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ANTIREFLECTION OPTICAL COATINGS FOR THE SPECTRAL RANGE $400-700\,\mathrm{nm}$, $400-900\,\mathrm{nm}$ AND $800-1600\,\mathrm{nm}$

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The work is devoted to the design of high performance antireflection (AR) coatings for VIS and NIR spectral range for volume production. The task was to overcome the difficulty to obtain high quality coatings, with optical constants and geometrical thickness to be in close tolerances: the first step was to use optical materials with stable optical constants, easy to be reproduced in the volume production and secondly, to reduce as much as possible the number of thin layers, in order to reduce the probability of errors. The design of such AR coatings is considered, taking into account the above mentioned conditions. The needle optimisation method, a synthesis method, was approached. To reduce the number of layers, the Herpin equivalent was used – to search for an equivalent layer made of a material with a refraction index very close to the equivalent refraction index of the equivalent layers. The optimisation process goes on in this circumstance until no more thin layers could be equivalently done.

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1. Introduction

The AR coating is the most used optical coating in all the optical systems, in order to reduce the losses. Thus, to achieve a high quality AR coating is a need in the optical systems. The design of a high quality AR coating is not an easy task to be done, since of the limitation in the optical materials diversity to be used in practice and the optimal thin film structure to be realised in order to obtain the lowest reflectivity. The optical AR coatings designed in this paper are valid for the spectral ranges $400-700\,\mathrm{nm}$, $400-900\,\mathrm{nm}$ and $800-1600\,\mathrm{nm}$, respectively. The following conditions have been designed using optical glass sorts with indexes in the range $1.48 \div 1.85$ (each optical coating has versions for index ranges as follows: $1.48 \div 1.56$; $1.56 \div 1.65$; $1.65 \div 1.75$; $1.75 \div 1.85$):

- *Visible antireflection coating:*
$R(\lambda)\langle 1\%$ for $400 \le \lambda \le 700\,\mathrm{nm}$;
$R(\lambda)\langle 0.4\%$ for $450 \le \lambda \le 650\,\mathrm{nm}$;
$R_{\mathrm{average}}(\lambda)\langle 0.3\%$, averaging on the spectral range $400 \le \lambda \le 700\,\mathrm{nm}$;
- *Antireflection coating for the spectral range* $400-900\,\mathrm{nm}$
$R(\lambda)\langle 1\%$ for $400 \le \lambda \le 900\,\mathrm{nm}$;
$R(\lambda)\langle 0.6\%$ for $450 \le \lambda \le 850\,\mathrm{nm}$;
$R_{\mathrm{average}}(\lambda)\langle 0.5\%$, averaging on the spectral range $400 \le \lambda \le 900\,\mathrm{nm}$;
- *Antireflection coating for the spectral range* $800-1600\,\mathrm{nm}$
$R(\lambda)\langle 1\%$ for $800 \le \lambda \le 1600\,\mathrm{nm}$;
$R(\lambda)\langle 0.6\%$ for $850 \le \lambda \le 1550\,\mathrm{nm}$;

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$R_{average}(\lambda)\langle 0.5\%$, averaging on the spectral range $800 \le \lambda \le 1600\,nm$;

The design of an optical AR coating can be started either analytically or numeric. The analytical design [1-7] start from the solved equations describing the reflection factor for a wavelength, a predetermined number of thin layers, optical thickness multiple of $\lambda/4$. With the optical constants already selected for some materials, the optical constants of the remained materials are determined. The solution providing a spectral range with a low reflection are (solution given for 1.52 substrate index, the counting of layers started from the incident medium, namely the air):

I) $\lambda/4$ - $\lambda/2$ - $\lambda/4$, with indexes: $n_1 = 1.38$, $n_2 = 2.2$, $n_3 = 1.62$;

II) $\lambda/4$ - $\lambda/4$ - $\lambda/4$ - $\lambda/4$, with indexes: $n_1 = 1.38$, $n_2 = 2.2$, $n_3 = 2.435$, $n_4 = 1.837$;

The problem of these solutions is that we don't find always optical materials having identical optical constants to those theoretically determined. Also, the optical materials (including the coating substrate) are dispersive, leading to the increase of the reflection factor. However, these solutions can be starting solutions for the design (optimisation) of some coatings using optical materials with optical constants very close to those theoretically deducted [8]. When there is no optical material, it can be equated to a combination of thin layers [9].

The numerical design appeals to the optimisation and synthesis methods. The optimisations methods start from a given combination of thin layers (the starting solution) which is optimised [10-15] to satisfy the imposed requests (the decrease of the reflection factor on an imposed spectral range). By using the optimisation methods, one can design high performance coatings [16-18], however with this methods, the starting solution [19-20] is very important. The synthesis methods [20-22] start from the requests imposed to the coating by the merit function and starting from a single layer, new layers are added, made of predetermined materials up to get the wanted performances. After introducing new layers, the coating is optimised.

Using the above-mentioned design techniques, very high performance optical coatings can be designed, however, they have a complicated solution the most of time. When the optical coating is intended to a large production, the optimum optical coating is that one giving the best performance (yield) during the manufacturing [23], disposing of a given technical endowment. So that an optical coating should be reproducible during the manufacturing process, the optical materials had to have reproducible optical constants in a very close tolerances, a minimal number of layers and to be stable at small errors that can appear during the manufacturing process.

2. Used materials

Generally, the optical AR coatings for VIS and NIR spectral range use optical materials such as ZrO_2, HfO_2, Ta_2O_5, Subs 2 (Merk) as high index material, CeF_2, MgO, Al_2O_3 as intermediate indexes materials and MgF_2, SiO_2 for low index materials. From our experience, the materials ZrO_2 [24-26] and HfO_2 [27] have a small dispersion of the refraction index, a low absorbance, a good mechanical resistance and chemical stability, however, the thin layers are non-homogeneous and the materials show difficulties in the evaporation process. To neglect the refraction index non-homogeneity results in getting non-performing optical coatings [28]. It is easy to evaporate Ta_2O_5, the index dispersion is low a good mechanical resistance and chemical stability, but generally the absorption is high, since of the lack of stoichiometry. To obtain non absorbent Ta_2O_5 layers it is recommended to use reactive deposition (ionized oxygen atmosphere) or ion assisted deposition. The last method is out of discussion for us. A high index material with a very good reproductibility of the optical constants is TiO_2. As a low index material it is used MgF_2 showing a good reproductibility of the optical constants. Considering all these features, the materials we can use in designing a high performance AR optical coating are: ZrO_2, Al_2O_3, TiO_2, and MgF_2 (we use maximum 4 materials since the electron beam evaporator ESQ 110 BALZERS, which is used by us, doesn’t allow more than 4 materials). The optical constants for the selected optical materials are:

MgF_2 - non-dispersive, non-absorbent, $n=1.38$;
Al_2O_3 - non-dispersive, non-absorbent, $n=1.63$;
ZrO_2 - dispersive, non-absorbent, non-homogeneous; the dispersion equation is:

$$n^2 = A_0 + A_1\lambda^2 + A_2\lambda^{-2} + A_3\lambda^{-4} + A_4\lambda^{-6} + A_5\lambda^{-8},$$

with:

$$A_0 = 4.6704998;\ A_1 = -4.1180861\times10^{-1},$$
$$A_2 = 9.9610612\times10^{-2}\quad A_3 = -7.3837191\times10^{-3},$$
$$A_4 = 1.76119701\times10^{-3},\ A_5 = -8.9841393\times10^{-5}$$

The refraction index decrease [24] from n to $n-\Delta n$, with $\Delta n = 0.24$, starting from the substrate, on a $60\,\text{nm}$ thickness, and then it remain constant.

TiO_2 - dispersive, non-absorbent; the dispersion equation is:

$$n^2 = A_0 + A_1\lambda^2 + A_2\lambda^{-2} + A_3\lambda^{-4} + A_4\lambda^{-6} + A_5\lambda^{-8}$$

with:

$$A_0 = 4.4275928;\ A_1 = -1.4550173\times10^{-2};$$
$$A_2 = 4.4787747\times10^{-1};\ A_3 = -1.1592131\times10^{-1};$$
$$A_4 = 2.0281209\times10^{-2};\ A_5 = -9.2502678\times10^{-4}$$

3. Design of optical coatings

In this paper we report the design of an AR coating for $400-900\,\text{nm}$ spectral range, using needle optimisation in the frame of program STRAT V6.2 [29] using as optical materials TiO_2 and MgF_2. The refining program of optimisation begins from the start solution: a MgF_2 layer of thickness 7λ, $\lambda = 500\,\text{nm}$. The resulting coating consists from 19 thin layers. The parameters of the coating are shown in Table 1. The spectral reflection factor is shown in Fig. 1.

Table 1. The coating parameters.

No.	Film	d, nm	No.	Film	d, nm
1	MgF_2	109.056	11	MgF_2	244.930
2	TiO_2	28.218	12	TiO_2	8.492
3	MgF_2	10.019	13	MgF_2	77.446
4	TiO_2	4.713	14	TiO_2	6.000
5	MgF_2	11.642	15	MgF_2	1.000
6	TiO_2	54.027	16	TiO_2	0.377
7	MgF_2	22.234	17	MgF_2	215.313
8	TiO_2	10.533	18	TiO_2	2.458
9	MgF_2	16.541	19	MgF_2	35.879
10	TiO_2	13.331			

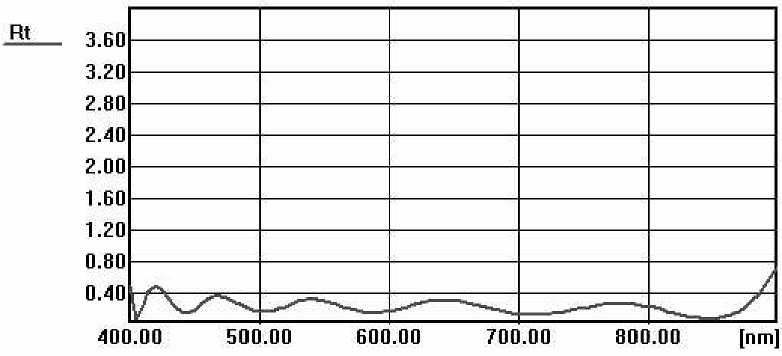

Fig. 1. Reflection factor for the $400-900\,\text{nm}$ antirefletion coating.

The designed coating contains relatively a great number of thin layers. The very thin optical thickness layers have been eliminated, after eliminating each layer, the coating has been reoptimised. The layers with optical thicknesses greater than 2λ have been reduced by multiples of 2λ (for example 2.3λ is reduced to 0.3λ), after each reduction, the coating has been reoptimised. After this operations some TiO_2 and MgF_2 groups of layers have been equivalent with a single layer of ZrO_2 or Al_2O_3, using the facilities of the computer program STRAT V6.2 regarding the equivalent indexes [30]. The selection of the equivalent layers is done by the designer. After each equivalent operation of the layers, the coating has been reoptimised. The resulted coating consists of 6 layers (for glasses with index $n = 1.65$ the number of the layers could be decreased to 5). The coating parameters are given in Table 2. The spectral reflection factor is shown in Fig. 2.

Table 2. Coating parameters (6 layers).

No.	Film	d, nm	No.	Film	d, nm
1	MgF_2	93.478	4	MgF_2	16.486
2	ZrO_2	66.162	5	TiO_2	21.097
3	TiO_2	83.960	6	Al_2O_3	79.678

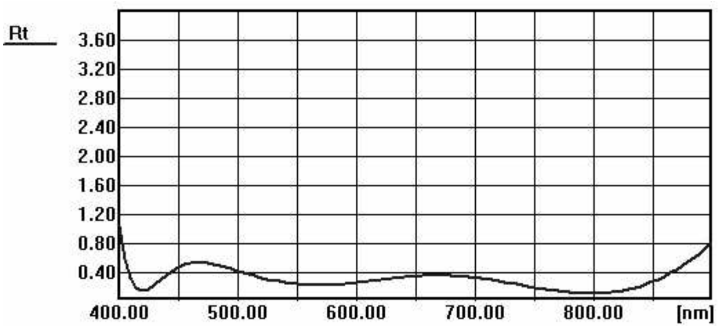

Fig. 2. Reflection factor for the $400-900\,\text{nm}$ antirefletion coating.

The optical coating obtained for the spectral range $400-900\,\text{nm}$ has been scaled and optimised on the spectral ranges $400-700\,\text{nm}$ and $800-1600\,\text{nm}$, respectively. The solutions of the optical coatings are given in Table 3.

Table 3. The antireflex coating for the spectral range 400 – 700 nm :

No.	Film	d, nm	No.	Film	d, nm
1	MgF_2	83.119	4	MgF_2	25.635
2	ZrO_2	39.624	5	TiO_2	12.634
3	TiO_2	88.313	6	Al_2O_3	25.325

The spectral reflection factor is shown in Fig. 3.

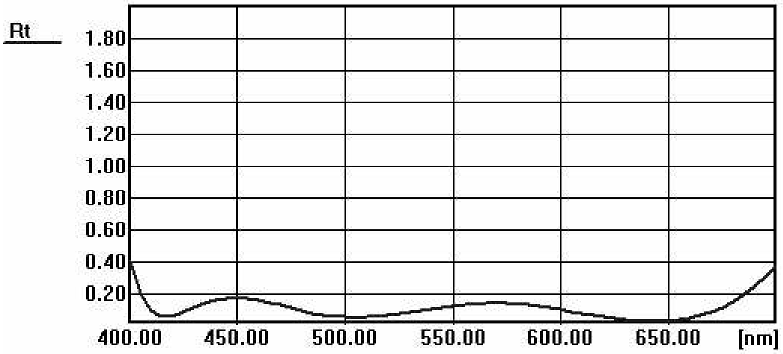

Fig. 3. Reflection factor for the 400 – 700 nm antirefletion coating.

This solution is very close to the (II) analytically solution.

Table 4. The antireflex coating for the spectral range 800 – 1600nm .

No.	Film	d, nm	No.	Film	d, nm
1	MgF_2	156.769	4	MgF_2	45.588
2	ZrO_2	90.238	5	TiO_2	29.767
3	TiO_2	224.517	6	Al_2O_3	76.631

The spectral reflection factor is shown in Fig. 4.

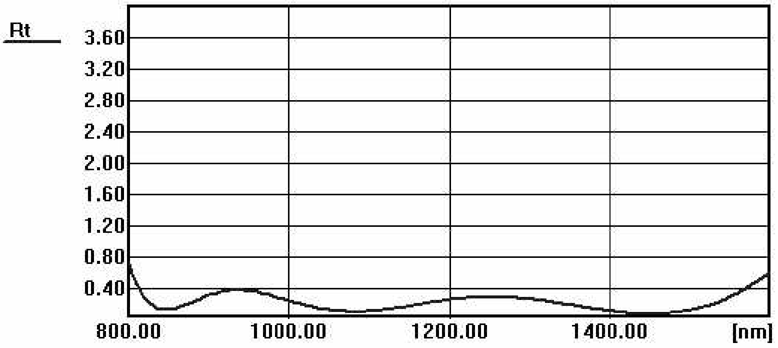

Fig. 4. Reflection factor for the 800 – 1600nm antirefletion coating.

4. Conclusions

The designed optical coatings satisfy the conditions for the imposed reflectivity and the advantage consists in using maximum one layer of ZrO_2, the optical thickness less than $\lambda/4$. Moreover, the optical materials have a good reproducibility of the optical constants. The solutions can be easily adapted for different glasses. The experimental results are in good agreement with the theoretical ones. For the spectral range $800 \div 1600\,\text{nm}$, the silicon dioxide (SiO_2) can be used instead of MgF_2.

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