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Origins of light scattering from thin film coatings

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ABSTRACT

The light scattering properties of multilayer coatings is substantially more complex than that of single surfaces. Yet new experimental methods and modeling techniques enable multilayer scattering to be investigated and analyzed in detail. In this article, the dominating factors influencing the scattering of near infrared suppressing interference filters are discussed. This is done by combining angle resolved light scattering measurements at different wavelengths with roughness metrology and simplified theoretical models. The impact of different sources of scattering, in particular substrate and coating roughness, interference effects, and local defects, are discussed in a quantitative manner. It will be demonstrated that the impact of nodular defects is negligible while the impact of interference effects is not.

1. Introduction

Light scattering of optical components can critically limit their performance. Light scattered out of the specular directions constitutes one of the main loss channels [1]. In addition, light scattered close to the specular directions can cause a significant decrease in image quality [Harvey2010].

The scattering properties of single optical surfaces like metallic mirrors are usually defined by their surface roughness and possible surface defects [2–6]. The scattering properties of interference coatings are substantially more complex [7–11]. The main factors are: (i) the nanostructural properties of all interfaces from the substrate to the top surface, (ii) the field distribution in the coating, and (iii) local defects below, within, and on top of the coating. The observed scattering is the result of a combination and interaction of these effects and usually strongly dependent on the wavelength of light and the multilayer design.

Because of the numerous potential sources of scattering and their interrelationships, multilayer scattering is virtually impossible to predict without detailed knowledge of all these influence factors. It is therefore of crucial importance to directly measure the scattering of coatings in the relevant spectral ranges. Scattering theories can then be used to analyze the observed scattering, to establish appropriate scatter models for the problem at hand, and, based on these models, to predict scattering properties for other sets of parameters.

In this paper, the light scattering properties of interference filters with high transmittance in the visible spectral range and broadband suppression of near infrared light are analyzed. Angle resolved scattering measurements at various wavelengths are used to quantify the scattering distribution and scatter losses. Additional surface roughness metrology and scatter modeling are then used to analyze the results and to assess the imperfections and their impact onto the performance of the coatings.

2. Samples

The filters were designed specifically for application in an instrument for spectral angle resolved light scattering measurements recently developed at Fraunhofer IOF and described in Section 3.2. The OPO light source used converts the light of an intense pulse laser (3ω Nd:YAG laser, wavelength 355 nm, pulse energy 500 mJ, pulse duration 5 ns) into two new collinear waves called signal and idler. While the signal wave can be tuned within the visible range between 445 nm and 710 nm, the corresponding idler wave is in the range from 710 nm to 1750 nm, both waves being linked with respect to their energies and phases [12,13]. Although not relevant for this paper, an additional frequency doubler can be used to extend the spectral range to 250 nm.

The NIR filter coating is used to suppress the idler signal without changing the beam direction during tuning. The requirements on the filter coating are thus: (i) high transmittance (>95%) in spectral range from 400 nm to 710 nm, (ii) low transmittance (<5%) from 710 nm to 1750 nm, (iii) low scattering (no quantitative specification), and (iv) high damage threshold (>1 J/cm^2).

The coatings were deposited by e-beam evaporation (Optorun e-beam deposition plant) on superpolished fused silica substrates with a diameter of 50 mm. Ta_2O_5 and SiO_2 were used as high index and low index materials, respectively. The substrate temperature was kept at 200 °C during deposition, and the deposition rates were 0.2 nm for the

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Ta_2O_5 and 0.6 nm for the SiO_2, layers. The film thickness was controlled with both optical and quartz thickness monitors. During deposition, the layers were densified with an RF-type ion source in order to produce coatings without any relevant shift after cooling and venting [14].

3. Measurement and modeling methodology

3.1. Roughness analysis

The nanotopographies of the samples before and after coating were measured using Atomic Force Microscopy (AFM; Bruker Dimension FastScan) at different positions and in different scan areas of $1 \times 1\ \mu m^2$, $10 \times 10\ \mu m^2$, and $50 \times 50\ \mu m^2$. In addition, White Light Interferometry (WLI; Zygo NewView™ 7300) was performed with 10x and 50x objectives. The surface power spectral density (PSD) functions were then calculated from the individual profiles and combined to Master PSDs as described in ref. [15].

The rms roughness, σ, can then be calculated according to [15]:

$$\sigma = \left(2\pi\int_{f_{\min}}^{f_{\max}} PSD(f)f\,\mathrm{d}f\right)^{-1/2} \tag{1}$$

where $f_{\min}$ and $f_{\max}$ are the lower and upper limits of the spatial frequency range of interest. Eq. (1) is valid for isotropic surface roughness, which is generally the case for polished and coated surfaces.

It has to be pointed out that while scattering is produced by all interfaces in coatings, the roughness measurements are only sensitive to the nanostructure of the uppermost surface. Therefore, additional models for the roughness evolution inside the coating are required to model the scattering properties as will be discussed in Section 3.3.

3.2. Light scattering measurements

Angle resolved light scattering (ARS) and total scattering (TS) are the main quantities to characterize the scattering properties of optical components. While TS is basically a number that corresponds to the scatter loss, ARS provides more detailed information about the scattering distribution and thus offers more information about the sources of scattering. ARS is defined as the scattered power normalized to the incident power and the detector solid angle. In addition, TS can be easily calculated from ARS by integration. More detailed information can be found, for example, in refs. [4,16], and the references therein.

The requirements on instrumentation for ARS measurements of high-quality optical components are challenging in particular with respect to sensitivity (scattered intensity down to $10^{-6}\ \mathrm{sr}^{-1}$), dynamic ranges (>10 orders of magnitude), linearity, and careful calibration to obtain absolute quantitative data [4,16]. Only specialized instruments (scatterometers) meet these requirements. Several instruments for highly sensitive ARS measurements in the visible spectral range have been developed at Fraunhofer IOF [11,17,18] and elsewhere [3,4,9,16]. Special setups even exist for the deep and extreme ultraviolet regions [19–21] and the mid- and far infrared [22–24].

All of these instruments are however restricted to certain laser wavelengths. More recently, instruments for spectral ARS measurements have been developed [25,26]. The instrument developed at Fraunhofer IOF and used for this study is described in more detail in ref. [26]. It is based on a high power optical parametric oscillator (OPO) light source that can be continuously tuned between 250 nm and 1750 nm with a spectral bandwidth of less than 0.05 nm. After passing a tunable attenuator system, a spatial filter consisting of two spherical mirrors and a pinhole is used to clean the incident beam. The beam diameter on the sample is approximately 2 mm. Arbitrary angles of incidence can be selected, although, for the present study, only quasi-normal incidence at 3° was used. The ARS is then measured by scanning a highly sensitive detector (photomultiplier tube) around the sample. Total backscattering (TS_b) and total forward scattering (TS_f) are determined by numerically integrating the ARS data over the reflection and transmission hemispheres, respectively.

In addition, a small sensor for rapid 3D ARS measurements was used [17]. For each position investigated on the sample, the 3D scattering distribution within a half-cone of 10° around the direction of specular reflection is measured with one shot (acquisition time 0.5 s). The integrated scattering, among other parameters, is retrieved from the ARS image and can be plotted against position on the sample (scatter map). Yet each data point is linked to an ARS image allowing for more detailed analysis of the sources of scattering.

3.3. Scatter models

The scattering of multilayer coatings is a complex process and for the purpose of this paper, only a brief and simplified description of the models used to describe such effects will be presented.

The angle resolved scattering of a multilayer coating consisting of N layers at the wavelength λ can be modeled using [7–9]. For the sake of simplicity, we confine ourselves to normal incidence and isotropic scattering:

$$\mathrm{ARS}(\theta_s) = \frac{1}{\lambda^4}\sum_{i=0}^{N}\sum_{j=0}^{N} C_i C_j^* \mathrm{PSD}_{ij}(f). \tag{2}$$

The optical factors C_i contain information about the field distribution inside the coating based on the design and interference properties. The PSD_{ij} are the PSD functions (for $i = j$) and the cross-correlation PSD functions (for $i \neq j$) of all interfaces. The link between the polar scatter angles θ_s, measured with respect to the sample normal, and the spatial frequencies f is given by the grating equation: $f = \sin\theta_s/\lambda$. Consequently, the spatial frequency range relevant for light scattering depends on the wavelength. For the present study, the total relevant spatial frequency range extends over two orders of magnitude in frequency from $0.02\ \mu m^{-1}$ to $2.49\ \mu m^{-1}$. The limits are determined by the smallest scatter angle (2°) at the longest wavelength (1750 nm) and the largest scatter angle (90°) at the shortest wavelength (400 nm), respectively.

Eq. (2) illustrates that the roughness-induced scattering from multilayer coatings depends on several factors: (i) the roughness properties of all interfaces from the substrate to the top surface, (ii) the cross-correlation properties of the interfaces, and (iii) the interference properties related to the design of the coating. In particular the lattermost factor implies a strong wavelength dependence in addition to the general $1/\lambda^4$ dependence also observed for other scattering mechanisms. This is discussed in detail, for example, in ref. [26] and will be important to understand the results of the present study.

The scattering from localized defects like particles, pits, or scratches is usually more difficult to describe than roughness-induced scattering. Theoretical models or experimental studies for the scattering from defects are presented, for instance, in ref. [27–32]. In contrast to roughness-induced scattering, the scattering from isolated defects depends on the size of the illuminating beam. Therefore, another quantity, the differential scattering cross-section (DSC), has to be used to describe the scattering properties [4]. For a single defect, DSC is simply ARS normalized to the area of the illumination spot: $\mathrm{DSC} = \mathrm{ARS}\ \pi D^2/4$, D being the beam diameter. The overall scattering of a sample will be the result of a superposition of the roughness- and the defect-induced scattering.

4. Results and discussion

4.1. Roughness analysis

Roughness is probably the most prominent source of scattering of optical components. It is known that the nanotopography, and thus the nanoroughness, of any interface in the coating is a result of a combination of: (i) the underlying interface topography replicated through