

Selective interferential filters with high optical efficiency and increased resistance in intense optical radiation

A. RIZEA

Optical Coatings Department of Pro Optica S.A., Bucharest, Romania

In this paper the results of a study and the found solutions for some interferential filters obtained through Physical Vapor Deposition method on optical support are presented. These filters have a good resistance to an intense optical radiation, as well a high optical efficiency in a large spectral domain (400 – 2000 nm). Both theoretical and experimental aspects will be discussed herein.

(Received January 13, 2007; accepted July 10, 2007)

Keywords: Interferential filters, Selective filters, Dichroic filters, Edge filters, Stop band, Pass band

1. Introduction

The application that stays at to the basis of this study has consists in the execution of some optical filters type “dichroic filters” which permit the transmission in the large spectral wavelength domain and block the radiation with smaller wavelengths. It was observed that the initial used absorbent filters were heated in excess by the very high density of energy of the incident radiation (40 J/cm², pulses of 10 ms, with repetition at 1 - 2s). In order to protect these filters, it was chosen the solution of an optical coating with an interferential structure which reflects a part of incident radiation thus bringing down the quantity of energy absorbed by the substrate. Also, the transmission in the interested spectral domain (600 – 2000 nm) will be increased against the uncoated filter.

The present paper shows a designing method and the solutions for the execution of an efficient and resistant optical coating. The presented calculation model is for a filter which has to work in the conditions $T_{avg} > 97\%$ for $\lambda \in [600-2000]$ nm; $T < 0.1\%$ for $\lambda < 500$ nm.

2. Experimental

2.1 Theoretical approach

For optimization of the starting formula of an interferential structure, it was applied the theory of equivalent layers with whose induction of “stop band” in a spectral domain is described from mathematical point of view. Thus, based on electromagnetic wavelength properties at the border of two media with different refraction index, the following equation is established [2]

$$\begin{pmatrix} E(z_1) \\ Z_0 H(z_1) \end{pmatrix} = M \cdot \begin{pmatrix} E(z_2) \\ Z_0 H(z_2) \end{pmatrix} \quad (1)$$

where:

$E(z_1)$ the intensity of electrical field of radiation at the incident boundary of thin layer

$E(z_2)$ the intensity of electrical field of radiation at the emergence boundary of thin layer

$H(z_1)$ the intensity of magnetic field of radiation at the incident boundary of thin layer

$H(z_2)$ the intensity of magnetic field of radiation at the emergence boundary of thin layer

$$Z_0 = \sqrt{\frac{\mu_0}{\epsilon_0}} = 377\Omega \text{ - the impedance of vacuum}$$

M is the characteristic matrix of thin layer

$$M = \begin{pmatrix} \cos \Phi & \frac{i \cdot \sin \Phi}{n} \\ i \cdot n \cdot \cos \Phi & \cos \Phi \end{pmatrix} \quad (2)$$

where:

Φ is the shift phase of the wave that pass through the thin layer

$$\Phi = \frac{2\pi}{\lambda} \cdot n \cdot g \cdot \cos \theta \quad (3)$$

$$i = \sqrt{-1}$$

λ = the wavelength of radiation

n = the refraction index of the thin layer

g = the geometrical thickness of a layer

θ = the angle under which the radiation crosses the layer

In the case of multilayers coating with q unabsorbent thin layers, the characteristic matrix of q layers ensemble will be the product of the all characteristic matrices of each component layer.

Thus,

$$M = M_1 \cdot M_2 \cdot \dots \cdot M_q \quad (4)$$

In this case, the relation (1) keeps its validity, but the matrix "M", obtained as the product of the all characteristic matrices of each component layer, will have a very complex form, almost impossible to use from mathematical point of view and to have a meaning from the physics point of view. For this reason, to make easily all those calculations and to put into evidence the physics phenomenon, it is used the equivalent layers theory.

The theory of equivalent layers:

A symmetrical sequence of thin layers is an ensemble of layers, which presents symmetry from both geometrical and optical constants point of view. Thus, if is noted with "H" (High index) a thin layer having the refraction index n_H and the optical thickness d_H and with "L" (Low index) another thin layer having the refraction index n_L and the optical thickness d_L , it said that the sequences as (H L H) or (L H L) are symmetrical sequences because the first layer together with half of from middle layer is "the image in mirror" of the second half of the middle layer together with the third layer. The advantage of such structure is that it can be assimilated with one layer characterized by an equivalent refraction index (N) and an equivalent thickness (Γ). Thus, the characteristic matrix of symmetrical structure will have the form of the characteristic matrix of one layer (the elements from the main diagonal line being equal) [2-3].

$$M_{sym} = \begin{pmatrix} \cos \Gamma & \frac{i \cdot \sin \Gamma}{N} \\ i \cdot N \cdot \sin \Gamma & \cos \Gamma \end{pmatrix} \quad (5)$$

Now we can repeat the symmetrical sequence by p times, without to affect the character of equality between the elements from the main diagonal line of resultant matrix.

The equation (1) becomes:

$$\begin{pmatrix} E(z_1) \\ Z_0 H(z_1) \end{pmatrix} = M \cdot \begin{pmatrix} E(z_{p+1}) \\ Z_0 H(z_{p+1}) \end{pmatrix} \quad (6)$$

where:

$$M = (M_{sym})^p \quad (7)$$

$$M_{sym} = \begin{pmatrix} M_{11} & i \cdot M_{12} \\ i \cdot M_{21} & M_{22} \end{pmatrix} \quad (8)$$

$$M_{11} = M_{22} = \cos \Gamma; M_{12} = \frac{\sin \Gamma}{N}; M_{21} = N \cdot \sin \Gamma \quad (9)$$

From ec (9) will result:

$$N = \sqrt{\frac{M_{21}}{M_{12}}} \quad (10)$$

$$\Gamma = \arccos M_{11} = \arccos M_{22} \quad (11)$$

Depending on the signs of the terms M_{12} and M_{21} , there are two cases [2]:

1. M_{12} and M_{21} have the same sign \Rightarrow

$$N = \sqrt{\frac{M_{21}}{M_{12}}} \text{ is a real value; } M_{11} M_{22} + M_{12} M_{21} = 1$$

$$M_{21} = 1$$

$$\cos \Gamma = M_{11} = \sqrt{1 - |M_{12} M_{21}|} < 1 \Rightarrow \cos \Gamma \text{ and } \sin \Gamma \text{ are trigonometrically real functions.}$$

2. M_{12} and M_{21} have different signs \Rightarrow

$$N = \sqrt{\frac{M_{21}}{M_{12}}} \text{ is an imaginary value}$$

$$\cos \Gamma = M_{11} = \sqrt{1 - |M_{12} M_{21}|} < 1 \Rightarrow \cos \Gamma \text{ and } \sin \Gamma \text{ are not trigonometrically real functions and become hyperbolic functions } \cosh \Gamma \text{ and } \sinh \Gamma.$$

In Fig. 1 are presented the aspect of variations with the wavelength of radiation of those two functions (N and Γ), for a symmetrical structure (H/2 L H/2).

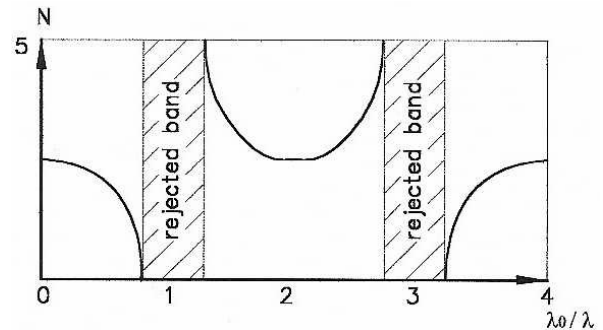


Fig. 1-a. The variation with the wavelength of the equivalent index for a structure (H/2 L H/2).

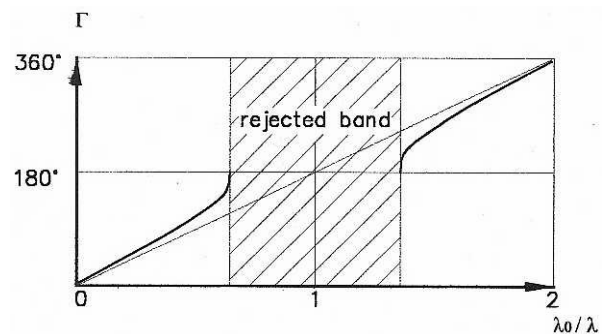


Fig. 1-b. The variation with the wavelength of the equivalent thickness for a structure (H/2 L H/2).

Returning to eq. (6), the characteristic matrix of a multilayers structure described as a succession of symmetrical sequences, assimilated according to the above theory with a succession of "p" equivalent identical layers, having the form $(H/2 L H/2)_1 (H/2 L H/2)_2 \dots (H/2 L H/2)_p$ or also written $(H/2 L H/2)^p$, is:

1. For N – real value:

$$M = \begin{pmatrix} \cos(p \cdot \Gamma) & \frac{i \cdot \sin(p \cdot \Gamma)}{N} \\ i \cdot N \cdot \sin(p \cdot \Gamma) & \cos(p \cdot \Gamma) \end{pmatrix} \quad (12)$$

2. For N – complex value

$$M = \begin{pmatrix} \cosh(p \cdot \Gamma) & \frac{i \cdot \sinh(p \cdot \Gamma)}{N} \\ i \cdot N \cdot \sinh(p \cdot \Gamma) & \cosh(p \cdot \Gamma) \end{pmatrix} \quad (13)$$

The elements of the characteristic matrix (M) are involved in total transmission as follow [2]:

$$T = 1 - R = \frac{4}{2 + \frac{n_0}{n_s} M_{11}^2 + n_0 n_s M_{12}^2 + \frac{1}{n_0 n_s} M_{21}^2 + \frac{n_s}{n_0} M_{22}^2} \quad (14)$$

From (12), (13) and (14) it can be observed that:

- in the case 1 (for N real value), the elements of characteristic matrix vary between the same minimum and maximum values. The result is that however many layers are deposited ("p" however large), in absence of absorption, the values of elements can be sized thus to have an acceptable transmission in this spectral domain. This is the **PASS BAND** domain.

- in the case 2 (for N complex value), it can be observed that the values of elements of characteristic matrix grow in the same time with the growing of number of periods "p", thus leading to a transmission which will decrease directly as growing of number of layers. This is the **STOP BAND** or **REJECTED BAND**.

Taking into account the above-presented theory, the designing of a selective interferential filter is reduced to three steps:

1. Selecting of a symmetrical sequence (equivalent layer) and repeating of this sequence until a very small transmission in the spectral "**STOP BAND**" domain is obtained and also a sufficient slope towards the spectral "**PASS BAND**" domain is got.
2. Designing of an antireflection coating between the equivalent layer and the incident medium of radiation.
3. Designing of an antireflection coating between the equivalent layer and the substratum.

2.2 Numerical simulation and optimization

For a graphic illustration of the dependence between the spectral transmission and the number of successive deposited symmetrical sequences (equivalent layers), a

numerical simulation with a software application ATTOL [6] is used. The chosen materials for to get the coating are:

- TiO₂ – material "**H**" (High index) – $n_{\text{TiO}_2} \cong 2.25$
- SiO₂ – material "**L**" (Low index) – $n_{\text{SiO}_2} \cong 1.45$

Note: From this point forward, the symbol "**H**" in discussed formulae of the interferential structures will be used and it will represent a layer of TiO₂ with optical thickness $d_{\text{TiO}_2} = \lambda_0/4$; $\lambda_0 = 500\text{nm}$ and the symbol "**L**", used in the same formulae, will represent a layer of SiO₂ with optical thickness $d_{\text{SiO}_2} = \lambda_0/4$; $\lambda_0 = 500\text{nm}$.

It was also taken into account the equation of dispersion of those both used materials for coating:

$$n^2 = A_0 + A_1 \lambda^2 + \frac{A_2}{\lambda^2} + \frac{A_3}{\lambda^4} + \frac{A_4}{\lambda^6} + \frac{A_5}{\lambda^8} \quad (15)$$

The coefficients A₀ ... A₅ for both two materials are presented in the Table 1 [5]:

Table 1. Coefficients of dispersion equation for both materials used for coating.

	A ₀	A ₁	A ₂	A ₃	A ₄	A ₅
TiO ₂	4.4276	-0.01455	0.4478	-0.116	0.0203	9.25027×10^{-4}
SiO ₂	2.10455	-0.00943	8.5857×10^{-3}	1.4142×10^{-4}	5.73×10^{-6}	8.55×10^{-7}

Using the "ATTOL" [6] software application, the dispersion curves for the two materials have been generated (Fig. 2) [5]:

In Fig. 3 are presented some graphics of the theoretical spectral transmission generated also with the helping of software application "ATTOL" [6], for different values of number of deposited equivalent layers.

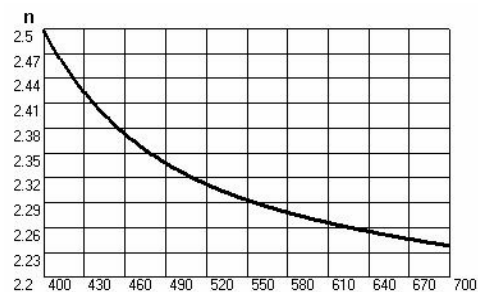


Fig. 2-a A dispersion curve for TiO₂.

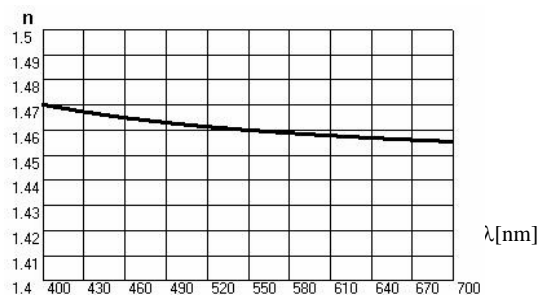


Fig. 2-b. A dispersion curve for SiO₂.

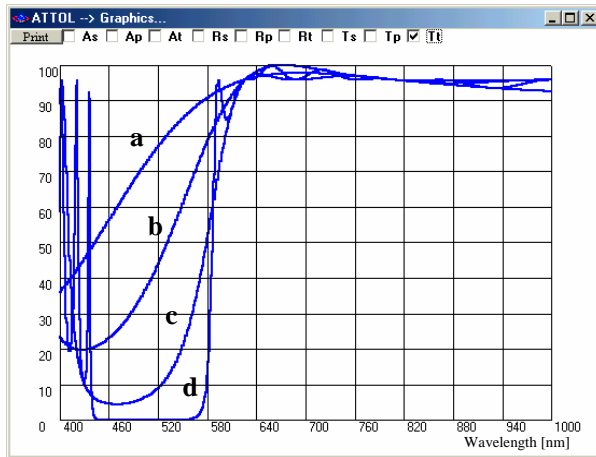


Fig. 3. The spectral transmission for an interferential structure formed from: a) 1 sequence $H/2 L H/2$; b) 2 sequences $H/2 L H/2 \Leftrightarrow (H/2 L H/2)^2$; c) 4 sequences $H/2 L H/2 \Leftrightarrow (H/2 L H/2)^4$; d) 12 sequences $H/2 L H/2 \Leftrightarrow (H/2 L H/2)^{12}$.

In Fig. 3 can be observed that the interferential filter, having the curve of spectral transmission “d” and the structure $(H/2 L H/2)^{12}$, performs all the conditions from optical point of view. From resistance point of view more constructive solutions have been verified, thus being obtained as result the fact that the most resistant structures are those which have a coating beginning with a TiO_2 layer and being ended with a thick SiO_2 layer.

The transmission is optimized in “Pass Band” spectral domain with the helping of software application ATTOL, being selected for optimization only four layers from the beginning and four layers of the ending of coating, the middle area remaining formed from optical thickness $\lambda_0/4$.

The final (optimized) structure of coating was obtained in the following way:

- a) It is started from the initial structure resulted from the multiplying by 12 times of the equivalent layers (Fig. 3, var.d):

$$\text{Air } (H/2 L H/2)^{12} \text{ Substrate} \quad (16)$$

In this configuration (16) there are 12 equivalent layers representing 25 physical layers (in alternation TiO_2 and SiO_2) with $\lambda_0/4$ optical thickness, excepting the first layer (TiO_2) and the last layer (also TiO_2), which have $\lambda_0/8$ optical thickness ($\lambda_0 = 500 \text{ nm}$). The theoretical curve of spectral transmission is presented in Fig. 4.

- b) The first layer of TiO_2 (that from the air) is eliminated and the next layer of SiO_2 is doubled in order to raise the resistance of coating to an intense optical radiation:

$$\text{Air } 2L H/2 (H/2 L H/2)^{11} \text{ Substratum} \quad (17)$$

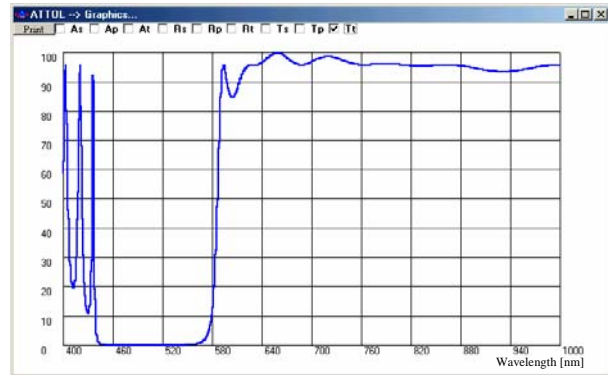


Fig. 4. The theoretical curve of a spectral transmission for an interferential filter having the structure from (16).

In this configuration (17) there are 24 physical layers with $\lambda_0/4$ optical thickness, excepting the first layer (SiO_2) which has $\lambda_0/2$ optical thickness and the last layer (TiO_2), which have $\lambda_0/8$ optical thickness ($\lambda_0 = 500 \text{ nm}$). The theoretical curve of spectral transmission is presented in Fig. 5.

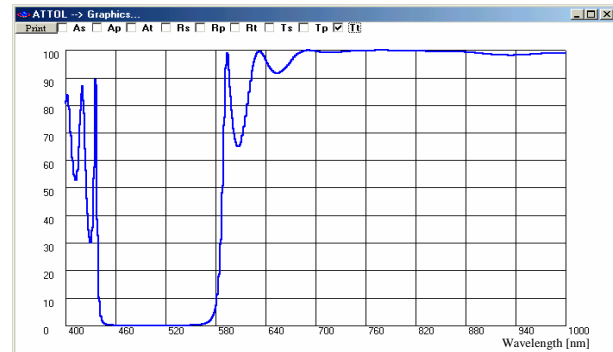


Fig. 5. The theoretical curve of a spectral transmission for an interferential filter having the structure from (17).

- c) To minimize the losses from reflection, the coating is optimized (the optimization is made only in first and last four layers thus being kept the structure of symmetrical layers with $\lambda_0/4$ optical thickness in the middle of coating).

- as result of optimization of transmission for the spectral domain [600-1000] nm the following formula is got:

$$\text{Air } 2L 0.84H 0.9L 0.455H (H/2 L H/2)^8 0.5H 0.82L 1.08H 0.84L 0.5H \text{ Substrate} \quad (18)$$

- as result of optimization of transmission for the spectral domain [600-2000] nm the following formula is got:

**Air 2L 0.6HL 0.5H (H/2 L H/2)⁸ 0.5H 0.9L 0.81H
1.1L 0.364H Substratum (19)**

The theoretical curves of a spectral transmission for those two optimized structures are presented in Fig. 6.

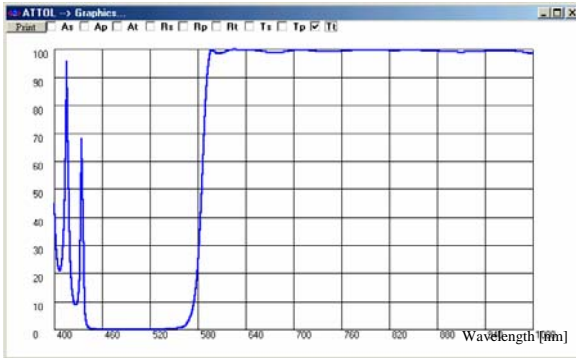


Fig. 6-a. The theoretical curve of a spectral transmission for an optimized interferential filter for 600 – 1000 nm spectral domain, having the formula (18).



Fig. 6-b. The theoretical curve of a spectral transmission for an optimized interferential filter for 600 - 2000 nm spectral domain, having the formula (19).

2.3 Technological features

For this aim to realize some interferential structures on basis of formulae (18) and (19) a Balzers BAK 550 equipment for depositions of thin optical layers through PVD method was used. The coating has been made on a substratum realized from optical glass filter type “GG” from Schott, but in the same charges some witness-plates from BK7 optical glass have been introduced.

- The monitoring of optical thickness of deposited layers was made through the measuring of reflection on 12 monitor-lamellas (one lamella for each two deposited layers, the equipment having the possibility to change the monitor-lamella during the technological process of the same charge).

- The layers of SiO₂ have been deposited in vacuum at the pressure of 10⁻⁵ mbar.
- The layers of TiO₂ have been deposited reactively through introducing of O₂ until a pressure of 10⁻⁴ mbar.
- The cooling of pieces was made very slowly in order to minimize the stress in the stack.

3. Results

In Fig. 7 a real curve of spectral transmission is presented for an optimized interferential filter in [400 2000] nm domain, deposited on a witness-plate from BK7 optical glass and measured with a “Beckman DK-2A” spectrometer with reference beam. The curve with a dotted line represents the transmission in the spectral domain [1200 2000] nm and the curve with a continued line represents the transmission of the same filter in [400 1200] nm spectral domain. For to compensate the losses from the PASS BAND area, through reflection in the second surface or through absorption in the substratum mass, on the reference beam of spectrometer an identical piece with the coating substratum has been laid. In this way it is put into evidence the gain or the loss of radiation through reflection in the covered piece instead of uncovered piece, represented in the graphic by the line of 100%. It is observed that in [600-1200] nm domain an obvious increasing of transmission is obtained.

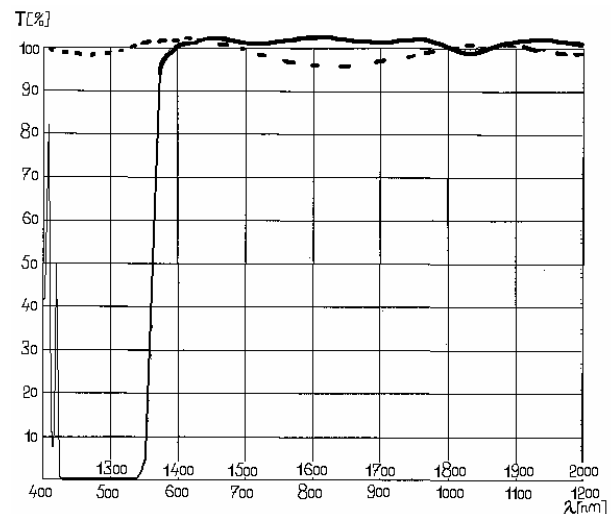


Fig. 7. The measured curve of a spectral transmission for an interferential filter.

The domain “STOP BAND” is between 430 and 540 nm. For wavelengths lesser than 430 nm, a very narrow series of peaks appears, the same with those from the theoretical curve (Fig. 6), which will be absorbed by the substrate (GG 475 - Schott) [7].

4. Discussion

Following the modeling of this paper, some filters with different wavelengths of cutting have been designed and realized, having similar characteristics, but being spectrally moved at the right or the left referring to the given example.

It is important to hold the fact that for to have a correct cutting band ($T < 0.1\%$ and an abruptly slope between STOP BAND and PASS BAND areas), it is necessary that the starting formula of coating to have a structure similar of $(H/2 L H/2)^p$, where the parameter “p” (number of equivalent layers) needs to be very large ($p_{\min} = 10$, corresponding to 21 physical layers with $\lambda_0/4$ optical thickness, where λ_0 is the middle of spectral domain “STOP BAND”). In order to get the resistance to an intensive optical radiation and for a mechanical resistance, the number of deposited layers will not be excessively increased and the layer from outside will be made from the hardest available material with a double thickness. From technological point of view, to get reproduction on many charges, it must be maintained a structure very similar with the initial one. From this reason, the optimization of transmission in PASS BAND area has been made only on the first and the last four layers, in order to let the structure from the middle with layers having $\lambda_0/4$ optical thickness. The optimization is made with specialized software for designing interferential optical coatings.

It is noticed the fact that both the forms of transmission curve and the cutting wavelengths of the measured filters vary very slowly in relation with the theoretical curve of transmission. This fact happens first of all because of differences between theoretical and real refraction indices, which are in correlation with other factors of technological process, including the human factor.

The final ensemble, composed from the substrate and the interferential structure, will have an extensive cutting band, beginning from ultraviolet range, where the filter glass and the deposited materials absorb (especially TiO_2) and continuing in visible domain until the wavelength of the end of the “STOP BAND” of designed interferential filter.

5. Conclusion

The interferential coatings prove to have an increased reliability, carrying out the role of protecting the substrate on which the coatings have been deposited and to improve the optical functional parameters.

References

- [1] Ion M. Popescu, “Macroscopic electromagnetic theory of the light” (roum.), Bucharest, Romania.
- [2] Alfred Thelen, “Design of Optical Interference Coatings” Mc Graw-Hill Book Company – 1989.
- [3] H. A. McLeod, “Thin – Film Optical Filters” Printed by J W Arrowsmith Ltd. Bristol 2001.
- [4] B. E. Perilloux “Dominant wavelength sensitivity of thin film color filters to spectral centering“ App. Optics 1 Oct. 1996 / Vol. 35 No. 28.
- [5] A. Rizea “Interferential Dichroic Filter” Scientific Bulletin of University Politehnica of Bucharest, Series A, Vol. 66 No. 2 – 4 / 2004.
- [6] A. Rizea “ATTOL” (Applied Theory of Thin Optical Coatings) – software application.
- [7] SCHOTT Catalogue of Optical Glass Filters 2005.

*Corresponding author: adrian.rizea@prooptica.ro