THE UNIVERSITY OF ROCHESTER

THE INSTITUTE OF OPTICS

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PROPERTIES OF MULTILAYER FILTERS

Final Report

Covering the Period

March 1, 1964 to February 28, 1967

Research Grant No. NsG 308-63

with

National Aeronautics and

Space Administration

Washington 25, D.C.

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ABSTRACT

The construction of optical interference bandpass filters for the ultraviolet spectral region, from 1200Å to 3000Å, is discussed. A survey is made of the metals and dielectric materials which are suitable for use in such filters.

Three types filters are analyzed. (1) The conventional Fabry-Perot, or aluminum-dielectric-aluminum (i.e. M D M) filter. (2) The One-M filter, which consists of a single aluminum film surrounded on either side with dielectric stacks. (3) The augmented M D M filter, which has additional dielectric films added to the basic M D M. Examples of both computed and measured transmittance curves are shown.

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I. Introduction

The objective of this N.A.S.A. grant is to investigate methods of producing interference filters in the ultraviolet spectral region below 3000Å. It is possible to produce filters for this spectral region by using the selective absorption of solid organic materials.[1] It is also possible to use the selective absorption of a single unbacked metal film to produce a filter in the extreme ultraviolet. For example, Hunter, Angel, and Tousey[2] have found that unbacked films of indium or aluminum exhibit a transmission "window" in the region near 800Å. However, in the present grant, we have investigated only filters which function by <u>interference</u> effects. The types of filter are are shown in Fig. 1:

(1) The Fabry-Perot, or M D M.

(2) The augmented Fabry-Perot.

(3) The one-M, which is sometimes called an "induced transmission" filter.

In this figure, the metal layers (which are aluminum in all cases) are shown as the cross-hatched film. It is evident that the transmission in each case depends on the interference effects in the layers and that there are one or more dielectric films (i.e. non-absorbing layers) in each of the filters. If the filter is to manifest substantial transmittance, then each of the film materials which is used in it must not have an excessive amount of absorption in the spectral region in which the filter is used. Therefore, it is appropriate to survey thin film materials.

II. Survey of Materials for Ultraviolet Filters

II-A. Metal Films

In order to be used as a component layer of a band-pass filter, a film material must possess two attributes:

(1) A substantial peak transmittance.

(2) A good rejection at wavelengths outside of the pass-band region.

As is pointed out by Berning and Turner,[3] a measure of the peak transmittance is the net radiant energy flow, ψ. This is a function of the thickness and optical constants, n and k, of the film, as well as the admittance of the medium which surrounds the film. However, for a film of given optical constants and specified thickness, there is maximum net radiant energy flow, which is ψ_{max}. The peak transmittance of a filter which contains the film can never exceed ψ_{max}. Consequently, this parameter is useful in establishing an upper bound for the peak transmittance of any filter which contains this film.

A parameter which is useful in estimating the rejection of a film is the transmittance of that absorbing layer when it is surrounded on either side by a medium of unit admittance. In other words, this is the transmittance of the film when it is stripped from its substrate and is surrounded on either side with a vacuum. Although such a condition is never achieved in practice, this transmittance is nevertheless a useful criterion in estimating the rejection of the absorbing film, when it is employed in a filter. There is usually negligible difference between the transmittance of this unbacked film and the film when it is attached to the substrate.

In the spectral region from 2000Å to 3000Å, aluminum is not only the best material to use in optical one-M and M D M filters but is possibly the only metal which can be used. However, there remains the question, "What metal films are best to use in filters in the spectral region below 2000Å?" In order to answer this question, the transmittance T_1 (for an unbacked film) and maximum net radiant energy flow ψ_{max} are computed for films of indium, gold, and aluminum.

Fig. 2 depicts T_1 and ψ_{max} for aluminum of thickness 200Å and 500Å. The abscissa extends from 50,000 cm^{-1} (2000Å) to 150,000 cm^{-1} (666Å). Both the transmittance and ψ_{max} increase monotonically with wave number. It is concluded that aluminum is quite a useful material to use in a one-M or M D M type of filter at wavelengths longer than 1200Å, but it does not have sufficient rejection to be useful at shorter wavelengths. The effect of the thin layer of aluminum oxide on the surface of the aluminum is not taken into account in these calculations. Its effect would be to decrease substantially the peak transmittance.

Fig. 3 shows the computed ψ_{max} and T_1 of a gold film of 200Å thickness. Not only is the ψ_{max} rather low at all wavelengths, but the rejection is not particularly outstanding. It is concluded that this material is unpromising as an optical filming material for this spectral region.

Fig. 4 depicts computed curves for T_1 and ψ_{max} for indium films of thickness 400Å and 1000Å. Only in the spectral region near 1000Å (100,000 cm^{-1}) does this material exhibit a reasonably large ψ_{max} and good rejection. At shorter wavelengths, ψ_{max} and T_1 are nearly equal and hence there is little promise of using this material in a filter in this region.

The results of the computations (shown in Figs. 2, 3 and 4) indicate that there is not much hope of combining interference effects in films of aluminum, indium or gold to produce band-pass filters in the spectral region below 1000Å.

The curves of T_1 and ψ_{max}, were computed by inputting the optical constants obtained from W. R. Hunter[4], of the U. S. Naval Research Laboratory into the 7074 digital computer. It is desirable to generalize this analysis so that it is possible to find the T_1 and ψ_{max} for any metal film, provided its optical constants, n and k, and its thickness (expressed in wavelengths) are known.

The contrast of a film is another useful parameter. This is a measure of the effectiveness of the film at rejecting the wavelength region outside of the pass-band. The contrast is defined as:

$$C = \psi_{max}/T_1$$

where ψ_{max} has been defined previously and T_1 is the transmittance of an unbacked thin film which is surrounded on either side with a vacuum. This T_1 was computed for aluminum, indium, and gold and is shown in Figs. 2, 3, and 4.

It is useful to have available curves which give ψ_{max}, and the contrast in terms of the n and k for a film of given thickness. Figures 5, 6, 7 and 8 depict contours of ψ_{max} and contrast versus n and k for thickness-wavelength ratios of 0.05, 0.1, 0.15 and 0.20, respectively. As an example of the use of these tables, let us investigate whether a copper film would be a useful material to incorporate in a filter in the wavelength region near 1100Å. We assume the thickness of the copper film is 220Å. According to the measurements of Canfield and Hass[5] the optical constants of copper at 1100Å are $n - ik = 1.0 - i\,0.75$. Since the thickness to wavelength ratio, d/λ, is $220/1100 = 0.20$, we utilize Fig. 8. At first glance, the properties look promising; the ψ_{max} is nearly 40%. However, although this film has a substantial ψ_{max}, the contrast is quite small, with a value of approximately 1.6. Hence, copper would definitely not function well as the metal film in a filter in this region.

Another convenient method of presenting these data is to plot ψ_{max} and contrast on the same graph for specified contours of n and k. As in the previous cases, the thickness-wavelength ratio, d/λ, is constant for a given graph.

Figures 9, 10, 11 and 12 depict such plots. The chief value of such a graph is that it immediately defines the range of n and k values which the metal film must have to provide a given contrast and ψ_{max}. For example, suppose that we determine that the ratio d/λ is 0.20. This might be dictated by the fact that the thinnest metal film which can be evaporated is about 100Å in thickness. This means that at short wavelengths, as for example at 500Å in the extreme ultraviolet, d/λ must be greater than 0.20. It is seen from Fig. 12 that if we specify that ψ_{max} must be 10% and the contrast be 100 or greater, that the n of the metal must be 0.8 or greater and the k should exceed 3.0. Thus it is possible to examine the measured optical constants of actual metals and see if they could be utilized in filters.

II-B. Dielectric Materials for U.V. Filters

In the foregoing section, the properties of various metals were considered. However, all of the band-pass filters which we desire to fabricate have at least one dielectric film in them. The one-M and the augmented M D M type filters require that we have at least two dielectric materials which can be used in the filter. These materials should have the largest possible mismatch in refractive index. What dielectric film materials can be used in the spectral region below 2500Å?

Some possible materials are:

(1) Lithium fluoride

(2) Calcium fluoride

(3) Cryolite

(4) Magnesium fluoride

(5) Thorium oxyfluoride

(6) Magnesium oxide.

The properties of each of these materials are briefly considered:

Both lithium fluoride and calcium fluoride transmit down to short wavelengths, but they have one serious drawback. When they are deposited as a thin film, they form a "transition layer" at the substrate, which lowers the reflectance of the film and makes its thickness difficult to monitor in the vacuum while it is being deposited. Lithium fluoride has the disadvantage of being slightly water-soluble.

Cryolite does not form such a "transition layer", but is still as water soluble as the LiF. Its transmittance is shown in Fig. 13. Magnesium fluoride is considerably more durable and evidently transmits to wavelengths near 1300Å.

The optical properties of magnesium oxide have been investigated by Apfel,[6] who found that it is transparent to 2000Å.

The transmittance of a quarter-wave film (at 2536Å) of thorium oxyfluoride is shown in Fig. 13. Both this material and the cryolite were obtained from Balzers Aktiengesellschaft, Liechtenstein, and both have been outgassed in a vacuum. These materials were deposited at a pressure of less than 10^{-5} torr by evaporation using an electron gun. The substrate is a polished lithium fluoride blank obtained from the Harshaw Chemical Company, Cleveland. In each case, the thickness of the film is a quarter-wave optical thickness at 2536Å.

After these films were deposited, some of the lithium fluoride blanks were examined under a microscope and it was found that the "polish" imparted by Harshaw is quite poor--and in fact the surfaces look as though they had been ground, rather than polished. There is a possibility that the relatively low transmittance could be attributed to the scattering from the LiF blanks. Also shown in Fig. 13 is the transmittance of the uncoated LiF blank (with the Harshaw "polish"). Shown for comparison is the transmittance of LiF as measured by Heath and Sacher.[7] It is concluded that the absorptance of films of cryolite and thorium oxyfluoride in this spectral region is a property of the films and cannot be attributed to the poor polish of the substrates. There still remains the question--what is the absorptance of thorium fluoride? Evidently there is little difference in the chemical properties of thorium fluoride and thorium oxyfluoride and an x-ray analysis of the crystal structure is the best way to differentiate between the two compounds.

III. M D M Filters

The simplest type of filter which can be fabricated is the metal-dielectric-metal "interference" filter. Numerous commercial firms now manufacture this type of filter. During the tenure of this grant, several filters of this type were produced for the following reasons:

(1) As a check on the optical constants. This filter is an extremely simple design and consequently when depositing it there is little opportunity to deposit a wrong thickness. The computed transmittance curves rely on the

tables of the optical constants (as a function of wavelength) which are used in the computer program. If these optical constants are actually representative of the aluminum films which we are depositing, then the experimental and computed transmittance curves should be similar.

(2) It appears that in the region of the spectrum below 1500Å it is difficult to build up a dielectric "stack" and hence this is the only type of filter which can be used.

The optical constants of aluminum which are used in our computer program were supplied by W. R. Hunter[4] of the U.S. Naval Research Laboratory. In order to check the accuracy of our monitoring of the thickness of the aluminum layers and also to ascertain that the aluminum is being evaporated under vacuum conditions similar to Hunter's, R. Maier prepared a conventional M D M filter. Figure 14 depicts the computed and measured transmittance of this filter. The computed transmittance is not corrected for the second surface reflectance loss of the quartz substrate. The agreement between the computed and measured curves is not unreasonable. This strengthens our confidence that the conditions in the vacuum under which we are depositing aluminum, are similar to those of Hunter.

As another example of some M D M filters, Figs. 15 and 16 show the spectral transmittance of M D M filters on a

Suprasil and a LiF substrate, respectively. The dielectric spacer between the aluminum layers is cryolite and is first order. The aluminum (estimated thickness 150Å) was deposited in approximately two seconds at a pressure gauge reading of 10^{-5} torr. The transmittance in Fig. 15 drops rapidly to zero at 1600Å due to the absorption of the quartz. Neither of these transmittance curves was corrected for the intrinsic absorption of the substrate.

Although the peak transmittance of these filters is adequate (compared to other u.v. filters), the width of the transmission band is quite broad. If the aluminum films were made thicker to increase their reflectivity, then the spectral band width will narrow, but at the expense of a decrease in the peak transmittance. A better method of producing narrower band filters is to either use second order or higher order spacer layers or to use more aluminum films--i.e. evaporate a M D M D M type of filter.

IV. One-M Type of Filters

The "one-M" type of ultraviolet filter, as shown in Fig. 1, consists of a single aluminum layer which is surrounded on either side by dielectric stacks. This filter is sometimes called a "metal spacer interference filter" or an "induced transmission" filter. As an ultraviolet filter, it has the advantages that:

(1) The filter has a single pass-band at a short wavelength and has a substantial attenuation at longer wavelengths.

(2) It is possible to obtain a relatively narrow bandwidth. However, the main disadvantage is that the filter contains many layers and the thickness of the layers in the center of the stack must be controlled with the utmost precision.

In order to design a one-M type of u.v. filter, this procedure is followed:

(1) The thickness of the aluminum film is chosen. For example, 300Å is a reasonable thickness to use at 2500Å. If a thicker film were used, then the peak transmittance of the filter would be lower, although the attenuation at longer wavelengths would be increased. Also, if a thicker aluminum film is used, the matching stack of dielectric films becomes much more difficult to deposit because the optical thickness of the layers must be controlled with greater precision.

(2) After the thickness of the aluminum layer is determined, the total transmittance, T_{total}, of the entire filter is determined by the admittance of the matching stacks on either side of the metal film. The matching stacks are composed of dielectric materials such as $ThOF_2$ and cryolite, and are shown in Fig. 17. If we specify that there is a single metal film in the center of the filter, then the admittance Y of the matching stacks is the same. If the refractive index of the incident medium (which is usually air) and the refractive index of the substrate (which is quartz in our filters) are different, then although the design of the two stacks is different, their admittance are still identical. As is shown in Fig. 17, the admittance of the matching stack is measured at the interface between the stack and the metal film.

(3) Berning and Turner,[3] who more than a decade ago devised a prototype one-M filter, outline a procedure for computing the admittance Y necessary to optimize the transmittance of the entire filter. As stated in a foregoing paragraph, the T_{total} depends upon the optical constants and thickness of the metal layer and the admittance of the matching stacks. For a <u>given</u> metal layer and at a specific

wavelength, however, T_{total} is a function only of the admittance, Y. It is possible to plot contours of a constant T_{total} as a function of the admittance, Y. Y is of course a complex variable,

$$Y = Y_r + j\,Y_j \qquad \text{where } j = (-1)^{1/2} .$$

Since the range of the admittance is large, it is more convenient to plot the admittance on a Smith Chart. Figure 18 depicts contours of T_{total} for an aluminum film at 2536Å whose physical thickness is 250Å. Once the admittance Y of the matching stacks is found, then the stack which would produce such an admittance is designed using graphical design techniques, such as the Smith Chart or the Kard Calculator.

The transmittance of several one-M type filters is shown: Fig. 19 depicts the measured transmittance of a filter in which the matching stack is composed of cryolite and thorium oxyfluoride. The center aluminum layer has a thickness of 300Å. The computed transmission curve is shown in Fig. 20. The thicknesses of all of the layers in this filter were monitored by reflection, with the exception of the center aluminum film. The measured transmittance of this filter, shown in Fig. 19, corresponds closely with the computed transmittance shown in Fig. 20. Although the experimental filter (Fig. 19) actually has two fewer layers than the computed design (Fig. 20), this should make only a small difference in their spectral transmittances. Although the monitoring wavelength is at 2536Å, the peak transmittance of the filter is at 2620Å. Part of this shift to longer wavelengths can be attributed to the fact that the angle of incidence of the beam in the optical monitoring system is 15^{o}. Also, the thickness was monitored by shuttering the evaporation source when the intensity of the reflected light attained either a maximum or a minimum. Inevitably, one "coasts by" the minimum or maximum a small amount--thus causing the film to deposit thicker.

As another example of a one-M filter, a filter was evaporated which used lead fluoride and cryolite in the stack. Since the lead fluoride has a refractive index of 2.0 at 2500Å, the matching stack can be composed of fewer layers than the matching stack of thorium oxyfluoride and cryolite. The single aluminum layer in the center of the stack is 400Å in thickness. The transmittance of the filter is shown in Fig. 21. The effect of the thicker aluminum film is to decrease the peak transmittance in the pass-band. However, the maximum <u>attenuation</u> (at T_{min} in Fig. 21) decreases much more rapidly than does the peak transmittance. Although the measured minimum transmittance of this filter is only 0.0015, as determined on the Cary model 14 spectrophotometer, it is probably somewhat lower, due to the influence of the residual scattered light in the spectrophotometer. Another interesting feature of this filter is that the spectral width of its pass-band is less than the pass-band of the same type of filter which utilizes thorium oxyfluoride and cryolite in the matching stack, as shown in Fig. 19. The narrowing of the pass-band in Fig. 21 can be attributed to the dispersion of the refractive index of the lead fluoride. Lead fluoride has an absorption edge at 2300Å and hence its index is changing rapidly in this spectral region.

An attempt was also made to deposit a one-M type of filter which would transmit at 1849Å. The thicknesses of the layers in the matching stack of dielectric films of cryolite and thorium oxyfluoride were monitored in reflection using the 1849Å emission line from a mercury discharge lamp. The intensity of the 2536Å line. Even though a filter was used which attenuated the 2536Å line by a factor of 100, this attenuation was not sufficient to evaporate the final matching stack of the filter, for the following reason.

This is the procedure which was followed to deposit the filter:

(1) The matching stack (composed of cryolite and $ThOF_2$) was deposited on the quartz substrate. This is shown as "matching stack I" in Fig. 22. The film thickness was controlled by reflection monitoring at 1849Å. Here, the small residual intensity of the 2536Å line did not interfere with the accurate thickness monitoring at 1849Å.

(2) The aluminum layer was deposited on top of this matching stack. Transmission monitoring was used to measure its thickness.

(3) The second matching stack was deposited on top of the aluminum. The thickness of the films was determined by reflection monitoring of the aluminum at 1849Å. As the successive layers of the matching stack were deposited, the reflectance at 1849Å decreased. In Fig. 22, the reflection shown by the dashed line would typically result after five layers had been deposited. When the entire filter is completed, the reflectance at 1849Å should go to zero, as shown by the solid line in Fig. 22. However, the reflectance at 2536Å in either case is essentially unaltered by the addition of the matching stacks and is close to 85%.

The net result is that the component of the 2536Å which "leaks" through the filter in front of the photomultiplier becomes stronger and stronger in comparison with the 1849Å as the one-M filter is completed.

The one-M filters which were evaporated had an adequate peak transmittance (20%) but the minimum transmission was poor (of the order of 2%). An acceptable one-M filter should have at least a 100:1 rejection ratio of the minimum transmittance compared with the peak transmittance.

V. Augmented M D M Filters

An augmented M D M filter has, in addition to the two metal layers separated by a dielectric spacer, further dielectric layers added to either side of the filter. These additional dielectric layers can perform two useful functions:

(1) They can enhance the rejection of the filter in a limited wavelength region.

(2) They can increase the peak transmittance of the filter in its pass-band.

As an example of the use of the additional dielectric layers to enhance the rejection of the filter, supplementary layers were added to a conventional M D M filter, which is designed to transmit at 1849Å, in order to reject the 2536Å emission line from a mercury lamp. This filter, the transmittance of which is shown in Fig. 23, essentially consists of a conventional Fabry-Perot aluminum-dielectric-aluminum filter with a quarter-wave stack superimposed to reject the 2536Å line. A similar design could be easily used at other wavelengths. This filter was manufactured for use in an optical film thickness monitoring system which utilizes the 1849Å emission line of mercury.

The design of a M D M filter which has an enhanced peak transmittance is based upon the concept of the optimization of the net flow of radiant energy through an absorbing film. This concept is briefly discussed in an earlier section of this report. In section IV, the "optimum" design of a one-M type of filter is discussed.

In this type of filter, once the thickness and optical constants of the metal film and the wavelength are specified, there is a systematic procedure by which a matching stack of dielectric layers is designed. If this procedure is followed, one maximizes the net flow of radiant energy through the entire filter, ψ_{max}. These same design considerations can apply to filters which contain two or more metal layers. The result is that the maximum transmittance of the conventional M D M filter can be considerably increased by adding stacks of dielectric matching layers to each side of the filter, as shown in Fig. 24. In this report, this latter type of filter is called a "transmittance-optimized" or simply a "T-optimized" M D M filter. Although this type of filter design is suggested in a previous publication,[3] to the best of our knowledge there are no published designs for such a filter for the ultraviolet.

Figure 25 depicts the spectral transmittance of the conventional M D M type of filter. The dielectric layer of cryolite has a quarter-wave optical thickness of 3490Å and the aluminum metal layer is 150Å in physical thickness. The maximum transmittance is 43% and the full width at $\frac{1}{2}\, T_{max}$ is 375Å. In actual practice, a thicker aluminum layer is usually used and hence the band width is slightly narrower. The <u>maximum</u> net radiant energy flow through a 150Å layer of aluminum is 91%. Hence the peak transmittance of the M D M (with 150Å of aluminum) could be as high as $(91\%)^2 = 83\%$, if the M D M were properly matched with suitable dielectric stacks. The result is that the maximum transmittance of the M D M can be nearly doubled and a narrower band width can also be achieved. However, this advantage is offset by the increased complexity of the filter and the side-transmission bands in the neighborhood of the main pass-band.

The procedure for designing an augmented M D M filter is as follows:

(1) The aluminum film thickness is specified; this is 150Å in this example. Then the matching stack, designated as "stack I" in Fig. 24, is designed so that the maximum net radiant flux is transmitted through the first aluminum film.

(2) A similar dielectric matching stack, shown as "stack II" in Fig. 24, is designed for the second aluminum layer. Since one matching stack is bounded by air and the other stack by the quartz substrate, they are not identical, although the optical admittance of the two stacks is the same.

(3) The phase shift upon reflection in the interior of the dielectric spacer layer is computed. The optical thickness of the spacer layer is chosen so that a resonance

condition obtains at λ_o, which is 2536Å in this example. The entire stack is assembled and the resulting filter is shown in Fig. 24:

$$\text{air } (H\ L)^7\ L''\ M\ D\ \ M\ L'\ \ L\ (H\ L)^8 \text{ quartz}$$

The H and L in this design represent quarter-waves of thorium oxyfluoride (index 1.55 at 2536Å) and cryolite (index 1.36). The computed spectral transmittance of the resulting filter is shown in Fig. 26. Its T_{max} of 80% is close to the optimum of 83%. Due to the effect of the dielectric stacks on the outside of the aluminum layers, the full width at $\frac{1}{2}\ T_{max}$ is reduced to 80Å, in comparison with the full width of 375Å for the M D M shown in Fig. 25. Figure 27 shows the transmittance of a similar T-optimized M D M filter which uses lead fluoride and cryolite in the matching stacks. The peak transmittance is 64%, in comparison with the 80% of the filter in Fig. 26. This difference is not due to improper design of the matching stacks, but can be attributed to the residual optical absorption in the lead fluoride at 2500Å. Using the data of Krebs,[8] the optical constant of lead fluoride at 2536Å is $\hat{n} = n - jk = 2.10 - j\ 0.02$. Even though the absorption in the lead fluoride is small, the

PbF_2 films are located in a part of the filter where the standing ratio of the electric field is large and consequently the small absorption of the films is enhanced. Another feature of the design shown in Fig. 27 is that the side-band transmission peak at 3000Å is much smaller than the comparable design in Fig. 26. This can be attributed to the dispersion of the refractive index of the lead fluoride.

The main advantage of this t-optimized M D M design is its improved peak transmittance. If three such filters were ganged in series so that the optical densities of the individual filters could be added, then a peak transmittance of $(80\%)^3 = 51\%$ would be attained. However, the side transmittance peaks would be suppressed to an optical density of 3 or 4. The success of such a filter would depend upon the suppression of the side-band transmission peaks.

VI. Conclusions

(1) Based upon our present knowledge of optical film materials, it appears that most bandpass filters in the spectral region below 2500Å will contain one or more aluminum layers.

(2) There is reasonable certainty that Fabry-Perot type of bandpass filter can be fabricated at wavelengths down to 1400Å.

(3) If it is possible to deposit dielectric materials which have a mismatch in their refractive index and which are nonabsorbing, then it is feasible to fabricate filters of the one-M design and also the augmented M D M design.

(4) A method of designing the one-M type of filter has been devised and successfully used. This method consists of plotting the isotransmittance contours on the admittance plane and then finding the admittance of a suitable matching stack.

(5) A one-M type of filter was manufactured, which has a peak transmittance of 55% (at 2610Å), a full width at $\frac{1}{2}$ T_{max} of 55Å and a full width at 0.1 T_{max} of 130Å.

(6) A Fabry-Perot type of filter, i.e. an M D M, was designed which had additional dielectric stacks added to enhance the transmittance in the pass band. In a specific example, the addition of the dielectric stacks increased the peak transmittance from 43% to 83% and the spectral band width of the filter was narrowed from 375Å to 80Å. However, this filter exhibits an objectionable long-wavelength transmission "window".

Direction of future investigations:

(1) The success of depositing multilayer band-pass filters largely depends upon the availability of dielectric film materials which are relatively absorption-free. Films of various materials should be deposited to determine their optical properties in the spectral region from 1200Å to 2500Å.

(2) Efforts should be made to fabricate one-M filters for the spectral region down to 1400Å.

(3) The properties of the augmented M D M filter should be investigated in more detail. At present, these designs have the advantage of having substantially higher peak transmittance than the conventional M D M filter, but exhibit an undesirable "leak" in the transmission on the long wavelength side of the passband. This should be eliminated.

(4) Finally, there are a myriad of experimental techniques which need to be perfected in order to deposit filters for the ultraviolet region, from 1200Å to 2500Å: the perfection of optical monitoring systems, investigation of methods of depositing aluminum and dielectric thin film materials, and the changes in the optical properties of

such thin film materials caused by a change in the conditions of evaporation.

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VIII Publications:

The following documents were published during this grant:

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(3) V. R. Costich, N.A.S.A. report CR70638, "Ultraviolet Interference Filters" (reproduction of Ph.D. thesis, Institute of Optics, 1965).

(4) Robert L. Maier, "2M Interference Filters for the Ultraviolet", Thesis for the Master of Science Degree in Optics, University of Rochester, 1966.

VIII. Personnel

The following individuals contributed to the work described herein:

Philip Baumeister, Assoc. Prof.

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Mrs. Richard Chadwick, part-time programmer

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Captions to the figures

1. The various types of bandpass filters which are used in the ultraviolet region: The M D M, the augmented M D M, and the one-M.

2. Computed maximum energy flow, ψ_{max}, and transmittance T_1 of an unbacked film of aluminum of thickness 200Å (dashed curve) and 500Å (solid curve).

3. Computed maximum energy flow, ψ_{max}, and transmittance T_1 (of an unbacked film) of a gold film 200Å in thickness.

4. Computed maximum energy flow, ψ_{max} and the transmittance T_1 (of an unbacked film) of films of indium of thickness 400Å (dashed curve) and 1000Å (solid curve).

5. Contours of ψ_{max} and contrast as a function of the optical constants, n and k, of a film of physical thickness 0.05 wavelengths.

6. Contours of ψ_{max} and contrast as a function of the optical constants, n and k, of a film of physical thickness 0.10 wavelengths.

7. Contours of ψ_{max} and contrast as a function of the optical constants, n and k, for a film of physical thickness 0.15 wavelengths.

8. Contours of ψ_{max} and contrast as a function of the optical constants, n and k, for a film of physical thickness 0.20 wavelengths.

9. The contrast and ψ_{max} of a film 0.05 wavelengths in thickness. The contours of constant n and constant k are shown, where n - jk is the optical constant of the film.

10. The contrast and ψ_{max} of a film 0.10 wavelengths in thickness. The contours of constant n and constant k are shown, where n - jk is the optical constant of the film.

11. The contrast and ψ_{max} of a film 0.15 wavelengths in thickness. The contours of constant n and constant k are shown, where n - jk is the optical constant of the film.

12. The contrast and ψ_{max} of a film 0.20 wavelengths in thickness. The contours of constant n and constant k are shown, where n - jk is the optical constant of the film.

13. The measured transmittance of coated and uncoated substrates of lithium fluoride 2mm in thickness, as measured on a MacPherson model 225 spectrophotometer.

(a) Bare LiF, Univ. of Roch. data.

(b) Bare LiF, data from Heath[7]

(c) LiF overcoated with a cryolite film of quarter-wave optical thickness at 2536Å.

(d) LiF overcoated with a $ThOF_2$ film of quarter-wave optical thickness at 2536Å.

In cases a, c, and d, the substrate is a polished LiF blank obtained from the Harshaw Chemical Company.

14. Computed and measured transmittance of a filter of the design: air M D M quartz where M represents a 150Å thick layer of aluminum and the cryolite spacer layer has an optical thickness of 872Å.

15. The measured transmittance of a M D M filter in which the M aluminum layers are 150Å thick. The cryolite spacer was deposited by monitoring to a minimum reflectance on gold substrate at 2536Å. The filter substrate is suprasil quartz.

16. The measured transmittance of a M D M filter which is substantially identical to the filter described in the caption to Fig. 15, but is deposited on a LiF substrate.

17. The basic design of a one-M type of bandpass filter. The admittance Y is measured at the surface of the dielectric matching stack.

18. Isotransmittance contours in the reflectance plane for an aluminum layer 250Å in thickness, at a wavelength of 2536Å.

19. The measured spectral transmittance of a one-M filter of the design Air $(H\ L)^6$ H' M L' $(L\ H)^9$ Q where H, L represent quarter-waves at 2536Å of thorium oxyfluoride and cryolite, respectively. H' is 0.73 of a quarter-wave and L' is 0.76 of a quarter-wave. The aluminum layer represented by M is 300Å in physical thickness and the substrate Q is Suprasil quartz.

20. Computed spectral transmittance of a one-M type of filter. Its design is substantially identical to that described in the caption to Fig. 19.

21. Measured spectral transmittance of a one-M filter in which the matching stack is composed of lead fluoride and cryolite. The aluminum layer M is 400Å in physical thickness.

22. The spectral reflectance at various stages of manufacture of a one-M filter. The partial filter in Fig. (a) consists of the inner matching stack and the aluminum film. In Fig. (b), the outer matching stack has been partially completed and its reflectance (shown as a dashed line) at 1849Å decreases as additional layers are added to it.
23. The measured transmittance of an augmented M D M band-pass filter which is designed to transmit the 1849Å emission line of mercury and attenuate the 2536Å line. The substrate is quartz. The film material designated as ThF_4 is actually $ThOF_2$.
24. The design of a T-optimized M D M filter.
25. The computed transmittance, reflectance (from the air side) and net flow of radiant energy of a M D M band-pass filter.
26. The computed transmittance, reflectance (from the air side) and net flow of radiant energy of a T-optimized M D M filter. The metal layer M is aluminum 150Å in physical thickness; L and H represent films of cryolite (index 1.36) and thorium oxyfluoride (index 1.55), respectively, of quarter-wave optical thickness at

2536Å. The films L_1', L_2', and L_3' are cryolite and are 1.825, 1.71 and 0.816 of a quarter-wave of 2536Å. The substrate is quartz.

27. The transmittance T and net flow of radiant energy ψ of a T-optimized M D M filter deposited on a quartz substrate. The metal layer M is aluminum of 150Å physical thickness; L and H represent quarter-waves at 2536Å of cryolite (index 1.36) and lead fluoride (which has a dispersive index). The layers L', L'', and S represent cryolite films of optical thickness 0.848, 1.85, and 1.67 of a quarter-wave at 2536Å, respectively.

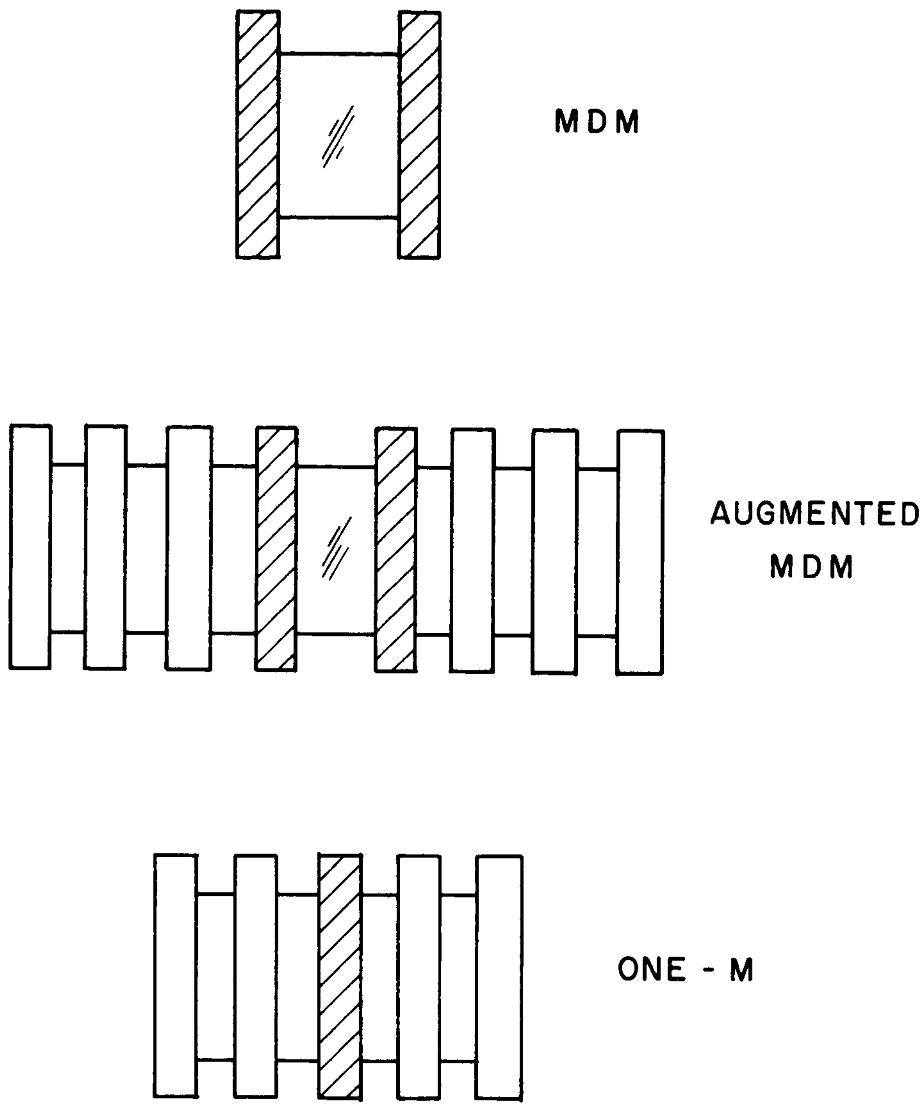
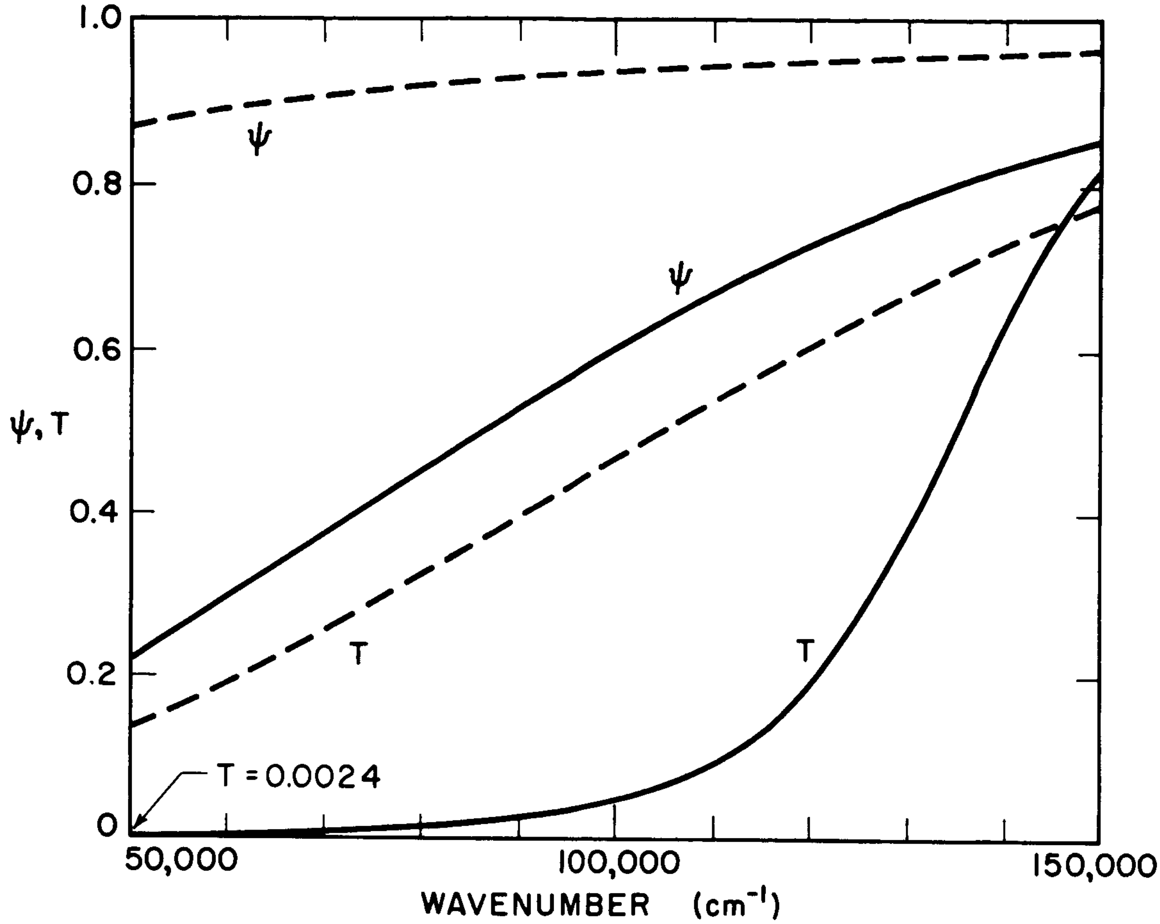
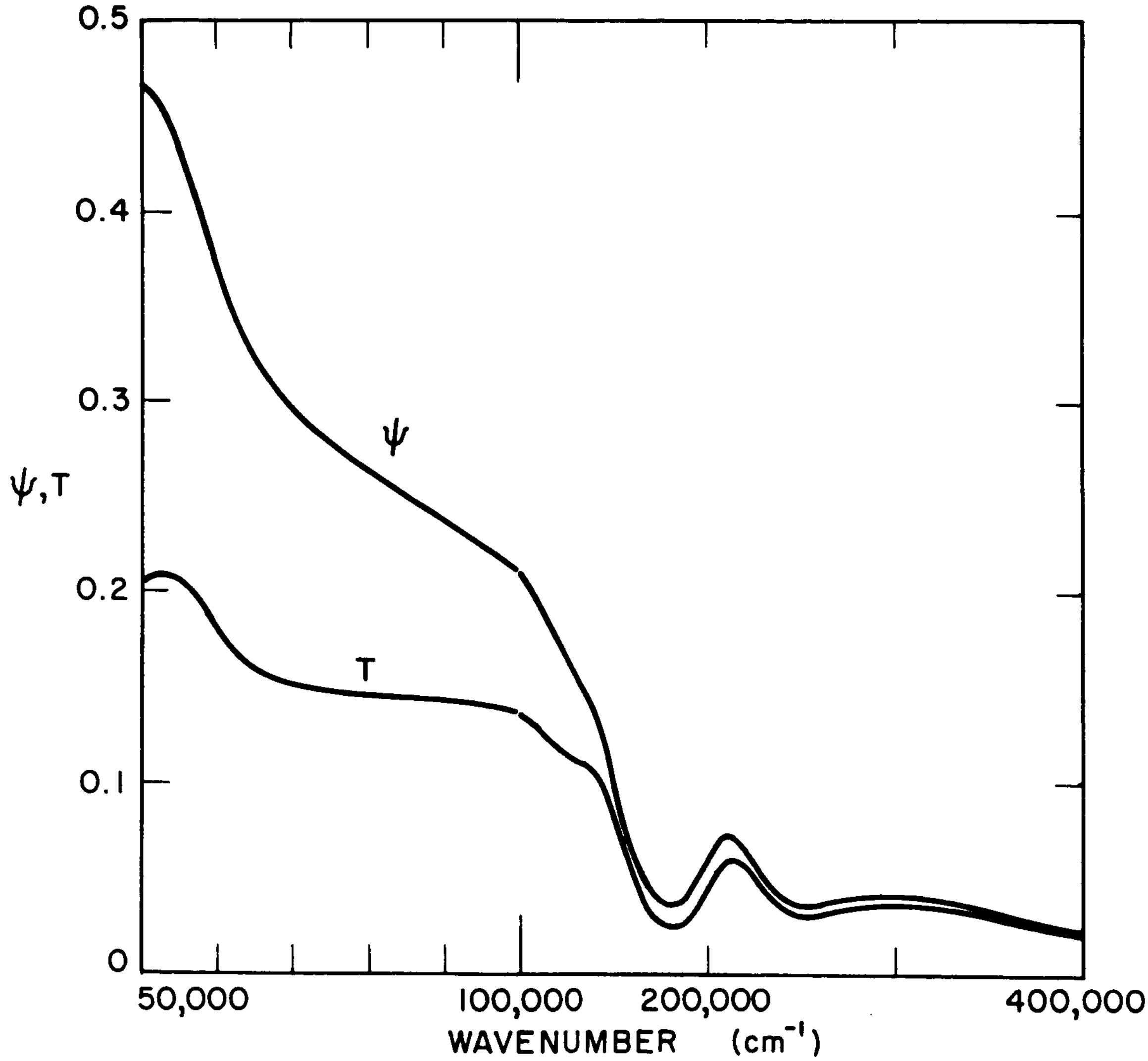


Figure 1



1.0
0.8
0.6
0.4
0.2
0
ψ, T
ψ
ψ
T
T
T = 0.0024
50,000
100,000
150,000
WAVENUMBER (cm⁻¹)

Figure 2



0.5
0.4
0.3
0.2
0.1
0
ψ, T
ψ
T
50,000
100,000
200,000
400,000
WAVENUMBER (cm⁻¹)

Figure 3

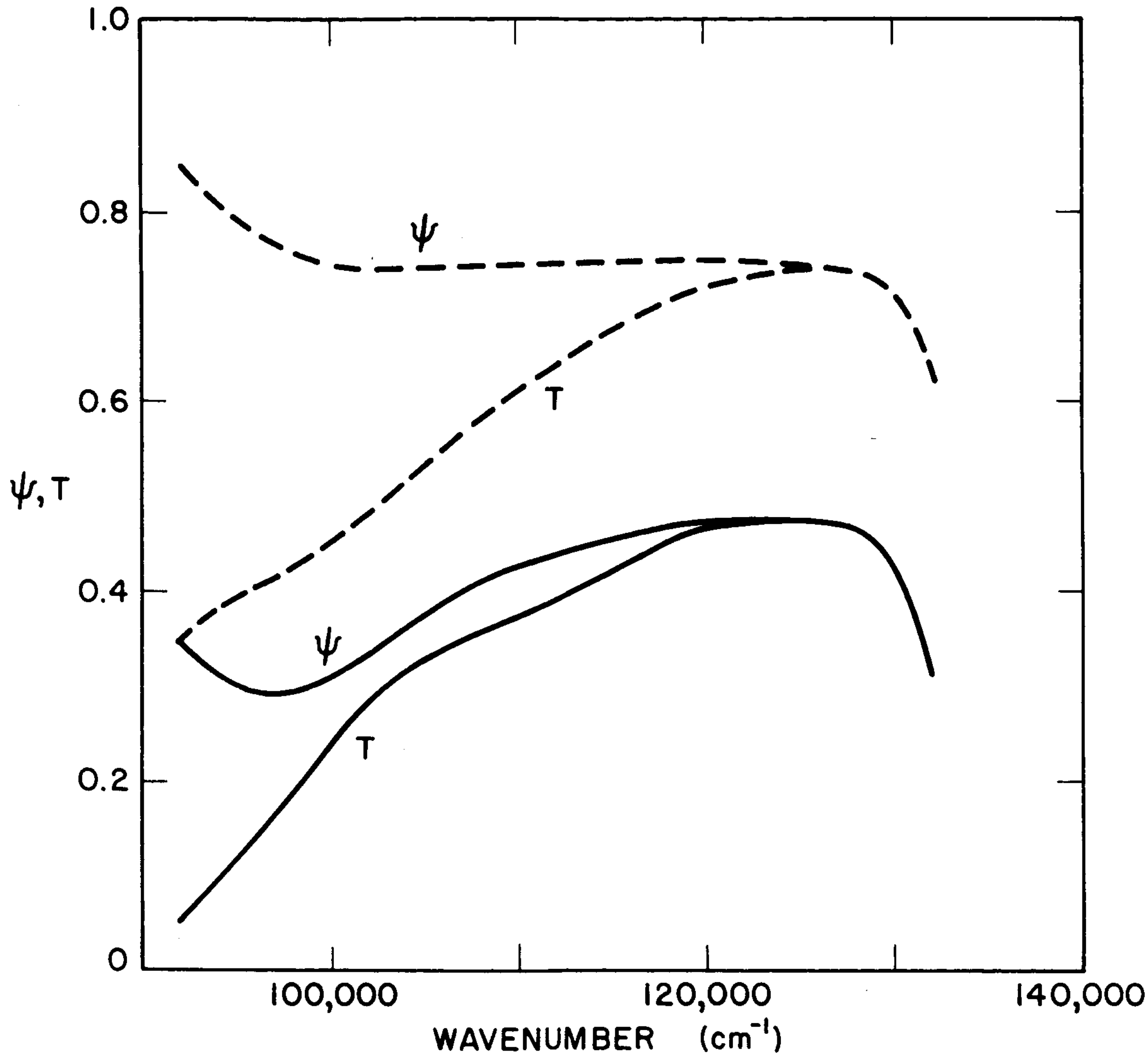


Figure 4

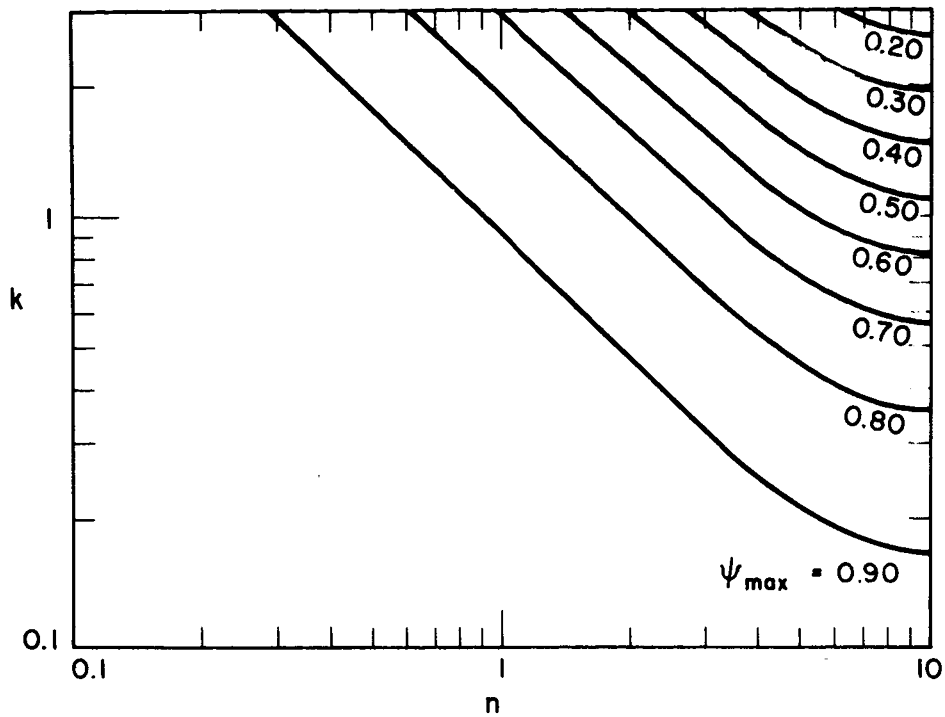


Figure 5a. ψ_{max} Contours on the Complex N Plane for d = 0.05λ

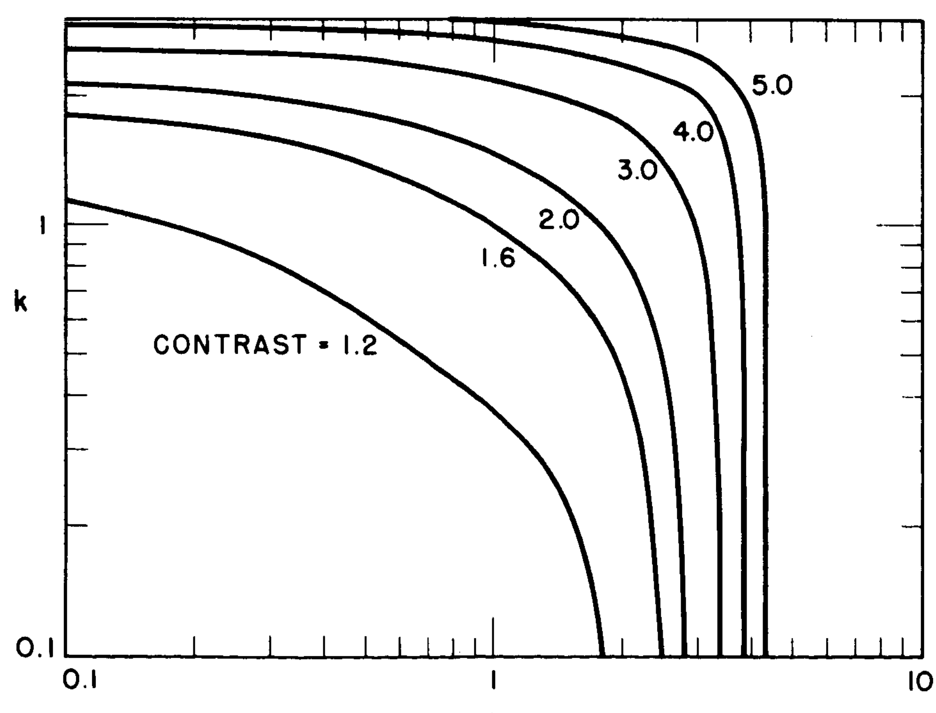


Figure 5b. Contrast Contours on the Complex N Plane for d = 0.05λ

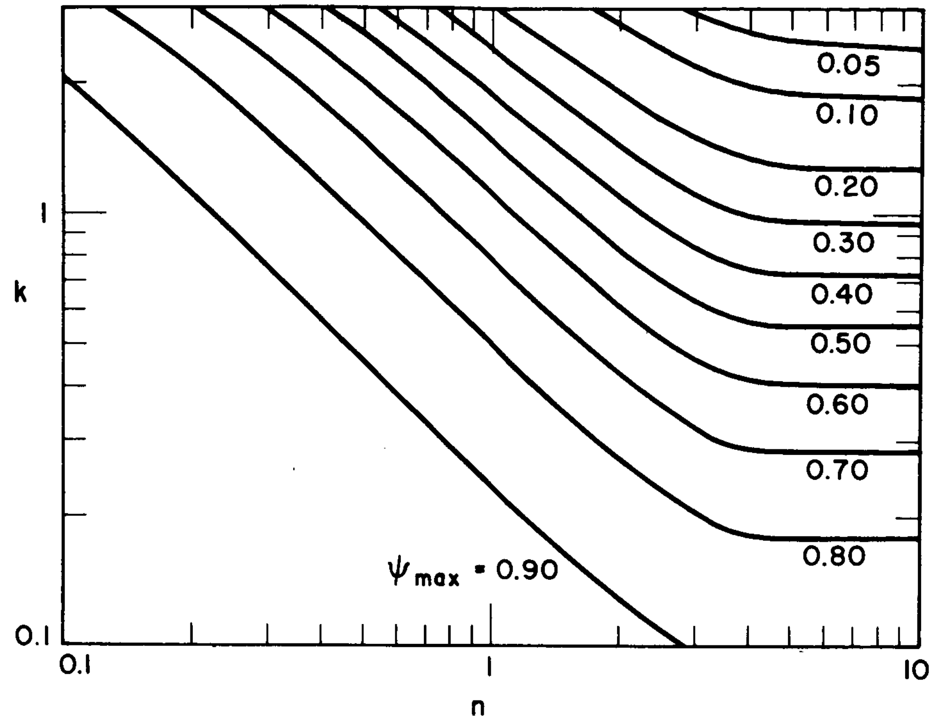


Figure 6a. ψ_{max} Contours on the Complex N Plane for d = 0.10λ

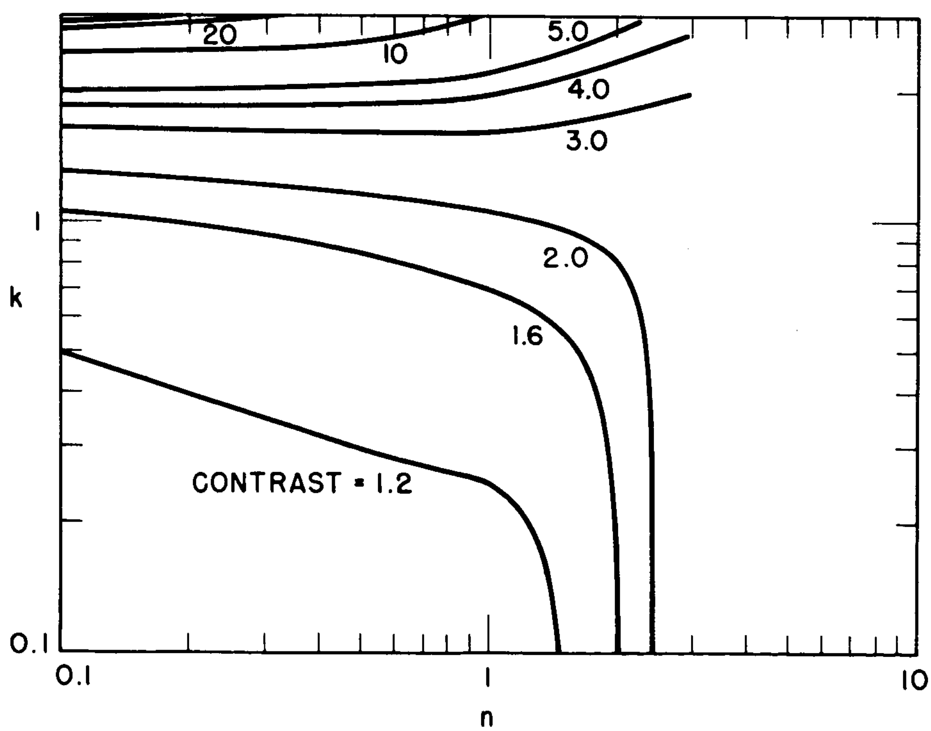


Figure 6b. Contrast Contours on the Complex N Plane for d = 0.10λ

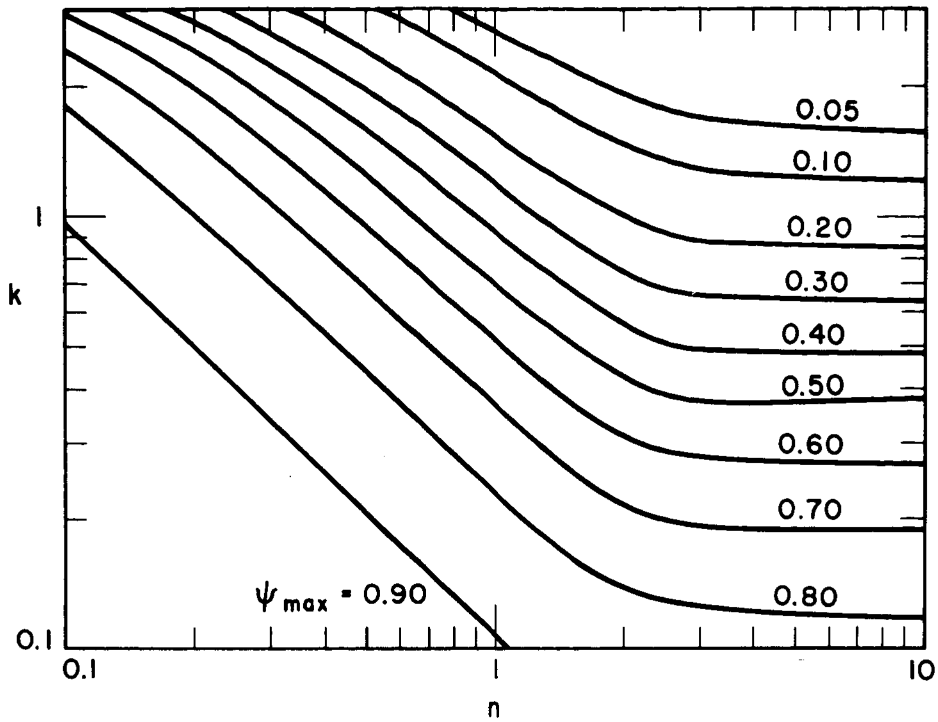


Figure 7a. ψ_{max} Contours on the Complex N Plane for $d = 0.15\lambda$

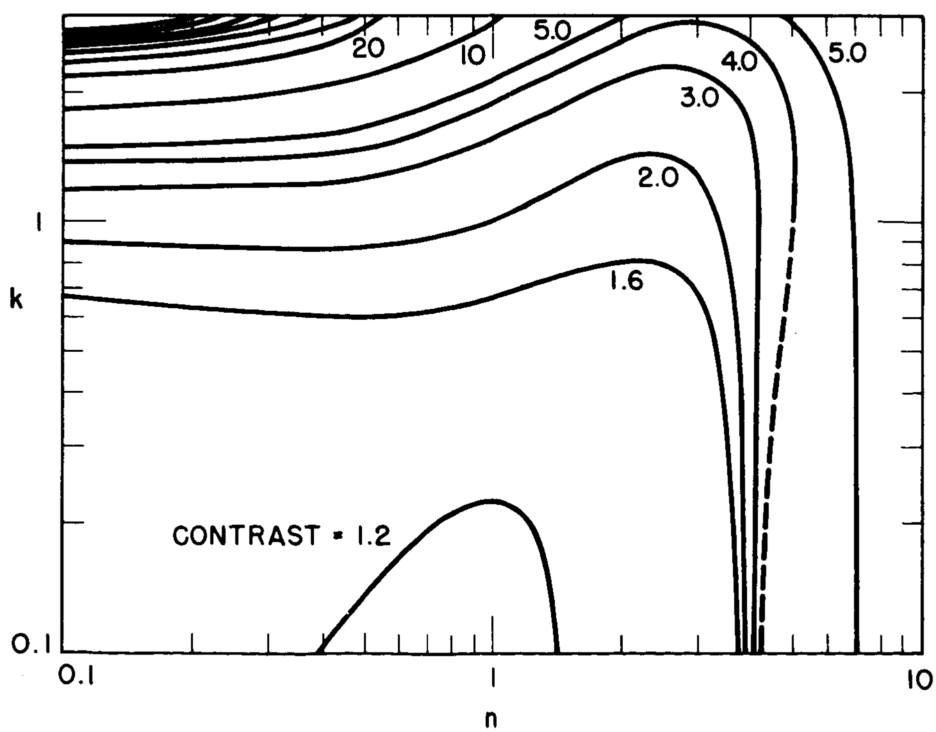


Figure 7b. Contrast Contours on the Complex N Plane for $d = 0.15\lambda$

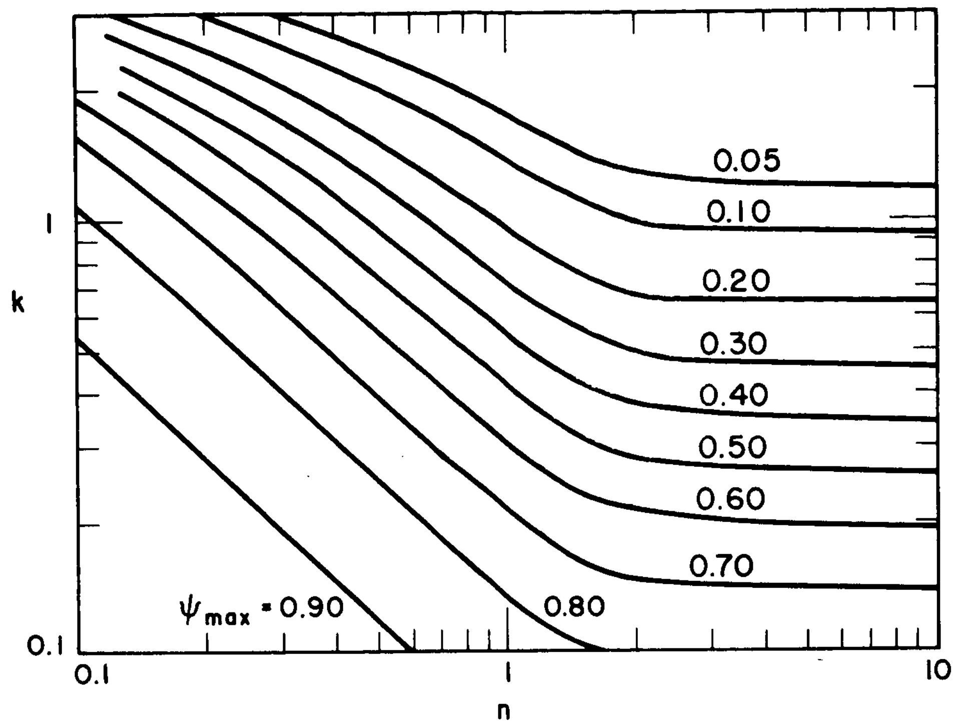


Figure 8a. ψ_{max} Contours on the Complex N Plane for $d = 0.20\lambda$

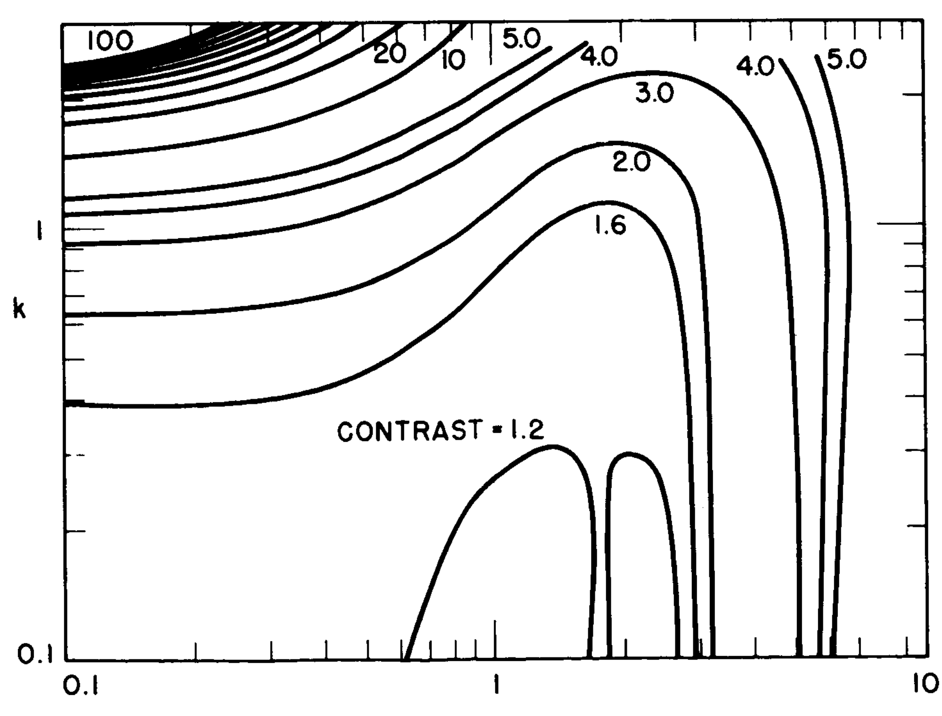


Figure 8b. Contrast Contours on the Complex N Plane for $d = 0.20\lambda$

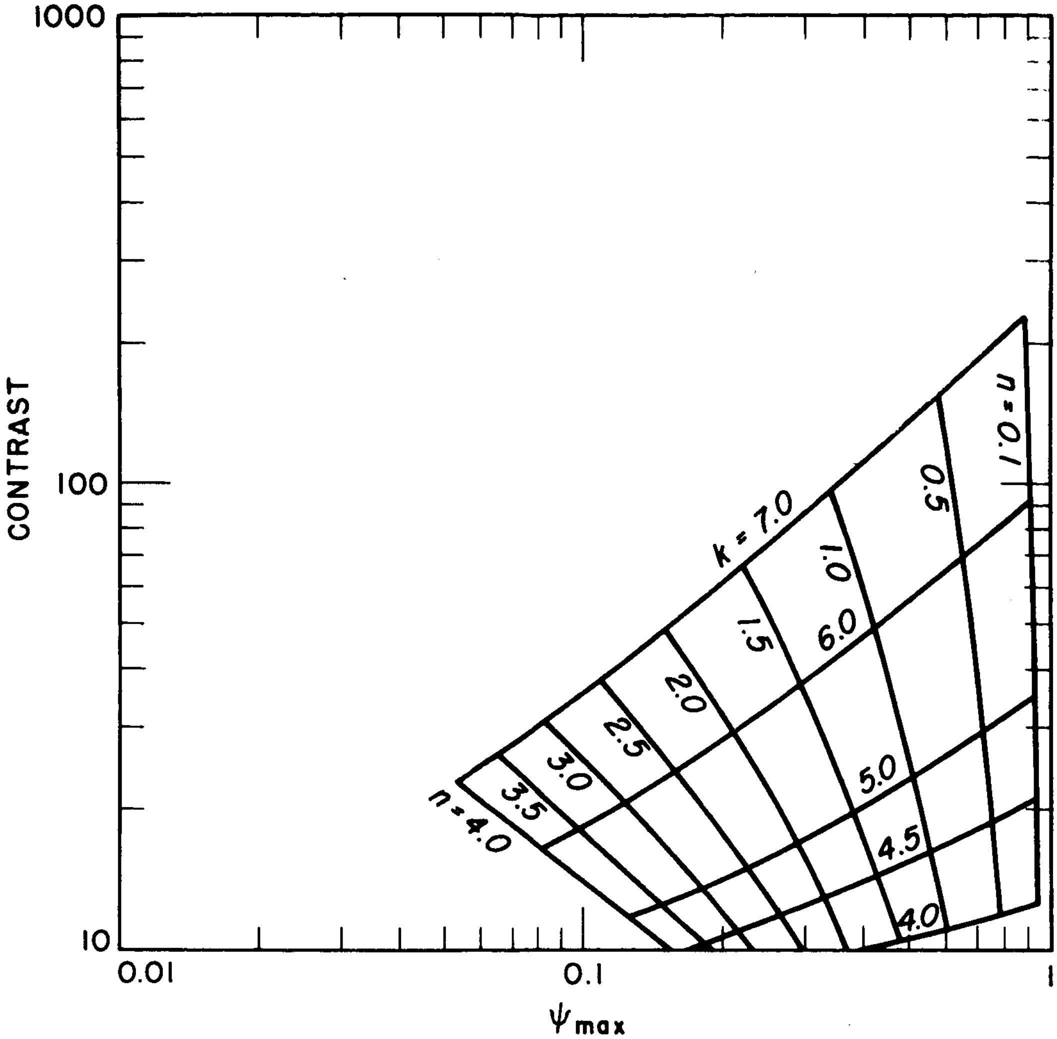


Figure 9. Complex N Mesh on Contrast versus ψ_{max} Coordinates for $d = 0.05\lambda$

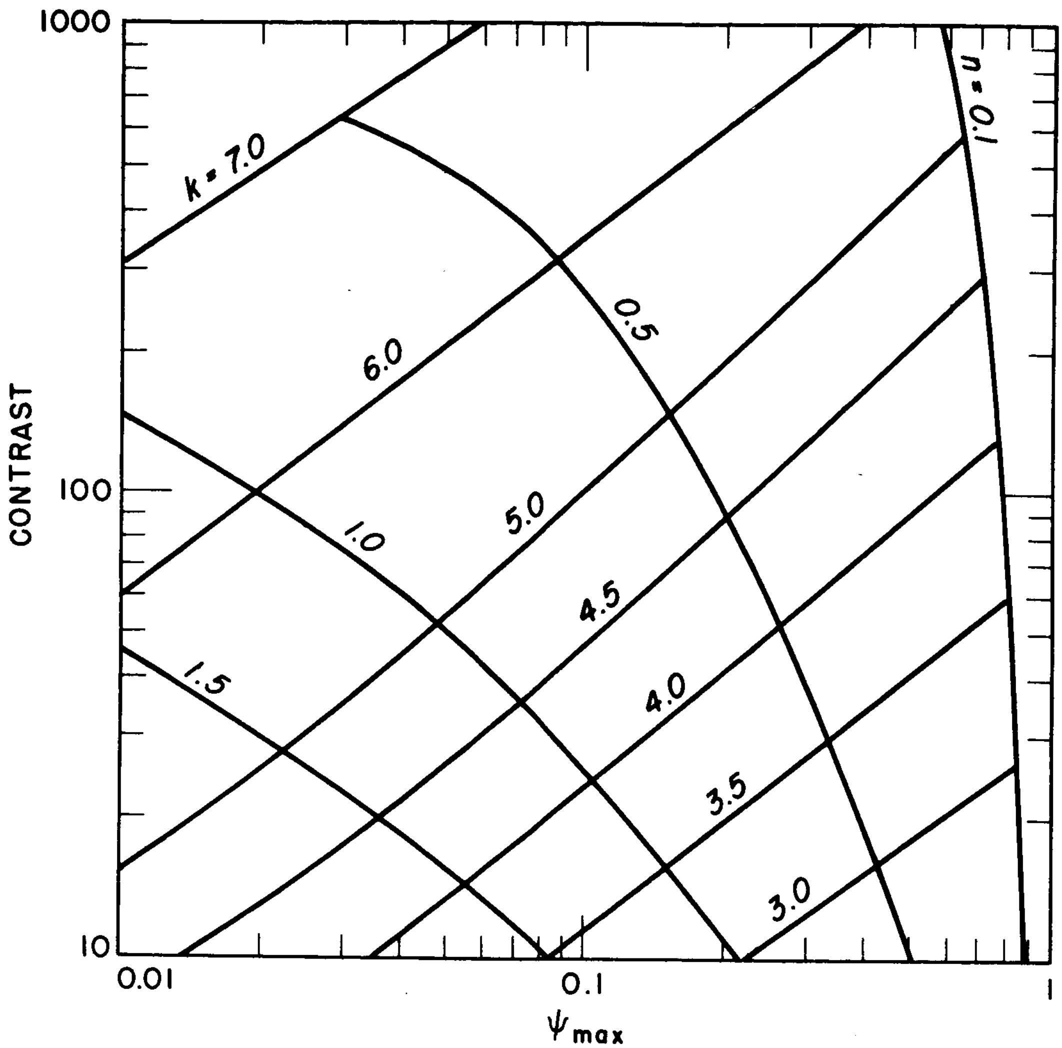


Figure 10. Complex N Mesh on Contrast versus ψ_{max} Coordinates for $d = 0.10\lambda$

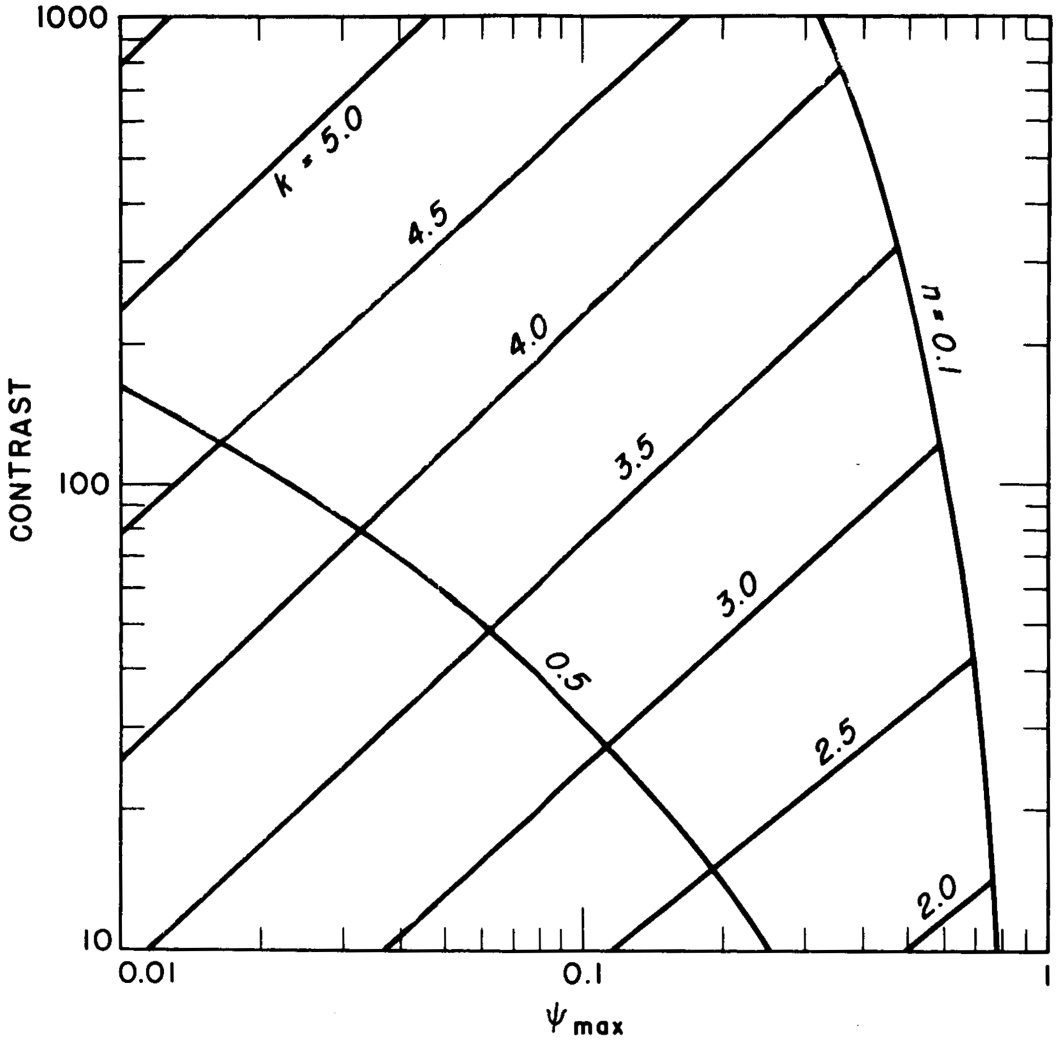


Figure 11. Complex N Mesh on Contrast versus ψ_{max} Coordinates for $d = 0.15\lambda$

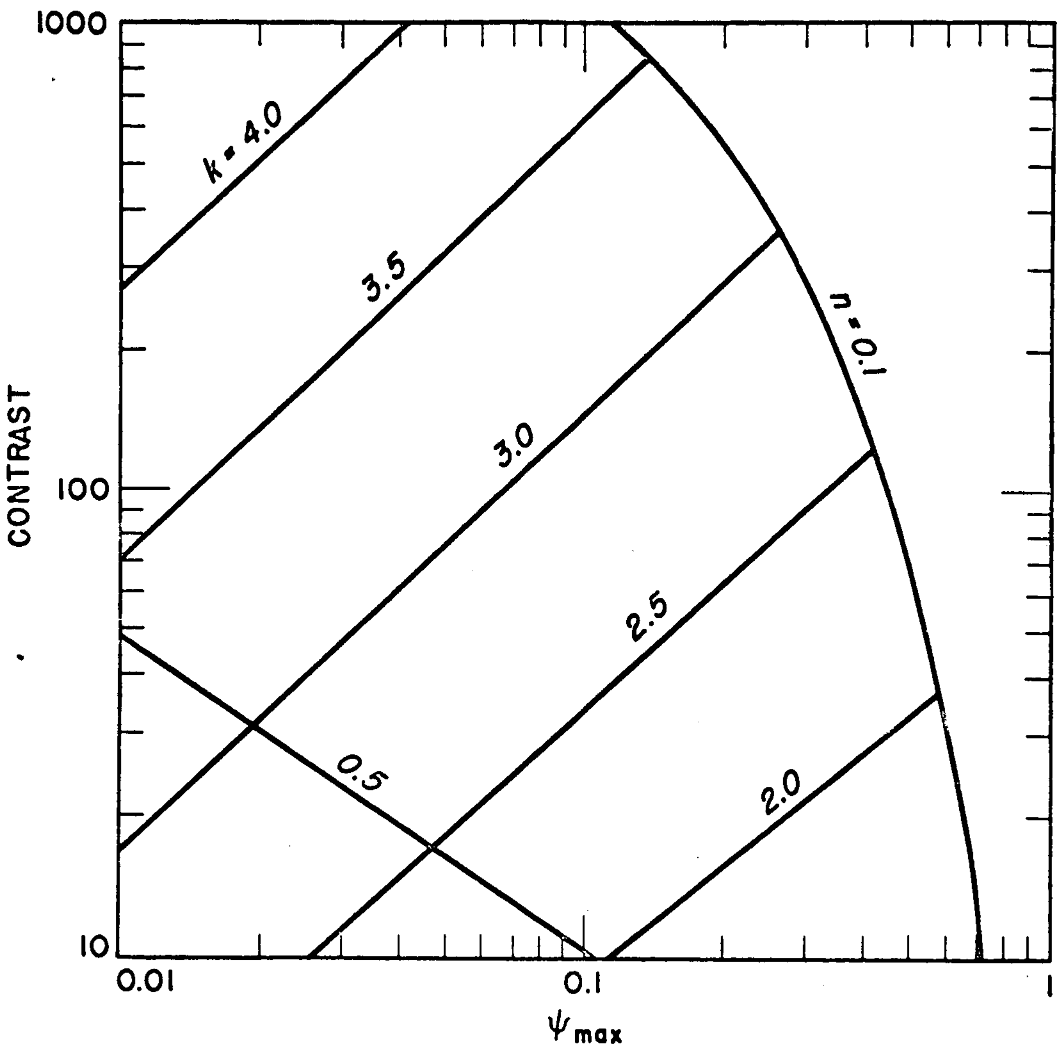


Figure 12. Complex N Mesh on Contrast versus ψ_{max} Coordinates for $d = 0.20\lambda$

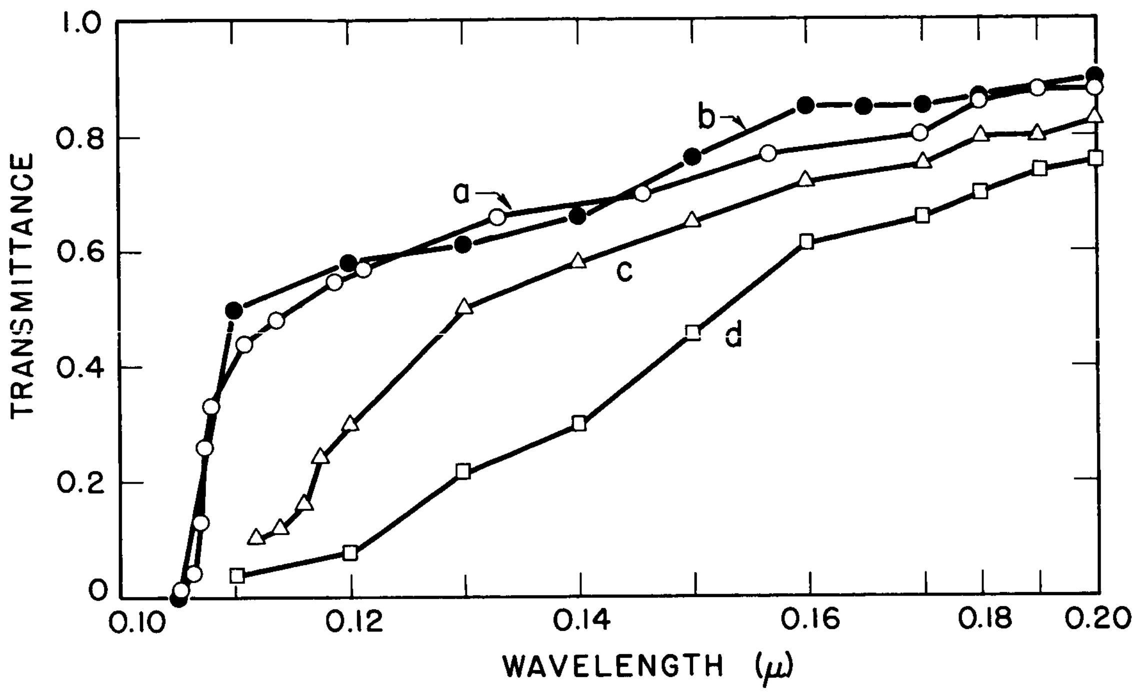

1.0
0.8
0.6
0.4
0.2
0
TRANSMITTANCE
0.10
0.12
0.14
0.16
0.18
0.20
WAVELENGTH (μ)
a
b
c
d

Figure 13

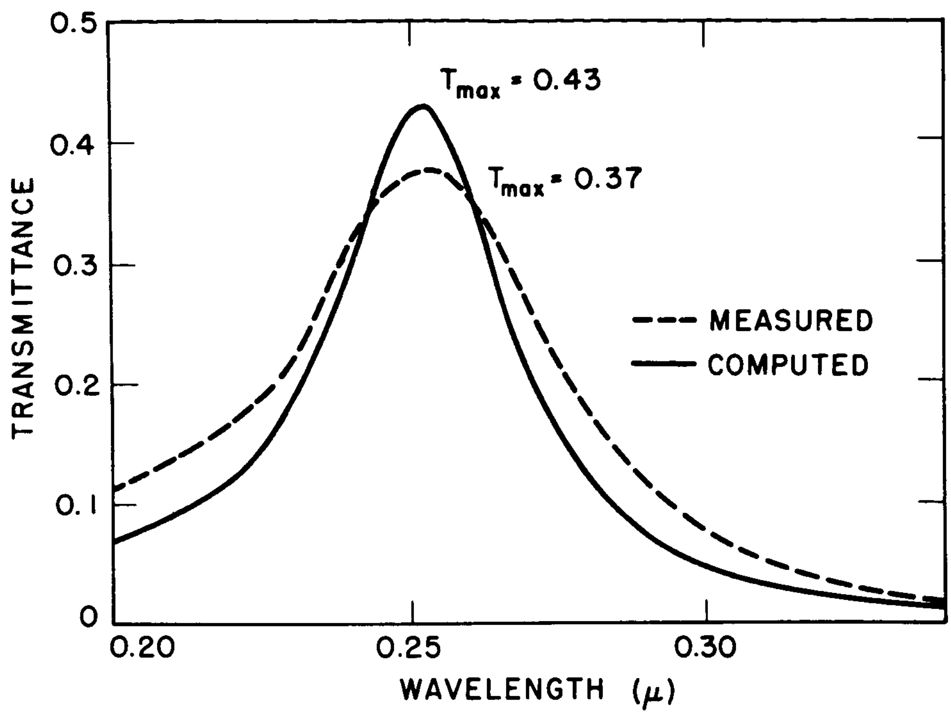

0.5
0.4
0.3
0.2
0.1
0
TRANSMITTANCE
T_{max} = 0.43
T_{max} = 0.37
MEASURED
COMPUTED
0.20
0.25
0.30
WAVELENGTH (μ)

Figure 14

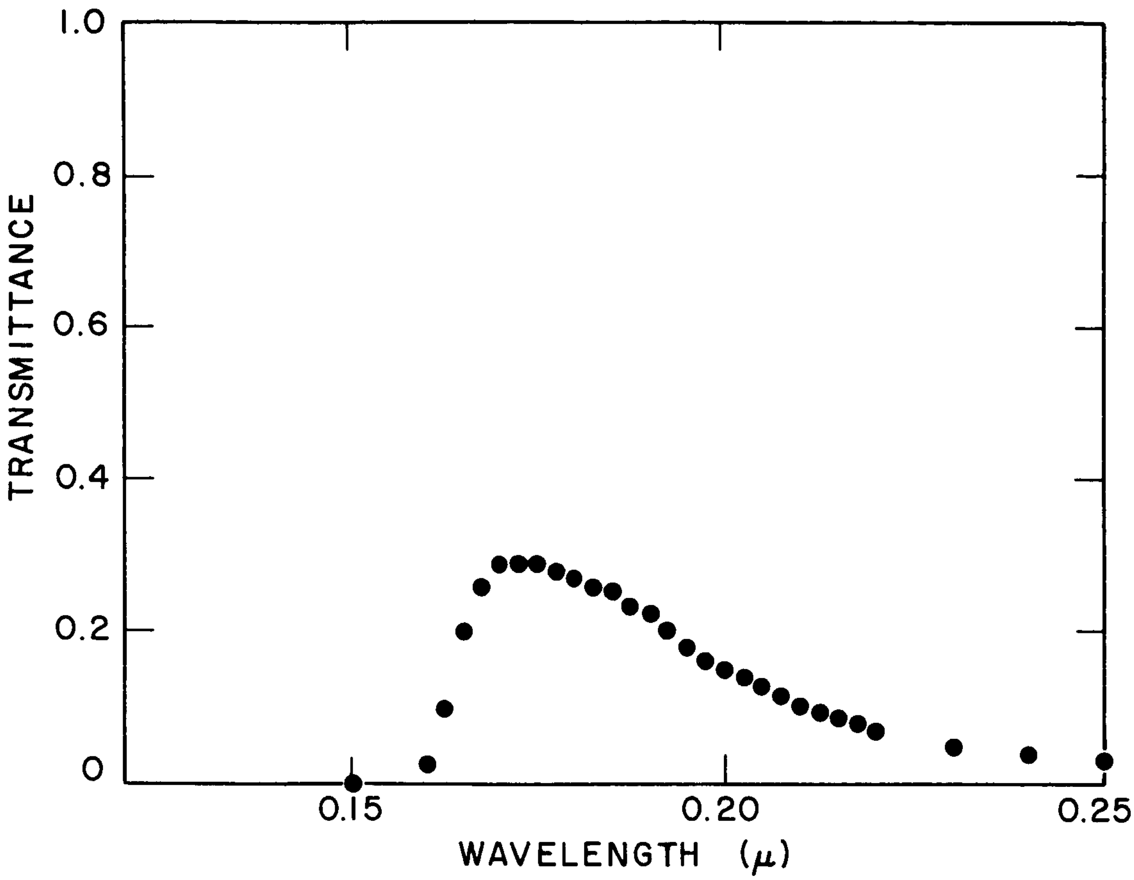


Figure 15

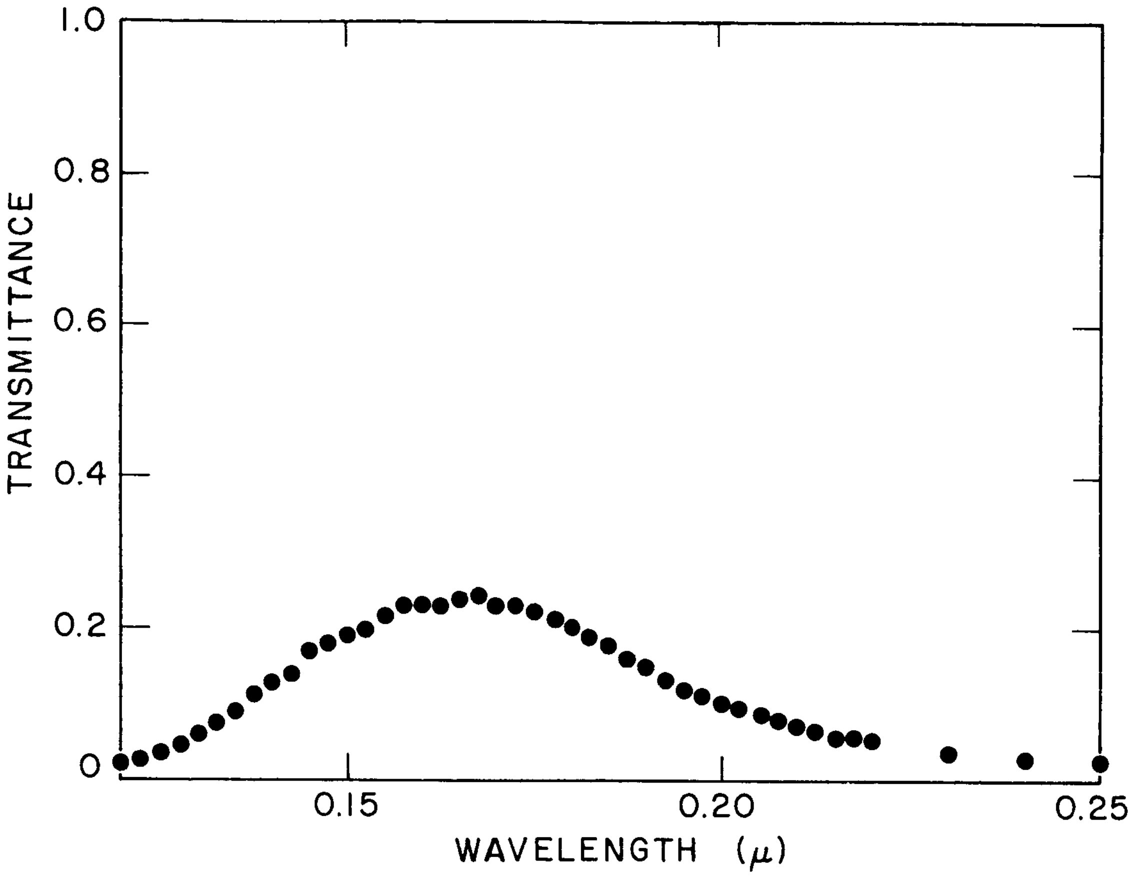


Figure 16

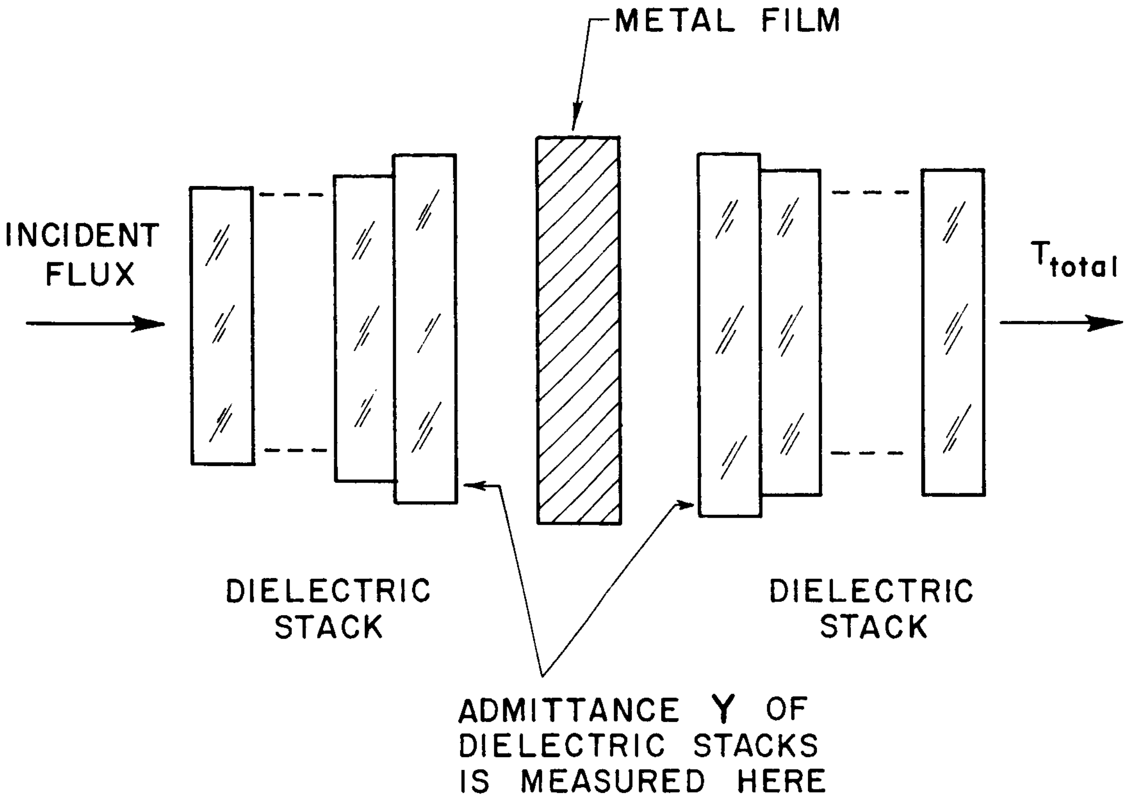

METAL FILM
INCIDENT FLUX
T_{total}
DIELECTRIC STACK
DIELECTRIC STACK
ADMITTANCE Y OF DIELECTRIC STACKS IS MEASURED HERE

Figure 17

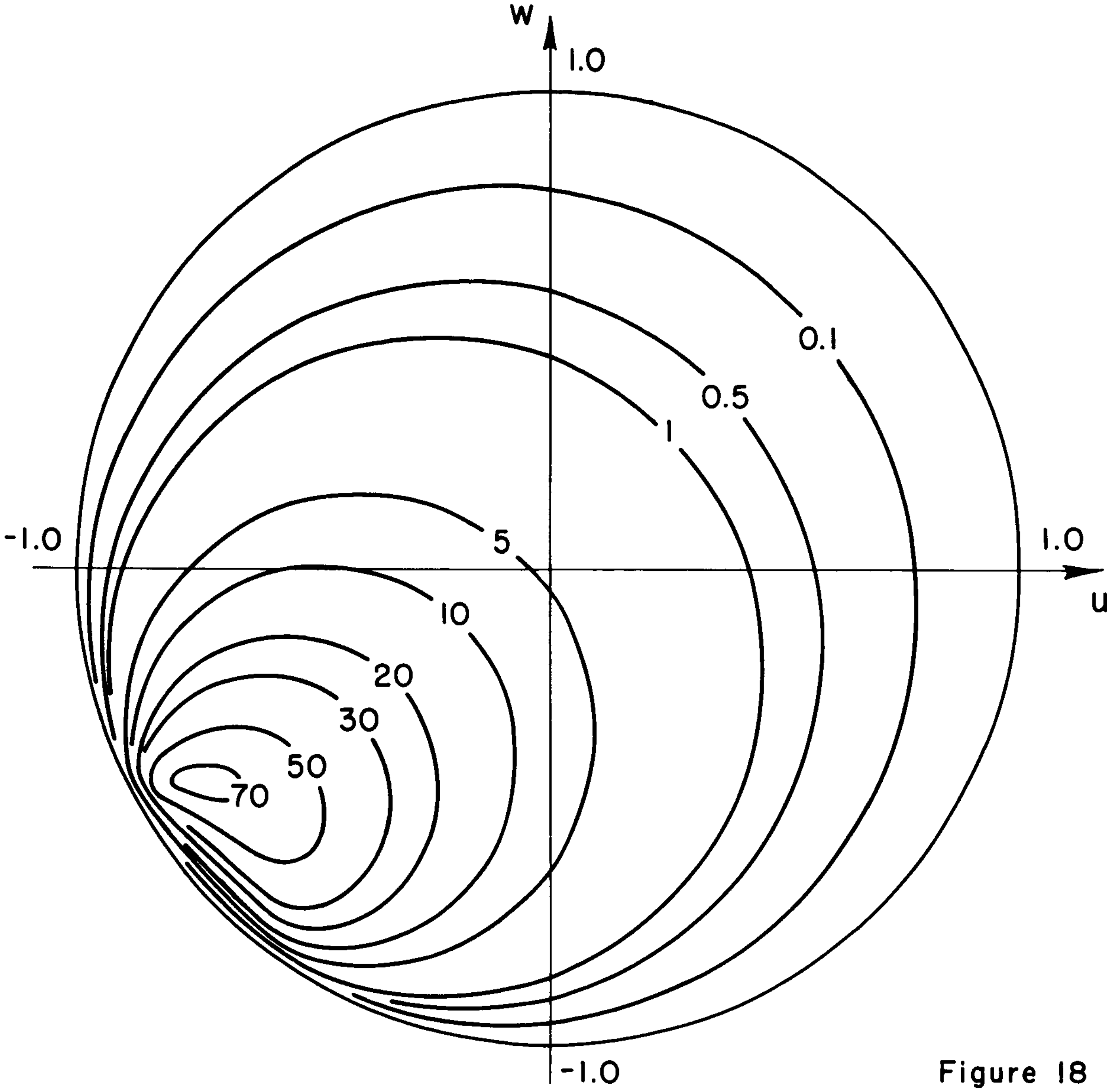
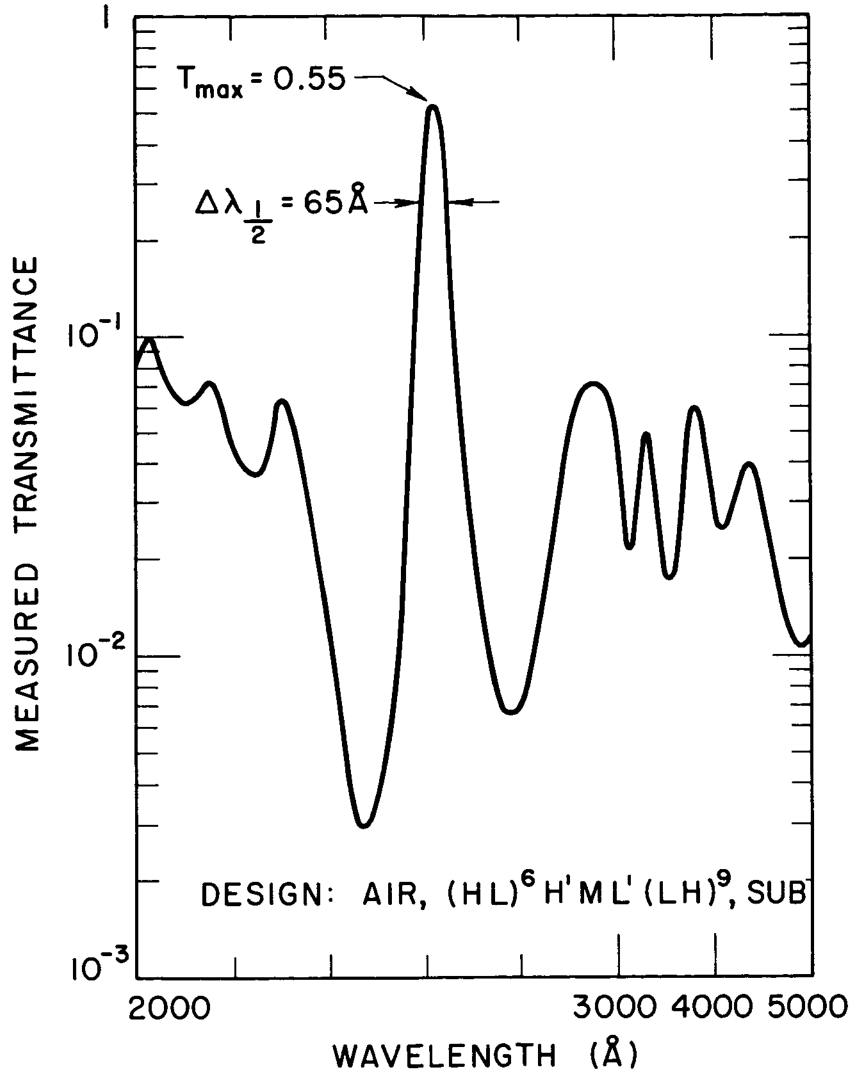


Figure 18



1
$T_{max} = 0.55$
$\Delta\lambda_{\frac{1}{2}} = 65 Å$
10^{-1}
10^{-2}
10^{-3}
MEASURED TRANSMITTANCE
DESIGN: AIR, $(HL)^6 H' M L' (LH)^9$, SUB
2000
3000 4000 5000
WAVELENGTH (Å)

Figure 19

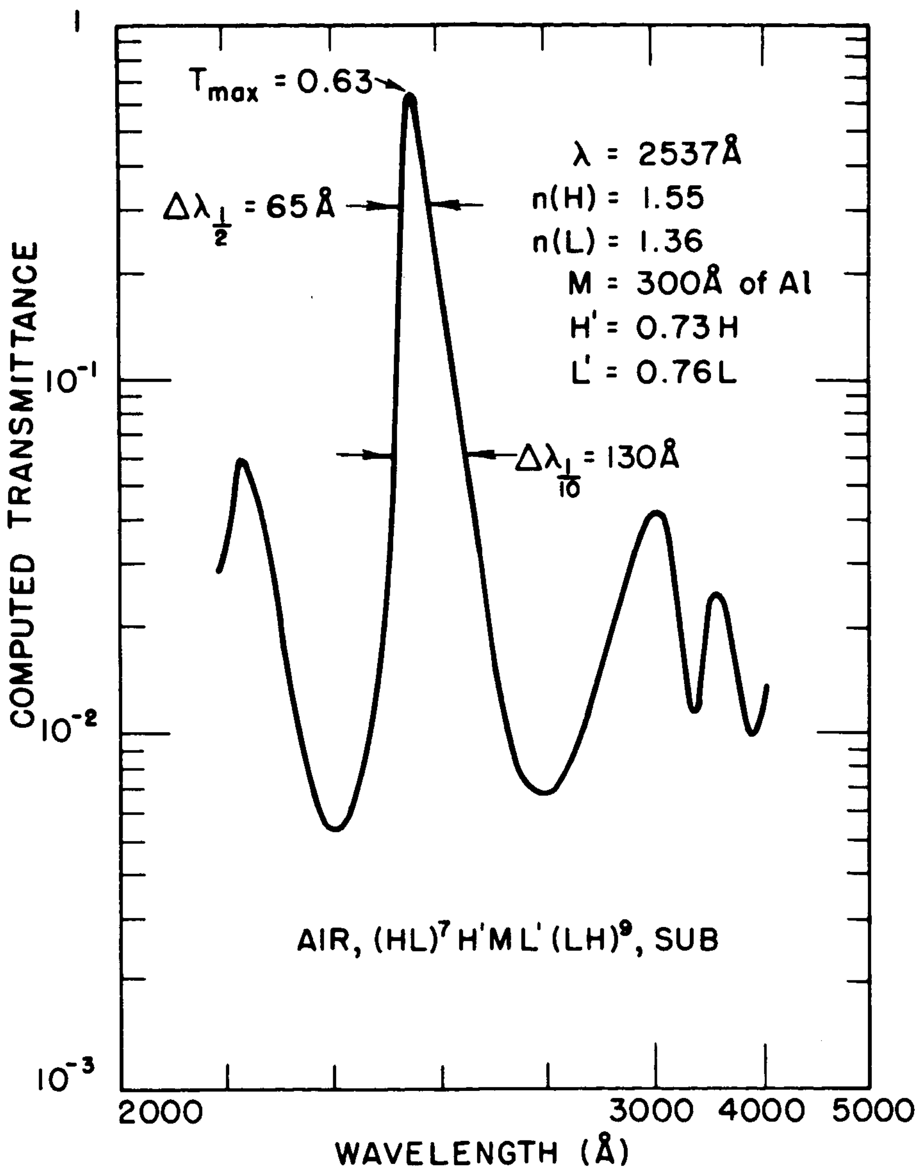


Figure 20. Computed Transmittance of a 1M Filter

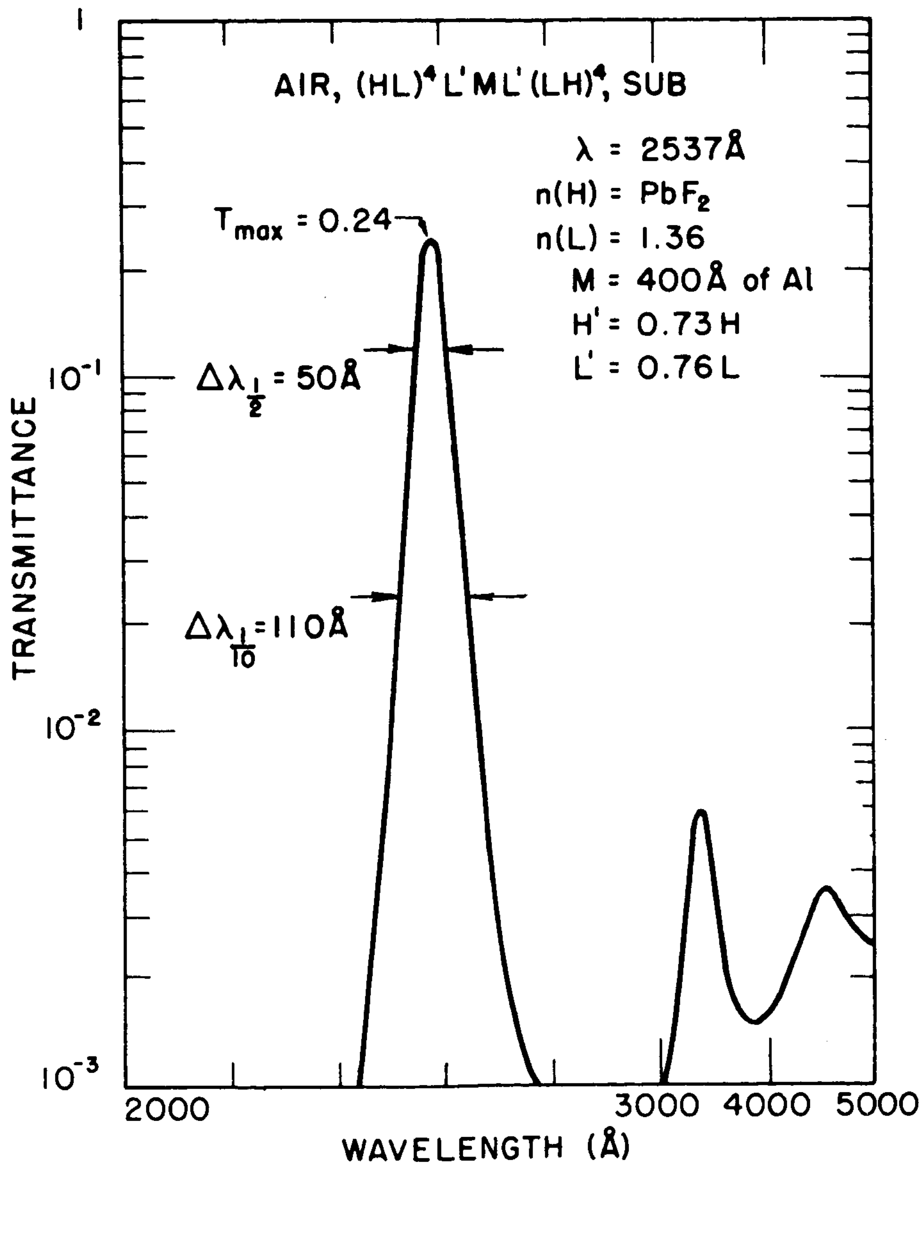


Figure 21. Transmittance of a 1M Filter Using PbF_2 as the High Index Material

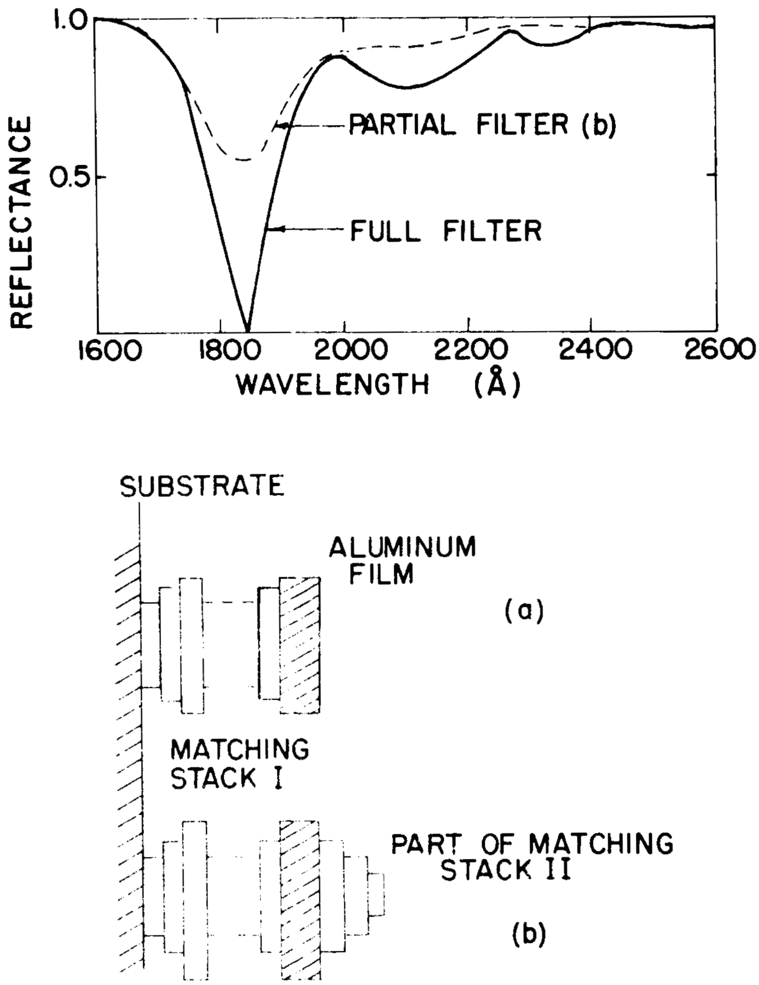
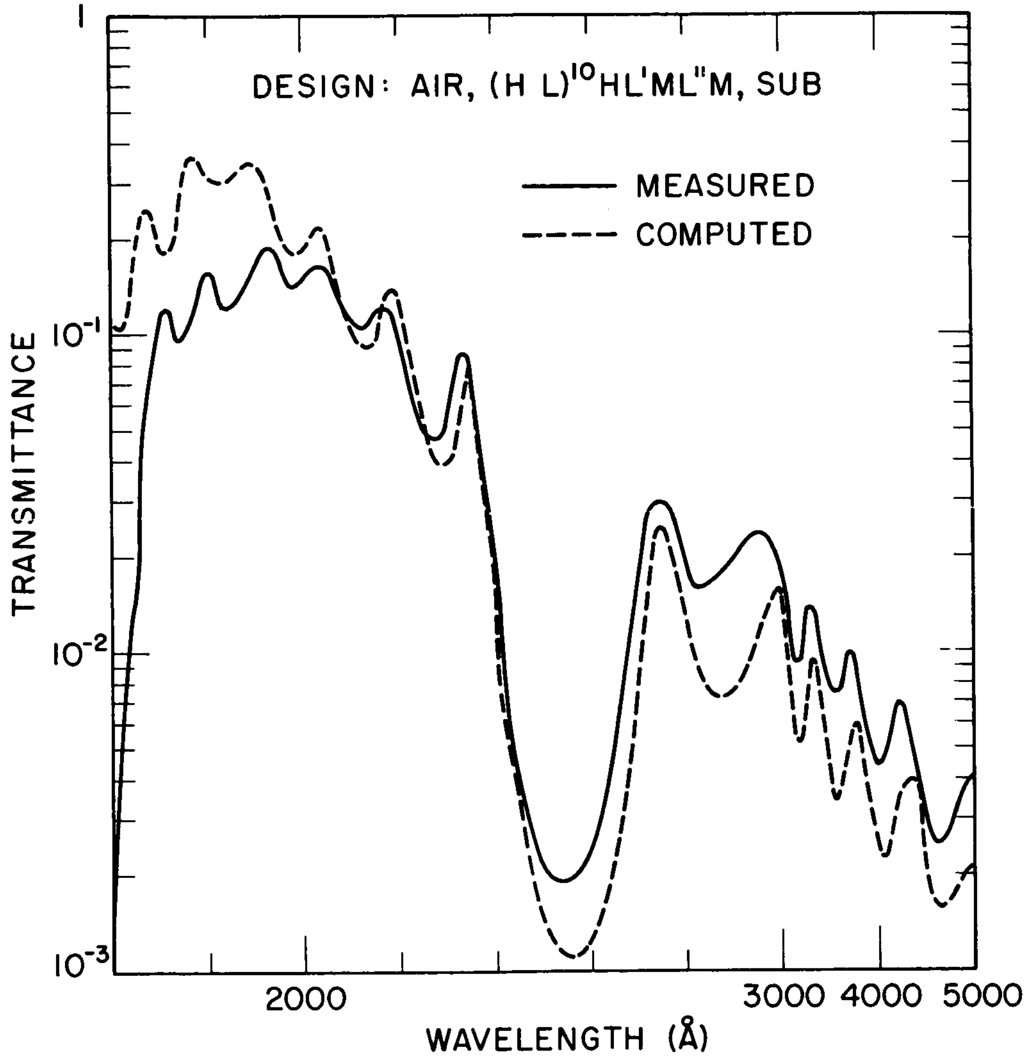
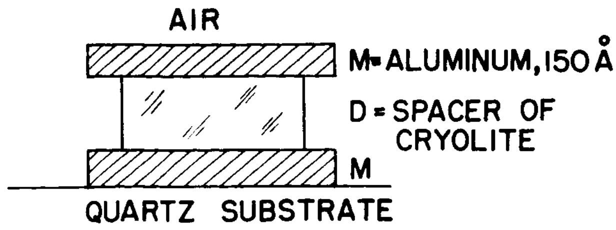

1.0
0.5
REFLECTANCE
PARTIAL FILTER (b)
FULL FILTER
1600
1800
2000
2200
2400
2600
WAVELENGTH (Å)
SUBSTRATE
ALUMINUM FILM
(a)
MATCHING STACK I
PART OF MATCHING STACK II
(b)

Figure 22

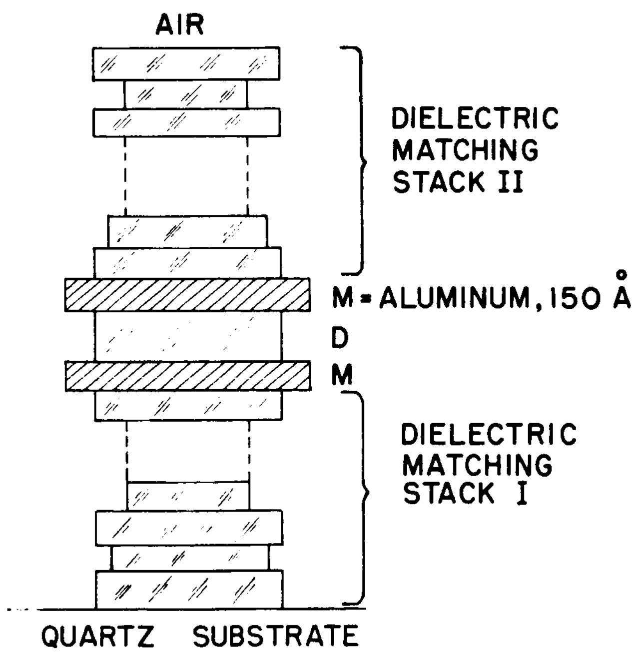


DESIGN: AIR, (H L)^10 HL'ML"M, SUB
MEASURED
COMPUTED
TRANSMITTANCE
1
10^-1
10^-2
10^-3
2000
3000
4000
5000
WAVELENGTH (Å)

Figure 23



CONVENTIONAL MDM FILTER



"T"- OPTIMIZED 2M FILTER

Figure 24

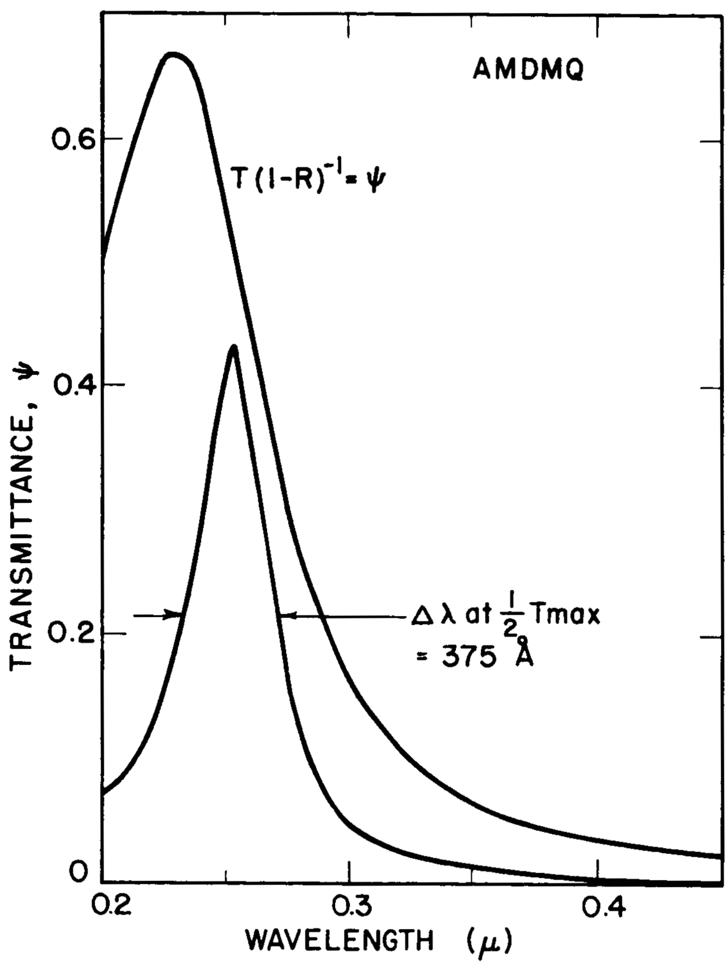

AMDMQ
$T(1-R)^{-1} = \psi$
$\Delta\lambda$ at $\frac{1}{2}$ Tmax
= 375 Å
TRANSMITTANCE, ψ
0.6
0.4
0.2
0
0.2
0.3
0.4
WAVELENGTH (μ)

Figure 25

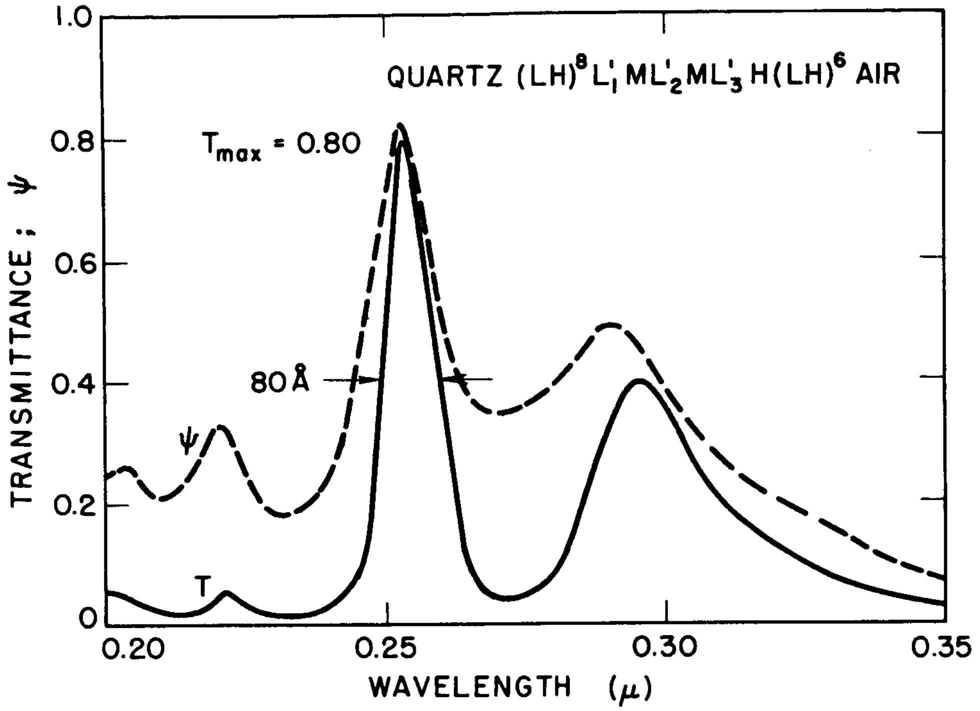
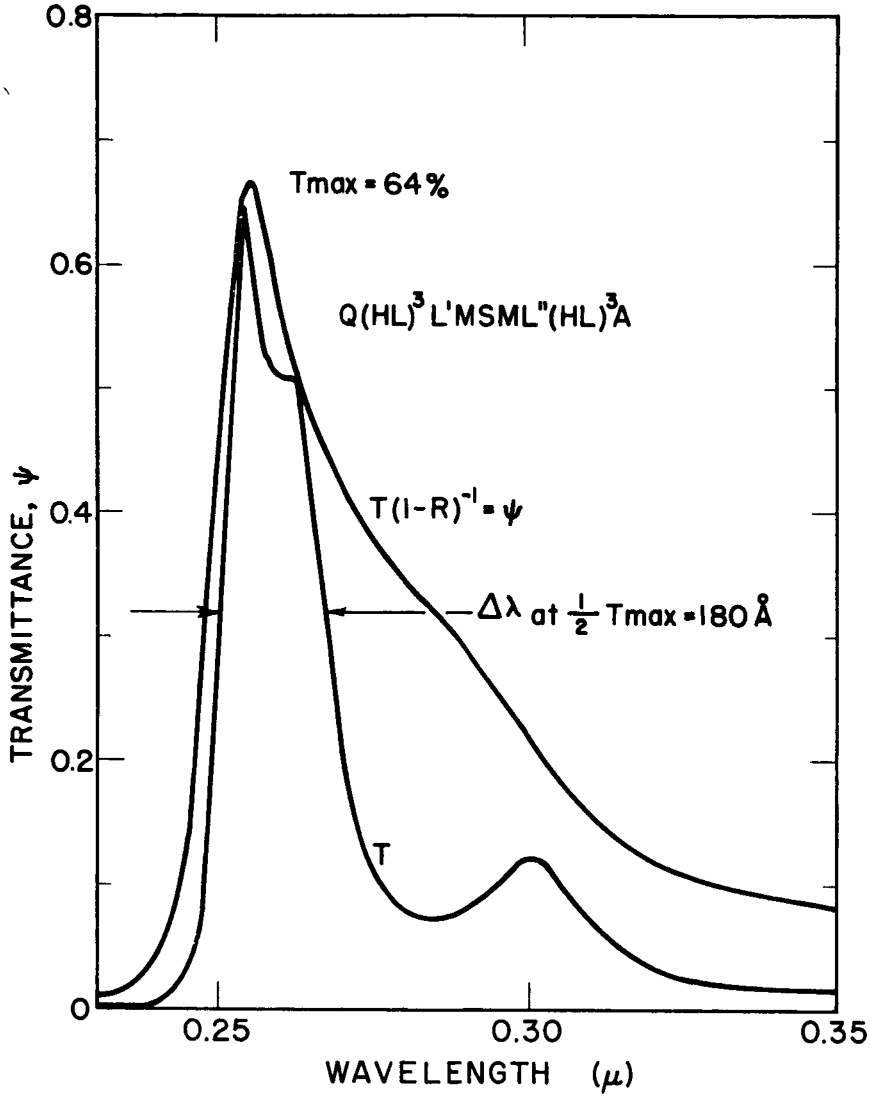

QUARTZ (LH)^8 L$'_1$ ML$'_2$ ML$'_3$ H(LH)^6 AIR
T_{max} = 0.80
80 Å
ψ
T
TRANSMITTANCE ; ψ
1.0
0.8
0.6
0.4
0.2
0
0.20
0.25
0.30
0.35
WAVELENGTH (μ)

Figure 26



Tmax = 64%
Q(HL)³L'MSML"(HL)³A
T(1-R)⁻¹ = ψ
Δλ at ½ Tmax = 180 Å
T
TRANSMITTANCE, ψ
WAVELENGTH (μ)
0.8
0.6
0.4
0.2
0
0.25
0.30
0.35

Figure 27