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MILLIMETER-WAVE IRIS BANDPASS FILTERS

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Waveguide bandpass filters have been designed and built for 69 to 77 GHz and 76.5 to 85 GHz bands in WR-10 guide. These filters were designed for Tchebyscheff response by an analytic technique programmed by J. Davis[1] augmented by an optimization algorithm programmed by myself to correct for iris thickness effects. The filters were fabricated by electroforming with the irises inserted into the Al mandrel prior to plating. Filter response was measured with a mm wave BWO sweeper. Design theory, fabrication procedures, and measured performance will be discussed in detail in this report.

Filter Design Procedures

The filter design was accomplished by a hybrid technique consisting of a preliminary Tchebyscheff design based on a lumped-element low-pass prototype followed by a final design adjustment performed by optimization of the performance calculated from a complete analysis routine.

The analytic Tchebyscheff design routine written by Jesse Davis proceeds by first computing the normalized element values (g_i) of the low-pass lumped-element filter prototype[2]. These g_i values are subsequently translated into normalized (X/Z_0) shunt inductance values relative to a quarter wave transformer prototype circuit. The program outputs required values of normalized shunt inductance (X/Z_0) and iris spacings for each section and plots the predicted filter response. Tables 1 and 2 show the design values generated for the two filters under discussion and Figures 1 and 2 show the predicted response.

The values of $(X_L/Z_0)\cdot(\lambda_g/a)$ obtained from the analytic design program were converted to physical iris dimensions using formulae given in the waveguide handbook (Marcuvitz). The physical iris dimensions and spacings obtained in this manner were used as the initial design input to the analysis routine to begin optimization.

The Analysis Routine

The filter analysis routine accepts as inputs filter physical dimensions and frequencies and subsequently computes response and plots loss versus frequency if desired. Wavelength dispersion and change of waveguide characteristic impedance with frequency are incorporated in the program. The equivalent circuit corresponding to a thick iris is shown in Figure 3. Element values for the equivalent circuit are obtained from expressions given in the waveguide handbook[3].

Iris Formulae

For a thin symmetric iris, the shunt inductive reactance is given approximately by the following expressions:

$$\frac{X}{Z_0} \cong \frac{a}{\lambda_g} \tan^2 \frac{\pi d}{2a} \left[1 + \frac{1}{6}\left(\frac{\pi d}{\lambda}\right)^2\right], \quad \frac{d}{a} << 1 \qquad (1)$$

$$\frac{X}{Z_0} \cong \frac{a}{\lambda_g} \cot^2 \frac{\pi d'}{a} \left[1 + \frac{2}{3}\left(\frac{\pi d'}{\lambda}\right)^2\right], \quad \frac{d'}{a} << 1 \qquad (2)$$

where a = waveguide width
d = width of opening in iris
d'= a - d

For the thick symmetric iris, Marcuvitz[3] gives the following formulae for the shunt inductive reactance and series capacitive reactances (see Figure 3).

$$\frac{X_L}{Z_0} = \frac{2a}{\lambda_g} \left(\frac{a}{\pi D'}\right)^2, \quad \frac{\pi D'}{\lambda} << 1 \qquad (3)$$

$$\frac{X_C}{Z_0} = \frac{a}{8\lambda_g} \left(\frac{\pi D_1}{a}\right)^4, \quad \frac{\pi D_1}{\lambda} << 1 \qquad (4)$$

where:

$$D' \cong \frac{d'}{\sqrt{2}} \left(1 + \frac{\ell}{\pi d'} \ell n \frac{4\pi d'}{e\ell}\right), \quad \frac{\ell}{d'} << 1 \qquad (5)$$

$$D_1 \cong \sqrt[4]{\frac{4}{3\pi} \ell d'^3}, \quad \frac{\ell}{d'} << 1 \qquad (6)$$

The range of validity of the thick iris formulae is for $d' \lesssim 0.3a$. However, the filter design requires irises for which $d' \gtrsim 0.7a$. Therefore, an attempt was made to improve the validity of the thick iris formulae in the range $0 \leq d' \leq 0.8a$. Since the thin iris formulae are accurate over the entire range, the first step in improving the accuracy of the thick iris equations is to modify them to agree with the values predicted by the thin iris equations for the case that ℓ is very small.

The X_L/Z_0 values given by thick and thin iris formulae are shown in Figure 4 at 80 GHz versus d/a for ℓ negligibly small. It is seen that the thick iris formula provides good agreement with the thin iris formula for $d \gtrsim 0.7\ a$, but that the thick iris formula does not approach zero properly as $d/a \to 0$. The residual value R_0 of the thick iris equation for $d' = a$ $(d = 0)$ must be subtracted in order to obtain zero reactance for this case.

$$R_0 = \frac{2a}{\lambda_g} \left(\frac{a}{\pi D'_0} \right)^2 \tag{7}$$

$$D'_0 = \frac{a}{\sqrt{2}} \left(1 + \frac{\ell}{\pi a} \ \ell n \ \frac{4\pi a}{e\ell} \right) \tag{8}$$

$$\frac{X_L^C}{Z_0} = \frac{X_L}{Z_0} - R_0 \tag{9}$$

The ratio of X_L/Z_0 given by the thin iris formulae to X_L^C/Z_0 given by equation 9 is plotted in Figure 5. Agreement is quite good (within 2.5%) over the range $0.5 \leq d/a \leq 1$. However, the thick iris formula does not approach zero in the same manner as does the thin iris formula in the range $0 \leq d/a \leq 0.5$. This is more readily observable in Figure 6 where the values of X_L/Z_0 are plotted independently for the various expressions. A linear correction to the thick iris formula in the range $0 < d < 0.5\ a$ may be used to remove this discrepancy.

$$\frac{X_L^{CC}}{Z_0} = \begin{cases} \dfrac{X_L^C}{Z_0} \left(0.125 + 1.75 \dfrac{d}{a}\right) & 0 < d < 0.5\ a \\[2ex] \dfrac{X_L^C}{Z_0} & 0.5\ a < d < a \end{cases} \tag{10}$$

Finally, the doubly corrected value X_L^{CC}/Z_0 is plotted with the values given by the thin iris formulae in Figure 7. The agreement is good over the range $0.1\ a \leq d \leq a$. Thus, the thick iris formula has been patched up to agree with the thin iris equations for the case that iris thickness is negligible (as it should). The variation of X/Z_0 with iris thickness can not be adjusted in a corresponding manner at this point since the thin iris formulae do not include this variable. However, some empirical renormalization of the iris thickness dependency may be possible based on experimental filter performance as will be discussed later. Appendix 1 lists the routine that converts X/Z_0 values from the prototype design into physical iris dimensions based on equations 3 thru 10.

Cascading of Sections

The filter performance is analyzed by cascading sections sequentially and incorporating the discontinuity impedance at the end of each section. For reasons of economy the program is presently set up to handle only symmetric (even number of sections) filters. However, handling of antimetric (odd numbers of sections) filters could be accommodated with a few branching statements with little increase of complexity.

The filter optimization routine is listed in Appendix 2. The analysis routine begins at line 1910. Parameter values are accepted from the optimization routine and converted into line lengths and iris widths. Then waveguide wavelength λ_g and characteristic impedance Z_0 are calculated (the routine is called separately for each frequency). The cascade is begun by loading the filter output with the line characteristic impedance (matched condition). Then, in order, the following steps are performed:

1. The capacitive reactance of one side of the iris tee equivalent circuit is added to the existing load impedance.
2. The resulting impedance is inverted by a subroutine which handles complex inversion to obtain an admittance.
3. The susceptance of the iris shunt inductance is added to the resulting admittance.
4. The admittance is inverted using the same subroutine to obtain an impedance.
5. The capacitive reactance of the other side of the iris tee equivalent circuit is added to the impedance.
6. The resulting impedance is rotated through the electrical length of the next filter section according to the expression:

$$Z_S = Z_0 \frac{Z_L + j\, Z_0 \tan \beta\ell}{Z_0 + j\, Z_L \tan \beta\ell} \tag{11}$$

7. The resulting impedance Z_S becomes the load impedance at the iris input of the next filter section and the algorithm is repeated from step 1 above through each filter section to the input.

Once the input is reached, the algorithm is repeated only through step 5 to include the effect of the first iris. Then the reflection coefficient ρ, and insertion loss of the filter are calculated from the effective load impedance according to the following expressions:

$$\rho = \frac{Z_L - Z_0}{Z_L + Z_0} \tag{12}$$

$$A = 10 \log_{10} \frac{1}{1 - |\rho|^2} \tag{13}$$

Cascading is performed for each frequency of interest and the results are returned to the cost function evaluation routine EVAL (see Appendix 2).

Optimization Procedure

Optimization is accomplished through the interaction of a numerical minimization algorithm with a cost function evaluation subroutine. The cost function is defined in terms of filter performance characteristics both in and out of the passband. For the filters designed here, the following cost function was used:

$$C = \sum_{i=1}^{NF} (A_i - A) * W_i > 0 \tag{14}$$

where:

C is the cost function (to be minimized)

NF = number of frequencies

A_i = desired attenuation (dB)

A = calculated attenuation @ $f = f_i$

W_i = weighting factor

The weighting factors W_i are chosen to be negative within the passband so that $A > A_i$ represents a positive contribution to the cost function. Negative contributions to the cost function are not counted as indicated by the logical > 0 indicated in eq. 13. Outside the passband the weights are positive so that attenuation less than desired contributes to the cost function. Weights of -5 within the passband, +1 at the lower (out-of) band edge and +2 at the upper (out-of) band edge were found to work well for design of the present filters.

Complete description of the minimization routine is beyond the scope of this report. A technique given by Powell[4] and modified by Zanqwill[5] is used. The algorithm does not use derivatives or gradients but proceeds by successive minimizations in discrete directions whilst building up the steepest descent directional coordinates from the results of previous directional minimizations. Initial directions are naturally the coordinate directions in parameter space. The routine is accurate and efficient but runs quite slowly on the 9830 calculator due to the slow speed of this machine and the large number of computations required.

Filter Design and Program Usage

The 69-77 GHz and 76.5-85 GHz bandpass filter designs described in Tables 1 and 2 were input to the optimization routine. One of these designs (69-77 GHz) will be used as an example to describe program operation.

To begin, the X_L/Z_0 values output from the low pass prototype design must be translated into iris dimensions which will produce the same reactance values. This is accomplished with a short program, reproduced in Appendix 1, that solves the thick iris equations for the width d' given X/Z_0, a, and ℓ.

The main analysis and optimization program starts by asking for the number of sections in the filter. An even number must be entered here as the program is now written. The number 8 obtained from the low-pass prototype program was entered for the 69-77 GHz filter. The program next asks for the lower frequency of interest $f_\ell = 68$, $\Delta f = 1$ and NF = 11. The program next asks for height and width of the waveguide in inches. The filter was fabricated in standard WR10 guide height = .050", width = 0.100". Next the program asks for iris thickness. A thickness of .006 inches was used.

The program now calls for entry of a scale factor which is used to obtain the normalized parameter increments in the directional searches. A value of .01 to .005 is usually given depending on problem sensitivity. Now the program asks for entry of a 1 if an attenuation plot is desired. If a 1 is entered, optimization does not occur, but a plot is produced of the filter insertion loss versus frequency for the design entered. To demonstrate this aspect of the analysis program, the analyzed performance of the initial low-pass prototype design is shown in Figure 8 for 61 frequencies from 68 to 80 GHz. This plot is actually very close to the desired design. Only the out-of-band attenuation at the high end 78 GHz is slightly lower than desired by about 2.5 dB.

If a plot is not deisred, a zero may be entered at the branch and the program will ask for desired loss and weighting factor to be used in the cost function at each frequency f_i. The values entered for the present design were:

Frequency	Desired Loss	Weight
68 GHz	20	1
69 GHz	.5	-5
70 GHz	.5	-5
71 GHz	.5	-5
72 GHz	.5	-5
73 GHz	.5	-5
74 GHz	.5	-5
75 GHz	.5	-5
76 GHz	.5	-5
77 GHz	.5	-5
78 GHz	20	2

The program next asks for parameter 1, parameter 2, etc. for a total of N/2 + 1 parameters, where N is the number of sections. The physical dimensions of the filter are parameterized in the following manner:

1. Parameters 1 to N/2 are the section lengths in inches. Since the filter is assumed to be symmetric, this specifies all the section lengths.

2. Parameter N/2 + 1 is a scaling factor for the iris widths. The actual normalized iris widths are entered directly as obtained from the low pass prototype.

Therefore, for this example the parameters entered into the program are as follows:

Parameter	Value
1	.1063
2	.1156
3	.1184
4	.1189
5	1.0

Once the parameter values are entered the program will ask for iris widths. The widths are entered as the value of d'/a, i.e. normalized to the waveguide width. The iris widths entered were:

Iris	Normalized Width
1	0.3550
2	0.4681
3	0.5142
4	0.5218
5	0.5234

At this point the program begins computing filter characteristics and attempting to optimize the design by varying parameters.

The time to compute one point in parameter space is dependent on both the number of filter sections and the number of frequencies which must be computed to evaluate the cost function. For an eight section filter evaluated at 11 different frequencies, the time per point is about one hundred seconds on the 9830. Since a total of up to about 100 points is required for convergence of a 5 parameter problem the total time is about 10^4 seconds or 2-3/4 hours. Use of a finer frequency mesh (calculating every 0.5 GHz) which is desirable for some problems will cause a corresponding linear increase in time e.g. 21 frequencies (which is the maximum the program will accept for optimization) would take about twice as long as 11 frequencies or about 5-1/2 hours.

The final design arrived at for the 69-77 GHz filter is shown in Figure 9. The numbers are very close to the original low-pass prototype design. The calculated performance of this filter is shown in Figure 10. It is seen that the out-of-band attenuation has been improved at the high end. The measured performance of this filter will be discussed in a later section.

The 76.5 to 85 GHz filter was also optimized using the program described above. A plot of the computed attenuation of the initial low-pass prototype design is shown in Figure 11. The passband is wider than desired by over 2 GHz. Also the high frequency band edge is not as steep as desired. The optimized filter design is shown in Figure 12 and the predicted performance is shown in Figure 13. The defects of the preliminary design are removed. Measured performance will be given in a later section.

Filter Fabrication

The filters were fabricated according to the dimensions shown in Figures 9 and 12 by the electroforming process. An aluminum mandrel was machined to the inner rectangular dimensions of the waveguide. Slots were cut in the aluminum at the proper spacing to support the irises. Irises were fabricated from Be-Cu sheet .0055 thick which was gold plated to a final thickness of 6 mils. The irises were inserted into the slots prior to electroforming the filter.

The filter was electroformed by first depositing a thin layer of copper to enhance plateability. Next a gold layer was plated to provide high electrical conductivity of the inner surface of the finished filter. Finally the thick copper body of the filter was plated up over a period of 7 or 8 days.

After electroforming, the filter body and ends were machined to accept flanges. Then the aluminum mandrel is dissolved out of the center of the filter. Flanges are soldered in place, and the thin copper layer on the inside is removed to expose the gold surface. The filters are given a final external gold plate to prevent tarnishing of the copper.

Measurement of Filter Response

The millimeter wave response of the completed filters was measured using a BWO sweeper and broadband detector combined with a precision attenuator. The detector response was calibrated across the band of interest by varying the attenuator setting. The filter was then inserted into the transmission path and its insertion loss was plotted versus the calibrated loss curves.

The measured response of the 69 to 77 GHz filter is shown in Figure 14. The passband extends from approximately 70.2 GHz to 75.7 GHz. The loss within the passband is nominally 3 dB. The band edges are sharp and steep, and the out-of-band attenuation is greater than 25 dB at both high and low ends within 1 GHz of the band edges. The center frequency is 72.9 GHz which is within 100 MHz or 0.14% of the design center of 73 GHz. This filter performs fairly well as designed except, of course, for the narrower (.69 ratio) than desired bandwidth and somewhat high loss.

Measured response of the 76.5 to 85 GHz filter is shown in Figure 15. The passband extends from about 80.2 GHz to 82.8 GHz. The passband loss is nominally 2 to 3 dB. The band edges are sharp but it was not possible to measure the out-of-band attenuation above 10 dB due to lack of sweeper power (or detector sensitivity). The center frequency is 81.5 GHz which is within 750 MHz or 0.93% of the design center of 80.75 GHz. Thus this filter also performs about as designed with the major exception that the bandwidth is only 30.6% of the design bandwidth.

Discussion

The design, fabrication, and performance results presented here represent an attempt to accurately design and fabricate fix tuned millimeter-wave bandpass filters to be used as image rejection filters for single sideband receiver measurements. The initial attempt at design and fabrication of these filters, which was not discussed in any detail in this report, produced one filter (nominally 69-77 GHz) with passband response between about 72.5 GHz and 75.6 GHz for about 39% of the desired bandwidth. The other filter resulting from this initial attempt, designed for 76.5 to 85 GHz exhibited no passband whatever. Compared to these early results the present performance is quite encouraging. However, there is obviously still room for substantial improvement in the design capability.

The analysis routine has been checked carefully and is believed to give accurate results limited primarily by ability to accurately model the waveguide discontinuities. The optimization program and associated cost function behave properly and converge to produce the desired design. The primary problem observed both in initial design attempts and with the most recent designs is that the filters exhibit substantially narrower bandwidths than calculated using the iris formulae described in this work. Since the bandwidth is primarily dependent on the filter Q which is a function of the iris VSWR's resulting from the X_L/Z_0 values, it is likely that the iris inductance is overestimated by the present expressions. An improvement in design capability at this point could be accomplished by either an empirical renormalization of the iris formulae (possibly given in the form of a multiplier expression for X_L/Z_0, e.g. $(1 - \alpha \ell/d)$) based on present results or preferably on a fresh, first principles, calculation of the thick iris equivalent circuit values.

Conclusions

An analysis program and optimization design technique for millimeter-wave waveguide iris bandpass filters have been described. The program runs on the HP 9830A calculator. Improvements to the expressions for equivalent circuit values of thick waveguide irises have been discussed. Filters designed and fabricated by this approach have exhibited performance very close to the design values with the primary exception of significantly reduced bandwidth. Further improvement of filter design capability for these frequencies is dependent on improvement in modeling the reactance of thick waveguide discontinuities. The design approach, techniques, and programming described herein should prove useful to a wide range of millimeter wave circuit design problems of which bandpass filter design represents just one subset.

A more complete theoretical treatment of the thick iris problem has come to the author's attention at the time of this writing[6]. This treatment should (hopefully) provide a firm basis for the analytic-optimization design approach described herein. However, in its present form, the more accurate iris modeling expressions are practically useless for optimization (particularly on the HP 9830A) due to the summations involved that must be performed every time a dimension is changed. If simple analytic expressions can be derived to represent the results of these (iris) calculations within the range of interest, then this treatment will be amenable to the design process described above.

REFERENCES

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[3] N. Marcuvitz, Waveguide Handbook, MIT Radiation Laboratory Series, McGraw-Hill, N.Y., 1951.

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APPENDIX 1

```
10 DISP "ENTER (XA/Z0)(WL/W0),W0,L";
20 INPUT X,W0,L
30 PRINT "(XA/Z0)(WL/W0)=";X;"W0=";W0;"L="L
40 R0=4.62291*W0/L
50 R0=LOGR0
60 R0=1+0.31831*L*R0/W0
70 R0=0.450158/R0
80 R0=R0*R0
90 D=PI*SQR(X/2+R0)
100 D=W0/D
110 A=D*SQR2
120 FOR I=1 TO 100
130 B=4*PI*A/L
140 B=LOGB-1
150 B=1+L*B/PI/A
160 B=A*B/SQR2
170 B=B-D
180 C=(1+L/PI/A)
190 A=A-B/C
200 IF ABS(B/D)<1E-06 THEN 240
210 NEXT I
220 PRINT "DID NOT CONVERGE"
230 STOP
240 PRINT "A=";A;"B=";B;"D'=";D
250 GOTO 10
260 END
```

```
10 REM MIN
20 DIM Y[21],X[10],R[10],S[16],T[16],U[16],V[16],W[10],P[10],D[10]
30 DIM Z[11,10],G[21],NI[10],II,JI,KI,LI,MI,NI,OI,HI
40 DISP "ENTER NO. OF SECTIONS";
50 INPUT N0
60 N3=N0
70 M=N0/2+1
80 DISP "ENTER F-LOWER,DELTAF(GHZ),NF";
90 INPUT F0,D0,N1
100 F0=F0*1E+09
110 D0=D0*1E+09
120 DISP "ENTER HEIGHT,WIDTH(IN)";
130 INPUT H0,W0
140 DISP "ENTER IRIS THICKNESS(IN)";
150 INPUT T2
160 T2=2.54*T2
170 W0=2.54*W0
180 PRINT N0;"SECTION FILTER, WIDTH=";W0;"(CM),IRIS THICKNESS";T2;"(CM)"
190 DISP "SCALE=";
200 INPUT Q0
210 DISP "ENTER 1 TO PLOT ATTENUATION";
220 INPUT P3
230 IF P3#1 THEN 270
240 PEN
250 SCALE F0,F0+D0*(N1-1),0,30
260 GOTO 310
270 FOR I=1 TO N1
280 DISP "ENTER DESIRED LOSS(DB),WT AT F";I;
290 INPUT Y[I],G[I]
300 NEXT I
310 FOR I=1 TO M
320 DISP "PAR("I")=";
330 INPUT U[I]
340 X[I]=U[I]
350 R[I]=Q0*(U[I]+(0=U[I]))
360 FOR J=1 TO M
370 Z[I,J]=1 AND I=J
380 NEXT J
390 NEXT I
400 FOR I=M+1 TO N0+2
410 DISP "ENTER IRIS WIDTH";I-M;
420 INPUT X[I]
430 PRINT "IRIS";I-M;"WIDTH=";X[I]
440 NEXT I
450 D=4.62291*W0/T2
460 D=LOGD
470 D=1+0.31831*T2*D/W0
480 D=0.450158/D
490 D=D*D
500 D=2*W0*D
510 GOSUB 1790
520 PRINT "INITIAL ERROR="E
530 FOR I=1 TO M
540 PRINT "PAR("I")="X[I]
550 NEXT I
560 E2=E
570 N[1]=M+1
580 FOR K=1 TO 20
590 N[3]=1
600 E0=E1=E2
610 FOR I=1 TO M
620 W[I]=U[I]
630 NEXT I
640 FOR J=1 TO N[1]
```

```
650 S[1]=1
660 E0=E2
670 L=J
680 FOR I=1 TO M
690 P[I]=Z[L,I]*R[I]
700 NEXT I
710 FOR N=1 TO 16
720 FOR I=1 TO M
730 X[I]=U[I]+S[N]*P[I]
740 NEXT I
750 GOSUB 1790
760 PRINT "E=";E
770 IF E>1.6*E2 AND 1=K AND 1=N THEN 850
780 V[N]=E
790 IF 1=N THEN 870
800 IF V[N] >= E2 THEN 920
810 E2=V[N]
820 IF 16=N THEN 900
830 S[N+1]=2*S[N]
840 GOTO 900
850 R[L]=R[L]/3
860 GOTO 680
870 D1=ABS(V[1]-E2)
880 IF V[1]<E2 THEN 810
890 S[2]=-S[1]
900 NEXT N
910 N=16
920 O=N
930 B0=E0
940 B3=0
950 IF 2=O THEN 980
960 B0=V[N-2]
970 B3=S[N-2]
980 B1=V[N-1]
990 B2=V[N]
1000 B4=S[N-1]
1010 B5=S[N]
1020 B2=(B0-B2)*(B3-B4)
1030 B1=(B0-B1)*(B3-B5)
1040 Q3=-(B2*(B3+B4)-B1*(B3+B5))/(B1-B2)/2
1050 FOR I=1 TO M
1060 X[I]=U[I]+Q3*P[I]
1070 NEXT I
1080 GOSUB 1790
1090 PRINT "ERROR="E" GAMIN="Q3
1100 FOR I=1 TO M
1110 PRINT "PAR("I")="X[I]
1120 NEXT I
1130 IF 2=N AND S[N]<0 THEN 1200
1140 IF E>E2 THEN 1230
1150 E2=E
1160 FOR I=1 TO M
1170 U[I]=X[I]
1180 NEXT I
1190 GOTO 1270
1200 IF E<E2 THEN 1150
1210 Q3=0
1220 GOTO 1270
1230 Q3=S[O-1]
1240 FOR I=1 TO M
1250 U[I]=U[I]+Q3*P[I]
1260 NEXT I
1270 T[J]=Q3
1280 D[J]=E2
1290 IF J#M THEN 1680
1300 Q4=0
```

```
1310 FOR I=1 TO M
1320 Q4=Q4+T[I]*T[I]
1330 P[I]=U[I]-W[I]
1340 X[I]=U[I]+P[I]
1350 NEXT I
1360 IF Q4 <= 0 THEN 1760
1370 Q4=SQR(Q4)
1380 GOSUB 1790
1390 E3=E
1400 IF E3>E1 THEN 1690
1410 N[3]=1
1420 D2=E1-D[1]
1430 FOR I=2 TO M
1440 D3=D[I-1]-D[I]
1450 IF D3<D2 THEN 1480
1460 D2=D3
1470 N[3]=I
1480 NEXT I
1490 F1=E1-2*E2+E3
1500 F2=E1-E2-D2
1510 F2=F2*F2
1520 F1=F1*F2
1530 F3=E1-E3
1540 F3=F3*F3
1550 F3=D2*F3/2
1560 IF F1 >= F3 THEN 1690
1570 IF E3>E2 THEN 1620
1580 E2=E3
1590 FOR I=1 TO M
1600 U[I]=X[I]
1610 NEXT I
1620 FOR I=1 TO M
1630 Z[N[1],I]=P[I]/R[I]/Q4
1640 FOR N=N[3] TO M
1650 Z[N,I]=Z[N+1,I]
1660 NEXT N
1670 NEXT I
1680 NEXT J
1690 D4=(E1-E2)/E1
1700 PRINT "ERR0="E1"ERR1="E2"DECR="D4
1710 FOR I=1 TO M
1720 PRINT "PAR("I")="U[I]
1730 NEXT I
1740 IF Q4>0.1 THEN 1770
1750 PRINT "STALEMATE EXIT"
1760 STOP
1770 NEXT K
1780 STOP
1790 REM EVAL
1800 E=0
1810 FOR I5=1 TO N1
1820 F=F0+D0*(I5-1)
1830 GOSUB 1900
1840 IF P3=1 THEN 1870
1850 A=(Y[I5]-Y1)*G[I5]
1860 E=E+A*(A>0)
1870 NEXT I5
1880 RETURN
1890 STOP
1900 REM VAL
1910 REM WAVEGUIDE IRIS FILTER ANALYSIS
1920 FOR I=1 TO M-1
1930 L[I]=2.54*X[I]
1940 L[N0+1-I]=L[I]
1950 H[I]=W0*X[M+I]*X[M]
1960 H[N0+2-I]=H[I]
```

```
1970 NEXT I
1980 H[M]=W0*X[N0+2]*X[M]
1990 K0=3E+10/F
2000 K1=1/K0/K0-1/4/W0/W0
2010 K1=1/SQR(K1)
2020 G=754*H0*K1/K0/W0
2030 R1=G
2040 R2=0
2050 FOR I=1 TO N0+1
2060 N2=I
2070 IF I5#1 THEN 2090
2080 GOSUB 2390
2090 R2=R2-B[I]*G/K1
2100 GOSUB 2540
2110 R2=R2-K1/A[I]/G
2120 GOSUB 2540
2130 R2=R2-B[I]*G/K1
2140 IF I=N0+1 THEN 2230
2150 T1=TAN(2*PI*L[N2]/K1)
2160 R4=R1*T1
2170 R3=G-R2*T1
2180 R2=R2+G*T1
2190 GOSUB 2340
2200 R1=G*X
2210 R2=G*Y
2220 NEXT I
2230 R3=R1+G
2240 R1=R1-G
2250 R4=R2
2260 GOSUB 2340
2270 R=SQR(X*X+Y*Y)
2280 A=1/(1-R*R)
2290 Y1=10*LGT(A)
2300 IF P3#1 THEN 2320
2310 PLOT F,Y1,-2*(I5=1)-(I5=N1)
2320 RETURN
2330 STOP
2340 C=R3*R3+R4*R4
2350 X=(R1*R3+R2*R4)/C
2360 Y=(R2*R3-R1*R4)/C
2370 RETURN
2380 STOP
2390 A=4.62291*H[N2]/T2
2400 A=LOGA
2410 A=1+0.31831*(H[N2]>1*T2)*T2*A/H[N2]
2420 A=0.707107*H[N2]*A
2430 A=0.31831*W0/A
2440 A=A*A
2450 A[I]=2*W0*A-D
2460 A[I]=A[I]*((H[N2]>0.5*W0)*(0.125+1.75*H[N2]/W0)+(H[N2] <= 0.5*W0))
2470 A=0.424413*T2*H[N2]*H[N2]*H[N2]
2480 B=PI/W0
2490 B=B*B
2500 B=B*B
2510 B[I]=0.125*W0*B*A
2520 RETURN
2530 STOP
2540 C=R1*R1+R2*R2
2550 R1=R1/C
2560 R2=-R2/C
2570 RETURN
2580 END
```

TABLE 1

```
                    WAVEGUIDE FILTER DESIGN

WAVEGUIDE WIDTH=  0.1000IN.    F1=  69.000GHZ.    F2=  77.000GHZ.
 20.0000    DB ATT. AT 68.0000    AND 78.0000    GHZ
REFLECTION COEFFICIENT= 0.3859               VSWR= 2.2570
 8.0000  SECTION TCHEBYSCHEFF FILTER WITH 0.7000  DB RIPPLE
    G  0= 1.0000
    G  1= 1.9306
    G  2= 1.1990
    G  3= 2.8494
    G  4= 1.2800
    G  5= 2.8882
    G  6= 1.2628
    G  7= 2.7055
    G  8= 0.8556
    G  9= 2.2565
LAMDA G0/A= 2.8443            A/LAMDA G0= 0.3516

 J  J+1  X(J,J+1)/Z0       X(J,J+1)/Z0*      B(J,J+1)/Y0       B(J,J+1)/Y0*
                             LAMDA G0/A                           A/LAMDA G0
  0   1       0.6931          1.9715            1.4427            0.5072
  1   2       0.3734          1.0622            2.6779            0.9415
  2   3       0.2956          0.8407            3.3834            1.1895
  3   4       0.2846          0.8095            3.5136            1.2353
  4   5       0.2824          0.8032            3.5410            1.2450
  5   6       0.2846          0.8095            3.5136            1.2353
  6   7       0.2956          0.8407            3.3834            1.1895
  7   8       0.3734          1.0621            2.6779            0.9415
  8   9       0.6931          1.9715            1.4427            0.5072

IRIS SPACINGS

L 1.0000  = 0.1063  INCHES
L 2.0000  = 0.1156  INCHES
L 3.0000  = 0.1184  INCHES
L 4.0000  = 0.1189  INCHES
L 5.0000  = 0.1189  INCHES
L 6.0000  = 0.1184  INCHES
L 7.0000  = 0.1156  INCHES
L 8.0000  = 0.1063  INCHES
```

TABLE 2

```
                     WAVEGUIDE FILTER DESIGN

WAVEGUIDE WIDTH=  0.1000IN.    F1=  76.500GHZ.    F2=  85.000GHZ.
 20.0000    DB ATT. AT 75.5000    AND 86.0000    GHZ
REFLECTION COEFFICIENT= 0.1843              VSWR= 1.4519
 8.0000  SECTION TCHEBYSCHEFF FILTER WITH 0.1500  DB RIPPLE
    G  0= 1.0000
    G  1= 1.2947
    G  2= 1.4113
    G  3= 2.2159
    G  4= 1.5588
    G  5= 2.2629
    G  6= 1.5264
    G  7= 2.0489
    G  8= 0.8918
    G  9= 1.4518
LAMDA G0/A= 2.1773              A/LAMDA G0= 0.4593

 J  J+1  X(J,J+1)/Z0        X(J,J+1)/Z0*       B(J,J+1)/Y0        B(J,J+1)/Y0*
                             LAMDA G0/A                             A/LAMDA G0
  0   1       0.7258         1.5803             1.3778             0.6328
  1   2       0.2843         0.6190             3.5175             1.6155
  2   3       0.2107         0.4588             4.7457             2.1796
  3   4       0.1997         0.4348             5.0074             2.2998
  4   5       0.1975         0.4299             5.0643             2.3259
  5   6       0.1997         0.4348             5.0074             2.2998
  6   7       0.2107         0.4588             4.7457             2.1796
  7   8       0.2843         0.6190             3.5175             1.6155
  8   9       0.7258         1.5803             1.3778             0.6328

IRIS SPACINGS

L 1.0000  = 0.0831  INCHES
L 2.0000  = 0.0930  INCHES
L 3.0000  = 0.0954  INCHES
L 4.0000  = 0.0958  INCHES
L 5.0000  = 0.0958  INCHES
L 6.0000  = 0.0954  INCHES
L 7.0000  = 0.0930  INCHES
L 8.0000  = 0.0831  INCHES
```

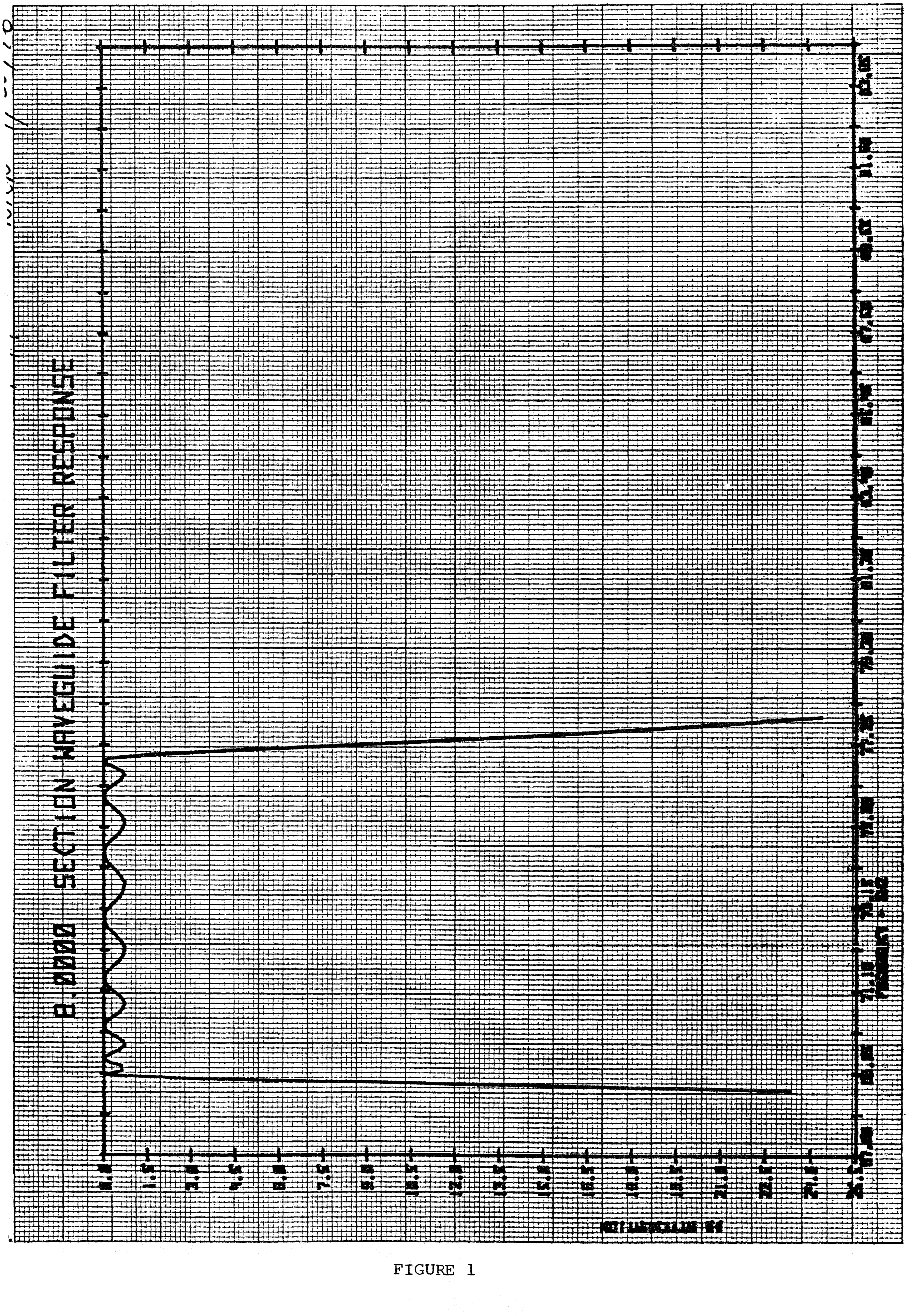

8.0000 SECTION WAVEGUIDE FILTER RESPONSE
0.0
1.5
3.0
4.5
6.0
7.5
9.0
10.5
12.0
13.5
15.0
16.5
18.0
19.5
21.0
22.5
24.0
25.5
DB ATTENUATION

FIGURE 1

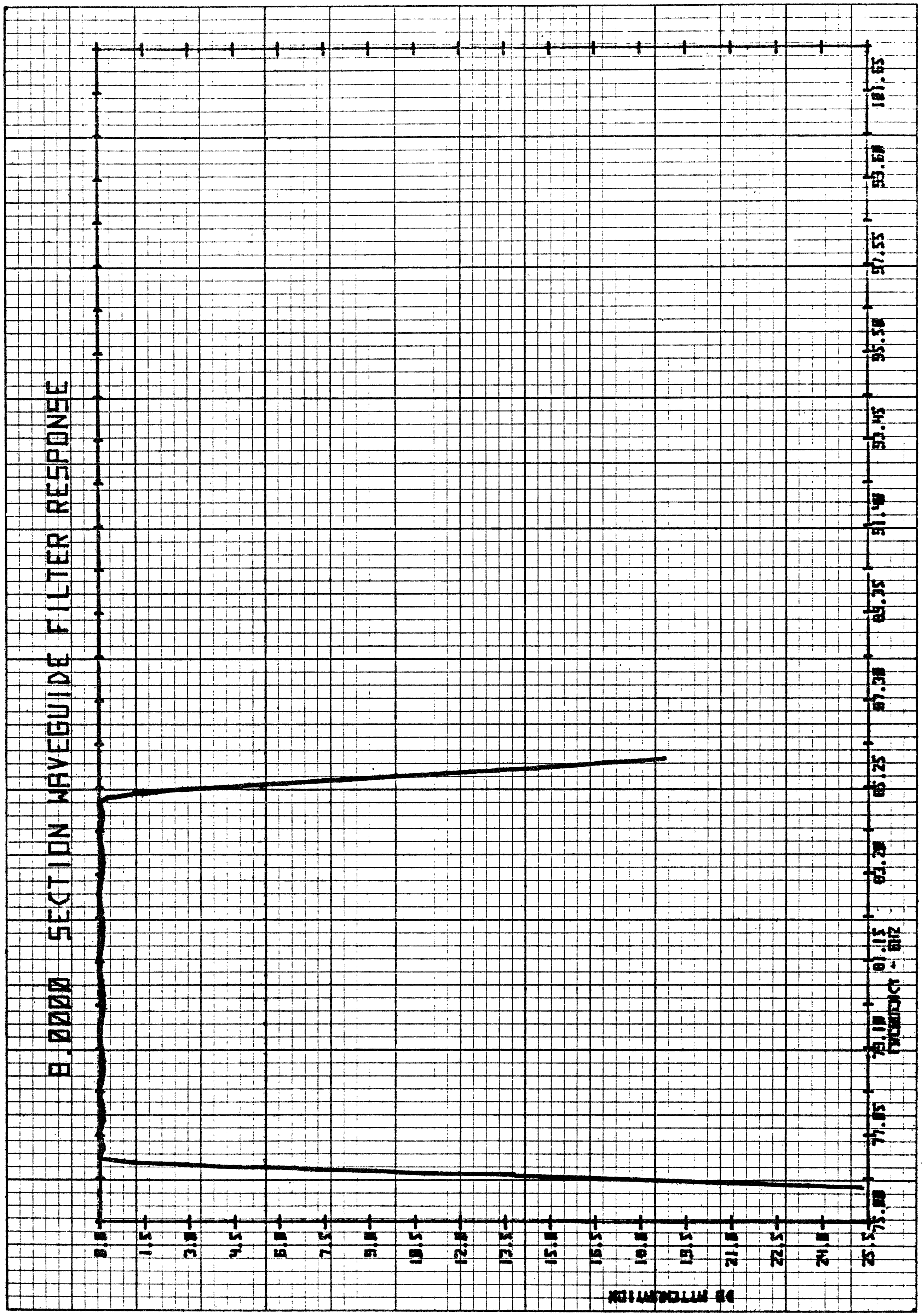

8.0000 SECTION WAVEGUIDE FILTER RESPONSE
0.0
1.5
3.0
4.5
6.0
7.5
9.0
10.5
12.0
13.5
15.0
16.5
18.0
19.5
21.0
22.5
24.0
25.5
DB ATTENUATION
75.00
77.05
79.10
81.15
83.20
85.25
87.30
89.35
91.40
93.45
95.50
97.55
99.60
101.65
FREQUENCY - GHZ

FIGURE 2

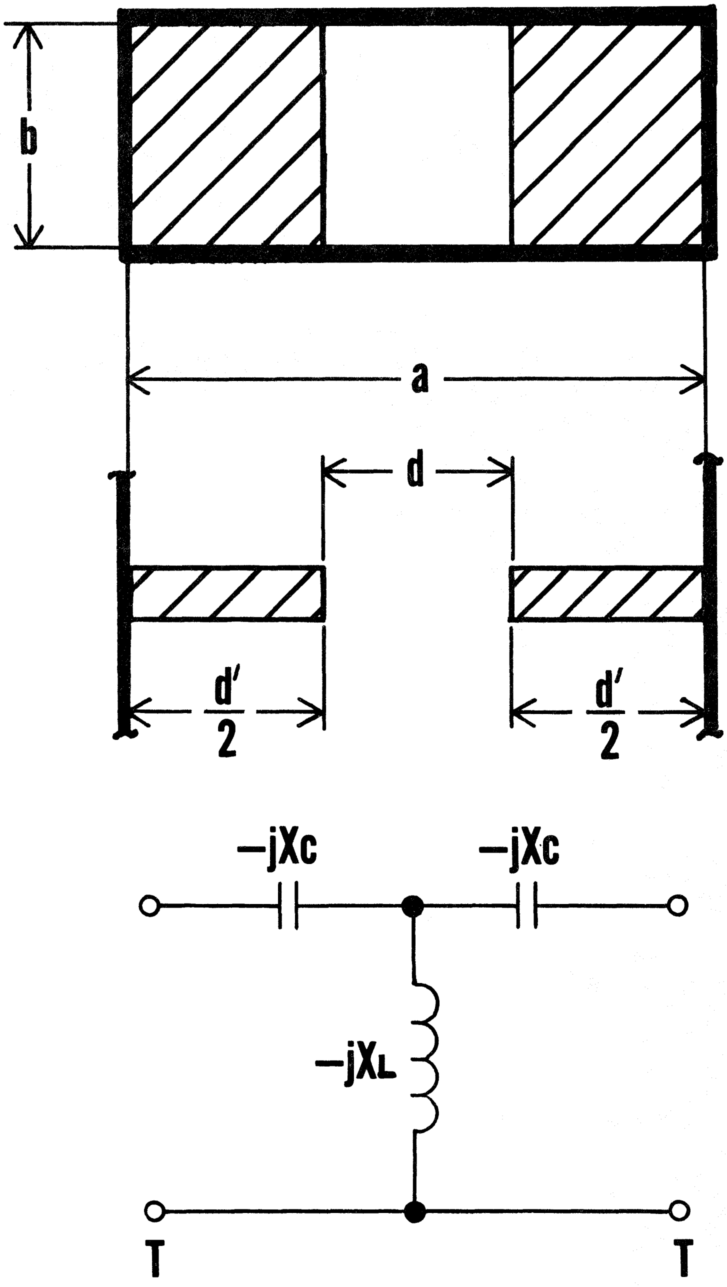


FIG. 3

Thick iris equivalent circuit

FIGURE 4

$\log_{10}(X_L/Z_0)$

9/30/76

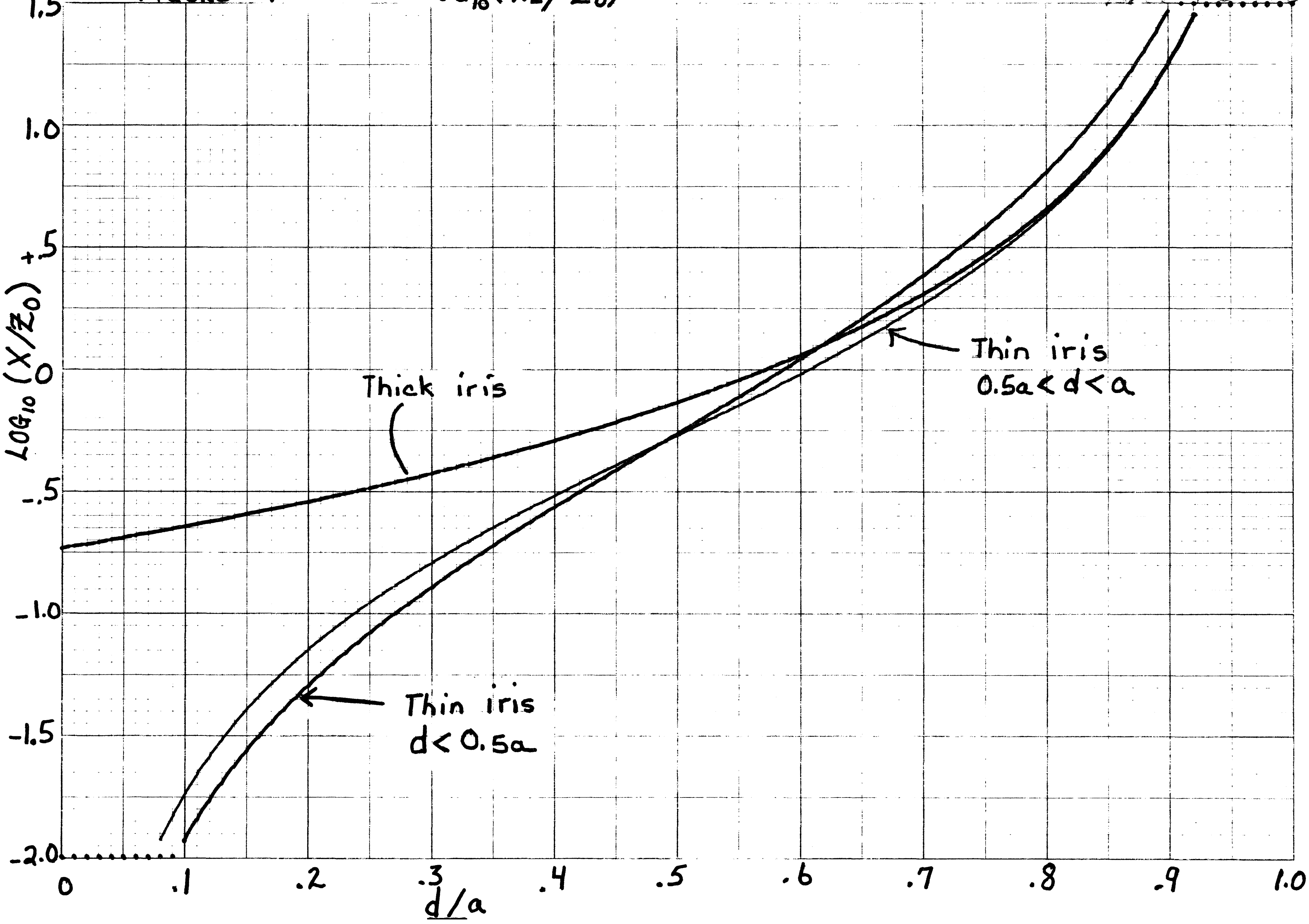


FIGURE 5 – $(X_L/Z_o)_{Thin}/(X_L^c/Z_o)_{Thick}$

DRD 12/10/76

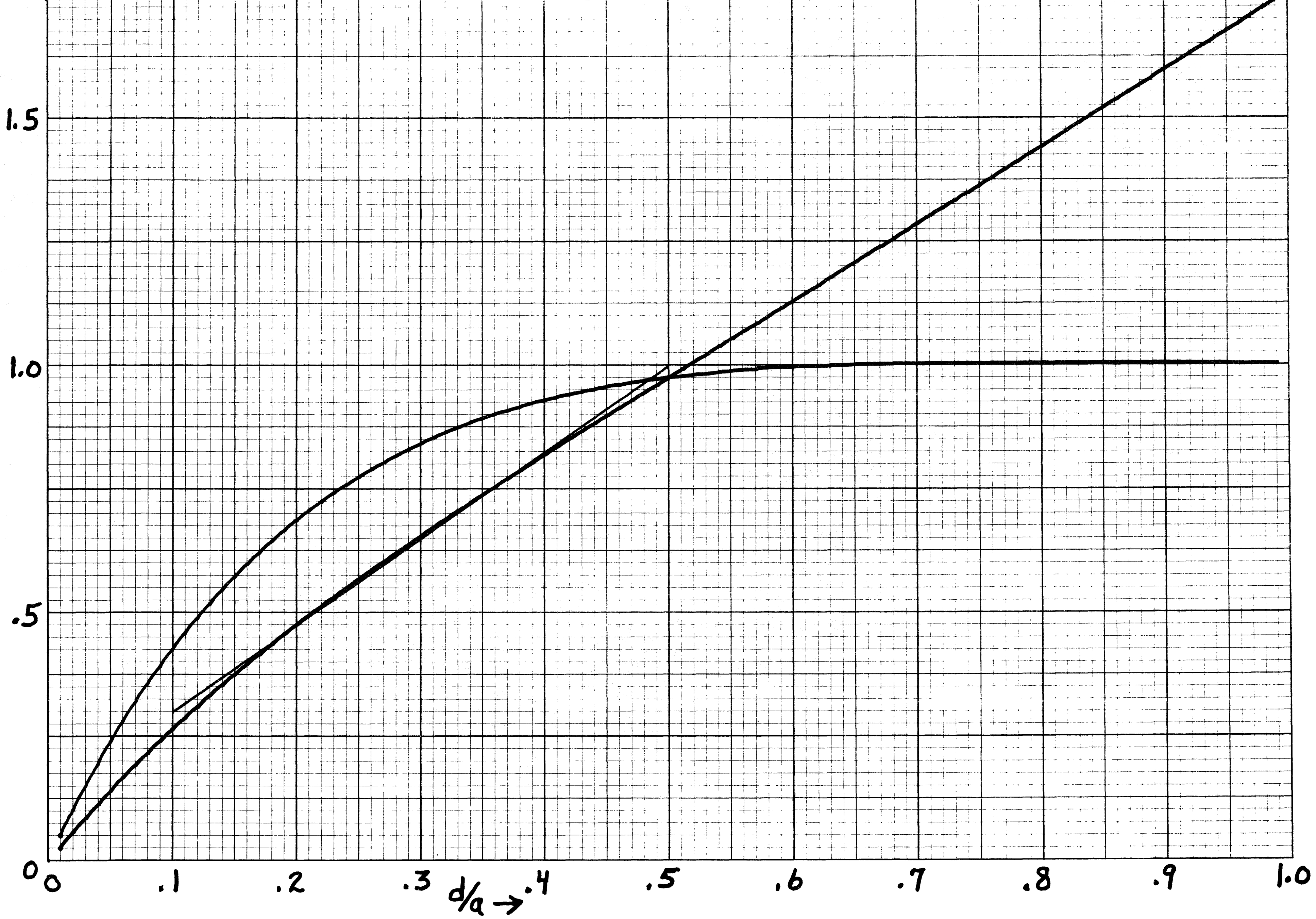


FIGURE 6 – $LOG_{10}(X_L/Z_0)$

DRD 9/30/76

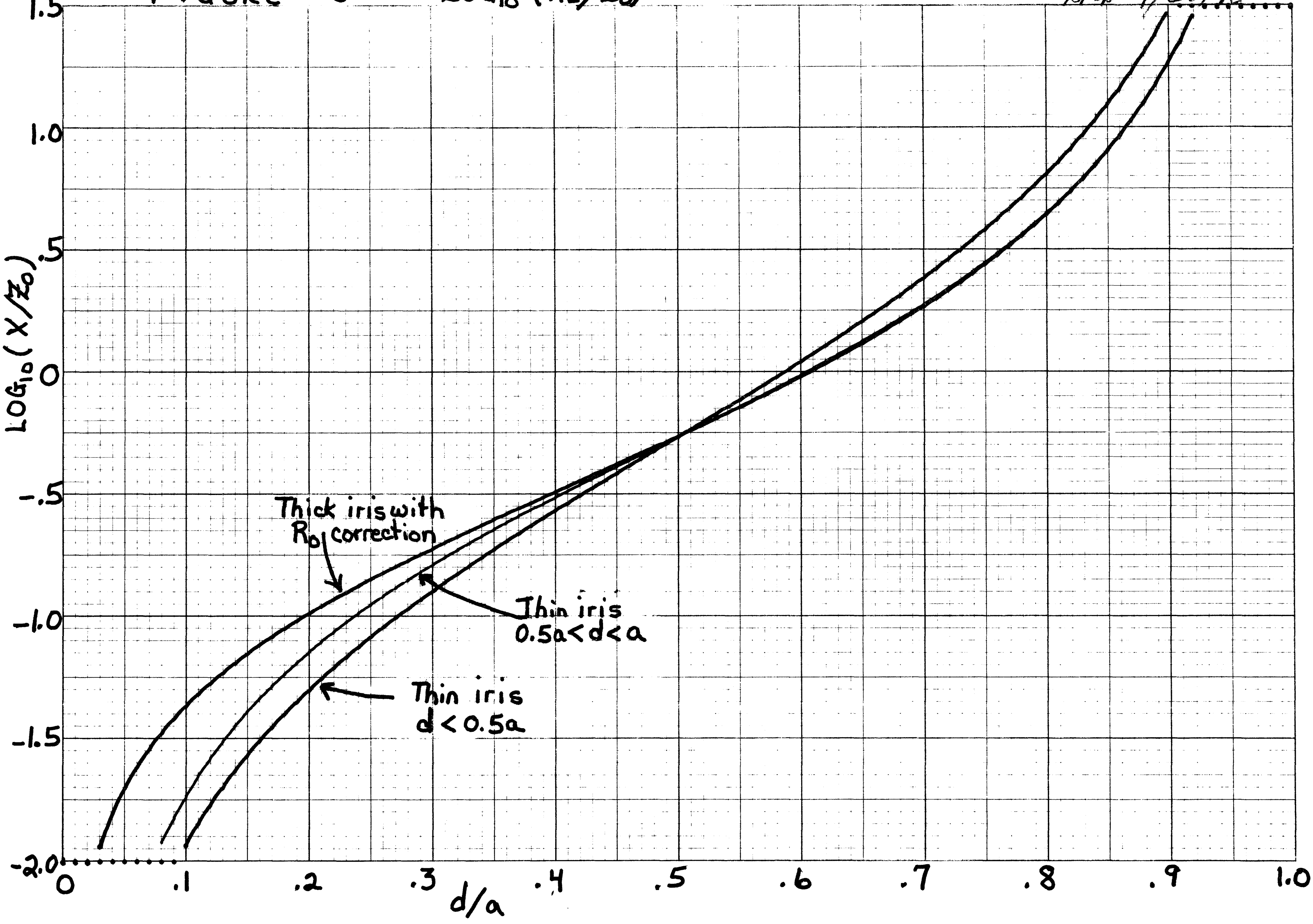


FIGURE 7 - $LOG_{10}(X_L/Z_0)$

DRD 12/10/76

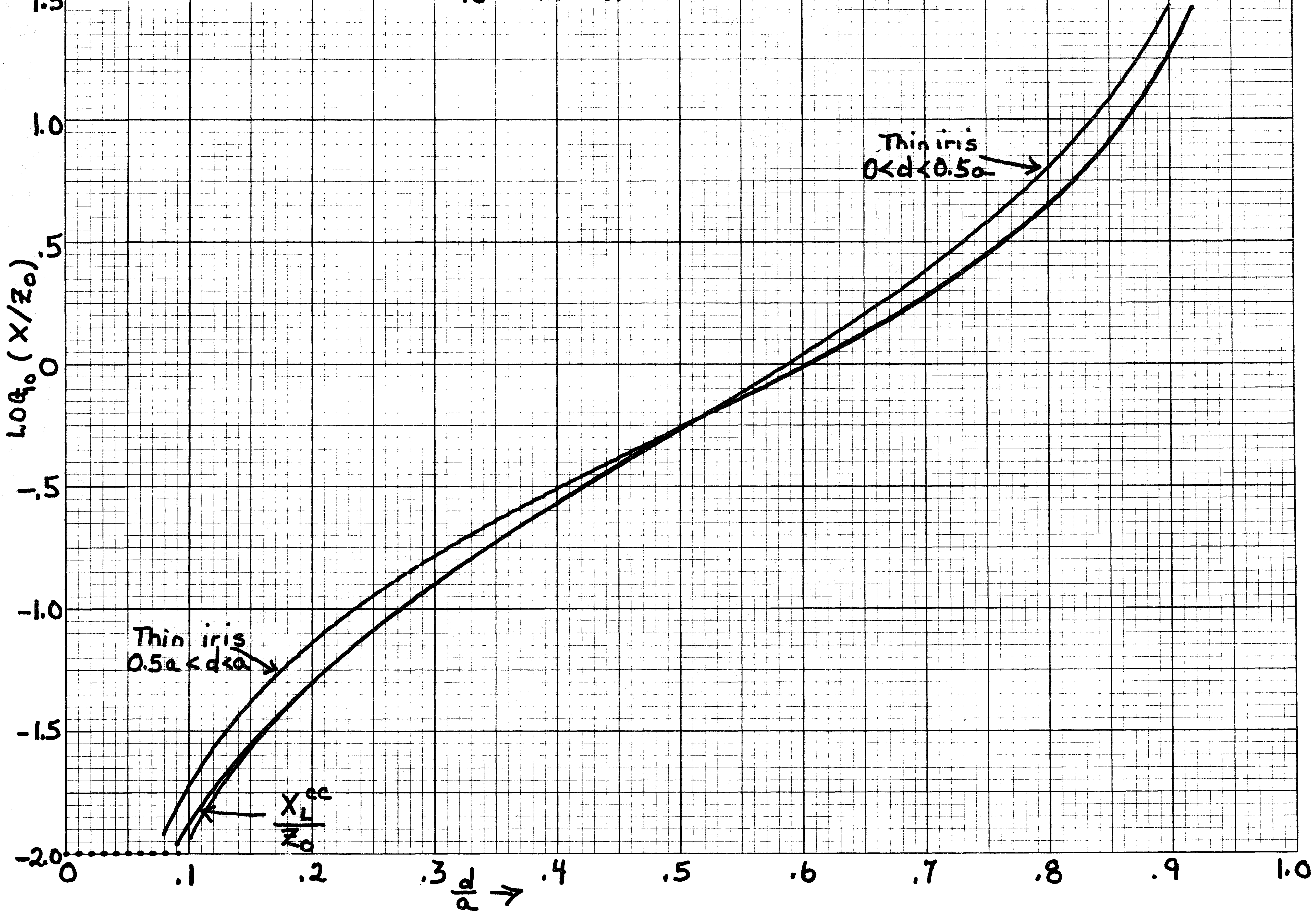
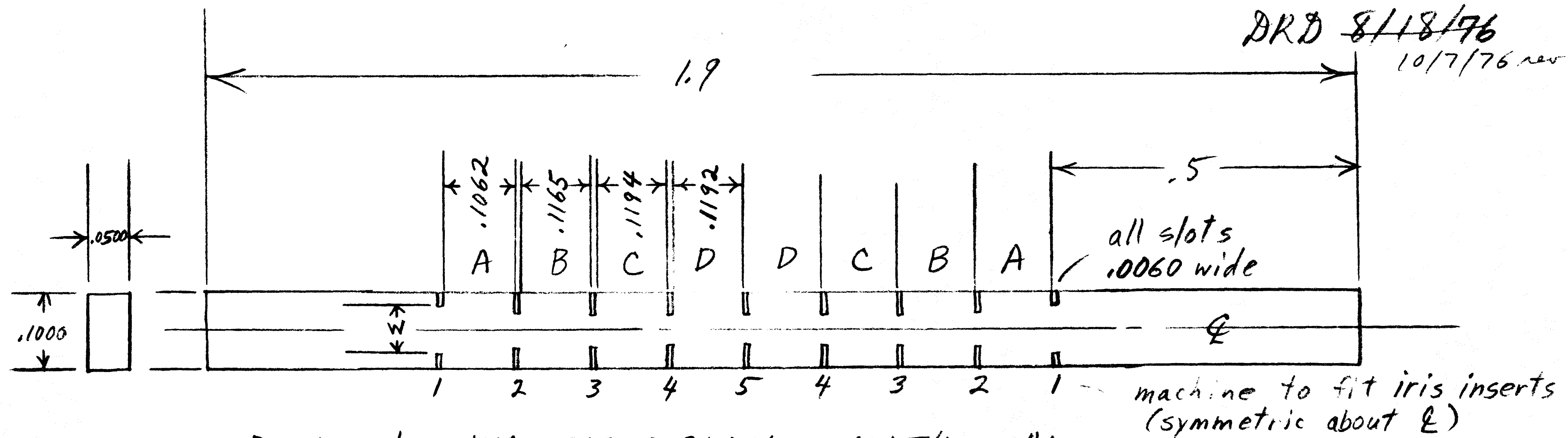


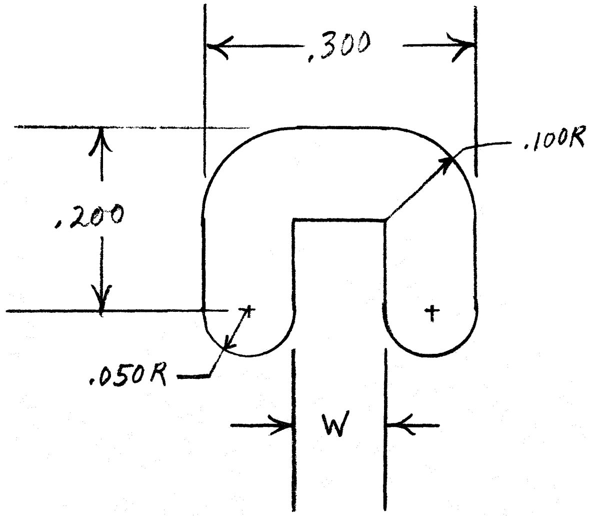
FIGURE 8 - ANALYSIS OF PROTOTYPE
69 - 77 GHz FILTER

DRL 12/14/76

DRD ~~8/18/76~~ 10/7/76 rev



DETAIL 1 - WAVEGUIDE BLOCK ; MAT'L : AL



DETAIL 2 - IRIS INSERT
MAT'L : BeCu , .005 TH'K
Au plate to about .0055

IRIS #	DIM. W	#REQ'D.
1	.0646	2
2	.0533	2
3	.0487	2
4	.0480	2
5	.0478	1

FIGURE 9

WAVEGUIDE B.P. FILTER
69 TO 77 GHz

FIGURE 10 - ANALYSIS OF OPTIMIZED
69-77 GHz FILTER

DPD 10/6/76

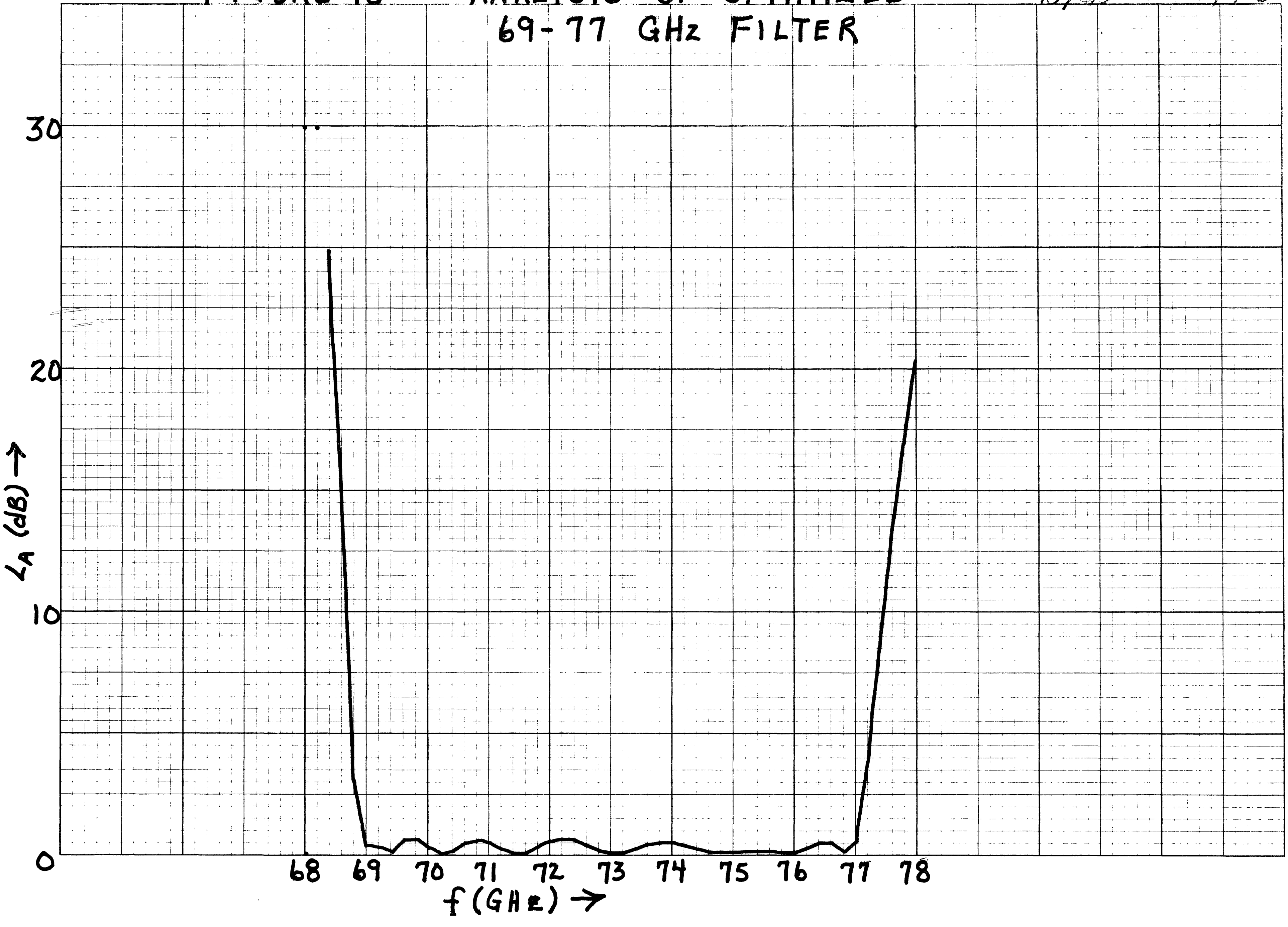
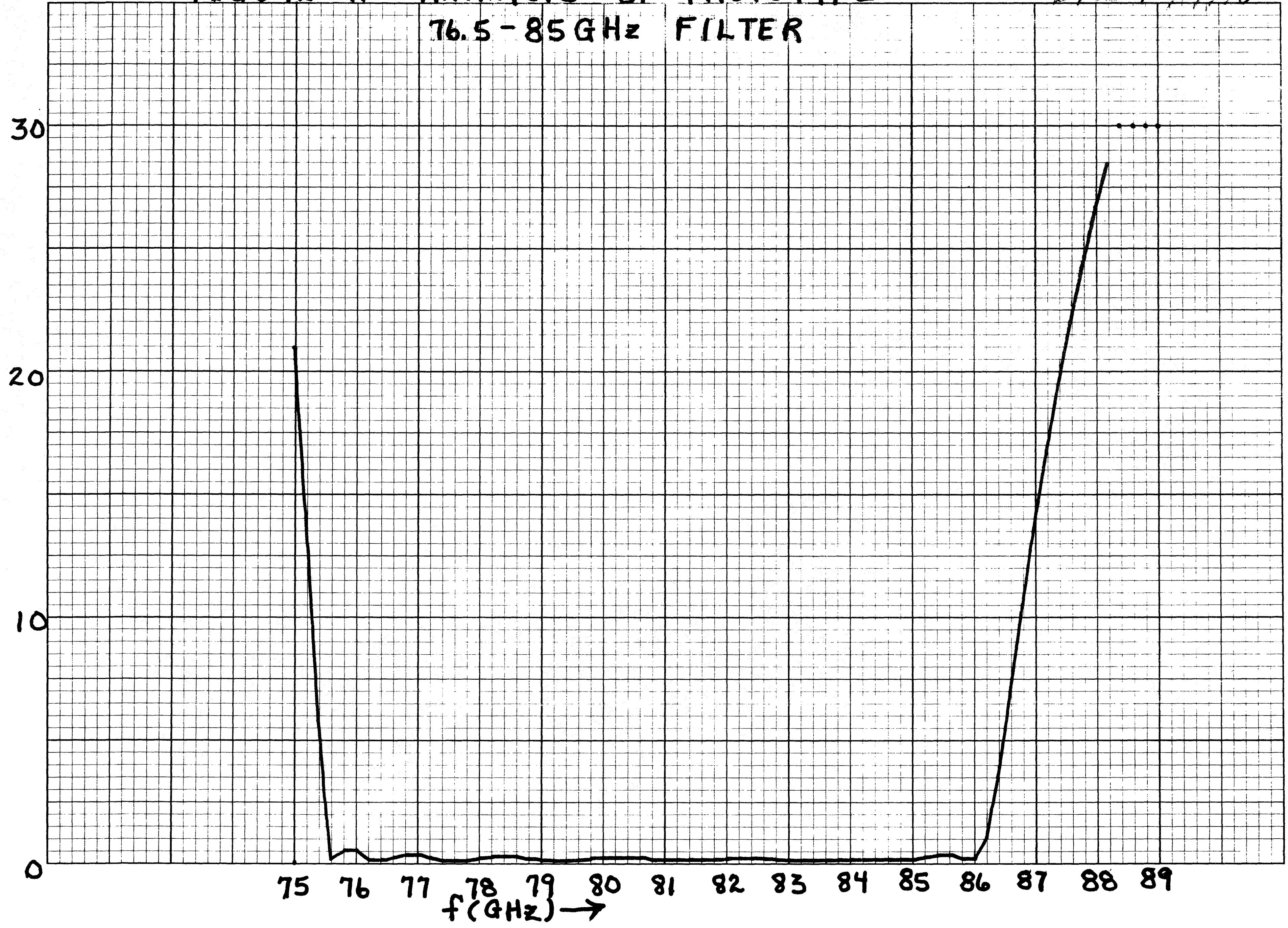
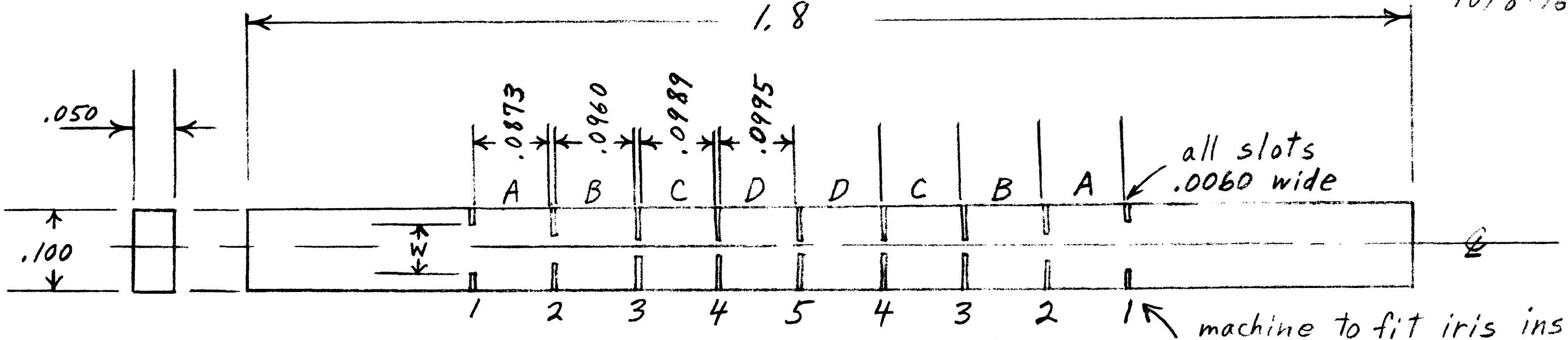


FIGURE 11- ANALYSIS OF PROTOTYPE 76.5-85GHz FILTER

DRD 12/14/76



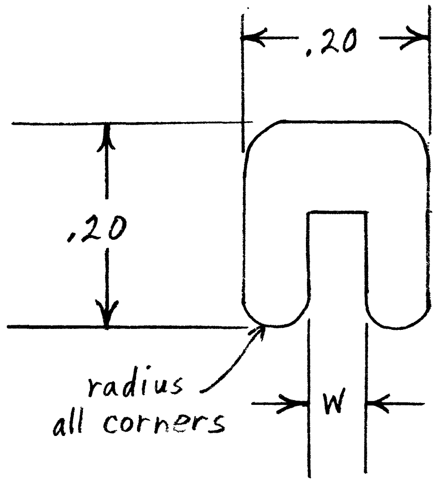
DRD ~~8/20/76~~
10/8/76 rev.



all slots .0060 wide

machine to fit iris inserts (symmetric about ℄)

DETAIL 1 - WAVEGUIDE BLOCK, MAT'L : AL



DETAIL 2 - IRIS INSERT
MAT'L : Be Cu, .005 TH'K
Au plate to about .0055

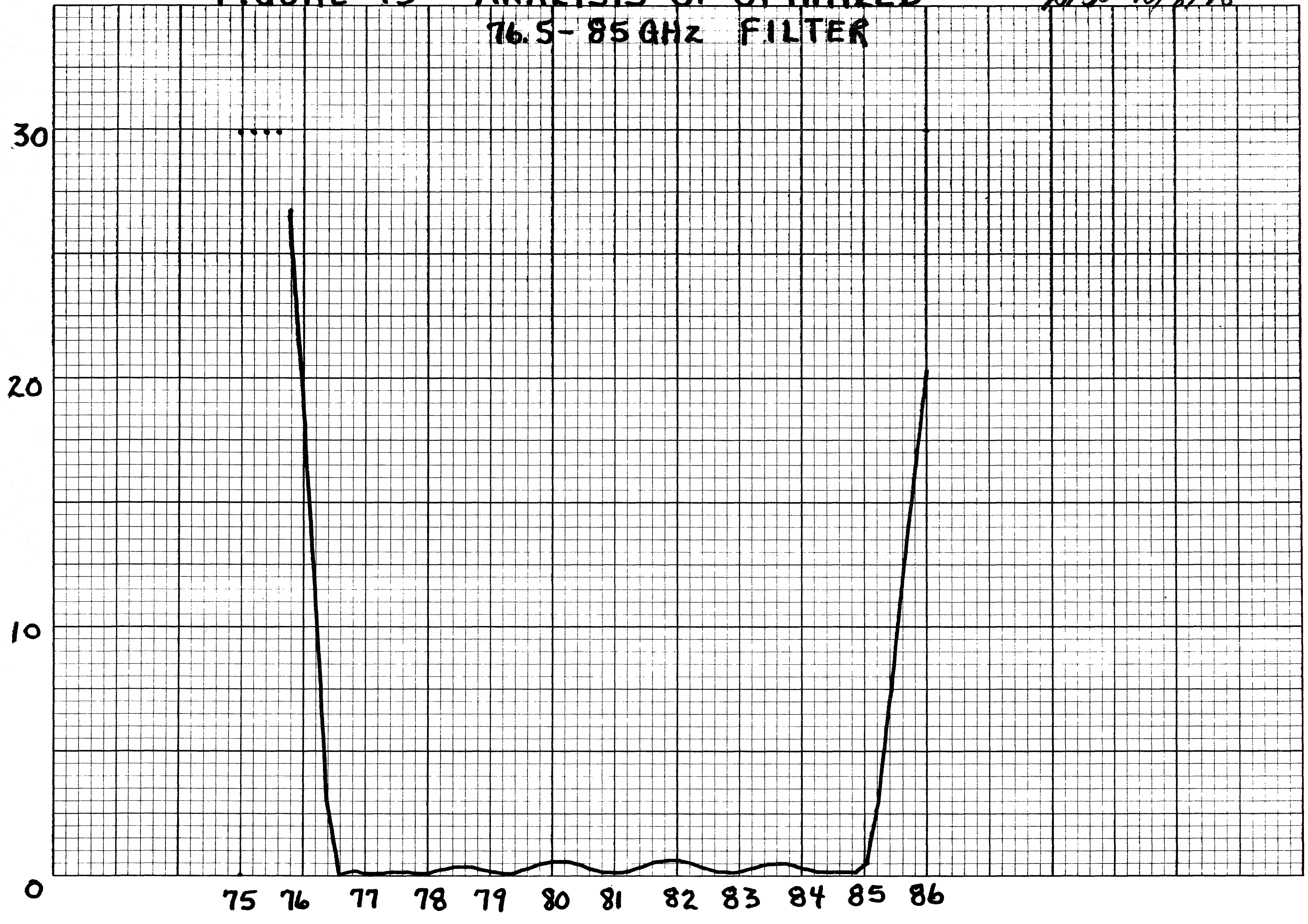
IRIS #	DIM. W	# REQ'D
1	.0568	2
2	.0368	2
3	.0303	2
4	.0291	2
5	.0289	1

FIGURE 12

WAVEGUIDE B.P. FILTER
76.5 TO 85 GHz

FIGURE 13- ANALYSIS OF OPTIMIZED
76.5-85 GHz FILTER

DRD 10/8/76



11/30/76

FIGURE 14 - MEASURED RESPONSE OF 69-77 GHz FILTER

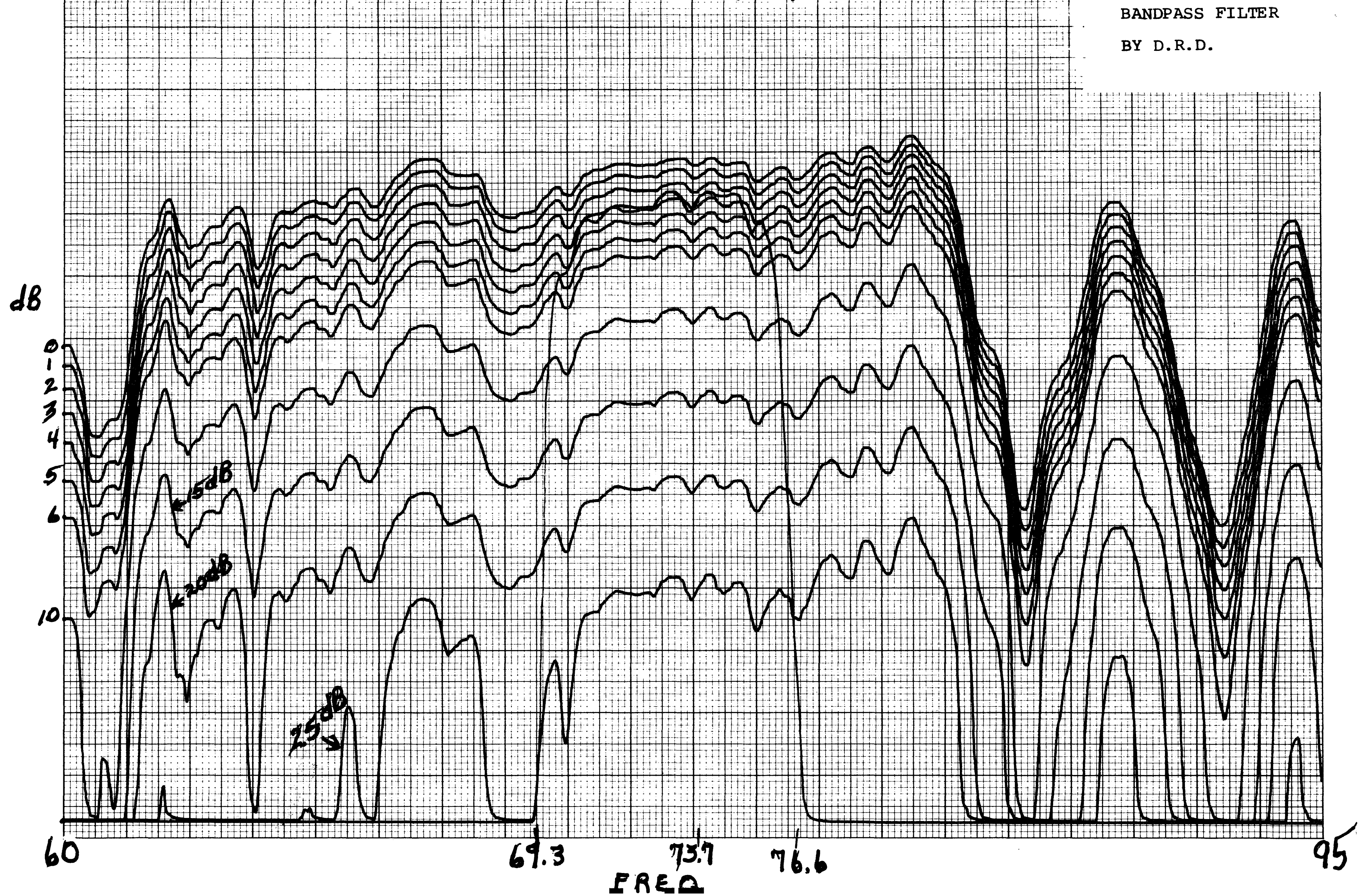


FIGURE 15 - MEASURED RESPONSE OF
76.5 - 85 GHz FILTER

DRD 12/2/76