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Rasheed M.A. Azzam

University of New Orleans, razzam@uno.edu

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Inverting the ratio of the complex parallel and perpendicular reflection coefficients of an absorbing substrate using a transparent thin-film coating

R. M. A. Azzam

Department of Electrical Engineering, University of New Orleans, Lakefront, New Orleans, Louisiana 70148

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An absorbing substrate can be coated with a transparent thin film of refractive index $N_1$ (within a certain range) and thickness $d$ such that the ratio of complex reflection coefficients for the $p$ and $s$ polarizations of the film-covered substrate $\rho = R_p/R_s$ is the inverse of that of the film-free substrate $\overline{\rho} = R_p/R_s$ at an angle of incidence $\phi$. A method to determine the relationship among $\phi$, $N_1$, and $d$ that inverts $\rho$ (i.e., makes $\rho = 1/\overline{\rho}$) for a given substrate at a given wavelength is described and is applied to aluminum and silver substrates at 0.6328- and 10.6-µm wavelengths, respectively. Sensitivity of the inversion condition to incidence-angle and film-thickness errors is analyzed. $p$-inverting layers can be applied to one of the two metallic mirrors of a beam displacer or axicon to preserve the polarization state of incident monochromatic radiation.

1. INTRODUCTION

In this paper we show that it is possible to invert the ratio $\rho = R_p/R_s$ of the complex parallel ($p$) and perpendicular ($s$) reflection coefficients $R_p$ and $R_s$ of an absorbing substrate at oblique incidence using a transparent-film coating of properly selected refractive index and thickness. Such $p$-inverting layers, as we call them, can be applied to only one of the two metallic mirrors of a parallel-mirror beam displacer or axicon to preserve the state of polarization of incident monochromatic radiation. Likewise, they can be used to equalize the transverse-electric (TE $= s$) and transverse-magnetic (TM $= p$) complex eigenvalues of 90°-rooftop reflectors and waxes.

2. CONDITIONS FOR INVERTING $\rho$

The ratio of complex $p$ and $s$ reflection coefficients of a monochromatic plane wave of light of wavelength $\lambda$ at the interface between a transparent medium of real refractive index $N_0$ and an absorbing substrate of complex refractive index $N_2$ can be written as

$$\overline{\rho} = \frac{R_p}{R_s} = \overline{\rho}(\phi, N_0, N_2),$$

where $\phi$ is the angle of incidence. If the substrate is coated by a transparent film of thickness $d$ and refractive index $N_1$, the ratio of complex reflection coefficients becomes

$$\rho = \frac{R_p}{R_s} = \rho(\phi, d, \lambda, N_0, N_1, N_2).$$

The inversion condition for given ambient and substrate media at a given wavelength can be put in the form

$$\rho_0 = \overline{\rho}(\phi, \phi, N_1) = 1.$$  \hspace{1cm} (3)

In Eq. (3) the fixed arguments $N_0$ and $N_2$ of the functions $\overline{\rho}$ and $\rho$ have been dropped, and

$$\zeta = d/D_\phi$$

is the normalized film thickness, where

$$D_\phi = \left(\frac{\lambda}{2}\right)(N_1^2 - N_0^2 \sin^2 \phi)^{-1/2}$$  \hspace{1cm} (5)

is the film-thickness period.

Equation (3) represents two constraints [e.g., $\text{Re}(\overline{\rho}) = 1$, $\text{Im}(\overline{\rho}) = 0$] on three parameters: $\phi$, $\zeta$, and $N_1$. To determine the relationship among $\phi$, $\zeta$, and $N_1$, that satisfies Eq. (3), and hence achieves inversion, we assigned values to one parameter ($N_1$) and solved for the other two ($\phi$, $\zeta$). (It is equally easy to set $\phi$ and solve for $N_1$ and $\zeta$.) The separation-of-variables method outlined below is applied by interchanging $N_1$ and $\phi$.

For a given $N_1$, we separate the determination of $\phi$ and $\zeta$ as follows.\textsuperscript{2-4} We rewrite the inversion condition [Eq. (3)] in the form

$$\bar{\rho}_p = \overline{\rho}(A + BX + CX^2)/(D + EX + FX^2) = 1,$$  \hspace{1cm} (6)

where $\bar{\rho}$, $A$, $B$, $C$, $D$, $E$, and $F$ are determined by the $p$ and $s$ Fresnel reflection coefficients at the ambient–substrate, ambient–film, and film–substrate interfaces,\textsuperscript{1} and

$$X = \exp(-j2\pi \zeta/\lambda).$$  \hspace{1cm} (7)

We solve quadratic Eq. (6) for $X$:

$$X = f_X(\phi)$$  \hspace{1cm} (8)

and require that

$$|X| = |f_X(\phi)| = 1$$  \hspace{1cm} (9)

for a transparent film. (The $+$ and $-$ correspond to the two roots of the quadratic equation.)

Equation (9) has $\phi$ as its only unknown; $\phi$ is readily found by direct numerical iteration. Once the solution, indicated by $\phi_{\text{inv}}$, has been determined, complex $X$ can be evaluated from Eq. (8). Next, $\zeta_{\text{inv}}$ is obtained from $X$ as

$$\zeta_{\text{inv}} = (1/2\pi)\text{arg } X.$$  \hspace{1cm} (10)

All possible film thicknesses that produce inversion are given by

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\[ d_{\text{inv}} = (\xi_{\text{inv}} + m) D_{\phi_{\text{inv}}} \]  

(11)

where \( m \) is an integer. In what follows we will consider only the least normalized and actual film thicknesses: \( 0 < \xi_{\text{inv}} < 1 \) and \( 0 < d_{\text{inv}} < D_{\phi_{\text{inv}}} \).

3. \( \rho \)-INVERTING DIELECTRIC LAYERS ON AN ALUMINUM SUBSTRATE AT \( \lambda = 0.6328 \mu m \)

As a specific example, the method outlined in Section 2 was applied to a system that consists of a transparent film of adjustable refractive index on an Al substrate of complex refractive index \( N_2 = 1.212 - j6.924 \) at the He-Ne-laser wavelength \( \lambda = 0.6328 \mu m \). For an assumed value of \( N_1 > 1 \), a solution is sought for Eq. (9). Figure 1 shows \(|X| - 1\) versus \( \phi \) for \( N_1 = 1.55 \); this is characteristic of an \( \text{Al}_2\text{O}_3 \) (or \( \text{Si}_2\text{O}_3 \)) film. The two curves in Fig. 1 correspond to the two roots of the quadratic equation in \( X \). Only one curve intersects the \( \phi \) axis once at \( \phi_{\text{inv}} = 75.8165^\circ \). From Eq. (10) we determine that \( t_{\text{inv}} = 0.49164 \). We also calculate \( D_{\phi_{\text{inv}}} = 0.26163 \mu m \). Thus a dielectric (oxide) layer of refractive index 1.55 and thickness 0.12863 \( \mu m \), when coated onto an Al substrate, inverts its ratio of complex \( \rho \) and \( s \) reflection coefficients at an angle of incidence of 75.8165\(^\circ\).

As a check on the accuracy of the inversion, \( \rho_n \) is computed from Eq. (3) at \( \phi_{\text{inv}} \) and \( \xi_{\text{inv}} \), and we always make sure that \( |\rho_n| - 1 \) and \( \Delta_n = \arg \rho_n \) are less than \( 10^{-6} \).

To examine the sensitivity of the inversion condition to deviations of the angle of incidence \( \phi \) from \( \phi_{\text{inv}} \) we plot, in Figs. 2 and 3, \(|\rho_n| - 1\) and \( \Delta_n \), respectively, versus \( \phi \), as computed for an \( \text{Al}_2\text{O}_3 \) layer (\( N_1 = 1.55 \)) of the correct \( \rho \)-inverting thickness (\( d_{\text{inv}} = 0.12863 \mu m \)) on the Al substrate at \( \lambda = 0.6328 \mu m \). The results indicate reasonable insensitivity to errors of incidence angle.

Figure 4 shows the magnitude and phase errors \(|\rho_n| - 1\) and \( \Delta_n \) that result from shifting the film thickness from the value required for inversion (\( d_{\text{inv}} \)) by as little as \( \pm 10 \) \( \AA \) (1 nm) while keeping \( \phi = \phi_{\text{inv}} \). It is apparent that the inversion of \( \rho \) is sensitively dependent on film thickness in this particular case.

To explore the \( \rho \)-inversion condition for all possible dielectric films on the Al substrate at \( \lambda = 0.6328 \mu m \), the procedure outlined in Section 2 was applied repeatedly for successively increasing discrete values of the film refractive index \( N_1 \) beginning with \( N_1 \) just slightly above 1. No inversion was found possible for \( N_1 < N_1 \approx 1.5 \) or \( N_1 > N_1 \approx 2 \). Furthermore, we find that, as \( N_1 \) increases from its lower limit to its upper limit, \( \phi_{\text{inv}} \) decreases from 90\(^\circ\) to 0, whereas \( d_{\text{inv}} \) decreases from \( \sim 0.14 \) to \( \sim 0.08 \mu m \), both monotonically. The results are summarized in Table 1 and in Fig. 5. For reference, the \( \rho \) and \( s \) reflectances \( R_\rho \) and \( R_s \) of the film–substrate
system, under the conditions of inversion, appear in Fig. 5. As a second example, we also considered $\rho$-inverting layers on a Ag substrate ($N_2 = 9.5 - j73$) at the infrared CO$_2$-laser wavelength of $\lambda = 10.6$ $\mu$m. The results are shown in Fig. 6. Notice, in particular, the extent to which $\bar{i}_{\text{inv}}$ remains near 0.5 ($\bar{i}_{\text{inv}} = 0.5$ for a perfect conductor) and the high reflectances (>95%) for both polarizations.

4. APPLICATIONS OF $\rho$-INVERTING LAYERS

An important direct application of $\rho$-inverting layers is the realization of the simplest possible polarization-preserving parallel-mirror beam displacers and biconical axicons. In these devices, light is reflected twice at the same angle. By leaving one metal surface bare and by coating the other with a $\rho$-inverting layer, polarization preservation is achieved upon double reflection. Coating only one mirror (or cone) with one layer is undoubtedly simpler than all other approaches previously suggested for polarization-correcting parallel-
mirror beam displacers and axicons. Similarly, the application of a \( p \)-inverting layer to only one of the two mirrors of a biplanar 90°-rooftop reflector or biconical waxicon can equalize its TE (s) and TM (p) complex eigenvalues (net reflection coefficients).10

5. CONCLUDING REMARKS

The use of a transparent thin-film coating to invert the ratio of the complex \( p \) and \( s \) reflection coefficients of a substrate is fundamentally and practically significant. It establishes another facet of the historically and practically important analogy between thin-film and transmission-line theories.11 In particular, it is well known that a quarter-wave section of a lossless transmission line terminated by a load impedance at one end inverts that impedance at the other.12 The inversion of \( p \) of a substrate (load) by a transparent thin film (transmission line) of properly chosen refractive index and thickness represents an optical analog of this effect. It is interesting also to note that the required film thickness is approximately a quarter wavelength of light in the film medium \((d \approx 0.5\lambda_0/N)\), when \( N_1 > N_0 \sin \phi \). If the incident light is linearly polarized at a 45° azimuth from the plane of incidence, \( p \) becomes a complex number that completely describes the reflected polarization state.13 Such a complex polarization number is analogous to impedance14 and is inverted by a \( p \)-inverting layer.15

\( p \) inversion at different angles of incidence can be pursued along lines similar to those developed here for inversion at the same angle. A change of one of the \( \phi \)'s in the inversion condition of Eq. (3) to \( \phi' \), where \( \phi' \neq \phi \), is required. This adds a degree of freedom that leads to more solutions. Perhaps \( \phi \) and \( \phi' \) can be constrained to satisfy a relation other than equality. For example, we may choose \( \phi + \phi' = 90° \) to represent the important case of light reflection at an arbitrary angle \(( \neq 45° \)) from a 90°-rooftop reflector or from a waxicon with cones of any apex angle.

The analysis in this paper also applies, with minor modification, to the more general case of an inverting layer on top of a multilayer substructure. In this case, the proper reflection coefficients at the interface between the inverting layer and its underlying substructure must be used. For multilayer stacks, \( p \) inversion may be possible by proper design of an inner (embedded) layer, as this is possible with the outer (top) layer. Additional flexibility becomes available when the characteristics of more than one layer are adjusted to achieve inversion. This further generalization lies outside the scope of this paper.

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REFERENCES

1. See, for example, R. M. A. Azzam and N. M. Bashara, Ellipsometry and Polarized Light (North-Holland, Amsterdam, 1977), Sec. 4.4.
2. This separation-of-variables technique proved useful before. See, e.g., Refs. 3 and 4.
11. See, for example, Z. Knittl, Optics of Thin Films (Wiley, New York, 1976), Sec. 9.7.
13. R. M. A. Azzam and N. M. Bashara, Ellipsometry and Polarized Light (North-Holland, Amsterdam, 1977), Sec. 1.7.
15. If \( \theta \) and \( \epsilon \) represent the azimuth and ellipticity angle, respectively, of the polarization ellipse of the reflected light from the bare substrate, \((\pi/2) - \theta \) and \( -\epsilon \) will be the corresponding parameters of the light reflected from the substrate coated with the \( p \)-inverting layer. (See Ref. 1, p. 40.)