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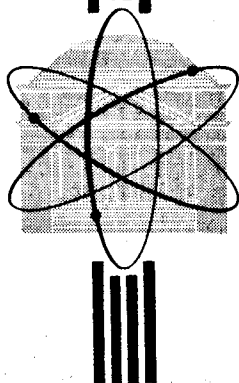
Report No. EE-4012-110-68U

July 1968

APPLICATION OF THIN FILMS TO
EXTREMELY HIGH FREQUENCIES

Semi-Annual Status Report
on
NASA Grant NsG-340

Submitted by:

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SECTION I
REPORT COVERAGE

This report covers the period from December 5, 1967 through June 5, 1968.

SECTION II
PRINCIPAL RESULTS TO DATE

Five important results have been attained during the first six month period of this grant.

(1) A new field of microwave technology and research has been opened up by the initial research carried out under this grant. This conclusion is substantiated by the international response, in the form of requests for copies of the following paper.

(2) Publication of the paper by the principal investigator (Ramey) and T. S. Lewis on Properties of Thin Metal Films at Microwave *Detached* Frequencies. Published in the Journal of Applied Physics, Vol. 39, No. 3, 1747-1752, 15 February 1968. A copy of this paper is also included in this report.

(3) A second paper, titled Microwave Transmission Through Thin Metal and Semiconducting Films by Ramey, Kitchen, Lloyd, and Landes has been accepted for publication by the Journal of Applied Physics and will appear in the July 1968 issue of that journal. This paper was summarized in the last Annual Status Report on NsG-340 dated January 1968. The results of this paper are very important to the possible design of microwave devices. Additional information, which has been developed since the submission of this paper is included in Section III of this report.

(4) As a result of the information encompassed by the above paper, research into device design employing thin films has been initiated. At present data is being taken on a basic form of switch-modulator. A thin film cavity configuration is also under consideration. The next semiannual report will contain more information on possible device applications.

(5) A basic study of the role played by higher order evanescent modes in waveguides has been made. Additional studies based upon higher order propagating modes (K-band) in X-band guide are presently being made. As soon as the combined information is assembled a detailed report of these findings will be submitted. Currently, we have found that some of the limited literature on this subject is in error. Modal analysis is important whenever lumped impedances (such as our films) are inserted in waveguide systems and when the basic operating frequency is not near the cut-off frequency of the waveguide.

A complete report on the presence and importance of higher order modes will be included in the next annual report.

A UNIVERSAL POWER TRANSMISSION PLOT
FOR THIN FILM WINDOWS

The transmission of microwave power through a thin film window which is placed in a waveguide system so that its surfaces are normal to the directions of propagation, was reported in the last Annual Status Report (No. EE-4012-109-68U) dated January 1968. This was a generalization of the original work reported in the preceding paper included in this report. The generalization permitted all materials; metal, semi-metal, and semiconductor to be treated in a universal manner. As mentioned in Section II, a paper describing this universal treatment of microwave power transmission through thin films will appear in the July issue of the Journal of Applied Physics.

The key to the generalized study of microwave power transmission, T, through thin film windows is the argument σd. It is important to note that these windows have all four edges shorted to the walls of the waveguide. Here σ is the measured thin film conductivity of the sample and d is the thickness of the film (usually measured with a multiple beam interferometer). With reference to the preceding report, the power transmission for any film is given by

$$T = \left| \frac{2}{2 + \frac{\omega \mu_o}{|\gamma_o|} \sigma d} \right|^2 \bullet \tag{1}$$

Where the free space propagation coefficient

$$\gamma_o = \left[(\frac{\pi}{a})^2 - \omega^2 \mu_o \epsilon_o \right]^{1/2} \tag{2}$$

For a given frequency this equation may be reduced to a simple expression. At the X-band frequency of 9.8 GHz Equation (1) reduces to

$$T = \left| \frac{2}{2 + 506\sigma d} \right|^2 \tag{3}$$

A more _universal_ form for Equation (1) can be obtained by introduction of the waveguide cut off frequency (TE_{10} mode):

$$f_c = \frac{1}{\sqrt{\mu_o \epsilon_o}} \left(\frac{1}{2a} \right) \tag{4}$$

where a is the width of the waveguide. Substitution of Equation (4) into Equations (1) and (2) yields

$$T = \left| \frac{2}{2 + \dfrac{\sqrt{u_o/\epsilon_o}}{\sqrt{1 - (f_c/f)^2}} \sigma d} \right|^2 \tag{5}$$

$$T = \left| \frac{2}{2 + \dfrac{376.73}{\sqrt{1 - (f_c/f)^2}} \sigma d} \right|^2 \tag{6}$$

Equation (6) is completely universal if we treat

$$\frac{\sigma d}{\sqrt{1 - (f_c/f)^2}}$$

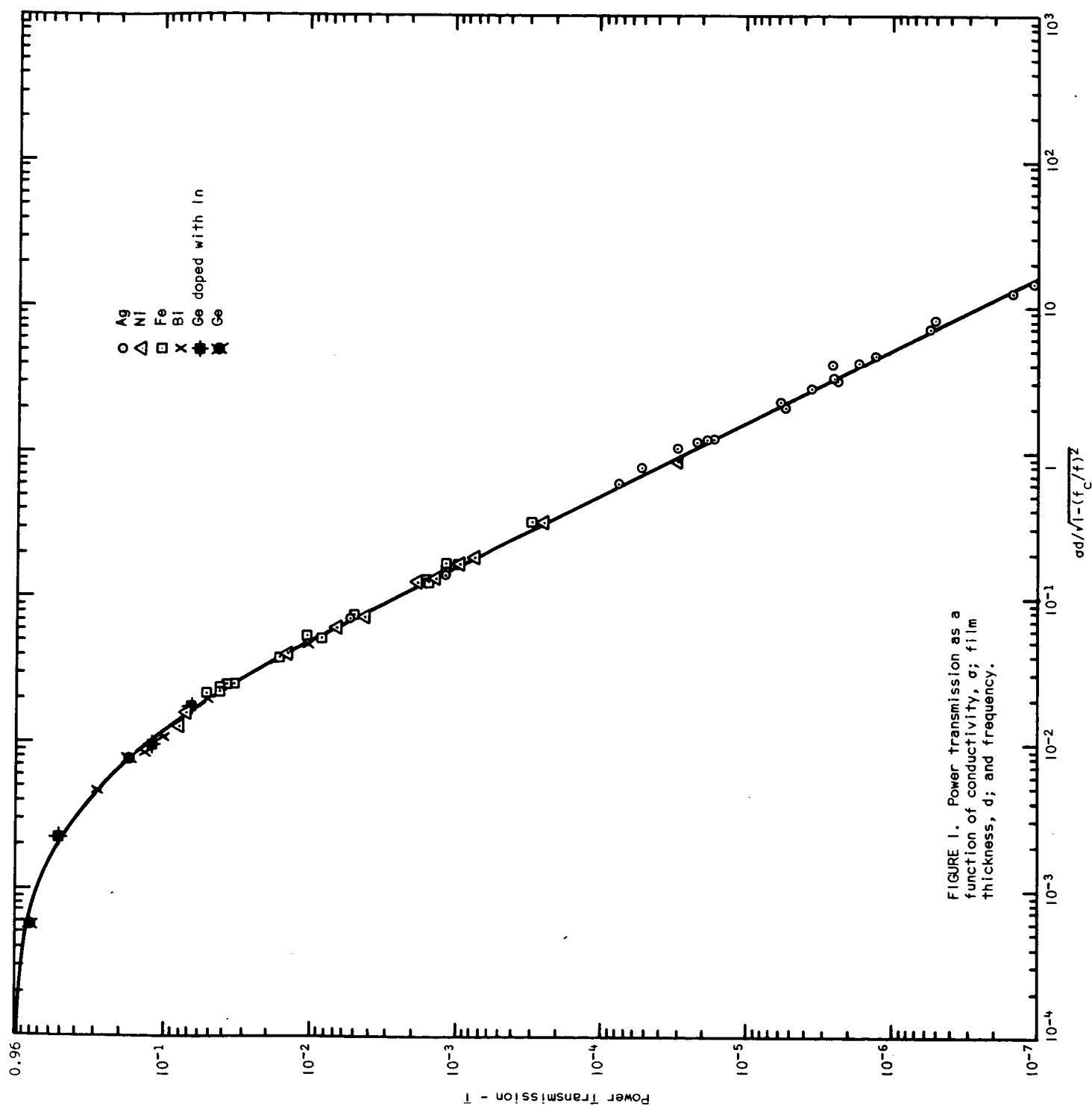as the argument when plotting this equation (See Figure 1).

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FIGURE 1. Power transmission as a function of conductivity, σ; film thickness, d; and frequency.

Legend:
- ○ Ag
- △ Ni
- □ Fe
- × Bi
- ✦ Ge doped with In
- ✶ Ge

x-axis: $\sigma d / \sqrt{1 - (f_c/f)^2}$

y-axis: Power Transmission $- T$

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To use Figure I or Equation (6) it is necessary to know the cut-off frequency of the waveguide and of course the operating frequency of the system. The following table lists the cut-off frequencies of some of the standard waveguides.

TABLE I

WAVEGUIDE FREQUENCY CHARACTERISTICS FOR TE_{10} MODE

Numerical Designation	Old Code	Cut-off Frequency (GHz)	Recommended Bandwidth (GHz)
WE 650	L	0.908	1.12 - 1.70
WE 430	LS	1.372	1.70 - 2.60
WE 264	S	2.078	2.60 - 3.95
WE 187	C	3.152	3.95 - 5.85
WE 137	XV	4.301	5.85 - 8.20
WE 112	XB	5.259	7.05 - 10.00
WE 90	X	6.557	8.20 - 12.40
WE 62	KV	9.486	12.4 - 18.0
WE 42	K	14.047	18.0 - 26.50
WE 28	V	21.081	26.50 - 40.00
WE 22	Q	26.342	33.00 - 50.00
WE 15	M	39.863	50.00 - 75.00

SECTION IV
FREQUENCY RESPONSE OF THIN FILM WINDOWS

The electrical properties of the films alone are independent of frequency (See the paper by Ramey and Lewis that is included in Section II). However, the window is not entirely independent of frequency, as is emphasized by Equation (6). The frequency dependence of the power transmission coefficient depends upon the product σd as well as the ratio (f/f_c). Figure 2 is a plot of T as a function of (f/f_c) for three values of σd.

It is apparent that those films with the smaller values of σd have the greatest power transmission factors and the best frequency dependence.
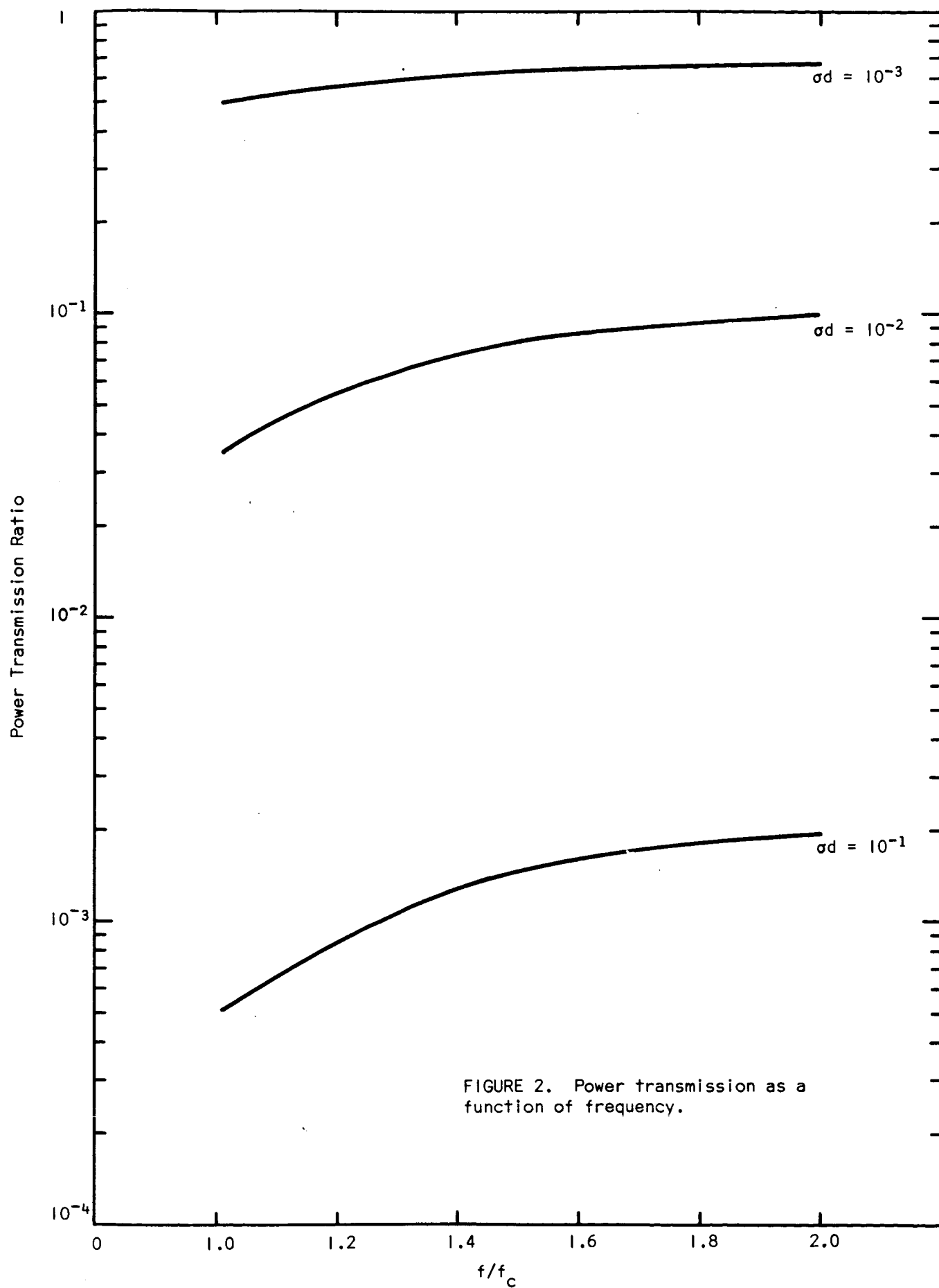
FIGURE 2. Power transmission as a
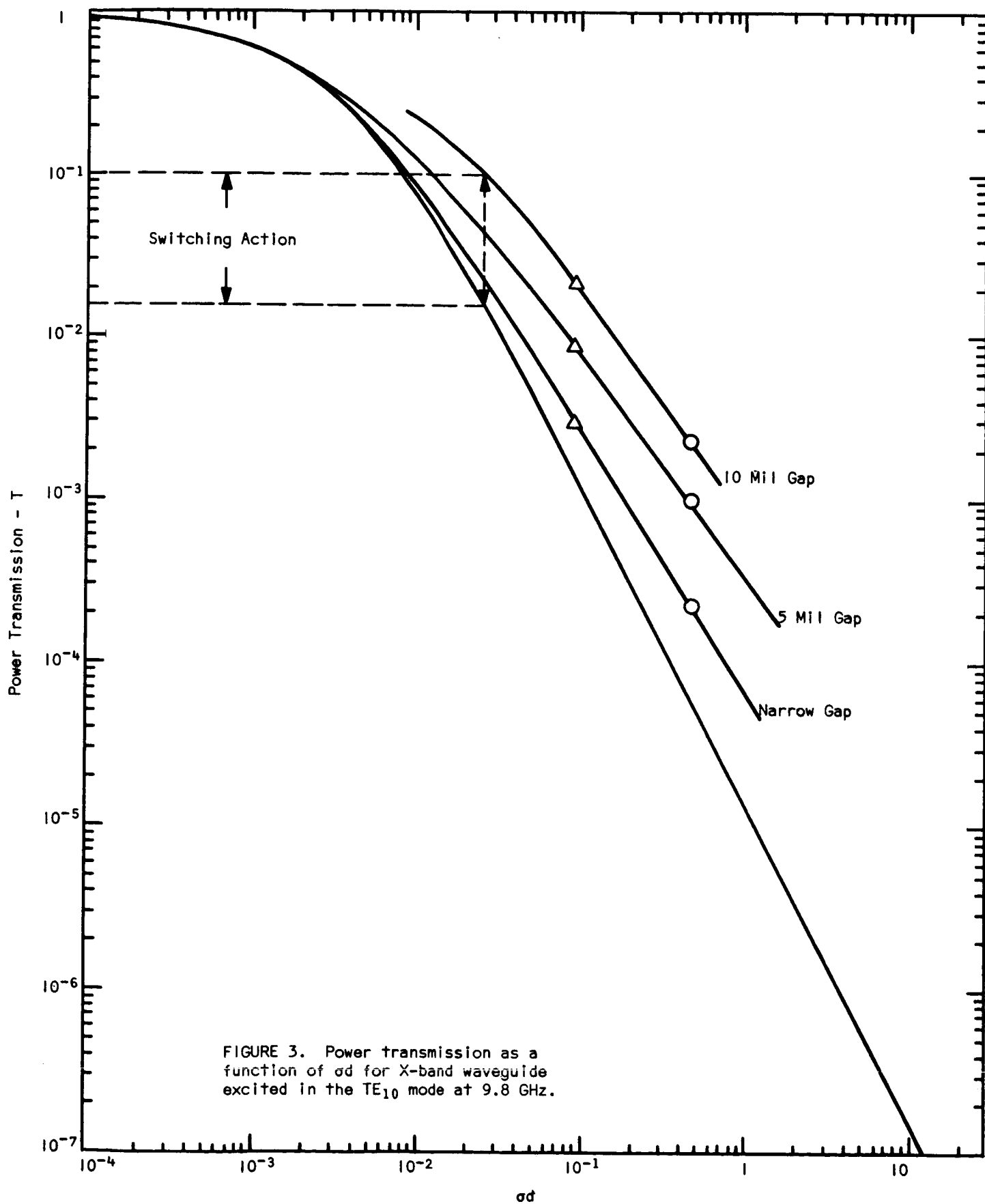function of frequency.

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SECTION V
THIN FILM WINDOW DEVICES

Numerous possible device configurations based upon the use of one
or more thin film windows in waveguide suggest themselves. These
promising possibilities are currently being investigated:

(1) Switch-Modulator based solely on the pronounced difference
in the power transmission when a thin film window is _floated_
electrically in the waveguide. That is, normally the windows are
carefully grounded to all four walls of the waveguide when the
transmission data represented by Figure 1 or Figure 3 is taken.
[Note that Figure 3 is quite similar to Figure 1, the difference
being that $f = 9.8$ GHz and $f_c = 6.557$ have been substituted into
Figure 3. Thus this plot applies to X-band guide only and an
operating frequency of 9.8 GHz.] If the window is floated free
of the guide walls (no electrical contact) then the power trans-
mission through the film increases by about 10 db over what it was
when the film was grounded.

The grounding of the film need not be around the entire
periphery of the film. It is sufficient to simply ground the film
as shown in Figure 4 as these are the points of maximum current.
The general idea is to next investigate the possibility of using
controlled devices to accomplish the grounding and thus be able to
switch or modulate the microwave signal. The region through which
we have been able to switch at present is indicated on Figure 3.
The maximum transmission ratio with the switch open was about 0.1
and with the switch closed it was 0.016. A nickel film was used.

For maximum transmission efficiency it will be desirable to
operate as high as possible on the curve of Figure 3. At present
we are experiencing a problem in achieving a complete open circuit

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FIGURE 3. Power transmission as a function of σd for X-band waveguide excited in the TE_{10} mode at 9.8 GHz.
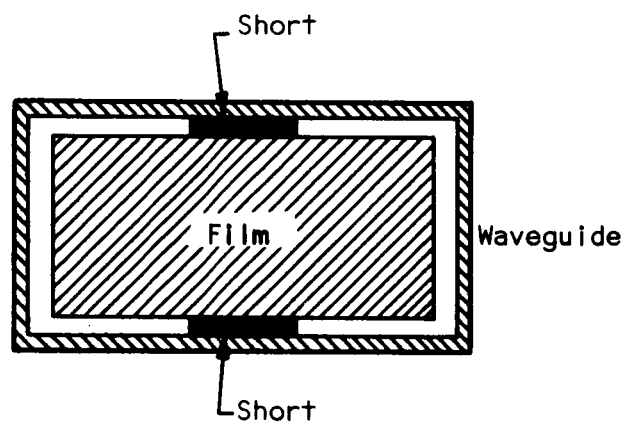
FIGURE 4. End view of waveguide showing a film that is connected to the guide walls at only two points.

between the film and the wall because of capacitive coupling. Consideration is being given to the possibility of tuning out this capacitive term by use of stub tuned lines connected between the film and the wall.

(2) Partial Reflector. We are preparing to study the partial reflection-transmission properties of these films where they are mounted at an angle in a waveguide "Tee". See Figure 5.

(3) Cavities and multicavity filters. Preparations are being made to evaluate the possible advantages of employing tuned cavities which are coupled into a waveguide system by means of a thin film window. If this is successful then multicavity filters will be constructed and studied. See Figure 6.
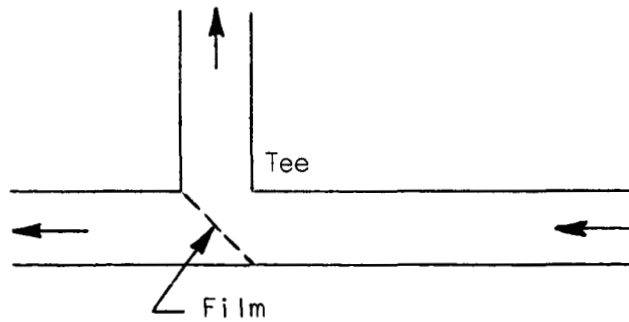
FIGURE 5. An arrangement using a thin
film window to partially transmit and
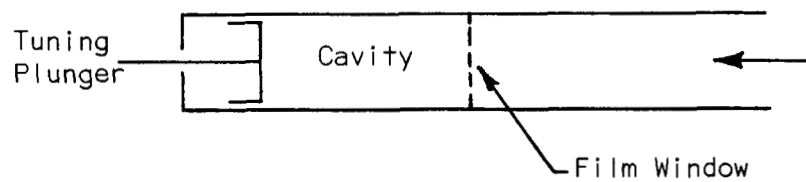partially reflect microwave energy.

FIGURE 6. A tuned cavity defined by a
thin film window.

SECTION VI
RESEARCH STATUS

We have completed our studies of the basic properties of all thin film windows. We are now concentrating on device design.

As of June 27, we have obtained a complete microwave capability at 19.6 GHz as well as 9.8 GHz.

One graduate student (W. J. Kitchen) just received his doctorate from research done on this grant. Another man will receive his doctorate next year based upon the research we are now doing.

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