Free-Standing Thin-Membrane, Zero *B*-Integral Beam Splitters

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Uncoated nitrocellulose pellicles have a maximum reflectivity of ~30% with negligible absorption in the near-infrared (NIR). Our application used nitrocellulose pellicle beam splitters with a pulse of 30 ps and 135 fs for 1053-nm and 1170-nm beams, at a damage threshold of 1.3 J/cm^2 for 500 fs, λ = 1053-nm pulses[1] for nitrocellulose; our requirements were not limited by the material. Typical pellicle thickness of 2 μm to 5 μm effectively eliminates the *B*-integral, whose minimization is critical for propagating high-power laser pulses through an optical medium. Alternatively, a typical uncoated glass beam splitter can be made thin to control *B*-integral contribution while maintaining optical flatness imaging in reflection for these applications. These glass beam-splitter substrates are limited by ratios greater than the ~4% yielded from the uncoated surface of the glass and as a result, require at least one thin-film dielectric coating to be applied. The application of dielectric coatings introduces mechanical stress, which can significantly warp the substrate, rendering it unsuitable for imaging in reflection.

Pellicles (125-mm-diam, 2.2-μm- and 1.56-μm-thick λ/4 flat nitrocellulose membranes) were used to replace the 3-mm-thick dielectric coated NBK-7 glass plates used as λ = 1053-nm and λ = 1170-nm beam splitters that became warped upon coating.

A generalized multilayer thin-film modeling program was written to determine the thickness of the pellicle film that yields the desired reflectivity at the wavelength, angle of incidence, and polarization of interest following the matrix method described by Thelen.[2] The solution used by Thelen expresses a system of equations that solve Maxwell's equation for *s* and *p* polarization at the interface boundaries Z_1 and Z_2 in Fig. 1 into a matrix form in Eqs. (1) and (2).

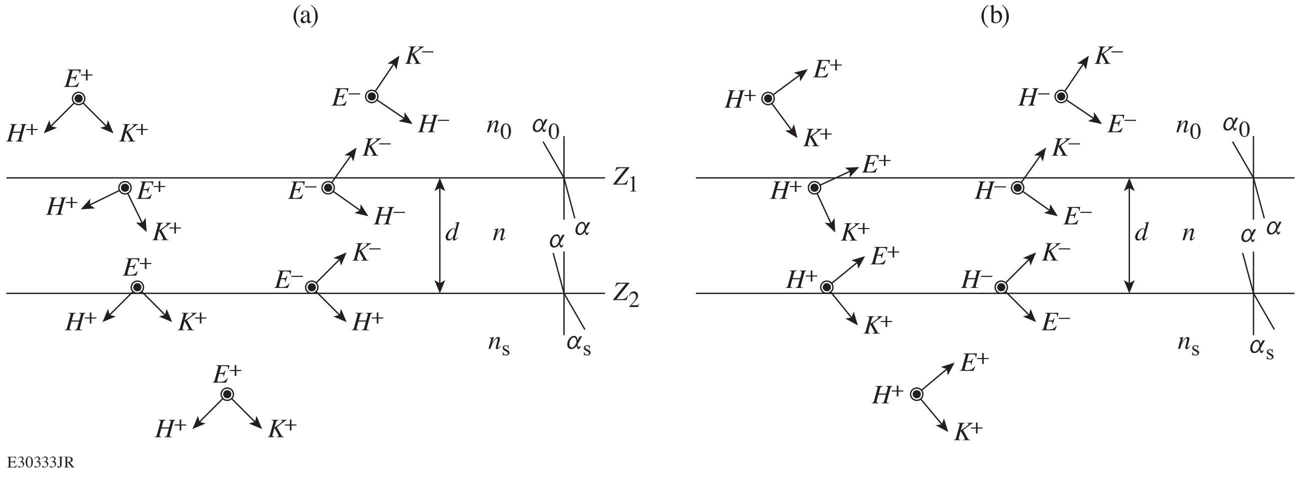

Figure 1
The electromagnetic fields at the boundaries of a thin film: (a) *s* polarization, where $\vec{E}$ is perpendicular to the plane of incidence and (b) *p* polarization, where $\vec{E}$ is parallel to the plane of incidence.

$$\begin{bmatrix} E(Z_1) \\ Z_0 H(Z_1) \end{bmatrix} = \begin{bmatrix} \cos\phi & \frac{i\sin\phi}{n} \\ in\sin\phi & \cos\phi \end{bmatrix} \begin{bmatrix} E(Z_2) \\ Z_0 H(Z_2) \end{bmatrix}, \tag{1}$$

$$\begin{bmatrix} E \\ ZH \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ n & -n \end{bmatrix} \begin{bmatrix} E^+ \\ E^- \end{bmatrix}. \tag{2}$$

Equations (1) and (2) provide the matrix transfer function [Eq. (3)] of the electric fields across the layer, where δ is an infinitesimal distance from the boundary layer and M_{11} through M_{22} are the elements of the 2×2 matrix in Eq. (1). A compact matrix transfer can be written as seen in Eq. (4) for a multilayer of thin films.

$$\begin{bmatrix} E^+(z_1-\delta) \\ E^-(z_1-\delta) \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ n & -n \end{bmatrix}^{-1} \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} \begin{bmatrix} 1 & 1 \\ n & -n \end{bmatrix} \begin{bmatrix} E^+(z_2-\delta) \\ E^-(z_2-\delta) \end{bmatrix}, \tag{3}$$

$$\begin{bmatrix} E^+(z_1-\delta) \\ E^-(z_1-\delta) \end{bmatrix} = \begin{bmatrix} Q_{11} & Q_{12} \\ Q_{21} & Q_{22} \end{bmatrix} \begin{bmatrix} E^+(z_2-\delta) \\ E^-(z_2-\delta) \end{bmatrix}. \tag{4}$$

Since there is no reflected wave in the exit medium, $E^-(z_2 + \delta) = 0$, the amplitude of the reflectance $\vec{R}$ is shown in Eq. (5) and the reflected and transmitted energy coefficients **R** and **T** in Eq. (7) are yielded by Eqs. (5) and (6) in the absence of absorption, where $\vec{R}^*$ is the complex conjugate

$$\vec{R} = \frac{E^-(z_1-\delta)}{E^+(z_1-\delta)} = \frac{Q_{21}}{Q_{11}}, \tag{5}$$

$$\mathbf{R} = \vec{R}\vec{R}^*, \tag{6}$$

$$\mathbf{T} = 1 - \boldsymbol{R}. \tag{7}$$

In our implementation of Thelen's matrix equations, we found solutions that correctly solve for the reflected and transmitted energy coefficients **R** and **T** while considering absorption as a factor in the thin-film layers.

Spectrophotometer measurements of various pellicles and illumination configurations agree well with the model predictions. Figure 2(a) shows agreement between the predicted and measured transmission of a 2.2-μm-thick pellicle at a 45° angle of incidence with unpolarized light. Figure 2(b) results led to the replacement of one of the coated BK7 substrate beam splitters.

The imaginary component of the index for nitrocellulose was included in the model so the effect of absorption on reflectivity and transmission at shorter wavelengths could be investigated. The transmission measurement of a 2.5-μm-thick nitrocellulose pellicle was used in conjunction with modeling to estimate the absorption coefficient, κ. These results are shown in Fig. 3.

A thin-film model was used in conjunction with transmission and reflection measurements of pellicles at UV and visible wavelengths to determine the absorption coefficient for nitrocellulose from 220 nm to 1.2 μm. When exploring the experimental setup of propagating high-power laser pulses through optical mediums, such as a pellicle beam splitter, understanding the absorption is crucial to understanding the properties in the UV to NIR. Future applications and explorations include a more-accurate determination of the complex index of refraction and its performance.

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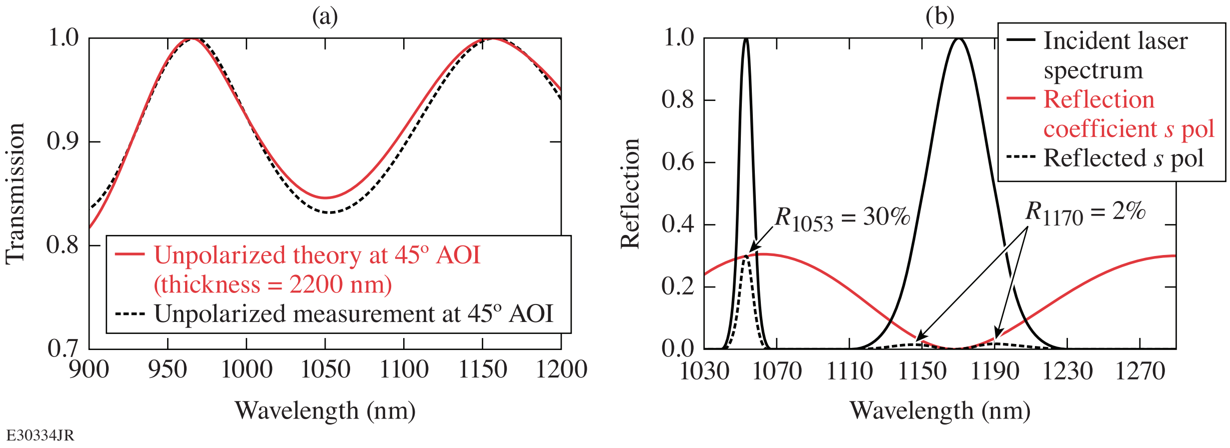

Figure 2
(a) Model prediction and measurement. Transmission of unpolarized light at a 45° angle of incidence (AOI) through a 2.2-μm-thick nitrocellulose pellicle.
(b) Pellicle beam-splitter replacement. Reflection of *s*-polarized light at a 45° AOI through a 2.2-μm-thick nitrocellulose pellicle.

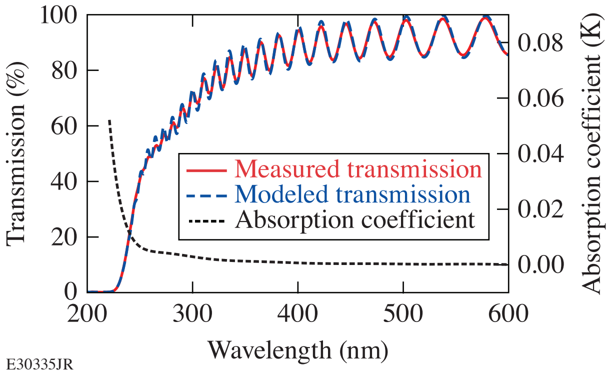

Figure 3
Measured and modeled pellicle transmission with absorption. Transmission of unpolarized light at normal incidence through a 2.2-μm-thick nitrocellulose pellicle and the absorption coefficient κ used in the modeling.

1. M. Kimmel *et al.*, Proc. SPIE **7132**, 71321O (2008).
2. A. Thelen, *Design of Optical Interference Coatings*, McGraw-Hill Optical and Electro-Optical Engineering Series (McGraw-Hill, New York, 1989).