ESD-TDR-65-315

Technical Note 1965-30

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A Noise Rejection Filter for Waveguide Carrying High Power

3 August 1965

Prepared under Electronic Systems Division Contract AF 19(628)-5167 by

Lincoln Laboratory
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Lexington, Massachusetts

The work reported in this document was performed at Lincoln Laboratory, a center for research operated by Massachusetts Institute of Technology, with the support of the U.S. Air Force under Contract AF 19(628)-5167.

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LINCOLN LABORATORY

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Group 46

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ABSTRACT

A novel design for a waveguide band-rejection filter carrying high power in its pass band is presented. The resonant cavities of the filter are mounted in pairs on the narrow walls of the guide and coupled to the guide through rectangular openings the full height of the guide. Thus there are no edges or radii on which electric field concentrations can occur. An X-band model having six cavity pairs had a rejection greater than 80 db over 45 Mcps in its stop band with an insertion loss under 0.05 db and VSWR under 1.02 in its pass band. With water cooling, the filter carried over 300 kw CW without breakdown.

Accepted for the Air Force
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Lt Colonel, USAF
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A NOISE REJECTION FILTER FOR WAVEGUIDE CARRYING HIGH POWER

I. INTRODUCTION

The M.I.T. Lincoln Laboratory Haystack Facility transmits 100 kw CW at 7750 Mcps while receiving at 8350 Mcps using the same antenna. A reject filter is used to reduce substantially the part of the transmitter noise that lies within the receiver pass band and couples into the receiver. This filter is placed in the transmitter waveguide between the generator and the diplexing arrangement. It strongly attenuates energy around the receive frequency while passing energy at the transmit frequency with very little attenuation or reflection.

Filters placed in very high power lines are typically of the absorbing, rather than reflecting, type in order to avoid large electric fields that might induce voltage breakdown in the structure and to provide a load in which the undesired energy can be dissipated. However, for Haystack it was decided to use a reflecting-type filter for the following reasons:

1. The resonators used would be tuned to the receive frequency and thus would allow only small voltages at the transmit frequency.
2. The novel design proposed had no edges or radii on which electric field intensification could occur.
3. A terminated high-power circulator located at the generator was available to absorb reflected energy.
4. A reflection filter could be made to have higher stop-band loss and lower pass-band loss than an absorption filter.
5. A reflection filter could be made smaller in volume and weight than an absorption filter.
6. The performance of a reflection filter is more accurately predictable than is the performance of an absorption filter.

A reflecting noise-rejection filter development program was begun that resulted in an interim filter design having a rejection band about 8050 Mcps and the final filter design with a rejection band about 8350 Mcps.

II. DESCRIPTION

Figures 1(a) and (b) show the noise-reject filters for 8050 and 8350 Mcps. The 8050 Mcps filter has three pairs of resonators while the 8350 Mcps filter has six pairs, since it was required to have a wider stop band than the 8050 Mcps filter.

The waveguide size is WR-137 with inside dimensions of 0.622 x 1.372 inches. The flanges are stainless steel CPR-137F, which are preferable to standard UG-344 flanges for high-power work. The pipes soldered to the broad walls of the filters are for the cooling water needed at high power levels.

The resonators are coupled to the waveguide through openings in the narrow wall of the waveguide. These openings run the full height of the guide so that upper and lower walls of the waveguide and resonators are flush and continuous, with no edges or protrusions that might cause electric field concentrations. If the resonators had been placed on the broad walls of the waveguide, as is usually done with reject filters, the edge of the opening between resonator and waveguide would have been in the region of greatest electric field intensity. The electric field would be further intensified along this edge, enhancing voltage breakdown.

The higher-order modes generated by resonators on the narrow walls of the guide are not greatly attenuated with distance along the guide because the cutoff frequencies of these modes are determined by the wide dimension of the guide. In contrast, the cutoff frequencies of higher-order modes generated by resonators mounted in the broad walls of the guide are determined by the narrow dimension of the guide and so are more strongly attenuated with distance. In any case, these higher-order modes provide undesired alternative coupling paths between adjacent resonators, broadening the stop bandwidth and reducing the maximum attenuation. Thus it is desired to suppress higher-order modes as much as possible.

The least attenuated higher-order mode for the reject filters shown in Figs. 1(a) and (b) is the TE_{20} mode. To prevent this mode from affecting filter performance, it was found necessary to place identical resonators identically tuned on either side of the waveguide at the same terminal plane. The symmetry of this arrangement prevents generation of the TE_{20} mode.

The next least-attenuated mode is the TE_{30} mode. In order to avoid adjacent cavity coupling by this mode, it was found necessary to space the resonators by five quarters of a guide wavelength rather than the usual three quarters. Small inductive irises can be seen just within the flanges of the two filters. These irises match out the residual reflection of the filter to give a very low VSWR in the pass band.

The large screws shown extending from the cavities are for fine tuning. They allow each pair of resonators to be set to the proper resonant frequency and to be put in electrical balance. No attempt to adjust these screws should be made in the field.

III. DESIGN PROCEDURE

The following specifications were assigned to the 8350 Mcps noise-reject filter.

Waveguide	WR-137
Rejection	60 db min over 8350 $\pm$ 15 Mcps
Pass-band loss	0.1 db max at 7750 Mcps
Pass-band VSWR	< 1.15
Power handling	100 kw CW min
Operating temperature	60° - 150°F

Simple calculations showed that the allowed temperature variation could change the center frequency of the filter by almost 7 Mcps. The 60 db rejection bandwidth was increased to allow for this variation and 3 Mcps more were added to allow for tuning tolerance. Thus a 60 db rejection bandwidth of 40 Mcps was used in the design of the filter.

Figure 4.03-4 of Ref. 1 showed that a 0.01 db ripple Tchebyscheff filter of six resonators would provide 63 db rejection over a 40 Mcps band at 8350 Mcps, and that this filter would have a total stop bandwidth of 128 Mcps.

This relatively narrow stop bandwidth (1.5%) insured that the pass band was well removed from the lossy range near the stop-band edge and allowed use of the approximate design procedure for filters with very narrow stop bands described in Chapter 12 of Ref. 1.

The equivalent circuit for the filter is shown in Fig. 2. All the resonators are tuned to the stop-band center frequency. It might be observed that the resonators are shown in the equivalent circuit as series-resonant circuits shunting the transmission line, although the actual resonators are anti-resonant structures attached to the side of the waveguide. This is not inconsistent because the effect is the same--open circuiting the waveguide at its side is the same as short circuiting it at the center, when viewed from some distance along the guide. In fact, as closely as it was practical to measure, it was found that the axial centerline of the cavity coincided with the terminal plane of the effective short circuit caused by the cavity at its resonant frequency. This is in basic agreement with the electromagnetic boundary-value solution for a similar structure given in Sec. 6.6 of Ref. 2. The structure of Ref. 2 is an iris-coupled H-plane T junction. It differs from the structure used in the filter in that it has a side arm on only one side of the main guide and because it uses very thin irises. Also, it is based on small apertures and does not apply near the second mode cutoff frequency, where the filter operates. These differences make the circuit of Ref. 2 only qualitatively useful in determining resonator and coupling iris sizes.

The low-pass prototype and procedure of Ref. 1 were used with the pertinent values given above to find the slope parameters for the resonators. Only three slope parameters are required because the structure is symmetrical about its center. The required slope parameters, normalized to the guide characteristic impedance, are

$$x_1 = 87.65,$$
$$x_2 = 45.65,$$
$$x_3 = 40.50.$$

These slope parameters are defined on a frequency, rather than reciprocal guide wavelength basis. The theoretical design calls for the characteristic impedance, Z_1, of the waveguide between resonators to be slightly less than the generator and load impedances, Z_o. In the interests of mechanical simplicity, such an impedance step was not incorporated in the actual structure. This omission causes negligible effect in the stop band and a slightly larger maximum reflection than predicted in the pass band. However, pass-band performance was not expected to agree with simple theory because the resonator spacing of 5/4 guide wavelengths at the stop-band center frequency was a poor approximation in the pass band to the frequency independent 90^o line lengths assumed by the theory. For this reason it was necessary to use small irises at the ends of the filter to obtain low VSWR in the pass band.

The simple resonators shown in Fig. 2 are good approximations to the actual situation in a narrow band around their resonant frequencies, but only when both cavities of a pair are identical. A more accurate equivalent circuit that allows for small differences between the cavities of a pair is shown in Fig. 3. It can be seen that if the elements of subscript 1 are identical to those of subscript 2, the circuit of Fig. 3 reduces to that of a single series resonator. However, if any differences exist between element values of subscripts 1 and 2, then the circuit has two impedance zeros separated by a pole.

The mutual capacitance C_o is needed to account for the fact that the two zeros do not converge to the same frequency as one resonator of the pair is tuned toward the frequency of the other but remain rather widely separated. Frequency differences of about 150 to 400 Mcps, increasing with decreasing slope parameter, were observed for the cavity pairs investigated for the filters described herein. Electrical balance of the two resonators occurs when the lower-frequency zero combines with the pole and both disappear. If the frequencies of the zeros are observed by monitoring transmission loss of a swept signal, the lower frequency zero will disappear only if $R_1 = R_2$; otherwise, the transmission loss at the lower frequency will simply pass through a minimum.

It is possible to use this phenomenon to determine when a pair of cavities is electrically balanced. Also, it is important to know where the secondary frequencies are, since they may lie at a pass-band frequency of interest and cause a loss peak there.

If the cavities are nearly the same and tuned nearly alike, it can be shown that the ratio of C_1/C_o is given by the equation

$$C_1/C_o = \frac{1}{2}\left[\left(\frac{f_u}{f_\ell}\right)^2 - 1\right] \quad , \tag{1}$$

where f_u and f_ℓ are the upper and lower observed frequencies of minimum transmission. Since the mutual coupling is presumably mostly by way of the TE_{30} mode, it should be possible to use this information to compute the proportions of energy stored in the waveguide in the TE_{30} mode and the energy stored within the resonators, but this will not be done here.

With the establishment of the physical configuration for the resonators, the frequencies involved, and slope parameters required, a test jig of adjustable iris opening and cavity length was made up. The cavity width was fixed at 1.00 inch because this made the cavity nearly square, which is a minimum-loss proportion. The test jig looked much like the filter of Fig. 1(a), but with only a single pair of resonators (Drawing A-74082).

The test procedure consisted of selecting a value of iris opening, then shimming to find the cavity length that resonated with this iris opening at the stop-band center frequency. Resonance was considered to be the frequency f_o of maximum transmission loss. A lumped-element equivalent circuit for the test jig, near cavity resonance is shown in Fig. 4. The voltage V of Fig. 4 is proportional to the voltage across a matched detector on the output side of the test jig. Analysis of the circuit of Fig. 4 shows that

$$R/Z_o = \frac{1}{2}\left(\frac{1}{10^{L_o/20} - 1}\right) \quad , \tag{2}$$

where L_o is the measured transmission loss in decibels at resonance.

Next, the bandwidth, Δf, was measured between two points having some convenient level of insertion loss L in decibels, typically 3 or 6 db. Then the slope parameter, x, of the resonator pair was found from

$$x = \frac{f_o}{\Delta f}\sqrt{\frac{(R + Z_o/2)^2 - R^2 10^{L/10}}{10^{L/10} - 1}} \quad . \tag{3}$$

If $R << Z_o$ and bandwidth between the 3 db points is used, this equation can be approximated by

$$x/Z_o \simeq \frac{1}{2}\,\frac{f_o}{\Delta f} \quad . \tag{4}$$

Since the simple equivalent circuit does not hold quantitatively in the pass band, it was necessary to measure the VSWR of each cavity pair at the pass-band center frequency so that a reasonable estimate of the filter reflection in the pass band could be made.

On the basis of the above-described measurements, graphs were prepared of cavity-length, x/Z_o, R/Z_o, and pass-band VSWR as functions of iris opening. The first two graphs were used to find the cavity lengths and iris openings appropriate to the required values of the slope parameters given in Sec. II. The graph of R/Z_o could have been used to predict the maximum attenuation of the filter (assuming no adjacent cavity coupling via higher-order modes) but this was not believed necessary. A calculated value for the electrical spacing of the resonators at the pass-band center frequency and the appropriate values of resonator VSWR as taken from the graph were used on a Smith chart to predict that the VSWR of the filter at the center of the pass band would be 1.24, before cancelling with irises.

The final internal dimensions of the 8350 Mcps reject filter are shown in Fig. 5 (Drawing S-17159). Iris thickness is 0.020 inches in every case. The cavities were made an additional 0.020 inch long to allow for tolerances and tuning.

IV. MEASUREMENT, TUNING AND PERFORMANCE

The basic scheme for tuning and measurement of rejection involved a swept-signal generator feeding two channels, one of which held the filter and the other of which allowed the insertion of calibrated attenuation up to 90 db. Essential to the operation of this technique was a low-noise TWT amplifier used just before detection. This amplifier allowed sufficient sensitivity to make accurate measurements in the stop band and acted as its own limiter when overloaded by the much stronger signal in the pass band. The limiting action was needed to prevent blocking and disabling the detector and following circuitry.

The tuning procedure began with all resonators detuned by the tuning screws. The first pair of resonators was tuned for maximum attenuation at the stop-band center frequency, 8350 Mcps. Subsequent pairs of resonators were brought in to the same frequency, with the requirement that the stop band remain centered on 8350 Mcps after tuning. Then the screws of each pair were adjusted the same amount but in opposite sense to reduce secondary resonances in the pass band without changing the frequency of maximum rejection. Finally, tuning for each resonator pair was touched up to minimize any discernible ripple across the stop band.

The cut-off of the tuned filter was very sharp. When the oscilloscope was adjusted to show both the pass-band response and the zero-signal base line, the transition between pass and stop bands appeared as an almost vertical line. Figure 6 is a plot of the attenuation between 55 and 80 db as a function of frequency. The slight step between 60 and 70 db on the lower-frequency side is caused by measurement error, not by the filter.

It can be seen that the 60-db bandwidth is about 52 Mcps, rather than the predicted value of 40 Mcps. With the clearer vision of hindsight, the cause of this discrepancy was traced to an erroneous measurement or test-jig fault for the test iris of largest opening. The displacement of this end point on the graph of x/Z_o vs. iris opening was interpreted as curvature rather than error. The result was that the four center cavity pairs have larger iris openings than they should for the proposed design. It had been demonstrated previously with the 8050 Mcps reject filter that the design technique gave good agreement with theory, and so no appreciable discrepancy was considered likely on that count.

Since the error was in the preferred direction, no attempt was made to rework the filter.

A VSWR of 1.32 was measured in the pass band (7750 Mcps) rather than the predicted value of 1.24. The difference was attributed to the same error discussed above. The size and location of matching irises at each end of the structure were found by an impedance-measuring technique related to the approach used by Kajfež[3] for matching waveguide two ports. Figure 7 is a plot of the VSWR of the iris-compensated filter from 7742.5 Mcps to 7762.5 Mcps. The VSWR is under 1.02 over most of this frequency range.

Attenuation measurements in the pass band of the filter are shown in Fig. 8. Insertion loss of 0.05 db or less was found by audio-substitution attenuation measurements under low power and corroborated by calorimetric attenuation measurements under high-power conditions.

High power in the pass-band frequency range was applied to the filter by incorporating it in a resonant ring circuit. The power was increased in steps from 50 kw to 305 kw CW. The filter carried the maximum power, 305 kw CW, that the ring could deliver. After ten minute's operation at this level without breakdown, the high-power test was ended. During the test cooling water was run at the rate of one gallon per minute through the pipes on both broad walls of the filter. At 305 kw CW, the maximum temperature of any cavity was 180°F, the minimum at any cavity 120°F, while the maximum temperature along the center of the waveguide was 155°F and the minimum 130°F. At the rated power of 100 kw CW, the maximum cavity temperature was 100°F and the minimum 75°F, while the average temperature on the waveguide was 95°F. During the test the input water temperature varied between 70° and 80°F, and the ambient temperature was 75°F.

The low-power measurements of stop-band rejection and pass-band attenuation and VSWR were made both before and after the high-power test. The only change that occurred was a small improvement in the VSWR after the high-power test. The VSWR plot of Fig. 7 is based on measurements taken after the high-power test.

V. CONCLUSION

A novel design for a reflecting-type, band-rejection filter for high-power waveguide has been presented and shown to operate essentially as predicted. It has reasonable size, large stop-band rejection, low pass-band loss and reflection, and carries large amounts of RF power without breakdown or excessive heating.

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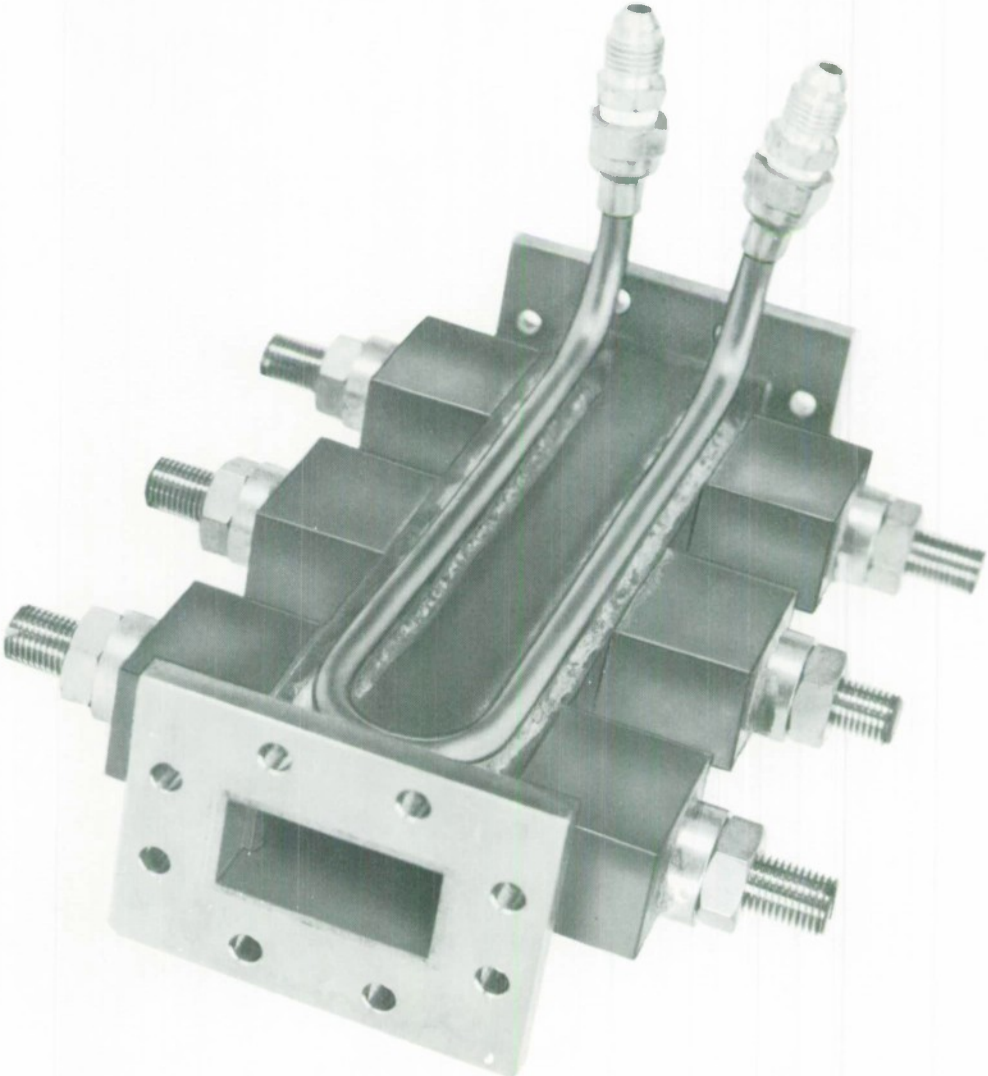

Fig. 1 (a) Three cavity pair 8050 Mcps reject filter

Fig. 1 (b) Six cavity pair 8350 Mcps reject filter

3-46-8736

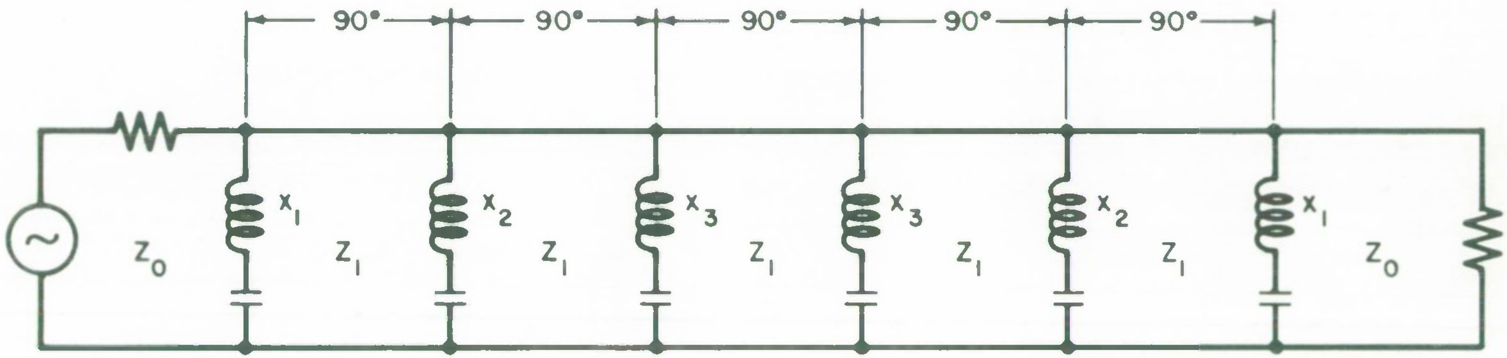

Fig. 2 Equivalent circuit for six resonator pair reject filter

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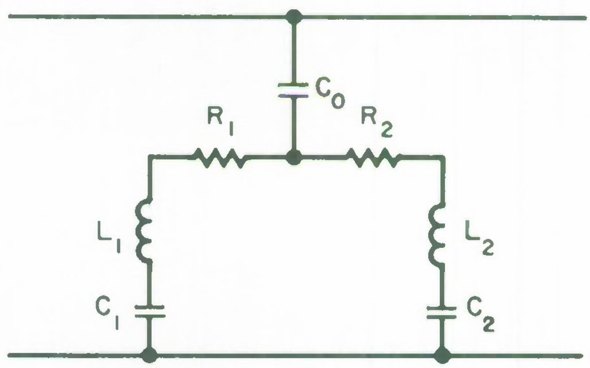

Fig. 3 Equivalent circuit for one resonator pair

3-46-8734

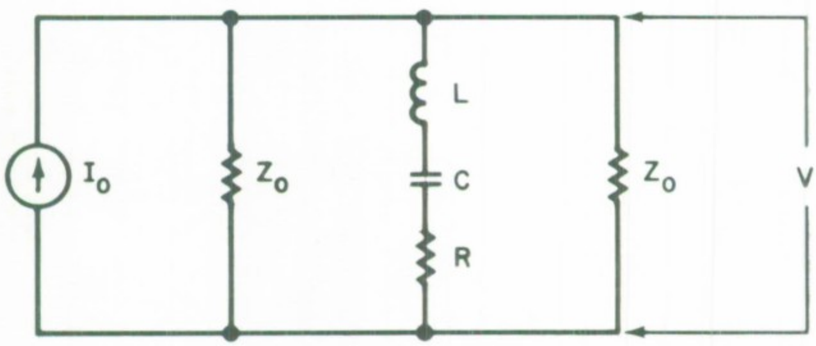

Fig. 4 Equivalent circuit for test jig

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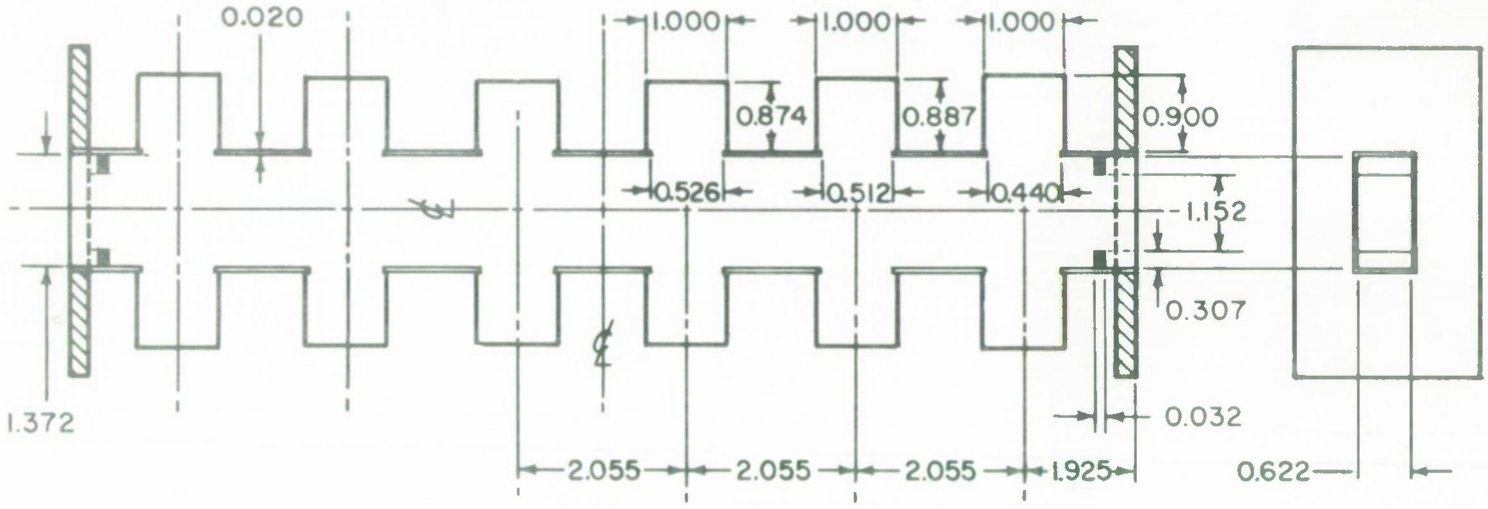

DIMENSIONS ARE IN INCHES

SYMMETRICAL ABOUT BOTH CENTER LINES

Fig. 5 Pertinent dimensions for 8350 Mcps reject filter

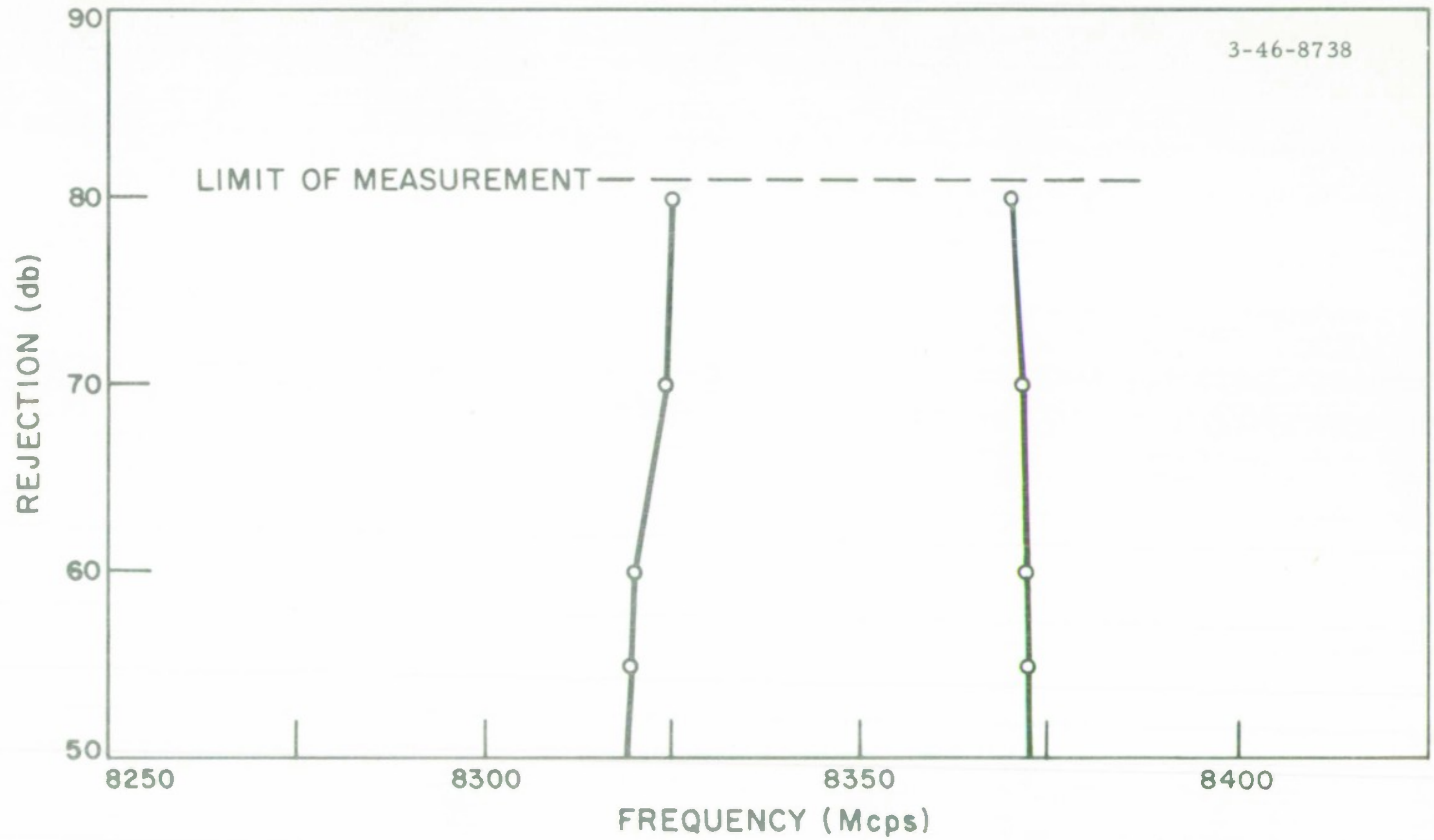

Fig. 6 Rejection vs. frequency for 8350 Mcps reject filter

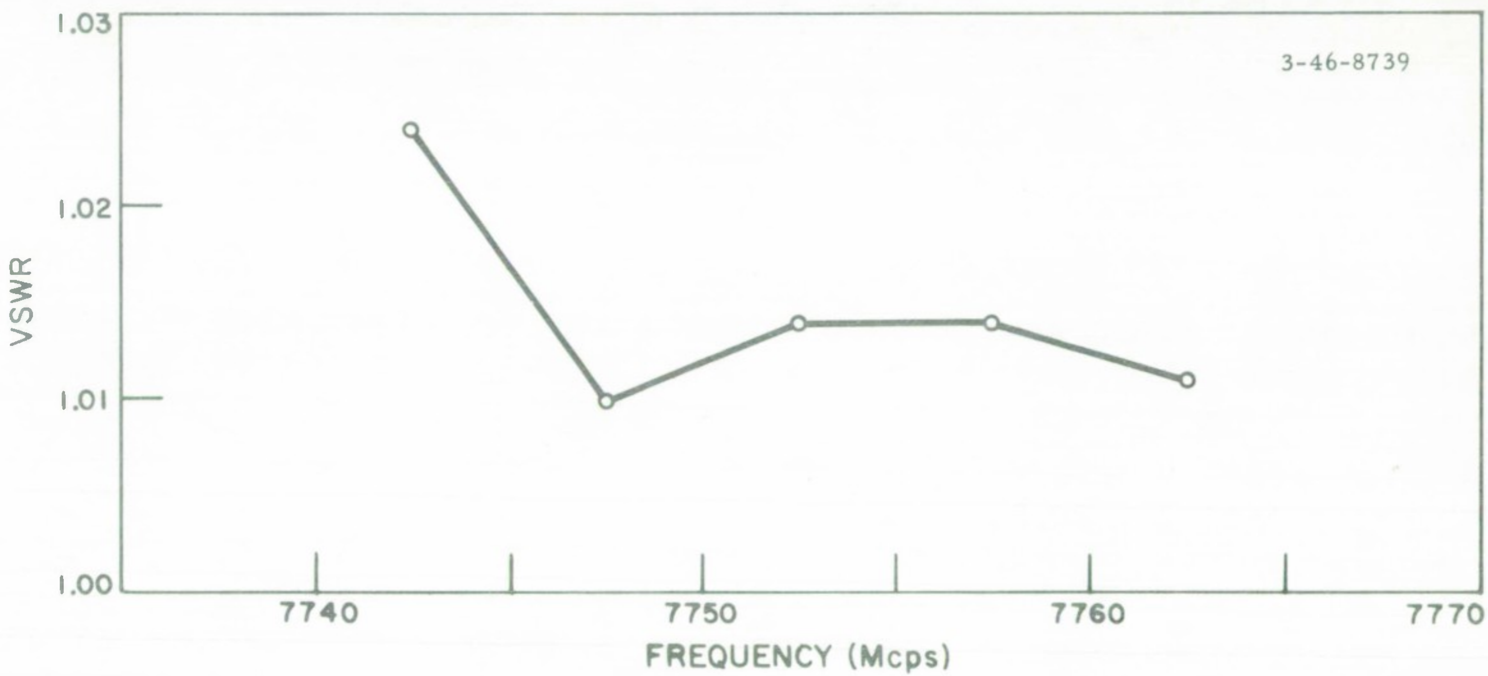

Fig. 7 VSWR vs. pass-band frequency for 8350 Mcps reject filter

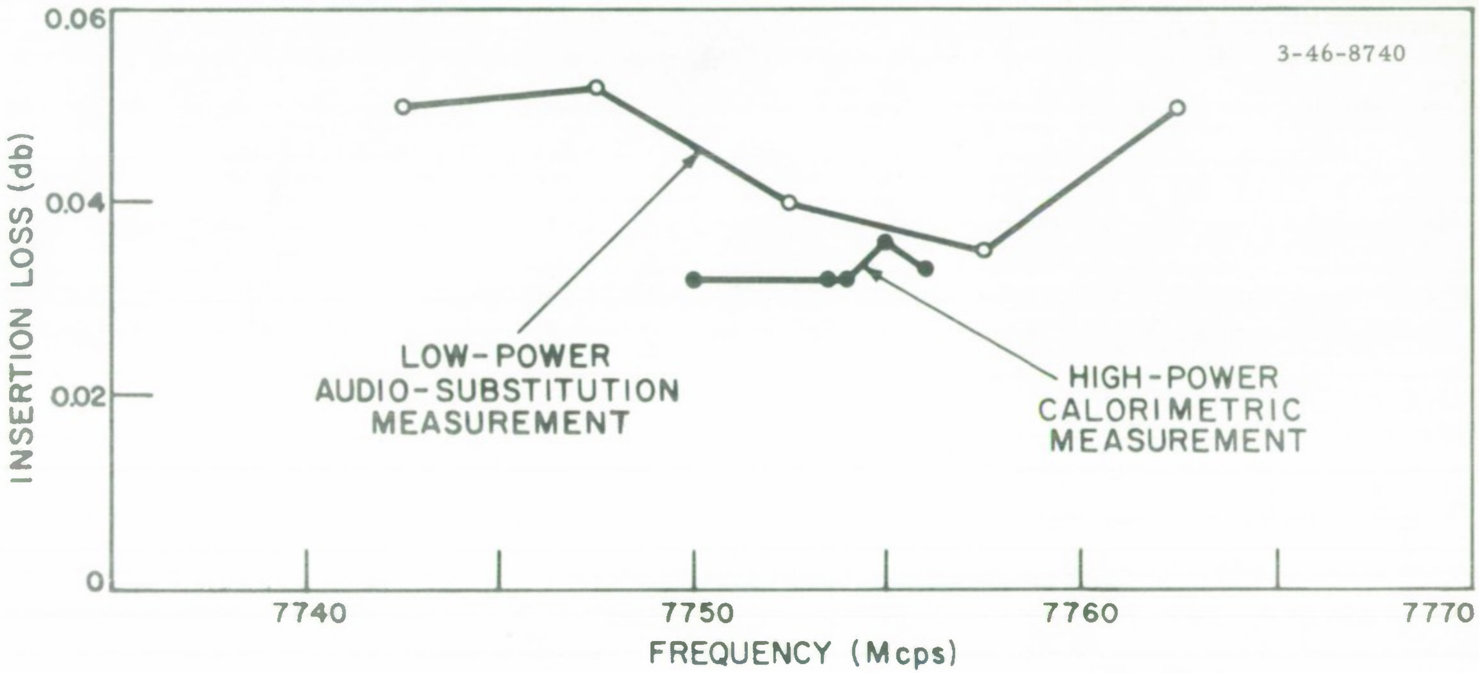

Fig. 8 Insertion loss vs. pass-band frequency for 8350 reject filter.

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(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)* Lincoln Laboratory, M.I.T.	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP None
3. REPORT TITLE A Noise Rejection Filter for Waveguide Carrying High Power	
4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)* Technical Note	
5. AUTHOR(S) *(Last name, first name, initial)* Getsinger, William J.	

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
3 August 1965	23	3

8a. CONTRACT OR GRANT NO. AF 19(628)-5167 b. PROJECT NO. c. None d.	9a. ORIGINATOR'S REPORT NUMBER(S) Technical Note 1965-30 9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)* ESD-TDR-65-315
10. AVAILABILITY/LIMITATION NOTICES None	
11. SUPPLEMENTARY NOTES None	12. SPONSORING MILITARY ACTIVITY Air Force Systems Command, USAF

13. ABSTRACT

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14. KEY WORDS

filters	reflection filter
high-power waveguide	noise rejection filter
X-band	Haystack
bandpass filter	