Design and production of antireflection coating for the 8–10 μm spectral region

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Abstract: A special design procedure allowing to trap layer thicknesses inside specified limits is applied for designing of antireflection coating (AR) for the infrared spectral band of 8–10 μm. The obtained AR design has no too thick layers that may cause delaminating of the deposited AR coating. A special monitoring procedure taking into account wavelength positions of monitoring signal extrema is applied for coating deposition. The manufactured coating features excellent AR properties in the requested spectral region and possesses high mechanical stability.

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1. Introduction

Antireflection (AR) coatings are the most widely used optical coatings. There are numerous publications devoted to the coatings of this type. Their main properties are considered in the well-known texts [1–3]. In these texts references to many early publications on methods for designing of AR coatings can be also found. About two decades ago it was demonstrated that designing of AR coatings is a relatively simple optimization problem and that series of excellent AR designs can be easily obtained [4–6]. Modern design techniques [7,8] enable one to design in a very short time AR coatings with spectral bands of several octaves for any set of thin film materials and substrates [9]. Nevertheless, developing of new approaches to the design of AR coatings still attracts attention of researchers [10,11]. In first turn this is connected with attempts to take into account additional practical demands that force one to search not for a formally optimal AR design but for a design meeting also additional feasibility conditions [12–15].

Formally optimal AR designs typically have several thick layers [9]. In the infrared (IR) spectral regions thicknesses of these layers can be about one micron and more. This may cause serious manufacturing problems because of delaminating of coatings with thick layers [16]. Thus there is a specific feasibility demand connected with manufacturing of AR coatings for IR spectral regions. This is obtaining of designs with layer thicknesses not exceeding some specified values. For this reason elaboration of a special design approach is required.

For AR coatings in IR regions above 5 µm zinc selenide (ZnSe) and yttrium fluoride (YF₃) are often used as coating materials. Sticking coefficients of these thin film materials are dependent on the temperature of the sample [17] and due to this fact it is practically impossible to apply indirect monitoring systems for layer thickness control. The reason is that indirect monitoring requires an accurate calibration of a monitoring system. This calibration is dependent on the temperatures of substrate and witness chips that are usually different. Because substrate and chips are transparent in the IR region, it is difficult to control their temperatures accurately and thus accurate calibration of indirect monitoring is also difficult. Therefore a special direct optical monitoring approach should be developed for the manufacturing of AR coatings for the 8–10 µm spectral region.

In Section 2 we present a special design approach that takes into account upper limits on thicknesses of AR coating layers. Our monitoring approach and production environment are discussed in Section 3. Final conclusions are presented in Section 4.

2. Design approach

We consider designing of AR coating for BaF₂ substrate with low reflectance in the spectral region of 8–10 µm. Layer materials are ZnSe and YF₃. Refractive indices of ZnSe and YF₃ are taken from II-VI Infrared [18] and Materion Resource Center [19] data, respectively, and are presented in Fig. 1.
Refractive index profile and reflectance of the “classical” AR design obtained using the gradual evolution design procedure [8] are presented in Fig. 2. The total physical thickness of the obtained design is more than 6.5 µm and five of seven design layers are quite thick with the thicknesses ranging from 0.85 µm to 1.78 µm. The obtained design has excellent antireflection properties but it is not feasible because coatings with so thick layers can easily delaminate from the substrate. So our goal is to design an AR coating with essentially thinner coating layers.

To design AR coatings with upper limits for layer thicknesses we apply a new feature of OptiLayer thin film software which is called “Trapping” [20]. This feature allows one to constrain thicknesses of certain design layers when applying various design techniques such as Needle Optimization or Gradual Evolution techniques [7,8]. During the design procedure thicknesses of such layers are trapped inside specified limits. We specify upper limits of 0.6 µm for the high index ZnSe layers and upper limits of 0.667 µm for the low index YF3 layers.

Having in mind the broad band monitoring procedure that will be applied for the manufacturing of AR coating (see the next Section), we also try to avoid too thin design layers. For this reason during the design procedure low limits of 0.05 µm are specified for all design layers.

The refractive index profile and reflectance of the AR design that was obtained using the Trapping option are presented in Fig. 3. Residual reflectance of the obtained design is a bit worse than that of the “classical” design but nevertheless it is still very low. It is less than 0.1% in the AR spectral region from 8 to 10 µm. At the same time the new design is nearly two times thinner. Its total physical thickness is only 3.5 µm. But the most essential fact is that it has no too thick design layers as before.
The sensitivity of the obtained result to possible production errors was investigated by performing 1000 statistical tests with randomly generated thickness errors and then the same number of tests with random errors in layer refractive indices. The red curve in Fig. 3(b) presents the mathematical expectation of the design reflectance for the case of thickness errors with 5% root mean square (rms) relative deviations of layer thicknesses from their nominal values. Grey area in this figure marks a corridor specified by the standard deviation of reflectance variations caused by these errors. In the case of errors in layer refractive indices about the same corridor of reflectance variations is observed when rms relative variations of layer refractive indices are only 2.5%. This result is in line with the results of [21] indicating a strong influence of errors in refractive indices on spectral properties of AR designs.

Fig. 3. Refractive index profile (a) and reflectance (b) of the AR design with constrained layer thicknesses (black solid curves). The red curve (b) presents the mathematical expectation of the design reflectance and the grey area (b) illustrates the influence of thickness errors on the design reflectance.

3. Monitoring and production

The designed AR coating was manufactured using vacuum chamber equipped with cryogenic pump, ion source for pre-production substrate cleaning, and broad band monitoring system based on NIRQuest512 spectrophotometer [22]. ZnSe layers were deposited by e-beam evaporation with 6–8 Å/sec rate while YF₃ were deposited by boat evaporation from molybdenum boat with 15–18 Å/s rate.

The NIRQuest512 spectrophotometer performs measurements in the essentially different spectral region than the planned AR region of 8–10 µm. In our case measurement data were collected in the spectral region from 1.3 to 2.3 µm. There are many other factors complicating reliable monitoring of layer thicknesses. These are: some non-linearity of monitoring signal in the 0–100% range, possible deviations of actual layer refractive indices from the used nominal data, growing in time contaminations of input and output windows of the optical monitoring tract, etc. Due to the above factors high deviations of the broadband monitoring measurement data from the theoretically predicted spectra are observed. It is therefore not reliable to monitor layer thicknesses only by the discrepancy between measurement and theoretical data. In [23] we proposed to terminate layer depositions also according to the correspondence between wavelength positions of measured spectrum extreme values and theoretically predicted positions of extreme values at the end of layer deposition. Figure 4 illustrates this approach by presenting measured transmittance and theoretically predicted transmittance at the end of deposition of layer number 7. In this case all deviations between measured and theoretical extremum positions are less that 1% of respective extremum wavelengths. Usually these deviations are smaller in the case of high index outer layers but for all layers they never exceeded 3% of respective extremum wavelengths.
The monitoring spectral region is located far away from the planned AR spectral region. Therefore layer optical thicknesses in these regions are noticeably different. The above monitoring approach works correctly only if relations between optical thicknesses in these regions are known accurately, i.e., only if dispersion behaviours of both layer material refractive indices are specified correctly. In our calculations we use ZnSe and YF$_3$ refractive indices from the reliable sources. It is possible that refractive indices of deposited films are somewhat different from these indices due to variations in film packing densities. This effect however may have only an insignificant effect on the ratios of refractive index values in different spectral regions. Therefore our monitoring approach works correctly for the AR spectral region of 8–10 µm.

Figure 5(a) compares measured transmittance of the manufactured AR coating with the theoretical transmittance of AR design in the spectral region from 2 to 10 µm. One can observe a very good correspondence between wavelength positions of measured transmittance extrema and theoretically predicted positions of transmittance extrema. This is an evidence of correctness of the applied monitoring approach as well as of correctness of the used dispersion behaviours of ZnSe and YF$_3$ refractive indices. In the AR spectral region from 8 to 10 µm the measured transmittance is close to the theoretical transmittance and it differs from 100% mainly due to the reflection from substrate back side (see Fig. 5(b)).
In summary it is necessary to underline that the manufactured coating possesses high mechanical stability along with excellent AR properties in the requested spectral region.

4. Conclusions and discussion

Classical AR designs for the IR spectral region have thick design layers that may cause delaminating of deposited coatings. A special design option called “Trapping” allows us to obtain the AR design without thick layers for the 8–10 µm spectral region. We use ZnSe and YF₃ as coating materials and deposit respective layers using e-beam and boat evaporations. Broad band optical monitoring of layer thicknesses is performed in the 1.3–2.3 µm spectral region. The proposed monitoring approach taking into account wavelength positions of monitoring signal extrema provides an accurate control of layer thicknesses. The manufactured AR coating has excellent spectral properties and posses high mechanical stability.

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