ANTI-REFLECTION FILMS ON GLASS*

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THE amount of light lost from a light beam by reflection when it strikes a glass surface increases with the refractive index of the glass. For ordinary window glass, the loss is 4% per surface; for the heaviest flint glasses, it may amount to 10%. For a plate of glass with its two surfaces, these figures must be doubled, but even then they do not seem large. However, the loss of light increases rapidly when we have several surfaces in series. For optical lens and prism systems, if we assume an average loss of 5% per surface, the presence of six surfaces will result in a 25% loss of light by reflection, cutting the transmission of the system to 75%.

Fig. 1 shows the reduction in transmission caused by reflection losses in optical systems with varying numbers of air-to-glass surfaces.

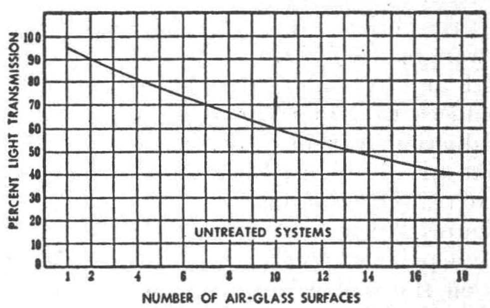

FIG. 1. Reduction in transmission of optical systems due to a 5% loss of light by reflection at each air-to-glass surface of lenses or prisms.

The method used to reduce the reflection losses from a glass surface is rather simple in principle. It consists of putting on a new surface.

When light strikes a plate of glass it is slowed up and a portion of the energy fails to penetrate the surface. The surface of the glass acts like a "bump," and in passing over it some of the energy of the light beam is jarred loose and goes to form a reflected beam. The greater the "bump," that is, the higher the index of the glass, the greater is the amount of the light jarred off the original beam. Now it seems plausible to try smoothing out this refractive index bump by letting the light penetration take place in steps. Over the surface of the glass plate we put a layer of material of lower index. Then the initial loss at the new surface will be lower than if the light struck the bare surface of the original plate directly, because the index of the new surface is smaller. Of course, we have added a new reflecting surface—the inner-face between the surface layer and the plate—but it turns out that the combined light losses at the two surfaces is less than the light loss by one reflection at the bare surface of the plate. One may easily check this assertion by use of the well-known formulae for computing the fractional amount of light lost by reflection at the two surfaces in question:

$$R_{AF} = \left(\frac{n_F - 1}{n_F + 1}\right)^2 \quad \text{and} \quad R_{FG} = \left(\frac{n_G - n_F}{n_G + n_F}\right)^2$$

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where R_{AF} and R_{FG} are the reflectances at the air-to-film and the film-to-glass surfaces resp., and 1 n_F, n_G are the indices of refraction of air, of the film, and of the glass. We can, in fact, cut down the reflection losses by 50% with the proper choice of the index of refraction of the surface layer.

Fig. 2 illustrates the reduction in reflection losses which can be effected with surface layers. Thick and thin layers of different substances are shown in contact with plates of two different kinds of glass, indices 1.52 and 1.66. The surface layers are of fluorite (CaF_2) and lithium fluoride (LiF) and water (H_2O). The numbers on the arrows of each combination give the total percentage of light reflected, that is, the sum of the energy in the beam from the front surface

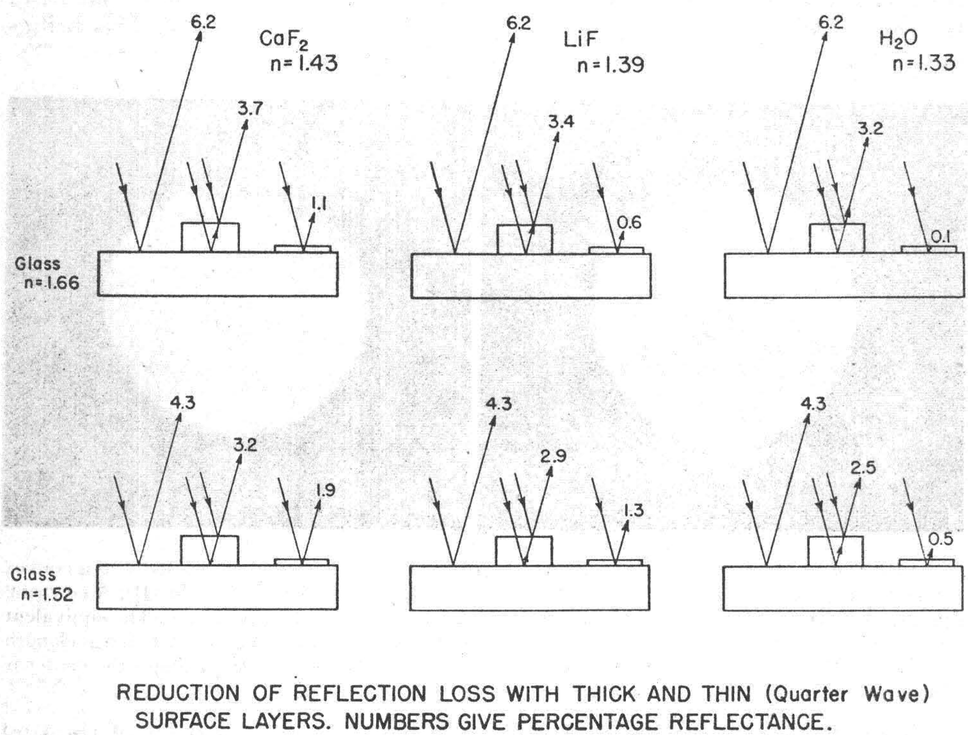

FIG. 2. Reduction of reflection loss with thick and thin (quarter wave) surface layers. Numbers give percentage reflectance.

plus that from the inner face. The water layers show the smallest amount of reflected light. It can be proved that minimum reflectance is obtained with either thick or thin layers if the index of refraction of the layer material is equal to the square root of the index of the glass to which it is applied. Of the three surface layer indices shown, that of water (1.33) most nearly satisfies this condition when it is on the 1.66 glass. The reflectance of this combination when the water film is thick is about half the reflectance of the bare glass. One transmission film material widely used, sodium aluminum fluoride, has an index very near that of water. Since the effectiveness of the film material depends only on the index of the film and that of the glass, it can be employed to lower the reflectance of the glass by practically the same amount as the water in our example.

On ordinary glass (index 1.52) a thick layer of water reduces the reflection loss from 4.3% to 2.5%. We have, no doubt, all enjoyed the benefit of the resulting 2% gain in transmission, although perhaps unknowingly. When driving in the rain, namely, with the windshield wiper spreading a layer of water over the windshield, the latter actually becomes more "transparent" and lets 2% more light through. Although it is true that the slight increase in brightness of the road will hardly be apparent to the driver, the effect of water in reducing the reflectance is often apparent on the windshield of an oncoming car, especially if there are dry portions. Compared with these dry parts, the wet patches appear dark because less light is reflected from them.

Noteworth in Fig. 2 is the much greater effectiveness of the thin films. With them the reflected light can be reduced to an almost negligible loss, that is, in the transmission of a plate of glass can be raised to nearly 100%. This brings up the question of how thick the thin films should be.

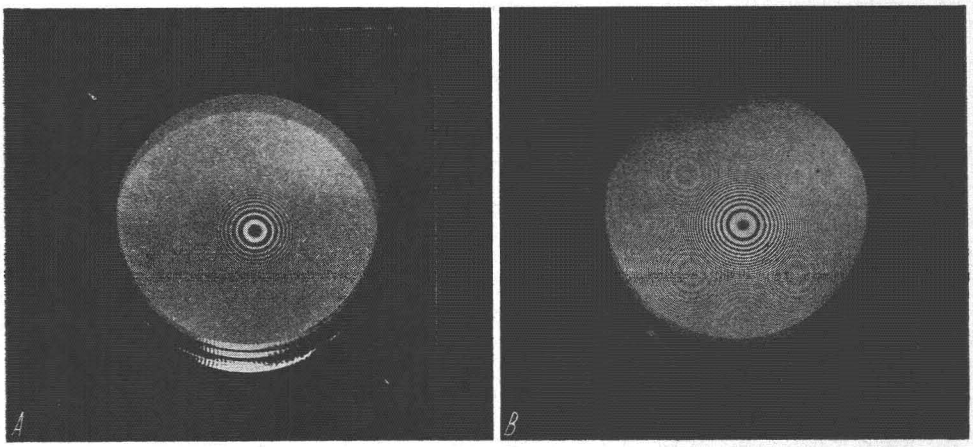

FIG. 3. Interference or "Newton's Rings" formed in the air film between a flat and a convex glass surface photographed in reflected white light (A), and monochromatic light (B). A new ring appears for every increase of the double air film thickness by a whole wavelength. The equivalent air film thickness at the center where the surfaces are in contact is not zero, but is a half wavelength due to the phase shift suffered by the light beam at the lower surface. Accordingly the center is black.

Reference was made above to the fact that the optimum *index* of the surface layer is the square root of the index of the glass. There is also an optimum *thickness* for the layer, or rather, film, since this thickness comes out to be only 4 millionths of an inch. Let us start with a thick reflection-reducing surface layer on glass. It may be a millimeter thick or a hundredth of a millimeter, it makes no great difference. We would find that the light reflected from it is not changed in color. The reflected light would simply not be as brilliant from the portion of the glass with the surface layer as from the bare glass. But if we continuously decrease the thickness, we find that around a thousandth of a millimeter the reflected light would become tinged with color. The colors change as the thickness is reduced and become at the same time more saturated. We are entering the region of thickness dimensions comparable with the dimensions of the light waves themselves and the wave nature of light puts in an appearance. The colors are due to the interference of the light reflected from the front surface of the film with the light reflected from the film-to-glass inner face. The interference phenomena do not start suddenly at some particular thickness, they merely become observable to the unaided eye in the very thin films.

Interference takes place in the thick films also, but here it cannot be observed under ordinary conditions.

Interference effects are not uncommon in our everyday life. The colors in soap bubbles, the colors of oil spots on the wet pavement, and the colors appearing in laminated safety glass which has split open are all due to light interference between two beams from the opposite sides of the thin film.

An easy way to obtain an air film is to press a convex glass surface against a flat glass surface—such as a lens against a flat plate. The resulting interference fringes are circular because of the circulary symmetry of the air wedge, and they are known by the name of "Newton's Rings." These rings can sometimes be seen between the components of an uncemented doublet lens, such as a telescope objective, where the elements have come into contact. Fig. 3 shows a picture of Newton's Rings between two glass plates taken (a) with white light, and (b) with monochromatic light. With the former the interference is visible only where the film is thinnest toward the center of the ring system, whereas in light of one wavelength the interference is visible out to the very edge of the plates where the film is thickest (about 0.02 mm in this case). These pictures were taken in reflected light, but the rings can also be seen in transmitted light.

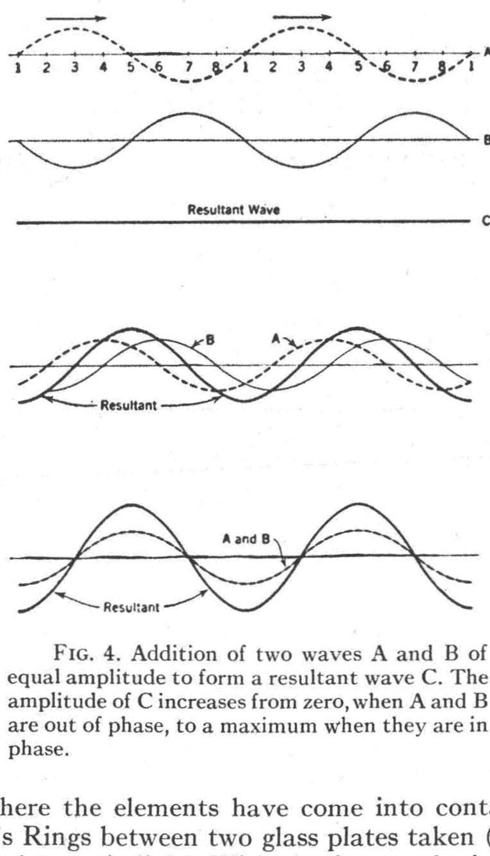

FIG. 4. Addition of two waves A and B of equal amplitude to form a resultant wave C. The amplitude of C increases from zero, when A and B are out of phase, to a maximum when they are in phase.

The most prominent characteristic of the rings when viewed by white light is their color, but this color display tends to direct attention away from the fundamental thing that is occurring, namely, the variation in reflecting power of the air film with its thickness. If we look at a set of Newton's Rings in monochromatic light (Fig. 3b) as by using a red filter, we simply see alternate light and dark rings. In other words, the air film reflects light at certain thicknesses and at others it does not. By the same token we find in looking through the rings that they represent regions of high and low transparency. The enhanced transparency of the alternate rings is obtained at the expense of a decreased reflectivity of the air film at these points. At positions of maximum transparency, the reflectivity of the air film, that is, of the combination of the two glass surfaces, is zero.

The explanation of the formation of the rings by interference is simple and is no doubt familiar to us all. It is vital to an understanding of the action of our anti-reflection films. Under proper conditions interference can take place between two beams of light because of their wave nature. Two waves of equal wave length with a definite phase relation between them can add up to zero on the one hand or to an augmented wave on the other, with a continuous variation between, depending on the phase relation, that is, on how much one wave is displaced with respect to the other. This addition of two waves is shown in Fig. 4.

In the reflected light from our air film, the two beams which interfere are those reflected from the two surfaces of the air film as is shown in Fig. 5.

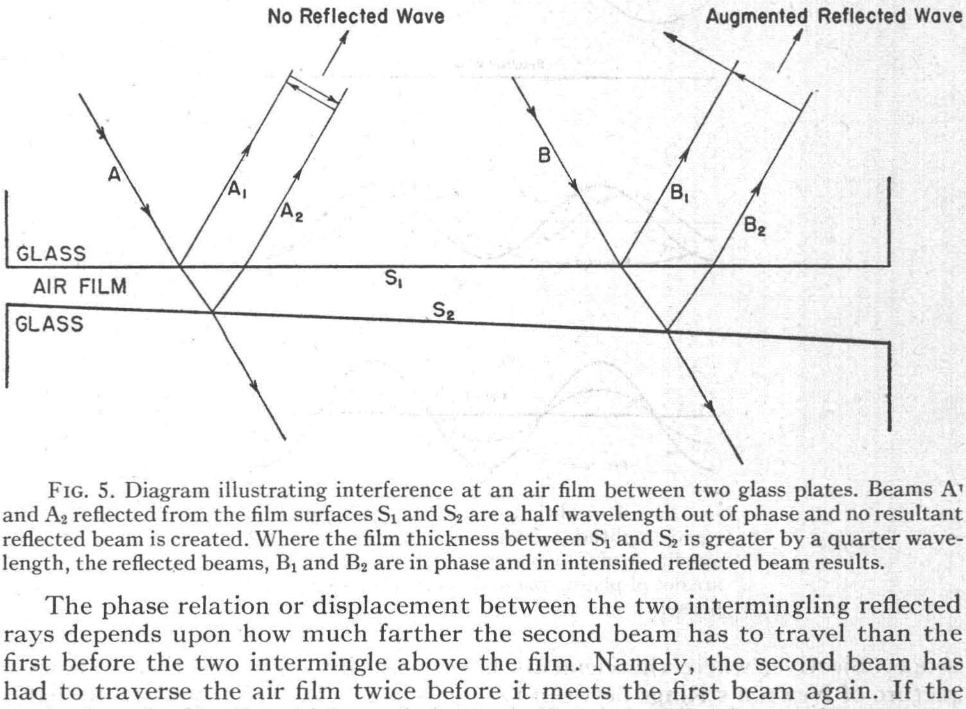

FIG. 5. Diagram illustrating interference at an air film between two glass plates. Beams A_1 and A_2 reflected from the film surfaces S_1 and S_2 are a half wavelength out of phase and no resultant reflected beam is created. Where the film thickness between S_1 and S_2 is greater by a quarter wavelength, the reflected beams, B_1 and B_2 are in phase and in intensified reflected beam results.

The phase relation or displacement between the two intermingling reflected rays depends upon how much farther the second beam has to travel than the first before the two intermingle above the film. Namely, the second beam has had to traverse the air film twice before it meets the first beam again. If the equivalent double film thickness is just a half wavelength, the two beams meet a half wave out of phase, and cancel if the two amplitudes are equal (Fig. 4) as they are if the two pieces of glass have the same index of refraction. On the other hand, if the path difference is a whole wavelength, the two beams meet in phase and an augmented reflected wave results. Since the energy of the reflected beam is tapped from the incident beam, the air film will show a decreased transparency in this second case, whereas when the reflected beam is quenched, the transmission becomes 100%.

If one of the dark interference bands in the air film were widened out to cover the whole surface of the glass, by making the air film of uniform and correct thickness, instead of being a wedge, then we would have an anti-reflection film, but it would hardly have any practical value. We have to make our films of something more tangible than thin air. Now actually the most important parts of the film are its two surfaces. Their presence gives us the two reflected beams to interfere, and it does not make a great deal of difference, optically, whether the solid material is outside the film as with the air film; or inside the film as with an anti-reflection film. One might say that the film merely serves to hold the surfaces apart at the correct distance.

There are several interesting ways of providing a piece of glass with a solid film which will have anti-reflection properties, but which cannot be described here for lack of space.

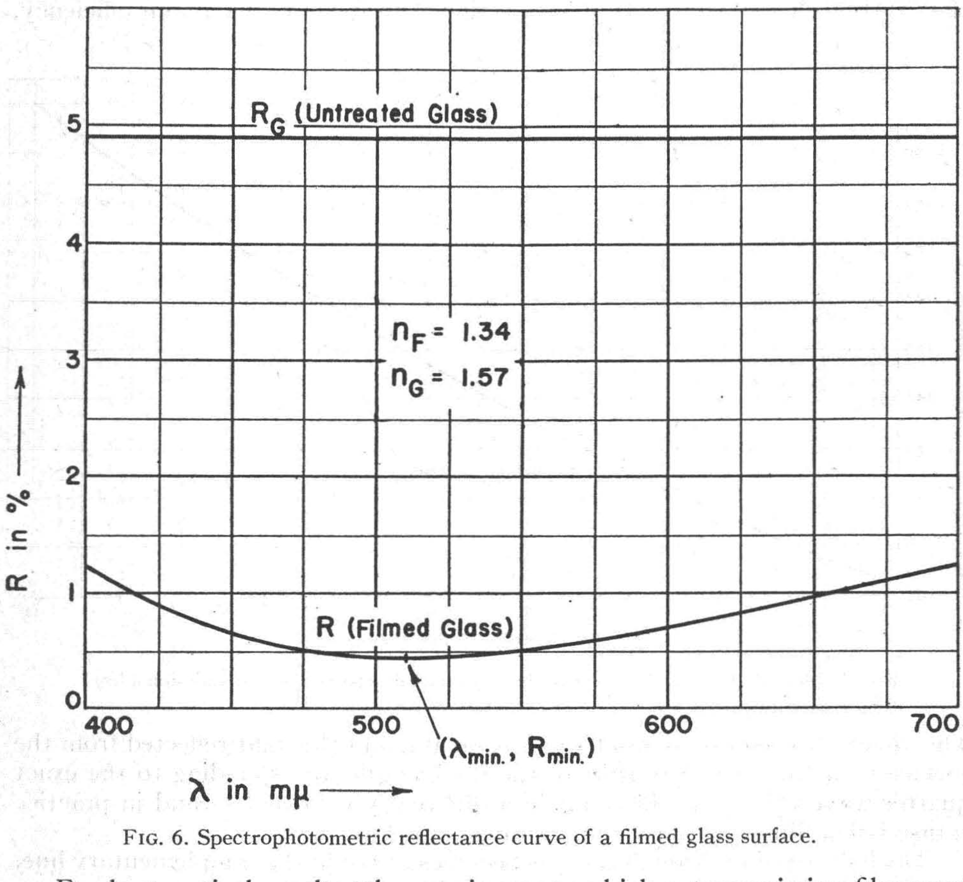

FIG. 6. Spectrophotometric reflectance curve of a filmed glass surface.

For best optical results, the requirements which a transmission film must meet are:

(a) the optical thickness of the film should be a quarter wavelength.

(b) the index of refraction of the film should be equal to the square root of the index of refraction of the glass to which it is applied.

Requirement (a) can always be met, and the thickness of the film is easily controlled. Requirement (b) is difficult to realize exactly, simply because Nature did not make many materials with sufficiently low indices for our purpose. However, in practice considerable deviation of the film index from its optimum value is allowable without affecting the efficiency of the films too seriously. Thus even LiF and CaF_2 with indices 1.39 and 1.43 make fairly good anti-reflection films on glass of index 1.66, although the optimum film index here is 1.29, the square root of 1.66.

When the light reflected from a filmed surface is measured in a spectrophotometer, we obtain a curve like that of Fig. 6. The film reflectance curve is not a straight line, since the film is a quarter wavelength thick only for one particular wavelength. At this point, the reflectance is a minimum (the transmission accordingly being a maximum) and it rises slowly toward longer and shorter wavelengths. The reflectance does not go to zero in this example because the index requirement (b) is not satisfied. For a glass of index 1.57 a film index of 1.25 would be necessary for zero reflectance at λ min.

A coated lens appears colored in reflected light, and Fig. 6 shows why. The film reflects, in this example, somewhat more in the violet and the red than in the blue-green, where it was designed to have its maximum efficiency.

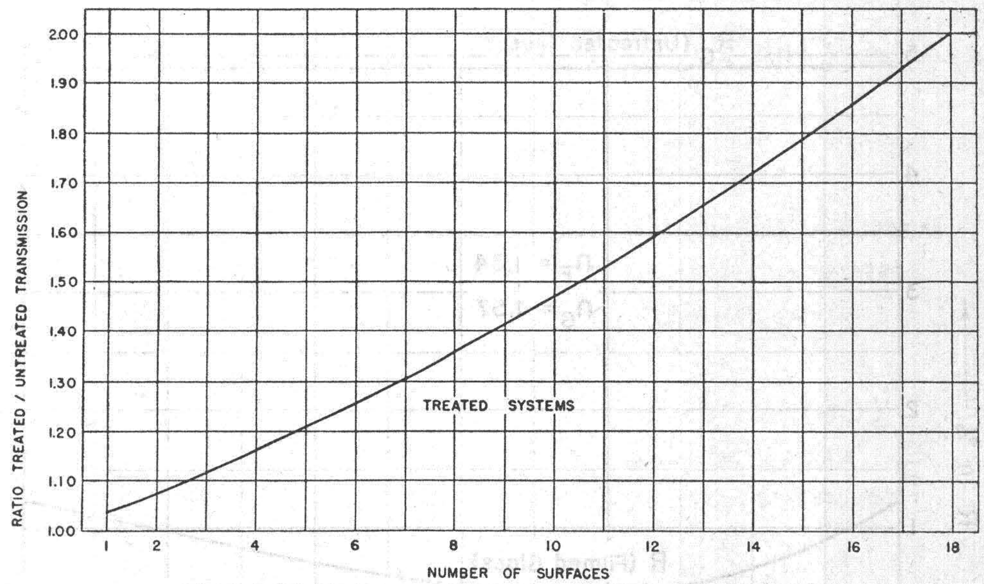

FIG. 7. Increased transmission of optical systems due to use of transmission films.

The violet plus red excess results in a magenta, and the light reflected from the surface is of this hue. Any shift of the wavelength corresponding to the exact quarter wave thickness will result in a differently colored film and in practice transmission films may have quite a range of colors.

The light passing through the lens becomes tinted in the complementary hue, but the effect is so weak as to be scarcely discernible unless many surfaces are used.

To sum up our general statements about reflection-reducing and transmission-increasing layers, we may say: by controlling the index but not the thickness, that is, by using a thick layer, we can cut the reflection loss in half. By controlling both the index and the thickness of the film, the reflection loss can be entirely eliminated, at least for monochromatic light, and practically eliminated for as large a wavelength range as is included in the visual spectrum.

In the practical application of the films to lens systems it is found that benefit is derived not only from the increased amount of light obtained (shown in Fig. 7) but also from the simultaneous decrease in reflected light. In an optical system this latter may be termed "misdirected" light and sometimes it is distinctly annoying because it may give rise to "ghost" images or create a veil of haze light which cuts down the image contrast. When anti-reflection films are used here, a "snappier," more "contrasty" image results.

We have been mentioning films a quarter wavelength in thickness. Just how thick such a film is in relation to the glass on which it is deposited can be visualized by the following example: If the glass carrying the film is two millimeters thick, and we magnify it to appear as thick as Mt. Washington is high, then the quarter wave film magnified in the same proportion would be like a 4-inch fall of snow on the mountain top.