DESIGN AND PRODUCTION OF ANTIREFLECTION COATINGS

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Multilayer thin films are widely used in science and industry for control of light. Optical surfaces having virtually any desired reflectance and characteristics may be produced by means of thin film coatings. These films are usually deposited on substrates by high vacuum evaporation. The applications range from high reflectance laser mirrors to high transmittance optical systems including interference filters, hot and cold mirrors, broad band reflectors and narrow band reflector, all of which are used in visual simulation systems and training devices. This paper will be concerned with the design and production of multilayer, dielectric, antireflection coatings for use in the visible spectrum from 400 to 700 nanometers.

Everyone who has seen colors exhibited by films of oil on water, and by soap bubbles, has observed the striking phenomena of interference in thin dielectric films. Interference in layers having fractional wavelength optical thicknesses remained a scientific curiosity until the 1930's when methods were developed for depositing one or more layers of solid dielectric of controlled thickness. The most common technique consists in vaporizing the dielectric in an oven, placed in a highly evacuated vacuum chamber, and condensing the vapor on the relatively cool surface of the substrate. Layer after layer of different materials of any desired optical thickness can be deposited in this way. The performance of dielectric thin film coatings is predicted well by a theory to be described later, which treats each layer as a homogenous medium, with sharply defined plane boundaries.

The nomenclature for a three-layer thin film coating is illustrated in figure 1. The n's are the five indices of refraction of the various media involved (the three layers plus the medium and substrate). The L's are optical thicknesses of the three layers (the medium and substrate are assumed to have infinite thickness). An optical thickness is simply the product of the physical thickness and the material's index of refraction. Note the S and P indicated on the incident wave; they are representative of polarization perpendicular or parallel respectively to the plane of incidence. The reflectance is the square of the absolute magnitude of the amplitude ratio of the reflected wave over the incident wave.

The numerical values of the reflected and transmitted wave amplitudes are governed, in general, by the boundary conditions on Maxwell's equations. More specifically, Fresnel's equations, which apply to the dielectric case, lead to a matrix formulation of thin film theory which lends itself very well to the computation of multilayer problems. The pertinent matrix relationships for normal incidence are given in figure 2.

In figure 2, M is the transfer matrix of the entire multilayer coating, r and t are the reflection and transmission coefficients,

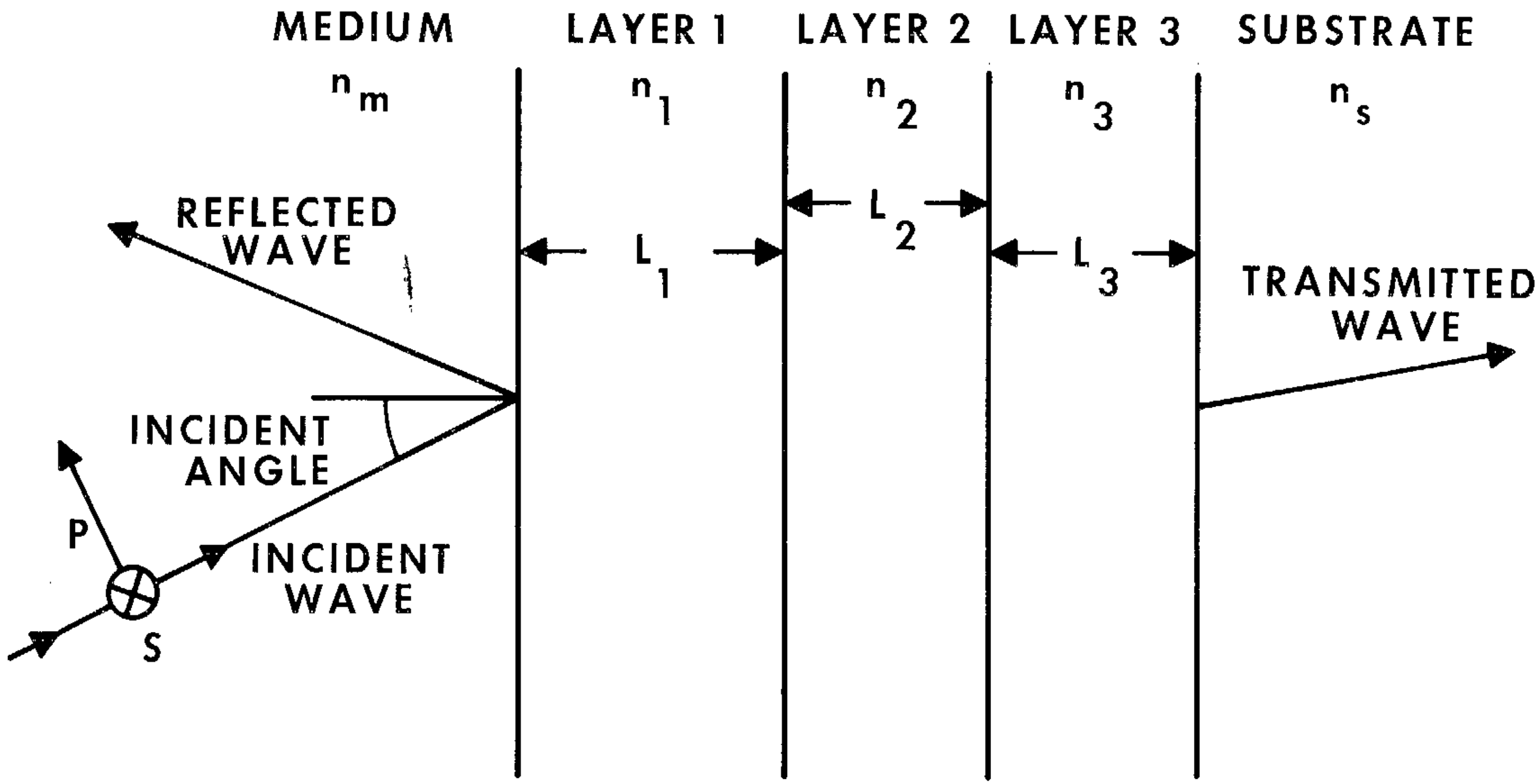

Figure 1. Schematic of Three-Layer Coating.

M_I is the transfer matrix of layer i, j is the square root of minus one, L_i is the optical thickness of layer i, and λ is the vacuum wavelength of the incident light.

Consider a system comprised of N layers. The problem is to find the reflectance at vacuum wavelength λ. Assuming the optical thicknesses are known the matrices MI can be obtained and subsequently the transfer matrix of the entire thin film system by simple matrix multiplication -- M_1 times M_2 times M_3, etc. times Mn. Substitution of M into equation 1 yields a known relation between r and t, the reflected and transmitted amplitudes. Another relation relating r and t is that $|r|^2 + |t|^2 = 1$ assuming no absorption. Using these two relations, a value for reflectance can be calculated.

For other than normal incidence the equations become more complex. The effect of incoming polarization must be taken into account as well as the angle of refraction at each surface boundary. Rather than repeat tedious calculations, I will just state that I have written a simple program for our programmable desk calculator, which can compute the reflectance from up to three-layer thin films, for incoming light of either S or P polarization at any angle of incidence. The program is designed to compute reflectance for wavelengths from 400 to 700 nanometers in 10 nanometer steps. The results, together with the input data, are printed out in tabular form.

Figure 3 is a sample printout which just repeats the input data. Figure 4 contains several curves drawn from data supplied by the calculator printout. The curve marked "Glass" is the expected constant 4% reflectance from a dielectric of index 1.5. Note no effort has been made to include dispersion or absorption in any of these or the following computations. The MgF_2 curve is the spectral reflectance as computed for a single 125 nanometer thick coating of index 1.38 on substrate of index 1.5. The triple layer curve is the reflectance for 125 nm MgF_2 index 1.38 + 250 nm Nd_2O_3 index 2.00 + 125 nm CeF_3 index 1.60 on glass of index 1.50.

Figure 5 contains similar curves where the material and thicknesses are the same as the triple layer coating on the previous slide, but angle of incidence and incident polarization have been varied. Note that reflectance of uncoated glass at 30° S polarization is 5.77% and at 60° P polarization is 0.18%. Obviously you are not always better off with AR coatings. Another point of interest, which is not immediately obvious from these curves, is that the region of lowest reflectance shifts toward the shorter wavelengths as the angle of incidence increases. This, by the way, is also true of narrow band interference filters.

The production of these coatings involves the deposition of controlled thicknesses of various materials on the desired substrate. Fortunately the thickness of each layer can be monitored individually without breaking the vacuum. In figure 6, the reflectance as a function of single layer film thickness for a single wavelength is plotted. The upper curve is for a film of higher index than the substrate and the lower curve is for a film of lower index than the substrate. The important characteristic of these curves is not so much the absolute

1. $$\begin{bmatrix} 1 \\ n_m \end{bmatrix} + \begin{bmatrix} 1 \\ -n_m \end{bmatrix} r = M \begin{bmatrix} 1 \\ n_s \end{bmatrix} t$$

2. $$M = \prod_{i=1}^{N} M_i$$

3. $$M_i = \begin{bmatrix} \cos 2\pi L_i/\lambda & -j\frac{1}{n_i}\sin 2\pi L_i/\lambda \\ -jn_i \sin 2\pi L_i/\lambda & \cos 2\pi L_i/\lambda \end{bmatrix}$$

Figure 2. Equations relating Reflection and Transmission of a Multilayer Coating

THREE LAYER
COATING

n_m = 1.000	L_1 = 125.00
n_1 = 1.380	L_2 = 250.00
n_2 = 2.000	L_3 = 125.00
n_3 = 1.600	
n_s = 1.500	

ANGLE 60.00

POLAR 1.0

Figure 3. Sample Input Data Reprinted by Desk Calculator.

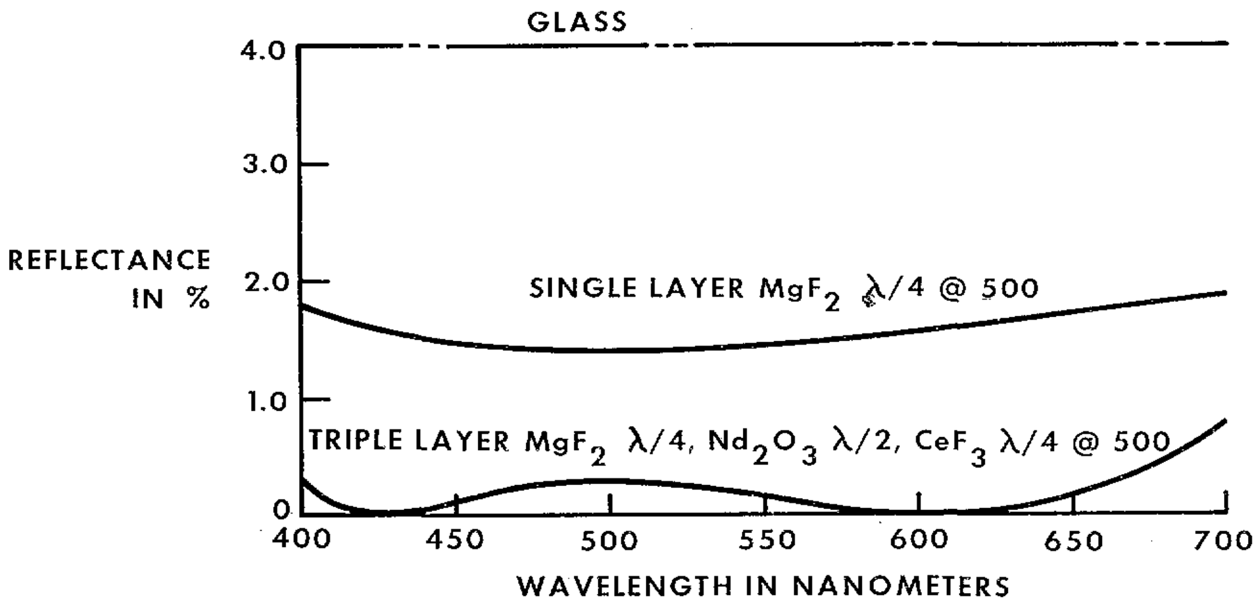

Figure 4. Reflectance as a Function of Wavelength at Normal Incidence.

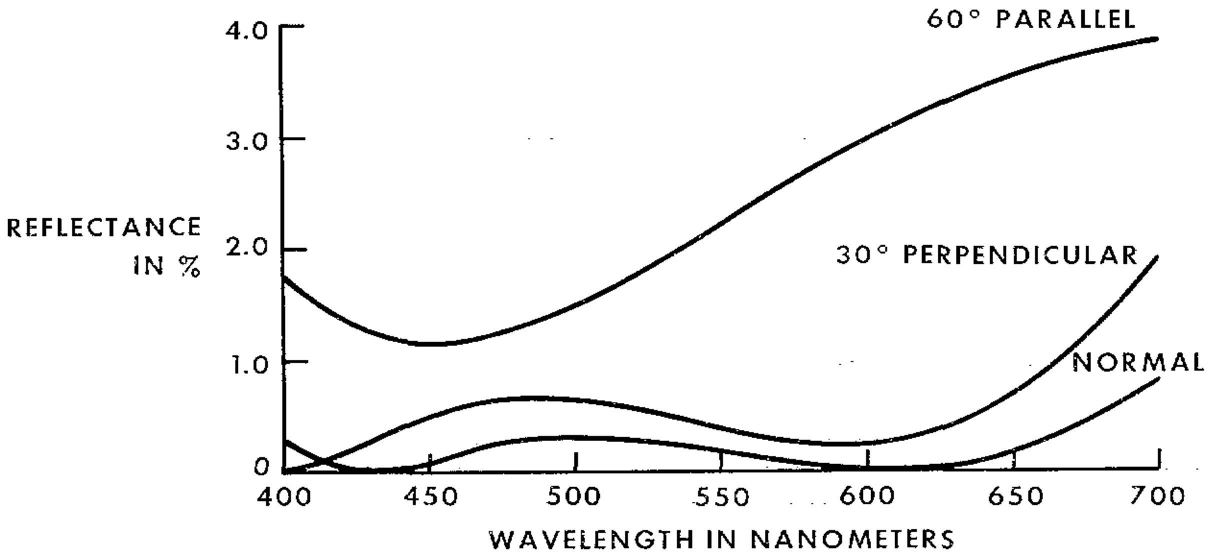

Figure 5. Spectra Reflectance as a Function of Angle of Incidence and Polarization.

value of the reflectance but the fact that they periodically reach maxima and minima. Therefore, if each layer is deposited on a test plate, the reflectance can be measured continuously at the design wavelength, while the coating is taking place, and the coating process can be stopped when the desired optical thickness is reached. If other than quarter wave multiples of thickness are desired, the monitoring wavelength can be changed to other than the design wavelength where the thickness would be in multiples of quarter wavelengths. In figure 7, the monitoring system which we were designing and installing at the time this paper was written, is pictured. Note that the test piece is apertured so that only the area being looked at by the viewing system is exposed to the coating material. As different materials are coated the test piece is manually rotated to expose a clean area. The substrate is continuously rotated off-center to allow uniform deposition during coating. We expect to achieve uniformity in optical thicknesses to 0.05% (1 Angstrom). Rotating offset fixtures are the only way to achieve this uniformity using thermal source with non-uniform distribution. The height of the substrate above the source should be approximately 25 cm with a 17 cm offset to center of substrate. The maximum non-uniformity will then be a linear function of the number of revolutions. Trade-offs on coating time and maximum RPM of substrate lead to an ideal coating time of approximately 2 minutes per layer. The test piece should be placed such that the area being coated has the same geometry as the center of the substrate. By having several sources available for deposition, many layers can be coated without breaking vacuum.

The application of multilayer thin film antireflection coatings in visual simulation systems and displays are many. The desire for high luminance, high contrast displays generated by many surface optical systems is satisfied in two ways by antireflection coatings. The first obvious effect is the increase of total light transmitted through the optical system. The second, not so obvious, effect is the suppression of out of focus ghost images which tend to degrade both the contrast and overall optical quality of the image. A straightforward calculation, assuming normal incidence at each surface, for a 32 surface optical train yields a transmission of 27% for uncoated glass, 62% for single layer MgF_2 coatings, and 94% for the specific three layer coating discussed above.

Our experimental investigations are presently directed toward durable antireflection coatings on low index substrates such as plastics. As of the time this paper was written, several experimental runs had been made with one, two, and three layer coatings. Since our results were incomplete, they are not reported in this paper.

Future work will also be directed toward programming up to 50 layers and production of laser mirror coatings, hot and cold mirrors, and narrow band interference filters.

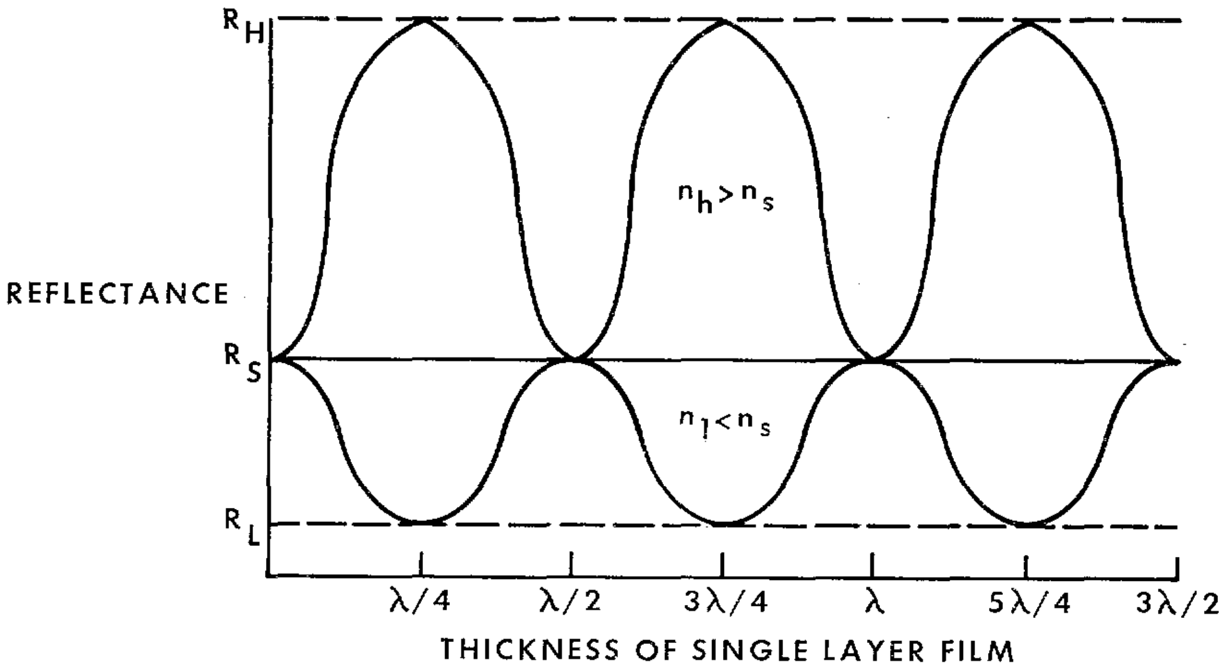

Figure 6. Reflectance as a Function of Thickness of Single Layer.

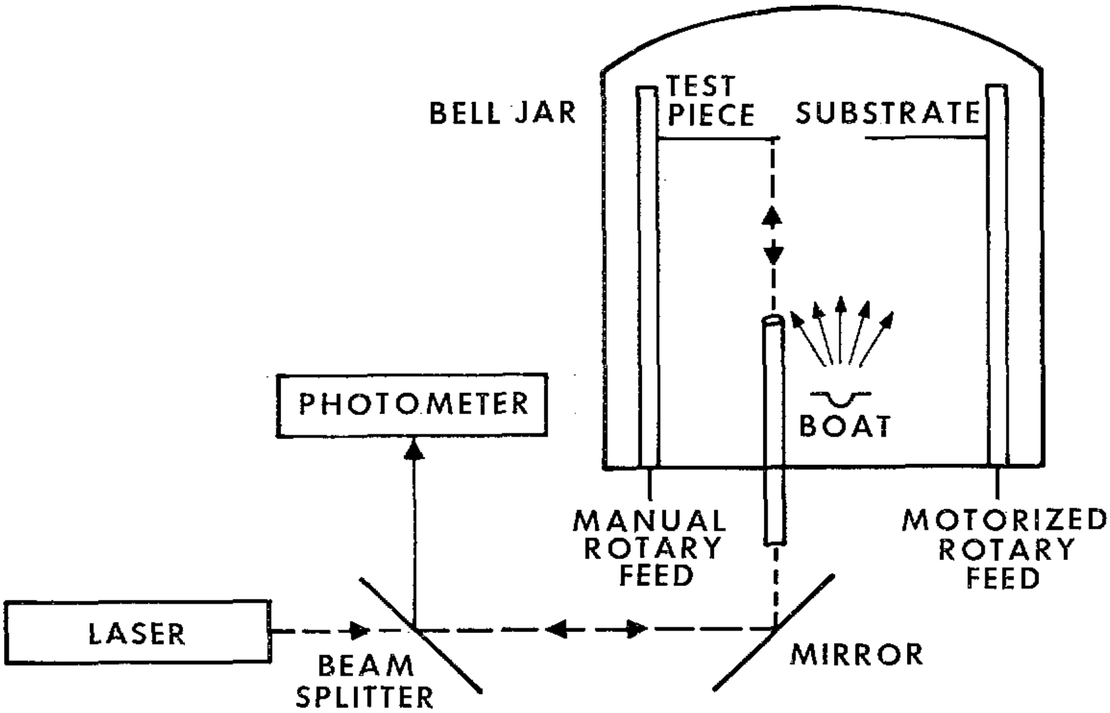

Figure 7. Film Thickness Monitoring System.