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The refractive index n_1 of a transparent layer of quarter-wave optical thickness coating a transparent substrate of refractive index n_2 can be chosen to produce half-wave retardation (HWR) in reflection and no change of polarization in refraction at any angle of incidence ϕ. The function $n_1(\phi, n_2)$, and the associated polarization-independent reflectance of the film-substrate system $\mathcal{R}(\phi, n_2)$ are determined. Such a coated surface can be used as a beam splitter with excellent characteristics (e.g., split fractions that do not depend on source polarization, a split beam whose polarization is identical to that of the incident beam and operation over a wide range of incidence angles). A concrete example of a coated Ge-slab beam splitter for 10.6-μm radiation at $\phi = 45°$ is given. The beam-splitter face of the slab is coated with the HWR layer, and the exit face is coated with a double layer that produces total refraction without change of polarization. Such a beam splitter is tolerant to film-thickness errors and is reasonably achromatic over a small (e.g., 10–11-μm) wavelength range. When used in a Michelson interferometer this beam splitter renders its operation totally independent of source polarization.

1. INTRODUCTION

I have recently[1] shown that the reflection and refraction of light of wavelength λ at an angle of incidence ϕ by the interface between two dielectric (linear, homogeneous, isotropic, and nonmagnetic) media of refractive indices N_0 and N_2 can be made completely insensitive to polarization by introducing an intermediate layer of refractive index

$$N_1 = (N_0 N_2)^{1/2} \quad (1)$$

and of thickness

$$d = (\lambda/4)(N_1^2 - N_0^2 \sin^2\phi)^{-1/2} \quad (2)$$

or an odd integral multiple thereof. This has led to a simple polarization-independent beam splitter[2] (PIBS) that divides the incident beam into two beams with constant reflectance and transmittance and with polarization identical to the incident polarization, for all incident polarizations. Equations (1) and (2) guarantee that

$$R_p = R_s \quad (3)$$

and

$$T_p = T_s, \quad (4)$$

where R_ν and T_ν are the complex-amplitude reflection and transmission coefficients for the $\nu = p$ and $\nu = s$ polarizations, parallel and perpendicular to the plane of incidence, respectively.

In this paper I show that, for given N_0, N_2, and ϕ, the refractive index of a layer of quarter-wave optical thickness, given by Eq. (2), can be chosen such that the following modified set of equations,

$$R_p = -R_s \quad (5)$$

and

$$T_p = T_s, \quad (6)$$

is satisfied simultaneously, instead of Eqs. (3) and (4). Equations (5) and (6) indicate that the layer reflects light as a half-wave retarder (HWR) and transmits it with no change of polarization. This leads to a new beam splitter with several significant characteristics: (1) the split fractions of the input power carried by the reflected and transmitted beams are constant independent of the input polarization; (2) the polarization state of the transmitted beam is always identical to that of the incident beam; (3) the reflected polarization is simply related to the incident polarization by a transformation that is exactly that produced by an HWR with fast and slow axes aligned with the p and s directions[3]; (4) the reflectance of this beam splitter is considerably higher, at lower angles of incidence, than that of the beam splitter of Refs. 1 and 2; and (5) all the preceding four properties remain virtually unchanged as the angle of incidence is varied from zero up to (and a little beyond) the design angle ϕ. Furthermore, a specific example of a coated Ge slab for 10.6-μm radiation (see Section 5) reveals that (6) the design is tolerant to appreciable film-thickness errors and, by consequence, (7) the beam splitter is reasonably achromatic over a limited (e.g., 10–11-μm) wavelength range.

Finally, we demonstrate in Section 6 that this new beam splitter, when used in a Michelson interferometer, renders it completely independent of source polarization.

2. FILM REFRACTIVE INDEX

For a layer of thickness given by Eq. (2), R_p and R_s become real and are given by[1]

$$R_p = (N_1^4 S_0 S_2 - N_0^2 N_2^2 S_1^2)/(N_1^4 S_0 S_2 + N_0^2 N_2^2 S_1^2), \quad (7)$$

$$R_s = (S_0 S_2 - S_1^2)/(S_0 S_2 + S_1^2), \quad (8)$$

where

$$S_m = (N_m^2 - N_0^2 \sin^2 \phi)^{1/2}, \quad m = 0, 1, 2. \quad (9)$$

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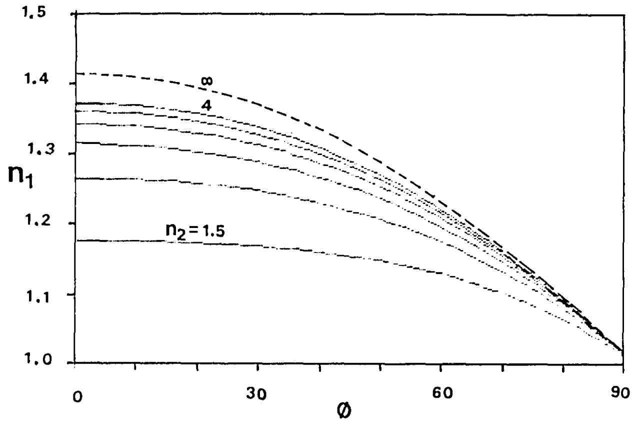

Fig. 1. Refractive index $n_1(\phi, n_2)$ [Eq. (12)] of a quarter-wave layer that, when deposited on a substrate of refractive index n_2, produces the half-wave retardation in reflection and no change of polarization in refraction at the angle of incidence ϕ. n_1 is plotted versus ϕ with n_2 as a parameter taking values from 1.5 to 4 in equal steps of 0.5. Both n_1 and n_2 are normalized with respect to the ambient (incidence-medium) refractive index [Eq. (11)]. The dashed curve at the top represents the limit of n_1 as $n_2 \to \infty$ [Eq. (14)].

Substituting Eqs. (7) and (8) into Eq. (5) gives, after simplification,

$$N_0 N_2 S_1^2 = N_1^2 S_0 S_2. \tag{10}$$

If S_m ($m = 0, 1, 2$) in Eq. (10) is replaced by its value from Eq. (9), and the normalization

$$n_1 = N_1/N_0, \qquad n_2 = N_2/N_0 \tag{11}$$

is used, the resulting equation can be solved for n_1^2 to give

$$n_1^2 = n_2 \sin^2\phi/[n_2 - \cos\phi(n_2^2 - \sin^2\phi)^{1/2}]. \tag{12}$$

Equation (12) gives an explicit solution for the refractive index n_1 of a quarter-wave layer that reflects light as an HWR in terms of the substrate refractive index n_2 and the angle of incidence ϕ. The function $n_1 = f(\phi, n_2)$, Eq. (12), is represented graphically in Fig. 1 by plotting n_1 versus ϕ with n_2 as a constant parameter taking values from 1.5 to 4 in equal steps of 0.5. At exact normal incidence, $\phi = 0$, the right-hand side (rhs) of Eq. (12) takes the form 0/0, and n_1 becomes indeterminate. This mathematical answer is justified physically because, when $\phi = 0$, $R_p = -R_s$ in the Nebraska (Muller) conventions[4] for *any* optically isotropic surface, coated or uncoated, and HWR is obtained independent of n_1. However, as $\phi \to 0$ the rhs tends to a specific limit given by

$$n_1^2 = 2n_2^2/(n_2^2 + 1). \tag{13}$$

For a given n_2, n_1 decreases monotonically from a maximum given by Eq. (13) to 1, as ϕ is increased from 0° to 90°, respectively, as is evident from Fig. 1. At any given ϕ an upper bound, $\hat{n}_1$, on n_1 is obtained by taking the limit of the rhs of Eq. (12) as $n_2 \to \infty$; this gives

$$\hat{n}_1 = \sqrt{2}\cos(\phi/2). \tag{14}$$

Thus the normalized film refractive index n_1 is always $< \sqrt{2} = 1.414$.

For the most practical case when the medium of incidence is air ($N_0 = 1$), values of $n_1 = N_1 \lesssim 1.2$ become unrealizable by a thin solid film.[5] From Fig. 1 it follows that the substrate must be optically dense, $n_2 \gtrsim 2$, and high angles of incidence should be avoided, $\phi < 60°$.

If the numerator and denominator of the rhs of Eq. (12) are divided by n_2 and Snell's law is applied, we obtain

$$n_1 = \sin\phi/(1 - \cos\phi\cos\phi'')^{1/2}, \tag{15}$$

where $\phi'' = \arcsin(\sin\phi/n_2)$ is the angle of refraction of light into the substrate. Equation (15) gives the required film refractive index in terms of the angles of incidence and refraction ϕ and ϕ''. If we denote by ϕ' the angle of refraction in the film, the following interesting result is obtained from Eq. (15):

$$\cos\phi' = (\cos\phi\cos\phi'')^{1/2}. \tag{16}$$

Therefore, for the film that produces HWR in reflection, the cosine of the angle of refraction in the film equals the geometric mean of the cosines of the angles of incidence and refraction into the substrate. In Appendix A, Eq. (12) is solved for ϕ for given n_1 and n_2.

3. REFLECTION COEFFICIENTS

Let us write

$$R_s = -R_p = R. \tag{17}$$

If we substitute Eq. (10) into Eq. (8), we get

$$R = (n_2 - n_1^2)/(n_2 + n_1^2), \tag{18}$$

which is a simple expression for the (complex) amplitude reflection coefficient of the HWR film-substrate system. To write R in terms of n_2 and ϕ, n_1^2 in Eq. (18) is replaced by its value from Eq. (12); this gives

$$R = \frac{(n_2 - \sin^2\phi) - (n_2^2 - \sin^2\phi)^{1/2}\cos\phi}{(n_2 + \sin^2\phi) - (n_2^2 - \sin^2\phi)^{1/2}\cos\phi}. \tag{19}$$

The intensity (power) reflectance,

$$\mathcal{R} = |R|^2, \tag{20}$$

is, of course, the same for the p and s (hence for all incident) polarizations. Figure 2 shows $\mathcal{R}(\phi, n_2)$ as a function of ϕ for constant values of n_2 from 1.5 to 4 in equal steps of 0.5, i.e., corresponding to the data of Fig. 1.

The normal-incidence limit on R is obtained from Eqs. (13) and (18):

$$R(0) = [(n_2 - 1)/(n_2 + 1)]^2, \tag{21}$$

and the corresponding intensity reflectance is

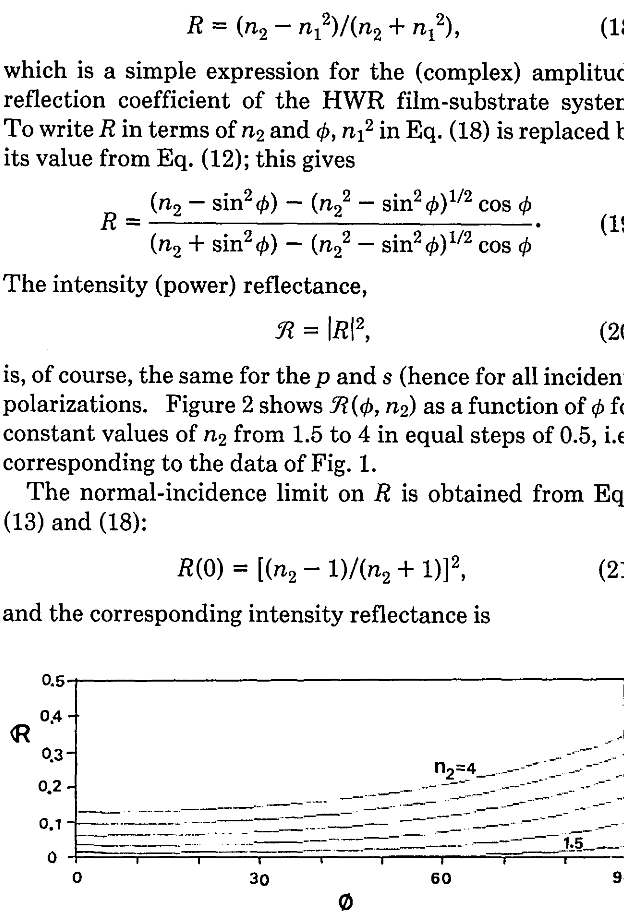

Fig. 2. Beam-splitter reflectance $\mathcal{R}(\phi, n_2)$ [Eqs. (19) and (20)] as a function of the angle of incidence ϕ, with the substrate normalized refractive index n_2 as a parameter taking values from 1.5 to 4 in equal steps of 0.5. The beam splitter uses a thin film whose properties appear in Fig. 1.

$$\mathcal{R}(0) = [(n_2 - 1)/(n_2 + 1)]^4 \tag{22}$$

$$= \bar{\mathcal{R}}^2(0), \tag{23}$$

where $\bar{\mathcal{R}}(0)$ is the (film-free) bare-substrate reflectance at normal incidence. Equation (23) is another curious result and indicates that the layer required to produce HWR near normal incidence reduces the substrate reflectance to its square.

The grazing-incidence limit is obtained by setting $n_1 = 1$ in Eq. (18):

$$R(90°) = (n_2 - 1)/(n_2 + 1), \tag{24}$$

$$\mathcal{R}(90°) = [(n_2 - 1)/(n_2 + 1)]^2 \tag{25}$$

$$= \bar{\mathcal{R}}(0). \tag{26}$$

Equations (25) and (26) indicate that the normal-incidence reflectance of the *bare* substrate represents an upper bound on the reflectance of the (all-dielectric) film-substrate HWR. In Fig. 2 the highest reflectance occurs for $n_2 = 4$ as $\phi \to 90°$ and is equal to $(3/5)^2$, or 36%. Figure 2 also shows that, for a given n_2, the rise of $\mathcal{R}$ with ϕ is relatively moderate. Recall from Section 2 that for $\phi > 60°$, n_1 becomes too close to 1 to be realizable by a thin solid film, so that this range of high angles is not useful.[6]

The reflectance levels attainable at $\phi < 60°$ are adequate for beam splitters and are considerably higher than those possible with the PIBS of Refs. 1 and 2 in this range of incidence angles. For example, by using a Ge substrate, $n_2 = 4$, the reflectances of the PIBS at 45° and 60° are 1.30 and 6.22%, as compared with 17.41 and 21.51%, respectively, for the present device. The reflectance gain at 45° exceeds 1 order of magnitude. The beam splitter application will be considered in detail in Section 5.

4. TRANSMISSION COEFFICIENTS

For a layer of quarter-wave optical thickness, Eq. (2), the complex amplitude transmission coefficients for the p and s polarizations are given by[7]

$$T_p = -j2(N_0N_1^2N_2)S_0S_1/(N_1^4S_0S_2 + N_0^2N_2^2S_1^2), \tag{27}$$

$$T_s = -j2S_0S_1/(S_0S_2 + S_1^2), \tag{28}$$

where S_m is defined by Eq. (9) and $j = \sqrt{-1}$. When the layer is chosen to make $R_p = -R_s$, i.e., the film-substrate system acts as an HWR in reflection, Eq. (10) is satisfied. Substitution of Eq. (10) into Eqs. (27) and (28) leads to

$$T_p = T_s = T, \tag{29}$$

where

$$T = -j2n_1^2 \cos\phi/(n_2 + n_1^2)(n_1^2 - \sin^2\phi)^{1/2}. \tag{30}$$

The normalized film and substrate refractive indices n_1 and n_2, Eqs. (11), are interrelated by Eq. (12).

Equation (29) leads to the important conclusion that the wave is refracted into the substrate *without change of polarization*. This in turn, suggests that this coated dielectric surface be used as a beam splitter with several advantages already stated in the Introduction.

In the following section a specific beam-splitter design is considered along with an examination of the effects of limited film-thickness, refractive-index, and incidence-angle errors.

5. COATED Ge-SLAB BEAM SPLITTER FOR 10.6-μm RADIATION AT 45° INCIDENCE ANGLE

As a concrete example, consider the reflection in air ($N_0 = 1$) of infrared radiation of wavelength $\lambda = 10.6$ μm (from a CO_2 laser) by a planar Ge surface ($N_2 = 4$) at an angle of incidence $\phi = 45°$. To achieve $R_p = -R_s$ and $T_p = T_s$, and to realize a beam splitter with excellent characteristics (see Section 1), a single-layer coating is deposited on the Ge substrate with refractive index and thickness given by

$$N_1 = 1.2824, \qquad d = 2.4770\ \mu\text{m}, \tag{31}$$

as obtained from Eqs. (12) and (2), respectively. The associated polarization-independent reflectance [calculated from Eqs. (19) and (20)] and transmittance[8] are 17.413 and 82.587%, respectively. By controlling the deposition conditions of BaF_2, for example,[9] the required refractive index of 1.2824 can be attained at 10.6 μm.

Deviations from the desired conditions of $R_p = -R_s$ and $T_p = T_s$ are determined by the behavior of the ratios[10]

$$\rho_r = R_p/R_s = \tan\psi_r \exp(j\Delta_r),$$
$$\rho_t = T_p/T_s = \tan\psi_t \exp(j\Delta_t), \tag{32}$$

as a certain design parameter is varied. Ideally, we should have $\psi_r = \psi_t = 45°$, $\Delta_r = 180°$, and $\Delta_t = 0$.

$R_p = -R_s$ and $T_p = T_s$ hold exactly at normal incidence ($\phi = 0°$) and at the design angle ($\phi = 45°$) and remain approximately correct at *all* angles in between. This remarkable stationary property of the film-substrate reflection HWR was previously established[11] and has been verified again for the present example. We find that ψ_r and ψ_t differ from 45°

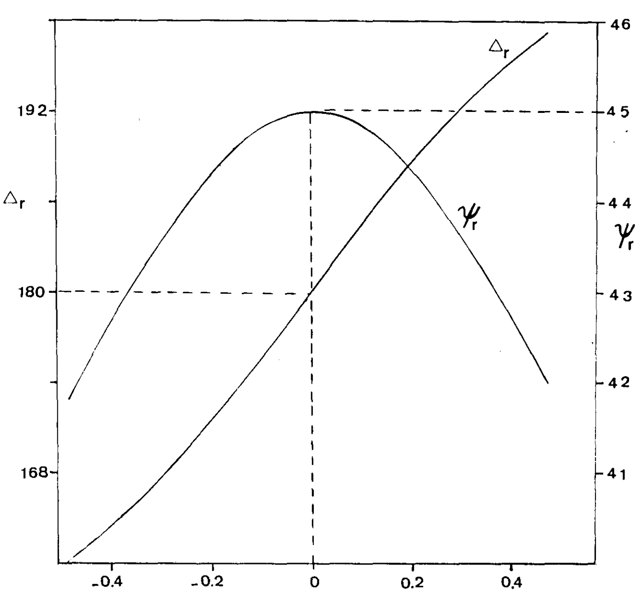

Fig. 3. Reflection ellipsometric angles ψ_r and Δ_r (in degrees) plotted versus small changes Δd (μm) of thickness of a transparent layer [Eqs. (31)] on a Ge substrate that reflects 10.6 μm radiation at a 45° angle of incidence as an HWR and refracts it without change of polarization. $\psi_r = 45°$ and $\Delta_r = 180°$ when $\Delta d = 0$, as expected.

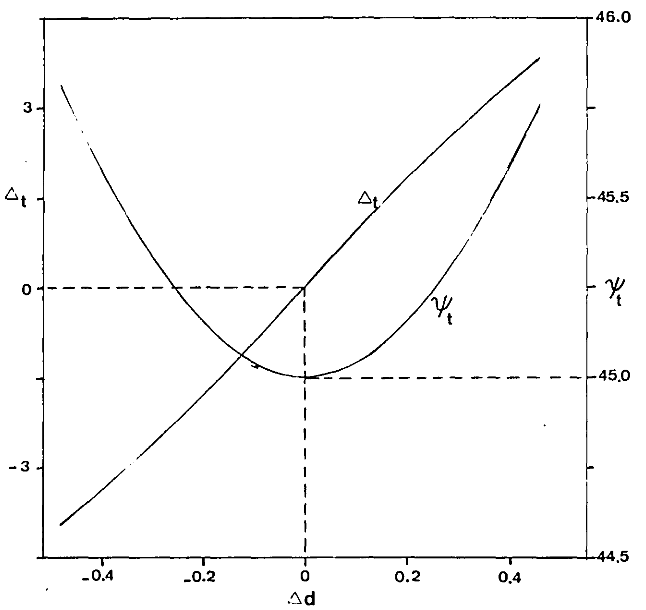

Fig. 4. Same as in Fig. 3 but for the associated transmission ellipsometric angles ψ_t and Δ_t. In this case, $\psi_t = 45°$ and $\Delta_t = 0$ when $\Delta d = 0$.

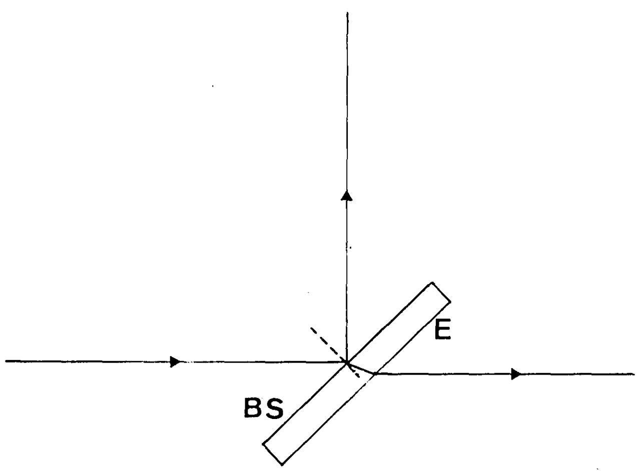

Fig. 5. Dielectric-slab beam splitter at 45° angle of incidence. The beam-splitting face BS is coated by a single layer to reflect light as a half-wave retarder and refract it without change of polarization. The exit face E carries a totally refracting, polarization-preserving bilayer.

by $< 1°$, $\Delta_r - 180° < 5°$, and $\Delta_t < 2°$, over the entire range $0 \leq \phi \leq 45°$. All errors change sign as the design angle, $\phi = 45°$, is passed, and the absolute errors remain within the limits stated above up to $\phi = 50°$. For $\phi > 50°$, the errors increase rapidly and become unacceptably large.

Figure 3 shows the effect on ψ_r and Δ_r of shifting the film thickness d by as much as $\Delta d = \pm 0.5$ μm around the design value of $d = 2.4770$ μm, and Fig. 4 gives the corresponding results for ψ_t and Δ_t. Notice that ψ_r and ψ_t are both locally stationary around $\Delta d = 0$, so that the condition $\psi_r = \psi_t = 45°$ is insensitive to film-thickness errors, to first order. It is safe to assume that d can be controlled to better than ± 0.05 μm (or 50 nm), which would keep the ψ error below a fraction of a degree. For the same level of thickness control, Δ_r stays within $\pm 2°$ of 180° and Δ_t within $\pm 0.5°$ of 0. In brief, appreciable film-thickness errors can be tolerated by this design.

Because changes of the wavelength of light around the design wavelength $\lambda = 10.6$ μm have essentially the same effect as equivalent film-thickness errors, neglecting material dispersion, it follows that this beam splitter is reasonably achromatic if the wavelength is scanned over a small range, e.g., between 10 and 11 μm. This may prove important if the beam splitter is used, e.g., in a Michelson interferometer (Section 6) to examine the spectral composition of the output of a CO_2 laser.

At the design point the condition $\psi_r = \psi_t = 45°$ is, to first order, unaffected by small shifts of n_1 around the required value of 1.2824. However, to limit the associated phase errors to a few degrees requires that n_1 be controlled to within ± 0.01, which is attainable using present-day thin-film deposition technology.

So far I have mentioned nothing about the exit face of the beam splitter. It is definitely desirable to use a plane-parallel slab (Fig. 5). With the incidence angle being 45°, one beam is reflected at 90° and the other is transmitted without any angular deviation (but with a small, inconsequential, lateral displacement that is proportional to the thickness of the slab). The beam-splitting face beam splitter is coated by a single layer with properties given by Eqs. (31) and sensitivity as has already been described. The exit face E must not produce a spurious change of polarization, or the purpose of the beam splitter will be defeated. This can be accomplished by a transparent (BaF_2–ZnSe) bilayer exactly as has been recently described.[12] Such a bilayer produces *total refraction without change of polarization* and fits perfectly the purpose of the present beam-splitter design.

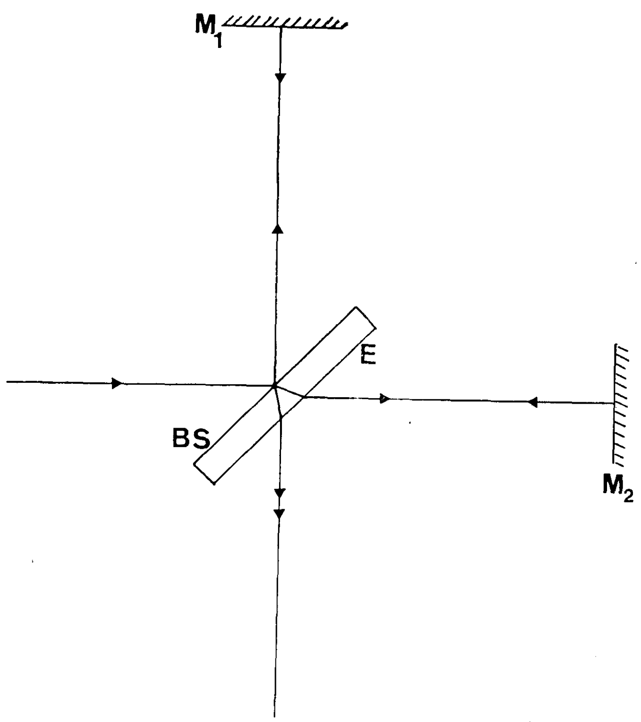

Fig. 6. Polarization-independent Michelson interferometer that uses the beam splitter of Fig. 5. The two recombining beams have equal intensities (when the isotropic return mirrors M_1 and M_2 have equal reflectances) and, more importantly, have the same state of polarization as the source beam, irrespective of the latter.

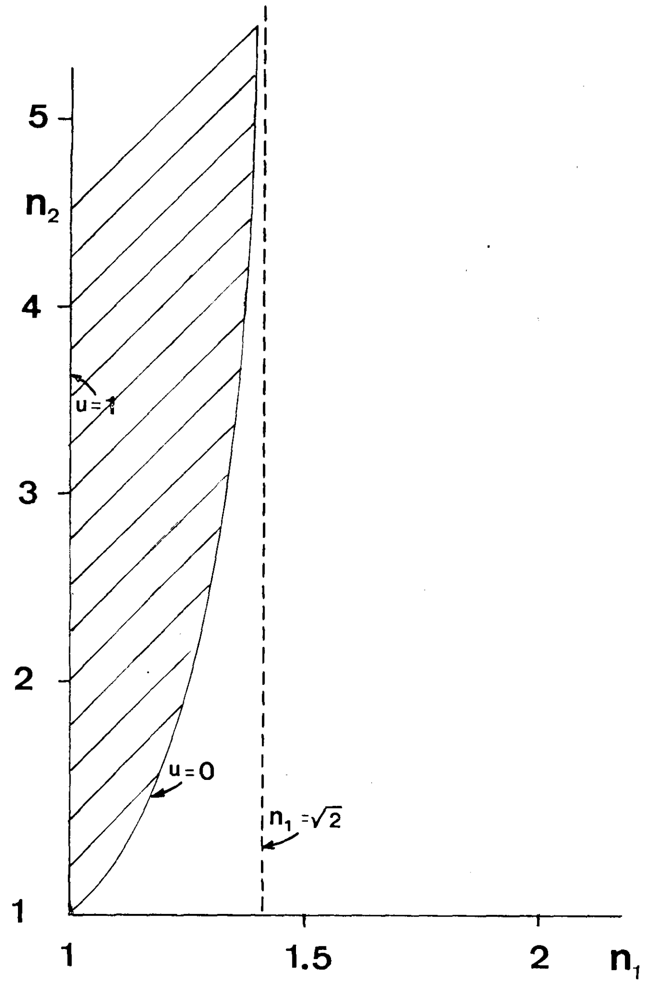

Fig. 7. Domain of all possible pairs of film and substrate refractive indices (n_1, n_2) that yield an acceptable answer, $0 \leq u \leq 1$, when substituted into the rhs of Eq. (A2).

6. MICHELSON INTERFEROMETER

Figure 6 shows a Michelson interferometer using the new beam splitter. If the effect of every reflection and refraction encountered in the path of each beam between the source and the detector is accounted for,[13] one can see readily that the two recombining beams (at the detector) are of equal intensity and have the same polarization as that of the incident beam, independent of the input polarization. We are unaware of any other equally simple beam-splitter design that imparts this remarkable property to the Michelson interferometer.[14]

APPENDIX A

For a given, all-dielectric, film-substrate system with known refractive indices n_1 and n_2 it is possible to determine the angle of incidence, $\phi = \phi_{\text{HWR}}$, at which half-wave retardation is attained in reflection with a layer of quarter-wave optical thickness at that angle. Equation (12) permits an explicit solution for ϕ. If we define

$$u = \sin^2\phi, \tag{A1}$$

then Eq. (12) can be manipulated to yield the answer

$$u = (n_1^4 n_2^2 + n_1^4 - 2n_1^2 n_2^2)/(n_1^4 - n_2^2). \tag{A2}$$

The refractive-index pair (n_1, n_2) must be such that Eq. (A2) gives

$$0 \leq u \leq 1. \tag{A3}$$

The limiting cases of $u = 0$ and $u = 1$ of Eq. (A2) define the two boundaries

$$n_1 = \sqrt{2}n_2/(n_2^2 + 1)^{1/2}, \tag{A4a}$$

$$n_1 = 1 \tag{A4b}$$

of the domain of the n_1n_2 plane of all possible pairs (n_1, n_2) that lead to HWR in reflection and the effect described in this paper. The boundary curve of Eq. (A4) has the line $n_1 = \sqrt{2}$ as an asymptote (as $n_2 \rightarrow \infty$), so that the solution domain lies entirely in the strip $1 < n_1 < \sqrt{2}$ of the n_1n_2 plane, as is shown in Fig. 7.

For a transparent film on an absorbing substrate with complex refractive index $n_2 - jk_2$, the analytical solution of this appendix gives an accurate estimate of ϕ_{HWR} when $k_2 \ll n_2$. The latter condition holds for semiconductors over an appreciable part of the visible spectrum.[15] If k_2 cannot be neglected (e.g., for metallic substrates), then the generally applicable numerical approach of Ref. 11 ought to be used.

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6. Except, of course, if a dense medium of incidence, e.g., glass, is used instead of air.
7. See. Eqs. (9) and (10) of Ref. 1.
8. The polarization-independent intensity transmittance for this lossless film-substrate system is given by $\tau = 1 - \mathcal{R}$, where $\mathcal{R}$ is the reflectance plotted in Fig. 2.
9. P. C. Kemeny, "Refractive index of thin films of barium fluoride," Appl. Opt. **21**, 2052–2056 (1982).
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incidence by a transparent bilayer coating on a high-index transparent or absorbing substrate," Appl. Opt. **24**, 4454–4459 (1985). The outer film of the bilayer on the exit face should have the *lower* refractive index of 1.2070, requiring a change of the evaporation conditions of BaF_2 (Ref. 9).

13. We assume that mirrors M_I and M_2 are optically isotropic and have equal reflectances, say, $\mathcal{R}_M$. Normal-incidence reflection from such mirrors is accompanied by the HWR, Ref. 3. Both external and internal reflections at the beam-splitting face also cause HWR. Total refraction at the exit face (caused by the bilayer coating) is, of course, inconsequential. Each of the recombining beams suffers two HWR reflections leading to a net *null* effect on polarization, and each suffers the *same* total intensity loss, given by the factor $\mathcal{R}_{BS}(1 - \mathcal{R}_{BS})\mathcal{R}_M$, where $\mathcal{R}_{BS}$ and $(1 - \mathcal{R}_{BS})$ are the reflectance and transmittance of the beam-splitting face, respectively.
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