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Design Of Nonpolarizing Achromatic Beam-Splitters With Dielectric Multilayer Coatings

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Abstract. Optical beamsplitters often consist of repeated pairs of high and low index quarter-wave layers. At oblique angles of incidence, such coatings typically have a fairly high polarization ratio. Reflectance, transmittance, and phase for the two orthogonal planes of polarization, s and p, are different in general. Here, we present the results of the design of all-dielectric beamsplitter coatings with very low polarization ratios. An initial sinusoidal refractive index profile, optimized with a refining computer program, yields a 50±1% beamsplitter in the 450 to 650 nm wavelength range, with less than 0.5% (abs.) difference between the s and p reflectance in most of this interval. Matching the elements of the characteristic matrix of this design with those of a generic homogeneous multilayer stack yields the starting design $A(HL)^7HS$ for a reflectance to transmittance ratio of R:T = 50:50% and 30:70% beamsplitters, which are optimized for the 500 to 600 nm wavelength range and angles of incidence of 40°, 50°, and 60° using a computer program based on a damped least squares refining technique. The average deviation from the nominal beamsplitting ratio is less than 0.5% for all given design examples. The maximum deviations are about 2% in this wavelength range.

Subject terms: polarization; beamsplitters; coatings; damped least squares design; dielectrics; gradient index; multilayers; thin films.

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CONTENTS

1. INTRODUCTION

Achromatic beamsplitters are necessary for many optical systems. If absorption can be tolerated, metal-dielectric thin film coatings[1] suit the purpose well and are easy to fabricate. For laser and electro-optical applications, the absorption losses of these beamsplitters are not tolerable, and all-dielectric designs are used. Dielectric multilayer stacks, however, have inherent polarization properties when used at angles of incidence off normal. For many applications it is desirable to separate (split) a light beam, coherent or incoherent, for instance into two orthogonal directions, without changing the polarization ratio of the incident light. Only a few papers on all-dielectric nonpolarizing beamsplitters have been published so far.[2–4] We propose a novel design strategy that may be extended to more general applications.

1.1. Polarization effects at a dielectric interface

For the following discussion, let us consider light as an electromagnetic wave of random polarization. When a beam of light interacts with solid matter at an oblique angle of incidence θ_o relative to the normal of the surface of the body, in general the electromagnetic wave reflected from or transmitted through this surface will have different amplitude and phase in the plane of light incidence than in the plane perpendicular to it. We refer to this as p and s polarization, respectively, p standing for parallel and s for "senkrecht" (German for perpendicular). We can calculate the amplitude reflection and transmission coefficients for the two planes of polarization, r_p,r_s and t_p,t_s, respectively, from Fresnel's formulas.

Curves SA in Fig. 1 illustrate the reflectance R_p and R_s for parallel and perpendicular polarization, respectively, as a function of the angle of incidence θ_o for the surface of a dielectric substrate S, for example, glass with an index of refraction $n_S = 1.52$, with air A as the ambient medium ($n_A = 1.00$). At the Brewster angle,

$$\theta_{oB} = \arctan \frac{n_S}{n_A} , \qquad (1)$$

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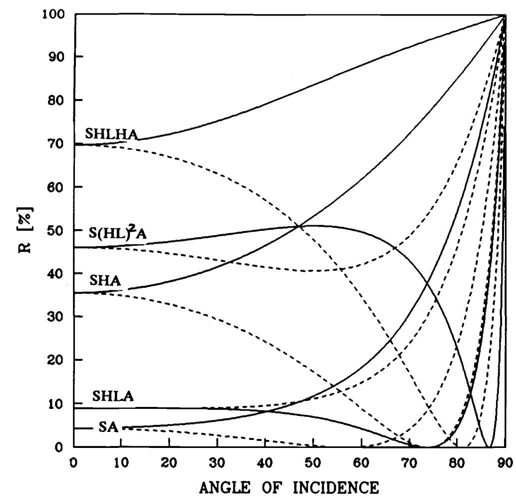

Fig. 1. Angular dependence of the reflectance R for s polarization (solid lines) and p polarization (dashed lines) of some quarter-wave thin film combinations H (n_H = 2.45) and L (n_L = 1.46) on a substrate S (n_S = 1.52). The A represents the ambient air (n_A = 1.00). The quarter-wave optical thicknesses for the H,L layers are matched for each angle of incidence θ.

the surface reflects only the lightwave polarized perpendicularly to the plane of incidence (R_s = 16%). The reflectance for parallel polarization is zero (R_p = O), so the interface acts as a polarizer. Intracavity Brewster windows or extracavity Brewster plates in lasers use this principle for defining the polarization of the laser beam.

1.2. Polarization effects in thin films

How does the polarization change when thin dielectric films are present on the glass surface? A thin film of TiO_2, for example, with an index of n_H = 2.45, increases the reflectance at normal incidence to 35,5% if the optical thickness n_Ht_H is one-quarter of the wavelength of the incident light. We describe such a high index quarter-wave thin film by the shorthand notation H. Accordingly, we denote a low index film of quarter-wave optical thickness (QWOT) by L, for example, SiO_2 with n_L = 1.46. With S standing for the substrate and A for the ambient medium (air), we find R_p and R_s for a TiO_2 single layer coating, depicted SHA in Fig. 1, as a function of the angle of incidence θ_o, with the QWOT continuously matched for θ_o. The Brewster angle for R_p = O has not changed very much from the one for the uncoated glass surface.

Adding a low index film L (e.g., SiO_2) of the same QWOT to the high index layer decreases the reflectance at normal incidence to 8.93%. However, the shapes of the s and p reflectance curves no longer agree with our previous experience. While R_s and R_p are almost equal for angles of incidence θ_o = 0 to 30°, now the s component, R_s, becomes zero at an angle of incidence of about 70° (SHLA in Fig. 1). Again, the QWOTs have been matched for the angle of incidence, θ_o. An additional high index film H increases the reflectivity to 70% (SHLHA), and the principal shapes of the R_p,R_s reflectance curves are similar to those of a single layer. We also find a Brewster angle again (where R_p = 0), now at θ_{oB} = 82°. At this angle, the coating would perform as a polarizing beamsplitter. Adding another layer L to the previous stack, we find that the R_s,R_p curves for the four-layer system $S(HL)^2A$ in Fig. 1 intersect at a particular angle; the coating would perform as a nonpolarizing beamsplitter. However, the $R_s = R_p$ condition is exactly valid only at that single angle of incidence for a single wavelength. Manufacturing tolerances will limit the usefulness of this approach.

Figure 1 shows that thin films of the same coating materials and thicknesses can produce different polarization effects, which depend on the arrangement and the number of layers. Use of just three layers, for example, using TiO_2 and SiO_2 as coating materials, results in a relatively strong polarization splitting at an angle of incidence of 80° (R_s = 96.4%, R_p = 0). With one additional low index layer and correspondingly matched film thicknesses, the coating becomes a nonpolarizing beamsplitter ($R_s = R_p$ = 45%) at an angle of incidence of 67°. However, the useful spectral range of these simple devices is rather narrow, and the angular sensitivity is quite high, making it difficult to align them.

1.3. Design strategy for achromatic nonpolarizing beamsplitters

In the following study, we present a novel design approach for nominally nonpolarizing beamsplitters with very low polarization over an extended wavelength range, with low angular sensitivity. For the starting design, we used an inhomogeneous coating with sinusoidal variation of the refractive index. After optimizing this starting design for minimum polarization (target function $R_s = R_p$) at the desired splitting ratio (R:T) in a given wavelength range, we converted the resulting graded-index coating into a multilayer stack of homogeneous layers by matching the characteristic matrices of the two coatings. Finally, we subjected this homogeneous layer design to a thin film optimization program, with R_s = R_p again being the target function for the desired splitting ratio in the given wavelength range. The flow chart of this whole procedure is shown in Fig. 2.

2. THEORY

2.1. Fundamentals

The amplitude reflection of a multilayer stack is given by

$$r = \frac{(m_{11} + m_{12}u_s)u_o - (m_{21} + m_{22}u_s)}{(m_{11} + m_{12}u_s)u_o + (m_{21} + m_{22}u_s)} , \tag{2}$$

where $u = (\varepsilon/\mu)^{1/2}\cos\theta$ for s polarization and $u = (\mu/\varepsilon)^{1/2}\cos\theta$ for p polarization.

The subscripts o and s correspond to the incident and final medium (substrate), respectively, and $m_{i,j}$ are the elements of the characteristic matrix **M** of the multilayer stack. For each polarization, the reflectance R of the stack is given by

$$R = rr^* , \tag{3}$$

with r* being the complex conjugate of r.

If the incident light is randomly polarized, then the overall reflection is the arithmetic mean of the values for the s and p components.

2.2. Homogeneous optical thin films

We refer to an optical thin film with a refractive index independent of its thickness as homogeneous. For a homogeneous

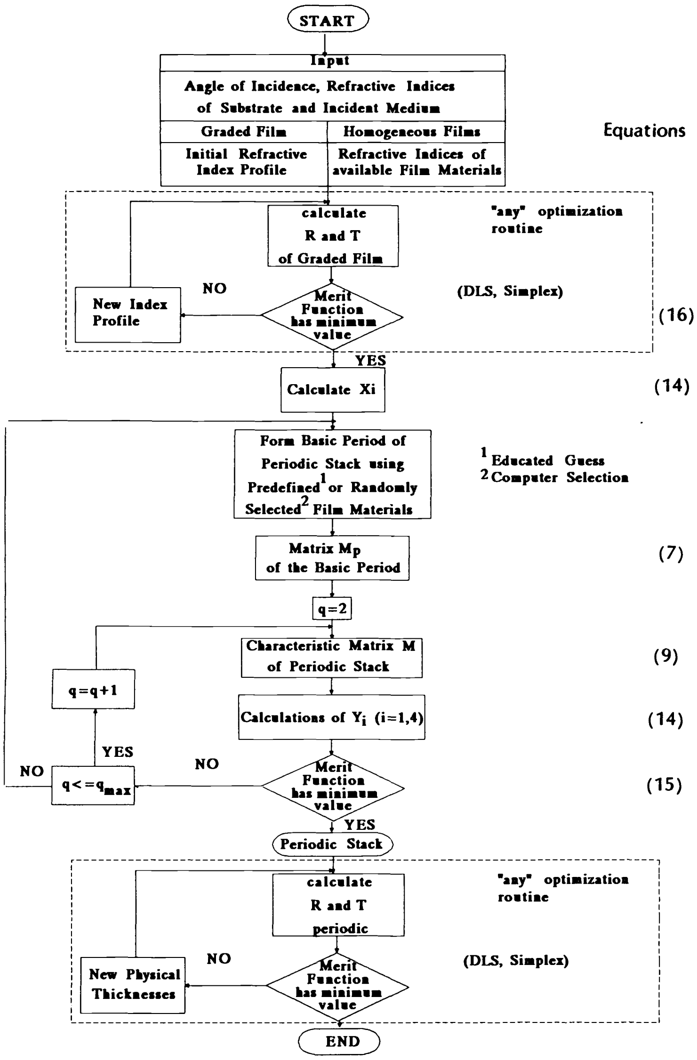

Fig. 2. Flow chart for the design of achromatic nonpolarizing beamsplitters.

layer of dielectric material, Maxwell's equations for s and p polarizations have the same simple form:

$$U'' + Uk^2n^2\cos^2\theta = 0 \,,$$
$$V'' + Vk^2n^2\cos^2\theta = 0 \,, \qquad (4)$$

where U and V are the complex amplitudes of the electric and magnetic fields, respectively, $k = 2\pi/\lambda$, and $n^2 = \epsilon$ ($\mu = 1$). The particular solutions, i.e., the elements of the characteristic matrix of the layer, are given by

$$m_{11} = m_{22} = \cos\phi \,,$$
$$m_{12} = \frac{m_{21}}{u^2} = \left(\frac{i}{u}\right)\sin\phi \,, \qquad (5)$$

where $\phi = (2\pi/\lambda)nt\cos\theta$, with t being the physical thickness of the layer, and θ is the angle of incidence.

2.3. Inhomogeneous (graded-index) optical thin films

We refer to an optical thin film as inhomogeneous or graded when its refractive index changes continuously along the axis

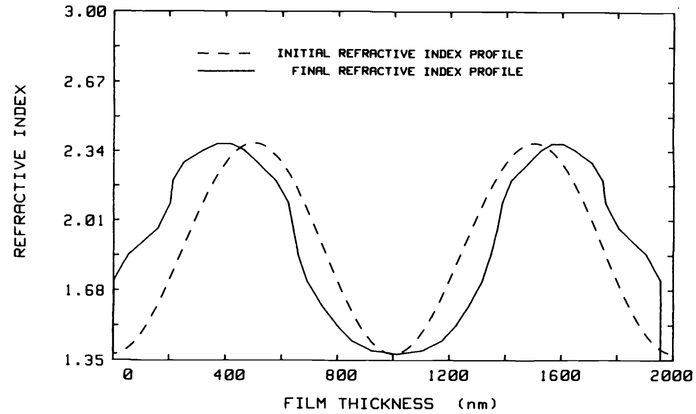

Fig. 3. Refractive index profiles of a low (nonpolarizing beamsplitter, showing initial (sinusoidal) and final (optimized) index profiles.

perpendicular to the film plane. For most optical materials $\mu = 1$ and Maxwell's equations for the electric field vector are

$$U'' + k^2(n^2 - S^2)U = 0 \,,$$
$$U'' - \left(\frac{2n'}{n}\right)U' + k^2(n^2 - S^2)U = 0 \,, \qquad (6)$$

for s and p polarizations, respectively, where S is Snell's constant. Primes indicate first and second derivatives with respect to the propagation direction of the light. These differential equations have analytical solutions for only a few real refractive index profiles.[5] Other profiles require either a numerical technique or an approximation technique for solving Maxwell's equations. One possibility for solving Eqs. 6 is to divide the inhomogeneous thin film into a number of homogeneous thin films. The calculation of the spectral performance of the film is then the same as for a homogeneous multilayer stack.[6] This method gives good results with a reasonable number of sublayers. The accuracy of this "slab" approximation can be controlled by direct integration of Maxwell's equations over the refractive index profile. We used the Runge-Kutta integrating technique with a suitable distribution of integration points.[7]

2.4. Design and refining technique

Intuitively, we chose the initial refractive index profile to be a sine wave. The refractive indices of the incident medium and substrate are such that they provide the light traveling through all boundaries near (not beyond) the critical angle. Such an initial design is shown in Fig. 3. The final refractive index profile is obtained by optimizing the profile to give equal s and p reflectance (or transmittance) for a given incidence angle and required intensity within a certain wavelength interval. The optimized index profile, also shown in Fig. 3, has the spectral performance shown in Fig. 4 for an angle of incidence of 45°. The average deviation from the nominal intensity splitting ratio (R:T = 50:50) is less than 0.5% in the wavelength interval 450 to 650 nm.

Usual thin film deposition equipment normally allows the deposition of homogeneous layers only. For the production of achromatic, all-dielectric beamsplitters it is therefore highly desirable to convert this (and any other) graded-index design

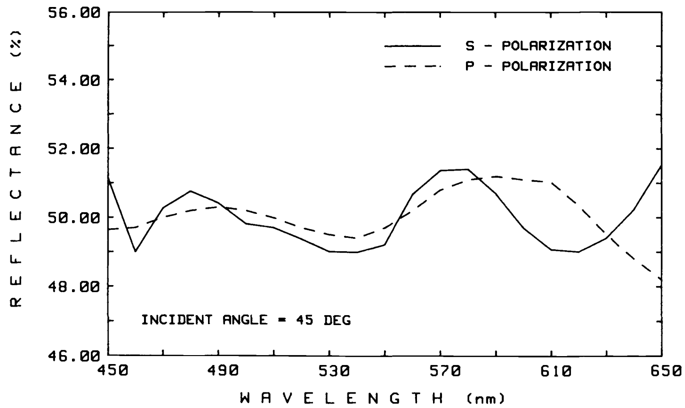

Fig. 4. Calculated spectral reflectance of the optimized nonpolarizing beamsplitter from Fig. 3, with a nominal splitting ratio of R:T = 50:50, in the wavelength interval 450 to 650 nm (θ = 45°).

into a stack of homogeneous thin films. One way to do this is to arrange the thicknesses and refractive indices of the replacing homogeneous multilayer stack such that it approximates the refractive index profile of the inhomogeneous (graded-index) film.[6] Our novel approach is to match the elements of the characteristic matrices for s and p polarization of the replacing periodic multilayer stack with the elements of the characteristic matrices for s and p polarization obtained in the graded-index film calculation.

To explain the matching procedure, we briefly review the matrix calculations for periodic optical multilayers. By definition, in a periodic multilayer stack a certain sequence of layers (the basic period) repeats itself two or more times. Let $\mathbf{M}_p$ be the characteristic matrix of this basic period, where

$$\mathbf{M}_p = \begin{bmatrix} m_{11} & i \cdot m_{12} \\ i \cdot m_{21} & m_{22} \end{bmatrix} . \tag{7}$$

If the sequence is repeated two times, then the characteristic matrix of the complete stack is given by

$$\mathbf{M}_2 = \mathbf{M}_p^2 . \tag{8}$$

For q repetitions ($q \geq 2$),

$$\mathbf{M}_q = \mathbf{M}_p^q = \begin{bmatrix} m_{11}S_{q-1}(a) - S_{q-2}(a) & i \cdot m_{12}S_{q-1}(a) \\ & \\ i \cdot m_{21}S_{q-1}(a) & m_{22}S_{q-1}(a) - S_{q-2}(a) \end{bmatrix} , \tag{9}$$

where

$$S_q(a) = \frac{\sin[(q+1)\cos^{-1}(a)]}{\sqrt{1-a^2}} \tag{10}$$

are the Chebyshev polynomials of the second kind,

$$a = \frac{1}{2} \mathrm{Tr}(\mathbf{M}_p) , \tag{11}$$

with Tr being the trace of the characteristic matrix, and $m_{i,j}$ are the real values of the elements of the characteristic matrix $\mathbf{M}_p$ [Eq. (7)] of the fundamental cell of the periodic stack.

Let $\mathbf{M}_g$ be the characteristic matrix obtained for a gradient-index profile[8] that satisfies certain spectral requirements.

$$\mathbf{M}_p = \begin{bmatrix} M_{11} & i \cdot M_{12} \\ i \cdot M_{21} & M_{22} \end{bmatrix} . \tag{12}$$

Then the matching conditions for a periodic stack of homogeneous layers at a given wavelength are

$$\begin{aligned} M_{11} &= m_{11}S_{q-1}(a) - S_{q-2}(a) , \quad M_{12} = m_{12}S_{q-1}(a) , \\ M_{21} &= m_{21}S_{q-1}(a) , \quad M_{22} = m_{22}S_{q-1}(a) - S_{q-2}(a) . \end{aligned} \tag{13}$$

The elements of the characteristic matrix are real at the main diagonal and imaginary elsewhere. For convenience, we introduce

$$\begin{aligned} X_1 &= M_{11} , \quad Y_1 = m_{11}S_{q-1}(a) - S_{q-2}(a) , \\ X_2 &= M_{12} , \quad Y_2 = m_{12}S_{q-1}(a) , \\ X_3 &= M_{21} , \quad Y_3 = m_{21}S_{q-1}(a) , \\ X_4 &= M_{22} , \quad Y_4 = m_{22}S_{q-1}(a) - S_{q-2}(a) . \end{aligned} \tag{14}$$

The merit function for the matching of the matrix elements $M_{i,j}, m_{i,j}$ ($i,j = 1 \ldots 2$) then can be defined as

$$F = \sum_{i=1}^{N} \sum_{j=1}^{4} |X_{i,j}^2 - Y_{i,j}^2|^2 W_i , \tag{15}$$

where N is the number of wavelengths, W_i are weighting factors at different wavelengths, and $X_{i,j}, Y_{i,j}$ are the X_j, Y_j from Eqs. (14) for the *ith* wavelength.

Next, we used the periodic multilayer stack obtained from the above matching procedure as the starting design for an optical thin film optimization program.[9] In fact, probably any commercially available thin film program[10] may be suitable and deliver the same results as those we obtained, provided its optimization routine [damped least square (DLS), simplex, simulated thermal annealing[11]] allows for a merit function for the spectral profile of a multilayer stack of the following general form:

$$F = \sum_{i=1}^{L} \sum_{j=1}^{N} \{W_{s_{i,j}}|R_{s_{i,j}} - R'_{s_{i,j}}|^2 + W_{p_{i,j}}|R_{p_{i,j}} - R'_{p_{i,j}}|^2\} , \tag{16}$$

where L is the overall number of specified angles, N is the number of specified wavelengths, R_s and R_p are the calculated reflectances, and R'_s and R'_p are the target values of the spectral functions for s and p polarization, respectively; $W_{i,j}$ are weighting factors. The optimization variables in the homogeneous multilayer stack calculations are the physical thicknesses of the layers. (In the optimization of the initial graded-index coating, the optimization variables were the refractive indices along the normal to the film boundaries.)

In our computer program, the iteration for each wavelength starts at $q = 2$ and ends when satisfactory matching is obtained or when the number of sequences (layers) gets too large. Chebyshev polynomials are oscillatory functions with the argument within the interval $(-1,1)$ and asymptotically approaching infinity at the end points of the interval; i.e., for $q \geq 2$,

$$S_q(-1) \rightarrow \pm\infty , \quad S_q(+1) \rightarrow \pm\infty . \tag{17}$$

Inspecting the trace of the characteristic matrix of the starting basic period may provide some useful information. For example, if $|a| = ½|Tr(\mathbf{M}_p)| > 0.8$, then the Chebyshev polynomials for $2 \leq q \leq 6$ have values $|S_q(a)| \geq 1$. This additional information helps in selecting the basic sequence of the initial design of the periodic multilayer stack.

In all examples given in this paper the basic sequence (fundamental cell) is of the form HL, where both H and L are not necessarily quarter-wave layers for a given reference wavelength. For all beamsplitters presented, the order of the Chebyshev polynomials is q = 7, which of course is also the number of repetitions of the basic sequence. However, it turned out to be an advantage to add an H layer to the repetition stack so as to make the starting design for the final optimization routine symmetric, i.e., $(HL)^7H$.

3. RESULTS

The spectral reflectance curves of the graded films (Fig. 4) were obtained by the slab approximation method. These results were verified by a Runge-Kutta integration of Maxwell's equations along the index gradient. For the optimization of both index profiles and homogeneous multilayer stacks we used a damped least squares technique.[9]

The initial multilayer design for achromatic beamsplitters at the three different angles of incidence investigated (θ = 40°, 50°, and 60°) turned out to be the same in all cases, and also for the two different beamsplitting ratios (50:50 and 30:70). With physical thicknesses of 220 nm Al_2O_3 for the H layer and 145 nm SiO_2 for the L layer, we started out with a $(HL)^7H$ design. Figure 5 gives the corresponding spectral curves, and Figs. 6 and 7 the refined performance. All optimized beamsplitter designs satisfy the imposed matching condition (of equal p and s reflectance) at more than two wavelengths within the wavelength region of 500 to 600 nm. The final design of the 50° beamsplitter for R:T = 30:70 has 14 layers. It is an antisymmetric stack. This is an interesting result since the matching started with the $(HL)^7H$ symmetric structure. Besides the HL fundamental cell, HLH may be used for the initial design with different materials and different order q with a good probability of successful refinement.

For all designs, the substrate material assumed is optical glass BK7 (n_S = 1.52, dispersive). For the ambient medium (incident medium), higher refractive indices had to be chosen for smaller angles of light incidence (measured inside the incident medium), as listed in Table I. For convenience, the indices given were selected from existing coating material files, which include dispersion (also assumed for the H and L layer materials).

The multilayer designs do not change the spectral performances with deviations of the angle of incidence of ±0.25°. They are probably useful (depending on the requirement) up to angle deviations of ±1°. The graded-index film design has lower angular sensitivity, as can also be expected from the extended spectral range.

4. DISCUSSION

The matching procedures have not yet been fully automated, still requiring some educated guesses from the designer (see flow chart in Fig. 2). Hence, there is room for further improvement. Once the fully automatic matching procedure exists, the designs obtained with discrete multilayers will give spectral performances still closer to those obtained for gradient-index films.

Bulk materials with the refractive indices chosen for the incident medium (listed in Table I) may be not readily available for the manufacture of beamsplitter prisms. In such cases, a prism made of lower index material (e.g., optical

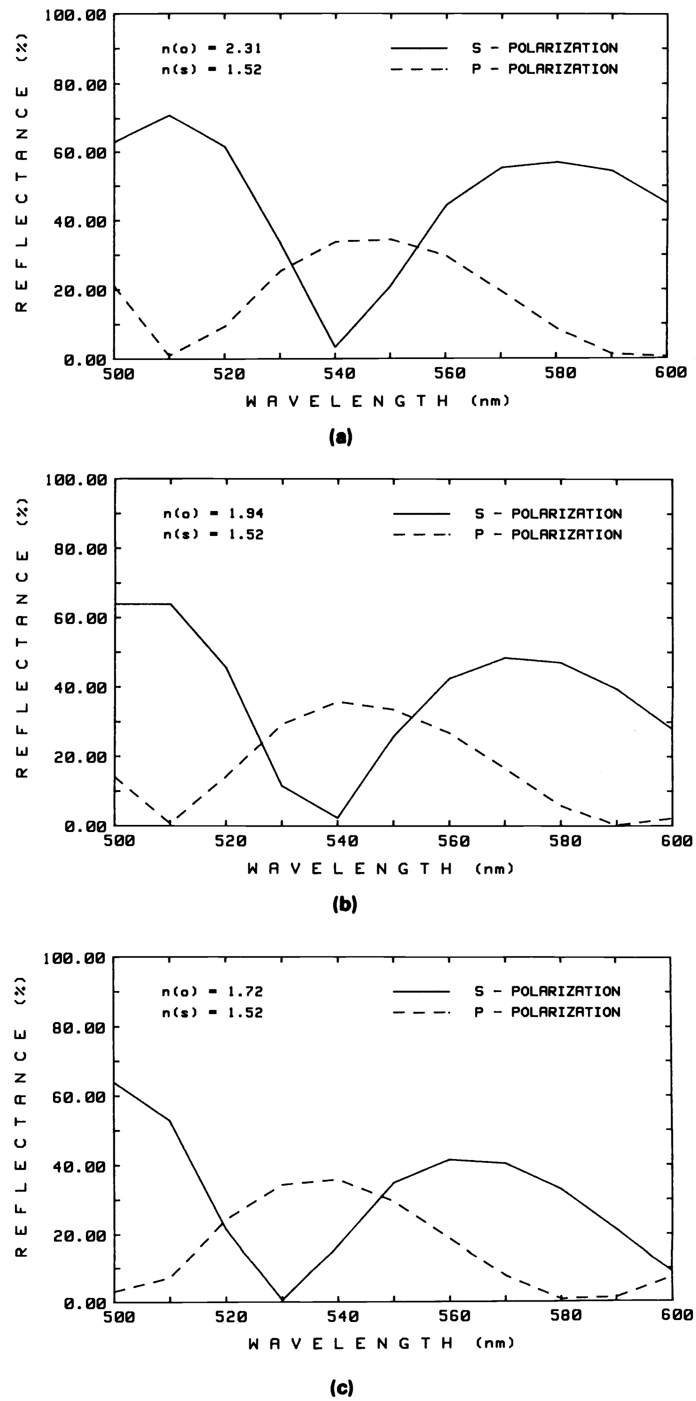

Fig. 5. Calculated spectral reflectance curves of the initial nonpolarizing beamsplitter designs shown in Table I, for (a) θ = 40°, (b) θ = 50°, and (c) θ = 60°.

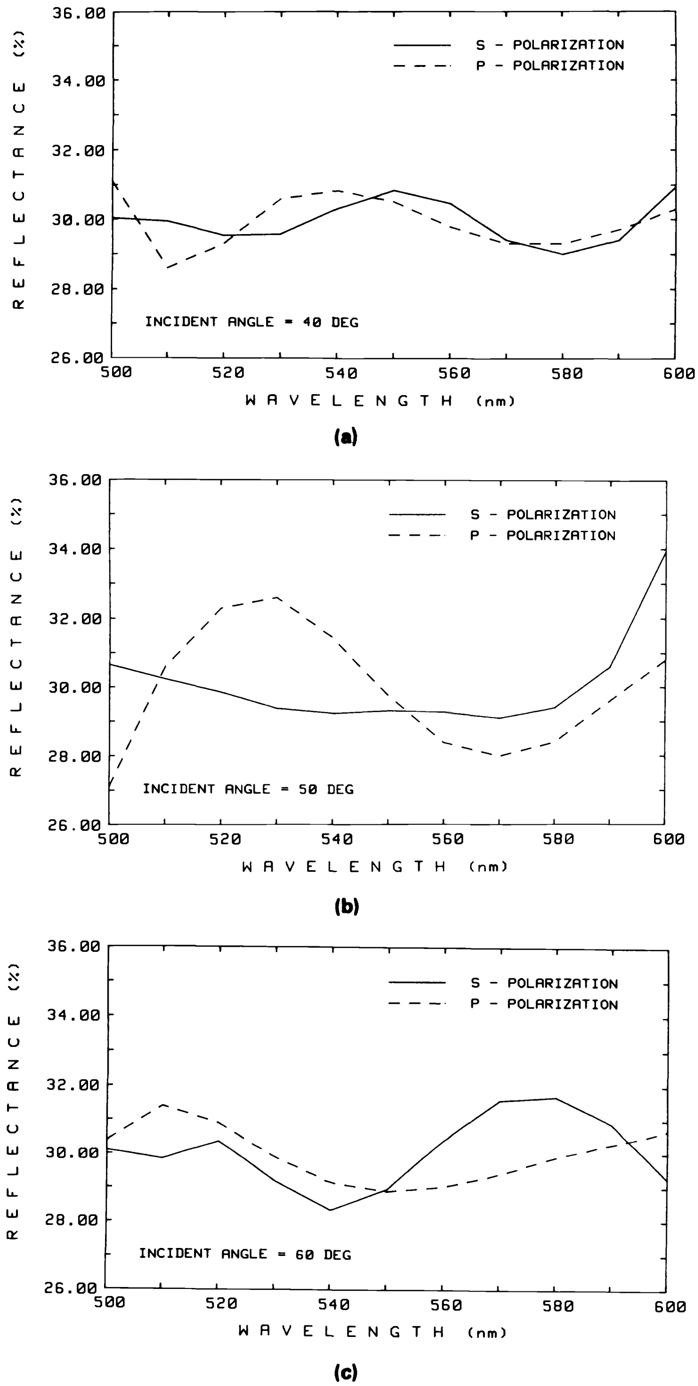

Fig. 6. Calculated spectral reflectance curves of the nonpolarizing beamsplitter designs shown in Table I, optimized for R:T = 30:70, for (a) θ = 40°, (b) θ = 50°, and (c) θ = 60°.

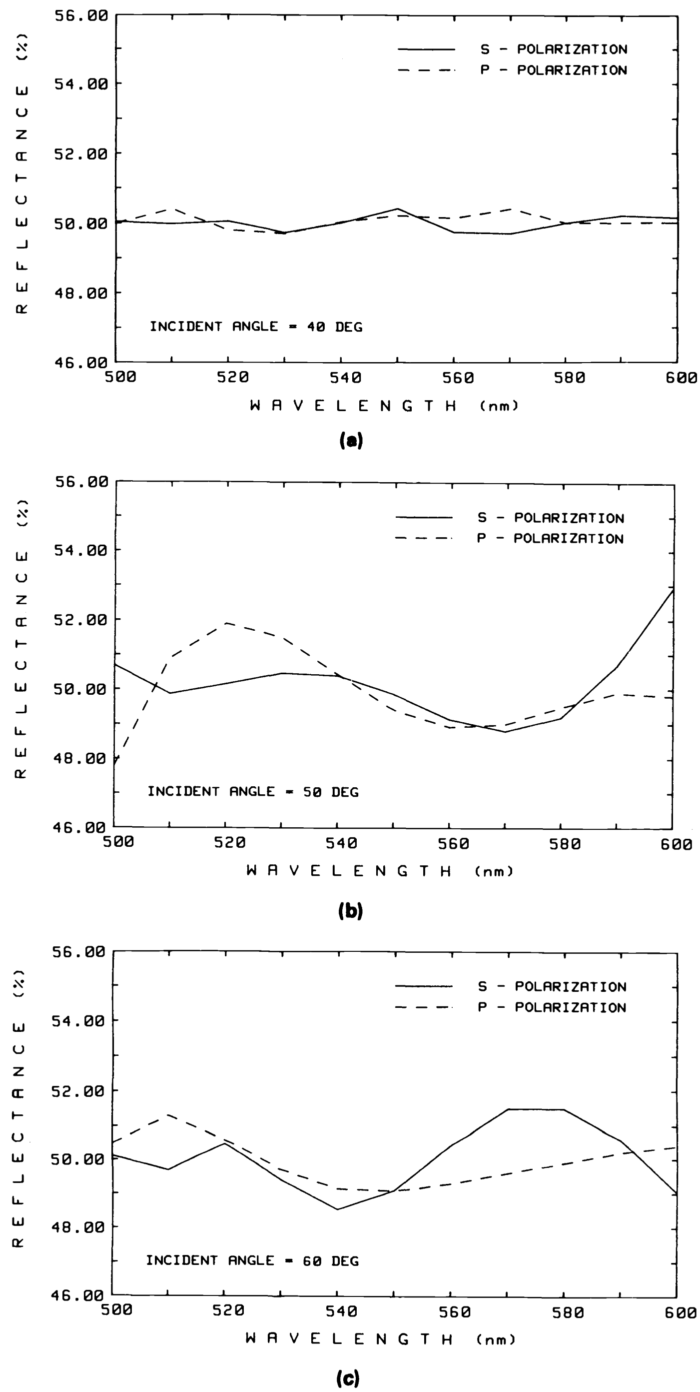

Fig. 7. Calculated spectral reflectance curves of the nonpolarizing beamsplitter designs shown in Table I, optimized for R:T = 50:50, for (a) θ = 40°, (b) θ = 50°, and (c) θ = 60°.

glass BK7) can be used if its hypotenuse is coated with a graded-index film with a decreasing index profile. Jacobsson[5] used a similar approach to satisfy the square root criterion for a single layer antireflection coating.

5. CONCLUSIONS

We have obtained a high degree of intensity matching for s and p polarization in a given wavelength interval, from 500 to 600 nm, in our particular examples, for homogeneous multilayer stacks derived from an initial graded-index film design by matching of the characteristic matrices. This graded-index film design maintains a very low polarization ratio for almost the complete visible region, covering a wavelength range about twice that covered by the derived homogeneous multilayer stack.

The described matrix matching technique may be useful for the transformation of a graded-index film with any desired spectral response into a multilayer stack of homogeneous layers with similar spectral performance.

TABLE I. Refractive indices and candidate materials for the incident medium beamsplitter prism for three angles of incidence (measured inside the medium).

	Angle of incidence θ_o		
	40°	50°	60°
Refractive index n_A	2.31	1.94	1.72
Optical materials	Anatas	SF59*	MgO, SF18*

*SF59 and SF18 are optical glasses from Schott.

6. ACKNOWLEDGMENTS

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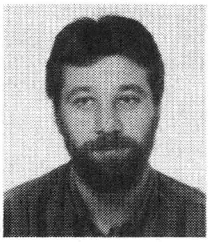

Muamer Zukic was born in Sarajevo, Yugoslavia, in 1956. He received the BS degree in physics from the University of Sarajevo in 1979. From 1981 to 1983 he worked for Optics Company ZRAK in the field of optical thin films. In 1983 he enrolled in the graduate studies program at Imperial College, London, where he received the MS degree in applied optics in 1984. After completion of graduate studies in England, he returned to Sarajevo and rejoined ZRAK where, from 1984 to 1987, he held the position of chief scientist in the Department for Research and Development of Optical Technologies. Mr. Zukic is presently enrolled in the Ph.D. program at the University of Alabama in Huntsville. The topic of his Ph.D. proposal is the design and fabrication of narrowband filters for the vacuum ultraviolet. Mr. Zukic's research interests include gradient index films and thin film refractive index dependence on the deposition conditions.

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