

Antireflection optical coatings design using needle optimization and equivalent films

Gh. Honciuc^a, Gh. Singurel^b, Clementina Timus^c

^aS.C. Pro Optica S.A., Aleea Bucovina 4, RO-74404,, Bucharest, Romania

e-mail: prooptic@fx.ro

^bDept. Of Physics, Univ. “Al. I. Cuza”, Iassy, Romania

e-mail: singurel@uaic.ro

^cInstitute of Atomic Physics, Laser Dept. P.O.Box MG-36, Magurele, Bucharest

e-mail: timus@ifin.nipne.ro

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 optimization 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 optimization process goes on in this circumstance until no more thin layers could be equivalent done.

Keywords: optical coating, coating design, antireflection

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 realized in order to obtain the lowest reflectivity. The optical AR coatings designed in this paper are valid for the spectral ranges 400-700 nm, 400-900 nm and 800-1600 nm respectively. The following conditions have been designed using optical glass sorts with indexes in the range 1.48 – 1.85 (each optical coating has versions for index ranges as follows : 1.48 – 1.56 ; 1.56 – 1.65 ; 1.65 – 1.75 ; 1.75 – 1.85):

- **Visible antireflection coating:**
 - $R(\lambda) < 1\%$ for $\lambda \in [400, 700]\text{nm}$;
 - $R(\lambda) < 0,4\%$ for $\lambda \in [450, 650]\text{nm}$;
 - $R_{\text{average}} < 0,3\%$, averaging on the spectral range $[400, 700]\text{nm}$;
- **Antireflection coating for the spectral range 400 - 900nm**
 - $R(\lambda) < 1\%$ for $\lambda \in [400, 900]\text{nm}$;
 - $R(\lambda) < 0,6\%$ for $\lambda \in [450, 850]\text{nm}$;
 - $R_{\text{average}} < 0,5\%$, averaging on the spectral range $[400, 900]\text{nm}$;
- **Antireflection coating for the spectral range 800 - 1600nm**
 - $R(\lambda) < 1\%$ for $\lambda \in [800, 1600]\text{nm}$;
 - $R(\lambda) < 0,6\%$ for $\lambda \in [850, 1550]\text{nm}$;
 - $R_{\text{average}} < 0,5\%$, averaging on the spectral range $[800, 1600]\text{nm}$;

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 thicknesses 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 (optimization) 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 optimization and synthesis methods. The optimizations methods start from a given combination of thin layers (the starting solution) which is optimized^[10-15] to satisfy the imposed requests (the decrease of the reflection factor on an imposed spectral range). By using the optimization 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 optimized.

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 Ta₂O₅ 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 TiO₂. As a low index material it is used MgF₂ 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: ZrO₂, Al₂O₃, TiO₂, and MgF₂. (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:

- **MgF₂** - non-dispersive, non-absorbent, n= 1.38;
- **Al₂O₃** - non-dispersive, non-absorbent, n= 1.63;
- **ZrO₂** - 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: $A_0 = 4.6704998$ $A_3 = -7.3837191E-3$
 $A_1 = -4.1180861E-1$ $A_4 = 1.7611970E-3$
 $A_2 = 9.9610612E-2$ $A_5 = -8.9841393E-5$

The refraction index decrease^[24] from n to n - Δn, with Δn = 0.24, starting from the substrate, on a 60nm thickness, and then it remain constant.

- **TiO₂** - 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: $A_0 = 4.4275928$ $A_3 = -1.1592131E-1$
 $A_1 = -1.4550173E-2$ $A_4 = 2.0281209E-2$
 $A_2 = 4.4787747E-1$ $A_5 = -9.2502678E-4$

3. Design of optical coatings

In this paper we report the design of an AR coating for 400-900 nm spectral range, using needle optimization in the frame of program STRAT V6.2^[29] using as optical materials TiO₂ and MgF₂. The refining program of optimization begins from the start solution: a MgF₂ layer of thickness 7λ, λ= 500 nm. The resulting coating consists from 19 thin layers. The parameters of the coating are:

1 MgF ₂	d = 109.056 nm	10 TiO ₂	d = 13.331 nm
2 TiO ₂	d = 28.218 nm	11 MgF ₂	d = 244.930 nm
3 MgF ₂	d = 10.019 nm	12 TiO ₂	d = 8.492 nm
4 TiO ₂	d = 4.713 nm	13 MgF ₂	d = 77.446 nm
5 MgF ₂	d = 11.642 nm	14 TiO ₂	d = 6.000 nm
6 TiO ₂	d = 54.027 nm	15 MgF ₂	d = 1.000 nm
7 MgF ₂	d = 22.234 nm	16 TiO ₂	d = 0.377 nm
8 TiO ₂	d = 10.533 nm	17 MgF ₂	d = 215.313 nm
9 MgF ₂	d = 16.541 nm	18 TiO ₂	d = 2.458 nm
		19 MgF ₂	d = 35.879 nm

The spectral reflection factor is shown in Fig. 1.

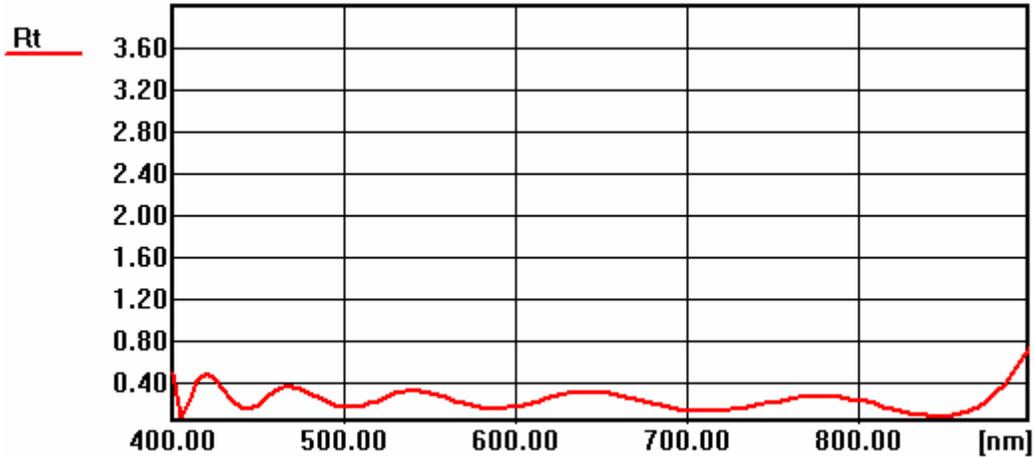


Fig. 1 Reflection factor for the 400-900nm antireflection coating

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 reoptimized. 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 reoptimized. 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 reoptimized. 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:

- | | |
|-----------------------------------|--|
| 1. MgF_2 $d = 93.478$ nm | 4. MgF_2 $d = 16.486$ nm |
| 2. ZrO_2 $d = 66.162$ nm | 5. TiO_2 $d = 21.097$ nm |
| 3. TiO_2 $d = 83.960$ nm | 6. Al_2O_3 $d = 79.678$ nm |

The spectral reflection factor is shown in Fig. 2.

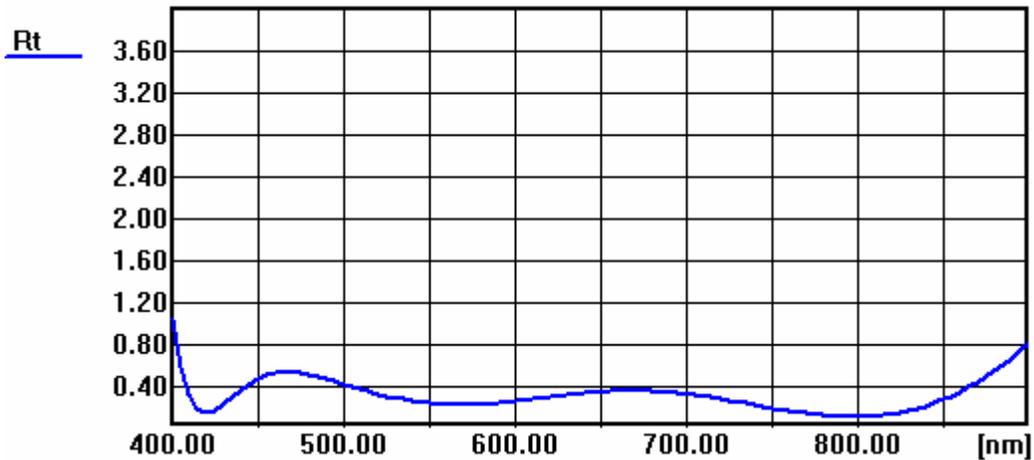


Fig. 2. Reflection factor for the 400-900nm antireflection coating

The optical coating obtained for the spectral range 400-900 nm has been scaled and optimized on the spectral ranges 400 –700 nm and 800- 1600 nm, respectively. The solutions of the optical coatings are:

The antireflex coating for the spectral range 400 - 700nm:

- | | |
|-----------------------------------|---|
| 1. MgF ₂ d = 83.119 nm | 4. MgF ₂ d = 25.635 nm |
| 2. ZrO ₂ d = 39.624 nm | 5. TiO ₂ d = 12.634 nm |
| 3. TiO ₂ d = 88.313 nm | 6. Al ₂ O ₃ d = 25.325 nm |

The spectral reflection factor is shown in Fig. 3.

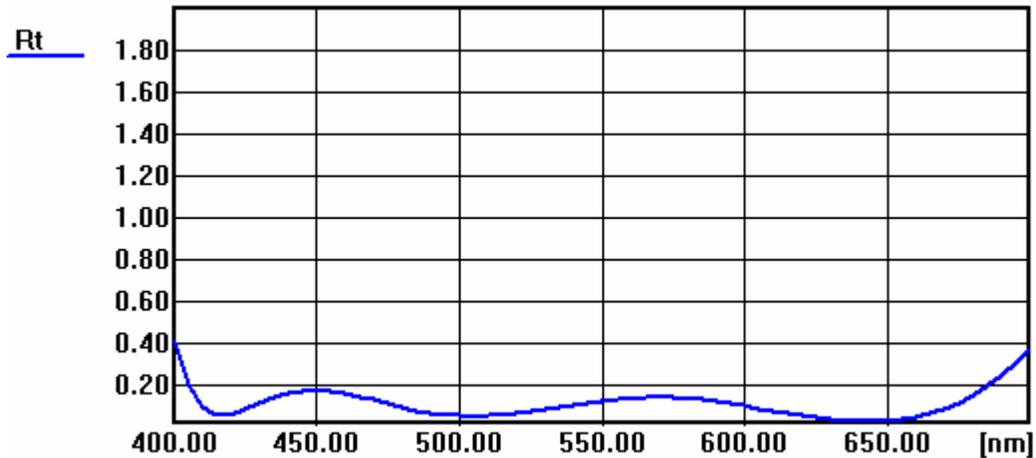


Fig. 3. Reflection factor for the 400-700nm antireflection coating

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

The antireflex coating for the spectral range 800 - 1600nm

- | | |
|------------------------------------|---|
| 1. MgF ₂ d = 156.769 nm | 4. MgF ₂ d = 45.588 nm |
| 2. ZrO ₂ d = 90.238 nm | 5. TiO ₂ d = 29.767 nm |
| 3. TiO ₂ d = 224.517 nm | 6. Al ₂ O ₃ d = 76.631 nm |

The spectral reflection factor is shown in Fig. 4.

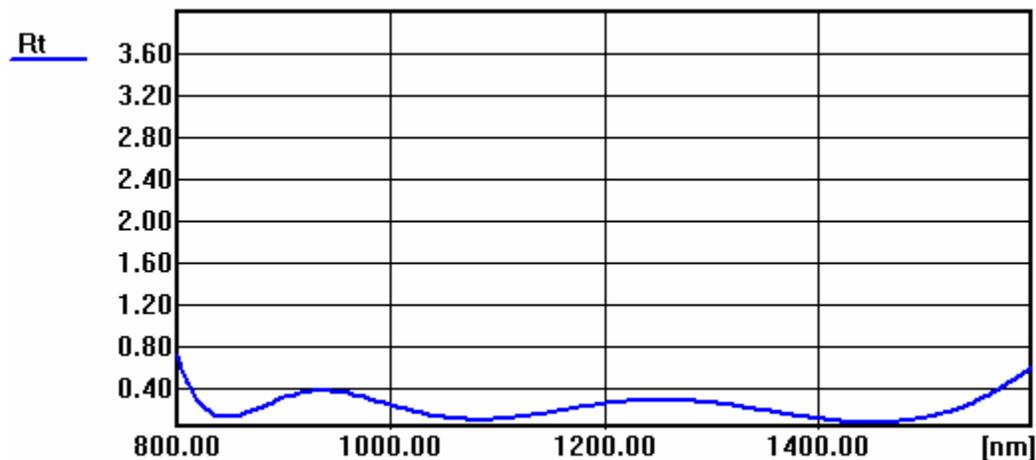


Fig. 4. Reflection factor for the 800-1600nm antireflection coating.

4. Conclusions

The designed optical coatings are satisfying 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 800-1600nm, the silicon dioxide (SiO_2) can be used instead of MgF_2 .

References

1. J.T. Cox and G. Hass, "Triple-Layer Antireflection Coatings on Glass for the Visible and Near Infrared", *J. Opt. Soc. Am.* **52** (9) 965 (1962).
2. J. Thomas and Georg Hass, "Antireflection Coatings for Optical and Infrared Optical Materials", Vol. 2, in: *Physics of Thin Films*, G. Hass, Academic Press, New York, 1963.
3. Hugo Anders, *Thin Films in Optics*, The Focal Press, 1967.
4. A. Musset and A. Thelen, "Multilayer Antireflection Coatings", in: *Physics of Thin Films*, G. Hass, Academic Press, New York.
5. A. Thetford, "A method of designing three-layer anti-reflection coatings", *Optica Acta* **16** (1) 37 (1969).
6. K. Rabinovitch and A. Pagis, "Multilayer antireflection coatings: theoretical model and design parameters", *Appl. Opt.* **14** (6) 1326 (1975).
7. C.L. Nagendra and G.K.M. Thutupalli, "Design of three-layer antireflection coatings: a generalized approach", *Appl. Opt.* **27** (11) 2320 (1988).
8. CH PATENTSCHRIFT 653 945, Dr. Alfred Thelen, Balzers Hochvakuum, 1975.
9. Peter H. Berning, "Use of Equivalent Films in the Design of Infrared Multilayer Antireflection Coatings", *J. Opt. Soc. Am.* **52** (4) 431 (1962).
10. P. W. Baumeister, "Methods of Altering the Characteristics of a Multilayer Stack", *J. Opt. Soc. Am.* **52**, 1149 (1962).
11. Arnold L. Bloom, "Refining and optimization in multilayers", *Appl. Opt.* **20**, 66 (1981).
12. J.A. Dobrowolski, "Versatile computer program for absorbing optical thin film systems", *Appl. Opt.* **20**, 74, (1981).
13. J.A. Dobrowolski, R.A. Kemp, "Refinement of optical multilayer systems with different optimization procedures", *Appl. Opt.* **29**, 2876 (1990).
14. J.A. Aguilera, et al., "Antireflection coatings for germanium IR optics: a comparison of numerical design methods", *Appl. Opt.*, **27**, 2832, (1988).
15. J.A. Dobrowolski and T. Sullivan, "Universal antireflection coatings for substrates for the visible spectral region", *Appl. Opt.* **35** (25) 4993 (1996).
16. G.L.Muscalu, "Low-loss antireflection coating for the visible ", *Proc. SPIE*, Vol. 2461 , 566-570, (1994).
17. H. Ganesha Shanbhogue, C.L. Nagendra et al. "Multilayer antireflection coatings for the visible and near-infrared regions", *Appl. Opt.* **36** (25) 6339 (1997).
18. Ronald R. Willey, "Predicting achievable design performance of broadband antireflection coatings", *Appl. Opt.* **32** (28) 5447 (1993).

19. Philip Baumeister, "Starting designs for the computer optimization of optical coatings", *Appl. Opt.* **34** (22) 4835 (1995).
20. J.A. Dobrowolski, "Completely Automatic Synthesis of Optical Thin Films Systems", *Appl. Opt.* **4**, 937 (1965).
21. Alexander V. Tikhonravov, Michael H. Trubetskov, and Gary W. DeBell, "Application of the needle optimization technique to the design of optical coatings", *Appl. Opt.* **35** (28) 5493 (1996).
22. 2. Brian T. Sullivan and J.A. Dobrowolski, "Implementation of a numerical needle method for thin-film design", *Appl. Opt.* **35** (28) 5484 (1996).
23. A.V. Tikhonravov and J.A. Dobrowolski, "Quasi-optimal synthesis for antireflection coatings: a new method", *Appl. Opt.* **32** (22) 4265 (1993).
24. R.E. Klinger and C.K. Carniglia, "Optical and crystalline inhomogeneity in evaporated zirconia films", *Appl. Opt.* **24** (19) 3184 (1985).
25. J.A. Dobrowolski, P.D. Grand, R. Simpson, and A.J. Waldorf, "Investigation of the evaporation process conditions on the optical constants of zirconia films", *Appl. Opt.* **28** (18) 3997 (1989).
26. David Reicher and Kenneth Jungling, "Influence of crystal structure on the light scatter of zirconium oxide films", *Appl. Opt.* **36** (7) 1626 (1997).
27. Robert Chow, Steve Falabella, et al. "Reactive evaporation of low defect density hafnia", *Appl. Opt.* **32** (28), 5567 (1993).
28. A.J. Vermeulen, "Influence of inhomogeneous refractive indices in multilayer anti-reflection coatings", *Optica Acta* **23** (1) 71 (1976).
29. Gh. Honciuc, Gh. Singurel, "Software for optical coatings design", *ROMOPTO '97*, SPIE 3405, 1183, (1997).
30. A. Thelen, "Equivalent Layers in Multilayer Filters", *J. Opt. Soc. Am.* **56** (11) 1533 (1966).
31. Torben Skettrup, "Three-layer approximation of dielectric thin film systems", *Appl. Opt.* **28** (14) 2860 (1989).