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Quarter-wave layers with 50% reflectance for obliquely incident unpolarized light

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The conditions under which light interference in a transparent quarter-wave layer of refractive index \( n_1 \) on a transparent substrate of refractive index \( n_2 \) leads to 50% reflectance for incident unpolarized light at an angle \( \varphi \) are determined. Two distinct solution branches are obtained that correspond to light reflection above and below the polarizing angle, \( \varphi_p \), of zero reflection for \( p \) polarization. The real \( p \) and \( s \) amplitude reflection coefficients have the same (negative) sign for the solution branch \( \varphi > \varphi_p \) and have opposite signs for the solution branch \( \varphi < \varphi_p \). Operation at \( \varphi < \varphi_p \) is the basis of a 50%–50% beam splitter that divides an incident totally polarized light beam (with \( p \) and \( s \) components of equal intensity) into reflected and refracted beams of orthogonal polarizations [Opt. Lett. 31, 1525 (2006)] and requires a film refractive index \( n_1 > (\sqrt{2} + 1)/\sqrt{2} \). A monochromatic design that uses a high-index TiO2 thin film on a low-index MgF2 substrate at 488 nm wavelength is presented as an example. © 2007 Optical Society of America

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1. INTRODUCTION

In a recent letter\(^1\) it was shown that it is possible to split a monochromatic light beam into two beams of equal power and orthogonal polarizations by reflection and refraction at the planar surface of a dielectric substrate at an angle of incidence below the Brewster angle. This requires a substrate of high refractive index, \( n_2 > 3 + 2 \sqrt{2} = 5.8284 \), e.g., PbTe in the IR. It was noted that a quarter-wave layer of high refractive index, which is deposited on a substrate of low refractive index, can also be used to accomplish the same novel beam splitting function. This thin-film coating design is now presented in this paper. For a succinct account of different types of beam splitters, see, e.g., the review by Dobrowolski.\(^2\)

In Section 2 an analytical design procedure is presented for achieving 50% reflectance of unpolarized (or randomly polarized) light that is obliquely incident on a transparent quarter-wave coating on a transparent substrate. The algorithm developed in Section 2 is applied in Subsection 3.A to the special case of a vanishing substrate (\( n_2 = 1 \)), i.e., an unsupported quarter-wave pellicle. It is also applied to quarter-wave coatings of varying refractive index \( n_1 \) on a (glass or plastic) substrate of refractive index \( n_2 = 1.5 \) in Subsection 3.B.

In Section 4 a beam splitter design that uses a TiO2 high-index quarter-wave coating on a low-index MgF2 substrate for 488 nm (Ar-ion-laser) light is considered as a specific example. An error analysis shows the effect of \( \pm 5^\circ \) shifts in the angle of incidence and of \( \pm 5\% \) shifts in wavelength or film thickness on the performance of this beam splitter. Section 5 gives a brief summary of the paper.

2. QUARTER-WAVE LAYERS THAT REFLECT 50% OF UNPOLARIZED LIGHT AT OBLIQUE INCIDENCE: ANALYTICAL TREATMENT

For light reflection in air (\( n_0 = 1 \)) by a transparent layer of quarter-wave optical thickness (equal to half the film-thickness period) and refractive index \( n_1 \) on a transparent substrate of refractive index \( n_2 \), the amplitude reflection coefficients of the \( p \) and \( s \) polarizations at oblique incidence at an angle \( \varphi \) are real and are given by\(^3,4\)

\[
R_p = \frac{S_p S_2 - S_1^2}{S_p S_2 + S_1^2},
\]

\[
R_s = \frac{n_1^4 S_p S_2 - n_2^2 S_1^2}{n_1^4 S_p S_2 + n_2^2 S_1^2},
\]

where

\[
S_i = (n_i^2 - u)^{1/2}, \quad i = 0, 1, 2,
\]

\[
u = \sin^2 \varphi.
\]

All materials are assumed to be optically isotropic and are separated by parallel plane boundaries.

In terms of the quantity

\[
P = \frac{S_p S_2}{S_1^2},
\]

Eqs. (1) and (2) are rewritten as
For a high-index transparent film on a low-index transparent substrate it is apparent from Eqs. (3)-(5) that \( P \) is real and positive and in the range \( 0 < P < 1 \), hence, only roots of Eq. (8) that satisfy this condition are accepted.

From Eqs. (3)-(5) we also obtain

\[
P^2 = (1 - u)(n_2^2 - u)(n_1^2 - u)^2.
\]  
(10)

Equation (10) can be rewritten as a quadratic equation in \( u \):

\[
b_2 u^2 + b_1 u + b_0 = 0,
\]  
(11)

with coefficients given by

\[
b_2 = P^2 - 1,
\]

\[
b_1 = (n_2^2 + 1) - 2n_1^2 P^2,
\]

\[
b_0 = n_1^4 P^2 - n_2^2.
\]  
(12)

The only acceptable roots of Eq. (11) are those for which \( 0 < u < 1 \). Finally, the angle of incidence \( \varphi \) at which the 50% reflectance for incident unpolarized light is achieved, for given \( n_1 \) and \( n_2 \), is given by

\[
\varphi = \arcsin(u^{1/2}).
\]  
(13)

3. QUARTER-WAVE LAYERS THAT REFLECT 50% OF UNPOLARIZED LIGHT AT OBLIQUE INCIDENCE: NUMERICAL RESULTS

A. Case of a Vanishing Substrate, \( n_2 = 1 \)

The algorithm of Section 2 is applied to determine the constraint between \( n_1 \) and \( \varphi \) such that Eq. (7) is satisfied when \( n_2 = 1 \) (i.e., for an unsupported quarter-wave layer or pellicle), by assigning values to \( n_1 \) between 1 and 6 in steps of 0.01 and solving for the corresponding values of \( \varphi \).

Figure 1 shows the two solution branches that we obtain: a high-angle branch (HAB), or solution 1, which is represented by the continuous line, and a low-angle branch (LAB), or solution 2, which is represented by the dashed line. The dash-dot curve in the middle represents the polarizing (Brewster) angle, \( \varphi = \varphi_B = \arctan^{-1} n_1 \).

Figures 2 and 3 show the real amplitude reflection coefficients \( R_p \) and \( R_s \) that are associated with the HAB and LAB, respectively, as functions of the film refractive index \( n_1 \). \( R_p \) and \( R_s \) are both negative for the HAB, Fig. 2, and have opposite signs \( (R_p > 0, R_s < 0) \) for the LAB, Fig. 3.

Figure 4 is a plot of \( R_p \) versus \( R_s \) and shows two separate arcs of the unit circle, Eq. (7), in the third and fourth quadrants, respectively. Points A and B correspond to the similarly marked points in Fig. 1.
Figures 5 and 6 show the intensity reflectances $R_p^2$ and $R_s^2$ for the HAB and LAB, respectively, as functions of $n_1$. The average value of $R_p^2$ and $R_s^2$ is constant $=0.5$, independent of $n_1$ as is required by Eq. (7).

An interesting feature of Fig. 1 is that $\varphi$ of the HAB reaches a minimum, $\varphi_{\text{min}}=71.8225^\circ$, at point A where $n_1 = 1.78$. Therefore, a pellicle of 1.78 refractive index and quarter-wave optical thickness (or an odd integral multiple thereof) functions as a 50%-50% BS for incident unpolarized light at $\approx 72^\circ$ angle of incidence. The starting point B of the LAB in Fig. 1 is at $\varphi=0$ and corresponds to $n_1 = (\sqrt{2}+1)/2 = 2.414$. Film materials that have this refractive index include diamond in the visible and ZnSe in the IR.\(^5,6\)

**B. General Case of $n_2>1$**

For an arbitrary substrate of refractive index $n_2$, the starting value of $n_1$ for the LAB is obtained by noting that at $\varphi=0$, $R_p^2=R_s^2=1/2$. It follows from Eqs. (6) that

$$R_s = (P - 1)/(P + 1) = -1/\sqrt{2},$$

$$P = (\sqrt{2} - 1)^2.$$  

If $u=0$ is substituted in Eq. (10), we get

$$n_1 = (n_2/P)^{1/2}.$$  

When Eqs. (15) and (16) are combined, we obtain

$$n_1 = (\sqrt{2} + 1)/n_2.$$  

As a specific example we take quarter-wave layers on a (glass or plastic) substrate with $n_2=1.5$. Figure 7 shows the two solution branches that we obtain using the algorithm of Sec. 2. When compared with Fig. 1 (for $n_2=1$), the HAB in Fig. 7 is displaced upward to higher angles,
and its minimum at point A now occurs at $\varphi_{\text{min}} = 81.6208^\circ$, $n_1 = 1.98$. The starting value $n_1 = 2.9568$ of the LAB at point B is predicted by Eq. (17).

In Fig. 7 the middle (dash-dot) curve gives the polarizing angle $\varphi_p$ as a function of $n_1$ as obtained from Eqs. (19) and (20).

In Fig. 8 the amplitude reflection coefficients $R_p$ and $R_s$ that are associated with the HAB of Fig. 7 plotted as functions of the film refractive index $n_1$. The significance of the point of intersection C is discussed in the text.

Fig. 8. Amplitude reflection coefficients $R_p$ and $R_s$ that are associated with the HAB of Fig. 7 plotted as functions of the film refractive index $n_1$. The significance of the point of intersection C is discussed in the text.

In Fig. 9 the middle (dash-dot) curve gives the polarizing angle $\varphi_p$ as a function of $n_1$ with $n_2 = 1.5$. To calculate the polarizing angle $\varphi_p$ we note from Eqs. (6) that $R_p = 0$ if

$$P = n_2^2/n_1^4.$$  (18)

Substitution of $P$ from Eq. (18) into Eq. (10) gives a quadratic equation,

$$c_2u^2 + c_1u + c_0 = 0,$$  (19)

in $u = \sin^2 \varphi_p$ with coefficients given by

$$c_2 = n_1^8 - n_2^8,$$

and its minimum at point A now occurs at $\varphi_{\text{min}} = 81.6208^\circ$, $n_1 = 1.98$. The starting value $n_1 = 2.9568$ of the LAB at point B is predicted by Eq. (17).

In Fig. 7 the middle (dash-dot) curve gives the polarizing angle $\varphi_p$ as a function of $n_1$ as obtained from Eqs. (19) and (20).

In Fig. 8 the amplitude reflection coefficients $R_p$ and $R_s$ that are associated with the HAB of Fig. 7 plotted as functions of the film refractive index $n_1$. The significance of the point of intersection C is discussed in the text.

In Fig. 9 the middle (dash-dot) curve gives the polarizing angle $\varphi_p$ as a function of $n_1$ with $n_2 = 1.5$. To calculate the polarizing angle $\varphi_p$ we note from Eqs. (6) that $R_p = 0$ if

$$P = n_2^2/n_1^4.$$  (18)

Substitution of $P$ from Eq. (18) into Eq. (10) gives a quadratic equation,

$$c_2u^2 + c_1u + c_0 = 0,$$  (19)

in $u = \sin^2 \varphi_p$ with coefficients given by

$$c_2 = n_1^8 - n_2^8,$$
\[ \begin{align*}
    c_1 &= 2n_1^2 n_2^4 - n_1^8 (n_2^4 + 1), \\
    c_0 &= n_1^8 n_2^2 (n_1^4 - n_2^2). 
\end{align*} \]  

Figures 8 and 9 show the amplitude reflection coefficients \( R_p \) and \( R_s \) as functions of the angle of incidence \( \varphi \) for a beam splitter that consists of a quarter-wave (43.51 nm) thin film of TiO\(_2\) on a MgF\(_2\) substrate at 488 nm wavelength. The angle of incidence is varied by \( \pm 5^\circ \) around the design angle \( \varphi = 46.04^\circ \).

\[ R_p = R_s = -1/\sqrt{2} = -0.7071, \quad n_1 = \sqrt{n_2} = 1.2247. \]  

This corresponds to a polarization-preserving (or polarization-independent) 50\%-50\% beam splitter in both reflection and transmission.\(^3\)

The associated intensity reflections \( R_p^2 \) and \( R_s^2 \) as functions of \( n_1 \) are shown in Figs. 10 and 11 for the HAB and LAB, respectively. Again, the average of \( R_p^2 \) and \( R_s^2 \) is constant (0.5) independent of \( n_1 \) as required by Eq. (7).

4. BEAM SPLITTER FOR PRODUCING REFLECTED AND TRANSMITTED BEAMS OF EQUAL POWER AND ORTHOGONAL POLARIZATIONS IN THE VISIBLE

Consider a high-index \( (n_1 = 2.895) \) thin film of TiO\(_2\) on a low-index \( (n_2 = 1.386) \) MgF\(_2\) substrate at wavelength \( \lambda = 488 \) nm. (Because we assume isotropic phases, the refractive indices are taken as averages of the ordinary and extraordinary indices \( n_o \) and \( n_e \) published in Ref. 6.) By use of the algorithm of Section 2, the operating angle of incidence \( \varphi = 46.037^\circ \) is obtained. The film-thickness period \( D_1 \) and quarter-wave metric film thickness \( d_1 \) are determined by

\[ D_1 = \frac{\lambda}{2} (n_1^2 - \sin^2 \varphi)^{-1/2}, \]

\[ d_1 = D_1/2, \]  

which give \( D_1 = 87.02 \) nm and \( d_1 = 43.51 \) nm. Under the ideal operating conditions, the average reflectance for incident unpolarized light is 1/2 and the reflection and transmission ellipsometric parameters\(^4\) satisfy the following relations: \(^1,7\)

\[ \Delta = \pi, \Delta_t = 0, \]

\[ \psi_p + \psi_s = \pi/2. \]  

To couple the refracted light out of the substrate into air, a prismatic substrate with prism angle equal to the angle of refraction \( (31.287^\circ) \) can be used, so that light leaves the prism normal to its exit face which is antireflection coated.\(^8\)

When the wavelength of light and metric film thickness are kept constant, and the angle of incidence is varied by up to \( \pm 5^\circ \), the average reflectance and ellipsometric pa...
parameters change in the manner shown in Fig. 12. From Fig. 12, it is apparent that the ideal conditions of Eqs. (23) are nearly maintained; hence, this novel beam splitter is tolerant to small angle-of-incidence errors.

If the wavelength of light and angle of incidence are fixed, but the film thickness is varied by ±5% around its design value \(d_1 = 43.51 \text{ nm}\), the average reflectance and ellipsometric parameters change in the manner shown in Fig. 13. Again, the ideal conditions of Eqs. (23) are approximately satisfied, to within a small error, and the coating design is not overly sensitive to small film-thickness errors around the quarter-wave thickness.

Finally, when the angle of incidence and metric thickness of the coating are kept constant, and the wavelength is shifted by ±5% around \(\lambda = 488 \text{ nm}\), the average reflectance and ellipsometric parameters change in the manner shown in Fig. 14. In Fig. 14, the deviations from the ideal conditions of Eqs. (23) are more pronounced; hence, the beam splitter is not considered achromatic.

5. SUMMARY

A transparent layer of quarter-wave optical thickness, a pellicle or a coating deposited on a transparent substrate, reflects 50% of incident unpolarized light under certain conditions that are completely determined. Two distinct solution branches are obtained that correspond to incidence below and above the \(p\)-suppressing polarizing angle of the film-substrate system. Operation below the polarizing angle makes possible a novel thin-film beam splitter that divides incident totally polarized light into reflected and refracted beams of equal power (50% each) and orthogonal polarizations. The performance of one such device that uses a high-index TiO\(_2\) quarter-wave coating on a low-index MgF\(_2\) substrate at 488 nm wavelength is presented.

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