REFLECTIVITY OF THIN FILMS

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INTRODUCTION

The reflectivity of a smooth glass surface, when treated with a thin monolayer film, may be lessened, or, when treated with a multilayer film, may be increased for a given wave-length of light. The effect produced depends on the thickness and index of refraction of the film.

There are three methods of preparing a film of appropriate thickness on a glass surface. First, by treating the surface chemically. This method was first developed in the experiments of H. D. Taylor (5) in 1892 and the recent experiments of F. L. Jones and H. J. Homer (4). A thin film is formed by treating the glass with a weak acid which will dissolve the oxides from a thin layer but not affect the silica.

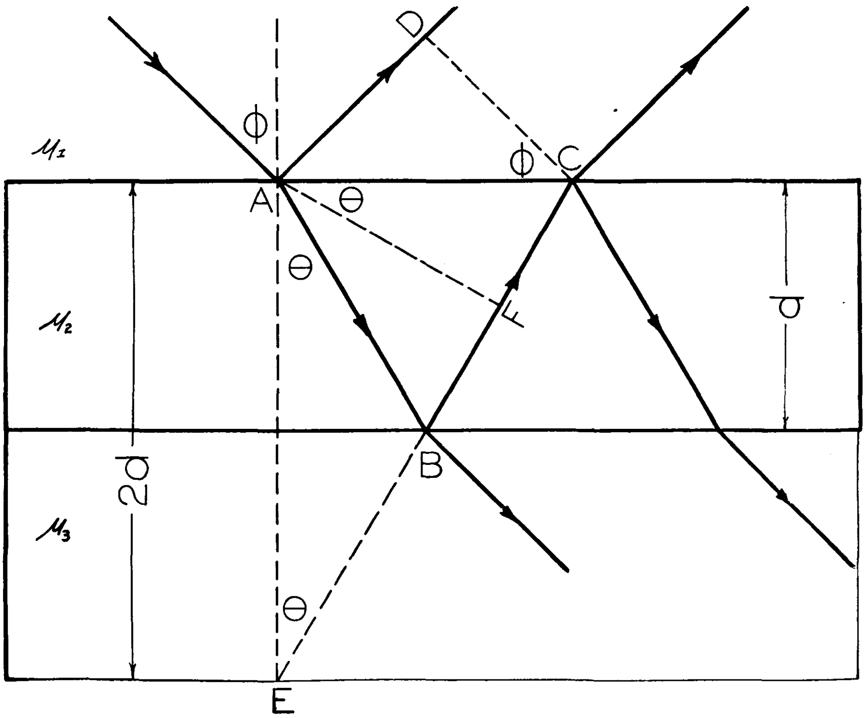

Fig. 1. A beam of light incident upon a film is partially reflected at A and partially refracted.

Secondly, by building up a film composed of successive applications of mono-molecular layers of certain metallic soaps, a process originated by K. B. Blodgett (1). The third method, developed by Cartwright and Turner (2), is that of evaporating suitable metallic compounds in a high vacuum and allowing the condensate to deposit on the glass surface.

The efficiency of spectrometers, telescopes, interferometers, and other optical instruments is increased by treating the glass surfaces with thin films. The purpose of this investigation is to develop an apparatus and procedure of applying such thin films to glass surfaces. The method of evaporating metallic compounds in a high vacuum is chosen as the most practical for a small optical laboratory.

THEORY

The effects mentioned above depend upon the interference of light. A beam of light incident upon a film (Fig. 1) is partially reflected at A and partially refracted. The refracted ray is reflected at the surface between the film and the glass at B and emerges from the film at C. If the path difference of the two rays is any whole number of wave-lengths, they will reinforce each other or if the path difference is an odd number of half wave-lengths, they will interfere destructively. A general expression for the retardation of the ray emerging at C is $2\mu d \cos\theta + \delta_1 + \delta_2$, where μ is the index of refraction of the film, d is its thickness, θ is the angle of refraction, and the change in phase which might occur at the two surfaces due to the different indicies of refraction is represented by δ_1 and δ_2.

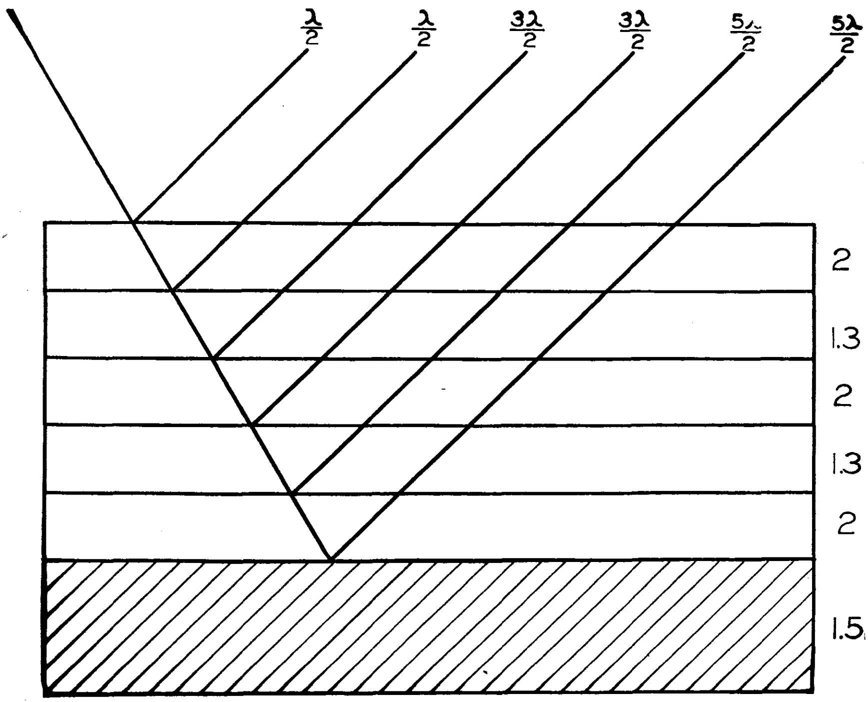

Fig. 2. A beam of light at normal incidence on the top surface.

In order to prepare a surface which will produce selective reflection for a given wave-length, multilayer films are deposited, composed of alternate layers of high and low index of refraction. Referring to Fig. 2, consider a beam of light at normal incidence to the top surface. Upon entering a medium more dense than air a change in phase of 180° occurs which can be represented as a path increase of ½ wave-length. The beam which is reflected from the second surface traverses the film twice but suffers no change in phase at this surface. If the films are ¼ of a given wave-length in thickness, then the path increase is ½ wave-length. The ray reflected at the third boundary traverses four thicknesses of the film and in addition suffers a change in phase making a path increase of 3/2 wave-lengths. If this is followed through for all the successive boundaries the emerging rays are in phase. The path difference is an integral number of whole wave-lengths, thus producing reinforcement for the given wave-length.

Two requirements must be met in order to produce a filmed surface of zero or nearly zero reflecting power. The monolayer film must be of such a thickness that the path difference of the rays reflected from the air-film surface and the film-glass surface is an odd number of half wave-lengths and secondly the amplitudes of the rays reflected at the two surfaces must be equal.

The first condition is satisfied by depositing a film of ¼ wave-length optical thickness. The second requirement is satisfied, by choosing a film of proper index of refraction according to the following theory.

Fig. 3 shows the reflections which take place at the two surfaces. Let r_1 and r_2 equal the percent of the incident amplitude reflected at the air-film surface and the film-glass surface respectively. The per cent of the amplitude transmitted upon entering and leaving the film is represented by t and t' respectively. If the amplitude of the incident ray is a, then the amplitude of the light reflected from the air-film surface is ar_1. The amplitude of the light reflected from the film-glass surface is

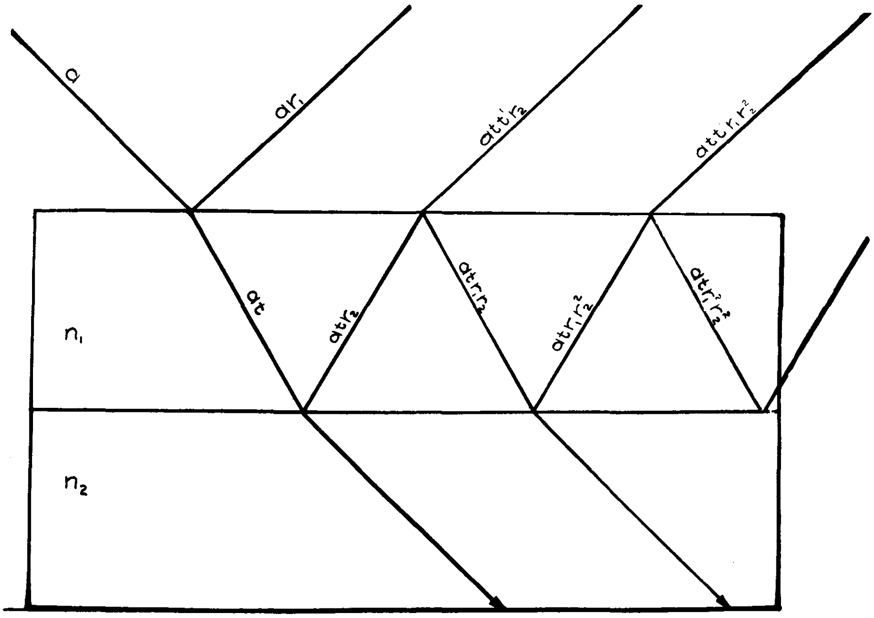

Fig. 3. Reflections which take place at the two surfaces.

the sum of all the rays due to the multiple reflections. The sum, R, of all these rays reflected at the film-glass surface is:

$$R = att'r_2 + att'r_1r_2^2 + att'r_1^2r_2^3 + att'r_1^3r_2^4 + \ldots\ldots$$
$$= att'r_2 (1 + r_1r_2 + r_1^2r_2^2 + r_1^3r_2^3 + \ldots\ldots)$$

The sum of the geometric series is $1/(1\text{-}r_1r_2)$. It can be shown (3) that $tt' = (1\text{-}r_1^2)$. Substituting these values:

$$R = a(1-r_1^2)r_2/(1-r_1r_2).$$

In order that the amplitudes be equal, R must equal ar_1. Putting $r_1 = r_2$ in the above expression, it follows that $R = ar_1$, and the second condition is fulfilled. Now $r_1 = (n_1-1)/(n_1+1)$ and $r_2 = (n_2-n_1)/(n_2-n_1)$ for normal incidence (6), where n_1 and n_2 are the indicies of refraction of the film and glass respectively. Equating these epxressions and solving for n_1:

$$(n_1-1) / (n+1) = (n_2-n_1) / (n_2=n_1)$$
$$n_1 = \sqrt{n_2}$$

Thus the index of refraction of the film must equal the square root of the index of the glass if the amplitudes are to be exactly equal.

This demand upon the index of refraction of the film is rather severe since the lower limit of indicies of materials is about that of water, namely, 1.33. Metallic flourides are among the substances of lowest index and also are evaporated readily. The index of the film can be lowered to the desired value by allowing the evaporation to take place in a poor vacuum but this is done at the expense of the mechanical strength of the film.

APPARATUS

The vacuum system consists of a circular steel plate and a bell jar ground to fit the contour of the plate which is ¾ inches thick and 18 inches in diameter. The jar is evacuated through a one inch opening in the plate by a single stage oil diffusion pump backed by a Cenco Megavac vacuum pump. The metallic compounds are vaporized in small electric furnaces, which are wound in the form of a helix of 20 mil. tungsten wire sealed with alundum cement, and baked out thoroughly before use. The current for the furnaces is supplied by a 10-volt 500 watt transformer. The current is led to the furnaces through the steel plate by two insulated electrodes and one grounded electrode. The glass specimen to be coated is held horizontally from an upright post threaded into the base plate.

PROCEDURE

Glass plates giving almost monochromatic reflection are prepared as follows: First a film having a high index of refraction is deposited on the glass surface to a thickness of ¼ wave-length of the color desired. The thickness of the film is controlled by observing the surface, continuing the evaporation until the surface first assumes the color desired when viewed by white light. Then a film of low index having the same thickness is deposited until the selected color reappears. Layers of alternate high and low index of refraction are deposited in this manner until the color is brilliantly reflected. Films of zinc sulfide ($n = 2.00$) and cryolite ($n = 1.36$) have very good physical qualities and are evaporated easily. Two furnaces, one containing the zinc sulfide and the other cryolite, are arranged so they can be heated alternately without destroying the vacuum for each new application of film.

For a low reflecting surface a monolayer film of magnesium fluoride, index of refraction 1.34, is deposited on the glass surface to a thickness of ¼ wave-length of the light for which minimum reflection is desired. Again the thickness is controlled by viewing the color of the reflected light. When the film is of proper thickness to produce interference in the blue, the surface takes on a brownish hue. As the thickness increases the spectral region of minimum reflectance travels toward the longer wave lengths. When the minimum is in the green the surface appears magenta and when it arrives in the red the color becomes blue.

For normal incidence the reflectance of a glass surface for monochromatic light can be reduced to a minimum of .4% by depositing the above mentioned film of magnesium fluoride. The reflectance of the untreated glass of index refraction 1.55 is about 4.4%. This is a reduction in reflection of 91%. In order to reduce the reflectance to zero the index of refraction must be reduced 25%. Since so little is gained by this reduction and the mechanical strength of the film is lessened, it is not advantageous to reduce the index of the magnesium fluoride.

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