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Interference Coatings

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Interference coatings are a broad classification of coatings that somehow alter the actual trend of electromagnetic radiation such as visible light to render either favorable or unfavorable results. There are endless numbers of possible combinations of coatings for all kinds of uses, but since we are mainly concerned with optics, and since the majority of uses for thin films is in optics, this report presents itself as a semi-general introduction in the basics of this coatings. Since these coatings are usually very thin so as to approach the wave length of light, the authors have presented this material or film rather than interference coatings. In optics, thin film in optics usually involves three main subdivisions: a) internal and external reflection being the most important, b) reflection, and c) the combinations of both reflection and refraction of species. This report will, therefore, tend to deal mainly with thin film in connection with the three main subdivisions.

The report can be broken down into the following areas:

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II) More Specific Introduction p. Seven
III) Production Properties and Manufacturing of Thin Films p. Twenty
IV) Theory, Calculations, and Formulas for Thin Films p. Twenty-One
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VII) References

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INTRODUCTION

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INTRODUCTION

certain special circumstances. The low state of order accounts for many of the apparent anomalies observed in the behaviour of thin films and poses a severe problem in the development of a theoretical approach.

1.2. METHODS OF FILM DEPOSITION

By far the most widely used method of depositing films, particularly for use in optical systems, is that of thermal evaporation and it is in this method that most attention is given in the next chapter. With no other method can so complete a measure of control be obtained. By the use of suitable shutters and diaphragms and by sublimation of the target during the deposition of the film, practically any distribution of material on a surface may be obtained. The intermediate application which springs to mind in this connection is that of producing the various aspheric surfaces which we know from geometrical optical studies to be so useful. Many such forms are extremely difficult to produce by methods other than the evaporation process—so difficult as to be of no practical interest. These and other applications of this type are discussed in the concluding chapter.

The multiplicity of variables attending the deposition process, by which such effective control may be obtained, is in some measure responsible for the lack of concordance which is so often evident in the results of thin film investigations made by different observers. Until an appreciation of the dependence of film properties on the conditions of formation of the film was obtained, little attention was directed to keeping the many important variables under control. Among the factors which are liable to influence the properties of a film are: rate of deposition, velocity of impinging atoms, structure and condition of target surface, history of film between deposition and examination, etc. Lack of information on these and the many other variables which may determine the nature of the film formed makes comparison of different workers' results very difficult. Electron-optical methods have enabled an appraisal to be made of the effect of the evaporation conditions on the structure and properties of films produced. We may now hope, therefore, for a greater degree of consistency among thin film results from different sources.

1.3. CALCULATIONS OF THE OPTICAL PROPERTIES OF THIN FILM SYSTEMS

When a beam of light traverses a stratified medium in which there are discontinuous changes in refractive index (or changes which take place in a distance small compared with the light wavelength)
iple reflections occur. If the distances between boundaries are so that the multiply-reflected beams are coherent with one her, then the intensity of light reflected or transmitted by the m is obtained from the algebraic sum of the amplitudes. The titudes to be summed are calculated from Maxwell's equations the application of the appropriate boundary conditions. For a c film bounded by surfaces of known reflectance, the reflectance transmittance are given by the Airy summation; this is the air case of the Fabry-Pérot etalon. The treatment is approxi me inasmuch as it is assumed that the change of phase on reflection be light at either side of the reflecting surfaces of the etalon is the c. In practice, where a metal reflecting surface is used, this is true. The error is small, however, for the case where high distances are used and this is the usual arrangement in an intermeter. If the properties of the etalon are to be calculated from optical constants of all the layers, instead of considering the silver ees as possessing an effective reflectance, then the problem be e very complicated. This, however, is a case of the general lem of calculating the optical properties of a set of films, from values of the optical constants and thicknesses.

1.4. Measurements on Thin Films

With the increasing importance of thin film work, the need has arisen for information on the properties of films and this has necessitated the development of methods of investigation suitable for dealing with thin layers. Many early methods of measuring film thickness required a knowledge of the refractive index of the film and vice versa. Procedures now developed which enable both quantities to be determined independently have shown how great is the need for methods which are independent of the assumption that any of the properties of a film (save, perhaps, its chemical composition) are the same as those of the material in bulk.

The greatest difficulties arise in connection with films of absorbing materials and especially with those in which the absorption is high (metals). Unequivocal determination of the optical constants of such films is possible only by making measurements of the amplitude and phase of light beams transmitted by and reflected from both sides of the film. These measurements are difficult to make with high accuracy. The pitfalls of earlier methods, which were unable to give the optical constants and thickness simultaneously, are well illustrated by the alarming ranges covered by the various reported values of the optical constants. Such differences may in part have arisen from the use of unsuitable methods of measurement and part from the fact that the optical constants of films may vary considera

bley with the conditions of preparation.

The violent variations with thickness of the optical constants of thin metal films have been shown to be a consequence of the aggre
gated nature of the films. The structure of metal films deduced from observations of the optical properties shows remarkable agreement with that observed directly by electron microscopy or deduced indirectly from electron diffraction and other experiments.

1.5. The Uses of Thin Films

With the rapid development of the design of demountable vacuum systems, the number and diversity of uses of thin films have increased apace. The small vacuum evaporation plant has become an almost essential part of the furniture of the research laboratory. On an industrial scale, the vacuum evaporation system has joined the ranks of routine industrial processes even to the point of being incorporated in a continuous belt system for lens blooming. (Paradoxically, it is now more difficult for a lens-producing plant to produce an un bloomed lens than a bloomed one, the greater hardness of the
THE USES OF THIN FILMS

bloomed surface making the bloomed product less susceptible to scratches than is the raw glass.)

In the laboratory, thin films find application in a wide variety of types of work. Electrical experiments may often be facilitated by the use of evaporated electrodes, which make intimate contact with the surface without causing mechanical damage. The hygroscopic optical components used in infra-red spectroscopy may be protected by coating with a suitable insoluble film. Reflecting surfaces may be similarly protected against deterioration by the atmosphere. Electrostatic charging, so often the bugbear of experiments employing fine suspensions, may sometimes be reduced by metallizing the offending components; the same process applied to the fluorescent screen of a cathode-ray tube both eliminates charging troubles and results in a brighter picture. The difficulties of measuring surface temperatures are largely overcome by the use of evaporated films as thermocouples whilst the bulk of optical measurements in the near infra-red depend on the photoconducting properties of layers produced by thermal evaporation (with a certain amount of additional persuasion).

Perhaps the most striking of the many developments have been in the field of multilayer filters. From the simple low-reflecting low-index layer and high-reflecting high-index layer, magnificently complicated multilayer systems have been evolved possessing impressive and useful optical properties. Narrow transmission bands, wide bands with steep edges, low- and high-pass filters may now be almost tailor-made to suit requirements. The fact that for some filters large numbers of layers are called for is of no consequence since the development of techniques of deposition and of monitoring have not lagged behind the theoretical work.

From the large number of papers which have appeared in the last few years on the optical properties of thin solid films, it is clear that an exhaustive treatise must be of encyclopaedic proportions. In this work examples have been drawn from a field in which progress is still rapid; they give a representative picture both of the potentialities and of the limitations of thin films in relation to optical studies.
The importance of thin film deposition in optics has increased to the point where there is a greater awareness for the need for more intensive research to develop the technique to its fullest potentialities. The uses of thin films are varied and increasing. Multi-layered coatings make possible numerous and different applications. However, they must be greatly refined and perfected so they may be even more widely used.

The enormous strides which have been made in the technology of vacuum-deposited thin films in the modern coating laboratories enable the realization of systems which were impossible only a short time ago. Progress has been made to the extent that in certain applications, the thin film itself has the basic and sole function in a system, while the role of the substrate is that of a vehicle which holds and positions the working film.

Vacuum deposited thin films are no longer exclusively used for the development of purely optical systems and components, but are being utilized in a varied range of fields which include electronics, medicine, architecture and the steel industry.

The most widely utilized vacuum deposited thin films are for: anti-reflection, achromatic beam splitters, color filters and band pass filters, narrow band band (interference) filters, semi-transparent mirrors, heat control filters, high reflectivity mirrors, polarizers and reflection filters. Most of these coatings will, in the very near future, be considered as standard as the single layer magnesium fluoride anti-reflection film is today. The standard magnesium fluoride anti-reflection coatings cannot, at present, in most cases, perform as efficiently as the multi-layer anti-reflection coatings.

These coatings, consisting of two, three and four layers, have the ability to reduce surface reflections to less than 0.2% over narrow and broad areas of the spectral region. To determine which of these coatings is most desirable, it is necessary to consider spectral reflectivity and angle of incidence. For example, if the requirement of minimum reflectivity is in a wavelength range of 5250 angstroms to 5750 angstroms, then a two-layer coating is generally called for. On the other hand, if a 4000 angstroms span of minimum reflectivity is required, then a three-layer coating is utilized. Further, if minimizing the vignetting effect is required, the anti-reflection coating on the surface should have a low reflectance at high angles of incidence, as well as at normal incidence.

As we have minimized the loss of light with improved anti-reflection coatings, we also minimize the loss of light in the basic reflecting mirrors. The regular front surface aluminum and silicon monoxide mirrors, so commonly used today, enable us to reflect a maximum of 80% of the incident light in the visible region of the spectrum. The loss of 12% to 14% of
the light from this type of mirror could conceivably prove fatal to our more complex systems. The enhanced aluminum mirrors which reflect 94% to 98% of the incident light enable an increase of approximately 3% per mirror. This increase of workable energy is an obvious asset to modern design.

Modern monitoring, modern vacuum equipment, improved techniques and research have brought multilayer coatings into greater practical use. The fabrication of these coatings is being done on a much greater scale.

The basic high-low quarter wave stacks to produce the high reflectivity (99.85%) demanded by laser researchers today pose few problems for the coating laboratories. However, refinement of the films still seems to be a problem with many. Scatter and film durability have lax standards of acceptance. Dielectric coatings are considered good if scatter points are held to a minimum, though still present, and if the coated surface can be cleaned at all without film deterioration or damage. Deposition techniques and the selection of dielectric thinning materials hold the key to these common coating problems. When one utilizes proven techniques and proper thinning materials, and accounts for polarization, the basic quarter wave stack type coating attains a perfection that, unfortunately, few can truly appreciate. This very coating when coupled with eighth, half or three-quarter wave layers can produce extremely satisfying results for varying requirements.

Another area of multilayer coating today is the beam splitter. In the past, thin metallic films were used as beam splitters; however, in many cases they proved inefficient due to the absorption of light. The multilayer beam splitter composed of nonabsorbing materials can produce reflection and transmission values adding up to 99.5% of the incident light. The color selective beam splitters or long-wave and short-wave pass filters are often called dichroic mirrors.

Another multilayer type mirror, the "heat control filter," more commonly referred to as a "cold mirror," has proven to be a useful tool. Its applications are many and it will undoubtedly be used to a greater extent in the years ahead. The basic principle of this design is to reflect visible energy and transmit the infrared. By its function, the heat control filter enables us to utilize radiant energy without the unwanted heat generally associated with it.

Much of the success of quality thin films lies in the hands of the vacuum technician, for it is his experience and background that determine whether a film is good, fair or poor. Ironically, fair and sometimes poor films will perform initially in a system. However, these same films may deteriorate badly in a short while causing serious malfunction of the system. Conditions in the vacuum chamber during evaporation, rate of evaporation during deposition, thorough familiarity with one's monitoring system, choice of materials, type of substrates and conditioning of substrates are but a few of the many factors which must be taken into account.

The involved and never-ending calculations for the design of thin film coatings, as well as the constant improvement of techniques for their fabrication, pose a great challenge. It is this very challenge that exciting us to improve and create the type of coating the future demands.
MORE SPECIFIC INTRO.

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2) INTERFERENCE IN THIN LAYERS p. 10
When light is reflected from a soap bubble or from a thin layer of oil on water, interference effects between the waves of light waves reflected at opposite surfaces of the thin film of soap or of oil. In Fig. 35-7, the line $ab$ is one ray in a beam of monochromatic light incident on the upper surface of a thin film. The lines at right angles to $ab$ indicate the wave surfaces in the incident beam. Part of the incident light is reflected at the first surface, as indicated by ray $bc$, and a part, represented by $bd$, is transmitted. At the second face a part is again reflected and of this part emerges as represented by ray $df$. Lines at right angles to $be$ and $cf$ indicate wave surfaces.* The beam has appreciable width, the wave surfaces will overlap and the reflected wave trains can produce interference effects.

For simplicity, we shall assume that light is incident at right angles to the film. Let $l$ represent the thickness of the film and $n$ its index of refraction. If $\lambda$ is the wavelength of the light waves in air, the wavelength in the film is $\lambda/n$, and the number of waves contained in the path length through the film and back, or $2l$, is $2\lambda/(\lambda/n)$. Suppose this is some integral number. Then a wave surface in the light that has traveled through the film and back emerges from the film at the same time that a wave surface in the incident wave train arrives and is reflected from the film. If no other considerations were involved, the waves reflected from the two surfaces would be in the correct relation to interfere constructively, that is, their displacements would add. However, at the upper surface the light is reflected from a medium of index greater than that in which it is traveling, while the reverse is true at the lower surface. As was shown with Lloyd's mirror, when a train of waves is reflected at the surface of a medium of higher index, the reflected wave train loses (or gains) half a wavelength. Hence the waves that have traveled through the film and back are exactly out of phase with the waves reflected at the upper surface and the wave trains interfere destructively. In other words, if the path length through the film and back contains an integral number of waves, no light is reflected. It can be seen without further detailed explanation that if the path length through the film and back contains an integral number of waves plus half a wave, conditions are right for constructive interference and there will be strong reflection.

If the film is extremely thin compared with the wavelength of light, the path length through the film and back is negligible and the only outstanding effect is the loss of half a wavelength in the waves reflected at the first surface. Then, regardless of wavelength, the waves reflected from the two surfaces are out of step and destroy one another. Hence no light is reflected and the film appears black by reflected light. (There is no violation of the principle of conservation of energy in destructive interference, since whatever energy is absent in the reflected light is found in the transmitted light.)

If the film is in the shape of a thin wedge of narrow angle, and is viewed by reflected monochromatic light, it will appear to be crested by parallel bright bands of the color of the light used, separated by dark bands. At the apex, the film will be dark. At a distance from the apex such that the film thickness is one-quarter of a wavelength, it will be bright. Where the thickness equals one-half a wavelength it will be dark, and so on. If the film is illuminated first by blue, then by red light, the spacing of the red bands is greater than that of the blue, as is to be expected from the greater wavelength of the red light. The bands produced by intermediate

*Fig. 35-7. Interference between light waves reflected from the upper and lower surfaces of a thin film.
wavelengths occupy intermediate positions. If the film is illuminated by white light, its color at any point is that due to the mixture of those colors which may be reflected at that point, while the colors for which the thickness is such as to result in destructive interference are absent. Just those colors which are absent in the reflected light, however, are found to predominate in the transmitted light. At any point, the color of the film by reflected light is complementary to its color by transmitted light.

The phenomenon of interference is utilized in the production of so-called "nonreflecting" glass. A thin layer or film of transparent material is deposited on the surface of the glass, as in Fig. 35-8. If the index of this material is properly chosen at some value intermediate between that of air and the glass, equal quantities of light will be reflected from its outer surface, and from the boundary surface between it and the glass. Furthermore, since in both reflections the light is reflected from a medium of greater index than that in which it is traveling, the same phase change occurs in each reflection. It follows that if the film thickness is one-quarter wavelength (normal incidence is assumed), the light reflected from the first surface will be 180° out of phase with that reflected from the second, and complete destructive interference will result.

The thickness can, of course, be one-quarter wavelength for one particular wavelength only. This is usually chosen in the yellow-green portion of the spectrum, where the eye is most sensitive. Some reflection then takes place at both longer and shorter wavelengths and the reflected light has a purple hue. The over-all reflection from a lens or prism surface can be reduced in this way from 4 or 5 percent to a fraction of 1 percent. The treatment is extremely effective in eliminating stray reflected light and increasing the contrast in an image formed by highly corrected lenses having a large number of air-glass surfaces.

Fig. 35-8. Destructive interference results when the film thickness is one-quarter of a wavelength of light in the film.
Lens Coating

This is based on the phenomenon of light interference already referred to. The thickness of the layer is usually adjusted to give maximum transmission in the green-yellow region of the spectrum. At first calcium fluoride was used for lens coating, but the layer was physically soft and was easily rubbed off. Other fluorides are now used which are as durable as the glass itself.

Coated lenses have the desirable characteristics of virtual absence of flare spots and ghost spots which are due to unwanted surface reflections. It might be imagined that because more light is transmitted by the coated lens some decrease in exposure would be needed. This is not so in practice. Surface reflections cause light from the brightest areas of the subject to be scattered over the shadows of the image formed in the camera thus increasing their density (in the negative). Thus if exposure is based on the shadows, more exposure would be needed to produce the same density because of the reduction of scattered light. The main effect of a coated lens is to give increased contrast and 'cleaner' colours when using colour materials. All complex lenses used in photography are now coated.

24 Interference in thin layers

The patches of oil on water which sometimes cause such beautiful colours are thin layers from which light is reflected at the top and bottom surface, causing the colours by interference; see figure 52. Because the oil is not of uniform thickness, the colour changes from place to place. The colours of soap bubbles arise in the same way.

Practically every user of an optical instrument has heard that the purple tint of his camera lens or of the lenses on his binoculars, or of his spectacles, is caused by 'coating'. In
In connection with the previous discussion we can now explain how this works and why coatings are used.

We examine to this end what happens if there is a layer $A$ (figure 53) with refractive index $n$ on a piece of glass $B$, whose refractive index is $n'$, such that $n$ is less than $n'$. The difference in the paths of the reflected beams is $2d$, where $d$ is the thickness of the layer. For the beam $a$ which comes from air (refractive index 1) on to $A$, there is a jump in phase equivalent to a loss of half a wavelength. The reflection at the interface between $A$ and $B$ also causes such a phase change, and we must, therefore, take as the path difference between $a$ and $b$ just the distance $2d$. There will, therefore, be an extinction where $2d$ equals a half a wavelength; to be precise the half of a wavelength in the medium $A$. The thickness is then one-quarter wavelength. Such layers are called quarter-lambda layers; lambda is the name of the Greek letter $\lambda$ which is always used to denote the wavelength of light.
If this wavelength, such that \[ \lambda = \frac{\text{a}}{2}, \] the light will be reflected, provided the beams \( a \) and \( b \) are of equal intensity. This is not generally the case. One can, however, find materials for which, when they are deposited on to glass in such a thin coating, the reflected light is less than one per cent of the total, if only for a given region of wavelengths.

The process of covering glass surfaces with such non-reflecting layers is called coating. The advantages are obvious. In a pair of binoculars for example (figure 19) there are ten glass-air surfaces. By reflections alone, about 40 per cent of the light would be lost, since one glass-air interface reflects 4 to 6 per cent of the light. By coating all the surfaces, this loss is reduced to 10 per cent.

There is another advantage, at least as important. The light reflected at the glass surface can, after subsequent reflections, go in the direction in which the image is formed (figure 54). The beams which reach either the film of the camera, or the eye of the observer after an even number of reflections do not, it is true, give rise to a sharp image, but they do form a haze over the direct image. They reduce the contrast. And the unpleasantness can take on quite serious aspects. The picture of a landscape can for example be fogged by the light of the sky above the landscape. The great expanse thereof causes a lot of stray light to reach the film; see figure 55. That is why one must not allow the sun to shine into the lens. The photograph in figure 55 is made with an uncoated lens.

The coating enhances the brilliance of the picture. From this discussion it will be clear that it is impossible to deal with the whole spectrum with one coating. If the \( \frac{1}{4} \lambda \) layer is right for green light with \( \lambda = 560 \text{ nm} \), it is obviously not right for red light with \( \lambda = 720 \text{ nm} \), or for violet light with \( \lambda = 400 \text{ nm} \). Those parts of the spectrum are, therefore, reflected, and this

...less the purple bloom of such layers in reflected light. Red blue-violet together make purple.

By having more than one layer and by choosing the materials carefully, it is possible to obtain an important action of reflection over the whole visible spectrum.

A few words about the making of these layers, whose thickness is only about a thousandth of a millimeter. For one layer, magnesium fluoride is used. If more than one layer is added, one can for example use alternately magnesium fluoride and zinc sulphide.

These substances are salts which melt and evaporate at low temperatures. They are placed in little boats of high-purity metal, in a vacuum chamber, which is pumped out to one hundred-millionths \((10^{-8})\) of an atmosphere. In the chamber, suspended above the boats, are glass surfaces to be coated. The boats are heated electrically. The salt melts and evaporates. The vapour hits the glass and condenses. By ensuring the reflection of light from one of the glass-surface...
PRODUCTION PROPERTIES AND MANUFACTURING OF THIN FILMS

1) SINGLE, DOUBLE, AND TRIPLE LAYERS

2) PRODUCTION OF NARROW BAND PASS FILTERS

3) A COMPLETE TECHNIQUE FOR THE PRODUCTION OF ANTI-REFLECTIVE COATING WITH A SINGLE LAYER OF MAGNESIUM FLUORIDE
2.1.5 THE PROPERTIES OF MANUFACTURED SINGLE, DOUBLE AND TRIPLE LAYER ANTIREFLECTION COATINGS.

2.1.5.1 Single layer. It is no exaggeration to assert that 95% of the anti-reflection coatings manufactured around the world are single layers. Magnesium fluoride ($n_1 = 1.38$) evaporated in high vacuo, is the material used almost exclusively nowadays. The procedure laid down by *Smakula* in his patent specification has been entirely successful. Magnesium fluoride is the only material of low refractive index from which mechanically robust and chemically stable films can be made.

Cryolite ($n_1 = 1.35$) which was very popular during the war is now rejected because it is water soluble; this is unfortunate because the refractive index, lower than that of magnesium fluoride, leads to more desirable optical properties. Using magnesium fluoride, the amplitude condition of equation (24) cannot be satisfied for most optical glasses. In Fig. 41 the measured results show that the reduction of reflectance is fairly good even for glasses of low refractive index. $\lambda_0/4$ layers of magnesium fluoride were deposited on glass wedges of different refractive indices and care was taken in measuring only the light reflected at the coated surface. Therefore the measured intensity gives the reflectance of one surface.

Single layer antireflection coatings have the following advantages compared with multi-layers: glasses of different refractive indices can be coated simultaneously with the same charge. Even a wrong choice of the optical thickness reduces the reflectance except for wavelengths $\lambda$ where the optical thickness is $\lambda_0/2$, $\lambda_0$, ..., and for these the reflectance is the same as for untreated glass. The reflectance is never greater (cf. p. 28). Skilled workers manufacturing thin films are able to choose thicknesses so that the best result for each problem is obtained. In the normal case for visual observation (binoculars, microscope, spectacles, etc.) the best antireflection property is achieved by choosing a minimum in the green, i.e. at 550 nm. Then white light incident normally on
the treated surface is reflected with a purple to blue-violet colour. For a yellow colour of the film the minimum is at the shorter wavelengths, for a blue, then the minimum is at the longer (Plate 3). The antireflection properties of the blue films are not very good because the reflectance increases more rapidly in the short than in the long wavelength range (cf. Fig. 41).

The manufacture of these blue films is preferred, due, no doubt, to the simpler manufacturing procedure. Once the reflectance colours of the film are blue they remain blue even for a displacement of the reflectance minimum of ±30 nm. Displacements of ±10 nm are easily seen for films of a purple colour.

A purple to blue-violet reflection colour of optics usually indicates antireflection coatings of high quality.

Departure from these film thicknesses may be advisable in special cases. Glasses of high refractive index in photographic objectives are often strongly absorbing in the shortwave region (yellow coloured glasses). By choosing the minimum of reflectance for an antireflection coating at 450 nm, for example, the reflection losses for this wavelength are very low and so the absorption of the glass is compensated by using a yellow antireflection coating. This is of importance in colour photography to maintain colour balance. On the other hand a red filter with an absorption edge at 600 nm and the minimum of reflectance between 620 and 650 nm gives a very low reflectance for transmitted red light. Plate 3 gives some impression of the change from yellow to blue of the reflected light for an increase in the film thickness.

Drawing tangents at the minima of the $R$-curves in Fig. 41 shows that these parallels to the $\lambda$-axis are nearer the axis for high refracting glasses and further for glasses of lower refractive index. This distance from the axis gives a measure of the residual reflected white light; it is high for low refracting glasses, and

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**Fig. 41** The antireflection properties of single layers deposited on substrates of different refractive indices. $R$ is the reflectance at one surface. (Carl Zeiss B-Lab.)
low for high. Coated glasses of low refractive index therefore exhibit little exaggeration of the colour while the converse is true for those of high refractive index. Therefore an estimation of the refractive index of the treated glass is possible from the saturation of the reflected colours.

2.1.5.2 Double layer. Only double layers with a single zero of reflectance (cf. p. 54) are discussed; other solutions are only practicable in exceptional cases. Examination of the theoretical curve (Fig. 24 III) and the measured R-curves (Fig. 40) shows that the reflectance increases rapidly near the zeros especially at shorter wavelengths. White light transmitted through a complicated optical system such as a binocular treated with a double layer with zero of reflectance at 550 nm emerges yellow-green coloured. In the neighbourhood of the zero of reflectance the advantage gained by using a double layer is always lost due to high reflection at the edge if a wide spectral region is used. Considerable advantages accrue by using a relatively narrow spectral region. Fig. 42 shows the advantage of using double layer antireflection coatings as photofilters. The high reflectance, 14%, for \( \lambda = 400 \) nm is not a disturbing influence when the red filter is used. Light of this wavelength is absorbed in the filter. Provided that the filter is always used then lens surfaces of the objective could
be treated with similar double layers. Optical observations are very often carried out in green light which is less fatiguing to the eye. In this case, the double layer offers a considerable reduction in the reflectance compared with the single layer.

In addition to the physical reasons which militate against the general application of double layers, there are important commercial reasons. Double layer antireflection coatings are considerably more expensive than the single even when it is technically possible to evaporate the additional highly refracting layer with ease.

Different film thicknesses are required for glasses of different refractive indices so that different glasses cannot be treated simultaneously.

Greater care is required in controlling the film thickness than for single layers. For the single layer an error in the thickness only means that the minimum (or zero of reflectance obtained by satisfying the amplitude condition) is shifted to another wavelength. By contrast an error in the film thickness of a double layer implies that no zero of reflectance occurs. This can be disastrous if an increase in reflectance is produced instead (cf. Fig. 42), i.e. if the wrong thickness is chosen. More disastrous, however, is the fact that the reflectance of the uncoated glass may be enhanced instead of reduced (cf. Fig. 42).

2.1.5.3 Triple layer. It is possible using a triple layer to reduce the reflectance over a wide spectral range; this is not, of course, possible with either the single or double layer. Measurements of a three-layer antireflection coating are displayed in Fig. 43; this was made in the author's own laboratory. The cost and manufacturing problems are even greater than for the double layer and so triple-layer films are only used when they are fully justified.

Triple layer antireflection coatings have improved the position for microscopes of the reflected light type and progress has been made in special cases. Three fundamental difficulties frustrate the search for a general solution to the problem:

(1) For glasses of higher refractive index it is necessary to increase the refractive index of the \( \lambda/2 \)-layer if the residual reflectance for such glasses is to be
kept as low as that shown in the example for BK7 glass (Fig. 43). In practice, one is fortunate to find even one highly refracting material satisfying the requirements for such a film. If the refractive index of the \( \frac{1}{2} \) film is unaltered while the refractive index of the substrate is increased then the bandwidth of the region of low reflectance is reduced. The residual reflectance for a triple layer is not much lower than for a single layer if the refractive index of the glass is greater than 1.65.

(2) Attainment of the desired optical characteristics of the triple layer is dependent on laying down films of accurate thickness. For surfaces with steep curvature this latter is very difficult to achieve. Nevertheless methods are available for vacuum coating such surfaces and even hemispheres can be coated with a layer of constant thickness. But lenses used in microscope-objectives are very tiny so that vaporization of a film of uniform thickness becomes very difficult.

(3) No suitable materials with refractive index in the range 1.65 to 1.8 which can be used in the manufacture of triple layers are known. Films of this intermediate refractive index \( n_3 \) in the theoretical treatment) must be produced by a mixture of high and low refracting materials or by equivalent layers (Geffcken\(^\text{89}\)). The film design must be changed for glasses of different refractive index and so simultaneous evaporation of triple layers on different glasses is impossible (i.e. as for the double layer).

Clearly then triple layers should only be used where the most stringent antireflection properties are required. In these cases a change in reflectance from 0.1% to 0.01% is of great importance. Therefore the optical thicknesses of the layers must be monitored very exactly.
2.4.4.6 The production of narrow band pass filters. First of all a great deal of equipment and practical skill are needed. The specification for \( \lambda_{\text{max}} \) must be satisfied to 2-5 nm and the specified half-width and background carefully matched. It is very important that a uniform film thickness is maintained over the whole filter surface; this ensures constant \( \lambda_{\text{max}} \) from point to point over the surface area. This last requirement clearly demands highly sophisticated instrumentation to attain the degree of control implied. From experience it is known that a filter with steep edges and low background is preferable to one with only a small half-width. Specialized firms such as Balzers in Lichtenstein and Schott & Gen in Mainz have solved this problem satisfactorily. Fig. 78 shows the transmission characteristics of the four most important filter types manufactured by Schott. The filter properties may be better appreciated by tabulation; the following are quoted from the Schott catalogue.

<table>
<thead>
<tr>
<th>Spectral region nm</th>
<th>Filter-type</th>
<th>( T_{\text{max}} ) %</th>
<th>HW nm</th>
<th>dW/HW</th>
<th>hW/HW</th>
<th>tW/HW</th>
</tr>
</thead>
<tbody>
<tr>
<td>390–800</td>
<td>Line filters</td>
<td>30</td>
<td>10</td>
<td>1.7</td>
<td>3</td>
<td>9</td>
</tr>
<tr>
<td>390–800</td>
<td>Line double filters</td>
<td>10</td>
<td>10</td>
<td>1.5</td>
<td>2</td>
<td>3.5</td>
</tr>
<tr>
<td>390–800</td>
<td>Band filters</td>
<td>60</td>
<td>20</td>
<td>1.7</td>
<td>3</td>
<td>9</td>
</tr>
<tr>
<td>390–800</td>
<td>Band double filters</td>
<td>30</td>
<td>16</td>
<td>1.5</td>
<td>2</td>
<td>3.5</td>
</tr>
<tr>
<td>400–700</td>
<td>Colour filters</td>
<td>30</td>
<td>10</td>
<td>3</td>
<td>10</td>
<td>—</td>
</tr>
<tr>
<td>800–1,000</td>
<td>Line filters</td>
<td>30</td>
<td>15</td>
<td>3</td>
<td>10</td>
<td>—</td>
</tr>
</tbody>
</table>

where \( T_{\text{max}} \) = maximum transmittance, HW = half-width, dW = tenth-width, hW = hundredth-width, tW = thousandth-width. It is seen that only the colour filter and the line filter for 800-1,000 nm are single Fabry-Perot types (the last two rows). The Fabry-Perot filter usually has a value of 3 for the ratio \( dW:HW \). This suggests that the line filter given in the first row must be a more complicated system to achieve the ratio 1.7.

Changing the thickness of the spacer layer shifts the position of \( \lambda_{\text{max}} \); this suggests a method of using a wedged layer as a spacer so that the position of \( \lambda_{\text{max}} \) may be varied continuously.* (Graded spectrum filters.)

2.4.4.7 Narrow band pass filters for the I.R. A special advantage of the interference filters is the possibility of shifting the band pass to any wavelength.

* This type of filter is available from Schott & Gen and is listed in the catalogue under the name "continuous running filter."
required by a change of the film thickness. The many possible theoretical solutions are often limited by the few suitable materials. It has been shown, for instance, that silver layers can only be used in narrow band filters in the range 350 to 2,500 nm. Aluminium layers may be used in U.V. filters to 200 nm. Highly refractive materials such as zinc sulphide or some metal oxides are satisfactory in the visible but absorbing in the U.V. Lead fluoride and magnesium fluoride respectively the high and low refracting materials serve as a highly reflecting multilayer system to the absorption edge of lead fluoride at 230 nm; but the reflection bandwidth is small because the difference between the refractive indices of the two media is small.

In the I.R. region, however, the conditions for producing filters by using alternate high index-low index films are even better than in the visible. Materials such as antimony sulphide, silicon, and germanium, which absorb in the visible, are non-absorbing in the I.R. over a wide range of wavelength and moreover have high refractive indices (germanium \( n = 4 \), silicon \( n = 3.5 \)). Hass and Turner\(^{41} \) produced efficient filters using such materials combined with a low refracting substance, e.g. cryolite \( (n = 1.3) \); in these circumstances only a few layers are required to achieve a high reflectance and therefore large reflection bandwidths.
A METHOD OF PRODUCING ANTI-REFLECTIVE COATING WITH A SINGLE LAYER OF MAGNESIUM FLUORIDE

By: Dr. Robert H. Leshne

This article is one of a series designed to explain the proven techniques for various types of optical coatings. A technique to produce anti-reflection coating with single layer magnesium fluoride is explained. The cleaning of substrates is described and the procedure to be followed is outlined. Substrate fixtures and methods of substrate mounting are suggested. Vacuum pressures and substrate temperatures for hard baked coatings and a glow discharge method for cold coatings are presented.

THE EVAPORATION OF MAGNESIUM FLUORIDE has been used for many years for basic anti-reflection coating in optics. The effectiveness of this type of coating has been thoroughly explored and evaluated.

The purpose of this paper is not evaluation of single layer magnesium fluoride films or anti-reflective effectiveness, but rather a method of producing a superior quality film economically and efficiently.

The method and procedures which follow have been thoroughly proven and used quite successfully for many years and are applicable for laboratory as well as production.

The major piece of equipment required for many optical coatings is a vacuum coating machine. The size of this is determined by the specific need. The machine discussed is a standard 18" glass bell jar type, with a 6" oil diffusion pump, a 15 cfm mechanical pump, a filament powered by a 2 KVA transformer wired to supply 20 volts, a substrate heater and a glow discharge power supply.

The Cleaning of Substrates

Clean substrates are a prerequisite for a successful coating. This stage has probably more variations than any other part of the coating process. However, experience has proven that there is no successful shortcut which can be utilized to produce desired results.

The following method of cleaning has been highly satisfactory for glass or quartz substrates, not plastic or optically polished metal. Calcium carbonate precipitate is mixed with distilled water to form a thick paste. A wad of cottonwool or several gauze pads are soaked in the paste. The substrate is wet by holding it under warm, running tap water. All surfaces to be coated are then robbed with a calcium carbonate impregnated pad. The substrate is rinsed again under running tap water. The surfaces that have been rubbed and rinsed now wet evenly. Then the substrate is placed in a plastic pan or tank of warm water, after lining the bottom with diaper cloth. The same calcium carbonate scrubbing is done to the remaining substrates that are to be coated.

One at a time the substrates are removed and dipped into a tray or pan containing an emulsifying detergent. Certain household liquid detergents have also proved successful. However, if they are used, the cleaned substrates must be coated immediately after cleaning, which is not necessary with the use of an emulsifying detergent.

Next, the substrates are dried thoroughly with clean cheesecloth. At this point, a breath pattern test may be done to see if the cheesecloth has produced any wipe marks. This need not be done to each substrate, unless a random sampling shows wipe marks.

Each substrate is placed in a tray lined with clean tannish free paper. They are placed with the side to be coated down. They are now ready for mounting in the fixture.

The importance of proper cleaning cannot be too strongly emphasized. The substrate must be scrubbed with the chalk paste with some degree of pressure. The final wiping should also be done with pressure and without fear of damaging the polished surface. Many substrates of reticle quality and research grade finish have been cleaned this way without any flecks or scratches developing. However, the solutions, scrubbing pads and wiping cloths must be discarded when contaminated, for this is generally how flecks occur during the cleaning process.
Should the described cleaning process seem overly time consuming, one must remember that the preparation of the substrates before they enter the bell jar chamber is as important to the successful coating as the actual evaporation. Attempts have been made to use faster cleaning procedures. However, none has proven as consistently and thoroughly dependable.

Substrate Fixture

The size of the glass to be coated determines whether one or hundreds of the lenses may be coated at the same time. Proper fixturing enables the coating of as many lenses as can be fitted into a chamber. Proper fixturing also permits control of film thickness so that all the substrates are coated to the proper requirements.

For large quantities of lenses or windows of the same diameter, a ring type fixture has proven most useful. The material best suited, considering cost, machine shop work, and the ability to withstand vacuum and heat is Type 6061-T6 or 6063-T6 Aluminum. Enough rings are cut from this material and are welded (heliarc) together to form a dome shaped fixture, as shown in Figure 1.

In an 18" bell jar, the distance from the source (magnesium fluoride) to the substrate should be at least 15" or more. With this distance, the radius of the dome fixture is not critical. The average dome can be constructed as shown in Figure 2.

In designing the aluminum rings, it is necessary to account for the coefficient of expansion of the optics and the metal fixtures. Therefore, the inside diameter of the ring must be larger than the diameter of the substrate—a reference table for most substrates follows.

**TABLE 1**

<table>
<thead>
<tr>
<th>I.D. OF RING</th>
<th>O.D. OF SUBSTRATE</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.008&quot;</td>
<td>larger than</td>
</tr>
<tr>
<td>0.012&quot;</td>
<td></td>
</tr>
<tr>
<td>0.015&quot;</td>
<td></td>
</tr>
<tr>
<td>0.018&quot;</td>
<td></td>
</tr>
<tr>
<td>0.022&quot;</td>
<td></td>
</tr>
<tr>
<td>0.025&quot;</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Up to 3/4&quot;</td>
</tr>
<tr>
<td></td>
<td>3/8&quot; to 1/3&quot;</td>
</tr>
<tr>
<td></td>
<td>1/4&quot; to 2/3&quot;</td>
</tr>
<tr>
<td></td>
<td>5/8&quot; to 4/3&quot;</td>
</tr>
<tr>
<td></td>
<td>4/3&quot; to 7/4&quot;</td>
</tr>
<tr>
<td></td>
<td>7/4&quot; and up</td>
</tr>
</tbody>
</table>

The resting ledge of the ring should be designed so that a practical maximum area of the substrate is coated. The procedure followed is presented below—see Table 2.

**TABLE 2**

<table>
<thead>
<tr>
<th>WIDTH OF LEDGE</th>
<th>O.D. OF SUBSTRATE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/2 mm</td>
<td>Up to 3/4&quot;</td>
</tr>
<tr>
<td>3/4 mm</td>
<td>3/8&quot; to 1/3&quot;</td>
</tr>
<tr>
<td>1 mm</td>
<td>1/4&quot; to 2/3&quot;</td>
</tr>
<tr>
<td>1 1/2 mm</td>
<td>5/8&quot; to 4/3&quot;</td>
</tr>
<tr>
<td>2 mm</td>
<td>4/3&quot; to 7/4&quot;</td>
</tr>
<tr>
<td>2 1/2 mm</td>
<td>7/4&quot; to 8 1/2&quot;</td>
</tr>
<tr>
<td>3 mm</td>
<td>8 1/2&quot; and up</td>
</tr>
<tr>
<td>3 1/2 mm</td>
<td></td>
</tr>
</tbody>
</table>

A typical cross section of a fixture ring is shown—see Figure 3.

Provisions should be made on the completed dome for a ring to hold the test lens. This test lens ring should be a permanent part of the dome. Its location is best at the front edge of the fixture, as shown in the photograph of Figure 1. Also, provisions for mounting the dome in the bell jar must be made.

It would be most desirable to have the test lens made of the same index as the substrate to be coated. This is impractical; therefore, all test lenses used should be of one index. The technician must acquaint himself with the slight variations in the refractive color of the different coated indices. Thus, the test lens which helps monitor the thickness of the film during evaporation can be coated to a thickness which will directly correspond to the thickness of the film on the substrate. The type of test lens used and found to be easy to work with, is a flint glass of index 1.649-33.8, with a convex radius of 3.399" and a concave radius of...
1.623". Diameter of the lens is 1.25". The test lens is set in the fixture so that the convex radius is coated. Coated or used test lenses may be reworked to remove the coating and used again. Another very practical type of coating fixture primarily for small quantities of substrates is the adjustable type as shown in Figure 4.

This fixture can accommodate substrates with diameters up to 6" or 8" x 10" rectangularly shaped. The substrates in this case are not in the same plane as the test lens in the dome type fixture. With this type of jig the substrates are closer to the source material and therefore will be filmed sooner than the test lens. The technician must account for this difference by allowing the test lens to be coated to a lighter color or thinner film thickness. With single layer films of magnesium fluoride, a reasonable degree of monitoring accuracy can easily be achieved with a little practice.

It is advisable for the technician who is not familiar with the refractive color changes associated with varying film thicknesses, to perform a test coating to observe this effect. After the test lens has left the light blue color and is once again white and the evaporation is continued, the color sequence will repeat itself, becoming yellow, straw, pink, pink-purple, blue, light blue, green-white. However, this is in the \( \lambda \) wave second order maximum. If the evaporation were to continue, the sequence would again be observed, this time in the 5/4 wave third order maximum.

The technician should concentrate his efforts on the color changes of the first order maximum. Once he becomes quite familiar with this sequence, inexpensive and quite effective monitoring has been achieved for single layer magnesium fluoride film.

---

**Figure 3**

The refractive color changes which the test lens will go through during evaporation are light yellow, straw, pink, pink-purple, blue, light blue and white. The pink-purple color would be considered \( \lambda \) wave for the middle of the visible spectrum (5250 A). Pink would be \( \lambda \) wave for the 4500 A area and blue \( \lambda \) wave for the 6250 A area, and white \( \lambda \) wave for 5000 A. The \( \lambda \) wave first order maximum is the desired thickness for anti-reflection coating. The single layer of magnesium fluoride is so broad in its anti-reflecting effect that most blueprints requesting an optical surface to be coated merely state the requirement of \( \lambda \) wave. This means that the substrate can be deep straw, pink, pink-purple or blue and still meet the requirements of the blueprint.

---

**Figure 4**

**Mounting Substrates**

After all the substrates have been cleaned, they must be mounted on the coating fixture. Care at this time must be taken to remove dust and lint from the substrates. An anti-static brush is of great help and careful brushing is important because lint or dust left on the substrates will produce pinholes and breaks in the coating. Finger cots should be used to pick up the substrates so that fingerprints are not left on the cleaned surfaces. Finger cots also prevent the bristles of the brush from coming in contact with the technician's hands while brushing the substrates. They insure against deposit and streaks of oil on the surfaces to be coated. When the coating fixture is full it is immediately placed in the bell jar and the vacuum pumping started. Mounting of the substrates should not be started until the coating chamber is open and ready for the next cycle. The mounted substrates standing and waiting to be put into the bell jar can easily become contaminated with dust and lint.

**Filaments**

For this type of evaporation, it is advisable to use a radiant heater of tungsten wire (wire diameter .020"

to .025") as shown below in Figure 5.

This type of filament can be purchased ready-made or can easily be made right in the coating room in a matter of minutes. To make these filaments, wire of .020" or .025" diameter can be secured in 50' rolls or longer. When this wire is ordered, clearly specify that the tungsten must be in the unrecrystallized form. With a little practice, unrecrystallized tungsten wire of this diameter can easily be bent without sintering or breaking by using a pair of snipe-nosed pliers.

![Figure 5](image)

Whether you buy the ready-made filaments or make them, before an evaporation a new filament should be straightened and cleaned. This is done in the following manner: First, mount the filament to the electrodes in the coating machine so that it is in the middle of the base plate. Next, slowly bring up the filament varia so that the filament glows red. At this point, with the snipe-nosed pliers straighten out any sag that has occurred. Once the filament is straight, turn the varia off. Next, lower the bell jar, and pump down to a pressure of at least 3 x 10^-4. Once again, turn up the varia slowly, so that the filament now glows white (about 3/4 amp). Let the filament burn this way for 30 or 40 seconds. Then, turn varia to off position and let the filament cool under vacuum for three or four minutes. The bell jar may now be opened. The filament should be straight and the wire clean. If, however, the filament has developed more sag and does not appear to be straight, repeat the sequence. The filament is now ready for use and will remain in good shape for many evaporation. If after using for several evaporation the filament develops some sag again, it must be straightened. This type of filament can be used for at least 40 to 50 evaporation.

Strip heaters and boats are also widely used. However, less spattering, better film distribution and pure uncontaminated films result with the use of a radiant heater.

**Preparation of Magnesium Fluoride for Evaporation**

Magnesium fluoride powder of optical quality is obtained and when not in use should be stored in a desiccator jar with desiccant. When preparing the magnesium fluoride for evaporation, a Coors porcelain crucible with a rim diameter of 37mm and 23mm height is quite suitable as a container. The powder is placed in the crucible with a small spatula, and the crucible is tapped on a hard surface so that the powder settles firmly and becomes compact. More powder is placed in the crucible and it is again tapped to settle the powder. When the crucible is completely full and the powder forms a slight mound in the center, a clean glass plate is firmly pressed on the top to level the magnesium fluoride with the crucible rim and to ensure that the crucible is very firmly packed. With a clean nail or pick 2" to 3" long and 1/32" diameter, form a hole in the center of the magnesium fluoride running from top to bottom. To do this, a hole can be drilled in the center of a piece of plexiglass just a few thousandths of an inch larger than the nail diameter. Then, placing the plexiglass plate over the top of the crucible, center the hole in the middle and push the nail through the hole until the nail touches the bottom of the crucible. Next, carefully draw the nail all the way out and lift off the plexiglass plate. This hole will help in the warm up and outgassing of the material and will result in fewer accidents of spatter. The magnesium fluoride is now ready for evaporation. The crucible is placed in the bell jar so that the filament is about 1/16" from the magnesium fluoride. This adjustment is necessary after every two evaporation. The crucible prepared this way can be used for at least seven to eight evaporation. It is advisable to prepare several crucibles with the magnesium fluoride and store them with the loose powder in the desiccator jar. The used magnesium fluoride can be reground to a powder in a mortar and pestle and re-used.

**Evaporation**

Once the substrates are in the bell jar, the filament and the magnesium fluoride in good order, the substrate heater in position, the pump down starts with the roughing cycle which, for an 18" chamber with a 15 cfm mechanical pump should take no longer than four minutes to reach below 50 microns. During the roughing cycle, the substrate heater should be turned on. Once below 50 microns, the roughing line is closed and the fore pressure line opened. Next, the high vacuum valve is opened while the rise in pressure of the fore line is carefully monitored. The vacuum machine will be left to pump with the substrate heater still on. To evaporate magnesium fluoride correctly, a pressure in the bell jar of 4 x 10^-6 or less is mandatory. It is a simple matter to evaporate at higher pressures. However, the film will be contaminated and will not stand up to all of the standard durability tests.
The pressure should be reached easily in approximately 50 minutes from the start of the roughing cycle. At this time, the substrate temperature must be greater than 250°C. (275°C is safe). Temperatures of this order are mandatory.

If the coating machine is not equipped with a thermocouple readout for substrate temperature, several test temperature runs may be made under vacuum conditions with a thermometer in the bell jar and the thermometer bulb in the substrate location. The technician should record numerous varicel settings which will enable him to reach a temperature of 275°C in 30 minutes and maintain this temperature for an additional 30 minutes. Once these varicel settings have been established and periodically checked, proper temperatures needed for durable magnesium fluoride coatings can readily be reached.

Assuming that temperature and pressure conditions have been achieved, the warm up and outgassing of the magnesium fluoride may be started. It is important to know the extent to which the varicel should be advanced until enough heat is generated to start evaporating the magnesium fluoride. The technician should run a few tests. He should advance the varicel slowly after some warm up of the magnesium fluoride and directly observe the magnesium fluoride surface through a filter with a density of 3. At no time should the filament be viewed directly with the unprotected eye. The point at which the magnesium fluoride starts to develop a depression or cavity around the center hole is the evaporation point and this setting should be noted.

As vaporization proceeds, he will note the various color changes of this image and cease the evaporation when proper color is achieved; the evaporation is stopped merely by turning the filament varicel to zero. With a small fluorescent light, the technician may check color again by holding the light so he gets a reflection of the coated surface of the test lens, as shown in Figure 7.

If proper color or film thickness has not yet been reached, the filament may be brought right up to the evaporation point again and additional film material added until the correct thickness has been attained. If, however, the proper thickness has been passed, it is not wise to continue the evaporation to reach the desired color in the second order maximum because the very broad characteristics of the 1/4 wave of the first order maximum will no longer exist.

As soon as the evaporation is stopped, the substrate heater is turned off, and the substrates allowed to cool. The cooling times will vary according to the physical shape of the substrates (thicker lenses longer than thinner lenses). Suggested cooling times are 35 minutes for glass thicknesses up to 8"; 50 minutes for glass thicknesses from 8" to 10"; one hour for glass thicknesses from 10" to 12"; etc. In the case of fused quartz, where one is not concerned with cooling down the substrates, the bell jar should still be kept under high vacuum for at least 10 minutes to allow the magnesium fluoride to cool under vacuum.
Before removing the coated substrates, the high vacuum valve should be closed tightly and air allowed to enter the bell jar slowly. The coating fixtures should be handled with padded or asbestos gloves. The substrates are placed in trays lined with fresh clean paper. If there are second surfaces to be coated on the same substrates, they must be washed again before being placed back in the vacuum chamber.

This process does not make use of glow discharge; although there can be no doubt as to its usefulness, a glow discharge is not necessary in producing good quality hard magnesium fluoride films. A glow discharge must, however, be used for substrates which are lminated, optically cemented, or which cannot withstand high temperatures. Here, the heating cycle is eliminated completely, and a glow discharge substituted. The coating cycle is performed as follows:

After the substrates are placed in the bell jar, the roughing cycle is started as we previously described, except that the substrate heater is not turned on. After securing pressures below 50 microns the coating machine is placed under high vacuum pumping and allowed to go to $8 \times 10^{-4}$. With the use of a needle valve, air is carefully admitted to the bell jar so that the pressure in the bell jar registers approximately 5 microns. At this point, the high vacuum valve is throttled almost to the closing point, which in turns the pumping speed of the diffusion pump to the bell jar, and an appropriate rise in pressure is noted. By carefully adjusting the high vacuum valve, the pressure rise in the bell jar can be easily controlled, so that a pressure of 10 microns can be maintained. Slowly advance the valve of the high voltage power supply so that not more than 125 milliamperes and at least 3500 volts or more register. The unit should be carefully monitored this way for the duration of the glow period. The length of time of the glow period will depend upon the substrates (generally, anywhere from 10 to 30 minutes). At the end of the glow period, the needle valve is immediately closed and the high voltage power supply turned off. The high vacuum valve is opened all the way and the coating machine allowed to pump down so that a pressure of at least $4 \times 10^{-4}$ is reached. From this point, the warm up and evaporation of the magnesium fluoride proceeds as it did before. When the filming is complete, the cool down time need not take longer than five to twenty minutes.

This type of magnesium fluoride coating is often referred to as a cold coating. The film durability will never measure up to a hard baked coating, but for many instances it will do.

For this type of cold coating, the high voltage electrode in the bell jar is secured to an aluminum ring (high density low porosity aluminum), placed about 10" to 12" from the substrates. The glow ring should be shielded from the evaporant, so that subsequent usage does not contaminate the substrates, which would drastically affect the film durability. Superior quality magnesium fluoride films can be achieved through various other techniques. However, the success obtained with the procedures outlined above advocate adherence to this method.

**Meet The Author**

Dr. Robert H. Lashne received his background in optics at Brooklyn College and Chicago College of Optometry. He has been directly associated with optics and thin film deposition for the past 18 years, and has done work for private industry, government and NASA. Currently, he is Vice President of Engineering at Broome Laboratories, Inc., in Plattsburgh, N.Y. Dr. Lashne is well known in the field for his development of thin film techniques. The publication of his book concerning practical coating techniques is forthcoming.
THEORY, CALCULATION, FORMULAS

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Blooming of glass surfaces

In the case of normal incidence at an air-glass surface, no material exists which will satisfy equation 7 except for very high index glasses. The layer is usually produced by evaporation in vacuum and the material now almost universally used is magnesium fluoride. This has a refractive index of about 1.36. The following table shows the minimum reflection factor obtainable for glass of refractive index $n$:

<table>
<thead>
<tr>
<th>$n$</th>
<th>1.3</th>
<th>1.5</th>
<th>1.7</th>
<th>1.8</th>
<th>1.95</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R$</td>
<td>0.11</td>
<td>0.005</td>
<td>0.002</td>
<td>0.0002</td>
<td>0</td>
</tr>
</tbody>
</table>

Thus, there is still a considerable advantage over uncoated glass, for which $R$ would range from 0.040 to 0.088 for the above values of $n$. If the thickness is adjusted to give zero $R$ at the middle of the spectrum, the residual violet and red reflection gives a characteristic purple tinge to the reflected light if, as is customary, $N$ is taken as zero in equation 6. Larger values of $N$ give the so-called higher-order coatings and for these the purple is less saturated since the reflectance increases more rapidly away from the zero.

The experimental details of the evaporation technique have been described by Holland and the method of computation by Mayer and Heavens.

In order to obtain an actual zero of $R$ with available materials, it is necessary to use two or more layers. To show how this can be done, we use an approximate method of determining $R$. If there are several layers $(n_i, 	heta_i, n_i')$ on a substrate $n_0$, the complex amplitude-reflection factors of the interfaces are given by the Fresnel formulae

$$r_{32} = \frac{n_3 - n_2}{n_3 + n_2}, \quad r_{21} = \frac{n_0 - n_2}{n_0 + n_2}, \quad r_{10} = \frac{n_1 - n_2}{n_1 + n_2}$$

The total complex amplitude reflected can be written as the vector sum of these with due allowance for the optical paths through the layers, as in Fig. 1. The

$$R = \frac{r_{32}^2 (r_{21}^2 + r_{21}^2 + 2(r_{21}^2 - r_{21}^2) \cos 2\theta_1 + (r_{21}^2 + r_{21}^2) (n_2 - n_1)^2 + 2(r_{21}^2 - r_{21}^2) \cos 2\theta_1 + (r_{21}^2 + r_{21}^2) (n_2 - n_1)^2)}{(r_{21}^2 + r_{21}^2 + 2(r_{21}^2 - r_{21}^2) \cos 2\theta_1 + (r_{21}^2 + r_{21}^2) (n_2 - n_1)^2 + 2(r_{21}^2 - r_{21}^2) \cos 2\theta_1 + (r_{21}^2 + r_{21}^2) (n_2 - n_1)^2)}$$

where

$$\theta_1 = \frac{2\pi}{\lambda} n_1 \cos \theta_1 \cdot k_1$$

If $u_i$ is intermediate in magnitude between $n_0$ and $n_2$, $R$ has a minimum at

$$R = (2N + 1)/2, \quad N = 0, 1, 2, \ldots$$

and if $u_i$ is outside the range $n_0$, $R$ will be zero at other points. In the most useful practical cases, $N$ is in the range 0 to 1. As $N$ increases, $R$ decreases at the middle of the spectrum and $R$ increases at the edges.

Holland and Putner have described in detail the production of such a coating of the structure shown in Fig. 2. The bismuth oxide is obtained by reactive sputtering and the magnesium fluoride by vacuum evaporation. Both materials are extremely durable mechanically and chemically.

By the use of more than two layers, it is possible to obtain more than one zero of $R$ alternatively to reduce $R$ in the regions where it rises too rapidly.
Surface Reflection. Vignetting and the cosine^2 law cause a reduction in image brightness off the axis of the lens, but aside from this the entire image suffers some brightness loss due to reflection of light at the lens surfaces and absorption by the optical materials themselves. In lenses of reasonable size the absorption is negligible, but light loss by reflection is not negligible. It has been stated previously that a substance, in order to transmit light, must have an elastic response to the frequency of the incident energy. Due to this elasticity some of the incident energy is reflected back into the original medium. For light at normal incidence to a surface the reflectance \( R \) may be found by the equation,
\[
R = \left( \frac{n' - n}{n' + n} \right)^2 = \left( \frac{1 - n/n'}{1 + n/n'} \right)^2
\]
where \( n \) and \( n' \) are the refractive indices preceding and following the surface, respectively. Ignoring absorption, the transmittance and reflectance must add up to one. We may therefore write for transmittance,
\[
T = 1 - \left( \frac{n' - n}{n' + n} \right)^2 = \frac{4nn'}{(n' + n)^2}
\]
where \( k \) is the number of air-glass surfaces in a lens.

The transmittance of a single lens in air is the product of the transmittances of the two surfaces. Similarly for a lens system the total transmittance is the product of all the surface transmittances. An air-glass surface where \( n' = 1.6 \) will have a transmittance \( T = 0.947 \). It is a satisfactory approximation, in figuring the net transmittance of a lens system, to assume an average \( T \) of 0.95 per air-glass surface. Thus we may say, for all practical purposes, that the net transmittance is
\[
T_{\text{net}} = 0.95^k
\]

The following table gives net transmittance for various numbers of surfaces, \( k \).

<table>
<thead>
<tr>
<th>( k )</th>
<th>2</th>
<th>4</th>
<th>6</th>
<th>8</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T_{\text{net}} )</td>
<td>0.90</td>
<td>0.81</td>
<td>0.74</td>
<td>0.66</td>
<td>0.60</td>
</tr>
</tbody>
</table>

It is seen from the above that a lens of five single elements, having ten glass-air surfaces, transmits only about 60% of the incident energy.

One of the problems confronting lens manufacturers throughout the years of the development of photographic optics has been the dilemma of the increase in required number of elements to improve aberrations, and the resulting reduction in transmittance. Thus the early complex lenses, such as the Dagor and Protar, were made with as many of the elements as possible cemented together, providing a relatively small index difference at all but four surfaces of the lens.

Reflections in a photographic objective not only result in reduced transmission, but, due to multiple reflections, glare light (i.e., nonimage-forming light) is reflected into the film plane causing reduced image contrast and definition. Furthermore, under certain adverse circumstances, halo images may be formed in the film plane.
Antireflection Coatings. Through the years many efforts have been made to reduce the reflections at glass-air surfaces. This is best accomplished by depositing a thin coating on the surface. To be fully effective this coating must fulfill two conditions: (1) the reflection at the air-coating surface must be equal in magnitude to the reflection at the coating-glass surface; and (2) the coating thickness must be such as to cause destructive interference of the two reflections. The first condition is met if the index ratios of air-to-coating and coating-to-glass are equal, i.e., \( \frac{n_{air}}{n_c} = \frac{n_c}{n_g} \). Since \( n_{air} = 1 \), this condition requires that \( n_c = \sqrt{n_g} \). The second condition can be met at only one wave length and only one angle of incidence, since the refractive index of the coating varies with wave length and the path traveled by a ray in the coating increases with obliquity. A coating will be very effective, however, if its thickness is determined for normal incidence of green light (\( \lambda = 550 \) nm). For destructive interference to occur the two reflections must be 180° out of phase. In other words, the reflection from the coating-glass surface must be one-half wave length behind the air-coating surface reflection. This condition is met if \( n_c \cdot d = \lambda / 4 \), where \( d \) is the coating thickness.

In addition to the above two optical conditions, an effective coating must be hard to withstand repeated cleaning. It should be unaffected by moisture, or any elements normally encountered in the atmosphere, and it must adhere firmly to the glass surface.

To meet all these conditions is indeed an impossible order, but fortunately the physical conditions are met by crystalline materials, such as magnesium fluoride, which can be evaporated onto glass in a vacuum. Also, fortunately, the optical conditions need be only approximately met to reduce the surface reflections of a lens to less than 1% per surface. As a practical rule of thumb, the net transmittance of a lens with coated surfaces is

\[
T_{net} (coated) = 0.99^m \quad (4.29a)
\]

Because evaporated crystalline coatings are costly, attempts are continually being made to develop means of coating glass surfaces by chemical reactions or by chemical deposits. The early so-called "soft" coatings were generally chemical coatings. They soon wore off the outer surfaces of a lens, but were useful on the inner element surfaces which were not subjected to handling and atmospheric effects. A hard, durable coating may be produced by an acid dip, which by chemical reaction will reduce the refractive index on a polished lens surface. This process, however, has been found difficult to control within desired tolerances of coating thickness, since the rate at which the reaction takes place is apparently very sensitive to the degree of surface polish and other surface factors.
An optical filter in which the wavelengths that are not transmitted are removed by interference phenomena rather than by absorption or scattering (see Interference of Waves). In addition to being able to duplicate most of the spectral characteristics of absorption color filters, these devices can be made to transmit a very narrow band of wavelengths. They can thus be used as monochromators to examine a radiation source at the wavelength of a single spectrum line. For example, the solar disk can be observed in light of the hydrogen line $H\alpha$.

and thus the distribution of excited hydrogen over the disk can be determined.

Most narrow-band interference filters are based on the Fabry-Perot interferometer (see Interferometry). The Fabry-Perot interference filter differs from the interferometer only in the thickness of the space between the partially reflecting layers. In the interferometer, this space can be several centimeters. In the filter, it is normally a few thousand angstroms. In the simplest filter, a glass plate is coated with a layer of silver which is covered by a layer of dielectric and in turn followed by another evaporated layer of semitransparent silver.

Basic properties. At all wavelengths at which the dielectric layer has an optical thickness of an integral number of half waves, the filter will have a passband. The number of half waves corresponding to a given passband is called the order of the passband. The transmission $T$ of the filter can be represented by the equation

$$T = \frac{1}{(1 - r)^2 + 4r \sin^2 (\frac{\delta}{2})}$$

where $r$ is the reflectivity of the silver film, $\delta$ the transmission of the film, and

$$\delta = \frac{4\pi d}{\lambda} (n^2 \sin^2 \theta)^{1/2} + 2\pi$$

where $d$ is the thickness of the dielectric layer, $n$ its refractive index, $\lambda$ the wavelength, $\phi$ the phase shift experienced by the light at the metal-dielectric boundary, and $\theta$ is the angle of incidence.

By inspection of this equation, it is apparent that maxima occur when $\delta/2 = m\pi$, where $m$ is an integer.

Some of the quantities which are of interest to the user of these filters are (1) the peak transmission, (2) the transmission between peaks, (3) the bandwidth, and (4) the angular field of view, that is, the angle through which the filter must be tilted to block the wavelength of peak transmission a distance equal to the bandwidth.

Each of these quantities can be determined theoretically from the preceding equation. A typical filter has a peak transmission of 40% at its peak wavelength of 5461 Å, a transmission between peaks of 0.2%, a bandwidth of 100 Å, and an angular field of view of 20°. These numbers represent nearly the best that can be done with the simple metal-dielectric filter.

Multilayer types. An increase in reflectivity can result in narrower bandwidths. There are techniques by which high reflectivities can be achieved which are lossless, that is, which have no absorption. This results in higher peak transmission and lower effective transmission. The first is the multilayer filter. In this device, the metal layers are replaced by a series of dielectric layers. The boundaries between adjacent layers of refractive index $n_1$ and $n_2$, respectively, are denoted by $r_{12}$ and $r_{21}$.

$$r = \left( \frac{n_1 - n_2}{n_1 + n_2} \right)^2$$

See Reflection (Electromagnetic Radiation).

By making several layers of alternate high- and low-index dielectric, it is possible to reinforce the reflectivity of a single boundary and build it up by multiple reflection to any desired value. It is necessary only that the layers be of such thickness that the reflections from successive boundaries are in phase. When each layer is optically $\lambda/4$ wavelength in thickness, this reinforcement takes place. A complete filter is sketched in Fig. 1. It might consist of seven alternate layers of high- and low-index dielectric of a thickness of $\lambda/4$ wavelength each, followed by the dielectric spacer which is an integral number of half waves and which is followed by seven more $\lambda/4$-wavelength layers.

![Fig. 1. Schematic diagram of 7-layer solid Fabry-Perot filter. (From D. E. Gray, ed., American Institute of Physics Handbook, McGraw-Hill, 1957)](image)

Fig. 1. Schematic diagram of 7-layer solid Fabry-Perot filter. (From D. E. Gray, ed., American Institute of Physics Handbook, McGraw-Hill, 1957)

![Fig. 2. Transmission of filter shown in Fig. 1 as a function of wavelength. (From D. E. Gray, ed., American Institute of Physics Handbook, McGraw-Hill, 1957)](image)

Fig. 2. Transmission of filter shown in Fig. 1 as a function of wavelength. (From D. E. Gray, ed., American Institute of Physics Handbook, McGraw-Hill, 1957)

Frustrated reflection. A second technique is the use of frustrated total internal reflection for the partially reflecting layers of the filter. Light is totally internally reflected when incident on the hy
If another prism is brought up to the first, as in Fig. 3, a part of the light is transmitted through the combination. The fraction transmitted depends on the separation between the prisms. The reflectivity can be made as high as desired. In a filter, the prism hypotenuse is coated with a low-index layer of a thickness chosen to give the proper value of the reflectivity. This is covered with a high-index layer whose thickness determines the wavelength of the passband, as in the normal Fabry-Perot filter. This is followed by a second low-index layer and a second prism. The first frustrated reflection is at the boundary between the first prism and the low-index layer. The second reflection is at the boundary of the high-index layer and the second low-index layer. The thickness of the low-index layer can be adjusted to give any value of reflectivity. The filter is lossless unless there is absorption within the layers. The resulting filter can be made to have a bandwidth of less than 6 A.

The process whereby two or more waves of the same frequency or wavelength combine to form a wave whose amplitude is the sum of the amplitudes of the interfering waves. The interfering waves can be electromagnetic, acoustic, or water waves, or in fact any periodic disturbance.

The most striking feature of interference is the effect of adding two waves in which the trough of one wave coincides with the peak of another. If the two waves are of equal amplitude, they can cancel each other out so that the resulting amplitude is zero. This is perhaps most dramatic in sound waves; it is possible to generate acoustic waves to arrive at a person's ear so as to cancel out noise that is disturbing him. In optics, this cancellation can occur for particular wavelengths in a situation where white light is a source. The resulting light will appear colored. This gives rise to the iridescent color of beetles' wings and mother-of-pearl, where the substances involved are actually colorless or transparent.

Two-beam interference. The quantitative features of the phenomenon can be demonstrated most easily by considering two interfering waves. The amplitude of the first wave at a particular point in space can be written

$$ A = A_0 \sin (\omega t + \varphi_1) $$

where $A_0$ is the peak amplitude, and $\omega$ is $2\pi$ times the frequency. For the second wave

$$ B = B_0 \sin (\omega t + \varphi_2) $$

where $\varphi_1 - \varphi_2$ is the phase difference between the two waves. In interference, the two waves are superimposed, and the resulting wave can be written

$$ A + B = A_0 \sin (\omega t + \varphi_1) + B_0 \sin (\omega t + \varphi_2) $$

This can be expanded to give

$$ A + B = (A_0 \sin \varphi_1 + B_0 \sin \varphi_2) \cos \omega t $$
$$ + (A_0 \cos \varphi_1 + B_0 \cos \varphi_2) \sin \omega t $$

By setting

$$ A_0 \sin \varphi_1 + B_0 \sin \varphi_2 = C \sin \varphi_2 $$

and

$$ A_0 \cos \varphi_1 + B_0 \cos \varphi_2 = C \cos \varphi_2 $$

Equation (4) becomes

$$ A + B = C \sin (\omega t + \varphi_2) $$

where

$$ C^2 = A_0^2 + B_0^2 + 2A_0B_0 \cos (\varphi_2 - \varphi_1) $$

(see SUPERPOSITION, PRINCIPLE OF). When $C$ is less than $A$ or $B$, the interference is called destructive.
When it is greater, it is called constructive. For electromagnetic radiation, such as light, the amplitude in Eq. (7) represents an electric field strength. This field is a vector quantity and is associated with a particular direction in space, the direction being generally at right angles to the direction in which the wave is moving. These electric vectors can be added even when they are not parallel. For a discussion of the resulting interference phenomena, see Polarized Light.

In the case of radio waves or microwaves which are generated with vacuum tube or solid-state oscillators, the frequency requirement for interference is easily met. In the case of light waves, it is more difficult. Here the sources are generally radiating atoms. The smallest frequency spread from such a light source will still have a bandwidth of the order of $10^9$ cycles. Such a bandwidth occurs in a single spectrum line, and can be considered a result of the existence of wave trains no longer than $10^{-4}$ sec. The frequency spread associated with such a pulse can be written

$$\Delta f = \frac{1}{2t^2}$$

(9)

where $t$ is the pulse length. This means that the amplitude and phase of the wave which is the sum of the waves from two such sources will shift at random in times shorter than $10^{-4}$ sec. In addition, the direction of the electric vector will shift in these same time intervals. Light which has such a random direction for the electric vector is termed unpolarized. When the phase shifts and direction changes of the light vectors from two sources are identical, the sources are termed coherent.

Amplitude splitting. The interference experiments discussed have all been done by splitting the wavefront of the light coming from the source. The energy from the source can also be split in amplitude. With such amplitude-splitting techniques, the light from the source falls on a surface which is partially reflecting. Part of the light is transmitted, part is reflected, and after further manipulation these parts are recombined to give the interference. In one type of experiment, the light transmitted through the surface is reflected from a second surface back through the partially reflecting surface, where it combines with the wave reflected from the first surface. This is illustrated in Fig. 8. Here the arrows represent the normal to the wavefront of the light passing through surface $S_1$ to surface $S_2$. The wave is incident at $A$ and $C$. The section at $A$ is partially transmitted to $B$, where it is again partially reflected to $C$. The wave leaving $C$ now consists of two parts, one of which has traveled a longer distance than the other. These two waves will interfere. Let $AD$ be the perpendicular from the ray at $A$ to the ray going to $A$. The path difference will be

$$\Delta = 2\mu(AB) - (CD)$$

(24)

where $\mu$ is the refractive index of the medium between the surfaces $S_1$ and $S_2$.

$$\begin{align*}
(AB) &= d\cos r \\
(CD) &= 2(AB)\sin r \cos i
\end{align*}$$

(25)  
(26)

From Snell's law,

$$\sin i = \mu \sin r$$

and thus,

$$\Delta = \frac{2\mu d}{\cos r} - \frac{2\mu d}{\cos r} \sin^2 r$$

(27)  
(28)  
(29)

$$\Delta' = 2\mu d \cos r$$

(30)

$$\Delta' = \frac{4\pi d \cos r}{\lambda}$$

(31)
light is reflected from the two surfaces and examined as in Fig. 8. One of the first experiments with fringes of this type was performed by Sir Isaac Newton. A convex lens is pressed against a glass plate and illuminated with monochromatic light. A series of circular interference fringes known as Newton's rings appear around the point of contact. From the separation between the fringes, it is possible to determine the radius of curvature of the lens.

**Thin films.** Interference fringes of this two-surface type are responsible for the colors which appear in oil films floating on water. Here the two surfaces are the oil-air interface and the oil-water interface. The films are close to a visible light wavelength in thickness. If the thickness is such that, in a particular direction, destructive interference occurs for green light, red and blue will still be reflected and the film will have a strong purple appearance. This same general phenomenon is responsible for the colors of beetles' wings.

**Channelled spectrum.** Amplitude splitting shows another condition that must be satisfied for interference to take place. The beams from the source must not only come from identical points, but they must also originate from the same points at nearly the same time. The light which is reflected from C in Fig. 8 originates from the source later than the light which makes a double traversal between S₁ and S₂. If the surfaces are too far apart, the spectral regions of constructive and destructive interference become so close together that they cannot be resolved. In the case of interference by wavefront splitting, the light from different parts of a source could only be considered coherent if examined over a sufficiently short time interval. In the case of amplitude splitting, the interference when surfaces are widely separated can only be seen if examined over a sufficiently narrow frequency interval. If the two surfaces are illuminated with white light and the eye is used as the analyzer, interference cannot be seen when the separation is more than a few wavelengths. The interval between successive wavelengths of constructive interference becomes so small that each spectral region to which the eye is sensitive is illuminated, and no color is seen. In this case, the interference can again be seen by examining the reflected light with a spectroscope. The spectrum will be crossed with a set of dark fringes at those wavelengths for which there is destructive interference. This is called a channelled spectrum. For large separations of the surfaces, the separation between the wavelengths of destructive interference becomes smaller than the resolution of the spectrometer, and the fringes are no longer visible.

**Fresnel coefficients.** The amplitude of the light reflected at normal incidence from a dielectric surface is given by the Fresnel coefficient

\[
A = A_0 \frac{n_1 - n_2}{n_1 + n_2}
\]
where $A_0$ is the amplitude of the incident wave and $n_1$ and $n_2$ are the refractive indices of the materials in the order in which they are encountered by the light. In the simple case of a dielectric sheet, the intensity of the light reflected normally will be

$$C^2 = A^2 + B^2 + 2AB \cos \phi$$  \hspace{1cm} (33)

where $B$ is the amplitude of the wave which has passed through the sheet and is reflected from the second surface and back through the sheet to join $A$. The value of $B$ is given by

$$B = \frac{n_2 - n_3}{n_2 + n_3}$$  \hspace{1cm} (34)

where the approximation is made that the intensity of the light is unchanged by passing through the first surface and where $n_0$ is the index of the material at the boundary of the far side of the sheet.

Nonreflecting film. An interesting application of Eq. (33) is the nonreflecting film. A single dielectric layer is evaporated onto a glass surface to reduce the reflectivity of the surface to the smallest possible value. From Eq. (33) it is clear that this takes place when $\cos \phi = -1$. If the surface is used in an instrument with a broad spectral range, such as a visual device, the film thickness should be adjusted to put the interference minimum in the first order and in the middle of the desired spectral range. For the eye, this wavelength is approximately in the yellow so that such films reflect in the red and blue and appear purple. The index of the film should be chosen to make $C^2 = 0$. At this point

$$(A - B)^2 = 0$$  \hspace{1cm} (35)

$$\frac{n_2 - n_3}{n_2 + n_3} = \frac{n_2 - n_3}{n_2 + n_3}$$  \hspace{1cm} (36)

$$n_1n_2 - n_2^2 + n_1n_2 - n_2n_3 + n_2^3 - n_3n_1 = 0$$  \hspace{1cm} (37)

This can be reduced to

$$n_2 = \sqrt{n_1n_3}$$  \hspace{1cm} (38)

In the case of a glass surface in air, $n_1 = 1$ and $n_3$ is 1.5. Magnesium fluoride is a substance which is frequently used as a nonreflective coating, since it is hard and approximately satisfies the relationship of Eq. (38). The purpose of reducing the reflection from an optical element is to increase its transmission, since the energy which is not reflected is transmitted. In the case of a single element, this increase is not particularly important. Some optical instruments may have 15-20 air-glass surfaces, however, and the coating of these surfaces gives a tremendous increase in transmission.

Haedinger fringes. When the second surface in two-surface interference is partially reflecting, interference can also be observed in the wave transmitted through both surfaces. The interference pattern will be complementary to those appearing in reflection. Their location will depend on the parallelism of the surfaces. For plane parallel surfaces, the fringes will appear at infinity and will be concentric rings. These were first observed by W. K. Haidinger and are called Haidinger fringes.

Multiple-beam interference. If the surfaces $S_1$ and $S_2$ are strongly reflecting, it is necessary to consider multiple reflections between them. For air-glass surfaces, this does not apply since the reflectivity is of the order of 4%, and the twice-reflected beam is much reduced in intensity.

In Fig. 9, the situation in which the surfaces $S_1$ and $S_2$ have reflectivities $r_1$ and $r_2$ is shown. The space between the surfaces has an index $n_3$ and thickness $d$. An incident light beam of amplitude $A$ is partially reflected at the first surface. The transmitted component is reflected at $S_2$ and is reflected back to $S_1$ where a second splitting takes place. This is repeated. Each successive component of the waves leaving $S_1$ is retarded with respect to the next. The amount of each retardation is given by

$$\phi = 4\pi nd \cos \theta$$  \hspace{1cm} (39)

Equation (7) was derived for the superposition of two waves. It is possible to derive a similar expression for the superposition of many waves. From Fig. 9, the different waves at a plane somewhere above $S_1$ can be represented by the following expressions:

- Incoming wave $= A \sin \omega t$
- First reflected wave $= A r_1 \sin \omega t$  \hspace{1cm} (40)
- Second reflected wave $= A (1 - r_1^2) r_2 \sin (\omega t + \phi)$
- Third reflected wave $= -A (1 - r_1^2) r_2^2 \sin (\omega t + 2\phi)$

By inspection of these terms, one can write down the complete series. As in Eq. (3), the sine terms can be broken down and coefficients collected. A simpler method is to multiply each term by $i = \sqrt{-1}$ and add a cosine term with the same coefficient and argument. The individual terms then are all of the form

$$Be^{-i\phi} \cos \theta$$  \hspace{1cm} (41)

where $m$ is an integer.
These can be easily summed. For the reflected wave one obtains

\[ R = \frac{r_1 + r_2 e^{-2i}}{1 + r_1 r_2 e^{-4i}} \]  

(42)

Again, as in the two-beam case, the minimum in the reflectivity \( R \) is obtained when \( \varphi = N\pi \), where \( N \) is an odd integer and \( r_1 = r_2 \). The fringe shape, however, can be quite different from the earlier case, depending on the value of the reflectivities \( r_1 \) and \( r_2 \). The greater these values, the sharper become the fringes.

It was shown earlier how two-beam interference could be used to measure the contour of a surface. In this technique, a flat glass test plate was placed over the surface to be examined and monochromatic interference fringes were formed between the test surface and the surface of the plate. These two-beam fringes have intensities which vary as the cosine squared of the path difference. It is very difficult with such fringes to detect variations in fringe straightness or, in other terms, variations of surface planarity that are smaller than \( \frac{\lambda}{2} \) wavelength. If the surface to be examined is coated with silver and the test surface is also coated with a partially transmitting metallic coating, the reflectivity increases to a point where many beams are involved in the formation of the interference fringes. The shape of the fringes is given by Eq. (42). The shape of fringes for different values of \( r \) is shown in Fig. 10. With high-reflectivity fringes, the sensitivity to a departure from planarity is increased far beyond \( \frac{\lambda}{2} \) wavelength.

It is thus possible with partially silvered surfaces to get a much better picture of small irregularities than with uncoated surfaces. The increase in sensitivity is such that steps in cleaved mica as small as 10 Å in height can be seen by examining the monochromatic interference fringes produced between a silvered mica surface and a partially silvered glass flat. See Interference Filters, Optical; Interferometry.

Reflection (electromagnetic radiation)

The return of electromagnetic waves from surfaces on which they are incident. When radiation crosses a boundary between two media and suffers a change in velocity, a fraction $R$ of its energy is reflected. The magnitude of $R$ depends on the difference in velocity and the angle of incidence.

Because electromagnetic radiation is capable of interacting with the charged particles which make up all matter, the velocity of propagation of radiation is different for each material, depending on the atomic, molecular, and crystal structure. The ratio of velocity in vacuum to that in a given material is called the refractive index (index of refraction) of the material. It is found to vary with the wavelength of the radiation, and can be represented by real (noncomplex) numbers for those wavelength regions sufficiently removed from absorption bands in the material. See Refraction of Waves.

Reflectivity is defined as the ratio of the intensity of the total reflected light to that of the total incident light. The theory of reflectivity of radiation is based on the application of Maxwell’s equations to the electric and magnetic properties of the incident and reflecting media. The solution ascribes to the material a complex refractive index, $\mu = \mu' - i\mu''$, where $\mu'$ is the real part of the index of refraction, $\mu''$ is the imaginary part, and $i$ is the square root of $-1$. For dielectric materials, the absorption vanishes because the electrons are bound to the atoms and are not free to take up energy from the electromagnetic field. For metals, in which the electrons are free to increase their energy, radiation of all wavelengths can be absorbed. The ratio at which energy is absorbed determines the reflectivity, and is determined by the number of electrons available in the metal. See Absorption (electromagnetic radiation).

The present article is concerned with specular reflection only, that is, reflection from surfaces which are optically smooth, and neglects effects of diffuse reflection and scattering.

REFLECTION FROM DIELECTRICS

Normal incidence reflectivity. When radiation is incident along a normal to an interface between two nonabsorbing media, the ratio of the reflected to the incident energy is

$$r = \left(\frac{\mu' - \mu''}{\mu' + \mu''}\right)^2$$

where $R = \frac{r}{r}$

$$r = \text{fraction of energy reflected}$$
$$\mu' = \text{refractive index of incident medium}$$
$$\mu'' = \text{refractive index of reflecting medium}$$

This expression, the standard Fresnel reflection law, indicates the phase shift on reflection to be zero when the incident medium has the higher index, and $180^\circ$ (since $r$ is negative) otherwise.

For many applications, the incident medium is air with $\mu' \approx 1$, giving

$$\frac{1}{1 + \mu''}$$

The curve $(1 - \mu'')/(1 + \mu'')$ vs. $\mu''$ is part of a branch of a hyperbola for positive values of $\mu''$. For many common optical materials, including most glasses, $\mu'' = 1.5$ giving $r = -0.20$ and $R = 0.04$. Therefore, approximately 4% of the incident light is reflected from a single glass surface. See Optical Materials.

Many of the materials transparent in the infrared spectral regions have much higher refractive indices. Germanium, transparent for wavelengths greater than 1.8 microns, has $\mu' = 4$, $r = -0.6$, $R = 0.36$. This high reflectivity seriously reduces its transmission unless the surfaces are coated with nonreflecting film.

The variation of reflectivity with refractive index for normal incidence in air is given in Fig. 1.

Plane parallel interfaces. If radiation is incident on a stratified medium (one which contains parallel interfaces, for example, a pile of plates), a simple relation holds for the reflectivity of the medium in terms of the reflectivity of the individual interfaces. If $r_1$ and $r_2$ are the fractions of reflected and transmitted energy for the $p$ individual interfaces, and if $R$ and $T$ are the corresponding values for the entire medium, then

$$R = \frac{p}{T}$$

Here the $r_i$ are computed from Eq. (1). This relationship includes the multiple reflections in the medium, but cannot be used if interference...
Reflection (electromagnetic radiation)
effects redistribute the energy between the reflected and transmitted waves.

Thin films. Many interesting reflection effects can be produced by taking advantage of interference between the multiply reflected components of a beam of light in thin films. The reflectivity from a dielectric may be made to take on any value from zero to nearly 100% through the use of one or more thin, nonabsorbing layers deposited on its surface.

To reduce the reflectivity to zero, a single thin film of index \( \mu_1 \) may be deposited on a dielectric of index \( \mu_2 \) to a thickness \( d_1 \) such that

\[
\mu_1 d_1 = (2n - 1) \frac{\lambda}{4}
\]

where \( n \) is an integer

\( \lambda \) = wavelength of the radiation

\( \mu_0 \) = refractive index of incident medium (air, \( \mu_0 = 1 \))

Under these conditions, the reflectivity is the same at each of the two interfaces. The multiply-reflected beams \( r_2, r_3, r_4, \ldots \), of Fig. 2 are all in phase, each one traveling an additional \( \frac{\lambda}{4} \) wave through twice the film thickness more than the previous beam, and in addition, suffering a phase shift equivalent to \( \frac{\lambda}{2} \) displacement at the second interface. The resultant amplitude of these beams is, therefore,

\[
r = r_0^2 + r_1^2 + r_2^2 + \ldots = r^2 r (1 + r^2 + r^4 + \ldots)
\]

\[
= \frac{r^2}{1 - r^2}
\]

since \( r^2 + r^4 = 0 \); that is, the transmitted and reflected beams contain all the energy. The first beam \( r_0 \) has an amplitude \( -r \) exactly 180° out of phase with the other beams because of its phase shift on reflection. Therefore, the resultant reflected amplitude is zero, no energy is reflected, and 100% transmission occurs.

The general equation for the amplitude of a wave reflected from a single quarter-wave film on a substrate is

\[
r = \frac{1 - r}{1 + r} \text{ or } \frac{1 - r}{1 + r} = \frac{1 - t_1}{1 + t_1}
\]

where \( t_1 = \mu_1 / \mu_0 \) and \( t_2 = \mu_2 / \mu_1 \). The accompanying table gives \( t_1 / t_2 \) as a function of \( \mu_1 \) and \( r \) as a function of \( t_1 / t_2 \). Knowing \( \mu_2 \) and \( \mu_0 \), \( t_1 \) and \( t_2 \) may be determined as a function of \( \mu_1 \).

The use of a \( \frac{\lambda}{4} \)-wave film whose index is greater than that of the substrate results in an increased reflectivity according to Eq. (6). By this means, a glass surface reflecting 4% can be made to reflect 32% by depositing \( \frac{\lambda}{4} \) wave of ZnS, index 2.3.

If wavelengths \( \lambda \) different from that for which the film has an optical thickness of \( \frac{\lambda}{4} \), are incident, the reflected amplitude will vary according to the more general relationship

\[
1 - r = \delta_i \tan \delta_i
\]

\[
1 + r = 1 - t_1 \tan \delta_i
\]

\[
\delta_i = \frac{2 \pi}{\lambda} \mu_0 d_1 = (n - \frac{\lambda}{2}) \pi \frac{\lambda}{\lambda}
\]

Solving this equation for the complex value of \( r \), one can determine the phase shift on reflection and also the reflected energy.

For the special case of a film \( \frac{\lambda}{4} \) wave thick, that is,

\[
\mu_1 d_1 = n \frac{\lambda}{4}
\]

\[
\delta_1 = \pi n \text{ and } \frac{1 - r}{1 + r} = t_1 = \frac{\mu_2}{\mu_0}
\]

This is identical to the reflectivity obtained without the \( \frac{\lambda}{4} \)-wave layer present. Therefore, a \( \frac{\lambda}{4} \)-wave layer can be disregarded in reflection computations.

The reflectivity of a dielectric surface can be increased to as close to 100% as one wishes by depositing alternating \( \frac{\lambda}{4} \) waves of high- and low-index materials. The peak reflectivity can be calculated by assigning to the \( m \)th interface in the pile (counting down from the air interface as 1) a value

\[
m = \frac{\mu_m}{\mu_{m-1}}
\]

where \( \mu_0 \) is the refractive index of the 0th layer.
and \( \mu_{m+1} \) that of the layer above. If there are \( n \) layers, there are \( n + 1 \) interfaces (Fig. 3).

\[
\begin{align*}
\frac{1 - r}{1 + r} &= \left( \frac{\mu_1}{\mu_0} \right) \left( \frac{\mu_2}{\mu_1} \right) \cdots \left( \frac{\mu_n}{\mu_{n-1}} \right) \\
&= \frac{\mu_1}{\mu_0} \left( \frac{\mu_2}{\mu_1} \right) \cdots \left( \frac{\mu_n}{\mu_{n-1}} \right) \\
&= \mu_1^{1+2} \mu_2^{2+3} \cdots \mu_n^{n+1} \\
&\quad \text{for an even number (10)} \\
&= \mu_1^{1+2} \mu_2^{2+3} \cdots \mu_n^{n+1} \\
&\quad \text{for an odd number of layers (11)}
\end{align*}
\]

If the alternate layers are identical, \( \mu_1 = \mu_2 = \mu_3 = \cdots = \mu_n = \mu \) and \( \mu_2 = \mu_4 = \mu_6 = \cdots \), then

\[
\begin{align*}
\frac{1 - r}{1 + r} &= \left( \frac{\mu_1}{\mu_0} \right) \left( \frac{\mu_2}{\mu_1} \right) \cdots \left( \frac{\mu_n}{\mu_{n-1}} \right) \\
&= \mu_1^{1+2} \mu_2^{2+3} \cdots \mu_n^{n+1} \\
&\quad \text{for an even number (11)} \\
&= \mu_1^{1+2} \mu_2^{2+3} \cdots \mu_n^{n+1} \\
&\quad \text{for an odd number of layers (11)}
\end{align*}
\]

For wavelengths both greater and smaller than \( \lambda_0 \) (the wavelength for which the layers are \( \frac{\lambda}{2} \) wave), the reflectivity falls off only slightly until a critical wavelength is reached, beyond which the drop is more rapid. The critical wavelengths \( \lambda_c \) are dependent on the ratio of refractive indices of the two materials, their values being given by

\[
\cos^2 \left( \frac{\pi \lambda_c}{2 \lambda_0} \right) = \left( \frac{1}{1 + (\lambda_0/\lambda_c)} \right)^2 \\
\]

(12)

The amount by which the reflectivity increases as an additional pair of layers is deposited increases according to the departure of \( \mu_1 / \mu_2 \) from unity. As the number of layers is increased, the curve of reflectivity vs. wavelength near \( \lambda_0 \) takes on the character of a square wave whose width decreases as \( \mu_1 / \mu_2 \to 1 \). In the vicinity of the wavelength for which the layers are \( \frac{\lambda}{2} \)-waves, that is, around \( \lambda_0 / 2 \), the curve has an undulating form, taking on a value equal to the reflectivity of the bare substrate at \( \lambda_0 / 2 \).

The particular advantages of utilizing multilayer films for filters lie in their efficiency (the energy not reflected is transmitted), the steepness of the slope \( (dR/d\lambda) \), and the possibility of depositing films to operate at almost any wavelength desired. See INTERFERENCE FILTER, OPTICAL.

Oblique incidence. In the case of nonnormal incidence for dielectric materials, the direction of propagation of the energy is no longer the same for all materials, but varies according to Snell's law. At each interface between media of different refractive indices \( \mu_1 \) and \( \mu_2 \), the light is deviated, the angles \( \theta_1 \) and \( \theta_2 \) made with the normal to the interface being related by

\[
\mu_1 \sin \theta_1 = \mu_2 \sin \theta_2
\]

(13)

If light is transmitted through a set of plane parallel interfaces, the direction of propagation in any medium is the same as it would be if the layers above it were removed. It depends only on the angle of incidence in the incident medium and the ratio of its refractive index to that of the incident medium.

Polarized components. Electromagnetic radiation also displays its characteristics as a transverse wave by separating into two polarized components when incident at oblique angles. They are conventionally considered to separate according to the plane in which the electric wave is located. The angle of incidence is that containing the direction of propagation and the normal to the surface at the point of contact. That part of the radiation with its resultant electric wave in this plane is designated as p-polarized (parallel) and the part vibrating perpendicular to this plane is called s-polarized.

Each component has its own reflection characteristic. Fresnel's equations for the two components are

\[
\begin{align*}
\frac{1 - r_p}{1 + r_p} &= \mu_2 \cos \theta_2 = t_p \quad \text{(p-polarization)} \\
\frac{1}{1 + r_s} &= \mu_1 \cos \theta_1 = t_s \quad \text{(s-polarization)}
\end{align*}
\]

(14)

These equations predict the reflectivity, in particular, under three interesting conditions. At grazing incidence, \( \cos \theta_1 \) vanishes, and the right side of both expressions becomes infinite, indicating 100% reflection for each polarization.

When \( \theta_1 \) and \( \theta_2 \) are complementary, the expression for the p-polarization becomes unity, making \( r_s \) vanish. The angle of incidence \( \theta_s = \tan^{-1} \left( \mu_2 / \mu_1 \right) \) is called the polarizing angle or Brewster's angle. The reflected and refracted waves are propagated at right angles to each other, the reflected wave containing only s-polarization. See POLARIZED LIGHT.

The third interesting condition occurs when \( \theta_s = \pi / 2 \) and \( \mu_1 \geq \mu_2 \). In this case, both expressions vanish because \( \cos \theta_1 = 0 \), and both components are completely reflected. Since this occurs...
only on reflection from a high-to-low-index medium, it is called internal reflection. The angle of incidence is designated as the critical angle \( \theta_c \) and satisfies the relation \( \sin \theta_c = \mu_2 / \mu_1 \). For angles of incidence greater than this, \( \cos \theta \) becomes an imaginary quantity. Solving for \( \mu_2 \) and \( \mu_1 \) yields complex expressions whose amplitude is unity (indicating 100% reflectivity), but whose argument shifts on reflection experienced by polarization.

Although no energy is transmitted into the lower-index medium, an attenuated wave is propagated along the interface, its amplitude tending off exponentially with \( d \), the distance from the interface. The presence of this wave can be detected when the low-index medium is air. Total reflection can be destroyed by bringing an object close to, but not touching, the interface, thereby disturbing the attenuated wave.

The reflectivity for the two polarizations is shown in Fig. 4 for incidence from a low- to high-index and high- to low-index interface.

**Thin films:** Reflectivity from thin films for oblique incidence can be treated similarly to the case for normal incidence, where one uses the \( \mu \)'s for each polarization at each interface, as defined in Eqs. (14). A further difference occurs in the effective optical thickness of a layer at oblique incidence. According to the interference produced by a thin film, its effective thickness is reduced by \( \cos \theta \), where \( \theta \) is the propagation angle in the medium, determined from Eq. (13). For example, a \( \frac{1}{2} \)-wave film at normal incidence would have an effective optical thickness of only \( \frac{1}{2} \) wave when light traverses it at a 60° angle.

Because of this effect, a multilayer filter in which the layers are matched at one angle of incidence will become mismatched at another. Each layer will change effective thickness according to its index, which through Snell's law, determines the angle. In general, the effect of this mismatching will be to reduce the peaks and slopes of the reflectivity-versus-wavelength curve.

**Selective reflection from crystals.** The discussion to this point has been concerned with reflectivity of nonabsorbing media for removed from absorption bands. These bands are located in the spectral regions where the frequency of the radiation corresponds to a resonance frequency of the atoms, molecules, or crystal lattice of the medium. Since this radiation is strongly absorbed, it is also strongly reflected. The metallic sheen of dye crystals, which have very strong absorption bands in the visible spectrum, is caused by selective reflection. Crystalline solids such as rock salt or quartz, the lattices of which are built up of atoms bearing net electric charges, show strong selective reflection in the infrared region at wavelengths near those of the strong absorption bands associated with lattice vibrations in the crystal. By reflecting an infrared beam several times from such a material, highly monochromatic radiation can be obtained at the specific wavelengths. These monochromatic beams are referred to as residual rays or residual light. Figure 6 indicates the residual rays for some common crystals. See IONIC CRYSTALS.

**REFLECTION FROM METALS**

In determining the reflective properties of metallic substances, the solutions derived for dielectrics apply, but the refractive indices and the angles determined from the indices through Snell's law become complex. The reflectivity of some common metals is given in Fig. 6. The reflectivity falls off
The fact that the difference in phase shift on reflection for the two components is exactly \( \pi / 2 \) at this angle, thus, the polarizing angle can be accurately determined by using a known plane to convert the elliptically polarized light to linear polarization. For any other angle of incidence, linear polarization will not result unless it is possible to reduce excitation for any direction of rotation.

An interesting property of metal reflection occurs when the extremely thin film (less than 100 A thick) is deposited on a transparent substrate. Although the reflectivity from the air side may be as high as 20%, that on the glass side is effectively reduced to zero. Contrast to the dielectric non-reflecting film, the low reflectively extends over a large part of the visible spectrum. With a film this thin, it is not the optical thickness that plays the predominant part in the interference effects, but the phase shift on reflection at the air metal and metal-substrate interfaces. If the back surface reflection of a beam splitter is a monochromatic beam gives a doubling of an image, it can be completely eliminated through the use of a thin metal film than a dielectric film. See Albedo; Mirror optics; Optics, geometrical; Reflection (sound); Reflection and Transmission coefficients.

INTERFERENCE FILTERS

Brief Definition: These are filters with narrow transmission bands which depend for their operation on the same interference phenomena which are responsible for the reduction of surface reflection losses. They are formed by the vacuum deposition of a series of thin layers of different materials, & interference arises between the rays which originate at every interface between two different media.

Ordinary color filters depend upon the selective absorption of light by colored glass, gelatin or cellulose acetate. Interference filters, as stated above, make use of the principle of light interference to give a selective transmission of any color in the visible spectrum within narrow limits of wavelength. (See figure 1.)

There are three major types of interference filters - 1. Solid Fabret-Perot, Multi-layer F.P. and Polarization.

The Solid Fabret Perot Filter. The active elements are an evaporated layer of silver covered by a layer of dielectric and followed with another layer of silver.

At all wavelengths at which the dielectric has an optical thickness of an integral number of half waves the filter will have a pass band. The number of half waves corresponding to a given passband is called the order of the passband.

The transmission of the filter can be represented by the following equation:

\[ T = \frac{t^2}{(1-r)^2 + 4r \sin^2 \frac{\delta}{2}} \]

where:
- \( r \) is the reflectivity of the silver film (a function of thickness)
- \( t \) is the transmission of the silver film
- \( \delta = \frac{4\pi d}{\lambda} n^2 \langle \sin^2 \Theta + 2y \rangle \)

\( d \) is the thickness of the dielectric, \( n \) is the dielectric index of refraction.
\( \lambda \) is the wavelength  
\( \gamma \) is the phase shift at the metal dielectric boundary  
\( \Theta \) is the angle of incidence  

The maximum transmittance is obtained when \( \Delta/2 \) is equal to \( m \pi \), where \( m \) is an integer.

Filter Properties to be found: peak transmissiion, transmission between peaks, passband width, and angular field of view. From the first equation  
\( T_{\text{max}} \) is equal to \( t^2/(1-r^2) \).  
\( T_{\text{min}} \) is equal to \( t^2/(1 + r)^2 \)

Bandwidth is defined as the distance between two points at which the transmission is 50\% of peak transmission. The formula for this being:

\[
\Delta v = \frac{K}{\pi nd} \sin^{-1} \left( \frac{1-r}{2\sqrt{r}} \right)
\]

The desired qualities for a filter are as follows. Narrow passband width, highest possible peak transmission, lowest minimum transmission possible, lowest possible separation between passbands. To make the bandwidth narrow, you increase the reflectivity and/or the thickness of the dielectric. But increasing the dielectric results in passbands coming closer together. The passband separation

\[
\Delta = \frac{K}{\pi nd}
\]

A thick dielectric is also undesirable because after four or five wavelengths it starts to crack. Increased reflectivity is fine but it changes the absorption, resulting in a reduction of peak transmission.

The specifications of a typical Fabret Perot (solid) filter might look like this:  
\( T_{\text{max}} \)- 35\%  
Wavelength (max)- 5461 \( \AA \)  
\( T_{\text{min}} \)- .2\%  
Passband Width 150 \( \AA \)
The Multilayer Filter (Fabret-Perot Type)

In this type metal layers are replaced by layers of dielectrics. The reflectivity is given by the standard Fresnel reflection law:

\[ r = \left( \frac{n_1 - n_2}{n_1 + n_2} \right)^2 \]

Placing several layers of alternate high and low index dielectrics together results in reinforcing the reflection of a single boundary, it can be built up by multiple reflection to any desired value. The only requirement is that reflection from successive boundaries be in phase. If they are out of phase there is no reinforcement. Reinforcement then, takes place only when each layer is optically 1/4 wavelength thick. A typical filter may consist of 7 alternate layers, dielectric spacer (integral number of 1/2 wavelengths, followed by 7 more layers. The layers are composed for the most part of NaF and ZnS. (See Diagram)

This results in built up reflectivity of 65% which improves transmission. It works out to a peak of 80% and a bandwidth of 30 Angstroms, Tmin is .03%.

A multilayer filter is superior to a metal one in three ways. But because of the constructive interference at odd number of 1/4 wavelengths, the region of low transmission is much smaller. A typical region of low transmission is only 1000 Angstroms wide. The solution to this problem is very simple. Place the filter layers on a gelatin filter. Then... a fantastically narrow pass band is transmitted. (see diagrams)

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ABSORPTION CURVES OF TRI COLOR FILTERS

FABRY-PEROT FILTER TRANSMISSION VS $\lambda$

SCHEMATIC DIAGRAM OF 7 LAYER SOLID
FABRY PEROT FILTER

g. fuller, r. smith
3\lambda_0/4, 5\lambda_0/4, \ldots \) In practice there exists no material which is free from absorption and also possesses a high enough refractive index. The following solution is therefore chosen: over the opaque mirror an absorption free film is deposited; this is then coated by a thin transmitting metal film. It may be shown theoretically that an electrical square resistance of 377 \( \Omega \) is necessary for the transmitting metal film to obtain zeros of reflectance. There are then zeros of reflectance for all wavelengths \( \lambda \) for which the phase thickness of the now absorbing film is \( \lambda/4, 3\lambda/4, 5\lambda/4, \ldots \) while the reflectance of the uncoated mirror is unchanged for the phase thicknesses \( \lambda/2, \lambda, 3\lambda/2, \ldots \).

To isolate a narrow band from a continuous spectrum by reflection at these filters a method used is analogous to that used for the polarization filter \((\text{Billings}^{16})\). The principle is illustrated in Fig. 79. It is seen that the film thicknesses in the ratio 1:2:4:8: \ldots have the same function here as doubly refracting plates in the Lyot filter. Here the reflectances of the constituent filters must be multiplied to obtain the resultant characteristic for the reflection filter while for the Lyot filter the transmittances must be multiplied. A disadvantage of this method is that the individual filter must all have different film thicknesses and that the thicknesses are very large.

Filter arrangements using the well-known reststrahlen method are much simpler to realize. The light is reflected at a set of identical reflection interference filters, i.e. manufactured in the same process. The band width may be reduced by multiple reflection as shown in Fig. 80. Curve I shows the measured results given by \(\text{Billings}^{16}\). A double reflection leads to curve II \((R_1^2)\), a triple to curve III \((R_2^3)\), etc. This method is not so efficient as the first but it has the advantage of simplicity of manufacture.

Quite complicated systems can also be synthesized using this type of filter. Reflection interference filters with two or more transmitting metal layers with embedded dielectric layers (cf. coupled systems, the band filter) have been described by \(\text{Turner}^{17}\) and the optical properties discussed. A treatment of this
absorbing in the visible. In spite of this, the reflectance of this 2/4 stack is unsatisfactory, especially in the short wave region. Mirror II which is more complicated (Schröder; deposition from solution) reflects very well in the visual spectral region. The same is true for mirror III produced by Zeiss Ikon.

2.4 Optical Filters

Filters are used to change the intensity or change the spectral distribution of the light emitted by a source. Neutral or grey filters reduce the intensity equally for all wavelengths. Filters which reduce the light intensity by a different amount for different wavelengths affect the colour of the light and are often used to change the colour temperature. Large spectral regions may be separated by an edge filter. Finally using monochromatic or narrow bandpass filters single lines of a line spectrum may be isolated or narrow bands from a continuous spectrum may be selected (monochromatic light).

The importance of thin films in the solution of these problems is now discussed.

2.4.1 Neutral Density Filters. Neutral filters play a very important part in spectral analysis. The exposure of a line spectrum in a spectroscope must be chosen so that even the lines of low intensity register on the photographic plate. Then the energy in the stronger lines causes over exposure and the density of the plate is no longer proportional to the product: intensity \( \times \) time, because the linear part of the \( \gamma \)-curve is exceeded and the shoulder of the operating characteristic must be used. These difficulties are surmounted by using step filters. A 3-step filter produced in the author’s laboratory for Q 24 is shown diagrammatically in Fig. 63. The step filter is placed as close as possible to the entrance slit and the line spectrum is then divided into three parts. As shown in Fig. 64, the line intensities are in the same ratio as the transmission of the three steps. Measurements of the density of a weak line transmitted through the 100% step and of a very intense line through the 10% step permit calibration to the 100%. Conversion to the real intensity from the density observed through the attenuating steps is quite simple when the transmission
is the same for all wavelengths. Metal films developed in the author's laboratory (Fig. 65) give a satisfactory solution for this purpose.

A very important application of neutral filters is in colour photography, especially in microscopy. If the image of a microscope specimen is too bright, the brightness may be reduced either by decreasing the voltage applied to the lamp or by closing down the aperture. The first method shifts the maximum of the light source intensity distribution to a longer wavelength so that the coloured picture looks too yellow. Stopping down the aperture reduces the resolution and the image quality. This difficulty is solved by introducing a neutral light filter to attenuate the light intensity. Schott NG glasses may be used when small attenuations are required. Increasing the absorption, however, causes an increase in the transmission of these glasses for long wavelengths so that a colour picture appears to be too yellow. For these reasons filters produced by evaporating neutral metal films on a colourless glass substrate are used. Since the density of a metal film increases with film thickness, it is possible to manufacture graded density filters on strips or disks.

2.4.2 Filters for which the transmission changes slowly with wavelength. Only two examples from the many applications and manufacturing
techniques are discussed. First, a filter to change the colour temperature and second, a filter for sunglasses.

Filters used to change the colour temperature, e.g. to change from daylight to artificial light and vice versa for colour photography, are usually coloured glasses. When the transmission characteristics of these glasses do not satisfy some stringent requirement then the addition of thin films should lead to a suitable improvement. Schröder considered a triple layer with a reflection maximum at 700 nm deposited on a colourless glass substrate. As shown in Fig. 66, this interference film changes the colour temperature 4,000° K to 5,000° K. With the precision control of thin film techniques, the interference film is more readily reproducible than the coloured glass.

This last also applies to the filters used to coat sunglasses. Reproducibility of absorption and colour tones is obtained more easily by evaporation than by colouring the glass melt. Fig. 67 shows measured results of the spectral transmission of coated sunglasses. These were produced by a technique devised by the author (see p. 77). In transmission these glasses appear grey-brown; this improves the contrast and reproduces the true colours. By contrast, the neutral filters appear blue and reduce the contrast. Thus filter coatings for sunglasses should produce an increase in transmission towards the longer wavelengths of the visible range.

2.4.3 EDGE FILTERS: CUT-OFF OR CUT-ON FILTERS. The spectral transmission characteristics of edge filters are such that the change in transmission from a low value over a wide spectral range to a high value over a wide spectral range occurs rapidly, Geffcken. Well known filters of this type are classified as U.V.-, yellow- and red-filters which are based on selective absorption in coloured glass (cf. the red filter, Fig. 42). These colour glasses transmit light in the long wavelength region, up to the absorption edge, while light in the short wavelength region is absorbed. Berger and Geffcken have shown that similar results may be obtained by evaporating the sulphides, selenides, and tellurides
APPLICATIONS
OF
THIN FILMS

1. Introduction

2. Applications of Thin Films

3. Conclusion

P. 4

P. 5
2.3.1 THE BACK SURFACE MIRROR. Nearly all mirrors in general use (car, pocket, etc.) are back surface mirrors manufactured by chemical deposition of a silver film on one side of a more or less plane substrate plate and either painted or cemented to a second glass plate. Back surface mirrors are used almost exclusively for illumination purposes in optical instruments, because in image forming systems unwanted reflections at the front surface and the extra glass path impair the image quality. No such distracting double images occur if prisms are used. In case there is a departure from the angle of total reflection to some smaller angle or some other agency upsets the total reflection, a back surface mirror is provided on the prism surface. Silver is most frequently chosen for the mirror metal. It has the highest reflectance in the visible region of the spectrum.

Below 400 nm the reflectance of silver decreases considerably and aluminium must be used if the light is U.V. Aluminium films are commonly deposited on the surface of the quartz dispersion prisms in monochromators. In this way the same resolution is obtained with one half prism as is normally achieved with a whole prism (saving material) and the whole spectral region in which quartz is transmitting is still available. The reflectance in the visible, however, is reduced from about 96% for silver to 86–87%.

No measurements on back surface mirrors are shown. This is because the spectral characteristics of the reflection are similar to those of surface mirrors although large differences may occur due to absorption in the glass.

2.3.2 THE FRONT SURFACE MIRROR. Surface mirrors must be used if good image quality is required. The thickness of the substrate plate is then chosen to fulfill the conditions for avoiding distortion and other changes in the surface which are often figured to an accuracy of a fraction of a wavelength.

Fig. 58 shows results for the spectral reflectances of some important mirror metals. Silver has the highest reflectance in the visible and infra-red. Gold and copper have good reflectance only above 600 nm. The reflectance of chromium 60% is similar to that of iron, nickel, manganese and titanium. Platinum, palladium, and rhodium reflect some 70 to 80% of the visible light. In Fig. 59 the reflectance of the normal and parallel polarized components at
Fig. 58 Reflectance of front surface mirrors of unprotected metal layers (at nearly normal incidence).
(Ag = silver, Al = aluminium, Au = gold, Cu = copper, Cr = chromium, Rh = rhodium). (Carl Zeiss B-Lab.)

Fig. 59 Reflectance of front surface mirrors of unprotected metal layers, the light, incident at 45°, being either normal or parallel linearly polarized. The departure of the ratio $R^+ : R^-$ from 1 is a measure of the reduction of $(R^+ + R^-)$. (Carl Zeiss B-Lab.)
an angle of incidence of 45° on the metal films are plotted for the visible region.* These measured results show clearly how the ratio \( R^2 : R \) departs from 1 with decrease in the reflectance for the natural light. (For natural light: \( R = \frac{1}{2} \sqrt{R + R} \).)

2.3.2.1 The aluminized front surface mirror (unprotected). From Fig. 58 it is evident that aluminium has good reflection properties from the short wave U.V. region to the infra-red. This and good chemical stability have combined to make aluminium the most important mirror metal.

For many years now, telescope mirrors have been aluminium coated by evaporation in a high vacuum. The coating of large diameter mirrors is a very difficult problem (see Strong* where a description of coating the 5 metre Mt. Palomar mirror is given).

Although a perfectly produced aluminium mirror is corrosion resistant the film must be replaced from time to time because dust or other dirt cannot be removed from the surface without risking damage to the film. For this reason the larger observatories are equipped with high vacuum apparatus so that the mirror coatings may be replaced without risking the expensive mirrors on journeys.

A very thin oxide film is formed immediately the aluminium is exposed to the air and this is why aluminium films possess high corrosion resistance. The oxide film is chemically resistant and very hard but the thickness of 20 to 30 Å is not sufficient to protect the aluminium below against mechanical damage.
PART 2

THE IMPORTANCE AND APPLICATION
OF THIN FILMS IN OPTICS

2.1 Antireflection Coatings

2.1.1 The Importance of Antireflection Coatings. By far the greatest number of thin films manufactured in optics are antireflection coatings. An extensive list of names is available for classifying such films in German; in English, however, the only terms used are antireflection or "blooming" the latter because the reflected light from the popular antireflection coating is the colour of ripe plums.

The widespread use of the antireflection coating is quite simply a measure of the important role they play in all fields of applied optics. Eminent authorities have remarked that the discovery and practical realization of antireflection coatings is one of the few fundamental advances in practical optics during the first half of the 20th century. The impact of this progress is now explained.

Neglecting the absorption of the glass, the transmission of an optical system is given by:

\[ T = (1 - R_1)(1 - R_2)(1 - R_3)(1 - R_4) \ldots \] (54)

where \( R_1, R_2, R_3 \ldots \) are the reflectances at the optical surfaces. \( R_1, R_2, R_3 \ldots \) for uncoated optics are calculated simply from the refractive indices of the glass. For light normally incident, equation (9) gives:

\[ R = r^2 = \left( \frac{n_0 - n_1}{n_0 + n_1} \right)^2. \]

Assuming the boundary of the first lens to be glass-air of refractive indices \( n_0 = 1.0, n_1 = 1.5 \) then \( R_1 = 0.04 \). For a second lens of refractive index \( n_2 = 1.80 \) then at an air-glass surface \( R_2 = 0.082 \), i.e. 8.2%. The reflectance at oblique incidence is calculated in a similar way from equations (7) and (8). If antireflection coatings are on the surfaces \( R_1, R_2, \ldots \) may be either calculated or measured.

A measurement of the light intensity transmitted through a non-absorbing optical system yields higher values than those calculated from equation (54). This may be explained as follows: Light reflected, for example, at the fifth interface traverses surfaces 4, 3, 2, 1 on the way back and may be partially reflected towards the exit pupil again at each of them. Part of this reflected light is again reflected back to the front lens. Equation (54) is only an approximate solution from energy considerations. Because the reflected light has not the same direction as the light refracted by the lenses, it meets the image plane...
in points where no light is desired. It is easily appreciated that, in general, the reflected light appears as a veiling glare which causes a reduction in the image contrast, i.e., it illuminates regions of the image which should be dark. Values calculated from equation (54) give the light actually forming the image. Any additional light leaving the system may be regarded as glare which necessarily reduces the image quality.

Clearly the light which contributes to the image formation \((T\) in equation (54)) is increased if any decrease in \(R_1, R_2, R_3, \ldots\) can be arranged. An additional benefit is that the reflected glare is simultaneously decreased. Ideally if: \(R_1 = R_2 = R_3 = \ldots = 0\) then \(T = 1\) and the glare vanishes. The following table shows the influence on the transmission and glare consequent upon a reduction of the reflection at a surface from 5% to 1%:

<table>
<thead>
<tr>
<th>Number of surfaces</th>
<th>(R = 5%)</th>
<th>(R = 1%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(T) in % for</td>
<td>90.2</td>
<td>98.0</td>
</tr>
<tr>
<td>Veiling glare in % for</td>
<td>0.3</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Practically the consequences of antireflection coatings are seen in Fig. 37 where the increase in transmission is apparent and in Plate 1 (opposite p. 80) which shows the improved contrast possible.

Quite fortuitously, lens surfaces may behave as plane, convex, or concave mirrors in addition to their planned role as refractors. In an optical system composed of many lenses these “mirrors” and lenses may form an image of some part of the object or of a diaphragm located near or even in the actual
image plane of the system. Such reflected secondary images occur even in the simplest system comprising only two surfaces, e.g. the spectacle lens where they can be a great nuisance. By using antireflection coatings these secondary images may be reduced so that they are only seen under extreme conditions (plate 2).

Summarizing then:
Antireflection coatings lead to an improvement of the image quality produced by optical systems in three ways:

1. The light transmission is increased.
2. The veiling glare is reduced.
3. Ghost images are reduced.

Now discussion of an example will show the importance of the antireflection coatings in a particular instrument: the Zeiss-Vario-Sonnar F/2, f = 12.5 to 75 mm (Fig. 38). This system has 15 lenses with 24 glass-air surfaces and many of the glass-types of high refractive index. Without antireflection coatings this system has a transmission of only 20%, using equation (54) (assuming that the glass is non-absorbing); the veiling glare is 18%. By reducing the reflectance at each surface to 1%, the transmission is increased to 80% and the glare reduced to 2%. A measure of this is the ratio of useful light:glare which is 40 times greater for the coated than for the uncoated objective. For the same lens configuration therefore the exposure can be reduced by a factor of 4 (Schwarzchild—Exponent = 1). Thus the Vario-Sonnar objective, which would be quite useless if the optics were uncoated, proves to be very good with antireflection coatings.

It might also be observed here that the discovery and practical realization of antireflection coatings has given the optical designer more freedom in choosing a greater number of glass-air surfaces, previously limited. This permits the aberration of an optical system to be further reduced. There are now no obstacles to the use of highly refracting glasses in improving the system correction; even with these glasses reduction of reflection is achieved simply and efficiently so that the glare is almost negligible. Optical instruments with 50 or more glass-air surfaces are no longer exceptional although without antireflection coatings such solutions would from energy considerations appear to
2.4.4.8 The importance of narrow band pass interference filters in spectrophotometry. Mention of this application leads naturally to a study of the vast field of spectrophotometry and especially of the filter photometer. This is obviously too big a subject to be explored deeply here. It is useful, however, to indicate the precautions required before a filter is deemed suitable for the photometer. The light source (e.g. continuous spectrum or line spectrum) is one factor, the test object (whether the properties vary rapidly or slowly with wavelength) a second, the spectral sensitivity of the receptor a third, the required accuracy of the measurement a fourth, and this last either alone or in conjunction with the others determines whether a filter of given properties can be used. For example, to separate two spectral lines with intensities in the ratio 1:100 using narrow band pass filters a filter transmitting 0.1% in the region of the
low energy line and 30% in that of the high energy line is suitable. If on the other hand the low energy line should be used for the measurement a filter transmitting 30% for the low energy line and 0.1% for the high energy line is not in general suitable because the ratio of the energy transmitted is 3:1. This filter can be used only if the sensitivity of the receptor is low for the high energy line. This example demonstrates the great importance of low transmission outside the band-pass. If light sources with a continuous spectral distribution are used the test piece alone determines whether a filter of given properties can be used successfully. For example, if the transmission characteristic of a neutral density filter must be measured the bandwidth of the filter used is of little consequence. If, however, the transmission curve of a neodymium glass sample is required the fine structure of the curve can only be resolved by using filters of sufficiently narrow bandwidth.

In comparison with monochromators, filters are easier to manipulate and also cheaper when measurements are only required at a few wavelengths. However these are not the main reasons for using filters in photometry. The main advantage is that even when the bandwidth of the filter and the monochromator are equal* (and the same light source is used) the intensity achieved with the filter is very much higher.

In the simplest terms this difference is explained by the ratio of the filter surface area to the area of the monochromator slits; the value of this ratio is many powers of ten. That means exactly that the product: surface area of the filter \times \text{the solid angle subtended by the incident radiation} is many powers of ten greater and also the intensity which is proportional to this product. A less sensitive and therefore simpler and more reliable detector may be used for the measurements in a filter photometer.

The development of interference filters is therefore an important supplement or, more properly perhaps, an extension of the earlier spectrophotometry.

2.1.4 ANTIREFLECTION COATINGS FOR INSTRUMENTS USING EXTREMELY WIDE SPECTRAL RANGES. Antireflection coatings have rarely been applied in instruments used over a wide spectral region, e.g. monochromators from the short U.V. to the infra-red. A single layer coating might be considered in this case. At all wavelengths for which the optical thickness of the layer is a multiple of the half wavelength the transmission of the instrument would not change provided that the film is non-absorbing in the required spectral region; the transmission would, however, increase to a greater or less extent for all other wavelengths.

Sufficiently thick non-absorbing inhomogeneous films would be ideal for this task. The main difficulties in making these films have been mentioned in Part I (p. 76).
2.5 Further Applications of Thin Films in Optics

2.5.1 The Protection of Glass Surfaces Against Mechanical or Chemical Damage. It has been pointed out already that surface mirrors must be protected from mechanical damage or chemical attack. Similar techniques may be used for sensitive glasses and occasionally for transmitting plastics. Sometimes it is possible to achieve an optical modification and the protection at one stroke (antireflection coating, filter properties, etc.).

In cameras, the film is guided over a plane surface of soft glass; fine scratches appear on the glass until, after a long period of use, the glass becomes "muddy". (The reasons for using these soft glasses sometimes need not concern us here.) This scratching is prevented by the deposition of either a protecting quartz film, SiO, or else a hard, strongly adherent metal oxide. Similar treatment should prevent the fine scratches which occur during simple cleaning procedures for most optical materials.

It should be noted that resistance to scratching, gouging or point-pressure in a bulk sense cannot be improved by hard thin films. The macroscopic hardness of the protected optical element cannot be altered to any great extent by films with thicknesses in the range 0.1 to 1 μ. Only the surface hardness can be improved. This is explained in the following example. An aluminium mirror, protected by a SiO coating, may be cleaned easily and safely by cloth and solvent without leaving any marks. If an unloaded needle tracks across a protected mirror no damage occurs. Should the needle penetrate a hole in the surface, however, scratching inevitably follows. The point of the needle reaches the glass substrate immediately and the protecting film has little resistance to the consequent shear forces developed by the needle. Soft glass is scratched in this way by rubbing with a grain of emery or a chip of hard glass caught up in a duster.

* The transmission bands are quite different in shape—the band pass of the monochromator is triangular provided that the exit and entrance slits are equal. Therefore more precisely: areas under the transmission curves must be equal.

The durability of glasses sensitive to corrosion by acid or weathering may be improved by using appropriate thin films. Only in particular cases, however, is it possible to guarantee protection. Gases and vapours can diffuse through protective films to some extent; this is due to the moderate thickness required and the porous structure. Chemical attack usually originates at the pores and is only stopped if the substrate tends to form a protective layer of limited thickness. The oxide overlay formed on an aluminium surface is an example. Under normal conditions the oxide layers grow to a thickness of 20 to 30 Å and only a film of this thickness can grow around the pores. Similar conditions are met with sensitive glasses. Attack stops as soon as the layer of glass formed by chemical interaction protects the glass below.

Unfortunately these conditions do not prevail for many glasses of high refractive index or for special glasses with extreme values of r and n. These glasses are frequently required for the correction of high quality optical systems. By applying these well-known procedures then it is usually possible to protect glass by thin films and so extend the normal lifetime in use.
2.5.2 THE PRODUCTION OF SCALES, RULINGS, DIAPHRAGMS ETC. So marked an improvement has been achieved in this field of practical optics that this application of thin films cannot be overlooked. Glass rulings are no longer made as a rule by diamond scratching or etching. Instead a lacquer film is deposited on to the glass substrate; the patterns, numbers, etc., which are required are engraved in the lacquer. Then the substrates are coated with a hard, adhesive metal film (e.g. chromium) in a vacuum. The lacquer and the evaporated film are then dissolved away except where the film was evaporated on to unprotected glass. Thus only the engraved patterns and numbers remain on the glass surface. In this way high accuracy graduations are obtained with sharper edges than with the etching or colouring methods. By using one of the well-known photo-chemical processes good copies can be produced in a similar manner. Anti-reflection methods for the metal films have been treated on p. 78 in detail.

2.5.3 ELECTRICALLY CONDUCTING FILMS. Most glass types and transmitting plastics are good insulators: it follows that a charge is developed if they are placed in electric fields or in contact with other insulators (contact or frictional electricity). The charge on the observation port of an electron microscope causes deviation of the rays and therefore a decrease of image quality. The charge due to contact electricity may cause a spark leading to glare or film damage. Furthermore electrically charged surfaces tend to attract and retain dust particles, etc.

Conducting layers may be deposited on the surfaces of glasses and plastics to permit a flow of charge and so prevent these disturbances. The simplest method is to evaporate a very thin transmitting metal layer (e.g. chromium). However, the attenuation of the light caused by the high reflection and absorption is usually undesirable. For many years, therefore, non-absorbing layers of the electrically conducting oxides of indium, cadmium, and tin have been used. By incorporation of disordered centres Schröder\(^6\) produced oxide layers with conducting properties. This is very important for it is then possible to obtain the electrical conductivity combined with prescribed optical properties (especially the antireflection properties).

2.5.4 THIN FILMS AS PHOTOCONDUCTIVE ELEMENTS. Finally, it is merely mentioned that thin films are used in the manufacture of bolometers, photocells, photo-elements, thermal-elements and also for the cathodes in electron multipliers. Besides metals and semi-conductors, non-conductors are used as coatings to reduce the reflectance at light sensitive layers and so to increase the efficiency. It is difficult to estimate the practical importance of thin films in this application nowadays because the production methods change so rapidly.
3.3 Conclusions

The actual level of attainment in the theoretical, physical, chemical, and technical aspects of the study of thin films has been discussed. A few thoughts on likely future developments should stimulate the reader.

Many new theoretical solutions to optical problems may be expected. Already unsymmetrical multi-layer systems have been designed using electronic computers. Numerous solutions have been optimized using the computer but no surprises have yet occurred and will probably not occur in the future either.

It seems likely that many improvements will be made in the physical and chemical aspects. A research of previously rejected materials must be carried through to see whether the better cleanliness and preparation methods and the vastly improved evaporation conditions might make films of such materials possible. The use of mixtures, organic compounds, and production by means of colloidal solution should be added to the already lengthy research programme.

Further improvement in the properties of films of well-known materials is probable. Pure scientists have frequently conjectured about the validity of the assumption that the interface between films is plane. The crystalline structure of some materials and the surface roughness would have to be included in the calculations described in Part I. In general this question is irrelevant. Nevertheless, considerable discrepancies between theory and practice are found for some systems, e.g. interference filters of non-absorbing alternate layers and by frustrated total reflection. It is possible to account for these discrepancies by surface roughness and other faults in the film structure. Such retrospective matching of prediction and behaviour is fairly simple but not very useful. Of more practical significance would be a systematic investigation to improve the film quality so that the theoretical values are nearly obtained. There are many indications that progress could be made in this direction.

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By using ultra-high vacuum apparatus, producing a vacuum better than 10⁻⁹ Torr, improvement in the quality of known films is obtainable. Bakeable equipment using metal seals and special pumps would be required to obtain such low pressures. Such equipment would only be sensible when substrate material, and evaporator can be out-gassed. Such plant would be very expensive with very long operating cycles (2 charges in 24 hours maximum) and could only be justified for special cases and research purposes. The general adoption of such apparatus for mass production of optical components is improbable.

High vacuum techniques were started and developed by scientists. Subsequent development and supervision has been the scientist's responsibility. It is to their credit that this process may be used reliably for mass production. Even if it is possible, it may take many years to develop the process to a point where scientifically trained personnel are no longer required for supervision. With the great urge to automation, business men and engineers will be anxious to introduce fully automatic thermal evaporation vacuum equipment. The automatic solution of complicated optical problems, however, is likely to remain a dream for many decades.
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