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Effect of dispersion on the spectral characteristics of multilayer thin films

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1. Introduction

Preparation of high-performance optical coatings is a complex process, which involves solving several independent problems such as design and requiring the knowledge of the physical and chemical properties of the materials as well as technological background of the thin film deposition.

In the first stage of the design process the dispersion of the refractive index of the coating materials is neglected, which appears to be a useful simplification.

The existence of some important effects of the refractive index dispersion in the case of a single layer, evidenced in papers [1, 2], has inclined us to study systematically these effects in the optical coating design in order either to avoid or to utilize their consequences on the optical parameters of the layers.

In this paper we show the effect of the refractive index dispersion of the coating components in a number of specific cases often utilized in the laser optics, namely:

— optical coatings operating at a single wavelength (mono or double antireflex layers, narrow-band filter, laser mirror),

— optical coatings operating at two or more wavelengths (antireflex for two wavelengths, antireflex for a wide band, beam-splitter, high reflectance mirror for a wide band, short-wave pass and long-wave pass optical filters).

2. Computation considerations

It is known that the dependence of the refractive index of the dielectric materials on the wavelength of the incident radiation is the transparence spectral range, described by a Sellmeier-type relation

$$n^2 = A_0+A_1\lambda^{-2}+A_2\lambda^{-4}+\ldots \tag{1}$$

where the constants A_0, A_1 ... are experimentally determined.

As in measurement of the reflectance R (or transmittance T) the precision is usually limited to 10^{-2} (or 10^{-3} with special procedures) it is convenient to limit the relation (1) only to the second order term

$$n = (A + B\lambda^{-2})^{1/2} \tag{2}$$

where A and B define the dispersion. This relation represents a better approximation than the linear expression utilized in [2].

In order to study the influence of the refractive index dispersion (both of the substrate and thin-layer materials) on the optical parameters of the coatings the algorithm for the computation of the reflectance and transmittance corresponding to a multiple dielectric thin-layer structure, and based on complex amplitude reflectance and transmittance [3], has been completed with the relation (2). The values of A and B constants were taken from papers [4, 5] for ZrO_2, MgF_2 and ZnS, respectively, and determined experimentally by the authors for TiO_2.

3. Application

The analysis performed with a computer for all the above mentioned coating types has evidenced a strong influence of the dispersion in some cases and its negligible effects in the other ones.

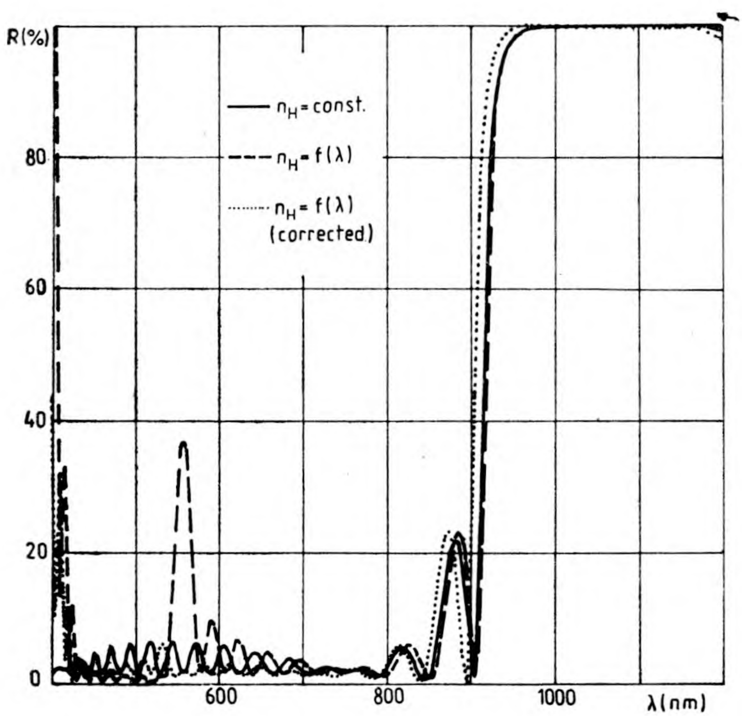

Fig. 1. The reflectance vs. wavelength calculated for a short wave-pass filter of the structure G|0.5 M(HL)^{9}H 0.5 L|A (calculated for n_H = constant ———, including the dispersion of $n_H = f(\lambda)$ — — — — , corrected curve ......)

i) In case of an optical coating for short wave-pass filter of the structure G | 0.5 M (HL)^9 H 0.5 L | A, where $n_H = 2.25$, $n_L = 1.45$, $n_M = 0.2$, intended to cut the laser radiation $\lambda = 1.06$ µm, it has been found that the dispersion of n_H (TiO: $A = 4.713$, $B = 362000$) results in a 30% dip in the transmission maximum of the filter. This effect is similar to that given by a systematic inequality of the optical thickness of the layer of high (H) and low (L) refractive indices: $(nd)_H > (nd)_L$ and can be completely eliminated by increasing the optical thickness of the L layers with respect to the H layers (Fig. 1, corrected curve).

ii) In case of a short wave-pass filter of the structure G | k_1 H k_2 L (HL)^6 k_3 H k_4 L | A (the layers 1, 2, 15 and 16 being correction layers, $k_1 = 1.304$, $k_2 = 1.107$, $k_3 = 1.179$, $k_4 = 0.489$), with $n_H = 2.3$, $n_L = 1.35$, used to cut the laser radiation $\lambda = 0.694$ µm, it has been stated that taking account of n_H dispersion (ZnS: $A = 4.709$, $B = 270000$) eliminates the effect of the correction layers in the maximum range of transmission. This effect can be, to a great extent, cancelled by the modification of the optical thickness ratio of the H and L layers in the equal thickness layer stack and the modification of the thickness of the correction layers (Fig. 2, corrected curve).

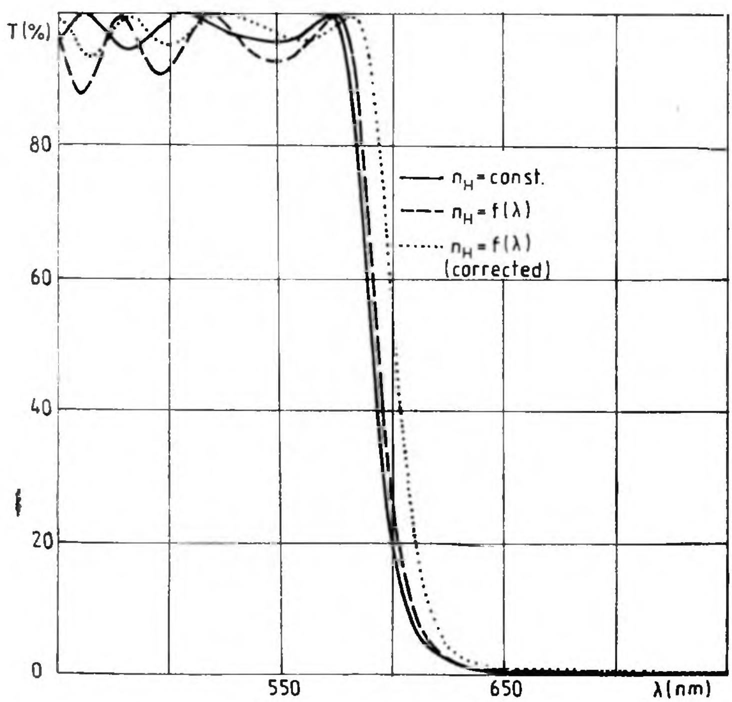

Fig. 2. The transmittance curve for a short wave-pass filter of the structure G | k_1 H k_2 L (HL)^6 k_3 H k_4 L | A (calculated for n_H = constant ———, calculated for $n_H = f(\lambda)$ — — — —, corrected curve .....)

iii) For a structure of the type G | 0.5 H (LH)^8 L 0.5 H | A, representing a long wave-pass filter, where $n_H = 2.45$, $n_L = 1.45$, the dispersion of the high refractive index material (TiO_2) gives rise to a spectral shift of the edge by approximately 20 nm, accompanied by the corresponding narrowing of the high reflectance region (Fig. 3). The modification of the optical thickness

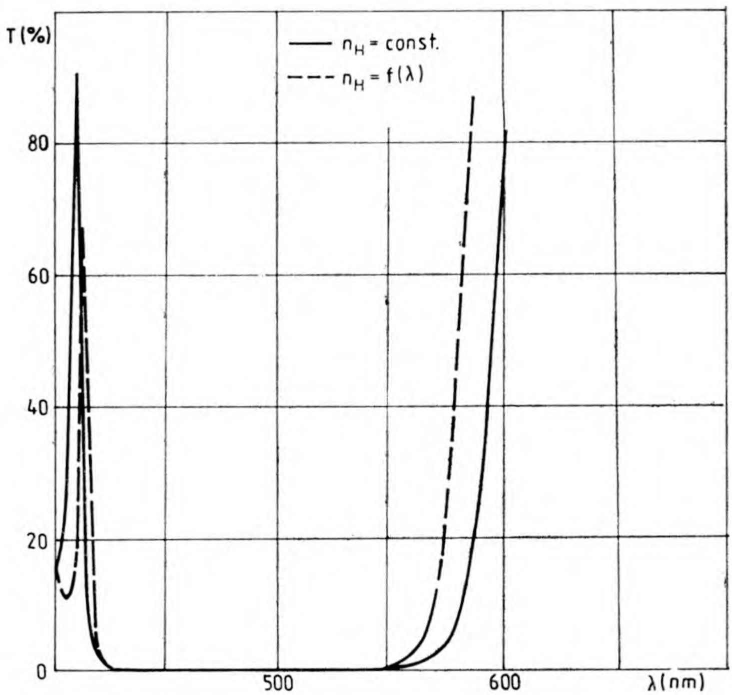

Fig. 3. The transmittance curve calculated for a long wave-pass filter of the structure G | 0.5 H (HL)^8 L 0.5 H | A (the case of n_H = constant ————, the case of $n_H = f(\lambda)$ — — — —)

ratio brings the edge to the desired wavelength, but it does not eliminate the narrowing effect of the high reflectance band.

iv) In case of a structure of the type G | (0.66 H 1.33 L)^9 0.66 H | A, representing a high reflectance mirror operating at 0.633 μm and 1.15 μm, where H = TiO_2 and L = SiO_2, the dispersion of the material refractive index, if taken into account, induces a spectral shift of the reflectance band centred at 0.633 μm with approximately 20 nm towards higher wavelengths, accompanied by the appearance of a 95 % peak at 0.435 μm (Fig. 4).

v) The reflectance of a structure G | k_1 (HLH) k_2 L k_3 H k_4 L k_5 H k_6 L k_7 H k_8 (LH) k_9 L k_{10} (HLH) | A, giving a high reflectance mirror in a large domain ($R \geq 90\%$ in the range of 400–730 nm, when H = ZnS and L = MgF_2, $k_1 = 1.669$, $k_2 = 1.610$, $k_3 = 1.391$, $k_4 = 1.694$, $k_5 = 1.513$, $k_6 = 1.249$, $k_7 = 1.257$,

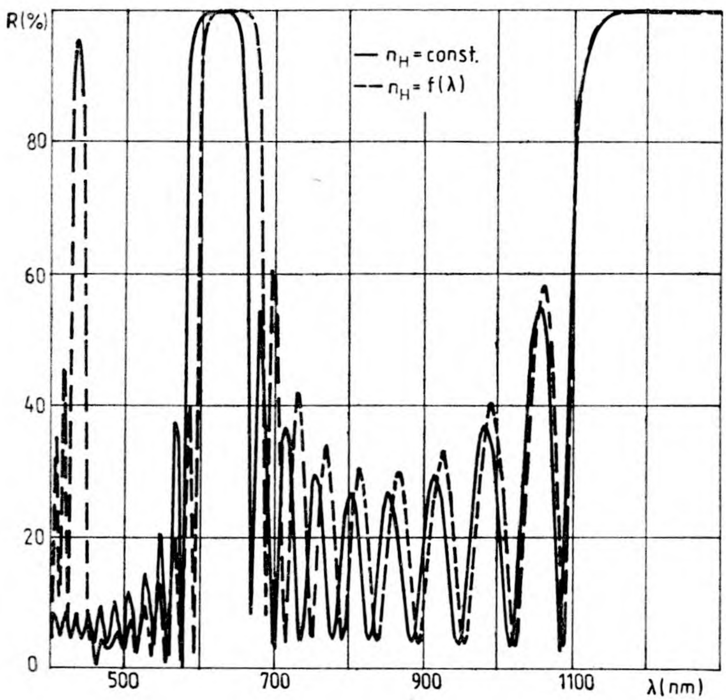

Fig. 4. The reflectance curve calculated for high reflection mirror at two wavelengths, structure G | (0.66 H 1.33 L)^9 0.66 H | A (calculated for n_H = constant ————, calculated for n_H = f(λ) – – – –)

$k_8 = 1.12$, $k_9 = 1.050$, $k_{10} = 1.048$, was calculated and represented in Fig. 5.

It is evident that the high reflection band becomes narrower (by about 30 nm) and some undesirable peaks appear in the central zone. This result is due to the dispersion effect of the high refractive-index material.

vi) In Figure 6 the results are presented for a structure G | k_1 H k_k L k_2 HL | A which gives a wide-band antiferlex coating. The substrate G is SF2 glass, H = TiO_2 and L = SiO_2, $k_1 = 0.33$, $k_2 = 0.5$. The dispersion of the high refractive-index material induces an about 25 nm narrowing of the low reflectance band.

vii) The interferential dielectric structure of the pass-band filter and beam-splitter exhibit a relatively low sensitivity to the dispersion of the high refractive index.

In the case of a pass-band filter with the structure G | (HL)^4 2 H(LH)^4 | A, where H = TiO_2, L = SiO_2, the dispersion of the high refractive-index material induces the narrowing of the self-blocking zone (Fig. 7).

The dispersion of the high refractive index in case of the structure G | 2 H (LH)^2 | A, representing a coating for a beam-splitter, is manifested in the lack of equilibrium of the curve $R(\lambda)$ – Fig. 8.

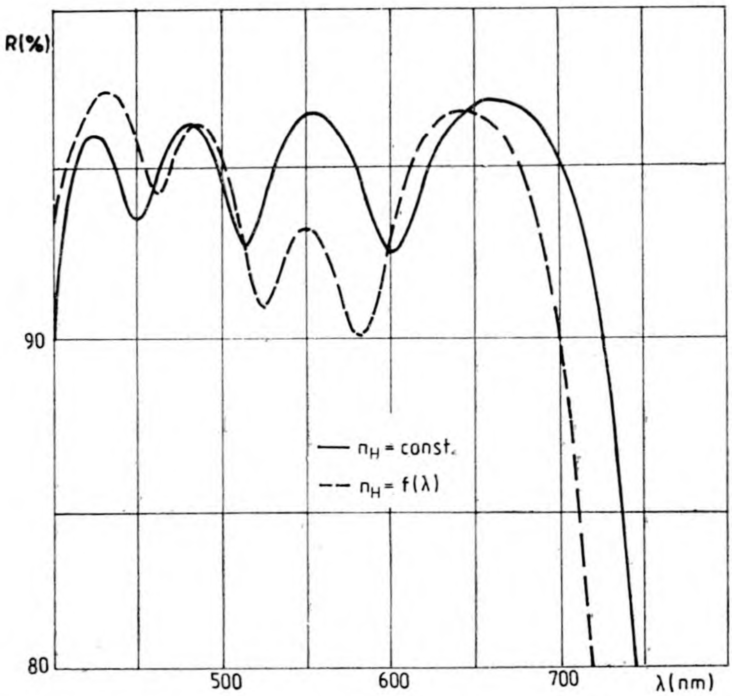

Fig. 5. The reflectance curve calculated for a structure G | k_1 (HLH) k_2 L k_3 H ... k_6 L k_7 H k_8 (LH) k_9 L k_{10} (HLH) | A representing a high reflection mirror for a large band (calculated, taking n_H = constant ———, calculated, taking $n_H = f(\lambda)$ — — — —)

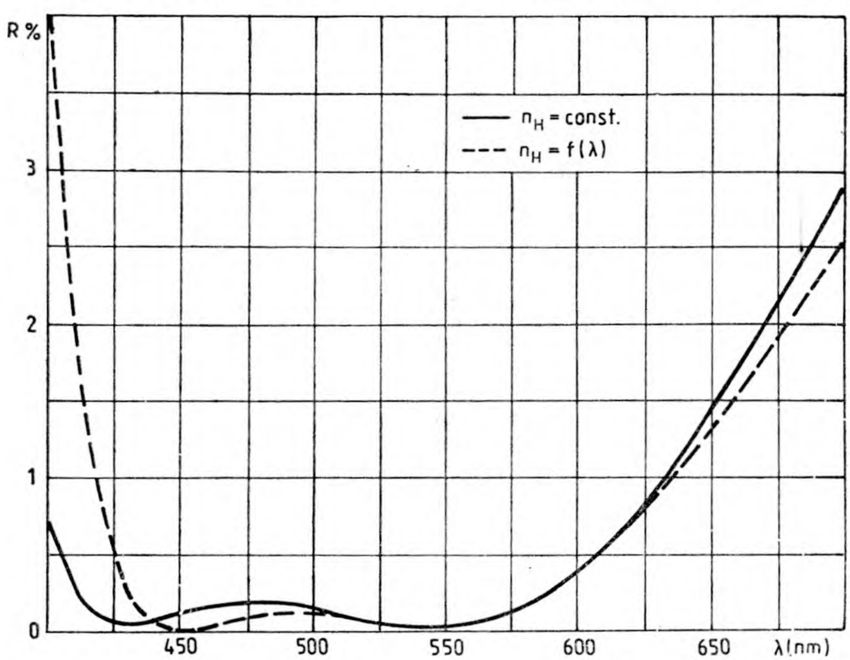

Fig. 6. The reflectance curve calculated for a wide band antireflex coating of the structure G | k_1 H k_1 L k_2 HL | A (the case of n_H = constant ———, the case of $n_H = f(\lambda)$ — — —)

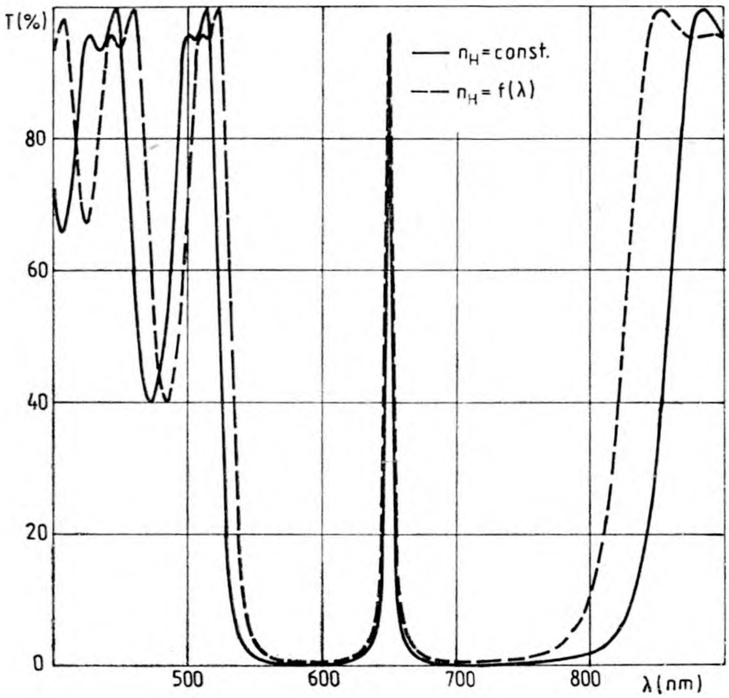

Fig. 7. The transmittance curve calculated for a pass-band filter of the strukture G|(HL)) 2 H (HL)[4] |A (calculated for n_H = constant ———, calculated for n_H = f(λ) — — — —

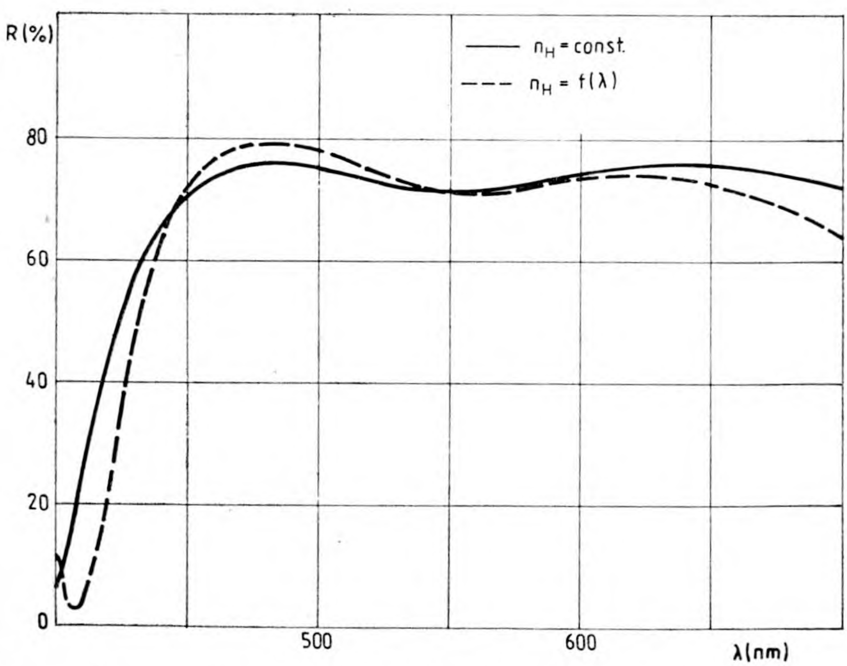

Fig. 8. The reflectance curve calculated for a beam-splitter of the structure G|2 H (LH)[2] |A (calculated for n = constant ———, calculated for n = f(λ) — — — —

viii) The following interference structures show negligible dispersion effects:

— G|L|A, antireflex monolayer, where L = MgF_2 (A = 1.90, B = 15400),

— G|k_1 H k_2 L|A, antireflex double layer with H = TiO_2 (ZnS) and L = SiO_2 (MgF_2),

— G|HML|A, antireflex for two wavelengths $\lambda_2/\lambda_1 = 2$, with H = ZrO_2 (A = 3.89, B = 91800), M = MgO and L = SiO_2.

— G|$(HL)^n$|HA, laser mirror for one wavelength, were H = TiO_2 (ZnS) and L = SiO_2 (MgF_2).

4. Summary and conclusions

From the considered examples it is evident that: spectral shifts, narrowing of the transmission band and appearance of undesired dips and peaks in the operating spectral zones are the principal effects of the refractive index dispersion of the optical coating materials. In most cases the effect can be confused with a systematic inequality of the optical thickness of the coating layers.

The technological importance of the computer simulation of the dispersion effects is evident, since during the transposition of a designed optical coating on a given equipment it allows the elimination of some false conclusions resulting from the spectrometric measurements.

Since the refractive index dispersion modifies the spectral characteristics of an optical coating in an undesirable manner, a proper adjustment in the computing process should be made to obtain the true and useful design of the coating.

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