A High Power Diplexing Filter*

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Summary—An L-band diplexing filter has been constructed with an estimated power-carrying capacity of 5 megw at atmospheric pressure (for a power safety factor of nearly four to one) and an insertion loss of less than 0.1 db.

The filter consists of two hybrid junctions and two high pass waveguide sections, which are arranged as in a balanced duplexer, with the "TR-tubes" replaced by the high-pass sections.

In the upper frequency band, the input VSWR is better than 1.10 over a seven and one-half per cent bandwidth, but deteriorates only slightly over a larger bandwidth. In the lower frequency band, the input VSWR is better than 1.32 over a 13 per cent bandwidth. The separation interval between these two bands is approximately 10 per cent between their nearest frequencies.

INTRODUCTION

DIPLEXING filters do not usually require high power handling capacity, since applications are more numerous in communication than in radar systems. Thus, in one such filter[1] in 2 by 1-inch waveguide, voltage breakdown was expected to occur at a power level somewhere in excess of 500 watts.

The *L*-band filter reported on here was required to pass up to 5 megw at atmospheric pressure in the upper passband (1250 to 1350 mc), but only relatively low power (up to 20 kw) in the lower passband (990 to 1130 mc), although the design method could readily be extended to handle much higher powers in the lower passband also. The filter insertion loss was less than 0.1 db. The other principal performance characteristics are summarized below.

VSWR at upper passband input:	1.10 maximum
VSWR at lower passband input:	1.32 maximum
Cross-coupling in upper passband:	36 db minimum
Cross-coupling in lower passband:	at least 60 db.

The cross-coupling figures were measured using a matched termination at the common output; the effect of a mismatched termination on the cross-coupling is described in a later section.

DESIGN CONSIDERATIONS

The high power capacity, low VSWR, and low insertion loss requirements led to the choice of the "balanced" or "branching"[2] filter structure shown schematically in Fig. 1. This depends on the properties of the two hybrid junctions and the two high pass waveguides.[3,4] The principle of operation is similar to that of a balanced duplexer, with the high pass waveguides replacing the TR-tubes. The performance is determined largely by the match of the two magic tee hybrids and the four identical matching transformers into and out of the two high pass waveguides.

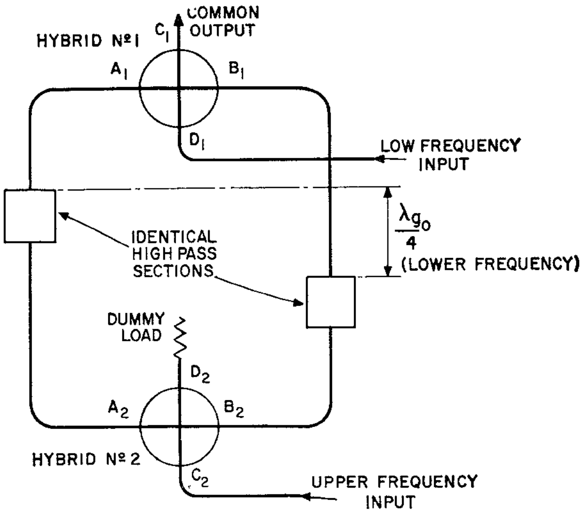

Fig. 1—Filter schematic.

Operation of the Filter

The operation of the filter is readily understood when certain assumptions are made:

1) The hybrid junctions are perfectly matched and balanced.
2) The identical high pass waveguides and associated transformers are perfect and lossless.

In the upper frequency band, a signal incident in arm C_2 of hybrid 2 (Fig. 1) divides equally between arms A_2 and B_2, passes through the perfect filters, and recombines in the hybrid 1, emerging from arm C_1. In this particular case, the operation would be the same from either end of the filter.

In the lower frequency band, a signal incident in arm D_1 of the hybrid 1 divides equally between arms A_1 and B_1. If the separation of the now cut-off waveguides were exactly one quarter wavelength at this frequency, then one component after reflection would travel one-half wavelength further than the other. This relative

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[1] M. E. Breese and S. B. Cohn, "Diplexing filters," 1954 IRE CONVENTION RECORD, vol. 2, pt. 8, Communications and Microwave, pp. 125–133.

[2] W. D. Lewis and L. C. Tillotson, "A Non-reflecting branching filter for microwaves," *Bell Sys. Tech. J.*, vol. 27, pp. 83–95; January, 1948. (Bell Telephone System Monograph B-1520.)

[3] Compare G. L. Ragan, "Microwave Transmission Circuits," McGraw-Hill Book Co., Inc., New York, N. Y., M.I.T. Rad. Lab. Series, vol. 9, p. 644 and p. 706; 1948.

[4] A different application of the cut-off effect to filters is described by P. A. Rizzi, "Microwave filters utilizing the cut-off effect," IRE TRANS. ON MICROWAVE THEORY AND TECHNIQUES, vol. MTT-4, pp. 36–40; January, 1956.

phase change of 180° is such that the signal now emerges from arm C_1. Thus with perfect components, there is no cross-coupling between input[5] ports C_2 and D_1.

Practical Limitations

In practice, however, the hybrids are not perfectly matched or balanced, nor are the high-pass sections perfectly matched in the upper frequency band. Such reflections contribute directly to cross-coupling from the upper to the lower frequency band. Consider again a signal in the upper band, incident in arm C_2. There is now some reflection from the high pass sections and, as the spacing is no longer a quarter wavelength at this frequency, the phase difference is no longer 180°. The reflected waves then couple to both arms C_2 and D_2, as well as being partially reflected back again into the imperfectly matched arms A_2 and B_2. Most of the power is coupled into arm D_2, where it would be completely absorbed if the dummy load on that arm were perfect; in practice, there is further reflection. The reflected waves are finally transmitted to the (lower frequency band) input arm D_1 with little further attenuation, causing cross-coupling between the two inputs at frequencies in the upper band.[6]

The cross-coupling in the lower frequency band presents few problems as the attenuation obtained from the 5 by 3-inch high pass (and now cut-off) waveguide is 40 db at 1130 mc, and is greater at lower frequencies. In addition, because of the symmetry of the filter, there is little direct coupling of the residual energy passing through the cut-off waveguides.

DESCRIPTION OF THE FILTER

A cross-section of the filter is shown in Fig. 2. There are three terminal ports. The common output is 8 by 2-inch waveguide; the higher frequency, higher power input is $6\frac{1}{2}$ by $3\frac{1}{4}$-inch waveguide, and the lower frequency, lower power, input is $\frac{7}{8}$-inch rigid coaxial line. All waveguide parts are made of aluminum.

High Pass Waveguide Section

The choice of five inch-wide rectangular waveguide for the filter, having a cut-off frequency of 1180 mc, ensures adequate attenuation at 1130 megacycles. A length of 26 inches gives 40 db at this frequency and a cross-section of 5 by 3 inches is adequate to transmit the peak power. The most difficult part of the development was the design of transformers effecting a good impedance match between the 5 by 3-inch waveguide and the 8 by 2-inch waveguide of the hybrids (Fig. 2) in the transmission band. The characteristic impedance of the 5 by 3-inch waveguide is appreciably larger than that of the 8 by 2-inch waveguide and the impedance ratio increases rapidly as cut-off is approached in the 5 by 3-inch waveguide.

The transformer was designed in two parts. One was an E-plane two-section quarter-wave transformer[7–10] and the other was a linear taper with cross-sections of constant aspect ratio. The E-plane quarter wave transformer takes the waveguide from 8 by 2-inch to 8 by 4.8-inch cross section; the maximum measured VSWR in the required passband was 1.03, which is close to the measuring accuracy of the test equipment.[11] The linear taper from 8 by 4.8-inch to 5 by 3-inch cross section was made 18 inches long and uses one inductive matching post at the narrow end; its VSWR over the transmission band is better than 1.18. This completes the transformation from 8 by 2-inch to 5 by 3-inch waveguide.

The complete high pass section, consisting of the 5 by 3-inch waveguide and associated transformers into 8 by 2-inch waveguides at each end, had a VSWR of better than 1.22 over the transmission band.

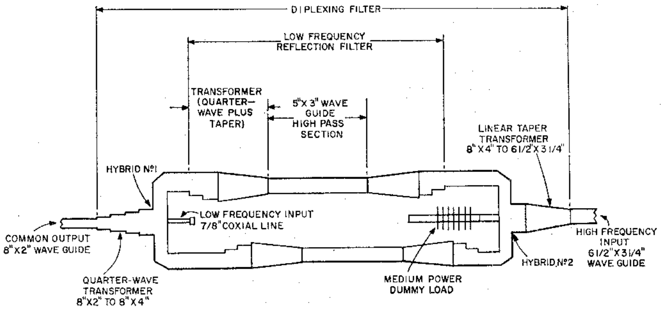

Fig. 2—*E*-plane section of diplexing filter.

Hybrids

The hybrids need not be exactly alike as their electrical requirements differ. Hybrid 1 must be well matched to the 8 by 2-inch transmission line leading to the common output arm C_1. Arm D_1, however, need only be well matched in the lower frequency band. The balance must be as good as possible in both bands. Hybrid 2 must be well matched to the $6\frac{1}{2}$ by $3\frac{1}{4}$-inch waveguide in the upper frequency band, and its arm D_2 requires good matching in the upper band. Both hybrids consist of

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[5] The two separate frequency ports will be referred to as inputs, for convenience. The combination port will therefore be referred to as the output. Obviously the terms input and output could be interchanged.

[6] It should be possible to reduce this cross-coupling by using a mismatched load on arm D_2, which would cause destructive interference between these waves. This, however, was not attempted.

[7] S. B. Cohn, "Optimum design of stepped transmission-line transformers," IRE TRANS. ON MICROWAVE THEORY AND TECHNIQUES, vol. MTT-3, pp. 179–185; April, 1955.

[8] R. E. Collin, "Theory and design of wide-band multisection quarter-wave transformers," PROC. IRE, vol. 43, pp. 179–185; February, 1955.

[9] H. J. Riblet, "General synthesis of quarter-wave impedance transformers," IRE TRANS. ON MICROWAVE THEORY AND TECHNIQUES, vol. MTT-5, pp. 36–43; January, 1957.

[10] Leo Young, "Tables for cascaded homogeneous transformers," IRE TRANS. ON MICROWAVE THEORY AND TECHNIQUES, vol. MTT-7, pp. 233–237; April, 1959.

[11] It can be shown theoretically that the VSWR of a two-section quarter-wave transformer of impedance ratio 2.4:1 can be made better than 1.01 over a bandwidth of up to 20 per cent.

the same basic unit, an E-plane T-junction with an 8 by 4-inch series arm, and two 8 by 2-inch colinear arms (Fig. 3). By a suitable choice of the height h of the wedge, a good match was obtained from arm C to arms A and B over both bands. The shunt arm is introduced through a hole in the center of the wedge in the form of a probe coupling to a $\frac{7}{8}$-inch rigid coaxial line.

This type of hybrid was chosen because of the inherent balance given by mechanical symmetry and because the impedance matching parameters of the series and shunt arms are almost independent. The cross bar was introduced primarily to give adequate mechanical support and to ensure alignment of the probe.

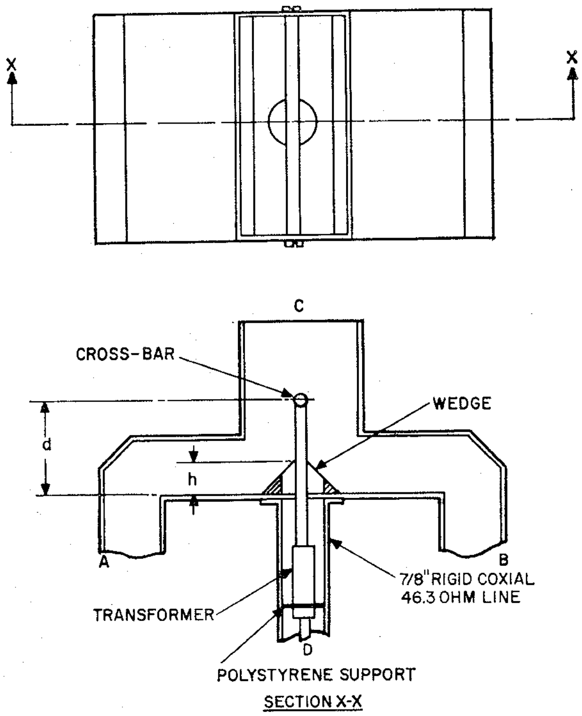

Fig. 3—Hybrid junction.

The VSWR into arm C of each hybrid is better than 1.02 over the lower frequency band, and better than 1.08 over the upper frequency band.

Arm D_1 was matched in the lower frequency band. A single quarter-wave transformer in the $\frac{7}{8}$-inch coaxial line (Fig. 3) and the height d of the probe were adjusted alternately to give a final VSWR better than 1.41.

Arm D_2 was matched in the upper frequency band. It is required to transmit efficiently to the dummy load that portion of the power which after reflection from the imperfectly matched high pass sections does not couple to arm C_2. Therefore the transformer in the coaxial line and the height d of the probe were together adjusted to give a low VSWR in the upper band looking into arm D_2, with matched dummy loads in arms A_2 and B_2. This VSWR was better than 1.62.

Terminal Transformers

A good transformer was required to match the 8 by 2-inch line to the 8 by 4-inch input to hybrid 1. In terms of guide wavelength, the bandwidth was 57 per cent, as both frequency bands use this transformer. A theoretical design[7-10] was calculated using a three-section quarter-wave transformer. The measured VSWR did not exceed 1.03 in the combined band.[12]

At input arm C_2 of the filter, a linear taper, 9.2 inches long, was used from 8 by 4-inch to $6\frac{1}{2}$ by $3\frac{1}{4}$-inch waveguide. The VSWR did not exceed 1.02 in the upper frequency band.

VSWR of Dummy Load

The medium high power dummy load on arm D_2 had a VSWR not exceeding 1.18 in the upper frequency band.

OVER-ALL PERFORMANCE

The principal performance characteristics of the filter have already been summarized in the Introduction.

VSWR

Fig. 4 shows VSWR against frequency plots at the two separate frequency inputs, with a matched termination on the common output.

Cross-coupling

Fig. 5 shows the cross-coupling in the upper frequency band as a function of frequency. A similar curve for the lower band could not be plotted as the measuring equipment readings were at the noise level, which indicated better than 60 db cross-coupling.

The effect of load mismatch on cross-coupling was investigated at 1260, 1290, and 1320 mc. Various sliding mismatches up to 2.1 in VSWR were connected to the output arm, and the worst cross-coupling at these frequencies remained better than 30 db (compared with 36 db for a matched load, shown in Fig. 5).

Insertion Loss

The insertion loss was too small to measure exactly. It is probably less than 0.05 db over most of the upper frequency band, and probably only slightly more in the lower frequency band.

High Power Carrying Capacity

No high power tests were conducted owing to lack of adequate test equipment. In the upper frequency band, the weakest section is probably the 5 by 3-inch waveguide which cuts off at 1180 mc. Assuming a maximum voltage[13] of 30,000 volts/cm, and a frequency of 1250

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[12] The theoretical optimum design for a three-section quarter-wave transformer of impedance ratio 2:1 and of 57 per cent bandwidth yields a maximum VSWR of 1.02.

[13] G. L. Ragan, *loc. cit.*, p. 191.

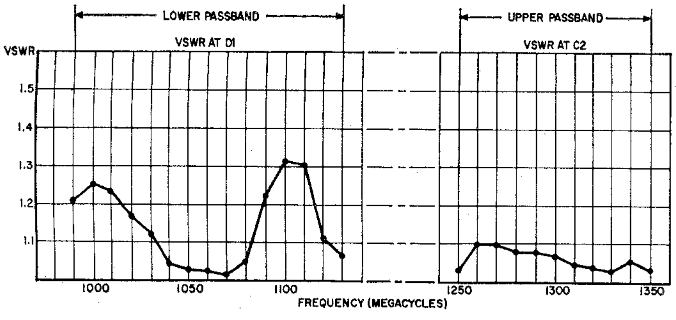

Fig. 4—Input VSWR of filter.

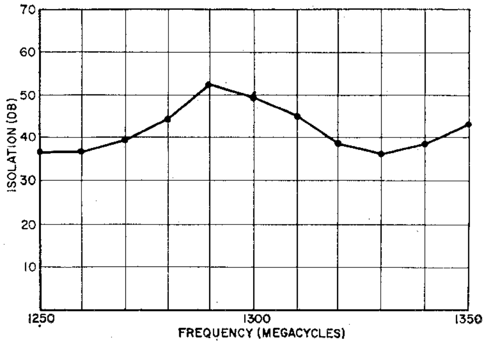

Fig. 5—Isolation in upper frequency band.

mc, the maximum power before voltage breakdown occurs at atmospheric pressure would be 18 megw. With a power safety factor of four to one, the maximum safe power is then $4\frac{1}{2}$ megw.

In the lower frequency band, the maximum power is determined by the $\frac{7}{8}$-inch coaxial line and connector; it should be over 40 kw in the present design, which uses a polystyrene bead support. If there were a requirement for high power capacity, an H-plane waveguide arm[14] could be used in place of the coaxial line, or the magic tee could be replaced by a short-slot[15] or a multi-slot[16] or a branch-guide directional coupler.[17,18]

VSWR Over Extended Band

The input VSWR was also measured from 1230 to 1370 mc and found to be better than 1.15. The performance of the filter may be expected to deteriorate only slightly over this extended band. The VSWR was found to remain below 1.20 up to 1400 mc, and below 1.45 up to 1560 mc, which suggests that it is an inherently more broad-band device than the present application calls for.

Conclusion

A diplexing filter with high power capacity, low insertion loss, and low VSWR, has been described. The isolation in the lower frequency band can be made as large as desired by making the cut-off waveguide sections sufficiently long.

Improved performance over conventional filters has been obtained by the use of a "balanced" filter, which is a relatively bulky and heavy structure, and incorporates a dummy load to reduce cross-coupling. A photograph of the filter is reproduced in Fig. 6.

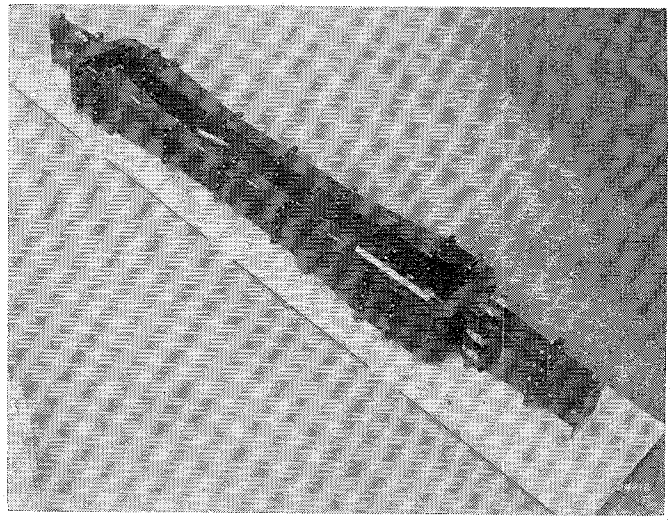

Fig. 6—Over-all view of the filter, with 12-inch rule in lower right.

ACKNOWLEDGMENT

This type of filter was originally proposed by C. C. Jones in 1952. The authors also wish to acknowledge the assistance of G. Valenzuela, who carried out many of the measurements and design calculations.

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[14] Patricia A. Loth, "Recent advances in waveguide hybrid junctions," IRE TRANS. ON MICROWAVE THEORY AND TECHNIQUES, vol. MTT-4, pp. 268–271; October, 1956.

[15] H. J. Riblet, "Short slot hybrid junction," PROC. IRE, vol. 40, pp. 180–184; February, 1952.

[16] H. J. Riblet and T. S. Saad, "A new type of waveguide directional coupler," PROC. IRE, vol. 36, pp. 61–64; January, 1948.

[17] Leo Young, "Branch guide directional couplers," *Proc. Natl. Elec. Conf.*, vol. 12, pp. 723–732; Chicago, 1956.

[18] P. D. Lomer and J. W. Crompton, "A new form of hybrid junction for microwave frequencies," *Proc. IEE*, vol. 104, pt. B, pp. 261–263; May, 1957, and *Proc. IEE*, vol. 104, pt. B, p. 586; November, 1957.