Hybrid Junction—Cutoff Waveguide Filters*

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Summary—**Low-pass and band-pass filter characteristics can be obtained in waveguide by the use of an arrangement of a waveguide hybrid junction and lengths of cutoff waveguide. Low-pass filters are obtained by terminating a conjugate pair of ports of the hybrid in identical cutoff waveguide sections through short lengths of phase correcting lines. Band-pass characteristics can be realized by introducing a third cutoff waveguide having a lower cutoff frequency at the input port of the hybrid.**

These filters have a matched input at all frequencies above the lower end of the pass band and are characterized by low-pass band insertion loss, steep skirt selectivity, and moderate rejection band attenuation. The power handling capabilities of the structure exceed those possible with conventional microwave filter circuits, and the design is particularly well suited for use at frequencies above 10 kmc. Simple techniques are available for constructing filters of this type having variable cutoff frequencies and variable bandwidths.

Introduction

THE waveguide filter design techniques most commonly used today are based upon the approximate equivalence of lumped networks to such structures as iris loaded waveguide, corrugated waveguides, and coupled cavity structures.[1–3] Recently a class of directional filters has been described which makes use of frequency selective couplers to extract a desired narrow band of frequencies from one port of a multiport structure.[4,5] These filters present a matched input impedance at all frequencies as signals in the rejection band are extracted from a third port of the filter rather than reflected back to the input. The filter to be described in this paper is related to the directional filter class in that it too delivers one band of frequencies to one port and the remaining frequencies to the other ports, and presents a matched input impedance in the rejection band as well as in the pass band. This filter makes use of a hybrid junction and relies upon the frequency selective reflections from cutoff waveguides rather than frequency selective coupling. Relatively wide band filters can be obtained by this technique. Another type of filter employing Tee junctions and cutoff waveguides has been described[6] which utilizes short-circuited lengths of cutoff guides as reactive elements to obtain low-pass and band rejection filters. The principle of operation and the performance of these filters are quite different from those of the filter to be described here.[7]

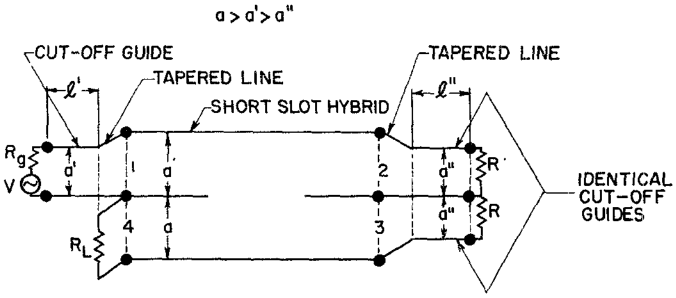

Fig. 1—Short slot hybrid band-pass filter.

Theory of Operation

A band-pass filter employing a short slot hybrid junction is illustrated in Fig. 1. Two conjugate arms of the hybrid (labelled ports 2 and 3) are connected to identical sections of cutoff waveguide through linear tapers. The cutoff sections are in turn terminated in matched resistive loads. The input to the hybrid (port 1) is connected through linear tapers to a waveguide having a lower cutoff frequency than that of the guides at ports 2 and 3. The output is taken from port 4. When a signal is applied to the input of the filter, only those frequencies above the cutoff of the input guide will enter the hybrid at port 1. In the ideal case, the power into the hybrid divides equally and appears at ports 2 and 3 with the signals at these ports 90 degrees out of phase. If the signal frequency is below the cutoff of the guides terminating these ports, the signal power undergoes complete reflection. Due to the 90 degrees difference in phase between the two signals reflected from ports 2 and 3, and the additional phase displacement each reflected signal experiences in traversing the coupler, the signals arrive in phase at port 4 and in phase opposition at port 1. Therefore, signals applied to the input port at frequencies between the cutoff frequency of the input guide and the cutoff frequency of

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[1] W. W. Mumford, "Maximally flat filters in waveguide," *Bell Sys. Tech. J.*, vol. 27, p. 684 ff.; October, 1948.

[2] S. B. Cohn, "Analysis of a wide-band waveguide filter," Proc. IRE, vol. 37, pp. 651–656; June, 1949.

[3] J. R. Whinnery, "Design of microwave filters," Proc. of the Symposium on Modern Network Synthesis, Polytechnic Inst. of Brooklyn, Brooklyn, N. Y.; April, 1952. This article presents a complete summary of the art of microwave filter design and has an extensive bibliography.

[4] F. S. Coale, "A traveling wave directional filter," IRE Trans. on Microwave Theory and Techniques, vol. MTT-4, pp. 256–260; October, 1956.

[5] S. B. Cohn and F. S. Coale, "Directional channel-separation filters," 1956 IRE Convention Record, pt. 5, pp. 106–112.

[6] Rizzi, P. A., "Microwave filters utilizing the cutoff effect," IRE Trans. on Microwave Theory and Techniques, vol. MTT-4, pp. 36–40; January, 1956.

[7] The author has recently learned that a similar approach employing hybrid junctions and band rejection filters has been described by W. D. Lewis of the Bell Telephone Labs. (U.S. Pat. No. 2,531,447.) However, Lewis did not consider the use of cutoff waveguide sections and the advantages gained by their use.

the two lines connected to ports 2 and 3 will arrive at port 4 and will suffer no attenuation in the ideal case. Signals at frequencies above the upper cutoff frequency will arrive at ports 2 and 3, be transmitted through the two guide sections and be absorbed by the resistive terminations to these two guides. Thus these signals will not appear at port 4 and band-pass characteristics are obtained between port 1 and port 4.

Fig. 2 shows a similar filter employing a magic-Tee junction in place of the short slot hybrid. The basic principle of operation in this case differs from the previous case in that there is no phase difference between the signals arriving at the conjugate arms 2 and 3. In order to cause signals reflected from these ports to emerge from port 4, it is necessary to reverse the phase of one of these reflected waves re-entering the Tee. This is accomplished by the introduction of a length of line l_1, whose electrical length is 90 degrees, between the terminals of port 2 (or port 3) and the cutoff terminating section. This length of line has no effect on the performance of the filter in its rejection band, although the presence of this length of line will affect the performance of cascaded filters of this type. While the assumption was made that the electrical length of the inserted line section was 90 degrees at all frequencies in order to explain the operation of the filter, it will be shown that when an actual line is used which has an electrical length of 90 degrees at the mid-frequency of the pass band, relatively wide pass bands can still be obtained. Low-pass filters can be obtained by omitting the cutoff waveguide section at the input to port 1.

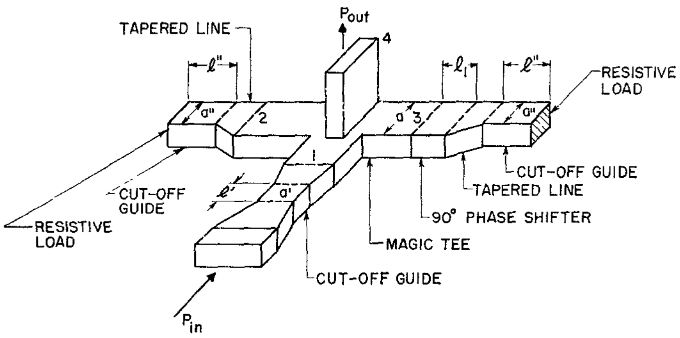

Fig. 2—Magic-Tee band-pass filter.

Linear tapers were used between the cutoff lines and the full width waveguide to improve the rejection band response of the filters. Their use does not affect the pass band performance of the filters as long as the two tapers at the outputs of ports 2 and 3 are identical, for they only serve to change the phase of the reflections from the cutoff guides by the same amount. In the rejection band, however, they serve to reduce the reflections from these guides, thereby insuring that the rejection band attenuation remains high. A step discontinuity, at this point, could introduce significant reflections, and this reflected energy would appear at port 4.

The performance of the hybrid junction-cutoff waveguide filters can be described by the following set of equations for the circuit illustrated in Fig. 3:

$$V_{r_1} = V_{i_1}(S_2 S_{12}^2 + S_3 S_{13}^2) \tag{1}$$

$$V_{r_4} = V_{i_1} S_{12} S_{13}(S_3 \pm S_2) \tag{2}$$

where

$$S_2 = \frac{V_{i_2}}{V_{r_2}} \quad \text{and} \quad S_3 = \frac{V_{i_3}}{V_{r_3}}.$$

Therefore,

$$\text{insertion loss} = 20 \log \left| S_{12} S_{13}(S_3 \pm S_2) \right| \tag{3}$$

$$\text{input reflection factor} = (S_2 S_{12}^2 + S_3 S_{13}^2). \tag{4}$$

These expressions were derived by making use of the symmetries in the scattering matrix of an ideal, lossless reciprocal hybrid, namely:

$$S_{ii} = 0 \qquad S_{12} = S_{34}$$

$$S_{14} = S_{23} = 0$$

$$S_{ij} = S_{ji} \qquad S_{13} = \pm S_{24}$$

where the positive sign applies to the short slot hybrid and the negative sign applies to the magic-Tee. The reflection factors of the terminations S_2 and S_3 are defined in Fig. 3 in terms of the incident and reflected voltages as defined for the four-port. It will be recognized that the voltage incident upon the port of the hybrid is the voltage reflected from the termination, and vice versa.

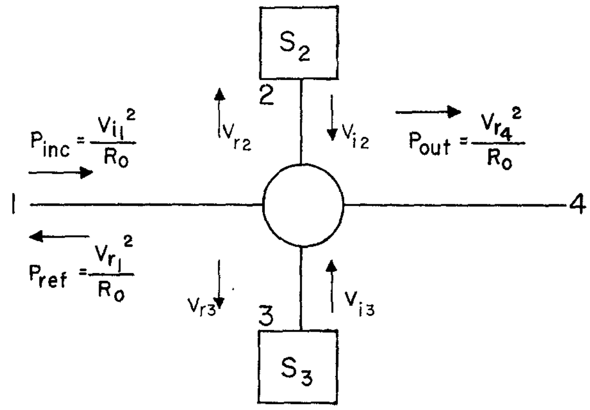

Fig. 3—Schematic diagram of a low-pass filter.

While these expressions are based upon the assumption that the hybrid junction exhibits ideal characteristics, they have been used to analyze the behavior of filters with imperfect hybrids. This was done by ascribing certain of the hybrid characteristics to the terminations S_2 and S_3. For small deviations from ideal hybrid performance, good agreement was obtained between calculated and measured results.

Filter Characteristics

Several factors affect the electrical performance of low-pass hybrid junction-cutoff waveguide filters. In those frequency bands where good hybrid junctions are available, it is simple to design waveguide sections having the required cutoff frequencies. These sections are cut off and will reflect almost all of the energy incident upon them in the pass band of the filter. For filters using short slot hybrids, there should be no relative phase difference between the reflections from the lines terminating a conjugate pair of arms. When a magic-Tee is used, however, one such termination must provide for a phase reversal of the reflected wave in order to obtain maximum output from the filter. The use of a quarter wavelength of line as a phase shifter will therefore affect the bandwidth of the filter, as such lines can have an electrical length of 90 degrees only at a single frequency. When the line length is not 90 degrees, some of the energy incident upon the filter will be reflected from the input port and the insertion loss of the filter will increase. Eqs. (3) and (4) have been used to determine the insertion loss of the filter over its pass band. When the phase difference between S_2 and S_3 is allowed to deviate from 180 degrees by ± 60 degrees, the insertion loss reaches a maximum of 2.5 db. As this deviation allows for a bandwidth of about 2:1, it is probable that the useful bandwidth of these filters will be limited by the bandwidths of the hybrid junctions rather than by the phase shifter. For a bandwidth corresponding to 180 degrees ± 10 degrees, a maximum VSWR of 1.2 and an insertion loss of only 0.06 db will be obtained as a result of the phase shifter. This analysis also serves to indicate the degree to which the two cutoff waveguides terminating the conjugate arms of a hybrid must be identical in order to insure a low-pass band insertion loss.

Two factors limit the isolation between the input and the output ports of the filter in the rejection band. One is the directivity of the hybrid junction, and the other is the reflections from the terminations to the conjugate hybrid arms which were assumed to be matched in the rejection band of the filter. As the directivity of a good hybrid rarely exceeds 30 db over an appreciable frequency band, this figure represents an upper limit on the rejection band attenuation. The filter attenuation will be further reduced if there are reflections at ports 2 and 3. In order to minimize such reflections, linear tapers were employed between all cutoff sections of waveguide and the full width waveguides. These proved to be adequate in the rejection region, although the match in the region close to cutoff could be improved.

The characteristics of both the low-pass and the band-pass filters in the regions near the cutoff frequencies of the filter are of particular interest. It is desirable to obtain filters exhibiting a low insertion loss in the pass band up to the cutoff frequency and a sharply rising attenuation above this frequency. The filter behavior near a cutoff frequency is dependent upon the particular cutoff waveguide section which begins to propagate at that frequency. Just above its cutoff frequency, a waveguide is operating in a region where the wall losses are high and the impedance of the guide is quite different from the impedance of the full width waveguides feeding this section. The input cutoff section which provides for the lower cutoff of the band-pass filter therefore increases the pass band insertion loss due to both reflection and dissipation of the input signal. This effect may prevent the application of this technique to very narrow band filters. The dissipation in the guides terminating the conjugate ports 2 and 3, which control the upper cutoff frequency, does not affect the performance of the filter, as these sections lead to matched absorbing loads, in the upper rejection band. However, the reflections due to the mismatch presented by these guides will have the proper phase so as to appear at the output of the filter, thereby lowering the rejection band insertion loss. While linear tapers, which were employed in the experimental models of these filters, provide for adequate matching well above cutoff, more sophisticated matching techniques may be required in order to obtain a rapid increase in attenuation above the upper cutoff frequency.

The sharpness of the slope of the attenuation curve at both ends of the pass band depends to a considerable degree upon the lengths of the cutoff waveguide sections. This is obvious in the case of the input guide section, as its attenuation at any frequency below cutoff is a direct function of its length. In the case of the upper cutoff frequency of the filter, the insertion loss of the filter is a function of the power reflected from the inputs to the pair of cutoff waveguides at ports 2 and 3. For lossless lines of finite length terminated in a resistive load, the input reflection factor is a function of the length of line. When such lines are below cutoff, the line has an imaginary characteristic impedance and attenuates rather than propagates the signal. The input impedance is given by

$$Z_{\text{in}} = Z_0 \frac{Z_t + Z_0 \tanh \alpha l}{Z_0 + Z_t \tanh \alpha l} \tag{5}$$

where

Z_0 = characteristic impedance of line
Z_1 = terminating impedance
α = attenuation factor of line
l = length of line.

For a line below cutoff, as Z_0 is imaginary and Z_t is real, Z_{in} is complex and approaches Z_t for small α or small l and approaches Z_0 for large α or large l. Thus, at frequencies just below cutoff the input impedance will have a large resistive component, while at frequencies far below cutoff this impedance will be largely reactive. The rate at which the impedance becomes reactive, and therefore has a high reflection factor, is a function of the length of line. Wall losses in the cutoff guide section will appear as a resistive component, and will therefore tend to reduce the rate at which the insertion loss rises near cutoff.

For most filter applications, it is sufficient to choose the lengths of the cutoff waveguide sections on the basis of the attenuation factor of a lossless line below cutoff.

General Considerations

Hybrid junction-cutoff waveguide filters are particularly well suited for use at frequencies above 10 kmc. Conventional filter design techniques generally lead to complex structures containing discontinuities which require fairly close mechanical tolerances in order to obtain the specified filter characteristics. The presence of these discontinuities also tends to lower the peak power handling capacity of the guide. Above X band these problems become more critical as the smaller sized waveguides used at these frequencies have limited power handling capacities. In addition, the dimensions required for the filter elements are smaller and therefore require closer tolerances. Fabrication of these smaller filters is also more difficult. Most of these difficulties can be minimized in the case of the hybrid junction-cutoff waveguide filters.

By making use of existing hybrid junction designs, a comparatively simple design procedure is required to adapt these junctions to filters. As the cutoff characteristics are determined by the widths of the waveguides terminating the various ports of the junction, and as this is the largest dimension associated with the guide cross section, the largest possible mechanical tolerance is obtained for a given tolerance on the cutoff frequency. As full height waveguide is employed throughout, and as there are no discontinuities in the filter structure outside of the hybrid junction itself, the power handling capacity of the hybrid junction can be approached. The fact that the power capacity of a waveguide decreases as its cutoff frequency is approached is, to a great extent, offset in the case of the filter by the fact that these guides become badly mismatched near cutoff and therefore reflect power. In order to insure proper behavior of the filter, it is necessary that the two cutoff sections terminating the conjugate arms of the hybrid be identical. Where machining of these parts to the desired tolerance becomes difficult, electroforming techniques can be employed to obtain the desired uniformity of construction.

These filters can be readily used in frequency band separating filter arrays. If ports 2 and 3 are fed into a second hybrid as shown in Fig. 4, rather than into matched loads, signals in the frequency band above the upper cutoff frequency will appear at one port of the second hybrid. Successive sections of similar filters can then be used in this manner to separate out any specified number of channels, provided that the over-all bandwidth of the array is no greater than the useful bandwidth of the input hybrid junction. Fig. 4 also shows how a tunable filter can be obtained by the use of sections of waveguide having variable cutoff frequencies.

When lengths of cutoff guides and hybrids are used to make a filter, the over-all length of the structure can be fairly large. This is admittedly not too advantageous in the waveguide sizes for L, S, C and X band. However, at the higher frequencies the smaller size of waveguide and the shorter wavelengths make it possible to obtain fairly compact filters. This technique of filter design may also prove to be useful at lower frequencies by making use of the space saving features of strip line. Hybrid rings and other types of hybrid junctions have been realized in strip line[8] and these can be combined with trough line[9] sections which have low frequency cutoffs and which can be readily fed from strip line structures.

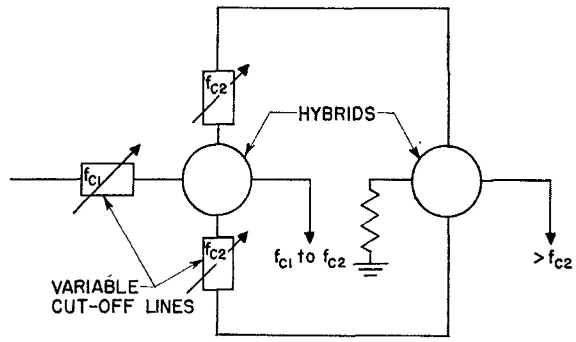

Fig. 4—Tunable filters and filter arrays.

Experimental Results

A number of filters using different types of hybrid junctions were constructed and tested. The experimental work was done at X band primarily because of the fact that hybrid junctions in X-band waveguide were readily available in the laboratory. Fig. 5 shows the insertion loss characteristics of a filter designed for a 600-mc pass band centered at 9200 mc. The hybrid junction used in this filter was a commercially available magic-Tee junction and the cutoff waveguides were machined from copper tubing. The cutoff sections were 5 cm long and had 10.2 cm long linear tapers at each end. The input section of cutoff waveguide was designed for a cutoff frequency of 8.9 kmc and the pair of guides terminating ports 2 and 3 were designed to cut off at 9.5 kmc. While the pass band insertion loss of this filter was fairly low, the use of electroformed cutoff sections was seen to lead to an improved performance, particularly near the upper cutoff frequency. This is shown in Fig. 6. This particular filter was assembled using a standard X band folded magic-Tee whose characteristics were found experimentally to be identical to the characteristics of the magic-Tee used with the first filter over the same frequency band. The cutoff guides were designed to have upper and lower cutoff frequencies at 9.0 kmc and 9.5 kmc, respectively. The higher losses which one would expect with narrow band filters is illustrated in Fig. 7, which shows the characteristics of a filter with a 200-mc bandwidth at 8950 mc. While

[8] J. K. Shimizu, "Strip line 3-db directional couplers," 1957 IRE WESCON Convention Record, pt. 1, pp. 4–15.

[9] H. S. Keen, "Scientific Report on Study of Strip Transmission Lines," Airborne Instruments Lab. Rep. No. 2830–2; December, 1955.

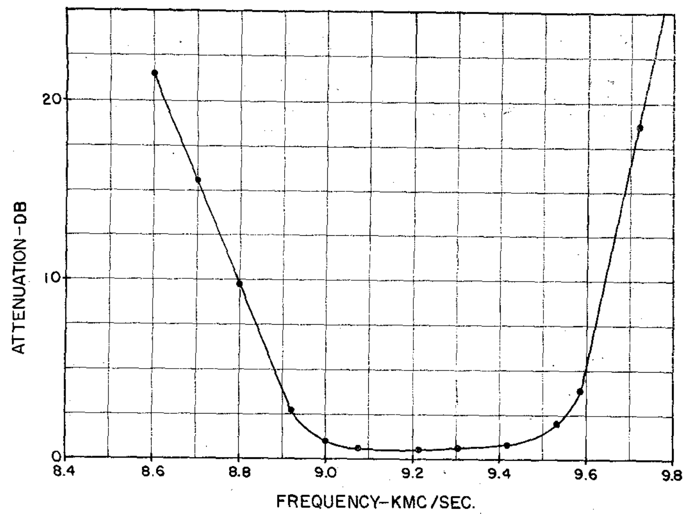

Fig. 5—Magic-Tee cutoff waveguide filter, $f_0 = 9.2$ kmc and bandwidth = 600 mc.

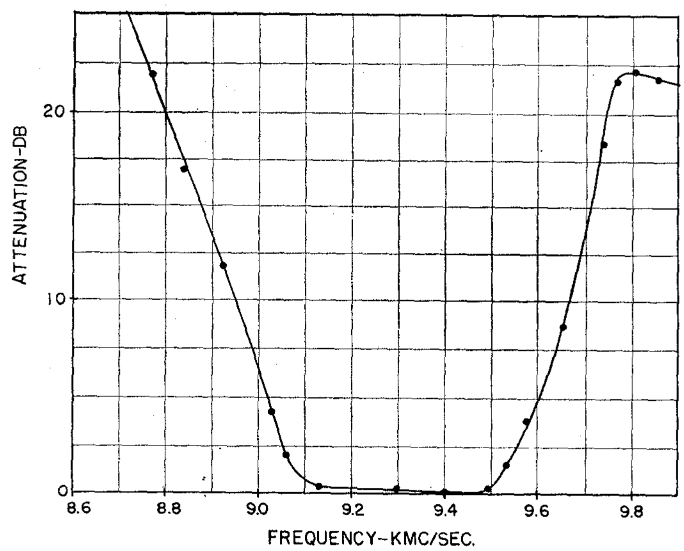

Fig. 6—Folded-Tee cutoff waveguide filter, $f_0 = 9.3$ kmc and bandwidth = 500 mc. Electroformed pair of cutoff waveguides.

the pass band insertion loss was somewhat higher for this filter than for the wider band filters, the midband loss was still only 0.5 db.

Due to the nature of the device, the input VSWR rises below the lower cutoff frequency of the filter. However, the filter presents a fairly well matched input impedance at all frequencies above this cutoff, including the range above the upper cutoff frequency of the filter. The measured input VSWR of the 200-mc bandwidth filter was less than 1.25 over the pass band and was 1.15

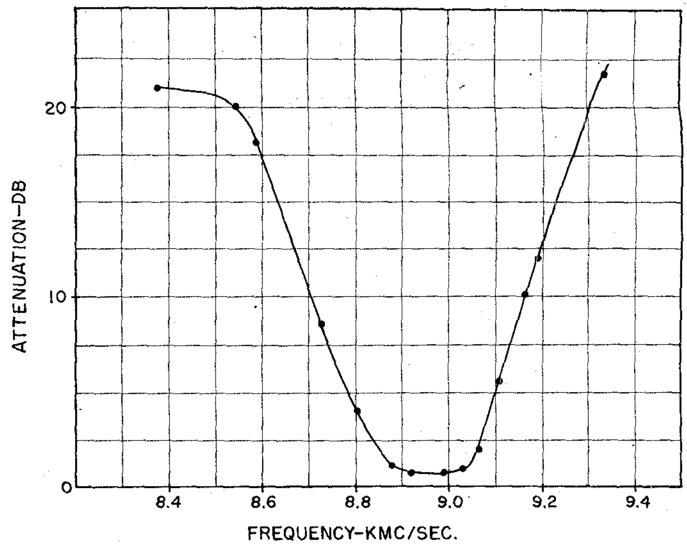

Fig. 7—Folded-Tee cutoff waveguide filter, $f_0 = 8.95$ kmc and bandwidth = 200 mc. Electroformed pair of cutoff waveguides.

at midband. The VSWR was less than 1.5 over the entire upper rejection band. Similar results were obtained for the other filters.

Conclusions

The hybrid junction-cutoff waveguide filters offer several advantages over conventional types of waveguide filters. Where the moderate rejection band attenuation does not present a handicap, filters which are simple to design and easy to construct can be obtained. These filters can make use of existing hybrid junctions and will have a power handling capacity which approaches that of the hybrid junction. Not only are the mechanical tolerances required by the cutoff sections not as critical as the tolerances required for irises and other elements of the more conventional filter types, but also simple tuning procedures, such as those which can be introduced to obtain variable pass band filters, can be employed to adjust the waveguide sections to the desired cutoff frequency. The technique described here can be readily adapted for multichannel filter arrays as well as to tunable filters. Above the lower cutoff frequency in the case of band-pass filters, and at all frequencies in the case of low-pass filters, these devices exhibit the matched input impedance associated with directional filters. The general technique can be extended to all frequency bands and to all types of transmission lines where hybrid junctions can be designed and where cutoff characteristics can be obtained.