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ANTIREFLECTION THIN FILMS ON TRANSPARENT MEDIA

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INTRODUCTION

Many optical systems have been developed by the Naval Training Device Center which contain numerous optical elements. As part of a training device, the optical system must provide an image of good quality and sufficient luminance over the required field of view. Typically, the optical system consists of objective lenses, field lenses, relay lenses, beam splitters, prisms, windows, mirrors, etc. In some instances the optical path passes through more than 30 surfaces. It is mandatory that the proper thin film coating be applied to each surface so that a useable image can be transmitted through such a system. Whenever light traverses an interface between two media of different refractive index, such as an air-glass interface of a lens, some of the light is reflected. Often the spacing of optical elements is such that these reflections are manifested in the image plane as "flare images" which degrades the image. Before the advent of antireflection coatings, many otherwise acceptable lens configurations were rejected because they produced these flare images of reduced luminance and low contrast. The coating of optical surfaces with thin film antireflection coatings has alleviated these problems.

The purpose of non-absorbing thin films is to modify the spectral reflection characteristics of the surface without loss of energy by absorption. In the past thirty years, the use of thin coatings of transparent material on optical elements has become widespread. "Thin" here implies a thickness of the order of magnitude of the wavelength of light. In addition to reducing the reflectivity of surfaces, these films are used for:

a. achromatic beam splitters,

b. color filters and band-pass filters,

c. color-selective beam splitters,

d. narrow pass-band interference filters, and

e. semi-transparent mirrors,

as described on page 20-1 and following of MIL HANDBOOK-141[1*] on Optical Systems. Although all these optical coatings are used by NAVTRADEVCEN, this paper is directed towards providing an increased insight into antireflection films.

The papers which are generally credited for providing the basic theory of the interference phenomena which occurs in thin films first appeared in the mid-1930s.[2,3] Many papers have appeared since that date. However, we should go back to the 1820s when Fresnel derived his formula for the reflection coefficients at optical boundaries. In 1886, Lord Rayleigh wrote a classical paper entitled "On The Intensity Of Light Reflected From Certain Surfaces At Nearly Perpendicular Incidence," which appeared in the Proceedings of the Royal Society.[4]

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* The superscript numbers refer to reference numbers.

After presenting his experimental findings, Lord Rayleigh stated: "A superficial layer of lower index, formed under atmospheric influence, even though no thicker than $\frac{1}{100000}$ inch, would explain a diminished reflection. Possibly a combined examination of the lights reflected and transmitted by glass surfaces in various conditions would lead to a better understanding of the matter. If the superficial film acts by diffusion or absorption, the transmitted light might be expected to fall off. On the other hand, the mere interposition of a transparent layer of intermediate index would entail as great an increase in the transmitted as falling off in the reflected light. There is evidently room here for much further investigation, but I must content myself with making these suggestions."

An unusual insight into the phenomena of antireflection film is contained in the above paragraph. Other experimentalists, such as Edison and Kollmorgen, had observed the antireflection properties of thin films.

SECTION II

REFLECTION AT A BOUNDARY

The basic phenomena of reflection and refraction of light may be deduced from the application of boundary conditions to the Maxwell equations for electro-magnetic waves. The boundary conditions require that the tangential components of the electric and magnetic fields be continuous as the boundary between two optical materials is crossed. The mathematics is simplified by considering the incident light to be composed of two orthogonal linear polarizations. Combining Maxwell's equations with the above boundary conditions and using the law of reflection and Snell's law, the following relations result.[5]

$$2.1 \qquad E_{r\parallel} = \frac{\tan(\phi - \phi')}{\tan(\phi + \phi')} E_{o\parallel}$$

$$2.2 \qquad E_{r\perp} = \frac{\sin(\phi - \phi')}{\sin(\phi + \phi')} E_{o\perp}$$

where

$E_{r\parallel}$ = Amplitude of reflected electric vector for incident parallel polarization.

$E_{o\parallel}$ = Amplitude of incident parallel electric vector.

$E_{r\perp}$ = Amplitude of reflected electric vector for incident perpendicular polarization.

$E_{o\perp}$ = Amplitude of incident perpendicular electric vector.

ϕ = Angle of incidence.

ϕ' = Angle of refraction.

The above equations are known as Fresnel's equations, named after Fresnel who first derived them empirically from experimental observations.

Since the intensity is proportional to the square of the electric field amplitude, the reflectance as a function of incident polarization is given by 2.3 and 2.4.

$$2.3 \qquad r = \frac{\tan^2(\phi - \phi')}{\tan^2(\phi + \phi')}$$

$$2.4 \qquad r = \frac{\sin^2(\phi - \phi')}{\sin^2(\phi + \phi')}$$

where

$r_{\parallel}$ = Reflectance for incident parallel electric vector.

$r_{\perp}$ = Reflectance for incident perpendicular electric vector.

Since natural light is unpolarized, it consists of equal parts of perpendicular and parallel electric vector polarizations. Therefore, the total reflectance of natural light is given by 2.5.

$$2.5 \qquad r_t = \frac{1}{2}\,\frac{\tan^2(\phi - \phi')}{\tan^2(\phi + \phi')} + \frac{1}{2}\,\frac{\sin^2(\phi - \phi')}{\sin^2(\phi + \phi')}$$

where

r_t = Total reflectance of natural light

For the special case of normal incidence from air, $n_0 = 1$, to a material of index of refraction equal to n 2.5 reduces to 2.6.

$$2.6 \qquad r_t = \frac{(n-1)^2}{(n+1)^2}$$

Before proceeding with an analysis of multi boundary problems such as thin film coatings, a digression concerning the implications of the above expression to many element optical systems is in order.

For a material having an index of refraction of 1.5 (typical for glass) the reflectance is calculated to be 4%. This means that at every glass-air interface at least 4% of the incident light will be lost. For angles of incidence other than normal, the reflectance is higher. For many surfaces this loss becomes very large. For example, in an optical system having 32 glass to air boundaries, the total transmitted light will be given by 2.7.

$$2.7 \qquad t_t = t_s^{\,N}$$

t_t = Total transmission.

t_s = Transmission per surface.

N = Number of surfaces.

For t_s = 1.00 -0.04 = 0.96

and N = 32 the total transmission is found to be 2.8.

2.8 $t_t = (0.96)^{32} = 0.27$

Therefore the maximum transmission through the 32 surfaces neglecting all other losses (non-normal incidence, scattering, absorption, aperture stops, etc.) will be 27%. This magnitude of loss is objectionable and demonstrates the need for antireflection coatings.

SECTION III

ANTIREFLECTION COATINGS

SINGLE LAYER COATINGS

The mathematical analysis of a thin film coated onto a substrate becomes somewhat more complex. The same boundary conditions must be satisfied at each surface but consideration must also be given to the phase relations between the various reflected and refracted waves.

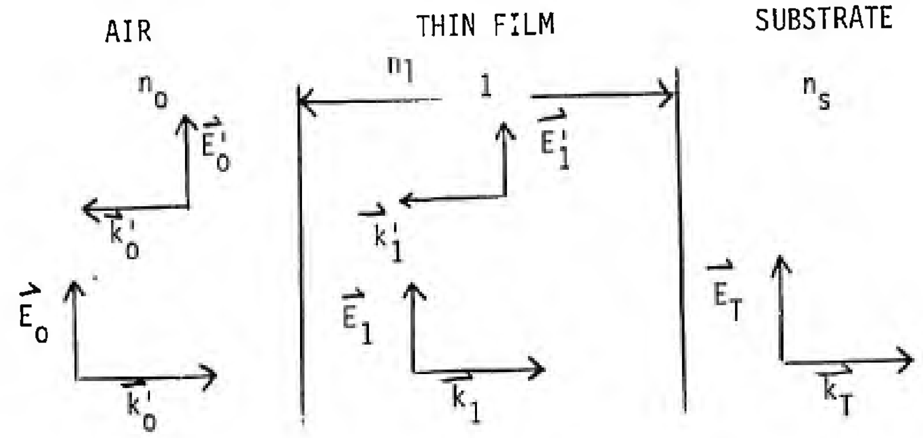

Figure 1. Incident and Reflected Waves at Single Layer Thin Film

To make the analysis simple it will be assumed that the incident light is normally incident and of a single wavelength.

In figure 1, the various quantities describe the situation for the general case of a wave normally incident on a surface coated with a thin film of thickness 1.

$\vec{E}_o$ = Incident electric field.

$\vec{k}_o$ = Wave vector of incident wave.

$\vec{E}'_o$ = Total reflected electric field.

$\vec{k}_o$ = Wave vector of reflected wave.

$\vec{E}_1$ = Electric field vector of wave traveling to right in film.

$\vec{k}_1$ = Wave vector of wave traveling to right in film.

$\vec{E}'_1$ = Electric field vector of wave traveling to left in film.

$\vec{k}'_1$ = Wave vector of wave traveling to left in film.

$\vec{E}_T$ = Transmitted electric field.

$\vec{k}_T$ = Wave vector of transmitted electric wave.

n_0 = Index of incident medium.

n_1 = Index of film.

n_s = Index of substrate.

l - Thickness of film.

Note that the magnitude of the wave vector is equal to 2π times the reciprocal of the wavelength, and is called wave number.

The boundary conditions on Maxwell's equations lead to the following relations.[6]

$$\begin{array}{lll} & \text{FIRST BOUNDARY} & \text{SECOND BOUNDARY} \\ 3.1 & E_0 + E'_0 = E_1 + E'_1 & E_1e^{ikl} + E'_1e^{-ikl} = E_T \\ & n_0E_0 - n_0E'_0 = n_1E_1 - n_1E'_1 & n_1E_1e^{ikl} - n_1E'_1e^{-ikl} = n_sE_T \end{array}$$

Combining these equations and eliminating E_1 and E'_1 there results

$$3.2 \qquad 1 + \frac{E'_0}{E_0} = \left(\cos kl - i\frac{n_s}{n_1}\sin kl\right) E_T / E_0$$

$$n_0 - n_0\frac{E'_0}{E_0} = \left(-in_1 \sin kl + n_s \cos kl\right)\frac{E_T}{E_0}$$

The above formulae have been derived using the Euler relations given in 3.3

$$3.3 \qquad e^{ikx} = \cos kx + i \sin kx$$

$$e^{-ikx} = \cos kx - i \sin kx$$

The reflection coefficient is defined as in 3.4

$$3.4 \qquad r = \left|\frac{E'_0}{E_0}\right|^2$$

Solving 3.2 for $\frac{E'_0}{E_0}$, r is found to be for $n_0 = 1$ (air) as in 3.5.

$$3.5 \qquad r = \left[\frac{n_1\,(1 - n_s)\cos kl \; - i\,(n_s - n_1^2)\,\sin kl}{n_1\,(1 + n_s)\cos kl \; - i\,(n_s + n_1^2)\,\sin kl}\right]^2$$

For $l = \lambda/4$, $kl = \pi/2$ and the above expression reduces to 3.6.

$$3.6 \qquad r_{\lambda/4} = \left(\frac{n_s - n_1^2}{n_s + n_1^2}\right)^2$$

In particular the reflectance will be zero if $n_1 = \sqrt{n_s}$

For $n_0 \neq 1$ 3.6 would be 3.7.

$$3.7 \qquad r_{\lambda/4} = \left(\frac{n_0\, n_s - n_1^2}{n_0\, n_s + n_1^2}\right)^2$$

Since the effect of interference has resulted in equation 3.7, the expression will be the same for a single layer of any odd number of $\lambda/4$ thick. By the same reasoning, a layer of any even number of $\lambda/4$ thickness will have the same reflectance as the uncoated substrate. For $n_1 > n_s$, however, the minimum reflectance will be that of the substrate with the maximum given by 3.7.

Equation 3.7 has another interesting implication. For cases where $r_{\lambda/4}$, i.e. when $n_1 = \sqrt{n_0 n_s}$, there are two possible values of n_1, which give the same spectral reflectance.

The relation satisfied by the two possible values of n_1 is given by 3.8.

$$3.8 \qquad n_1'\, n_1'' = n_0\, n_s$$

where n_1', n_1'' are the two possible values of n_1.

This means that for a specific spectral reflectance characteristic there are two choices of coating material.

DOUBLE LAYER COATINGS

The formulae involving reflectance characteristics of double layers are derived in a similar fashion to that outlined above.[7] Since there are more parameters involved, there are more possibilities for flexibility in choice of coatings. After solving the boundary value problem, the reflectance for two layers each having a thickness of an odd number of quarter wavelengths is found to be 3.9.

$$3.9 \qquad r\ \lambda/4 = \left(\frac{n_1^2\ n_s - n_2^2\ n_o}{n_1^2\ n_s - n_2^2\ n_o} \right)^2$$

One solution for zero reflectance is immediately obvious to be 3.10.

$$3.10 \qquad n_1^2\ n_s = n_2^2\ n_o$$

Equation 3.10 represents an important film construction which gives zero reflectance when the thickness of each layer is an odd multiple of quarter wavelengths.

Another not so obvious relation which gives zero reflectance for two layers is given by 3.11.

$$3.11 \qquad n_1\ n_2 = n_o\ n_s$$

This relation is utilized in what are known as stepdown coatings. In a stepdown coating, the indices of the film decrease going out from the substrate. In this coating also, the films are equally thick at odd integral multiples of a quarter wavelength.

For cases where the inside layer is twice as thick as the outside layer a more complex relation is found in equation 3.12.

$$3.12 \qquad n_2^3 - \frac{1}{2}\ \frac{n_2\ n_s}{n_o\ n_1}\ (n_o^2 + n_1^2)\ (n_1 + n_2) + n_1\ n_s^2 = 0$$

The simplest example of a coating which could satisfy the above criteria is a quarter-half coating in which the inside layer is $\lambda/2$ thick and the outside is $\lambda/4$ thick. This coating will exhibit a maximum in reflectance at the value of λ but will have a zero of reflectance on each side of the peak.

For two layers not related by an integral multiple simple conditions on indices in general cannot be written down. The effect of such variations in thickness should be considered only with a particular problem in mind.

TRIPLE LAYER COATINGS

In a similar manner as above, the boundary value problem for three layers on a substrate is solved to give relationships between the various parameters of thicknesses and indices of refraction.

For each layer one-quarter wavelength thick, there are two relations which will give zero reflectance. These are given in 3.13 and 3.14.

3.13 $$n_1 n_3 = n_2^2 = n_o n_s$$

3.14 $$n_1 n_3 = n_2 \sqrt{n_o n_3}$$

Equation 3.13 leads to three zeros in the reflectance curve, while 3.14 results in only a single zero in reflectance.

When the layer thicknesses have a one-quarter, one-half, one-quarter relation, the indices must satisfy 3.15.

3.15 $$n_1^2 n_s = n_3^2 n_o$$

When equation 3.15 is satisfied, the reflectance curve will only have a single zero but the low reflectance will be much broader than a quarter-quarter-quarter curve.

For layer thicknesses having the relation quarter-half, three quarters the relation in 3.15 must still be satisfied. This coating will have three reflectance minima which gives it a wider region of low reflectance which then rises more steeply than a quarter-quarter-quarter coating.

FOUR AND MULTILAYER COATINGS

As the number of films increases, the mathematics of the general case becomes more complex. However, certain relationships also begin to become apparent. For example, the index relation for a four layer coating having thickness relation quarter-half-quarter-quarter is given by 3.16.

3.16 $$n_1 n_4 = n_3 \sqrt{n_o n_s}$$

Note the similarity to 3.14. This coating has three minima in the low reflectance region. The spacing of the minima is governed by the value of n_2, but the value of the reflectance is independent of n_2.[7]

SECTION IV

PRACTICAL CONSIDERATIONS

INTRODUCTION

In this section some of the practical aspects of specifying or producing the types of coatings considered in the previous section will be discussed. Most of the problems apply to all types of coatings but may be discussed only under one heading because of the example chosen. The comments which will be made apply to the specific example with the implication of more general application.

COATING MATERIALS

Before proceeding with specific problems and comments, a listing of some commonly used coatings and substrates is in order. These are contained in tables 1 and 2.[9] The indicated index of refraction in table 1 is for light of wavelength 500 nm.

TABLE 1. COATING MATERIALS

Material	n	Advantages	Disadvantages
Cryolite	1.34	Easy to evaporate.	Not hard as M_gF_2.
Magnesium Fluoride	1.38	Very hard, tenacious	Substrate must be heated for hard film.
Thorium Fluoride	1.45		
Silicon Dioxide	1.46		
Cerium Fluoride	1.62		
Magnesium Oxide	1.62-1.77		
Silicon Monoxide	1.55-2.0		
Zirconium Dioxide	2.10		
Zinc Sulfide	2.3	Easy to evaporate. Tough and adherent.	High absorption for 400 nm.
Cerium Dioxide	2.35	Durable	High index.
Titanium Dioxide	2.4,2.6	High index, low absorption.	Thickness control difficult.

In table 1 note the range of index for some materials. A value of index within the range is determined by the method or speed of deposition. Thus, for example, silicon monoxide deposited slowly (slow S_i 0) has a low index while fast S_i 0 has a high index.

TABLE 2. SUBSTRATES

Material	Index
Vycor	1.46
Plexiglass	1.45 - 1.49
Glass	1.48 - 1.80
Sapphire	1.59 - 1.85
Arsenic Tri Sulfide Glass	2.37 - 2.66
Si	3.42 - 3.50
Ge	4.00 - 4.10

SINGLE LAYER COATINGS

The variation in reflectance for a quarter wave single layer coating as a function of index relation $n_1 / \sqrt{n_o n_s}$ is given in figure 2.

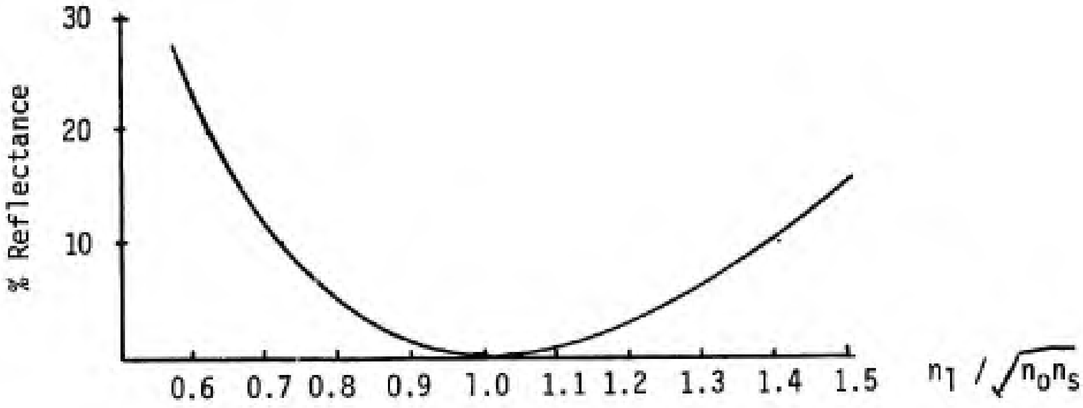

Figure 2. Reflectance vs. $n_1 / \sqrt{n_o n_s}$ for Single Layer Coating

As can be seen in figure 2, the choice of coating material index is relatively critical. The choice of coating materials which will give the proper index for the specific substrate is very limited especially when the substrate is glass.

As derived in the previous section for a single layer coating, the index of the film must be equal to the square root of the index of the substrate and that the thickness of the coating be equal to a quarter wavelength. The thickness of the film if it is to be used for white light is usually chosen to be λ /4 at 500 nm.

For a coating to produce zero reflectance on crown glass ($n_s = 1.51$) in air, the film index would have to be 1.23. A durable material with such a low index is not available.[7,8] Good practical compromises are M_gF_2 with an index of 1.38 or cryolite with an index of 1.34. M_gF_2 is preferred since it results in harder, more durable coatings.

Choosing a quarter-wave layer of M_gF_2 ($n_1 = 1.38$) on glass of $n_s = 1.51$ for light of $\lambda = 500$ nm, the reflectance minimum is found to be 1.3%.

Figure 3 shows the variation in reflectance as a function of wavelength for several incident angles with a $\lambda/4$ coating of M_gF_2 on glass $n_s = 1.51$.[7]

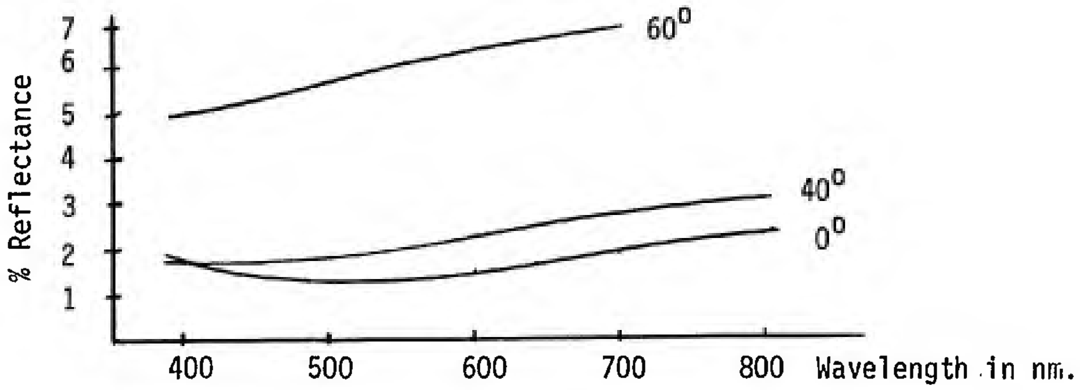

Figure 3. Variation in Spectral Reflectance as a Function of Incidence Angle.

Note in figure 3 that the average reflectance for white light at 0° incidence is approximately 1.5% as compared to 4% for uncoated glass. This means that in the example cited in Section II, the total transmission for 32 surfaces (air to coating to glass interface) will be 4.1.

4.1 $t_t = (0.985)^{32} = 0.62 = 62\%$

which is more than twice the transmission over uncoated glass under the same conditions.

The variation of reflectance with incident angle is due to the different optical path lengths and corresponding departures from the quarter-wavelength criteria. The effect of dispersion (change of index with wavelength) will have a similar effect but it will not be as severe and it would only be considered when an extremely wide bandwidth is required.

The most common single layer coating is that of the above example. M_gF_2 has been found to be most durable if applied onto glass which has been properly cleaned and heated to at least 300° C. The reflectance minima varies from 1.3% for crown glass to 0.0% for a glass of index 1.9.

DOUBLE LAYER COATINGS

Although single layer coatings are adequate in some applications, they have some serious limitations. For crown glass the lowest reflectance obtainable with magnesium fluoride is 1.3%. For high index materials, such as germanium, the reflectance curve rises very sharply giving only a small spectral region of low reflectance. By the use of two or more layers both of these limitations can be reduced.

An example of a double layer coating of the quarter-quarter type[7] is in table 3 with the corresponding reflectance in figure 4, for various angles of incidence.

TABLE 3. QUARTER-QUARTER ON GLASS

Layer	Material	Index	Thickness
1	M_gF_2	1.38	λ/4
2	Slow Si O	1.7	λ/4
Substrate	Crown Glass	1.51	

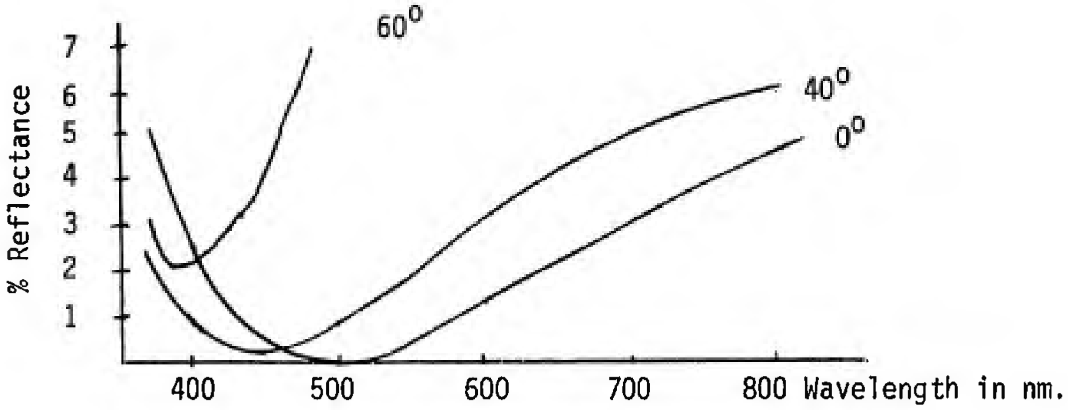

Figure 4. Quarter-Quarter Coating on Glass

The coating of table 3 is superior to a single layer only over the relatively narrow spectral range from 450 nm to 600 nm. This is because the reflectance curve for a double layer quarter-quarter coating rises much more steeply than that of a single layer. For this type coating the reflectance is very sensitive to the thickness of the low index layer but relatively insensitive to similar variations in the high index layer.

From figure 4, it is apparent that the reflectance averages approximately 0.5% over the entire visible spectrum at 0° incidence. For the case of 32 surfaces mentioned in Section II, this reflectance would lead to a total system transmission (again neglecting other losses) as given by 4.2.

$$4.2 \qquad t_t = (.995)^{32} = 0.85 = 85\%$$

which is far superior to the 27% found in 2.8.

An example of a quarter-quarter stepdown coating is given in table 4 with the corresponding spectral reflectance curve given in figure 5.

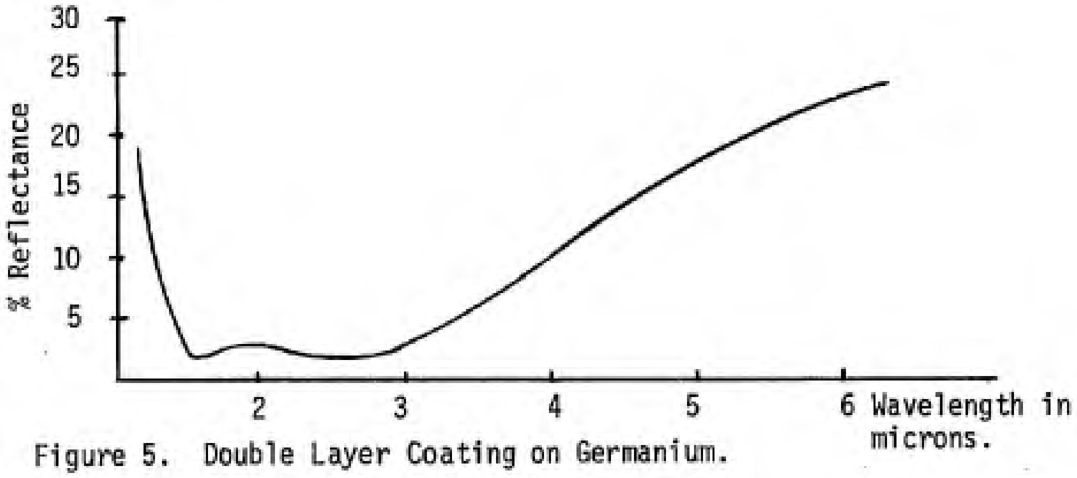

Figure 5. Double Layer Coating on Germanium.

TABLE 4. QUARTER-QUARTER STEPDOWN ON Ge

Layer	Material	Index	Thickness
1	Cryolite	1.35	$\lambda/4$
2	Zinc Sulfide	2.3	$\lambda/4$
Substrate	Germanium	4.0	

Figure 5 shows the type of curve which may be expected for a double layer coating on germanium. Note that a single uncoated surface of germanium will have a reflectance for normal incidence found from equation 2.6.

$$r = \left(\frac{n-1}{n+1}\right)^2 = 0.36$$

$$r = 36\%$$

which can be reduced to approximately 2% at 2 microns as seen from figure 5. This demonstrates that the transmission for high index substrates is greatly affected by antireflection coatings.[10] Because of the high reflection from uncoated germanium, which is widely used in infrared technology, it becomes extremely important to antireflection coat even optical systems of 1 element (two surfaces).

In a two layer quarter-half coating the reflectance is found to be below that of a single coating (on glass) but has a large percentage variation throughout the visible region and rises steeply above the single layer beyond the visible range.

THREE LAYER COATINGS

The proper deposition of a quarter-half-quarter layer requires a good technique for monitoring the thickness of each layer. If a rapid scan spectrophotometer is not available, it will be necessary to monitor the thickness of each layer with a separate piece of glass. The quarter-half-quarter coating has been found most useful for extending the region of low reflectance.

An example of a triple layer applied to plexiglass is found in table 5 with the reflectance given in figure 6.

TABLE 5. QUARTER-HALF-QUARTER ON PLEXIGLASS

Layer	Material	Index	Thickness
1	M_gF_2	1.38	$\lambda/4$
2	Z_rO_2	2.10	$\lambda/2$
3	C_eF_3	1.65	$\lambda/4$
Substrate	Plexiglass		

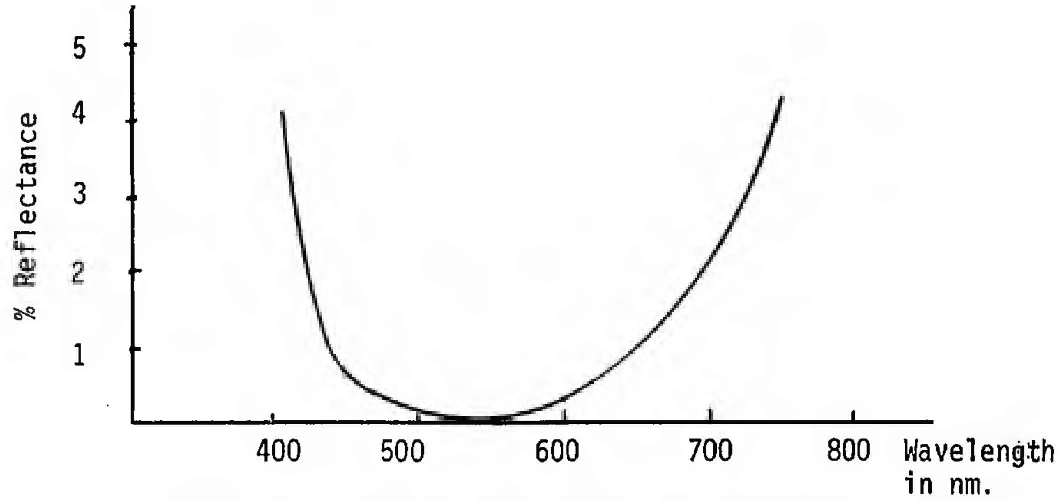

Figure 6. Quarter-Half-Quarter on Plexiglass

Note that the plexiglass cannot be heated to a very high temperature and as a consequence the $M_g F_2$ will not be as hard or as durable as the same coating on glass.

MULTILAYER COATINGS

More than three layers are used when the specific application justifies the additional design work, materials problems, and expense. Examples of applications where multilayers are sometimes required are low index substrates and low loss optics for laser transmission. In addition, greater flexibility in spectral reflectance characteristics is provided.

SPECIFICATION OF COATINGS

Substrate. The choice of substrate material to fit the desired application is usually made before the antireflection characteristics are specified. There may be some cases, however, where a high index substrate could be substituted for a low index substrate without affecting the performance of the system, e.g. a plane window. In a case like this, a single layer coating on the high index substrate would have better antireflection characteristics than the same coating on the low index substrate with no system sacrifice.

Consideration should also be given to the other physical properties of the substrate such as its spectral transmittance, durability, hardness, resistance to moisture, and resistance to chemical attack.

Coatings. The index of refraction in the desired spectral range of each layer and the layer thickness are specified by the coating design. Consideration must be given to the environmental conditions to which the finished product may be subjected, when coating materials and type of deposition are specified. A comprehensive outline of a single layer coating specification is given below, as an example.[12]

Material	Magnesium Fluoride.
Film Thickness	Greater than a quarter wavelength at 450 nm. Less than a quarter wavelength at 600 nm.
Uniformity	Variations within the thickness range will be allowed.
Reflectance	The minimum reflectance will be at a wavelength within the limits 450 nm to 600 nm.
Minimum Reflectance	The minimum reflectance value will be a maximum of 1.6% for glass substrate of index 1.51.
Minimum Reflectance at Limits	The minimum reflectance at 450 nm shall be 2.5% and at 600 nm shall be 2.1% for glass substrate of index 1.51.

Coated Area	Coating shall be applied over entire surface to within not less than 3/4 mm of edge.
Surface Quality	Films shall be sensibly free from holes, solid particles of the coating materials, and other imperfections.
Solubility	The coated optical elements shall be immersed for a period of 24 hours in a solution of salt water (6 ounces of salt per gallon of water) and then visually inspected for deterioration.
Humidity	The coated optical elements shall be exposed for a period of 24 hours to a relative humidity of between 95% and 100% humidity at $120^0 \pm 4^0$ F, and then visually inspected for deterioration.
Abrasion Resistance	The coating shall not exhibit any deterioration after being subjected to 20 rub eraser test. This test consists of rotating the coated element at 100 rpm and rubbing it with a force of 2.0 to 2.5 pounds.

In addition to the above specifications, a specification on adherence is also given in the form of a cellulose tape test. This test consists of placing the tacky surface against the coating, firmly rubbing it, then removing it quickly.

Problems of adherence become important when certain substrates are used. In particular, a plexiglass substrate could not be heated to the 300^0 C temperature required to give a very hard coat of magnesium fluoride. Alternative coatings applied on a warm, 40^0 C, plexiglass substrate is one possible solution.[13,14,15]

COMMERCIAL COATINGS

Before an attempt is made to design and specify an antireflection coating, the characteristics of commercially available coatings [16,17,18] should be studied to determine their applicability to the specific situation. An example of a commercial coating spectral reflectance curve is given in figure 7.

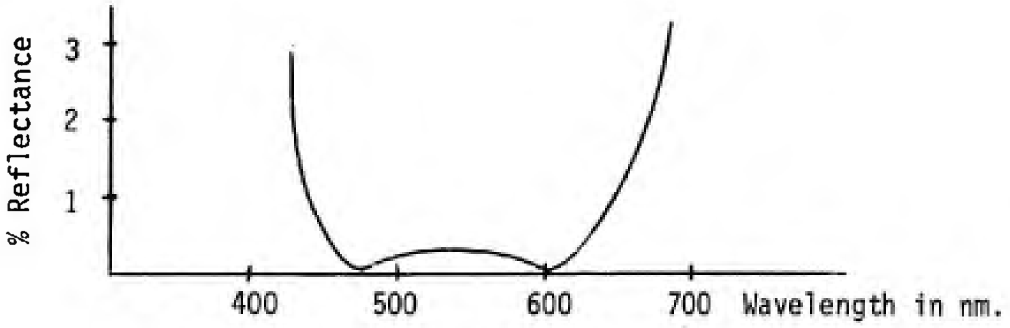

Figure 7. Commercial Low Reflectance Coating

This coating[19] can be applied to substrates having an index of refraction within the range 1.47 - 1.55. The curve in figure 7 is for angles of incidence of 15°. The hardness of the coating is sufficient to pass a 150 rub test with one pound of force with cheesecloth. The coating also qualified under the tape tests and temperature and humidity tests, as stated in the preceding paragraph.

SECTION V

CONCLUSION

From the above discussion the application of thin film technology greatly reduces transmitted light losses in many surface optical systems. For specific applications requiring extremely low reflectance over the entire visible spectrum throughout a wide range of incident angles, complex multilayer coatings are required. The problems involved in designing the required number of layers, the index of each layer, and the optical thickness of each layer for a specific application have been solved with computer programs.[20,21,22] The actual deposition of the film requires an empirical knowledge of the material properties of the films and substrate.

The physical size of the elements to be coated also is a consideration since it will be limited to the size of the vacuum chamber as well as the method of deposition required to give uniform coat over the entire surface.

The Hass text[7] and the MIL-HDBK 141[1] should be consulted for greater depth of analysis and more complete development of the material in this report.

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