matrices.

The transmittance of the multilayer stack is given by the ratio of the transmitted-field to the incoming-field amplitude. In the case of non-absorbing layers, i.e. the imaginary parts of the refractive indices are zero, the transmittance can be directly expressed as a function of the matrix elements M_{ij} (with n_0: refractive index of the surrounding medium, n_T: refractive index of the substrate):

$$T = 1 - R = 4\left(2 + \frac{n_0 M_{11}^2}{n_T} + \frac{n_T M_{22}^2}{n_0} + n_0 n_T M_{12}^2 + \frac{M_{21}^2}{n_0 n_T}\right)^{-1} . \tag{7.2.4}$$

The matrix method can be easily transferred in computer codes [80Lid] and has been developed to a standard tool in optical thin-film technology. Often, the unit QWOT (Quarter-Wave Optical Thickness) is used in these software tools to express the optical thickness D_m of the layers at the design wavelength λ_d:

$$D_m = \frac{4 n_m d_m}{\lambda_d} \quad \text{[QWOT]} . \tag{7.2.5}$$

At integer QWOT-values, corresponding to multiples of $\lambda_d/4$, the matrices M_m reduce to simple expressions for normal incidence. Also, these thickness values represent an extreme value in the spectral behavior, because the according phase shift φ_m is a multiple of π. As a consequence,

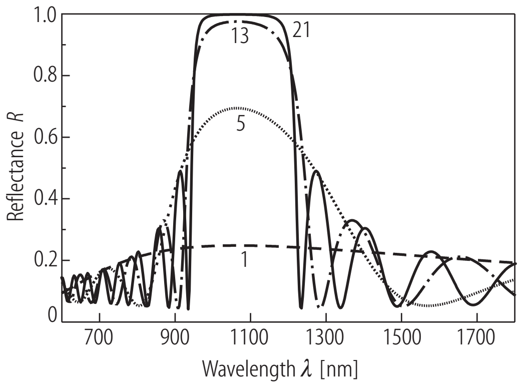

Fig. 7.2.2. Reflectance spectra of QWOT-coating stacks of Ta_2O_5/SiO_2 with different numbers ($k = 1, 5, 13, 21$) of single layers for a design wavelength of 1.064 μm.

layers with integer QWOT-values can be accurately deposited on the basis of monitoring the reflection or transmission at the wavelength λ_d during the production process. If such an optical thickness is approached, the extreme values in the transfer behavior of the growing layer can be precisely detected, and the deposition can be stopped. Thus, the unit QWOT is mainly of practical importance, and most of the layer system designs used in thin-film production are based on QWOT-layers of two deposition materials. The designs are often expressed using the notations H for a QWOT layer of the high-index material and L for the low-index material, respectively. For example, a periodic stack composed of an odd number k of QWOT layers is denoted by the following expression:

$$\underbrace{H|L|H|L|\cdots|L|H|}_{k \text{ layers}} \text{ substrate} . \tag{7.2.6}$$

Such a HL-stack is the basic design for dielectric high-reflecting mirrors and output couplers. For normal incidence, the reflectance at the design wavelength can be directly determined:

$$R_k = \left(\frac{n_H^{k+1} - n_0 n_T n_L^{k-1}}{n_H^{k+1} + n_0 n_T n_L^{k-1}} \right)^2 \approx 1 - 4 n_0 n_T \frac{n_L^{k-1}}{n_H^{k+1}} . \tag{7.2.7}$$

The approximation in (7.2.7) is meaningful for the condition $(n_H/n_L)^k \gg 1$, which can be fulfilled by most combinations of deposition materials used in practice. Obviously, the reflectivity of the QWOT-stack increases with the refractive-index contrast between the deposition materials and the number k of layers. Typical spectra for a QWOT-stack of Ta_2O_5/SiO_2 are illustrated in Fig. 7.2.2 for different numbers of layers. Around the reflectance band, the spectra oscillate with decreasing amplitude originating at the reflectivity of the uncoated substrate as minimum value. If the angle of incidence is tuned from 0° to higher angles, the spectral characteristic is shifted towards shorter wavelengths, and the reflectivity of the mirror decreases. In most cases, a dielectric mirror with optimized reflectivity for an angle of 0° will be nearly transparent if it is applied at an angle of 45° at the same wavelength.

Besides mirror coatings, antireflective coatings are fundamental thin-film systems in optical technology. Depending on the wavelength range, the substrate, and the intended residual reflectivity, antireflective coatings may be composed of non-QWOT-layers of more than two materials. A typical example for a demanding application is ophthalmology, where antireflective coatings on eye-glasses have to cover the whole VIS-range and must be resistant against mechanical and chemical influences. For most applications in laser technology, only one or a few wavelengths have to be considered resulting in less complicated designs. A total suppression of the residual reflection for a single wavelength is already achievable with two non-QWOT layers for most optical materials, see Fig. 7.2.3. This so-called V-coating can be routinely produced for all laser wavelengths and possesses good optical properties as well as high laser-induced-damage thresholds.

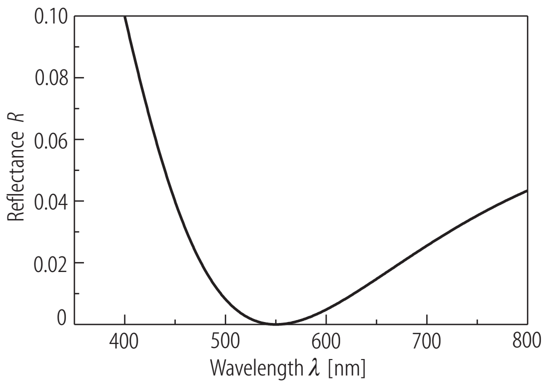

Fig. 7.2.3. Reflectance spectrum of a two-layer antireflective coating for the wavelength 550 nm. Design: 0.37H(Ta_2O_5, $n_H = 2.03$)/1.30L(SiO_2, $n_L = 1.45$).

7.2.3 Production of optical coatings

The production process for high-quality thin films can be divided into stages which are nearly independent of the optics type and the thin-film deposition process applied. First, a thin-film design which defines the sequence of single layers and their materials is elaborated. This design has to meet the requirements of the user including the spectral transfer function, the stability, and the optical quality of the coatings. In the next step, the optical coating system is deposited on the optical components with a process selected in view of the individual specifications of the application. Finally, the coated product is inspected and characterized with respect to the critical operating parameters within the quality management system of the manufacturer.

The design of even highly complicated optical coating systems is no longer an obstacle. Nowadays, commercial computer programs are available which automatically calculate the desired design on the basis of advanced calculation algorithms and optimization techniques including special needle methods and genetic codes [88Bau]. For most software products, the spectral transfer function needed is loaded, and the computer produces suggestions for coating designs. Of course, the power of the software environments must be combined with the expert knowledge of a scientist possessing experience in the properties of different coating materials (see Fig. 7.2.4) and their combination.

Presently, the production of a coating system according to a specific design is the primary difficulty in thin-film technology. Most industrial coating areas are still dominated by thermal processes like e-beam evaporation, which has been introduced in the 1960ies, or even by boat evaporation techniques, which date back to the 1940ies. In these thermal processes, the coating material is evaporated and condenses as film on the optical components under vacuum conditions.

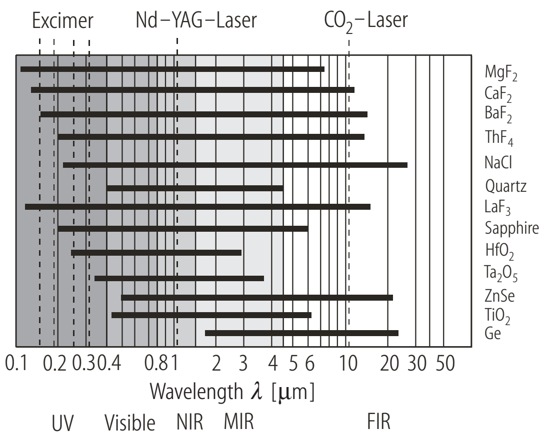

Fig. 7.2.4. Spectral transmission bands of materials often used for thin films or substrates.

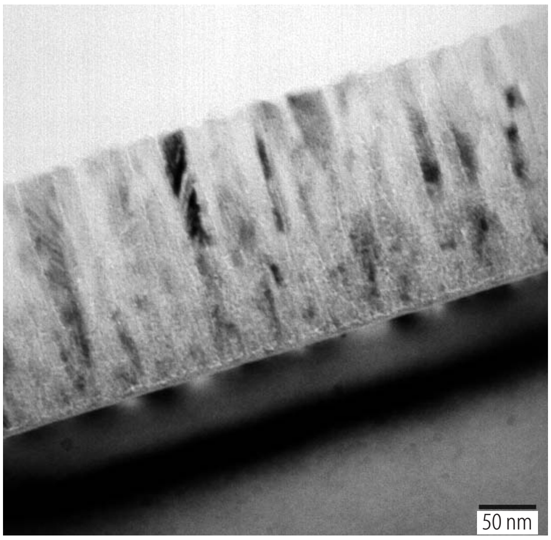

Fig. 7.2.5. Microstructure of a single layer of MgF_2 deposited by conventional boat evaporation on a silicon substrate [99Ris].

Since the typical kinetic energy of the admolecules is confined to a few tenths of an eV, they attain a very limited mobility on the surface of the growing layer and can reach only bonding positions near to their location of incidence. This low-energy growing mechanism results in a porous microstructure with severe disadvantages for the mechanical and optical film quality, see Fig. 7.2.5. For example, water and other contaminants from the atmospheric environment are strongly adsorbed by this porous microstructure leading to high optical absorption values and an elevated thermal shift of the layer systems. In addition, the porous microstructure suffers from a reduced mechanical stability, and it is the origin of high total scatter values of the coating system. In order to increase the mobility of the admolecules and to improve the quality of thermally deposited films, the substrates often have to be heated to temperatures in the range from 200 to 350°C. Thus conventional coating processes cannot cover the broad spectrum of temperature-sensitive optical components, as plastic optics and many crystal materials used in laser technology. For the demanding specification of many modern technology fields, the quality of conventionally deposited optical coatings is not sufficient. As a consequence, several new concepts have been developed to overcome the specific difficulties of thermal evaporation processes during the last two decades [92Gue].

Considering the condensation process of the layers, two basic approaches can be discussed to improve the optical and microstructural quality: In the first concept, the Ion-Assisted Deposition (IAD), the mobility of the admolecules is enhanced by an additional bombardment of the growing layer with ions of inert or reactive gases. In this process, auxiliary energy is transferred by collisions with the ions resulting in a longer mean free path of the admolecules, which accordingly can reach locations with nearly optimal bonding conditions in the growing layer. Hence, the ion-assisted deposited thin-film structure possesses a higher packing density with improved mechanical and environmental stability. Furthermore, especially for oxide materials, the stoichiometry and consequently, the optical quality of the layer can be optimized by employing oxygen for the generation of the assisting ions. Also, the coating of temperature-sensitive substrates is possible with IAD-processes, because heating of the substrates is no longer necessary. As an additional technical and economical advantage, IAD-processes can be easily integrated in existing deposition plants for conventional deposition by installing an appropriate ion source.

As the second alternative for an improvement of the coating quality, a direct increase of the admolecule energy by sputtering processes can be considered. In these deposition concepts, the coating material is sputtered from a target by high-energetic ions which are produced within a discharge maintained in the deposition plant or by a separate ion gun (Ion-Beam Sputtering: IBS,

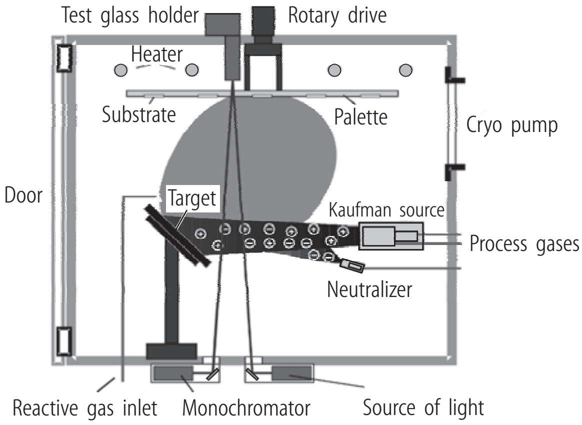

Fig. 7.2.6. Principle of an ion-beam sputtering process. Sputtering of the target material is achieved by inert ions, which are produced in a Kaufman ion source.

Fig. 7.2.7. Microstructure of a high-reflecting stack for the wavelength 633 nm produced by ion-beam sputtering. (Detail of a surface of the break through the system).

[78Wei], see Fig. 7.2.6). In contrast to thermal evaporation, the kinetic energy of the sputtered molecules ranges on a significantly higher level between 5 to 20 eV. Therefore, the microstructure of layer systems deposited by sputter processes is compact and extremely stable, see Fig. 7.2.7. As a result of the separation of the process steps, ion generation, sputtering of the coating material, and finally the condensation of the layer structure, these coatings exhibit also extremely low defect densities and contamination levels. Actually, coatings produced by IBS-processes achieve nearly ideal properties with lowest total optical losses below 1 ppm for laser mirrors in the visible and near-infrared spectral region. Therefore, IBS processes are presently employed for a variety of special coating challenges including filter systems for telecommunication, low-loss mirrors for optical measurement techniques, high-power laser applications, and coating of optoelectronic circuits. With respect to the economic efficiency, IBS-processes still suffer from the small effective deposition area and the low deposition rates, which range between a factor 5 to 10 below typical rates of evaporation processes. Several industrial and institutional research groups are presently investigating techniques to improve the economy of IBS-processes and to simultaneously advance or maintain the extremely high quality of the coating products.

7.2.4 Quality parameters of optical laser components

Some of the quality parameters frequently considered in laser technology and optics are compiled in Table 7.2.1 in conjunction with the corresponding measurement techniques. Besides the spectral transfer functions $R(\lambda)$ and $T(\lambda)$, which are determined by spectrophotometry, laser-induced damage thresholds and optical losses must be carefully thought about for most laser applications. The measurement of these laser-specific parameters requires adapted measurement facilities described within International Standards which are frequently updated with respect to the latest developments in laser technology [06ISO2]. The measurement procedures for absorptance (ISO 11551 [97ISO3]) and total scatter (ISO 13696 [02ISO]) have been tested in several international interlabo-

Table 7.2.1. Selected quality parameters of optical laser components and the corresponding characterization techniques.

Specification	Parameter	Unit	Standard	Measurement principle
Laser-Induced Damage Threshold (LIDT)	cw-LIDT	W/cm	ISO 11254-1:	cw-laser irradiation
	1 on 1-LIDT	J/cm^2	ISO 11254-1:	irradiation with single pulses
	S on 1-LIDT	J/cm^2	ISO 11254-2:	repetitive irradiation with pulses
	certification	J/cm^2	DIS 11254-3:	irradiation sequence
optical losses	absorptance	ppm	ISO 11551:	laser calorimetry
	total scattering	ppm	ISO 13696:	integration of scattered radiation
transfer function	reflectance	%	FDIS 13697:	precise laser ratiometric method
	transmittance	%	ISO 15368:	spectrophotometry
surface quality	form tolerances scratch/digs roughness	λ/N	ISO 10110:	17 parts containing different types of imperfections
stability	abrasion		ISO 9211:	different test methods
	environmental stability		ISO 9022:	more than 20 parts containing a variety of conditioning methods

ratory tests. Also, the practicability of the standards for the measurement of laser-induced damage thresholds (ISO 11254, parts 1 and 2, [01ISO2]) has been confirmed by detailed investigations at a variety of different operation conditions of the test lasers [05Las]. Additional parameters for the surface quality and environmental stability of optical laser components are described in many national and international standards, which have been elaborated by the optics industry and users during the last five decades [97ISO1, 97ISO2, 06ISO1]. In laser applications, especially the surface quality of the optics is a crucial factor, because the optical losses and the power handling capability of the coatings are directly dependent on the surface roughness and defects. The environmental stability should be always considered for industrial laser applications, extreme climates, or high-power laser systems. For example, the spectral characteristic of a coating may be shifted under the influence of high temperatures or extreme humidity.

7.2.5 Measurement of critical parameters of laser components

Compared to application in optics, laser technology imposes much higher demands on optical coatings with respect to their optical losses and damage thresholds. For projecting a laser system, these specifications have to be discussed also in the context of their specific measurement methods. Therefore, a short outline on the determination of absorption, scattering, and laser-induced damage threshold will be given in the following sections.

7.2.5.1 Calorimetric measurement of absorption

Absorption in optical laser components leads to a conversion of a fraction of the impinging laser power into heat, which dissipates in the bulk of the component and induces distortion effects. For

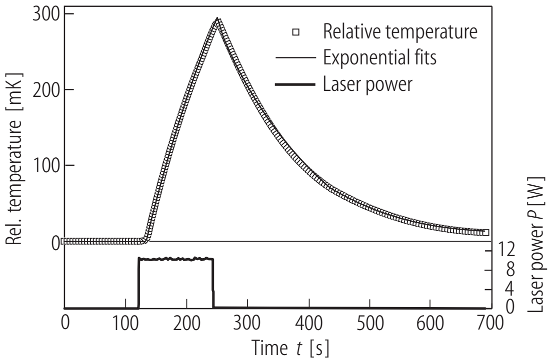

Fig. 7.2.8. Exponential method for the evaluation of temperature recorded during a calorimetric absorptance measurement according to ISO 11551. The irradiation time is indicated by the rectangular graphs at the bottom of the diagram.

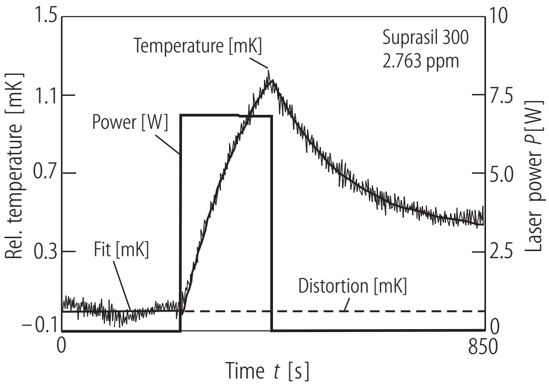

Fig. 7.2.9. Example for a laser calorimetric measurement with high sensitivity on an uncoated fused silica substrate (thickness: 1 mm, measured absorptance: 2.8 ppm) at 1.064 µm. The temporal behavior of the laser power is also indicated.

example in laser material processing, these thermal distortion effects can induce a shift of the focal plane on the work piece, which in turn, deteriorates the process result. The determination of absorptance according to ISO 11551 is based on the laser calorimetric method [76Gib, 88DeB, 98Wil], which provides the means for absolute measurements by uncomplicated calibration techniques. For the calorimetric measurement, a temperature sensor is attached to the specimen which is located in a thermally isolating chamber. After thermal equilibrium between the sample and the environment is reached, the sample is irradiated by a laser beam with known power P starting at the time t_1 for a heating period with a duration t_{B}. During this heating period, the temperature of the specimen increases according to the absorbed laser power. At a defined time t_2, the laser is switched off, and the temperature of the specimen decreases as a consequence of heat dissipation to the environment. For the evaluation of the calorimetric measurement, the recorded temperature curves of the heating and cooling cycles are considered. In most cases, the temperature behavior is modeled directly on the basis of a solution for the heat conduction equation with the boundary conditions according to the sample geometry. For a sample with infinite thermal conductivity and small temperature increases, the corresponding solutions of the heat equation can be expressed by exponential functions:

$$\text{heating curve:} \quad T(t) = T(t_1) + \frac{\alpha P}{\gamma C_{\mathrm{eff}}} \left(1 - \exp(-\gamma(t - t_1))\right) \,,$$

$$\text{cooling curve:} \quad T(t) = T(t_1) + \frac{\alpha P}{\gamma C_{\mathrm{eff}}} \left(\exp(-\gamma(t - t_2)) - \exp(-\gamma(t - t_1))\right) \,,$$

where α denominates the absorptance, and γ represents the coefficient for heat losses induced by radiation and convection, respectively. The effective heat capacity C_{eff} is combined of the contributions from the sample and the holder in conjunction with additional heat contact effects to other arrangements in the calorimetric chamber. An example for an evaluation of a calorimetric measurement according to this exponential method is depicted in Fig. 7.2.8. The advantage of this data reduction technique, which is recommended for lower laser powers and exposure times longer than 60 s, is the involvement of all measured data points in the procedure. For an absolute determination of the absorptance value, the laser power P must be measured with a calibrated power monitor.

The laser calorimetric method had been qualified in various global round-robin tests and by fundamental investigations in the sensitivity of the method, see Fig. 7.2.9. Nowadays, absorptance values according to ISO 11551 are given in product catalogs of most optical companies.

7.2.5.2 Measurement of total scattering

In laser technology, the amount of radiation scattered by the optical components is of major concern. For example, scattering may deteriorate the quality of laser material processing or it may limit the precision in laser metrology applications. In the UV-spectral range, losses by optical scattering may directly impair the economic efficiency, because the production of UV-laser photons is expensive compared to most other prominent wavelengths. Also, laser safety aspects have to be considered in high-power laser applications, where even low optical scattering may lead to dangerous laser power levels in the environment of the laser and beam-steering system. For the measurement of Total Scattering (TS) by laser components, the International Standard ISO 13696 is applied by most companies and research institutes. In this standard procedure, the radiation scattered by the specimen is collected and integrated by an Ulbricht-sphere [1900Ulb] or a Coblentz-hemisphere [13Cob]. The power of the scattered radiation is measured by a detector and related to the corresponding power of a 100% diffuse reflecting standard. Depending on the halfspace of integration, total backward and total forward scattering are distinguished.

A typical measurement facility, which is equipped with an Ulbricht-sphere for the visible and near-infrared spectral range, is depicted in Fig. 7.2.10. This apparatus consists of separate chambers for the beam preparation and the scatter measurement device, which can be flushed with gases in order to reduce the contribution of Rayleigh scattering to the zero signal of the system below 1 ppm. The integrating performance of the Ulbricht sphere is sensitively dependent on the diffuse reflectivity of the coating on the inner walls. For wavelengths below 200 nm, appropriate materials with the required diffuse reflectance above 99% are not available. Therefore, Coblentz-hemispheres coated with adapted high-reflecting metal and protection layers are preferred for TS-measurement in the deep and vacuum UV-spectral range. In comparison to the integration principle of the Ulbricht-sphere, the collection effect of the Coblentz-sphere can be considered as an optical imaging of the scattered radiation onto the detector, which is positioned at the conjugate point with respect to the sample.

The total scatter value of a coated component is directly dependent on the surface quality of the substrate and the reflectance of the coating. Therefore, substrates for laser applications should

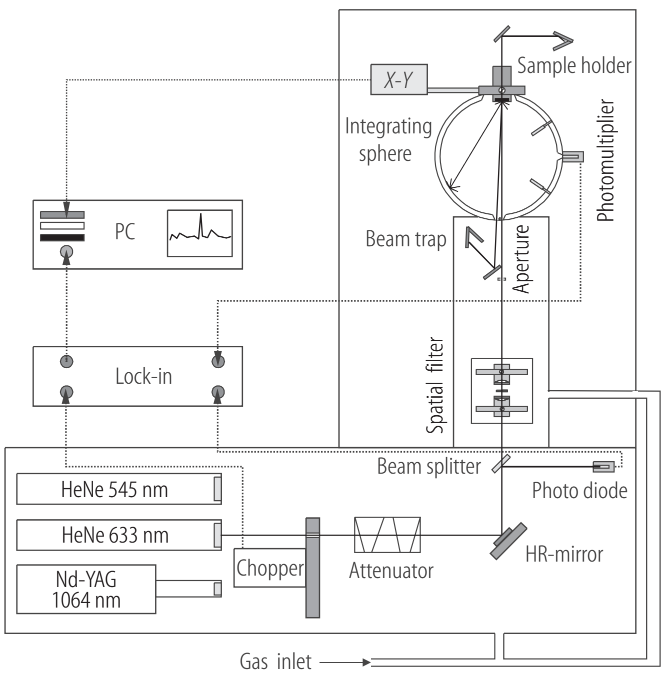

Fig. 7.2.10. Example for a measurement facility for total scattering according to ISO 13696 with an Ulbricht-sphere for the visible and near-infrared spectral range.

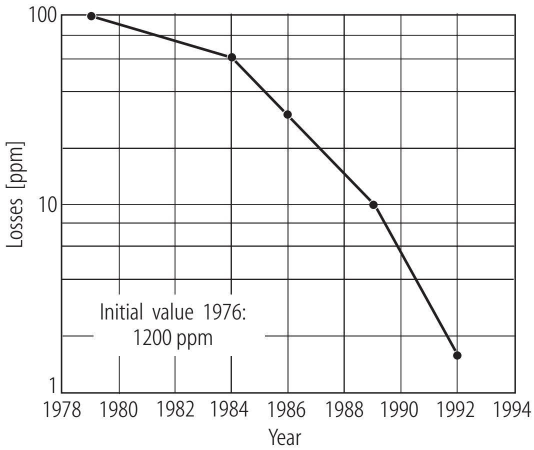

Fig. 7.2.11. Global learning curve for total losses of high-reflecting mirrors at 1.064 μm produced by different ion-beam sputtering processes [98Ris].

have a surface roughness well below 1 nm rms and surface imperfections better than $(5/1) \times 0.010$ according to ISO 10110.

An introduction into the problems of surface roughness and scattering is given in [99Ben]. As an example for the influence of reliable loss measurements on the progress of optical thin-film technology, a learning curve is presented in Fig. 7.2.11 for the optical losses of high-reflecting mirrors produced by ion-beam sputtering. An improvement in optical losses by more than three orders magnitude to values around 1 ppm could be achieved since the introduction of IBS-technology.

7.2.5.3 Laser-induced damage thresholds

The Laser-Induced Damage Threshold (LIDT) of an optical component is one of the most important quality parameters in the development and application of high-power laser systems. Even today, the power handling capability of optical components is a limiting factor in many laser applications including nuclear fusion technology, material processing, or laser medicine. In many laboratories, LIDT-values are determined on the basis of the International Standard ISO 11254, which describes a protocol for the objection of selected sites on the specimen to a focused high-power laser beam with defined output energy or power. After the test, each irradiation site is optically inspected (see Fig. 7.2.12), and the state of damage is documented in conjunction with the corresponding laser power. For the evaluation of these raw data, the so-called survival curve [83Sei] is deduced, which represents the damage probability as a function of the laser power. In this technique, the damage threshold is defined by the highest power value with a damage probability of zero. Besides 1 on 1- and cw-tests outlined in ISO 11254-1, which are of interest for fundamental research of optical coatings, irradiation sequences with repetitive laser pulses (S on 1-tests) are also considered in ISO 11254-2. These S on 1-tests represent the typical operation condition of a component in practical applications.

Even though the fundamental principle of LIDT-measurements is uncomplicated, the experimental expense is considerable. For comparable measurements, laser systems operating in single transversal and longitudinal modes are recommended. Also, a precise beam diagnostic package has to be installed in order to characterize the beam parameters at the specimen or a conjugate location. Besides online damage detection systems, an inspection using a differential interference contrast microscope is prescribed for a reliable identification of the damage state of the irradiated sites.

Extreme care must be taken, if damage thresholds of optical components are compared for different operation conditions. Scaling laws of LIDT-value have been studied for the main param-

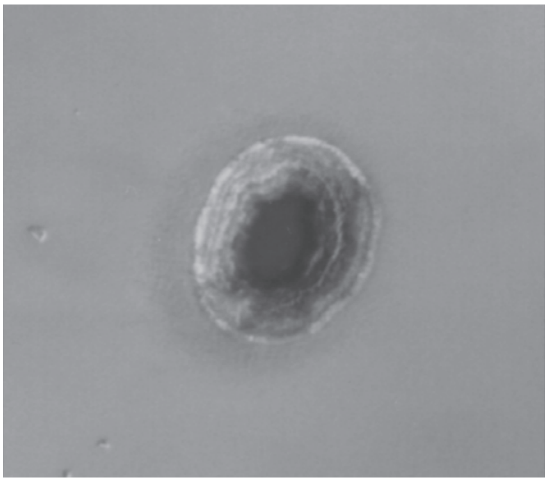

Fig. 7.2.12. Damage site on chirped mirror for fs-lasers (TiO_2/SiO_2). The damage occured at an energy of 0.1 J/cm^2 during an S on 1-test.

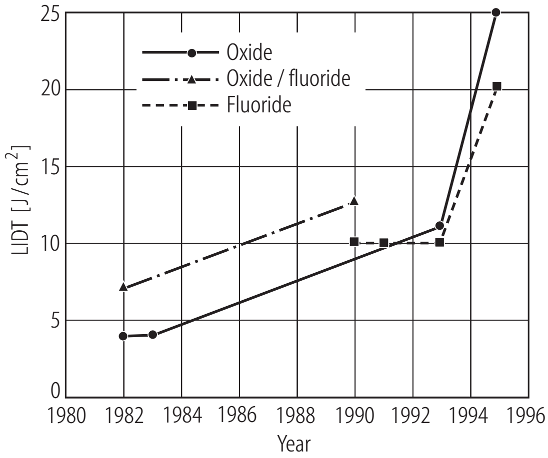

Fig. 7.2.13. Learning curve for high-power laser mirrors at 248 nm produced with different coating materials by thermal evaporation [98Ris].

eters wavelength, pulse duration, and spot diameter [81Wal] and are only applicable, if the actual damage mechanism is clearly identified. Even though 1 on 1-damage tests are not representative for the operation conditions of optical components in typical applications, they are still listed in catalogs of optics manufacturers and considered for a comparison of the power handling capabilities of competing products.

Reliable LIDT-measurements are often the key factor for the optimization of optical coating systems. A typical example is illustrated in Fig. 7.2.13 for high-reflecting mirrors applied in KrF-excimer lasers. Meanwhile the first decade of intense research in high-power UV-coatings was dominated by the combination of oxides and fluorides in one stack, the improved layer systems consist of only one material class. Best results of more than 20 J/cm^2 are presently achieved for HR-stacks of the material combination Al_2O_3/SiO_2, which are deposited by a conventional, low-contamination PVD-process.

7.2.5.4 Quality parameters of laser components: present state

In Table 7.2.2 quality parameters of optical laser components for prominent laser systems are compiled. Besides optical absorptance and total scattering, typical LIDT-values are reported for operation conditions in practical applications. Particularly, the LIDT-value for cw-operation is given in units of linear power density, because most cw-damage mechanisms are thermal effects, which can be scaled with linear power density [97Put]. Moreover, a scaling of cw-LIDT-values in units of W/cm^2 would lead to an overestimation of the power handling capability of the component and could lead to fatal failures in its application. This aspect is of essential importance in the field of CO_2-laser material processing, where optical components often consist of hazardous materials, which can cause severe health problems and contamination of the environment when emitted during catastrophic damage. The table also reflects the specific advantages of the IBS-process in comparison to conventional evaporation: Extremely low losses and high LIDT-values can be achieved for HR-coatings in the visible and near-infrared spectral region. However, thermal processes still cover the entire spectral range from the vacuum ultraviolet to the far infrared and enable an efficient production of coatings with highest damage thresholds. Coatings for the

Table 7.2.2. Selected quality parameters of optical coating systems for laser applications (types: HR: high-reflecting mirror, AR: antireflective coating, th: thermal evaporation, IBS: ion beam sputtering).

Laser	Wavelength	Type	Absorption ISO 11551	Total scattering ISO 13696	Laser-induced damage threshold, ISO 11254
F_2-excimer	157 nm	HR/th		1…4%	
ArF-excimer	193 nm	AR/th	0.7…2.5%	0.2…0.5%	1…2 J/cm^2 (1on1, 20 ns)
		HR/th	0.4…2.0%	0.2…2.5%	2…4 J/cm^2 (1on1, 20 ns)
KrF-excimer	248 nm	AR/th		< 0.025 %	10 J/cm^2 (1on1, 30 ns)
		HR/th	< 500 ppm	< 0.2 %	> 20 J/cm^2 (1on1, 30 ns)
		HR/IBS		< 0.1 %	> 3 J/cm^2 (1on1, 30 ns)
HeNe-laser	633 nm	HR/th	< 30 ppm	< 30 ppm	–
		HR/IBS	< 5 ppm	< 5 ppm	–
Nd:YAG	1.064 µm	AR/th	< 20 ppm	< 100 ppm	> 60 J/cm^2 (12 ns, 0.25 mm)
		HR/th	< 50 ppm	< 100 ppm	> 100 J/cm^2 (12 ns, 0.25 mm)
		HR/IBS	< 1 ppm	< 1 ppm	> 80 J/cm^2 (12 ns, 0.25 mm)
CO_2-laser	10.6 µm	AR/th	< 0.16 %	–	> 20 J/cm^2 (100 ns, 1.4 mm)
					> 2 kJ/cm^2 (1.2 ms, 250 µm)
					> 3 kW/mm (cw, 100 µm)
		HR/th	< 0.10 %	–	> 25 J/cm^2 (100 ns, 1.4 mm)
					> 2 kJ/cm^2 (1.2 ms, 250 µm)

ArF- and F_2-excimer laser are presently optimized by several working groups for semiconductor lithography and material processing. Therefore, the corresponding data are preliminary and may be significantly improved in the near future.

7.2.6 Examples for advanced laser components

The rapid development of laser technology imposes ever increasing demands on optical components and their production methods. Besides extreme requirements on the optical quality and spectral properties of optical coatings, often a flexible production with short delivery time for small numbers of components is inquired of the optical companies. The presently established development process for high-quality components, which involves a variety of iteration steps, is not adapted to these requirements. An ideal process concept would be linear, starting with the coating design, loading the design in the manufacturing system, and ending with coatings according exactly to the design specifications. Present research activities in thin film technology are focused on such a "Rapid Manufacturing" of optical coating systems.

Adapted on-line monitoring, process-tracing algorithms, and error detection during the deposition process are probably the key to rapid-manufacturing concepts in thin-film technology [02Dob]. Therefore, several approaches on the basis of different high-energetic deposition processes in combination with advanced on-line monitoring techniques are presently pursued by many research teams. As deposition processes with high potentiality for integrated manufacturing of optical coatings, IBS and magnetron sputtering techniques are considered. Besides an extremely high process reliability and stability, these concepts allow for the production of coatings with excellent optical quality. In most systems, broad-band spectrophotometers with high accuracy and spectral resolution are employed for a direct spectral evaluation of the actual coating part during the deposition.

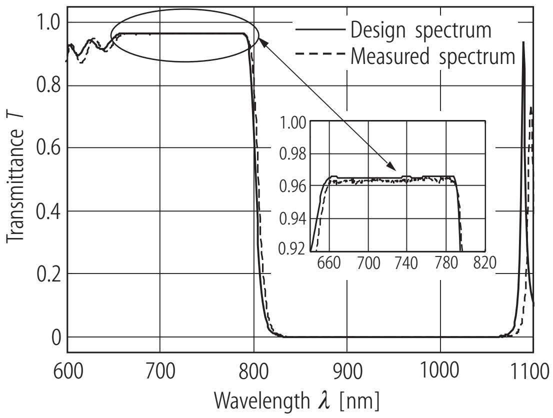

Fig. 7.2.14. Spectra of a band-pass filter produced in a rapid-manufacturing cycle by ion-beam sputtering. The spectrum of the realized filter is compared to the spectrum of the design calculated for this application [01Gro].

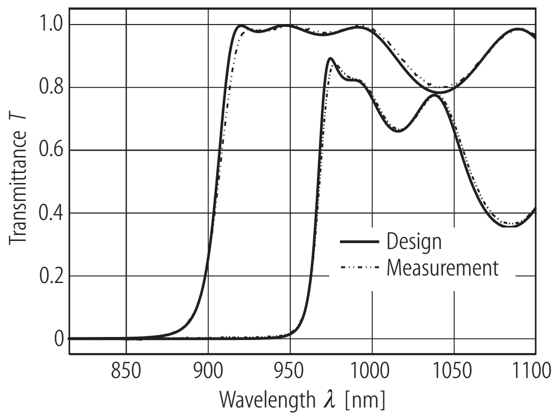

Fig. 7.2.15. Thin-film polarizer for high-power laser applications. The spectrum of the realized polarizer is compared to the spectrum of the design which was optimized by a thin-film design program [01Gro].

For this purpose, calibrated spectra are periodically read into a computer system, which calculates the current state of the film structure on the basis of specially developed process tracing models. By comparing the present state of the deposition to the target design of the layer system, the switching between the single layers can be controlled, and errors can be detected. For some applications in laser technology, rapid-manufacturing processes are already employed in a laboratory scale. As an example, the spectra for a band-pass filter are depicted in Fig. 7.2.14. This band pass was designed for a special application in solid-state laser technology, where a high-reflecting region between 840 nm to 1060 nm was required, meanwhile the filter should transmit light in the wavelength range from 665 nm to 790 nm without losses and coloration effects. The filter system was produced by IBS in a single rapid-manufacturing cycle and fulfills the requirements within an error margin of less than 0.25%. In Fig. 7.2.15 a high-power thin-film polarizer deposited by IBS is illustrated. This layer system consists of 27 non-QWOT layers of TiO_2/SiO_2 with a total thickness of 3.2 μm and enables polarization losses below 2.5%. Considering the present state of the art, an implementation of rapid-manufacturing techniques in the industrial production environment can be expected for this decade.

7.2.7 Summary and future trends

The production of optical thin films is an enabling technology for the development and application of future-oriented laser systems. Meanwhile the theoretical background for the design is mastered and implemented in commercial software environments, major deficiencies still exist for a reliable production and characterization of optical coatings. Intensive research and the development of new deposition processes as well as manufacturing strategies are necessary to meet the ever increasing demands of laser technology and modern optics. Besides the optimization of advanced deposition concepts with superior stability, rapid-manufacturing strategies are considered as a major tool to overcome the present limitations in optical thin-film technology.

Future trends in thin-film technology are governed by outstanding laser applications, which act as pace-makers for progresses in high-technology fields. A major driving force can be seen in semiconductor lithography, where on the way up to an ever increasing packing density the wavelength of the stepper systems is continuously reduced. According to Moore's law, the capacity of microchips is doubled every 18 months, meanwhile the production costs are halved. Presently, major activities of semiconductor lithography are concentrated on the wavelength 193 nm in conjunction with immersion techniques and on the implementation of next-generation lithography based on EUV sources operating in the wavelength range between 10 nm to 14 nm. Especially for the stepper systems operated with excimer lasers in the DUV spectral range, fluoride coatings are often employed for production of the optical components. The dominating coating process for these large aperture optics, which have a well defined surface figure and demand for reduced deposition temperature, is still conventional thermal deposition resulting in coatings with low mechanical and environmental stability. Therefore, IBS processes for the deposition of fluorides with improved stability, which have been investigated for many years [92Kol] within the framework of excimer laser development, have gained new interest [97Dij, 00Que, 04Yos]. For a realization of this so-called next-generation lithography in the EUV-range, mirrors for a wavelength of 13 nm are presently optimized within extensive international research initiatives. Besides reflectivity values of around 70%, a high thickness homogeneity has to be achieved over diameters of more than 300 mm. The present state in EUV thin-film technology can be described by a maximum reflectivity of approximately 69% for a Mo/Si Bragg reflector deposited by rf-magnetron sputtering. For the production of the masks for 13 nm lithography, IBS-concepts with broad ion-beam sources are presently studied in detail.

In the course of the development of new laser sources and frequency conversion systems with broad spectral emission ranges, an increasing demand for optical coatings with transfer properties specified over extended wavelength ranges can be observed. In this context the concept of "rugate filters", which are based on a continuous variation of the refractive index in the depth of the layer, is often discussed. As a major benefit, rugate filters can be designed to suppress higher-order stop bands in the spectra and to create spectral bands with extremely small variations in transmittance or reflectance. Furthermore, recent investigations indicate an advantage in the power-handling capability of these coatings in comparison to conventional optical coatings, which are composed of discrete layers with preset indices of refraction. For the realization of coatings with a defined variation of the refractive index, different approaches involving simultaneous evaporation from two independent deposition sources or ion-assisted deposition with varying composition of the reactive gas were investigated in thermal processes. Especially ion-beam sputter processes offer additional options for example by means of a target with two different material zones which is moved in the beam area allowing for the deposition of the pure materials and mixtures with compositions depending on the actual position of the target with respect to the ion beam [04Lee, 05Lap]. Recent results on these IBS-techniques document a clear prospect for the precise production of rugate filters and for the related progresses in optical thin-film technology.

Currently, ultra-short-pulse lasers are considered as an innovative tool for material processing, laser medicine, and biology, as well as the analysis and control of chemical reactions. For the development of these fs-lasers with ever increasing output power and improved beam parameters, special high-power broad-band coating systems are required. Besides an optical transfer function defined over an extremely extended spectral range, these coatings have to fulfill also demands with respect to their group delay dispersion for the compensation of dispersion effects in the laser systems. These coatings can be only achieved on the basis of complex designs, which are sensitive to thickness errors well below 0.1%. Improved production and controlling techniques are presently developed in order to adapt these coating types to the future demands of fs-technology.

In addition to the aspects outlined before, a variety of other challenges are imposed on thin-film technology by new developments in the laser field. Besides new crystal materials and micro-optics, coatings combining optical functions with other properties have to be mentioned. New approaches including rugate filter designs and advanced production techniques have to be considered to keep pace with the rapid progresses in laser technology.

References for 7.2

1900Ulb Ulbricht, R.: Die Bestimmung der mittleren räumlichen Lichtintensität durch nur eine Messung; Elektrotech. Z. **29** (1900) 595.

13Cob Coblentz, W.W.: The diffuse reflecting power of various substances; Natl. Bur. Stand. (U.S.) Bull. **9** (1913) 283–325.

64Bor Born, M., Wolf, E.: Principles of optics, Oxford: Pergamon Press, 1964.

76Gib Gibbs, M., Wood, R.: Laser induced damage of mirror and window materials at 10.6 μm. Laser induced damage in optical material; NBS Spec. Publ. U. S. **462** (1976) 181–188.

78Wei Wei, D.T., Louderback, A.W.: US 4,142,958: Method for fabricating multi-layer optical films, 04, 1978.

80Lid Lidell, H.M.: Computer-aided techniques for the design of multilayer filters, Bristol: Adam Hilger Ltd, 1980.

81Wal Walker, T.W., Guenther, A.H., Nielsen, P.: Pulsed laser induced damage to thin film optical coatings, Part I: Experimental, Part II: Theory; IEEE J. Quantum Electron. **17** (1981) 2041–2065.

83Sei Seitel, S.C., Porteus, J.O.: Towards improved accuracy in limited scale laser damage testing via the "onset method"; NBS Spec. Publ. U. S. **6988** (1983) 502.

88Bau Baumeister, P.: Computer software for optical coatings; Photonics Spectra **22**(9) (1988) 143–148.

88DeB DeBell, G., Mott, L., von Gunten, M.: Thin film coatings for laser cavity optics. Proc. laser optics for intracavity and extracavity applications; Proc. SPIE (Int. Soc. Opt. Eng.) **895** (1988) 254–270.

88The Thelen, A.: Design of multilayer interference filters; New York, St. Louis, San Francisco, Auckland, Bogota, Hamburg, London, Madrid, Milan, Mexico, Montreal, New Delhi, Panama, Paris, Sao Paulo, Singapore, Sydney, Tokio, Toronto: McGraw-Hill Book Company, ISBN 0-07-063786-5, 1988.

92Gue Guenther, K.H.: Optical thin films deposited by energetic particle processes. Proc. SPIE (Int. Soc. Opt. Eng.) **1782** (1992) 344–355.

92Kol Kolbe, J., Schink, H.: Optical losses of dielectric VUV-mirrors deposited by conventional evaporation, IAD, and IBS. Guenther, K.H.: Thin Films for Optical Systems; Proc. SPIE (Int. Soc. Opt. Eng.) **1782** (1992) 435–446.

97Dij Dijon, J. et al.: High damage threshold fluoride UV mirrors made by ion beam sputtering. Proceedings of the 29th Annual Symposium on Optical Materials for High Power Lasers; Proc. SPIE (Int. Soc. Opt. Eng.) **3244** (1997) 406–416.

97ISO1 ISO 9022: Optics and optical instruments – environmental test methods, Parts 1–21. International Organization for Standardization 1996, 1997.

97ISO2 ISO 10110: Preparation of drawings for optical elements and systems. Parts 1–12. International Organization for Standardization 1996, 1997.

97ISO3 ISO 11551: Test method for absorptance of optical laser components. International Standard, 1997 (revised version published in 2003), International Organization for Standardization.

97Put Puttik, V.K., Holm, R., Ristau, D., Natzschka, U., et al.: Continuous wave CO_2 laser induced damage thresholds in optical components. Proceedings of the 29th symposium on laser induced damage in optical materials; Proc. SPIE (Int. Soc. Opt. Eng.) **3244** (1997) 188–198.

98Ris Ristau, D.: Optics characterisation in thin film technology. Proceedings of the 4th International Workshop of Laser Beam and Optics Characterization, VDI-Verlag, 1998, p. 546–571.

98Wil Willamowski, U., Ristau, D., Welsch, E.: Measuring the absolute absorptance of optical laser components; Appl. Opt. **37**(36) (1998) 8362–8370.

99Ben Bennett, J.M., Mattsson, L.: Introduction to surface roughness and scattering. Second edition, Washington, D.C: Optical Society of America, 1999, ISBN 1-55752-609-5.

99Ris Ristau, D., Arens, W., Bosch, S., Duparré, A., Masetti, E., Jacob, D., Kiriakidis, G., Peiró, F., Quesnel, E., Tikhonravov, A.: UV-optical and microstructural properties of MgF_2-coatings deposited by IBS and PVD processes. Proceedings of the conference on advances in optical interference coatings; Proc. SPIE (Int. Soc. Opt. Eng.) **3738** (1999) 436–445.

00Que Quensel, E. et al.: Optical and microstructural properties of MgF_2 UV coatings grown by ion beam sputtering. J. Vac. Sci. Technol. A **16**(6) (2000) 2869–2876.

01Gro Groß, T., Starke, K., Lappschies, M., Ristau, D.: Rapid prototyping of optical thin film filters. Proceedings of the 2nd international conference THE-coatings in manufacturing and engineering, Erice, Italy, Sept. 23–27, 2001, p. O2-1-O2-7.

01ISO2 ISO 11254: Test methods for laser induced damage threshold of optical surfaces. Part 1: 1-on-1 test, 2000; Part 2: S-on-1 test, 2001.

02Dob Dobrowolski, J.A., Browning, St., Jacobson, M., Nadal, M.: 2001 OSA topical meeting on optical interference coatings (OIC2001): Manufacturing problem; Appl. Opt. **41**(16) (2002) 3039–3052.

02ISO ISO 13696: Test method for radiation scattered by optical components; International Standard 2002, International Organization for Standardization.

04Lee Lee, C.-C. et al.: Rugate filters made with composite thin film by ion beam sputtering. Proceedings of the Conference on Optical Interference Coatings, July 1st, 2004, OSA Technical Digest, p. THD10.

04Yos Yoshida, T., Nishimoto, K., Etoh, K.: Fluoride antireflection multilayers with high transmittance for ArF excimer laser by ion beam sputtering method. Jpn. J. Appl. Phys. **43**(2B) (2004) L258–L260.

05Lap Lappschies, M., Görtz, B., Ristau, D.: Optical monitoring of rugate filters. Proceedings of Advances in Optical Thin Films; Proc. SPIE (Int. Soc. Opt. Eng.) **5963** (2005) 1Z1–1Z9.

05Las Laser-induced damage in optical materials. Proceedings of the Boulder damage symposium. NIST Spec. Publ. and SPIE-Publications, 1969 to 2005. The publications of the first thirty years are available as CD-version: Laser induced damage in optical materials. Collected papers. Published by the International Society of Optical Engineering, Washington, 98227-0010, 2005.

06ISO1 ISO 9211: Optical coatings, Parts 1–4, International Organization for Standardization 1994–2006.

06ISO2 Working groups of ISO/TC 172: Optics and photonics. International Organization for Standardization, website: `http://www.iso.org/iso/en/stdsdevelopment/tc/`.