A simple system for measuring small phase retardation of an optical thin film

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ABSTRACT

This paper describes an experimental arrangement to determine phase retardations with changing signs around zero degree. In the experiment the phase retardation is caused by reflection from a non-periodic multilayer thin film reflector. A prism retarder is introduced in a common polarimetric measurement to act as a compensator in order to enable the measurement around zero degree phase retardation. Phase retardation within plus/minus a few degrees is measured in a broad spectral range using a fiber coupled spectrometer.

Keywords: Thin-film, Phase retardation, Optical mirror, Polarimetry.

1. INTRODUCTION

Optical thin films are used in a wide range of sensors and analytical instruments. Ultra-hard-coated (UHC) optical thin-films are of increased importance in all of the applications due to their good environmental stability and enhanced optical performance [1], [2]. An UHC thin-film can be deposited using one of several ion-assisted-deposition techniques. With the improvements to the process equipment and monitoring techniques in the last few years, up to several hundreds of layers can now be deposited on a single side of a substrate. This in turn has led to an increased performance of many filters with accompanying benefits in various fields e.g. classical fluorescence microscopy [3]. Depositing all layers on one substrate also means there is no need to glue several substrates together, which helps to reach a higher damage threshold in applications where high light intensities are used.

In many instruments however, there is also a need for thin-film coatings that are not only designed and optimized to have a high transmission and/or reflection in specific bands. In applications where laser beams are used, the exact polarization state of the beam can be of importance. When making such components there is a need to carry out a polarimetric measurement of the produced coating in the specified wavelength regions. Spectroscopic ellipsometers can be used for this but are often expensive, and depending on their configuration they can exhibit poor sensitivity in measuring polarization states with phase-retardation close to zero [4].

For this paper a dielectric thin-film coating with specific phase retardation characteristics was synthesized using proprietary thin-film design software [5]. The coating acts as a reflective mirror for 45 degrees angle-of-incidence (AOI) as well as inducing a spectrally dependent phase retardation on the incident light upon reflection. The phase retardation of the produced mirror was characterized using the setup described in this paper. The retardation angle was close to zero and changed sign several times within the bandwidth region under investigation. In order to accurately test the deposited thin-film coating an achromatic and temperature insensitive prism compensator was introduced in a simple polarimetric setup. Introducing the prism leads to a predictable off-set in phase retardation as described in [6]. This allowed the measurement of the phase retardation around zero degree to be easily carried out.

2. METHODOLOGY

The phase retardation was characterized using the polarimetric setup shown in Figure 1. The light source and detector were integrated in a Carl Zeiss Multi-Channel System; MCS-500, equipped with a CLH500 halogen lamp and a MCS501 UV-VIS spectrometer.

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Multimode fiber light guides are used to carry the light between the multi-channel system and the optical arrangement. The spectrometer records the broad band spectrum from the lamp, in effect covering the range from 350nm – 1050 nm, with a 0.8 nm/pixel resolution. The entire spectrum is acquired in one acquisition. Typical integration time for each measurement is about 20 ms. Two polarizers are used in the setup of the type Corning Polarcor^{TM} WIDE Band^{TM} with a specified extinction ratio > 40dB. A prism made of Schott Bk7 glass is inserted in the light path after the first polarizer. The coated thin film stack that is to be measured is positioned in a turning fixture that allows for the angle of incidence to be changed. The detector arm is moved to collect the light when the angle is changed.

Initially, the light is made linear polarized along an axis tilted at +45 degrees with respect to the plane-of-incidence of the coating by setting the angle of the first polarizer, P_p, to $\psi_p = +45$ degrees. In the setup shown below the light is then directed on to a prism where it experience total internal reflection at $\theta_{prism} = 45$ degrees. This induces a fixed phase retardation to the light as described in the analysis below. The light reflects off the coating at the designated angle θ, and the final state of polarization of the beam is analyzed by performing two measurements of the intensity with the polarization axis of the analyzer, P_a, in two different positions $\psi_a = +45$ degrees and $\psi_a = -45$ degrees. Before each measurement a reference- and a background signal are collected by the MCS-500 system.

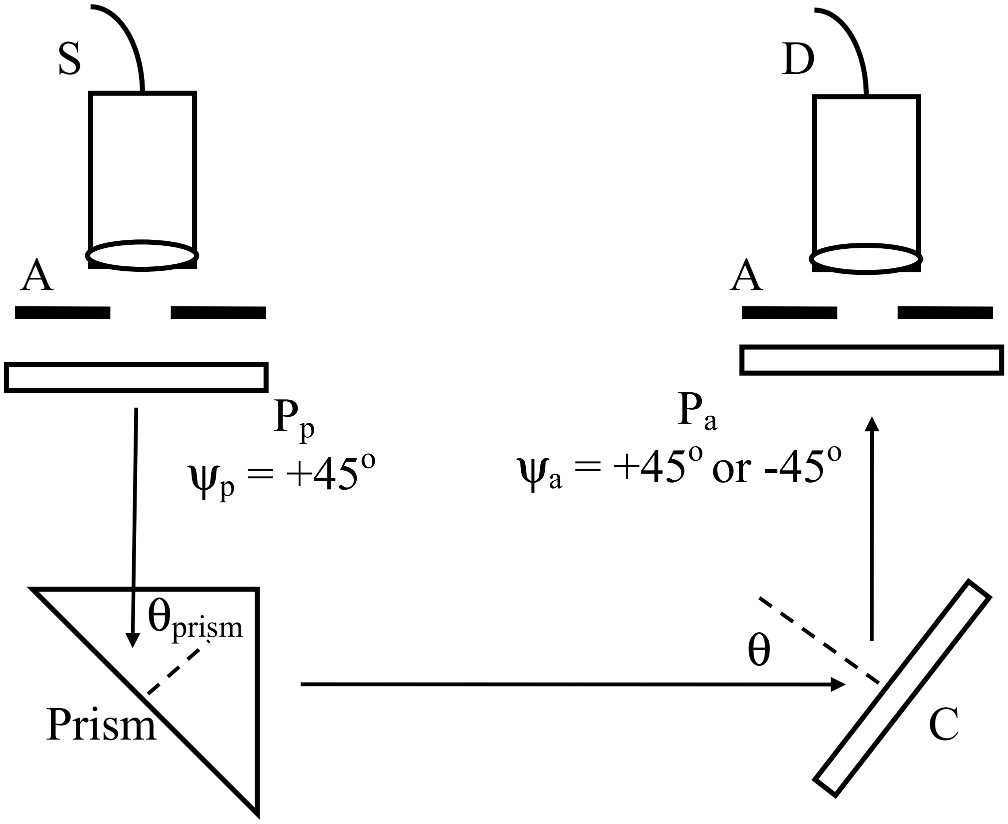


Fig. 1. Experimental arrangement for measuring phase retardation near 0^o: S source (CLH500); A aperture; Pp polarizer; C mirror coating that is to be characterized, Pa analyzing polarizer; D detector (MCS501). The angle of the polarization axis of the two polarizers to the plane-of-incidence of the light is ψ. The light is guided to the board using optical fibers.

The total transmitted intensity, I of the light impinging on the detector at a certain wavelength can be calculated using the Mueller matrices of the components. Following the analysis given in [6] [7] we write the intensity I relative to the input intensity I_0 as:

$$\frac{I}{I_0} = \frac{1}{2} \times \left\{ 1 + \cos\left(2\left[\psi_p - \psi_a\right]\right) \times \cos\left(\Delta + \delta_{prism}\right) \right\} \tag{1}$$

Here, $\Delta = \delta_p - \delta_s$ is the phase retardation introduced by the coating that we wish to know and δ_{prism} is the phase retardation introduced by the prism. Recording the spectrum at the two angles +45 degrees and -45 degrees of the analyzer, as indicated in Fig 1, we obtain from (1) a simple expression for deducing the phase retardation:

$$\frac{I_1 - I_2}{I_1 + I_2} = \cos\left(\Delta + \delta_{prism}\right) \tag{2}$$

Note, if the prism had not been inserted in the setup, the right hand side of (2) would only read $\cos(\Delta)$. From such a measurement it would not be possible to tell the sign of the argument when Δ changes around 0^o (or 180^o). The expression for the phase retardation of the prism as shown in [6] is:

$$\delta_{prism} = 2 \times \arctan\left\{ \sqrt{1 - \frac{1}{n^2 \sin^2\left(\theta_{prism}\right)}} \Bigg/ \tan\left(\theta_{prism}\right) \right\} \tag{3}$$

Here n is the refractive index of the prism. In the geometry chosen in Fig 1, θ_{prism} = 45 degrees which simplifies the right hand side in (3) to:

$$\delta_{prism} = 2 \times \arctan\left(\sqrt{1 - 2/n^2}\right) \tag{4}$$

The advantage of this approach is that the refractive indices for standard glasses are accurately known; hence δ_{prism} can be calculated with high precision. After performing the two measurements with the analyzer rotated in between the two angles, the phase retardation of the coating under investigation can be extracted from (2) and (4). This method was employed to extract the phase retardation curves shown in Section 3. Using data available from the Schott home page [8], the refractive index for Bk7 can e.g. be calculated using the Sellmeier dispersion equation:

$$n^2(\lambda) - 1 = \frac{B_1 \cdot \lambda^2}{\left(\lambda^2 - C_1\right)} + \frac{B_2 \cdot \lambda^2}{\left(\lambda^2 - C_2\right)} + \frac{B_3 \cdot \lambda^2}{\left(\lambda^2 - C_3\right)} \tag{5}$$

with the constants listed in Table 1. Similarly a relationship linking the refractive index change to a temperature change can be found in [8]. From (4) and (5) one finds that the prism introduces a nearly constant off-set in the phase retardation. In the ~170 nm bandwidth region under investigation in this paper the phase retardation of the prism e.g. changes by less than 1.3%.

Table 1. Sellmeier coefficients for Schott Bk7 glass [8].

B_1	1.03961212
B_2	0.231792344
B_3	1.01046945
C_1	0.00600069867
C_2	0.0200179144
C_3	103.560653

3. RESULTS

3.1 Design and production of a phase retardation mirror.

In order to design a thin-film coating with a specific phase retardation characteristic, the function-of-merit which describes the deviation of the coating from the desired target performance should include the appropriate terms for the P- and S-polarization phase delays. The method employed for synthesizing e.g. the coating described in this paper is presented by H. Fabricius elsewhere in this proceeding. Figure 2 shows the predicted transmission of the mirror for P- and S-polarized light at AOI = 45 degrees. The transmission is shown for +/- 10% bandwidth (BW) centered at the design reference wavelength λ_{ref} = 850 nm.

The mirror is designed and produced using TiO2 and SiO2 as layer materials. After designing the coating, the layer code is transferred to a commercial available coating system; SyrusPro from Lebold Optics in Germany [1]. The SyrusPro machine uses an advanced plasma source to densify the coating material evaporated from the electron guns. During deposition the growth is optically monitored through a witness glass. The error of an individual layer thickness during deposition is estimated from the transmission data and the data saved for subsequent analysis. Note however, that it is the optical compensated error which is of importance for the final transmission characteristic of the coating [9]. For the coating shown in Figure 2 the thicknesses of the layers were realized with an optical compensated error of less than 3%.

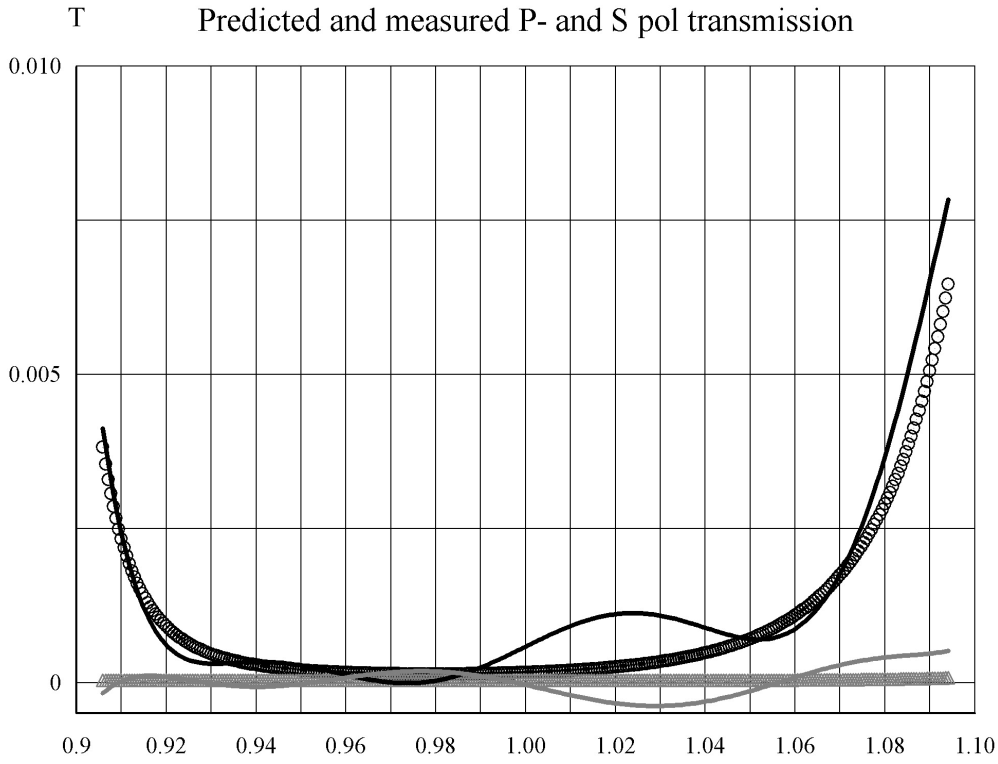


Fig. 2. Predicted transmission for P-pol (o) and S-pol (Δ) at AOI = 45 degrees for the mirror investigated in this paper, as a function of λ/λref. Measured transmission for P-pol (black line) and S-pol (grey line). The deviations are caused by noise due to the low light intensities from inserting a small aperture in the beam-path in the spectrophotometer during measurement.

After the component was produced the transmission was measured on a Perkin Elmer Lambda900 spectro-photometer. When performing the scan at 45 degrees, a polarizer was inserted in the beam path before the object and an extra aperture was used to reduce the opening angle. By turning the polarizer the P- and S-pol transmissions were successively measured. Special care was taken to avoid erroneous results from any height displacement of the beam in between the baseline scans and the scans of the mirror. The result of the measurement is also shown in Figure 2. The deviations of the measured and predicted curves observed are due to the finite integration time chosen that leads to noise in the measurement.

3.2 Result of phase retardation measurement

The phase retardation was measured using the experimental arrangement shown in Figure 1. In Figure 3 the curves obtained are shown together with that of the predicted phase retardation upon reflection at three different angles; 45^o and 45^o+/-7^o. The phase retardation is measured in the entire bandwidth region and passes continuously through 0 degrees at a number of instances. Note that no fitting was applied to the curves shown.

From the equations in Section 2 it is expected that uncertainties from the prism retarder to the phase retardation would shift the measurement up/down in the plots. The typical error however would be a fraction of a degree as indicated in the calculation after (8); Section 4 below. At the same time however, it is well known, that an offset in wavelength relative to the optical monitoring when depositing the coating would cause the spectral characteristic to shift, which in Figure 3 would translate the measured curve left/right.

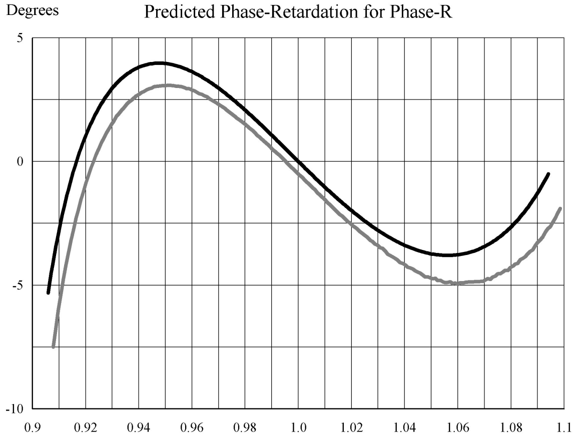
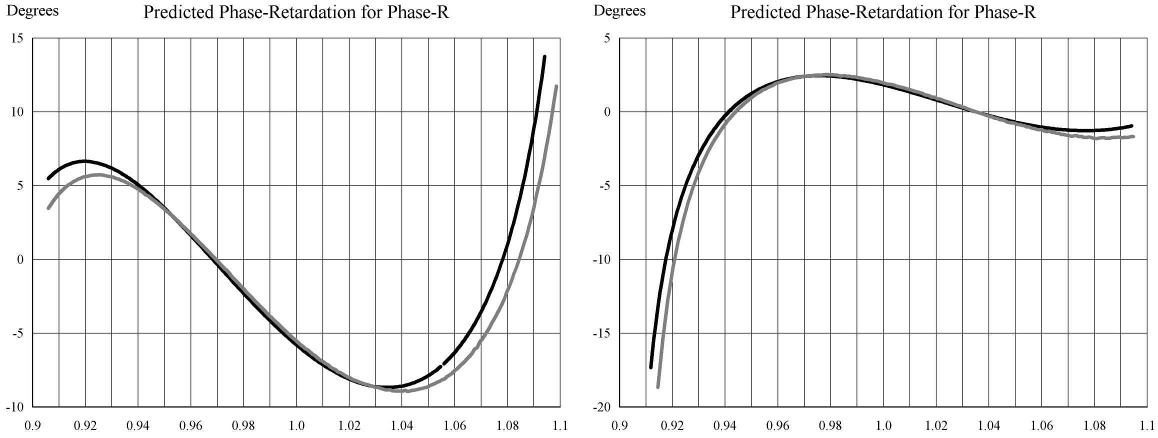


Fig. 3: Predicted (black) and measured (grey) phase retardation, as a function of λ/λref. *Left*: AOI = 45^o; *Lower left*: AOI = 52^o; and *Lower right*: AOI = 38^o. Deviations between measured and predicted performance is discussed in the next section.



4. DISCUSSION AND CONCLUSION

The influence of the prism on the sensitivity of the polarimetric measurement was analyzed thoroughly in [6]. It was shown that in general the higher the refractive index of the prism, the smaller the wavelength and temperature dependencies of the phase retardation. For the prism, as used in this experiment, it was shown that:

$$\left(\frac{\partial\delta}{\partial\lambda}\right)_{prism}=\frac{2}{\left(n(\lambda,T)^2-1\right)\sqrt{n(\lambda,T)^2-2}}\times\left(\frac{\partial n}{\partial\lambda}\right)_{prism} \tag{6}$$

Using (5) we calculate a value for $(\mathrm{d}\delta/\mathrm{d}\lambda)_{\mathrm{prism}}\sim -5.23\times10^{-5}$ rad/nm at λ_{ref}. From the expression for the dependence of the temperature [6]:

$$\left(\frac{\partial\delta}{\partial T}\right)_{prism}=\frac{2}{\left(n(\lambda,T)^2-1\right)\sqrt{n(\lambda,T)^2-2}}\times\left(\frac{\partial n}{\partial T}\right)_{prism} \tag{7}$$

and with the help of the equation for the refractive index change to temperature change [8], we estimate that $(\mathrm{d}\delta/\mathrm{d}T)_{\mathrm{prism}}\sim 2.41\times10^{-5}$ rad/K at λ_{ref}. The sensitivity of the phase retardation measurement to the angular alignment of the prism $(\mathrm{d}\delta/\mathrm{d}\theta)_{\mathrm{prism}}$ was also deduced in [6] and for the arrangement in Fig. 1 the expression is :

$$\left(\frac{\partial\delta}{\partial\theta}\right)_{prism}=\frac{2\times n\times\left(3-n^2\right)}{\left(n^2-1\right)\times\sqrt{n^2-2}} \tag{8}$$

This is an important measure as it includes the measurement limits both towards production tolerance on the prism as well as mechanical alignment and vibrations of the setup. Using the value of n for Bk7 at the design reference wavelength, we calculate that $(\mathrm{d}\delta/\mathrm{d}\theta)_{\mathrm{prism}} = 3.2149$. Hence with an uncertainty of e.g. $\mathrm{d}\theta = 4'$ the error on the phase retardation measurement as introduced by fabrication uncertainty in the prism and in the mechanical the setup is $\mathrm{d}\delta\sim 3.735\times10^{-3}$ rad or about 0.21 degrees. Given the experimental conditions, it is concluded that the largest contribution to an uncertainty in the phase retardation measurement as resulting from the prism, is caused by the mechanical alignment and production tolerance of the prism.

As noted from the numbers above the discrepancy observed for the curves in Figure3 can not solely be explained by the uncertainty introduced by the prism. However it is seen that the deviations in Figure 3 between the theoretical and measured phase retardation is mainly shifts in the vertical and horizontal directions. These shifts are well within the variations expected for the coating, taking into account the typical optical compensated errors on the thicknesses of the layers achieved in our deposition. In general the effect of layer errors on the design can be simulated in the design software [5]. An analysis of the errors recorded during deposition for the case of the mirror shown in Figure 3, shows that the horizontal shift is due to a wavelength offset of +0.5% while the vertical shift is mainly due to an extra -0.6% error on the thickness of the outermost layer in the stack. Introducing these changes to the design layer code, the phase retardation is calculated again and compared to the measurement. Figure 4 shows the improved correlation between theory and measurement. For continuous production of the mirror the wavelength offset can be corrected by introducing an offset in the optical monitoring wavelength.

In conclusion we have presented a simple experimental arrangement that allow to measure low value phase retardations around 0 degrees. The solution presented incorporates a prism that off-sets the retardation. In some spectroscopic ellipsometers a compensator is used to apply an off-set in the phase retardation, to allow the measurement of Δ around 0^{o} and 180^{o}, in a way similar to that of the prism above. The compensator typically has been reported as a wave- plate or Fresnel Rhombs e.g. [4] [7]. For the configuration displayed in this paper, the off-set created by the prism is highly achromatic and insensitive to temperature changes as shown. A calculation of the uncertainties introduced by inserting the prism show that prism tolerances and mechanical stability is of importance when establishing the setup. Creating different offsets by turning the prism in principle allows one to determine the phase retardation unambiguously of an unknown coating.

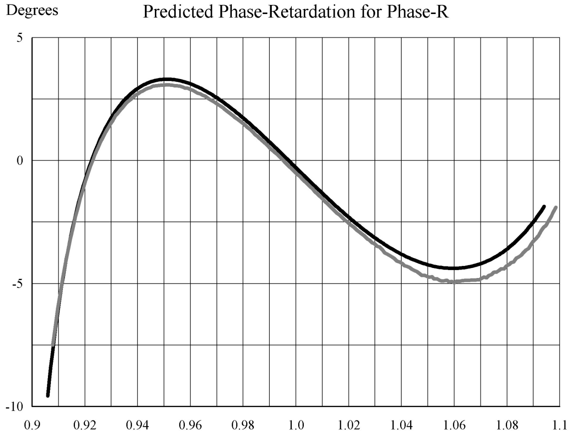
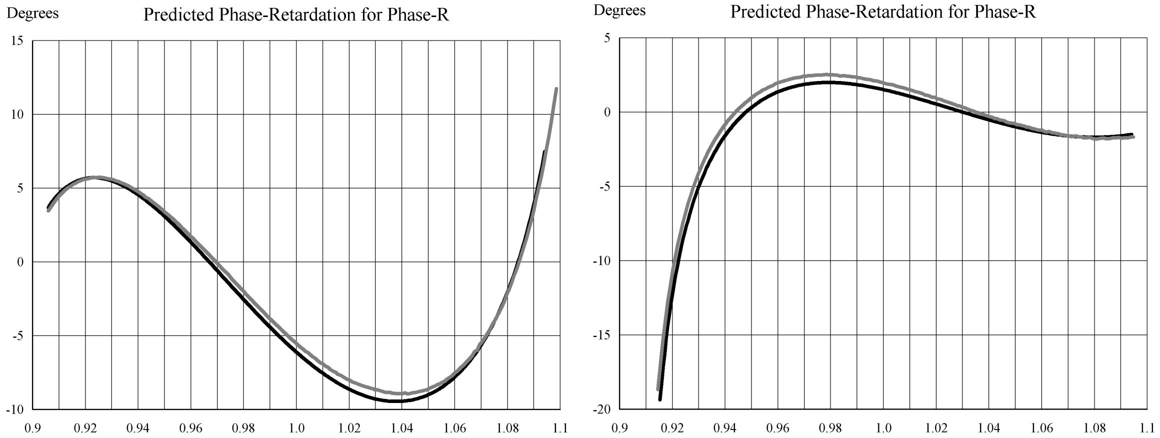


Fig. 4. Predicted (black) and measured (grey) phase retardation. *Left*: AOI = 45°; *Lower left*: AOI = 52°; and *Lower right*: AOI = 38°, as a function of λ/λref. The theoretical curve was corrected with a wavelength off-set corresponding to +0.5% and the last layer was made thinner with 0.6% in accordance with the error registered during deposition.



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