12-1-1986

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Polarizing beam splitters for infrared and millimeter waves using single-layer-coated dielectric slab or unbacked films

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Received 16 June 1986.

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An ideal polarizing beam splitter (PBS) is a device that separates two cotraveling orthogonally linearly polarized components of an incident light beam (usually denoted by \(p\) and \(s\)) into two beams that propagate in different directions, with each split beam being purely polarized in one of the original orthogonal linear states. Practical PBSs are based on the phenomenon of double refraction, crystal polarizers such as the Rochon and Wollaston prisms, or interference in a multilayer coating embedded inside a (glass) cube.

The objective of this paper is to describe a simple alternative PBS (Fig. 1) that consists of a plane-parallel optically isotropic dielectric slab of refractive index \(n_2\) that is as low as possible, which is coated on both sides by a transparent thin film of refractive index \(n_1\) that is as high as possible. The slab is oriented so that light is incident (from air, \(n_0 = 1\)) at an angle \(\phi_p = \arcsin(u_1^{1/2})\), where \(u\) is the root between 0 and 1 of the quadratic equation

\[
au^2 + bu + c = 0,
\]

where

\[
a = n_1^2 - n_2^2, \quad b = 2n_2n_4 - n_1(n_2^2 + 1), \quad c = n_2^2(n_1^2 - n_2^2).\]

At \(\phi_p\), the \(p\)-polarized component (parallel to the plane of incidence) is totally transmitted \((R_p = 0, T_p = 1)\) when the thickness of the film equals

\[
d_p = (\lambda/4)(n_1^2 - u)^{-1/2}
\]
or an odd multiple thereof. To achieve an acceptable PBS the \(s\) component must be nearly totally reflected \((R_s = 1, T_s = 0)\). The intensity reflectance for the \(s\) polarization of one coated surface takes the simple form

\[
x_1 = a/\alpha, \quad x_2 = b/\alpha.
\]

The single important parameter \(\alpha\) can be determined in a simple calibration step in which ROE is illuminated by totally linearly polarized light of arbitrary azimuth (by placing a good linear polarizer in the path of the incident beam), and the corresponding Fourier amplitudes \(a_1\) and \(b_1\) of the output calibration signal are recorded. Then we can use the fact that

\[
x_1^2 + x_2^2 = 1
\]

for total incident linear polarization to obtain, using Eqs. (14),

\[
\alpha = (a_1^2 + b_1^2)^{1/2}.
\]

The calibration signal can be put in the form \(\ell = \ell_0[1 + \alpha \cos(2\theta - 2\theta_0)]\), where \(\theta_0\) is the azimuth of the incident linear vibration from the reference plane and \(\alpha\) represents the modulation depth. This identifies \(\alpha\) with the parameter \(m_c\) of Ref. 1. This can also be verified by manipulating Eq. (12) as follows. Let \(R_p\) and \(R_s\) be the detector surface reflectances for incident \(p\)- and \(s\)-polarized light. Then we can write

\[
R = \frac{1}{2} (R_p + R_s),
\]

\[
\cos 2\phi = \frac{1 - \tan^2 \phi}{1 + \tan^2 \phi} = \frac{1 - (R_p/R_s)[1 + (R_s/R_p)]}{(R_s - R_p)/(R_s + R_p)}.
\]

If \(R\) and \(\cos 2\phi\) in Eq. (12) are replaced by their values from Eqs. (17), one gets

\[
\alpha = (R_s - R_p)/(2R_s - R_p) = m_c.
\]

It should be noted that \(\alpha\) is a function of wavelength and must be measured over the useful spectral range of the detector for spectroscopic applications.

To summarize: we have shown that the rotating-detector ellipsometer (ROE), first described in Ref. 1, can be used to measure the three Stokes parameters of incident light which is in a general state of partial polarization. This considerably widens the scope of possible applications of this unique and simple instrument.

The author sincerely appreciates the kind hospitality of the Département de Physique, du Solide, Université de Provence, Marseille, France, where this work was done. A Fulbright Senior Research Scholar Award is also gratefully acknowledged.

References

About the best that one can do in the visible spectrum is to have \( n_1 = 2.5 \) (e.g., \( \text{TiO}_2 \) film) and \( n_2 = 1.4 \) (substrate of a fluoride material). In this case Eq. (4) gives \( R_s = 0.818 \), which is not high enough. However, two or more such coated slabs placed in parallel and in succession make a useful transmission polarizer.\(^{4,5}\)

The situation is significantly favorably different in the IR where semiconductors become transparent and present an excellent choice of high-index thin-film coating material. For example, Ge has a refractive index of 4 (a higher value is possible depending on evaporation conditions) over a wide (3-13-\( \mu \)m) IR spectral range. Lower-index substrates are also available in the IR, such as Irtran 1 and Irtran 3 (hot-pressed polycrystalline compacts of \( \text{MgF}_2 \) and \( \text{CaF}_2 \), respectively)\(^6\) with \( n_2 < 1.4 \) for \( \lambda > 5 \) \( \mu \)m.

As a first specific example let us take a Ge/Irtran 3 film-substrate system at wavelength \( \lambda = 10.6 \) \( \mu \)m of the CO laser. From Ref. 6 we find that \( n_1 = 4 \) (Ge) and \( n_2 = 1.28 \) (Irtran 3) at this wavelength. From Eqs. (1) and (2) we get \( u = 0.98585 \), \( \phi = 83.17^{\circ} \). From Eq. (3) \( \delta_p = 683.90 \) nm, and Eq. (4) gives \( R_s = 0.9747 \). This reflectance is high enough to make this Ge-coated Irtran 3 slab a simple useful (although not ideal) PBS. The reflected light is, of course, totally s polarized. The transmitted light is dominantly \( p \) polarized with a small residual \( s \) component. The extinction ratio \( ER \) is transmission is given by

\[
ER_t = T_p/T_p' = (1 - R_s)^2
\]

\[
= 6.4 \times 10^{-4}.
\]

The degree of polarization \( P \) of transmitted light for incident unpolarized light is given by

\[
P_t = (T_p - T_s)/(T_p + T_s)
\]

\[
= 0.99987,
\]

which confirms that the transmitted radiation is indeed almost totally \( p \) polarized.

Performance approaching even closer the ideal PBS is attained if IR-transparent (4-20-\( \mu \)m) PbTe with refractive index \( n_1 = 6.1 \) is used as the film material.\(^7\) Assuming \( n_2 = 1.28 \) as before (Irtran 3 slab, \( \lambda = 10.6 \) \( \mu \)m), we get \( R_s = 0.9904 \); this impressively high reflectance falls short of the ideal by \(<1\%\). From Eqs. (5) and (6) we calculate \( ER_t = 10^{-4} \) and \( P_t = 0.99989 \). Because the reflection is perfectly polarizing, \( ER_s = 0 \) and \( P_s = 1 \). These results clearly demonstrate that this PBS is very practical.

For completeness, we indicate that \( \phi_p \) reverts back to the Brewster angle of the film, i.e., \( \phi_p = \tan^{-1}n \) [75.96 and 78.91\(^\circ\) for \( n = 4 \) (Ge) and 5.1 (PbTe), respectively]. From Eq. (4), the \( s \) reflectance of the unbacked film at \( \phi_B \) is obtained by setting \( n_1 = n \) and \( n_2 = 1 \):

\[
R_s = [(n^4 - 1)/(n^4 + 1)]^2.
\]

For a semi-infinite phase of film material

\[
R_s = [(n^2 - 1)/(n^2 + 1)]^2
\]

at \( \phi_B \). From Eqs. (7) and (8), we may write

\[
R_s = f(n)\overline{R}_s,
\]

where

\[
f(n) = (n^2 + 1)/(n^2 - 1)^2.
\]

\( f(n) \) represents the enhancement factor of the \( s \) reflectance due to interference in the quadratic film. Figure 2 shows that \( f(n) \) falls monotonically from a maximum of 4 at \( n = 1 \) (or infinitesimally \( \overline{R}_s \) to 1 as \( n \to \infty \). Returning to Eq. (7) we get \( R_s = 0.9845 \) when \( n = 4 \). [For this \( R_s \), \( \overline{R}_s = 0.7786 \) and \( f(4) = 1.2645 \).] For a two-film PBS, \( ER_t = 2.4 \times 10^{-4} \) and \( P_t = 0.9995 \). When \( n = 5.1 \), we have \( R_s = 0.9941, ER_t = 3.47 \times 10^{-5}, \) and \( P_t = 0.9999 \). Together with \( ER_s = 0 \) and \( P_s = 1 \), these results indicate the best performance by a simple system of two unbacked films. Even with one unbacked high-index film (\( n > 5 \)), a PBS with acceptable characteristics is obtained.

A finding that adds to the importance of PBS using unbacked films is that performance is essentially achromatic over at least one spectral octave (neglecting material dispersion) and is only slightly affected by large errors of thickness around the quarterwave condition. A drastic change would be to reduce the normalized thickness by half. For an unbacked film of one (three or any odd multiple of) eighth-wave optical thickness, it can be proved that the \( s \) reflectance at the Brewster angle (\( \phi_B = 0 \)) is given by

\[
R_s = \frac{n^8 - 2n^4 + 1}{n^8 + 6n^4 + 1}.
\]
When \( n = 4 \), Eq. (11) gives \( R_s = 0.9695 \). Compared with \( R_s = 0.9845 \) for the quarterwave film, the one-half reduction of film thickness (or the equivalent doubling of wavelength) lowers the reflectance by only 0.015! For a pair of eighth-wave unbacked films of \( n = 4 \), we calculate \( ER_t = 9.3 \times 10^{-4} \) and \( P_t = 0.9981 \).

PBS using unbacked high-index quarterwave (or near-quarterwave) films is expected to prove especially useful for the now important far-IR and millimetric waves. The reason is obvious: unbacked films will require no special art to make. One will need only look for transparent materials of the highest possible refractive index.

The kind hospitality of the Département de Physique du Solide, Université de Provence, where this work was done, and a Fulbright Senior Research Scholar Award are gratefully acknowledged.

References

4. Ref. 1, p. 10–100.
5. Ref. 2, p. 8–74.
7. Ref. 6, p. 7–111.