Measurement of real refractive index of thin layers

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Several methods have been published recently for measurement of refractive indices (RI) of nearly transparent films.[1,2] In this Letter a simple method is presented that is particularly suitable for solvent-coated materials, enabling measurement of n to the third decimal place. It can be used for simultaneous measurement of RIs of several layers in a stack of materials coated on top of each other on a prism. The thickness of the layers is not critical.

For explanation of the principles of the method, consider a stack of dielectric films $1\ldots N$ with RIs $n_1\ldots n_N$, where n_1 is the RI of the substrate. Let the interfaces $(i-1,i)$ $i = 2\ldots N$ be planes parallel to each other and a collimated light beam be incident on the multilayer from the substrate (see Fig. 1).

Using Snell's law, we can define the constant

$$S(\theta_1) = n_i \sin\theta_i \qquad i = 1\ldots N, \tag{1}$$

where θ_1 is the angle of incidence at the (1,2) interface, and θ_i is the angle of propagation within the ith medium.

For each layer j with RI smaller than n_1 there exists an angle θ_1^j for which $S(\theta_1^j) = n_j$. Let n_L be the lowest RI in the multilayer. When $\theta_1 < \arcsin(n_L/n_1)$, light passes all the way through the stack. However, at $S(\theta_1^L) = n_L$ total internal reflection (TIR) occurs at the interface $(L-1,L)$. Various well-known methods of determining n_L/n_1 by TIR involve measurement of θ_1^L, using

$$n_L/n_1 = \sin\theta_1^L. \tag{2}$$

If, for example, the final medium is air, $L = N$ and $n_L = 1$, and the measured angle will yield n_1 irrespective of the other multilayer RIs. Thus TIR is a useful method for measuring n_1 or n_L but does not yield information about the other RIs in the stack.

It will now be shown how it is possible to determine the RIs of some of the other layers. Restricting ourselves to the $L-2$ layers between the substrate and L, let the lowest RI be n_M and $n_1 > n_M$. For angles θ_1 close to but smaller than θ_1^M, the incident beam propagates through M, and interference (in the form of straight-line fringes) between the reflection from the $(M-1,M)$ plane and the TIR from the $(L-1,L)$ plane becomes increasingly visible (since the Lth plane is air $n_M > n_L = 1$). When $\theta_1 = \theta_1^M$, TIR occurs at the $(M-1,M)$ plane instead of at the $(L-1,L)$ plane, and all effects due to light passing through M promptly disappear. This transition permits accurate determination of θ_1^M and thus of n_M, since $n_M = n_1 \sin\theta_1^M$. The procedure can be repeated for other layers between the substrate and M if the above requirements are met. Generally stated, the RI of any layer in a stack can be measured relative to the substrate if all the layers preceding it have larger RIs, including the substrate.

The novelty of this method is in the extension of TIR techniques to angles larger than the TIR angle θ_1^L. The accuracy of the method depends on the accurate determination of θ_1 in the substrate. The method is best practiced by using a prism of high refractive index as the substrate, on which the layers to be measured are coated either singly or in sequence of declining RI. Intermediate layers (which are sometimes necessary for isolation) will have no effect if they have a high index. Referring to Fig. 2, if a collimated beam is incident from air onto the prism at an angle γ relative to the face normal,

$$\phi = \arcsin(\sin\gamma/n_1), \tag{3}$$

$$\theta_1 = \alpha + \phi, \tag{4}$$

where α is the prism apex angle. Hence at θ_1^M,

$$n_M = n_1 \sin[\arcsin(\sin\gamma_M/n_1) + \alpha]. \tag{5}$$

Thus for a prism of known α and n_1 it is sufficient to measure γ_M at the transition angle. Note that γ is positive when measured from the face normal in the clockwise direction, as in Fig. 2.

In practice a prism made of EK911 glass was used as the substrate. This is an Eastman Kodak Company rare-earth glass of high RI. Using a He–Ne laser and a goniometric table, we measured the prism apex angle: $\alpha = 40.10° \pm 0.02$. The RI at 633 nm was determined by TIR: $n_1 = 2.0848 \pm 0.0008$.

With the same experimental configuration, γ_M is measured for any layer M of RI lower than 2.084 coated on the prism, by observation of the transition in the TIR beam falling on the matt surface of the prism base. The inverse sensitivity $dn/d\gamma$ ranges from 0.013/deg at $n_M = 1.35$ to 0.004/deg at $n_M = 1.9$. Thus an accuracy of $\Delta n = \pm 0.001$ is easily attained in this system.

As an example, poly(n-butyl methacrylate), having a handbook value of $n_D = 1.483$ at 20–25°C, was coated on the prism, and a film of oil having $n_D = 1.400$ at 20–25°C was spread over it. Two transitions were observed at +4.25° and +10.77°, corresponding to RIs of 1.399 and 1.480, respectively, at 633 nm. To extend the method to other wavelengths, noncoherent sources can also be used if they are suitably apertured, filtered, and collimated.

References

1. A. B. Buckman and C. Kuo, Appl. Opt. 17, 3636 (1978).
2. A. M. Goodman, Appl. Opt. 17, 2779 (1978).

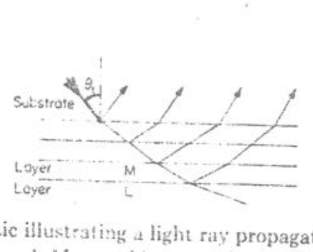

Fig. 1. Schematic illustrating a light ray propagating from a substrate through M coated layers and into air (layer L).

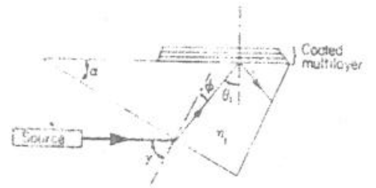

Fig. 2. Schematic of the experimental configuration.