Antireflection optical coatings for the visible spectral range

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In this paper, a design for a reliable antireflection coating is proposed. This is, probably, among the best combinations of a maximum imposed number of six layers for an antireflection coating, heaving a very good efficiency, a good reproducibility and a durable coating package. The applications refer to visible spectral range, widely ordered in optical industry.

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1. Introduction

The role of antireflection coatings is to reduce the stray reflections on the surfaces of optical components and to increase the transmission. Depending on the refractive index of glass, that undesirable reflection may have values, mostly between 4% and 8% of incident radiation, according to the Fresnell low [1, 2]:

$$R = \left(\frac{n_1 - n_2}{n_1 + n_2} \right)^2 \qquad (1)$$

where:
n_1 is the refractive index of medium of incidence (mostly air, $n_1 = 1$);
n_2 is the refractive index of the optical glass.

Over years, many solutions was presented in the literature for antireflection coatings, from a single layer to more than fifteen layers package and with action from a single wavelength to wide spectral domains [3 - 9], but this article is attempt to share a reliable formula that combine four important characteristics:
- excellent reduction of reflection on a wide spectral domain: [400 700] nm;
- a minimum number of layers (only six layers package);
- a combination of coating materials with high compatible internal stress;
- high technological reproducibility.

2. Coating design

In this application, in order to obtain an antireflection formula for the visible spectrum, we will start from a minimum of four quarterwave layers, in the best combination of materials, in terms of internal mechanical stress [10]. Thus, a package of four layers of TiO_2 ($n_d \approx 2.3$) and SiO_2 ($n_d \approx 1.46$) with $\lambda_0/4$ optical thickness (where $\lambda_0 = 440$ nm) was chosen to make the coating on a BK7 optical glass surface ($n_d \approx 1.52$), according to formula (2)

$$\text{Air} - SiO_2\ TiO_2\ SiO_2\ TiO_2 - \text{BK7} \qquad (2)$$

were:
Air is the incidence medium
BK7 is the emergent medium
SiO_2 is a layer of SiO_2 with $\lambda_0/4$ optical thickness, where $\lambda_0 = 440$ nm
TiO_2 is a layer of TiO_2 with $\lambda_0/4$ optical thickness, where $\lambda_0 = 440$ nm

Based on the theory of thin optical layers [3, 4], the software application ATTOL (Applied Theory of Thin Optical Layaers) was created, in order to generate theoretical transmission and reflection graphs for this type of optics. In this respect, formula (2) was generated the graph of reflection, on visible spectral domain, presented in Fig. 1.

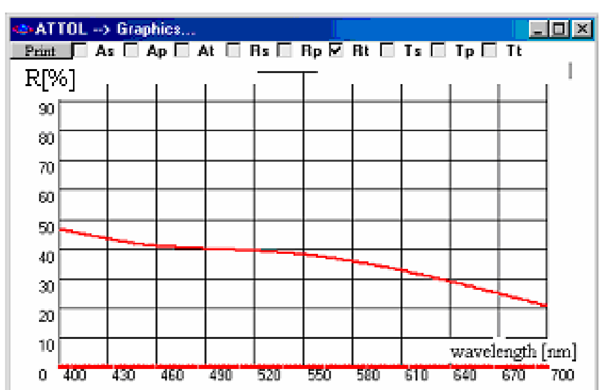

Fig. 1. Theoretical spectral reflection on a coated BK7 glass according to formula (2).

Of course, this is not an antireflection coating but, in order to obtain a decreasing in reflection, will be made an optimization. In this respect, ATTOL was enriched with a merit function "M" (3) and an optimizing algorithm.

$$M = \frac{\left[\sum_{i=1}^{N_T} (V_i^T - V_i)^2 \right]^{\frac{1}{2}}}{N_T} \tag{3}$$

where:

V_i^T is the value of target;

V_i is the value of function at the step "i", during the optimization;

N_T is the number of targets.

The optimizing algorithm consist in repeated cycles, when each layer of structure is decreased with a value δg_q and then is increased with the same value, resulting three values of Vi (optimized function) and three values of merit function, according to the three values of layer thickness (g_q; $g_q - \delta g_q$ and $g_q + \delta g_q$). Thus, at each step in a cycle, will be compared the three values of the merit function and the smallest value will set the new thickness of the "q" layer.

In this respect, setting δg_q as 1% of initial thickness of each layer, step of calculation as 2 nm, $V_i^T = 0$ and working spectral domain as [400 700] nm, after optimization, formula (4) and a spectral reflection according to the grapf from Fig. 2 were obtained:

Air – 1.39SiO_2 0.55TiO_2 0.54SiO_2 0.38TiO_2 - BK7 (4)

where the coefficients are fractions of $\lambda_0/4$ optical thickness and λ_0 = 440 nm

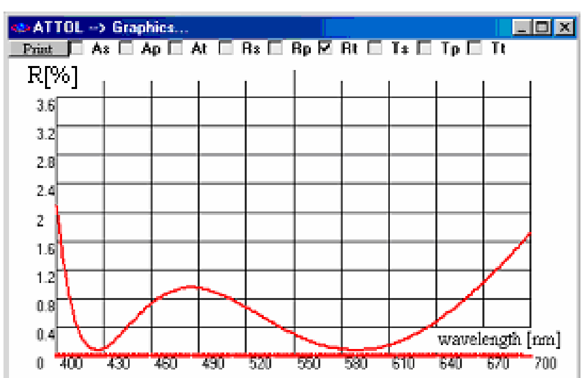

Fig. 2. Theoretical spectral reflection on a coated BK7 glass according to formula (4).

Although this coating is not achieved a significant reduction in reflection, is important to note that the package have a multi-layer structure with high compatibility in terms of internal stress [10] and the optical properties can be improved by adding a new pair of layers. This time, in order to maximize optical efficiency, will be chosen the largest difference of refractive indices available: TiO_2 ($n_d \approx 2.3$) and MgF_2 ($n_d \approx 1.38$). Adding these two new layers with optical thickness $\lambda_0/4$ (where λ_0 = 440 nm) to the interferential package from formula (4) and making a new optimization, formula (5) and a theoretical spectral reflection curve, according to the grapf from Fig. 3 will be generated.

Air – 1.36MgF_2 0.51TiO_2 0.50SiO_2 0.61TiO_2 0.63SiO_2 0.22TiO_2 - BK7 (5)

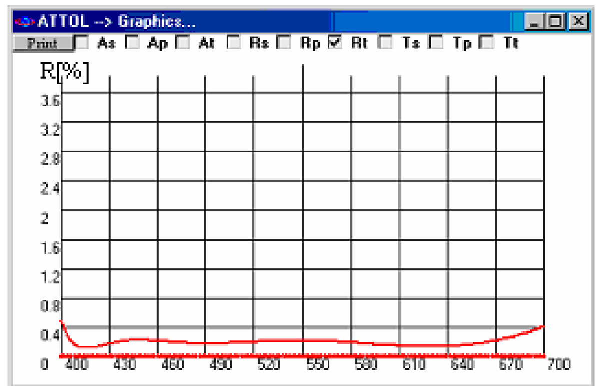

Fig. 3. Theoretical spectral reflection on a coated BK7 glass, according to formula (5).

Now we got an excellent formula in terms of optical properties too. Another way to get an advanced antireflection formula, using the optimizing algorithm described above is to make an optimization, directly, starting from quarterwave multilayer stack (formula (6) and Fig. 4).

Air – MgF_2 TiO_2 SiO_2 TiO_2 SiO_2 TiO_2 - BK7 (6)

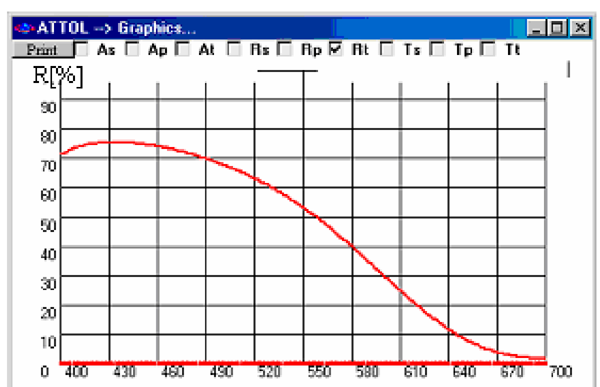

Fig. 4. Theoretical spectral reflection on a coated BK7 glass, according to formula (6).

Setting the same parameters as with the first optimization, and making a new numerical refinement, formula (7) and a theoretical spectral reflection curve, according to the grapf from Fig. 5, will be generated.

Again, an advanced theoretical antireflection curve was obtained.

$$\text{Air} - 1.28MgF_2\ 0.62TiO_2\ 0.33\ SiO_2\ 0.88TiO_2\ 0.49SiO_2\ 0.30TiO_2 - \text{BK7} \quad (7)$$

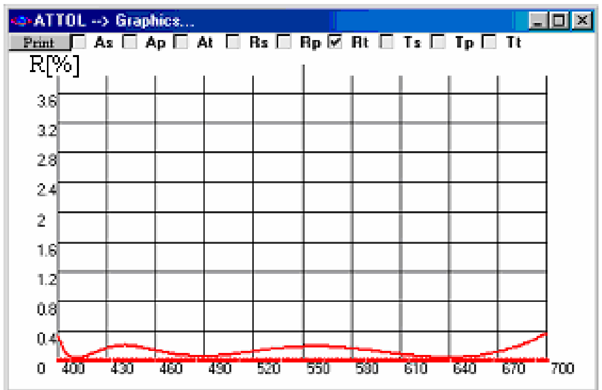

Fig. 5. Theoretical spectral reflection on a coated BK7 glass, according to formula (7).

3. Experimental results

Fig. 6 represent a real spectral reflection curve, measured on a BK7 glass plate, coated with an antireflection package according to formula (7). The experimental results were obtained with a Balzers BAK 550 coating machine. The graph presented is one of the most similar to the theoretical one (Fig. 5), but depending on a variety of physical and human factors, that define the real parameters of a coating technological process, the shape of spectral reflection curve can differ from a charge to another. However, if not occurring an unwanted incident during the coating process, the relative spectral reflection curve will fit every time less than a maximum value of 0.3% in most of the spectral range of interest.

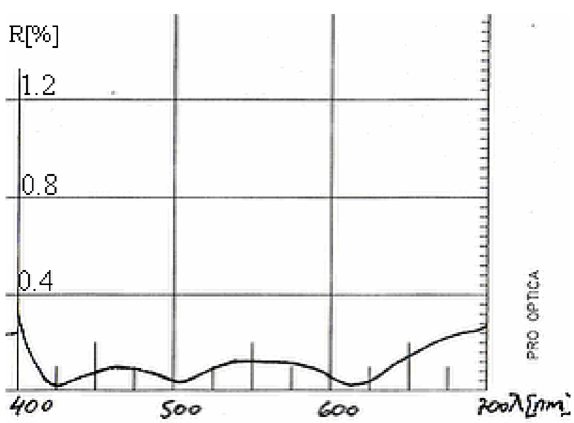

Fig. 6. Measured spectral reflection on a coated BK7 glass, according to formula (7).

4. Conclusion

A reliable technique for designing an antireflection coating that reduces the total reflection from 4.2% to less than 0.2%, in the case of a BK7 optical glass, was presented. Also, were presented experimental results obtained with a Balzers BAK550 coating machine. The design was made using the stress compatibility criteria in selecting of optical materials to forming the main body of interferential package and a combination of a properly constructed merit function (2) and a properly constructed optimizing algorithm (described in the paragraph 2). In this way we avoided the use of inhomogeneous optical materials such as ZrO_2, or other combination of materials, generating stress in multilayer structure. Finally, to get a good concordance between theoretical and experimental results, optical parameters of the materials should be regularly verified by different techniques, such as ellipsometry, evanescent wave techniques [11], spectrometric measurements etc.

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