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ROCHESTER, NEW YORK

PROPERTIES OF MULTILAYER FILTERS

Interim Report

Covering the Period

September 1, 1965 to February 28, 1966

Research Grant No. NsG 308-63

with

National Aeronautics and

Space Administration

Washington 25, D. C.

Principal Invesitgator: P.W. Baumeister

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ABSTRACT

The circuitry and calibration of a solenoid-actuated shutter for the rapid firing of aluminum is described. An ultraviolet band-pass filter with an improved peak transmittance and narrower band width is designed. The filter consists of the conventional metal-dielectric-metal type filter augmented with dielectric stacks on either side of the metal layer:

air (diel.stack) M (spacer) M (diel.stack) substrate.

If M represents a 150Å thick aluminum layer, a computed peak transmittance of 80% is attained.

Experimental Program

RAPID SHUTTERING OF THE ALUMINUM A solenoid-actuated shutter was completed and is being calibrated. As shown in Fig. 1, the shutter consists of a Ledex rotary solenoid which is "potted" inside a metal can so that it does not contaminate the vacuum system. The shaft of the solenoid passes through a rotary vacuum lead-through to the shutter blade. The "pump out" enables us to leak-test the system while it is on the bench outside of the vacuum system. The O-ring seals for the cover are conventional and are not shown in the Figure. The shutter blade is in close proximity to the electron beam and if often "sprayed" with stray electrons--hence the blade is made of a refractory metal, such as tantalum. The electrical leads for the solenoid are not shown in Fig. 1. Fig. 2 is a photograph of the shutter.

ELECTRONIC CIRCUITRY

The electronic circuit which automatically closes the shutter is depicted in the block diagram of Fig. 3. The details of the individual circuits are given in a previous report.[1] The components in the boxes in Fig. 3 marked "A, B, C" are new additions to the circuitry.

The thickness of the aluminum film is measured by optical transmission monitoring. As aluminum is deposited on the substrate, the intensity of the 2536A radiation from the mercury lamp decreases. This light source--which is modulated at 400 cps--is imaged onto a photomultiplier. As shown in Fig. 3, this A.C. signal eventually reaches the full-wave rectifier, shown in box "A". The D.C. output is thence fed into the "Threshold trigger" via the cathode follower. The purpose of the "Threshold trigger" is to close the relay when the voltage drops to predetermined level. This relay in turn closes the solenoid shutter. This picture of the circuit is oversimplified for purposes of illustration. In the actual circuit, there are many other relays and interlocks. For example, when the solenoid shutter closes, it also shuts off the high voltage to the electron gun. This is essential, since the aluminum is evaporating at a quite rapid rate and the aluminum must be conserved. There are also numerous other interlocks in the circuit which prevent the shutter from closing until the actual evaporation is underway.

CALIBRATION OF SHUTTER

There are some time delays in the closing of the shutter--not the least of which is the time for the relay to close. There is also appreciable mechanical inertia in the rotary solenoid and also the "electrical inertia" of the inductance of the solenoid. Thus calibration runs were made with the automatic shutter in order to find the "transmission obtained" in terms of the "transmission setting." Aluminum was evaporated on a set of monitor plates at a pressure gage reading of 10^{-5} torr. The aluminum was evaporated with the electron beam (at 5 k.w. power) from a container in the shape of a "chalice" composed of TiB and BN. The aluminum-covered Suprasil test plates were removed from the vacuum chamber and their transmittance was measured on the Cary 14 spectrophotometer within 20 minutes after their exposure to air. The results are shown in Table I:

TABLE I

Desired transmittance at 2536A in %	Transmittance measured at 2500A in %	Plate number
10	8.9	1
10	15.3	2
10	12.4	3
10	15.0	4
10	14.8	5
5	7.9	6
5	6.9	7
5	7.3	8

With one exception, the transmission which was attained is larger than setting on the Varley potentiometer. This is probably due to the oxidation of the aluminum and, in fact, we observe that the transmission of the aluminum increases a day after it has been removed from the chamber.

1-M FILTER AT 1849A

Several evaporations have been made to deposit a "1-M" type of filter for 1849A. The thickness of the matching stack of dielectric films of of cryolite and thorium fluoride were monitored in reflection using the 1849A emission line from a mercury discharge lamp. The intensity of the 2536A line from the lamp is at least ten times stronger than the 1849A line. Even though a filter was used which attenuated the 2536A line by a factor of 100, this attenuation was not sufficient to evaporate the final matching stack of the filter.

The procedure used to deposit the filter is as follows: (1) The matching stack (composed of cryolite and ThF_4) is deposited on the quartz substrate. This is shown as "matching stack I" in Fig. 5. These films are deposited by reflection monitoring at 1849A. Here, the small residual intensity of the 2536A does not interfere with the accurate monitoring at 1849A.

(2) The aluminum layer is deposited on top of this matching stack. Here, transmission monitoring is used to measure its thickness.

(3) The second matching is deposited on top of the aluminum. The thickness of the films is determined by reflection monitoring off of the aluminum at 1849A. As the successive layers of the matching stack are deposited, the reflectance at 1849A decreases. As depicted in Fig. 5, the reflectance shown by

the dashed line would typically result after five layers had been deposited. When the full filter is completed, the reflectance should go to zero, as shown by the solid line in Fig. 5. However, the reflectance at 2536A in either case is essentially unaltered by the addition of the matching stacks and close to 85%. The net result is that the component of the 2536A which "leaks" through the filter in front of the photomultiplier becomes stronger and stronger in comparison with the 1849A as the "1-M" filter is completed.

The "1-M" filters which were prepared had an adequate peak transmittance--20%--but the contrast--i.e., rejection was poor--of the order of 2%. Since an acceptable 1-M filter should have at least a 100:1 rejection ratio of the "side transmittance" compared with the peak transmittance, these filters are not adequate. Hence, no transmittance curves are included for these filters.

Theoretical Program

OPTIMUM DESIGN OF M D M TYPE OF FILTER A previous publication[2] has discussed the "optimum" design of a "1-M" type of filter. 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 radiant energy which is transmitted through the entire filter, which we have designated as T_{max}. These same design considerations can apply to filters which have two or more metal layers in them. The net effect is that the maximum transmittance of the conventional MDM filter can be markedly increased by adding stacks of dielectric matching layers to each side of the filter, as shown in Fig. 6. In this report, this latter type of filter is called a "transmittance-optimized" or simply a "T-optimized" 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.

COMPARISON OF FILTERS

Fig. 7 depicts the spectral transmittance of the conventional MDM type of filter. The dielectric layer of cryolite has a quarter-wave optical thickness of 3490A and the aluminum metal layer is 150A in physical thickness. The maximum transmittance is 43% and the full width at $\frac{1}{2} T_{max}$ is 375A. In actual practice, a thicker aluminum layer is usually used and hence the bandwidth is slightly narrower. The maximum transmittance through a 150A layer of aluminum is 91%. Hence the maximum transmittance of the MDM could be as high as $(91)^2 = 83\%$, if the MDM were properly matched with dielectric stacks. Thus, the maximum transmittance of the MDM can be nearly doubled and a narrower bandwidth 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.

DESIGN PROCEDURE

The design procedure for the augmented MDM filter is as follows: (1) We specify that the aluminum film is 150A in thickness. Then the matching stack (designated as "stack I" in Fig. 6) is designed so that the maximum net radiant flux is transmitted through the aluminum film. This is accomplished using graphical data computed by Costich[2]. (2) A similar dielectric matching stack (designated as "stack II" in Fig. 6) is designed for the other 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 from inside of the "D" spacer layer is now computed. The optical thickness of the spacer layer is chosen so that a "resonance" condition is obtained at λ_o , which is 2536A in this example. The entire stack is assembled and the resulting filter:

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

as shown in Fig. 6, is obtained. The H and L in this design represent quarter-waves of thorium fluoride (index 1.55 at 2536A) and cryolite (index 1.36). The computed spectral transmittance of the resulting filter is shown in Fig. 8. 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 80A, in comparison with the full width of 375A for the MDM shown in Fig. 7. Fig. 9 shows the transmittance of a similar "T-Optimized" MDM filter, but with a stack of lead fluoride and cryolite for the matching stack. The peak transmittance is 64%, in comparison with the 80% of the filter in Fig. 8. This difference is not due to an improper design of the matching stack, but can be attributed to the residual optical absorption in the lead fluoride at 2500A. Using the data of Krebs,[4] the optical constant of lead fluoride at 2536A is $n = n - ik = 2.10 - i\ 0.02$. 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 is large and hence the small absorption of the films is enhanced. Another feature of the design shown in Fig. 9 is that the "side-band" transmission peak at 3000A is much smaller than the comparable design in Fig. 8. This can be attributed to the dispersion of the refractive index of the lead fluoride.

PROPERTIES OF THE MDM FILTER

The main advantage of this type of "T-Optimized" design is its high peak transmittance. Thus, 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. However, the success of filter would depend upon the suppression of the "side-band" transmission peaks. It would be fruitful to study methods of achieving this side-band suppression.

TRANSMISSION CONTOURS FOR 1849A

Since we are designing and constructing 1-M type filters for the spectral region near 1849A, we have computed a set of transmittance contours for a film 250A thick aluminum film at 1849A. The optical constants of the aluminum were supplied by W. R. Hunter at the Naval Research Laboratory. These contours are similar to those described in a previous report for aluminum at 2536A. They are shown in Figs. 10 and 11.

PERSONNEL During the previous six-month period, the following persons contributed to the projects described in this report:

P. W. Baumeister, Principal Investigator

Robert L. Maier, who is working on a M.S. Thesis on ultraviolet filters. The filters depicted in Figs. 6, 7, 8 were designed by Mr. Maier and are part of his M.S. Thesis. He also calibrated and "debugged" the automatic shutter.

References to the Literature

1. Report of NsG 308-63 in the period 3/1/64 to 8/31/64.
2. V. R. Costich, Ph.D. thesis, Univ. of Rochester, 1965. Figs. 11-14. Dr. Costich is presently preparing this thesis for publication.
3. P. H. Berning and A. F. Turner, J. Opt. Soc. Am. 47, 230 (1957). This general type of design is shown in Fig. 4 of this ref., although no specific details or examples are given.

4. G. Honcia and K. Krebs, Z. Physik 165, 202 (1961).

5. Report of NsG 308-63 in the period 3/1/64 to 8/31/64, Fig. 3.

6. P. W. Baumeister, V. R. Costich and S. C. Pieper, App. Opt. 4, 911 (1965).

Captions to the Figures

1. Cross section of the solenoid-actuated shutter. This is not to scale.
2. Photograph of the solenoid-actuated shutter mounted in the evaporator. The shutter is in the open position and the electron gun evaporation source is exposed.
3. Block diagram of the circuitry which actuates the solenoid shutter.
4. The threshold trigger circuit which actuates the relay which in turn closes the solenoid.
5. Showing the spectral reflectance at various stages in the manufacture of a 1-M filter. The partial filter in Fig. (a) consists of the first matching stack and the aluminum film. In Fig. (b) the second matching stack has been partially completed and reflectance (shown as dashed line) is decreasing at 1849Å as additional layers are added to the matching stack.

6. Design of: (a) A conventional M D M type filter using aluminum and a cryolite "D" spacer. (b) A "T-Optimized" M D M type filter in which dielectric matching stacks are added to each half of the filter.

7. The computed spectral transmittance of a M D M filter on quartz substrate. The M layer is aluminum of 150A physical thickness and the "D" layer is cryolite (index 1.36) which has a quarter-wave optical thickness of 3490A. The net energy flow, Ψ , is also shown.

8. The computed spectral transmittance and net energy flow, Ψ , of a "T-optimized" 2-M filter deposited on a quartz substrate, Q . The metal layer M is aluminum 150A in thickness and L , H represent films of cryolite (index 1.36) and thorium fluoride (index 1.55), respectively of quarter-wave optical thickness at 2536A. The matching films L' and L" represent cryolite films of .825 and .816 QWOT at λ = 2536A, respectively, and the spacer layer S is 1.71 QWOT at the same wavelength.

9. The transmittance T and net energy flow, Ψ , of a "T-optimized" 2-M filter deposited on a quartz substrate Q . The metal layer M is aluminum of 150A in thickness and L, H , represent films of cryolite

(index 1.36) and lead fluoride (whose index is dispersive) respectively of quarter-wave optical thickness at 2536A. The layers L', L" and S represent cryolite films of quarter-wave optical thickness .848 QWOT, .85 QWOT, and 1.67 QWOT, respectively, at λ = 2536Å.

10,11. Contours of constant transmittance (shown in percent) in the reflectance plane for an aluminum film of 250Å physical thickness at 1849Å. The optical constant of the aluminum is

n = n - i k = 0.11 - i 1.95 .

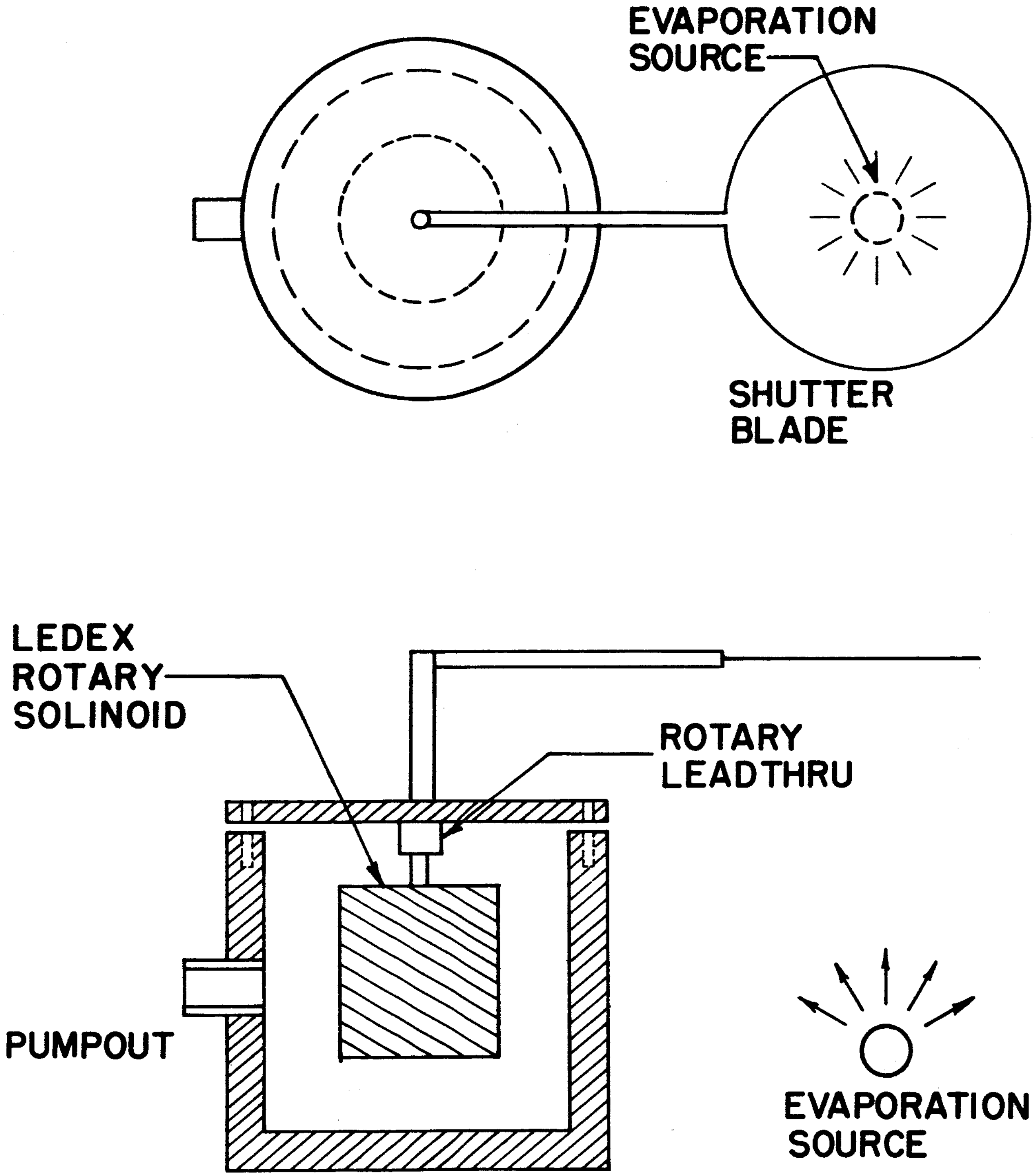
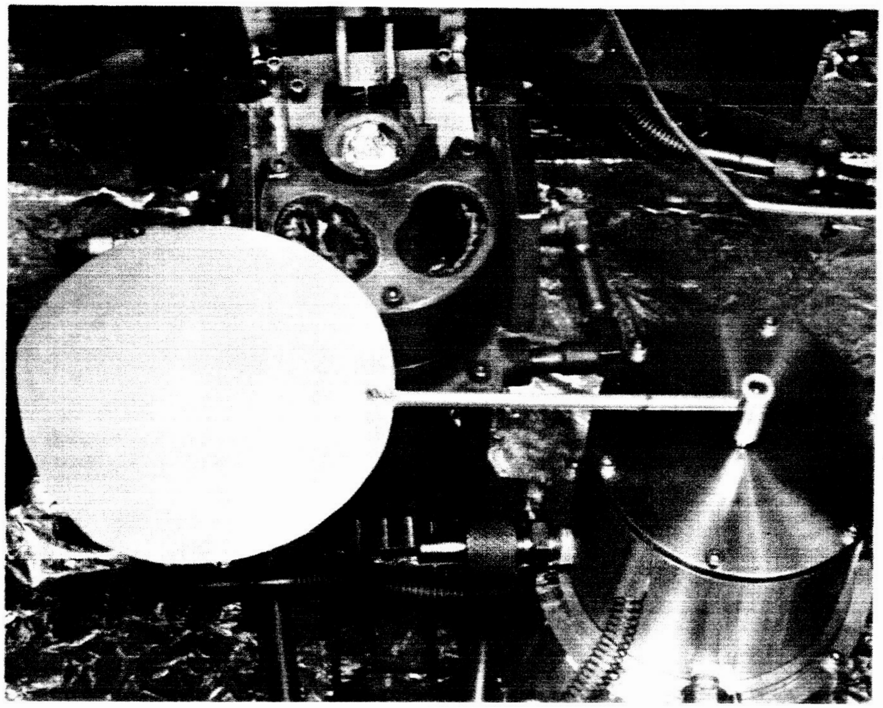

EVAPORATION
SOURCE
SHUTTER
BLADE
LEDEX
ROTARY
SOLINOID
ROTARY
LEADTHRU
PUMPOUT
EVAPORATION
SOURCE

FIG. 1



Photograph of the solenoid shutter as it is installed in the vacuum chamber. The shutter blade is at the left and the electron-beam evaporation source is at the upper center

F I G U R E 2

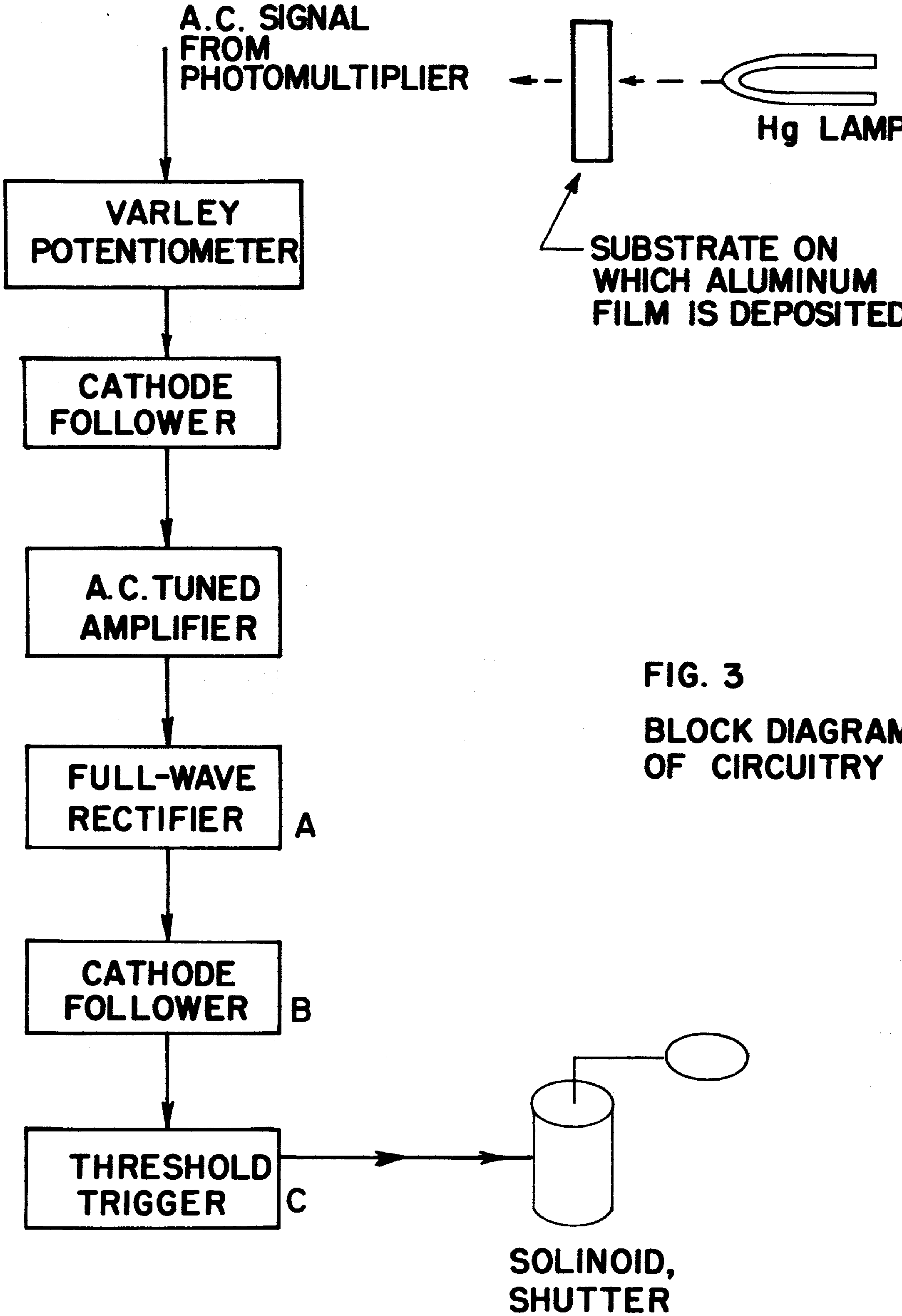
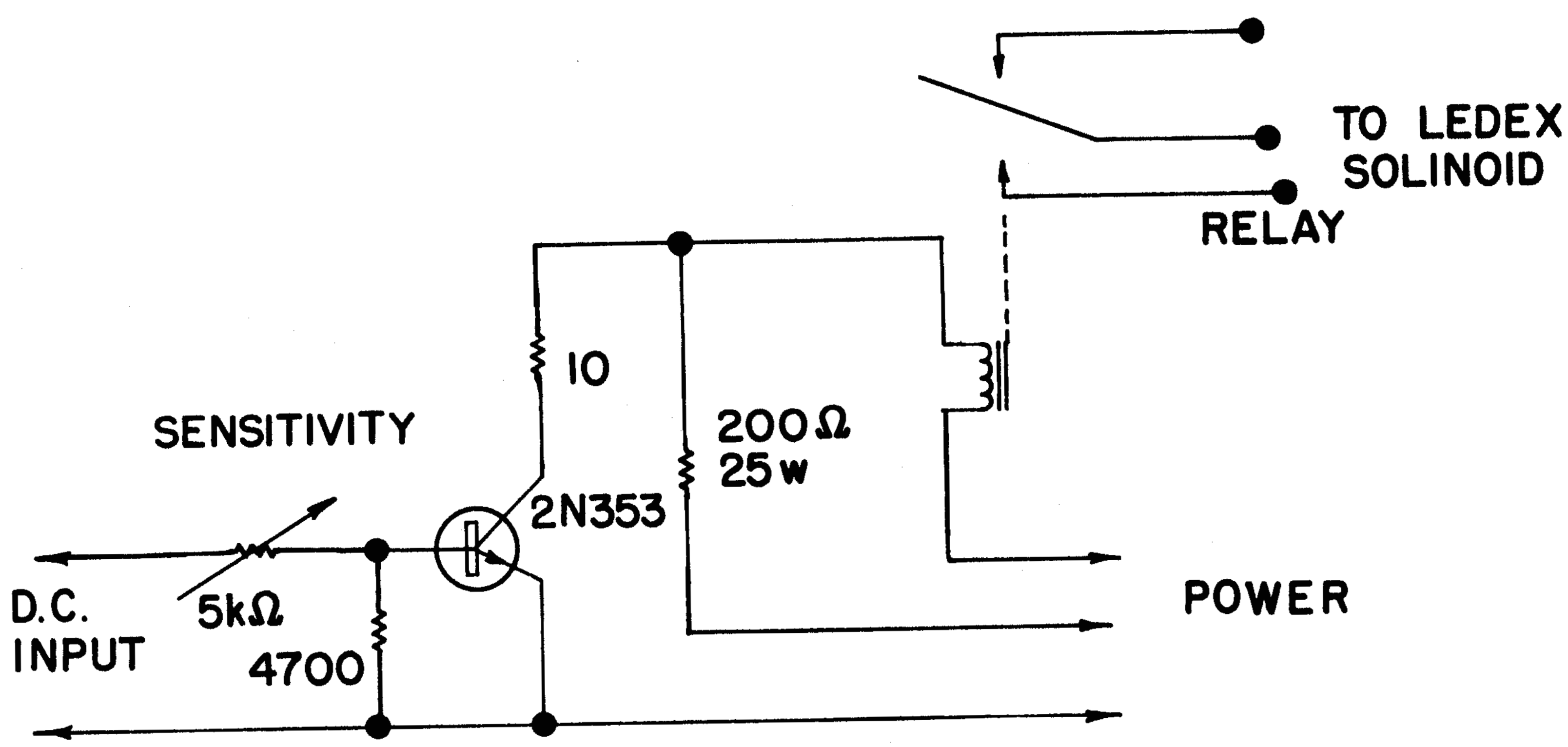


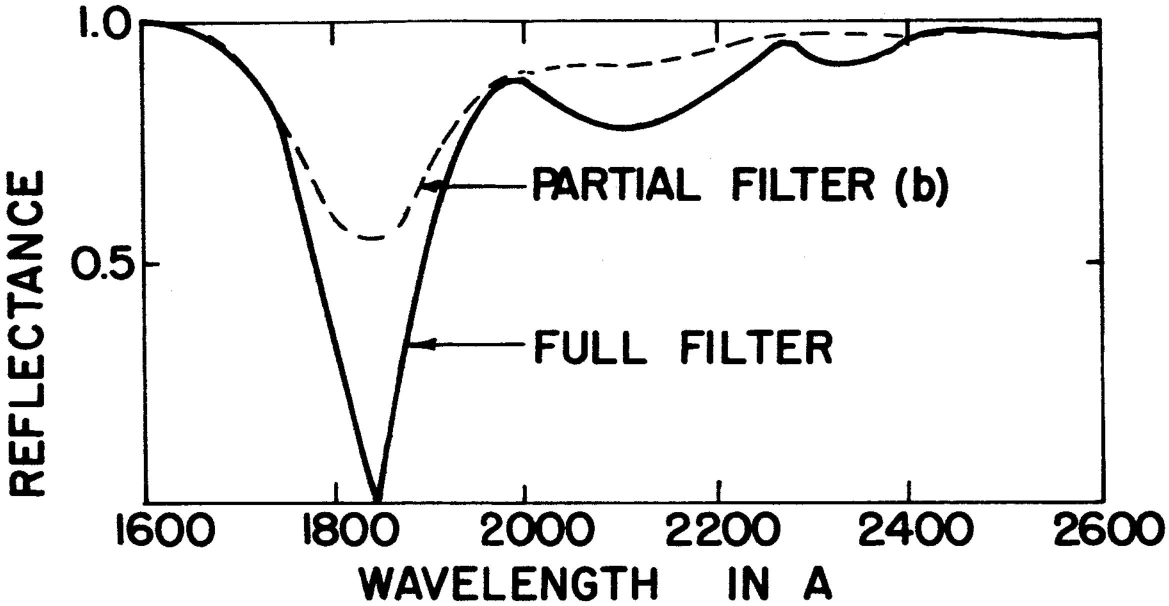
FIG. 3

BLOCK DIAGRAM
OF CIRCUITRY



TO LEDEX
SOLINOID
RELAY
10
SENSITIVITY
200Ω
25 w
2N353
D.C.
INPUT
5kΩ
4700
POWER

FIG. 4


1.0
0.5
REFLECTANCE
PARTIAL FILTER (b)
FULL FILTER
1600
1800
2000
2200
2400
2600
WAVELENGTH IN A

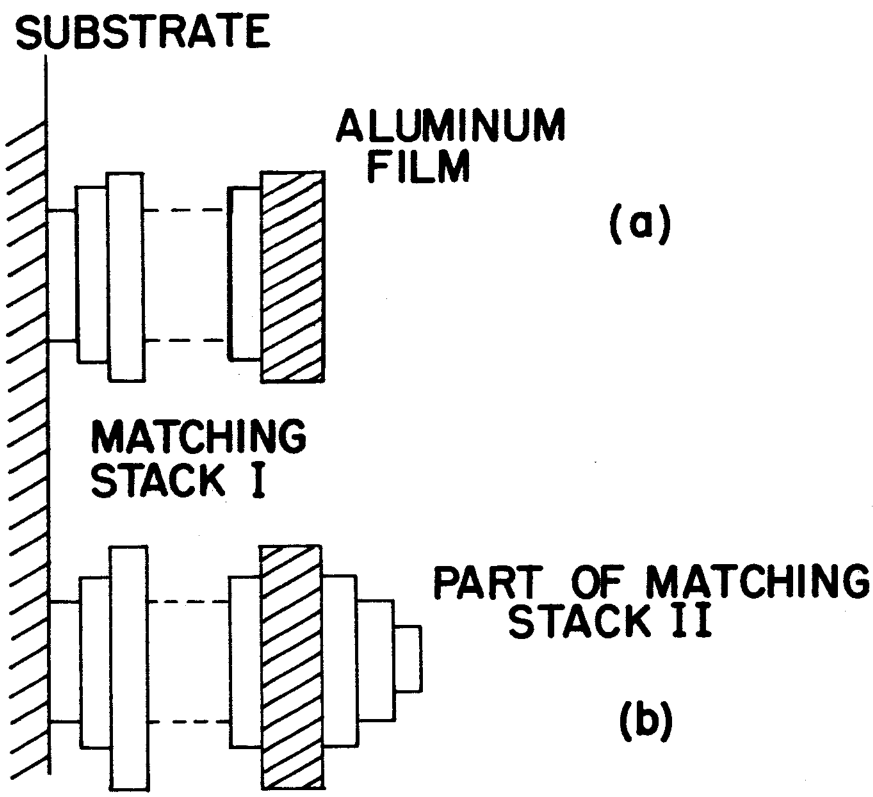
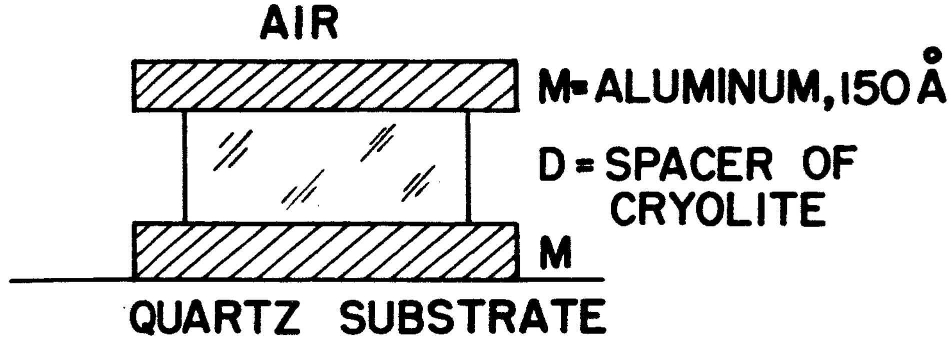
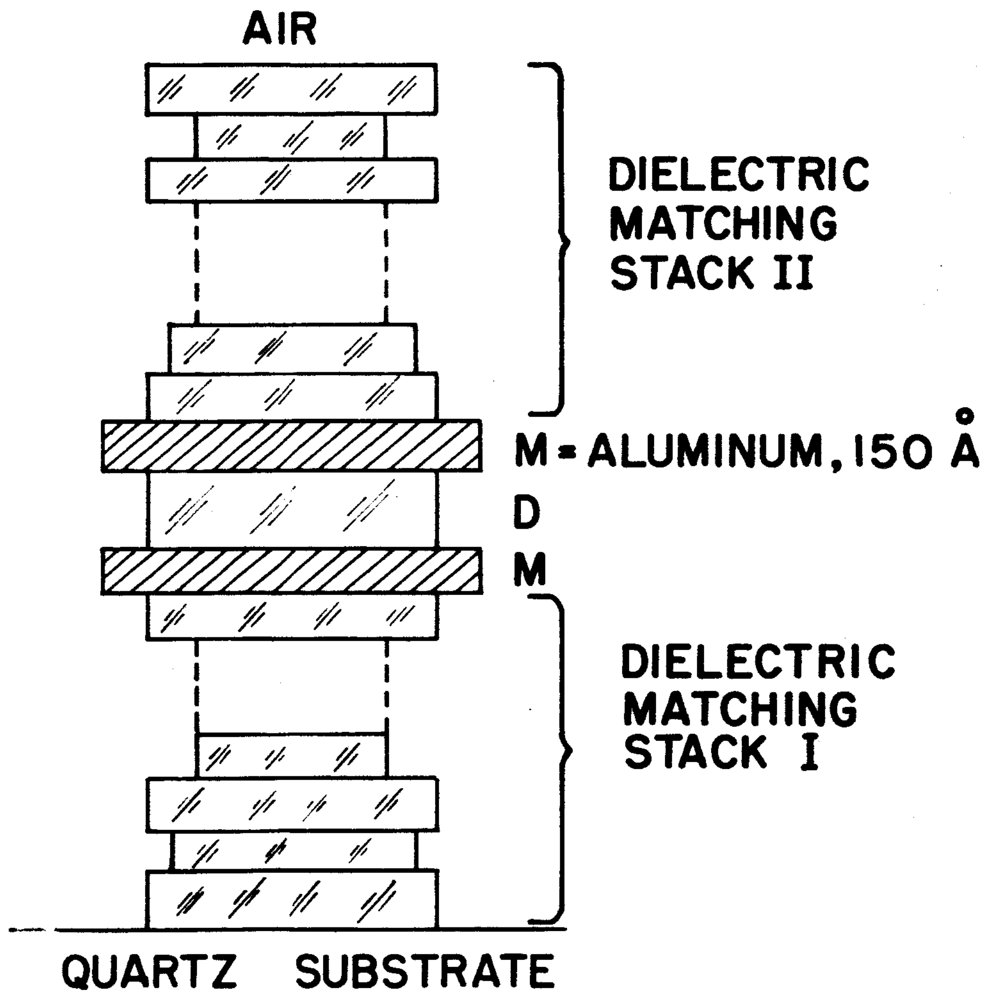

SUBSTRATE
ALUMINUM FILM
(a)
MATCHING STACK I
PART OF MATCHING STACK II
(b)

FIG. 5



CONVENTIONAL MDM FILTER



"T"- OPTIMIZED 2M FILTER

FIG. 6

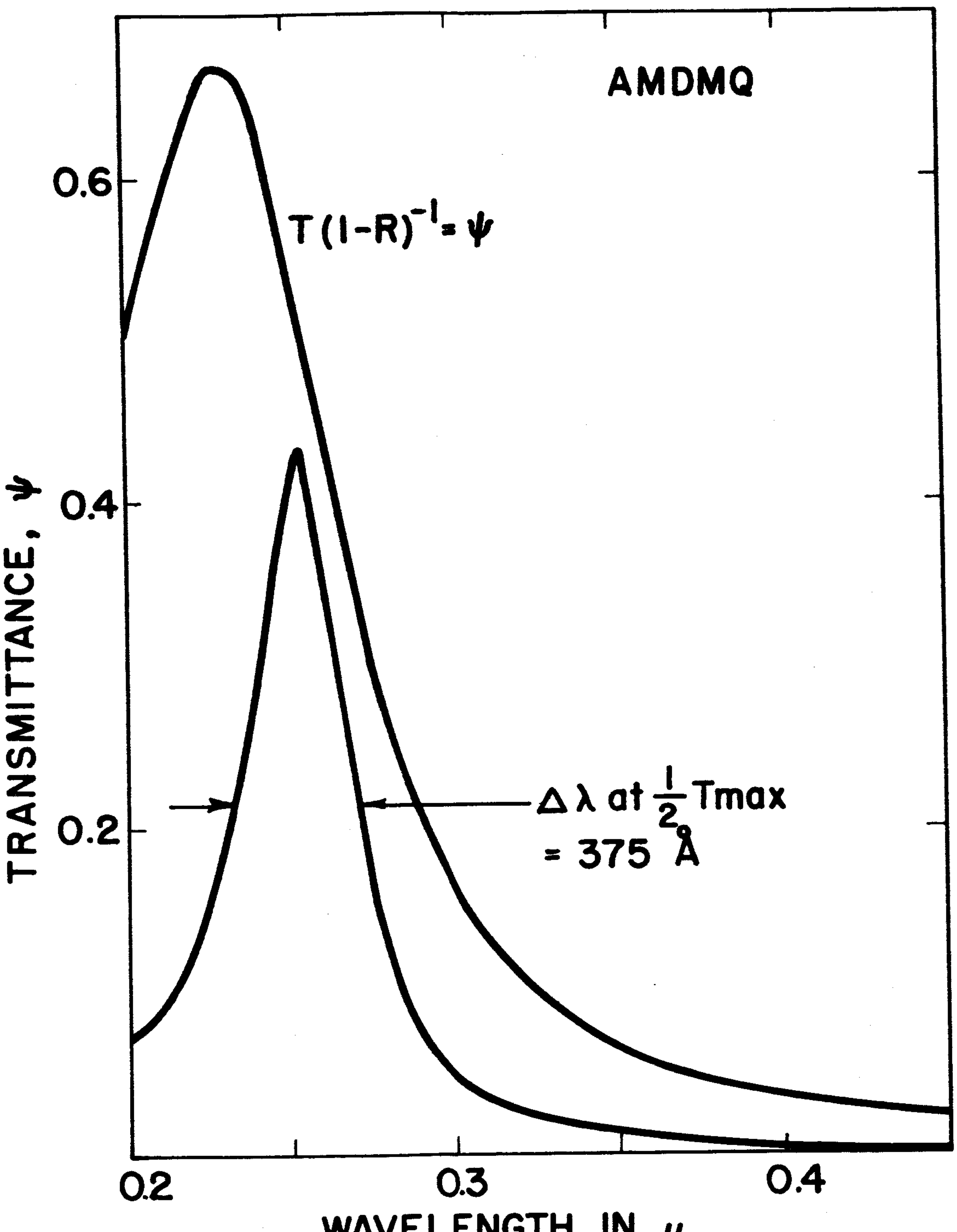
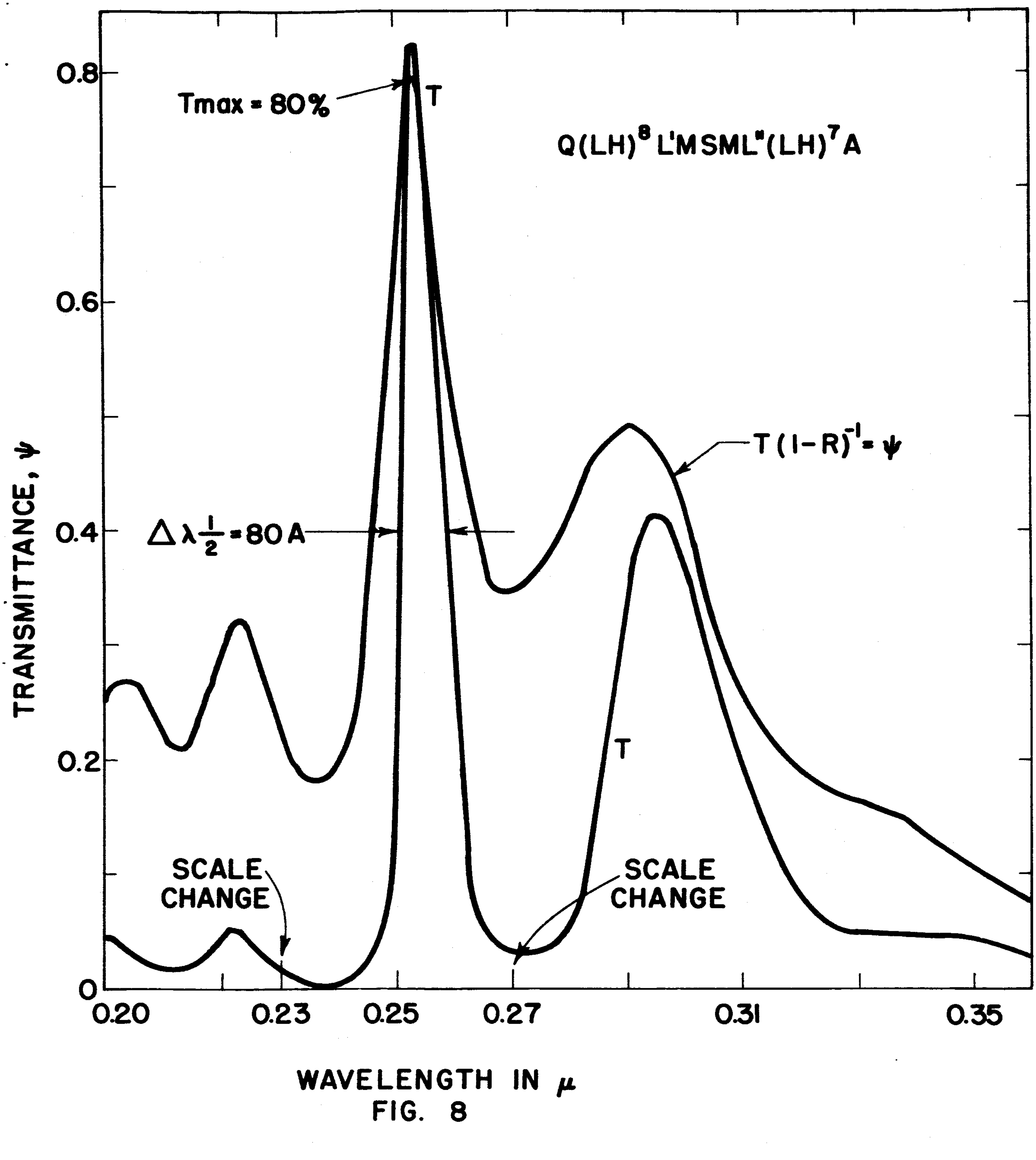
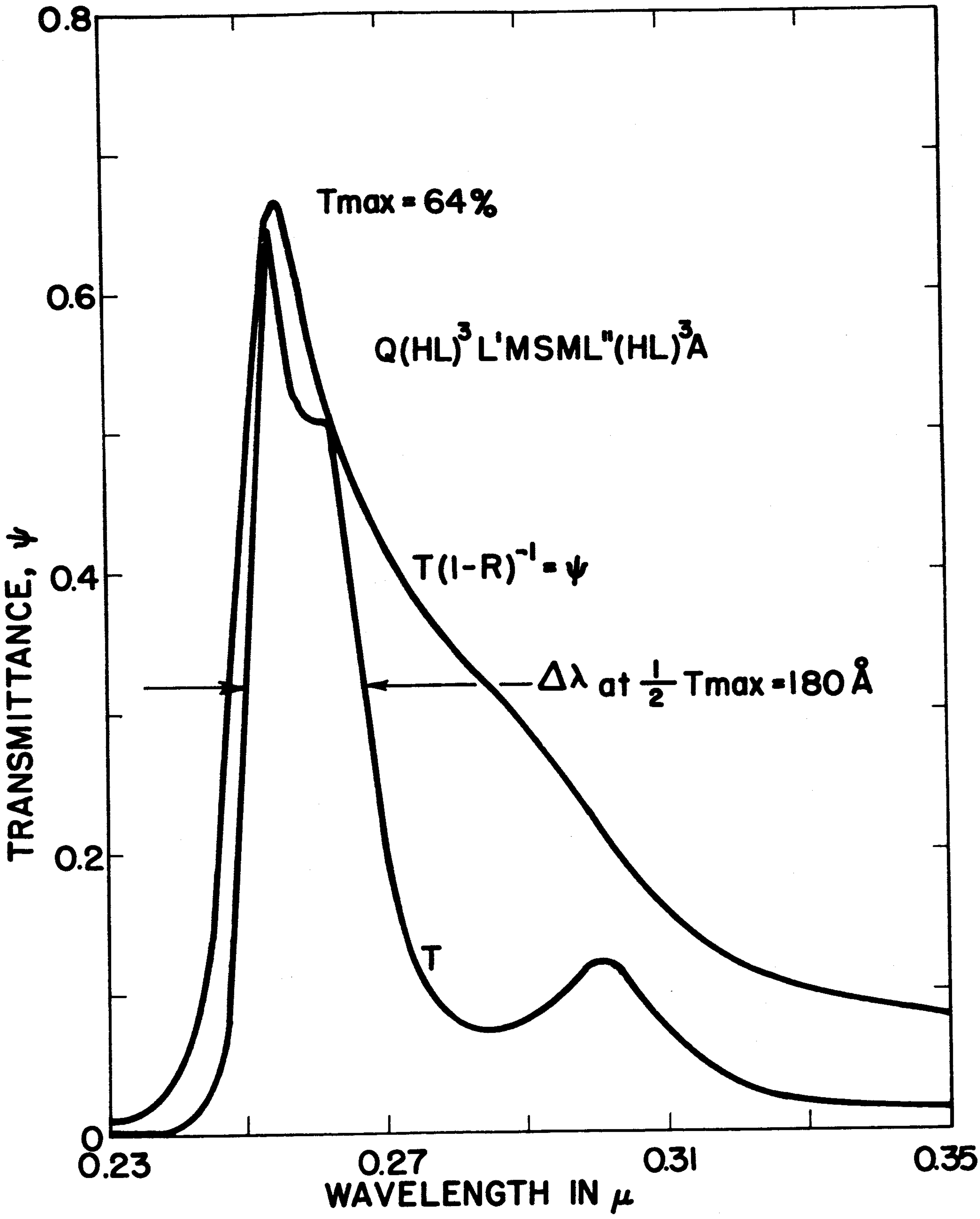

AMDMQ
T(1-R)^-1 = ψ
Δλ at 1/2 Tmax
= 375 Å
0.6
0.4
0.2
TRANSMITTANCE, ψ
0.2
0.3
0.4
WAVELENGTH IN μ

FIG. 7



TRANSMITTANCE, ψ
0.8
0.6
0.4
0.2
0
Tmax = 80%
T
Q(LH)8 L'MSML"(LH)7A
T(1-R)-1 = ψ
Δλ 1/2 = 80 A
T
SCALE CHANGE
SCALE CHANGE
0.20
0.23
0.25
0.27
0.31
0.35
WAVELENGTH IN μ

FIG. 8



Tmax = 64%
Q(HL)^3 L'MSML''(HL)^{3}A
T(1-R)$^{-1}$ = ψ
Δλ at ½ Tmax = 180 Å
T
TRANSMITTANCE, ψ
0.8
0.6
0.4
0.2
0
0.23
0.27
0.31
0.35
WAVELENGTH IN μ

FIG. 9

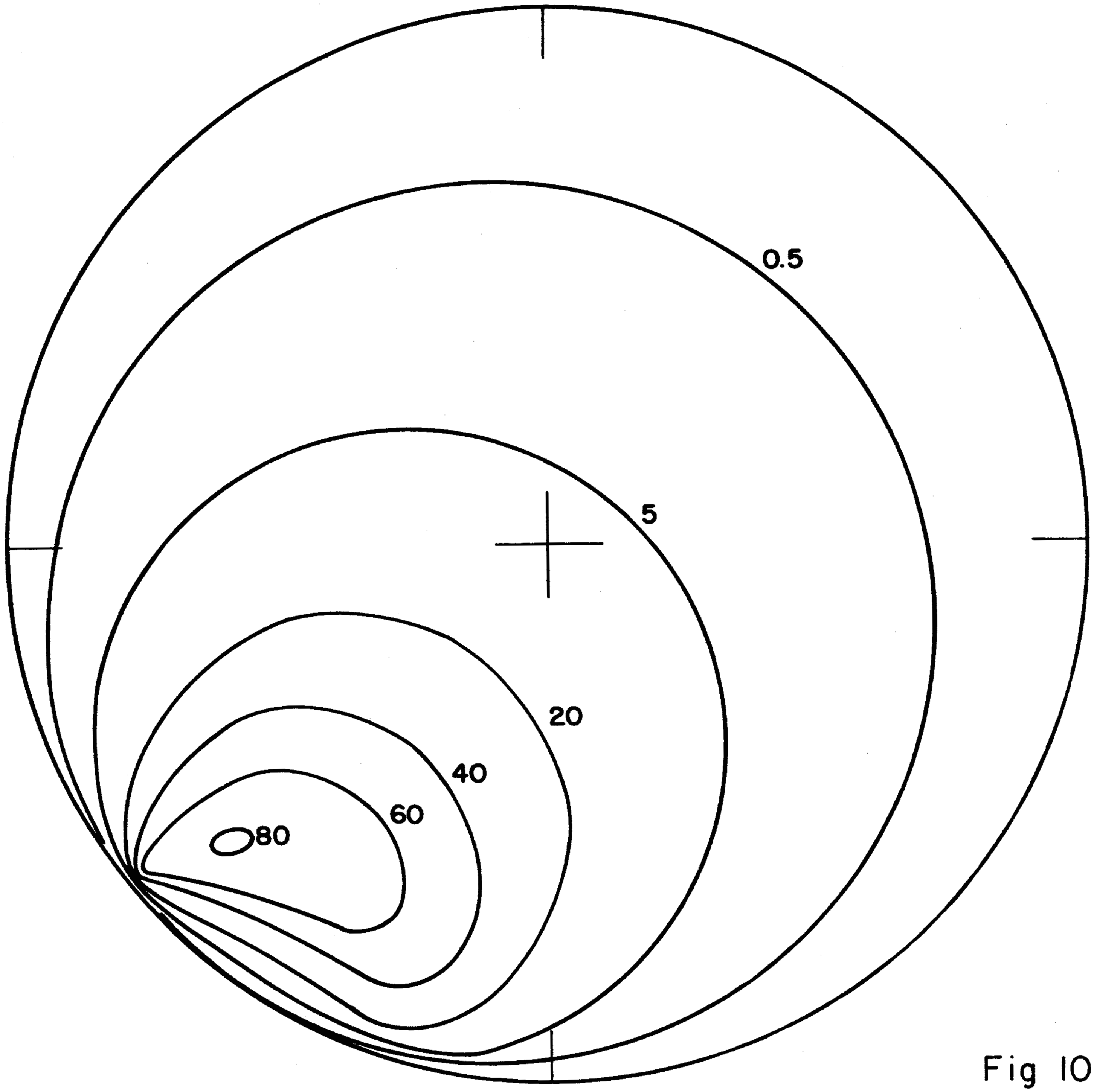


Fig 10

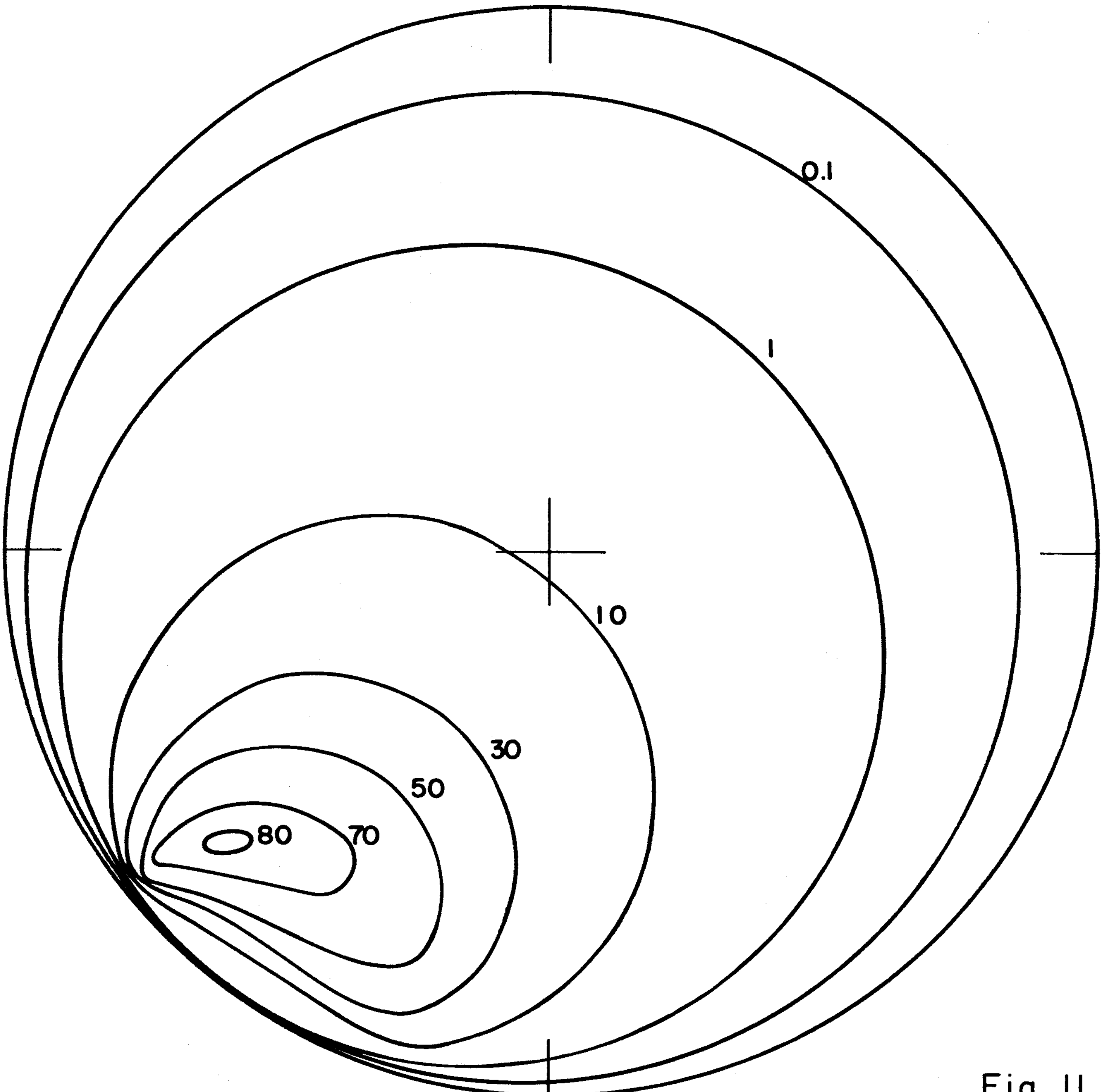


Fig 11