A High-Quality Waveguide Directional Filter

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A high-quality, narrow-band, bandpass-bandstop directional filter for use in the microwave frequency range is described. This new design does not require any hybrid junctions or circulators; the directional filter merely consists of one waveguide T-junction and a pair of complementary waveguide filters. The configuration is structurally simple and quite compact.

After presenting some of the considerations pertaining to the choice of the new structure, a complete synthesis procedure is developed. In the final section, experimental results obtained from a trial design at 4 GHz are reported. The agreement between theory and experiment is very good.

I. INTRODUCTION

The purpose of this paper is to describe at high-quality, narrow-band bandpass-bandstop directional filter for use in the microwave frequency range. Filters of this type are commonly used for channel separation and channel combination in microwave radio systems.*

In rather general terms, a bandpass-bandstop directional filter can be described as a passive 3-port (Fig. 1), whose $| S_{11} | = 0$ for all frequencies, whereas $| S_{21} |$ exhibits a bandpass characteristic and $| S_{31} |$ exhibits a bandstop characteristic around a midband frequency f_o. The 3-port may be reciprocal or nonreciprocal, lossless or lossy.†

For quite a number of applications in the microwave frequency range, the bandwidth of low attenuation ($\leqq$3 dB) between port 1 and port 2 and of high attenuation ($\geqq$3 dB) between port 1 and port 3

* For a rather complete account on microwave directional filters see Ref. 1 (diplexers and directional filters). Additional references may be found there.

† From an even more general viewpoint the strict condition $|S_{11}| = 0$ might be replaced by $|S_{11}| \approx 0$. Such "approximately constant resistance directional filters" are of technical interest and have been developed by lumped element network synthesis. However, in order to properly limit the following discussion, the strict condition $|S_{11}| = 0$ is applied throughout and the term "directional filter" shall be synonymous to such a network.

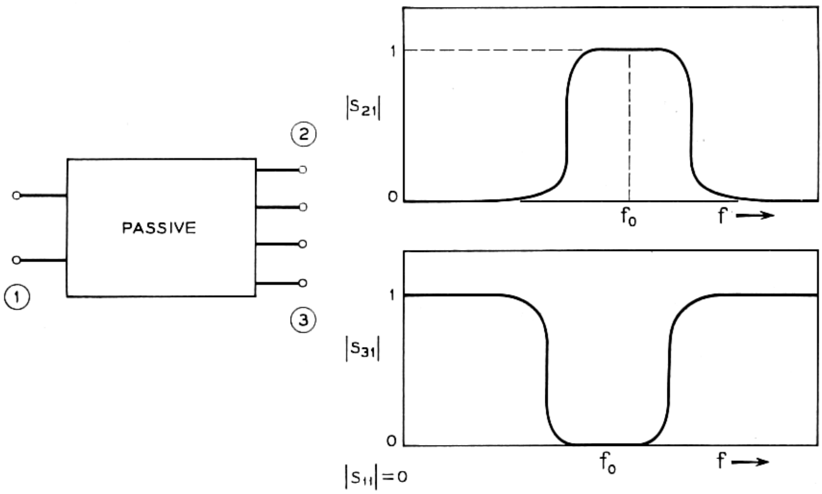


Fig. 1 — General bandpass-bandstop directional filter.

is less than one percent of f_o. Such filters may be classified as "narrow-band, bandpass-bandstop directional filters". The following discussion pertains to these filters with f_o located in the microwave frequency range.

II. DEVELOPMENT OF THE STRUCTURE

In reviewing the techniques used in lumped-element network synthesis, two realizations are found for bandpass-bandstop directional filters which are particularly attractive for their simplicity, namely, the front series and the front parallel connection of a lossless bandpass-bandstop filter pair (Figs. 2(a) and (b)).[2] In order to have $|S_{11}| = 0$ for all frequencies, the two filters in each case have to be a "complementary pair".[3]

An attempt will be made to "translate" these structures into microwave directional filters, since it is expected that the microwave realizations will also be attractive for their simplicity. To this end, suitable microwave configurations must be selected to replace the three "building blocks" of the lumped-element bandpass-bandstop directional filter, namely, the bandpass filter, the bandstop filter, and the front series or the front parallel connection. The remaining paragraphs of this section are concerned with these selections, the considerations motivating them and the limitations imposed by them.

There are many structures realizing microwave bandpass and bandstop filters. However, only a few of these can be used as "building blocks" of a narrow-band microwave directional filter as it is considered here, since the resonators for filters of such narrow bandwidth must possess high intrinsic Q's, otherwise the dissipation losses would quickly become intolerably high. At present only waveguide filters offer a reasonable compromise between the required high intrinsic Q's and mechanical complication and size.* It is therefore decided to use waveguide filters.

There are various well established design techniques for waveguide bandpass and bandstop filters, of which the structures described by Refs. 5 and 6 are most widely used, because they represent very good compromises between performance, size, and mechanical precision required. Therefore, the structure described in Ref. 5 shall be used to

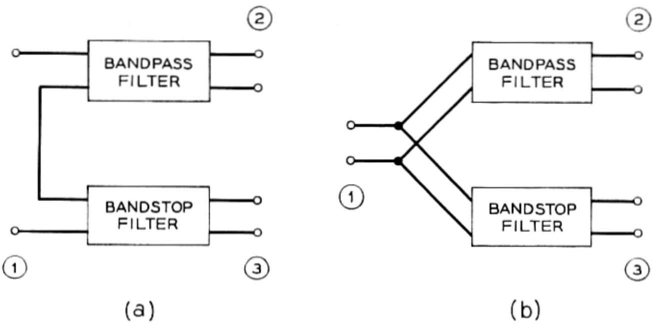


Fig. 2—Bandpass-bandstop directional filter configurations.

realize the waveguide bandpass filter and the structure described in Ref. 6 shall be used to realize the waveguide bandstop filter.

This choice, however, imposes restrictions on the obtainable response characteristics of the microwave directional filter. These restrictions originate from the fact that the waveguide filters described in Refs. 5 and 6 are related to lumped-element, low-pass prototype filters with all transmission zeros at ∞ (see Ref. 5) and to lumped-element high-pass prototype filters with all transmission zeros at 0 (see Ref. 6). The pertinent frequency transformation is, in both cases,

$$\Omega = Q_T\left[\frac{\lambda_{go}}{\lambda_g} - \frac{\lambda_g}{\lambda_{go}}\right], \qquad (1)$$

* Filters employing dielectric resonators as described by Ref. 4 are still much too temperature sensitive.

where

Ω = normalized frequency of the prototype filter,
λ_g = waveguide wavelength,
λ_{go} = waveguide wavelength at f_o,
Q_T = selectivity factor of the waveguide filter.

Since the two waveguide filters of the microwave directional filter have to be a complementary pair, the same frequency transformation (1) (i.e., with the same λ_{go}, Q_T and λ_g) has to be valid for the bandpass filter and for the bandstop filter, and this transformation has to transform the microwave bandpass-bandstop directional filters of Fig. 2 into the lumped-element low-pass high-pass prototype directional filters shown in Fig. 3. The low-pass prototype filter and the high-pass prototype filter must be a complementary pair, and all transmission zeros of the low-pass prototype filter must be at ∞ and all transmission zeros of the high-pass prototype filter must be at 0.

The only lumped-element prototype directional filter, which satisfies all these conditions, is obviously the maximally flat amplitude (both around $\Omega = 0$ and around $\Omega = \infty$) low-pass high-pass directional filter. Fig. 4 (compiled from Ref. 7) summarizes the necessary information for these prototype filters for the degrees n from 1 to 5. The networks are normalized with respect to frequency and impedance in the usual fashion, i.e., the normalized impedance of l and c is $j\Omega l$ and $1/j\Omega c$ and the networks behave according to the following equations:

$$\begin{aligned} S_{11} &= 0, \\ |S_{12}|^2 = |S_{21}|^2 &= \frac{1}{1+\Omega^{2n}}, \\ |S_{13}|^2 = |S_{31}|^2 &= \frac{\Omega^{2n}}{1+\Omega^{2n}}, \\ |S_{22}|^2 &= \left[\frac{\Omega^{2n}}{1+\Omega^{2n}}\right]^2, \\ |S_{33}|^2 &= \left[\frac{1}{1+\Omega^{2n}}\right]^2, \\ |S_{23}|^2 = |S_{32}|^2 &= \left[\frac{\Omega^{n}}{1+\Omega^{2n}}\right]^2. \end{aligned} \tag{2}$$

Now a suitable choice must be made for the third "building block", namely, the front series or the front parallel connection of the two

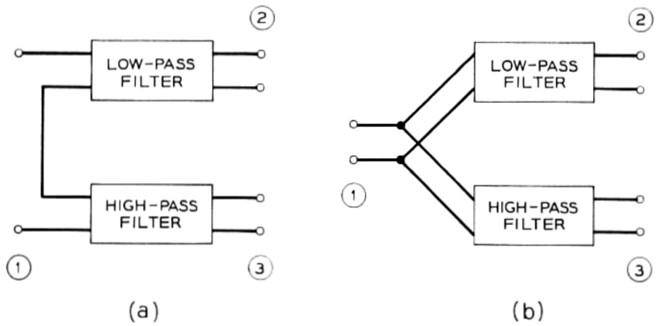
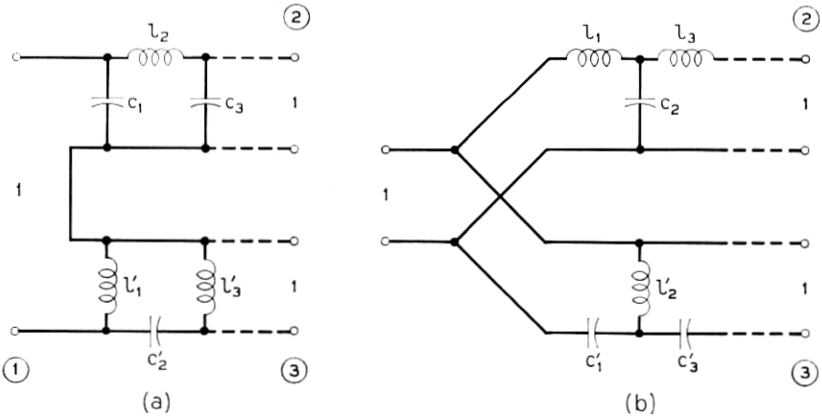


Fig. 3 — Low-pass high-pass directional filter configurations.

waveguide filters. For each of these a realization possibility is shown in Fig. 5. These realizations are very promising for the following reasons:

(*i*) All three ports are of the same waveguide cross section. This is usually required.

(*ii*) The bandpass filter is coupled to a straight waveguide run by



$n = 1$: $c_1 = 1.000$

$n = 2$: $c_1 = 1.414$, $l_2 = 0.7071$

$n = 3$: $c_1 = 1.500$, $l_2 = 1.333$, $c_3 = 0.5000$

$n = 4$: $c_1 = 1.531$, $l_2 = 1.577$, $c_3 = 1.082$, $l_4 = 0.3827$

$n = 5$: $c_1 = 1.545$, $l_2 = 1.694$, $c_3 = 1.382$, $l_4 = 0.8944$, $c_5 = 0.3090$

$$c_\nu = l_\nu = \frac{1}{c'_\nu} = \frac{1}{l'_\nu}$$

Fig. 4 — Lumped element low-pass high-pass prototype directional filters.

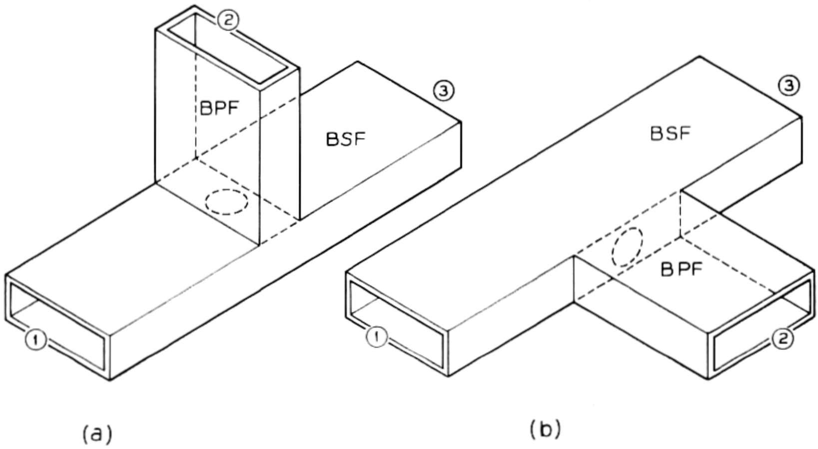


Fig. 5—Proposed realizations for the front series and front parallel connection of the waveguide filters.

means of an iris, which is used as the first obstacle of the bandpass filter. This means, that except for the immediate vicinity of f_0 (where this resonator is resonant), the waveguide wall is virtually left intact. Considering the fact that the broadband transmission from port 1 to port 3 is always more likely to present problems then the narrow band transmission from port 1 to port 2, this is a very good arrangement.

In order to get a more exact picture of the situation, it is necessary to examine the proposed junctions in greater detail. Fig. 6 shows the junction of Fig. 5(a) (intended for the circuit of Fig. 2(a)) together with its equivalent circuit (obtained essentially from Ref. 8). The iris is assumed to be infinitely thin. Fig. 7 shows the junction of Fig. 5(b) (intended for the circuit of Fig. 2(b)) together with its equivalent circuit (modified from Ref. 8). Again the iris is assumed to be infinitely thin. Notice, that in Fig. 7 an adjustable element corresponding to the adjustable stud in Fig. 6 is missing. The stud in Fig. 6 results in the two capacitive susceptances b_a. The corresponding element in Fig. 7, which is necessary for the intended application, would have to result in two inductive reactances in series to the ports T_1 and T_2. A convenient physical realization for such an adjustment has not yet been found. Hence, this junction—although attractive in all other respects—is not suitable for the realization of the circuit of Fig. 2(b) and the remaining discussion is therefore confined to the application of the junction of Fig. 6 to the realization of the circuit of Fig. 2(a).*

* During the development it came to the author's attention by a reference of Ref. 9, that a similar configuration has been described in Ref. 10.

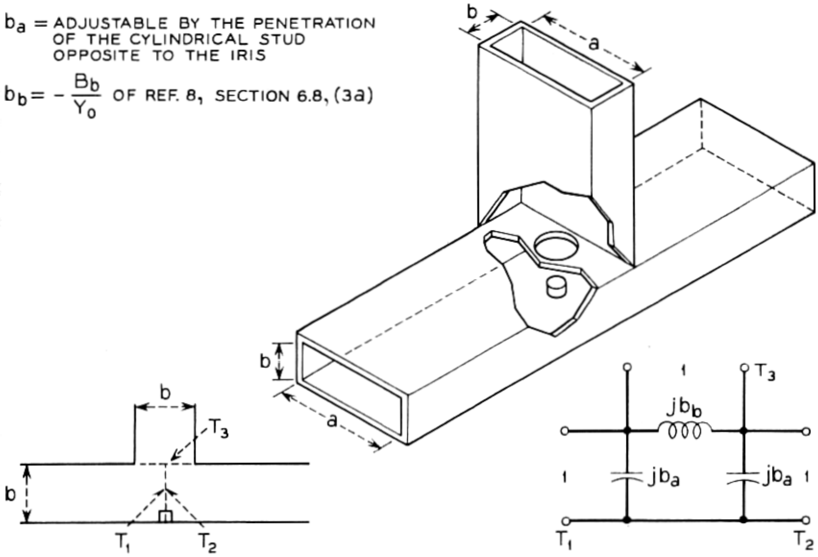


Fig. 6—Junction of Fig. 5(a).

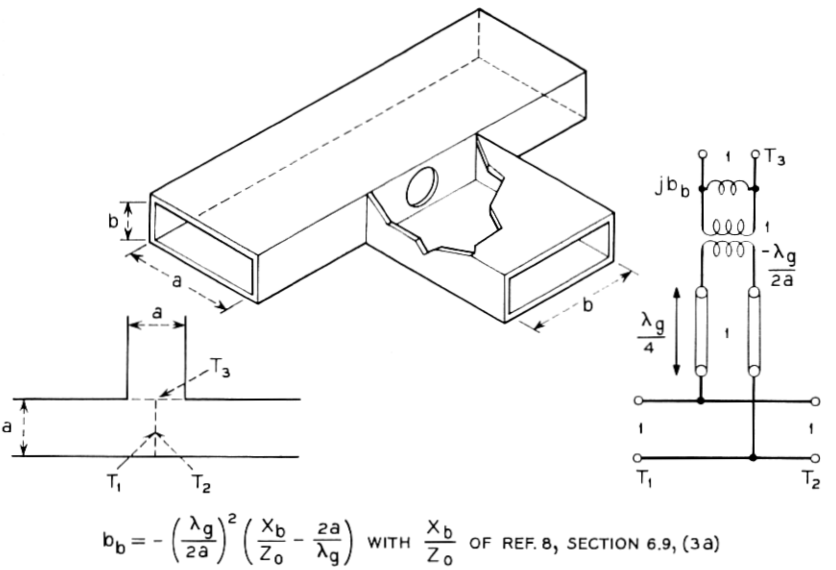


Fig. 7—Junction of Fig. 5(b).

III. SYNTHESIS

In this section, the synthesis procedure for the proposed directional filter is presented. However, before embarking on this subject, the important steps of the synthesis procedure for the waveguide bandpass filter[5] and for the waveguide bandstop filter[6] have to be described. Parts of both these synthesis procedures will be used in the synthesis of the directional filter. In addition, two circuit identities have to be derived, which also will be used later in the synthesis of the directional filter.

Fig. 8 shows the important steps of the synthesis procedure for the

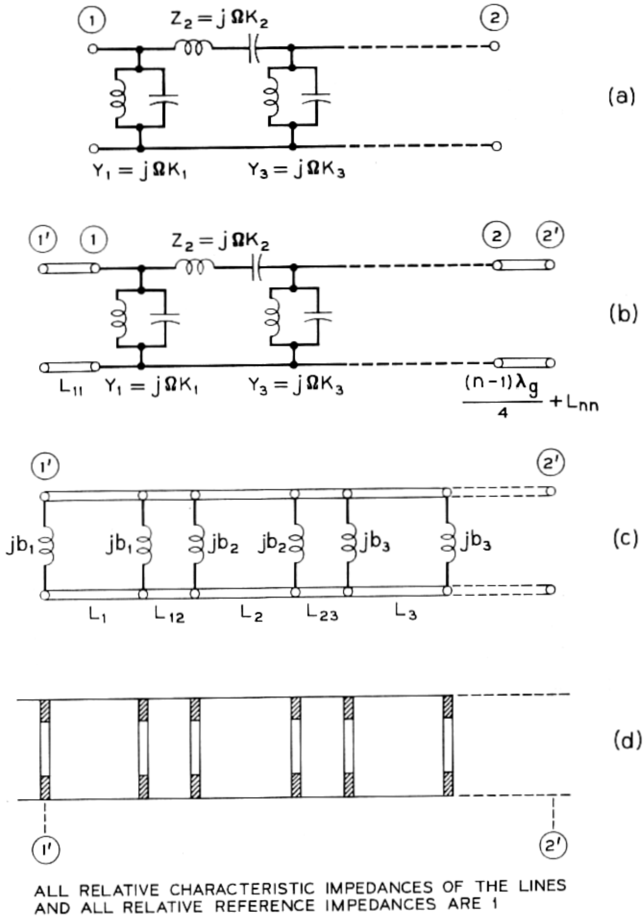


Fig. 8—Synthesis steps for waveguide bandpass filters.

waveguide bandpass filter.[5] Fig. 8(a) shows the transformed prototype circuit. The quantities k_1, $k_2 \cdots$ are positive real numbers. In Fig. 8(b) both ports have been shifted by the indicated line lengths. The length L_{11} is usually less than $0.1\lambda_{go}$. The following two steps, the step from Fig. 8(b) to 8(c) and the step from Fig. 8(c) to 8(d) (actual physical structure with all dimensions), are those needed for the synthesis of the microwave directional filter. They are discussed in detail by Ref. 5 and hence, need not be repeated here. It is emphasized, however, that all these steps can be performed successively, provided that the circuit of Fig. 8(a) is given, that the frequency transformation (1) is known and that the cross-sectional dimensions of the waveguide are given.

Fig. 9 shows the important steps of the synthesis procedure for the waveguide bandstop filter.[6] Fig. 9(a) shows the transformed prototype circuit. The quantities k_1', $k_2' \cdots$ are positive real numbers. In Fig. 9(b) port 2 has been shifted by the indicated line length. The following two steps, the step from Fig. 9(b) to 9(c) and the step from Fig. 9(c) to 9(d) (actual physical structure with all dimensions), are those needed for the synthesis of the microwave directional filter. They are discussed in detail by Ref. 6 and hence, need not be repeated here. Again it is emphasized that all these steps can be performed successively, provided that the circuit of Fig. 9(a) is given, that the frequency transformation (1) is known and that the cross-sectional dimensions of the waveguide are given.

Fig. 10 shows two circuits. If

$$b_b' = -2b_a \frac{1 + b_a^2}{1 + 4b_a^2}, \tag{3a}$$

and

$$L_{11}' = \frac{\lambda_g}{2\pi} \operatorname{arc\,tan} \left(\tfrac{1}{2} \tan \frac{2\pi}{\lambda_g} L_{11} \right), \tag{3b}$$

then the two circuits are identical, if

$$b_a = \tfrac{1}{2} \tan \frac{2\pi}{\lambda_g} L_{11} . \tag{3c}$$

The reader himself may verify this identity by direct comparison of the two circuits. For the purposes of the synthesis procedure of the directional filter (3) are approximated as follows. If, for $|L_{11}| \ll \lambda_{go}$ and for $\lambda_g \approx \lambda_{go}$,

$$L_{11}' = \tfrac{1}{2} L_{11}, \tag{4a}$$

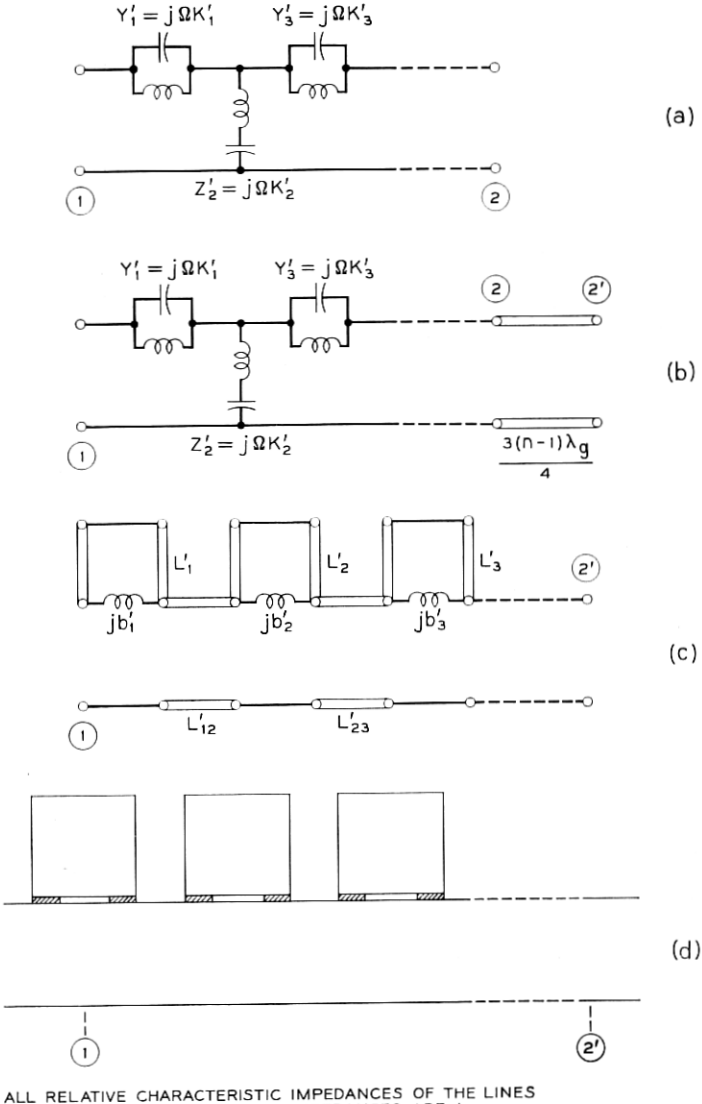


Fig. 9 — Synthesis steps for waveguide bandstop filters.

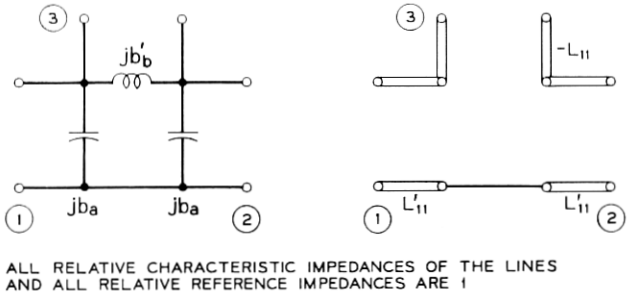


Fig. 10 — Circuit transformation.

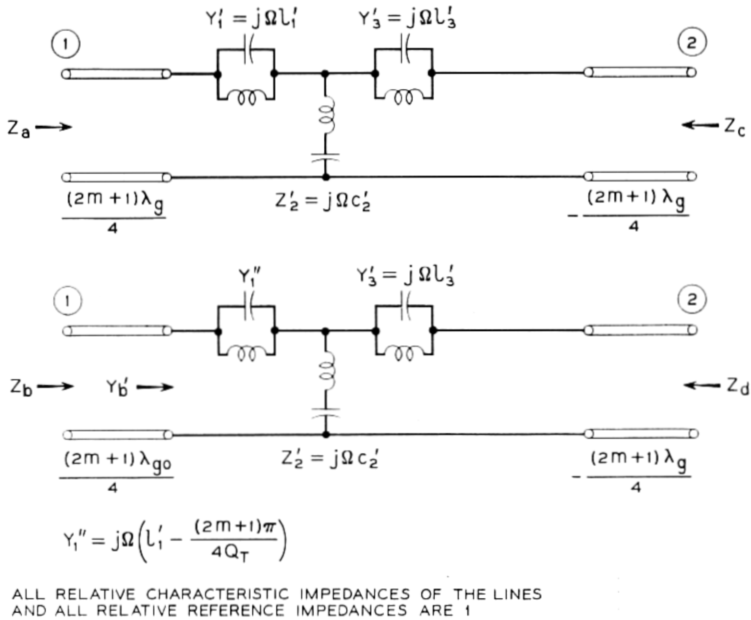


Fig. 11 — Circuit transformation.

then the two circuits are approximately equal, if

$$b_a = \pi \frac{L_{11}}{\lambda_{go}}, \tag{4b}$$

$$b_b' = -2\pi \frac{L_{11}}{\lambda_{go}}. \tag{4c}$$

Fig. 11 again shows two circuits. The reader's attention is called to the fact that for the first circuit, the line length at port 1 is $(2m + 1)\lambda_g/4$, whereas it is $(2m + 1)\lambda_{go}/4$ for the second circuit. m is a nonnegative integer. The line length at port 2 is the same for both circuits. The input impedances Z_a and Z_b of the two circuits (both terminated with 1 at port 2) are approximately equal for $\lambda_g \approx \lambda_{go}$. This is seen by the following argument:

$$Z_a = \cfrac{1}{\cfrac{1}{j\Omega l_1'} + \cfrac{1}{\cfrac{1}{j\Omega c_2'} + \cdots}} \approx j\Omega l_1', \tag{5a}$$

$$Y_b' = \cfrac{1}{\cfrac{1}{j\Omega\left(l_1' - \frac{2m+1}{4}\frac{\pi}{Q_T}\right)} + \cfrac{1}{\cfrac{1}{j\Omega c_2'} + \cdots}}$$

$$\approx j\Omega\left(l_1' - \frac{2m+1}{4}\frac{\pi}{Q_T}\right), \tag{5b}$$

and

$$Z_b = \frac{1 + jY_b' \tan\left[(2m+1)\frac{\pi}{2}\frac{\lambda_{go}}{\lambda_g}\right]}{Y_b' + j\tan\left[(2m+1)\frac{\pi}{2}\frac{\lambda_{go}}{\lambda_g}\right]}$$

$$= \frac{Y_b' - j\cot\left[(2m+1)\frac{\pi}{2}\frac{\lambda_{go}}{\lambda_g}\right]}{1 - jY_b'\cot\left[(2m+1)\frac{\pi}{2}\frac{\lambda_{go}}{\lambda_g}\right]}. \tag{5c}$$

Equation (5c) combined with (5b) and with the following approximation valid for $\lambda_g \approx \lambda_{go}$

$$\cot\left[(2m+1)\frac{\pi}{2}\frac{\lambda_{go}}{\lambda_g}\right]$$

$$\approx -(2m+1)\frac{\pi}{4}\left(\frac{\lambda_{go}}{\lambda_g}-\frac{\lambda_g}{\lambda_{go}}\right) = -(2m+1)\frac{\pi}{4Q_T}\,\Omega, \qquad (5d)$$

results in the desired approximate relation

$$Z_b \approx j\Omega l_1' \approx Z_a\ . \qquad (6)$$

Since furthermore—as is readily seen—the impedances Z_c and Z_d of the two circuits (both terminated with 1 at port 1) are also approximately equal in the vicinity of λ_{go}, the unitary condition for the scattering matrix of lossless reciprocal 2-port networks permits the conclusion, that the two networks shown in Fig. 11 are approximately equal in the vicinity of λ_{go}. This is the desired result, which will be used later in the synthesis of the directional filter.

This synthesis procedure can now be explained. First a prototype filter (Fig. 4, circuit *a*) and a frequency transformation (1) must be determined; i.e., n, Q_T and λ_{go} must be computed. This can be done with the aid of (1) and (2), provided that the wide dimension a of the rectangular waveguide is given or chosen and that sufficient requirements are imposed on the amplitude response of the directional filter

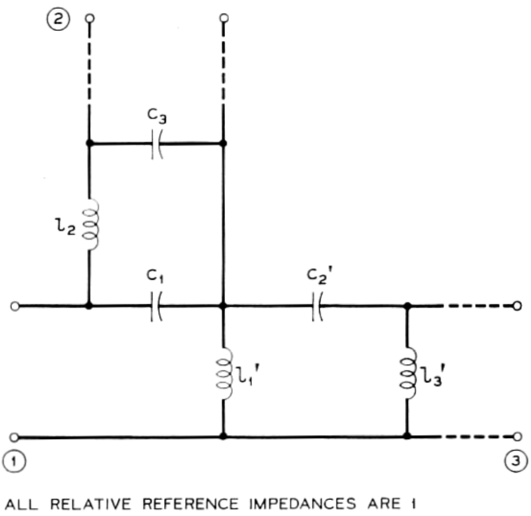


Fig. 12—Lumped-element low-pass high-pass prototype directional filter.

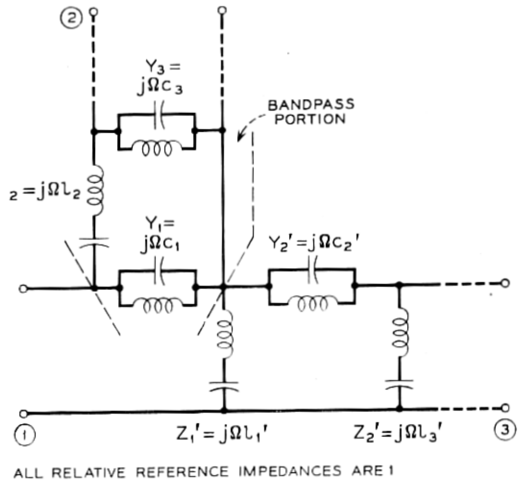


Fig. 13 — Lumped-element bandpass-bandstop directional filter.

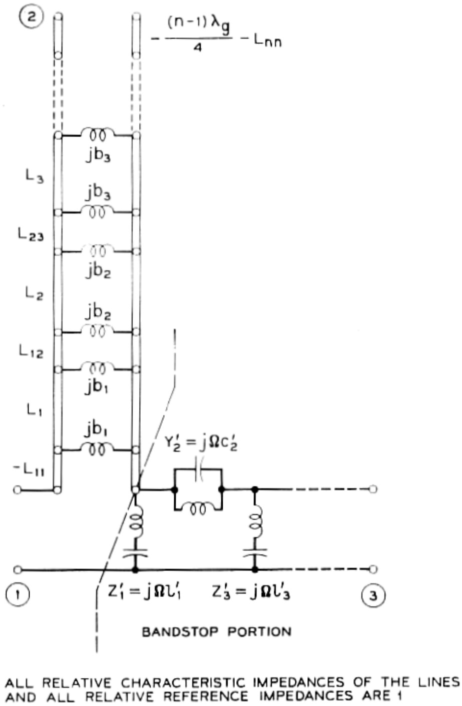


Fig. 14 — Transformed circuit of Fig. 13.

(magnitudes of the scattering matrix elements of (2)). The specific procedure to determine n, Q_T and λ_{go} varies largely with the way the amplitude response of the filter is specified. It is, however, always a straightforward and simple procedure, and hence, need not be discussed any further.

It can, therefore, be assumed that a prototype filter as shown in Fig. 12 is known. The frequency transformation, which is also known, transforms this circuit immediately into the circuit shown in Fig. 13. All elements are known. Now the step from Fig. 8(b) to 8(c), described in Ref. 5, is made for the bandpass portion of Fig. 13. This results in the circuit shown in Fig. 14 with all elements being known. The length L_{11} is usually very small compared to λ_{go}, as was already

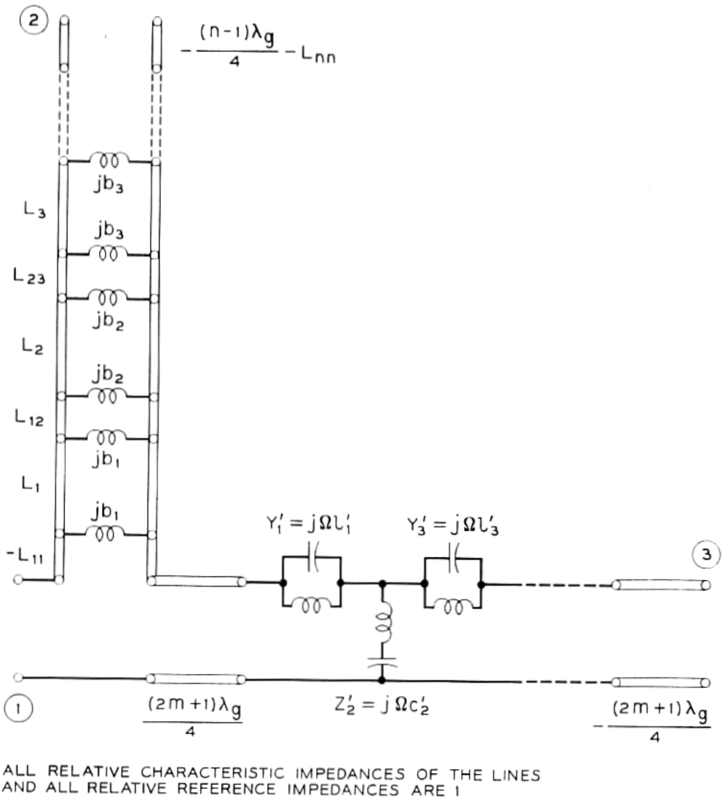


Fig. 15—Transformed circuit of Fig. 14.

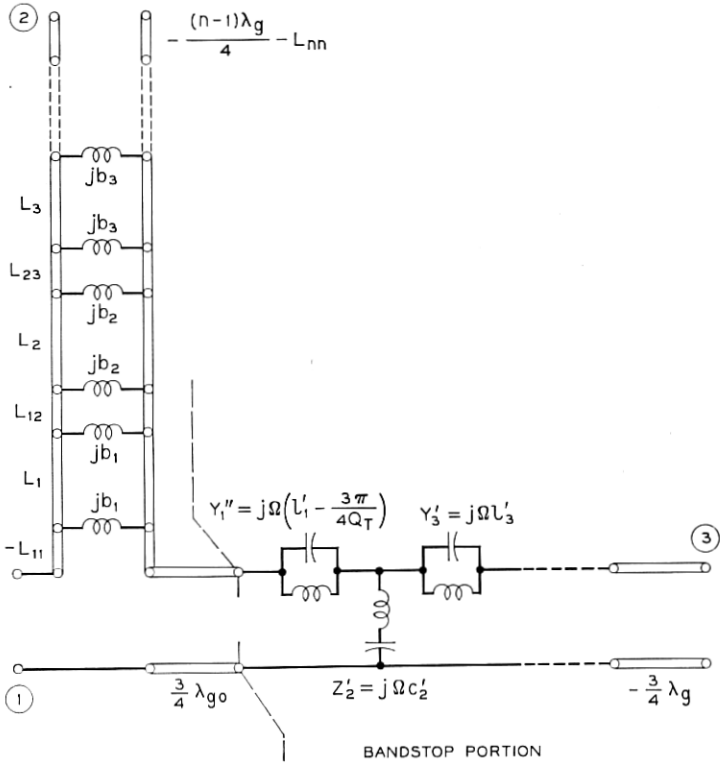


Fig. 16—Transformed circuit of Fig. 15.

mentioned. Now the bandstop portion of Figure 11b is represented by its dual circuit shifted by a length $(2m + 1)\lambda_g/4$ to the right, resulting in Fig. 15. Again all elements are known except for the nonnegative integer m, which, as will be justified later, is chosen to be 1. Application of the approximate equivalence of the two circuits in Fig. 11 results in the circuit of Fig. 16 with all elements being known. Now the step from Fig. 9(b) to 9(c), described in Ref. 6 is made for the bandstop portion of Fig. 16. This results in the circuit of Fig. 17. Again, all elements are known. Next, the equivalence of the two circuits shown in Fig. 10 is utilized together with the approximate equations (4). These approximations are justified, since $| L_{11} | \ll \lambda_{go}$, as was stated previously. The circuit shown in Fig. 18 is the result; all elements are known. Appropriate line lengths are added now to each of the three ports of the circuit to cancel the negative lengths present in Fig. 18. This procedure only changes the phase characteristics of the network, and hence, is of no consequence, since the filter requirements pertain only to the amplitude response. The resulting circuit is shown in Fig. 19. This circuit, of which all elements are known, is reduced to the physical structure shown in Fig. 20 by the following procedure:

(*i*) The bandstop portion is realized as described in Ref. 6. This is the step from Fig. 9(c) to 9(d).

(*ii*) The bandpass portion is realized as described in Ref. 5. This is the step from Fig. 8(c) to 8(d).

(*iii*) Of the remaining circuit the line length $3\lambda_{go}/4 - L_{11}/2$ is realized as such, and the junction is realized as shown in Fig. 6 by consulting Ref. 8, or better (finite thickness of the iris!) by using meas-

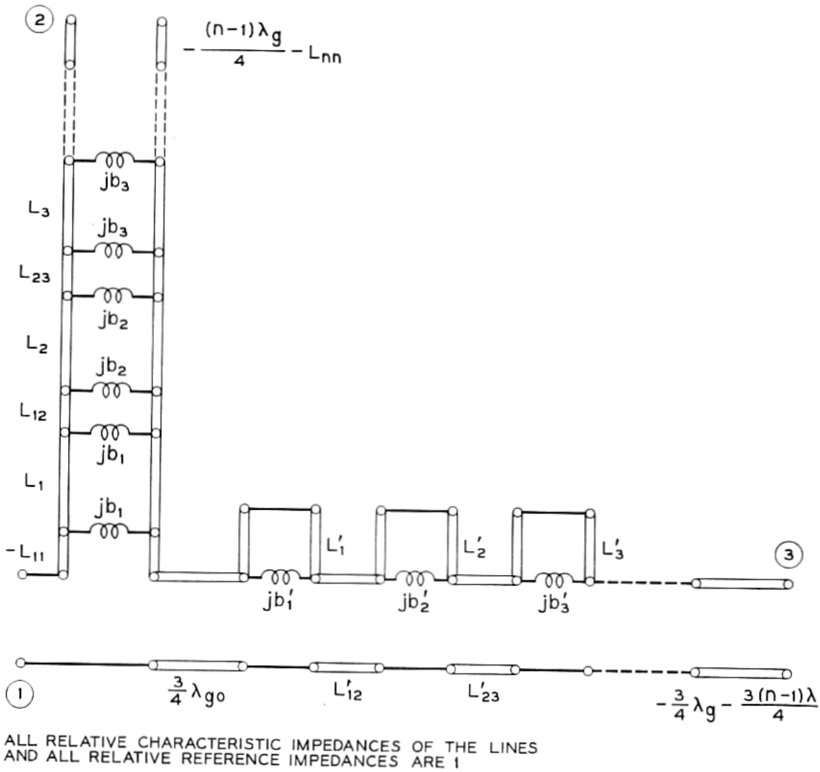


Fig. 17—Transformed circuit of Fig. 16.

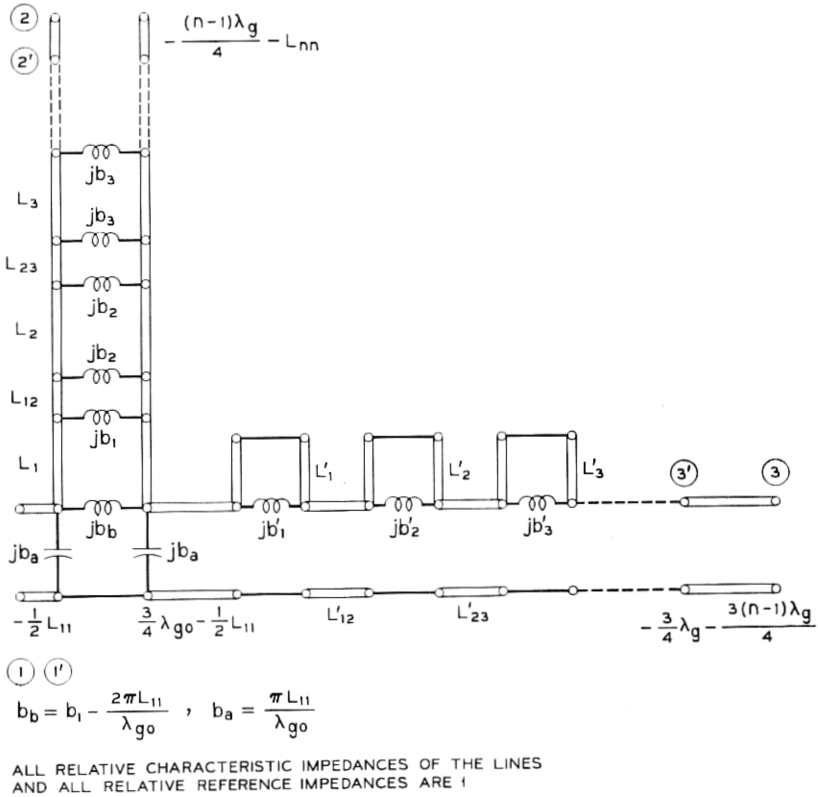


Fig. 18—Transformed circuit of Fig. 17.

ured data. The penetration of the stud opposite the iris (Fig. 6, adjustment of jb_a) must always be found experimentally.

For these three steps, the knowledge of the narrow dimension b of the rectangular waveguide is required. Therefore, this quantity must either be known or be chosen.

This completes the synthesis procedure. The only remaining detail is to explain why the nonnegative integer m of Fig. 15 was chosen to be 1. As has been shown by experiments described in Ref. 6, $m = 0$ is inadvisable because of excessive interaction of the higher-order modes excited at adjacent coupling holes, in this case, the hole of the junction and the hole of the first bandstop cavity. Since it is desirable to keep the total length of the filter as small as possible, $m = 1$ was chosen.

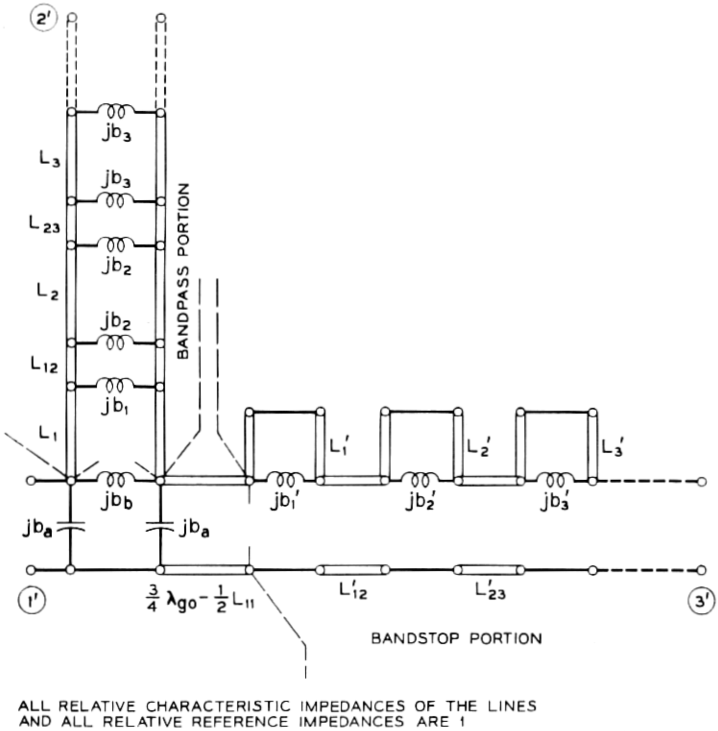


Fig. 19—Reduced circuit of Fig. 18.

IV. EXPERIMENTAL RESULTS

A trial filter was designed for the following specifications:

Midband frequency: $f_o = 3950$ MHz,
Upper 3-dB crossover frequency: $f_1 = 3967$ MHz,
$n = 3$,
Waveguide: $a = 2.290''$, $b = 1.145''$.

Since the upper 3-dB crossover frequency corresponds to $\Omega = 1$, (1) results in

$$Q_T = 67.05.$$

Fig. 21 shows a sketch of the constructed filter. All irises are 0.040 inch thick and all cavities are foreshortened by 0.050 inch and equipped with tuning screws to provide sufficient tuning range. The studs op-

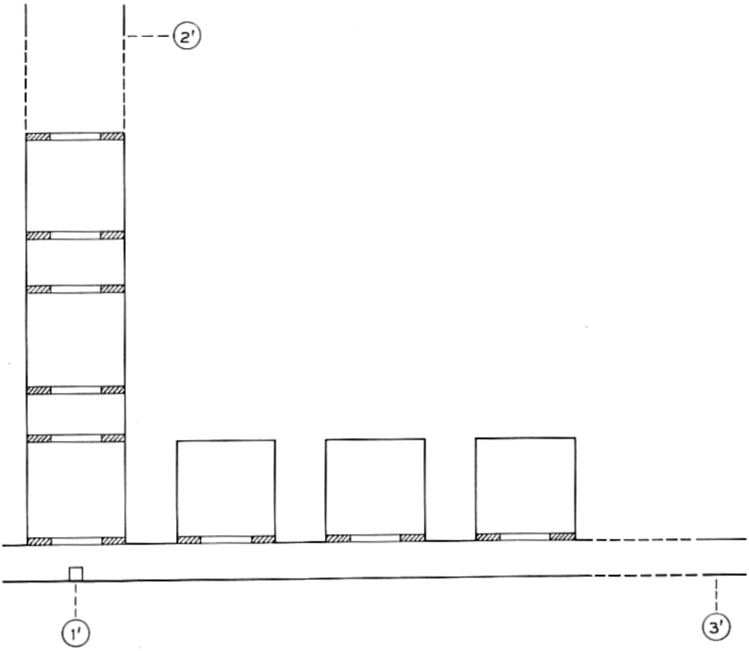


Fig. 20 — Physical realization of the circuit of Fig. 19.

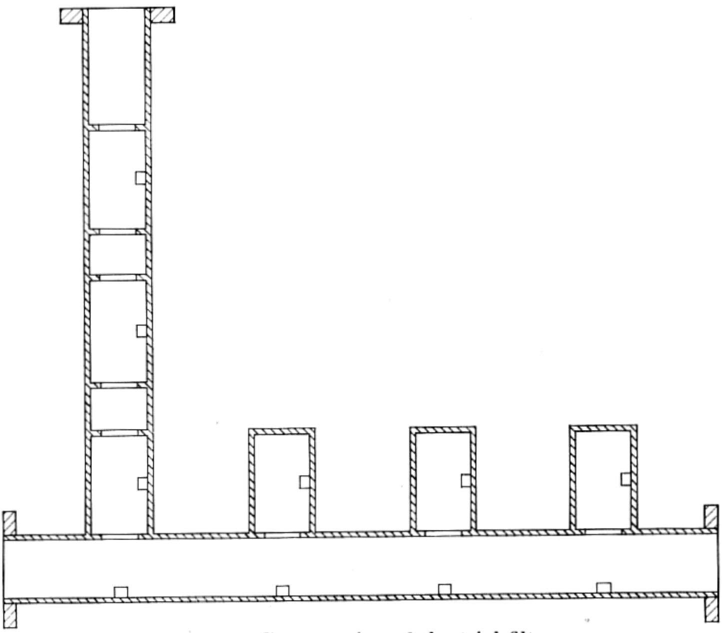


Fig. 21 — Cross section of the trial filter.

posite to the irises are also realized as screws in order to be adjustable.

Both filters were first tuned individually. Then the bandpass filter was attached to the junction and—after retuning the first cavity—the response of the resulting 3-port was compared to the theoretical behaviour. This comparison indicated that the hole diameter of the iris in the junction should be changed from 0.871 to 0.900 inch. After this change was made, the 3-port performed very close to the theoretical expectations. Then the bandstop filter was attached and the complete

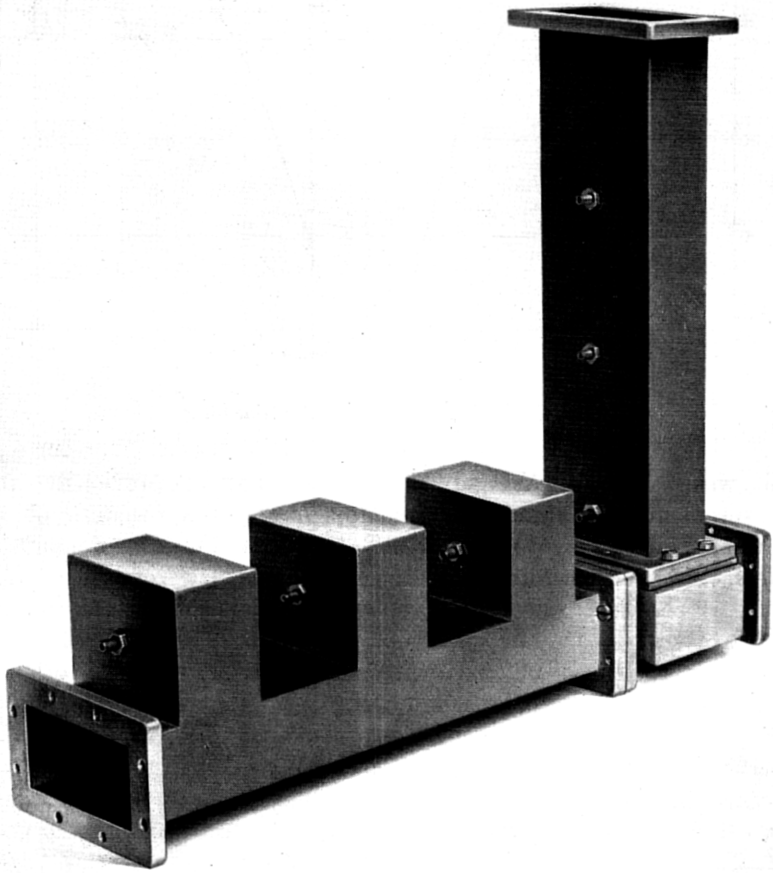


Fig. 22 — Photograph of the trial filter.

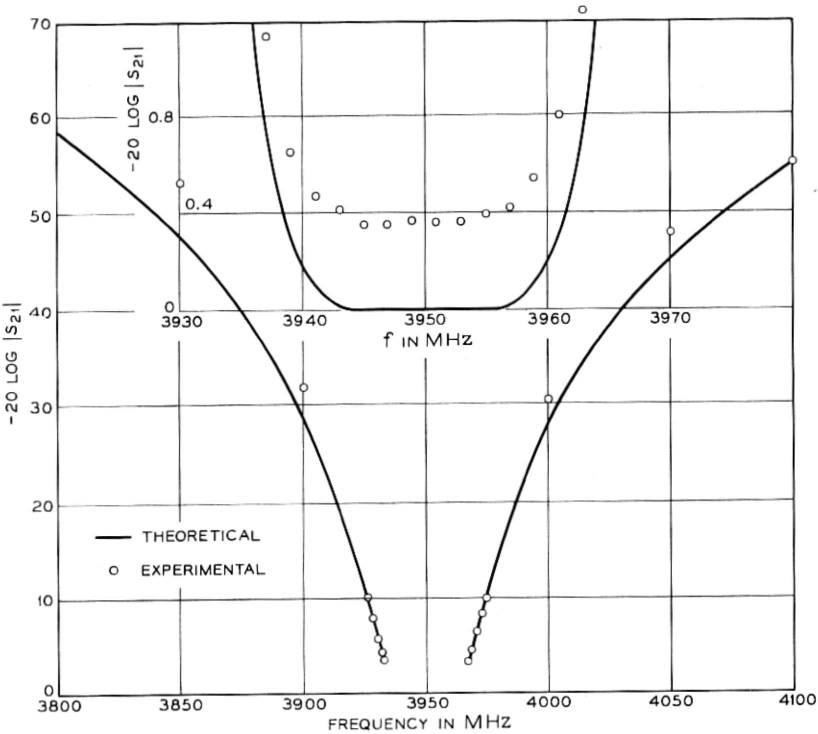


Fig. 23 — $|S_{21}|$ response of the trial filter.

unit was measured. As had already been noticed previously from measurements on individual bandstop filters, the response of the bandstop filter was too narrow.* Therefore, a number of bandstop filters was made with different design values for Q_T from $Q_T = 67.05$ to $Q_T = 54.70$. Experimentally, it was then determined that the unit with a design Q_T of 63.7 performed best. Fig. 22 is a photograph of this filter and Figs. 23, 24, and 25 show the electrical performance in comparison with the computed response (the computed response for Fig. 25 is ∞). Considering the presence of dissipation losses (all cavities were made from copper) and the fact that return losses in excess of 30 dB are generally difficult to achieve with presently available filter design techniques, the agreement appears to be remarkably good.

* This discrepancy is presently under investigation. The results of this study will be the subject of a forthcoming publication.

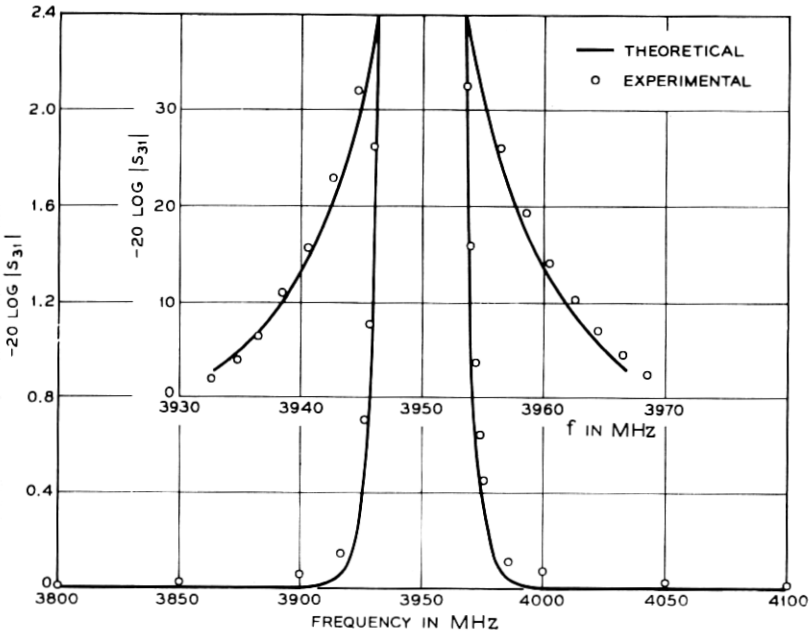


Fig. 24 — $|S_{31}|$ response of the trial filter.

V. ACKNOWLEDGMENTS

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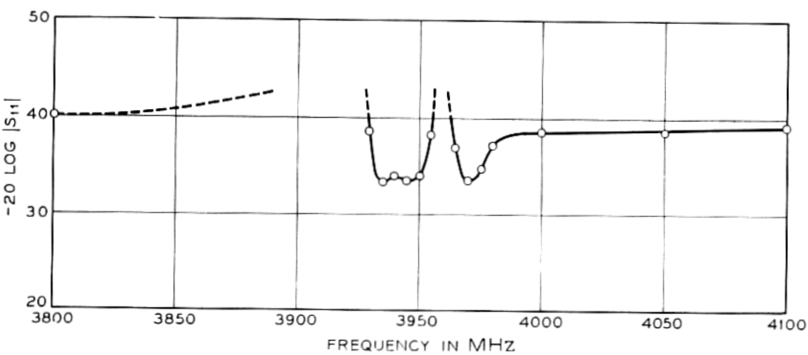

Fig. 25 — $|S_{11}|$ response of the trial filter.

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