Microwave Filters—1965

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Abstract—A review of recent and current work on microwave filters is presented, and an extensive bibliography of recent articles is appended. The review is largely qualitative and pictorial, rather than mathematical. Among the microwave filter topics discussed are band-pass filters with cascaded lines or cavities; band-pass and band-stop filters with stubs and parallel-line coupling; low-pass and high-pass filters; the connection between dissipation loss, group delay, and power-handling capacity; delay equalizers; diplexers; directional filters; tunable filters, especially magnetically tunable filters; dielectric-resonator filters; filter techniques applied to semiconductor devices; the connection between filters and directional couplers; filters with open walls; and filters for millimeter waves and higher frequencies.

I. Introduction

THE PRESENT PAPER is a review paper with emphasis on developments of the past three years. (Although most of the referenced papers have been published since September 1962, the bibliography is classified and sufficiently extensive so that the reader should have little difficulty in finding earlier publications of interest to him.)

Filters are at the heart of many design problems. They are used to separate or combine different frequencies, as in frequency converters or multipliers, or in multiplex communications. The electromagnetic spectrum is limited and has to be shared; filters are used to confine the radiation from high-power transmitters within assigned spectral limits; conversely, other filters are used to protect receivers from interference outside their operating bands. Filter-like networks occur in impedance matching, as between two transmission lines of different characteristic impedances; or between a resistive generator and a reactive load, such as a diode in a parametric amplifier. Sometimes it is necessary to obtain certain phase (or time delay) characteristics, as for pulse stretching; or to compensate for the distortion produced by another filter or dispersive structure (like a length of waveguide). There is need for filters at all frequencies, from very low through microwave to optical frequencies and beyond.

One may approach the subject of microwave filters from the point of view of waves in a transmission line or waveguide (this might be called the physicist's point of view), or one may extrapolate from lumped-constant filters (this view is adopted by perhaps most electrical engineers). The latter point of view has proved the more useful for the systematic design of microwave filters. For this reason, we shall start by referring the reader to a few relevant publications [1]–[12] on lumped-constant networks. References [1]–[5] are textbooks. References [4], [6]–[9], together with Chapter 4 of Reference [13], contain numerical tables for lumped-constant filters useful as prototypes for the design of many microwave filters.

Figure 1 shows typical response curves for four types of lumped-constant low-pass filters, all of which may be used as prototypes for lumped-constant high-pass (Fig. 2), band-stop (Fig. 3), and band-pass filters (Fig. 4), as well as for microwave filters. Numerical tables for filters having the type of response shown in Figs. 1(a) and (b) will be found in Chapter 4 of Reference [13]; similarly, Fig. 1(c) goes with References [7] and [9], and Fig. 1(d) goes with Reference [6]. The changes necessary to convert from the low-pass prototype to the other lumped-constant types is indicated in Fig. 5. The most common low-pass prototype, corresponding to Figs. 1(a) and (b), is shown in Fig. 6.

II. Microwave Filters [13]–[18]

The electromagnetic radiation fields from a short wire carrying RF current exceed the magnetic induction field and the electric transition field at distances greater than one-radian wavelength (about one-sixth of a wavelength) from the wire. Thus, radiation can no longer be neglected, as it conventionally is neglected for lumped-constant circuits, when the physical dimensions of the network approach one wavelength. Nevertheless, it is possible to design a resonant cavity or shielded resonator as if it were a resonant LC circuit over a *small* bandwidth since both have certain fundamental properties in common. (They both store energy which continually oscillates between electric and magnetic form, and they both couple to one or more outside resistive circuits; in other words, they both behave like a damped simple harmonic oscillator.)

An exact method of designing microwave filters is based on Richards' transformation [18], which holds only for microwave circuits with commensurable line lengths. This transformation maps the entire real-frequency axis of the lumped-constant prototype onto finite portions of the real-frequency axis of the transmission-line circuit, and then the response pattern is repeated periodically. (See Sections III and V.) Physically, this repetition corresponds to repeated increments of one-half wavelength in the electrical line lengths of the transmission-line circuit, as the frequency increases. These repetitions in the behavior of the circuit as the frequency increases are usually undesirable and are then referred to as spurious responses. In addi-

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tion, spurious responses will arise in microwave filters at high enough frequencies because of the occurrence of higher-order modes.

A flow chart showing many kinds of filter using commensurable line lengths, and other filters derivable from them, is presented in Fig. 7. This chart will become clearer after reading the following sections.

Microwave filters may be classified by function (band-pass, band-stop, etc.), by mode of operation (reflecting, absorbing, etc.), by physical structure (coaxial line, rectangular waveguide, etc.), by application (tunable or fixed-tuned), by loading (singly terminated, doubly terminated, etc.), by energy manifestation (electromagnetic, spin-wave, acoustic, etc.), and so on. Most of these types will now be described, but it must be remembered that the groupings are somewhat arbitrary and there is bound to be considerable overlap under any classification scheme.

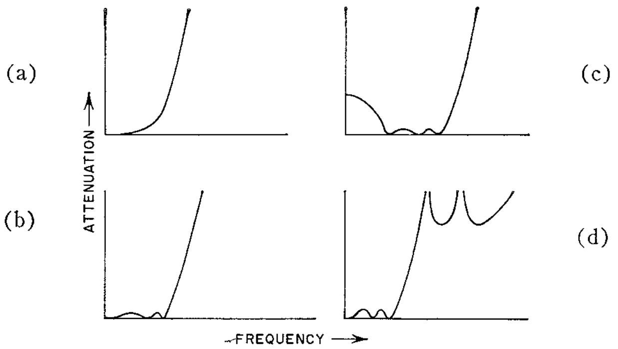


Fig. 1. Lumped-constant low-pass filter characteristics; (a) maximally flat, (b) Chebyshev, (c) Chebyshev transformer, and (d) elliptic-function.

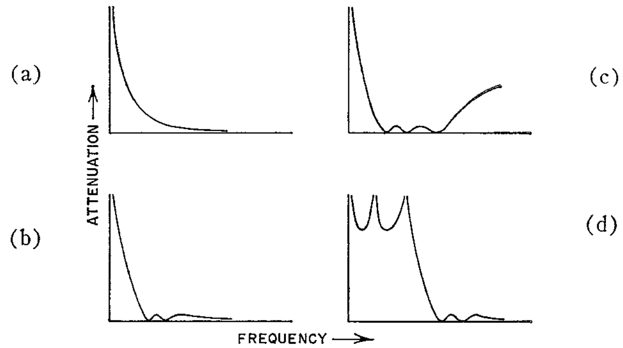


Fig. 2. Lumped-constant high-pass filter characteristics; (a) maximally flat, (b) Chebyshev, (c) Chebyshev transformer, and (d) elliptic-function.

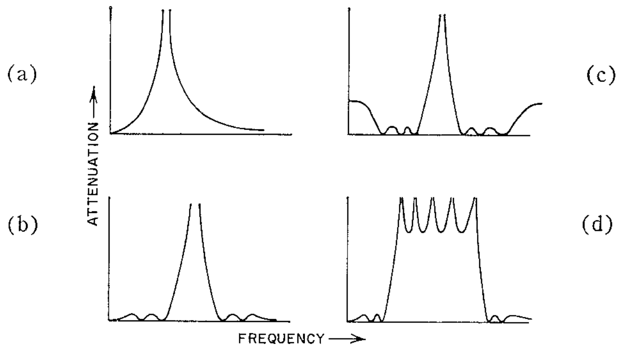


Fig. 3. Lumped-constant band-stop filter characteristics; (a) maximally flat, (b) Chebyshev, (c) Chebyshev transformer, and (d) elliptic-function.

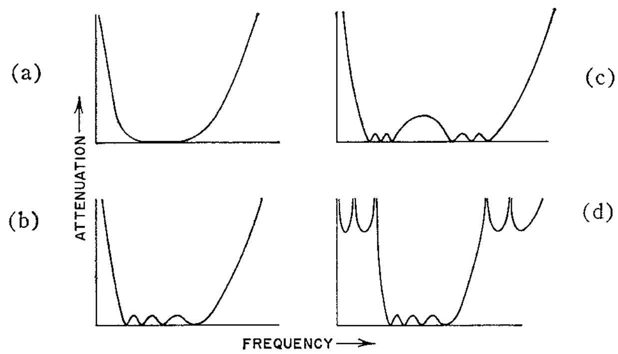


Fig. 4. Lumped-constant band-pass filter characteristics; (a) maximally flat, (b) Chebyshev, (c) Chebyshev transformer, and (d) elliptic-function.

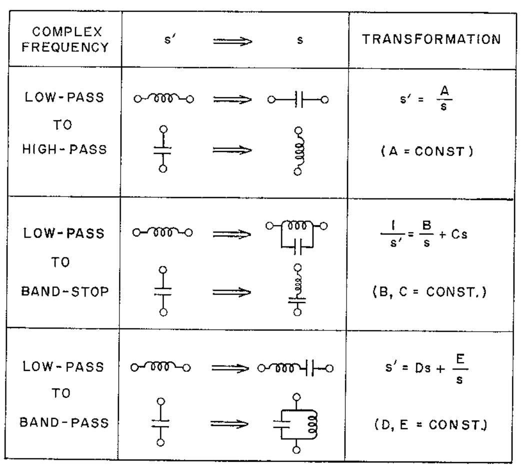


Fig. 5. Element substitutions corresponding to frequency transformations to turn a low-pass filter into a high-pass, band-stop, or band-pass filter.

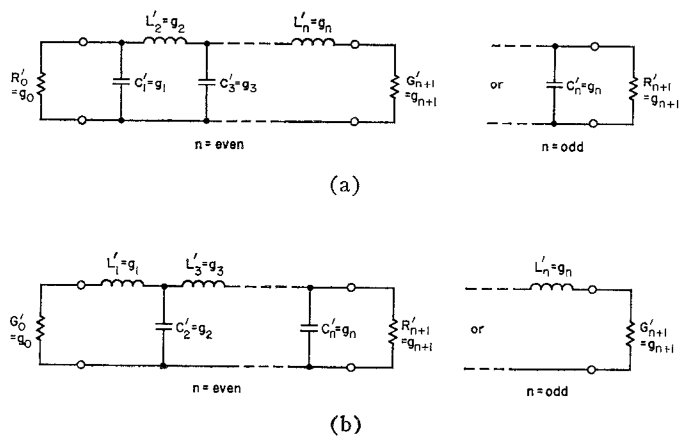


Fig. 6. The four lumped-constant low-pass filter prototype circuits.

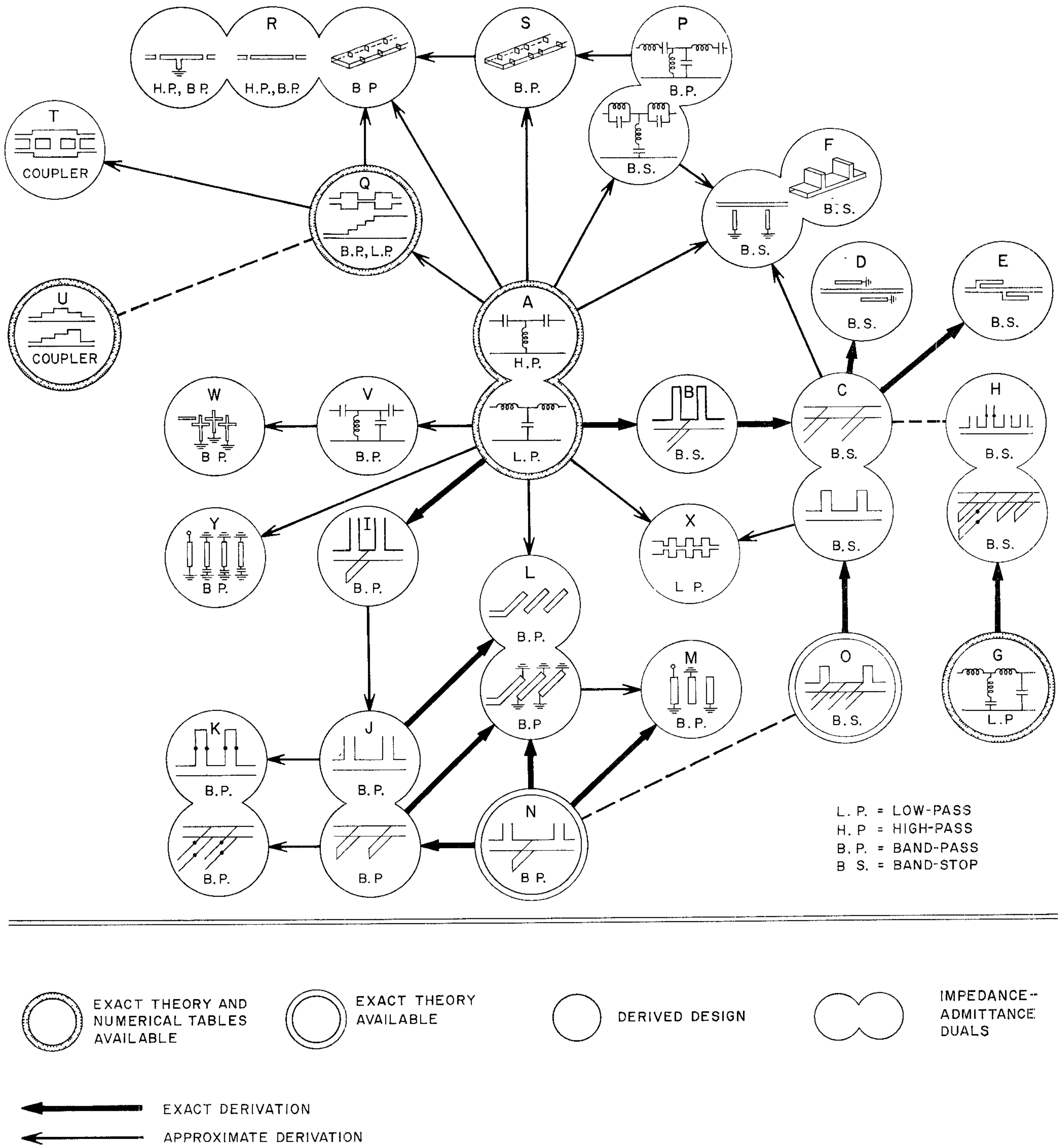


Fig. 7 Flow chart showing derivation of filters with commensurable (or nearly commensurable) line lengths

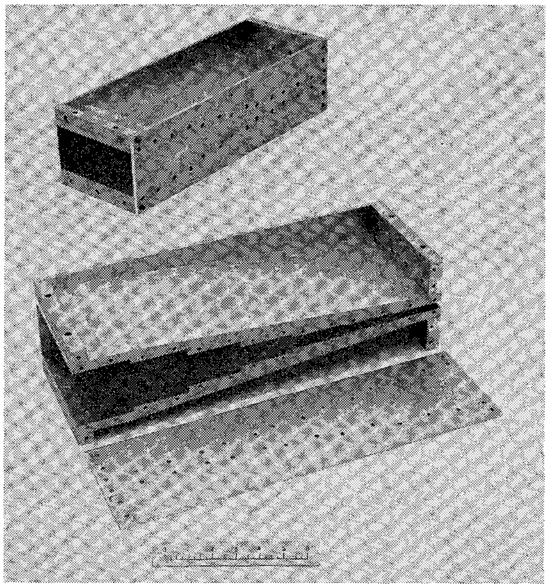


Fig. 8. An *L*-band seven-section quarter-wave transformer in waveguide [150].

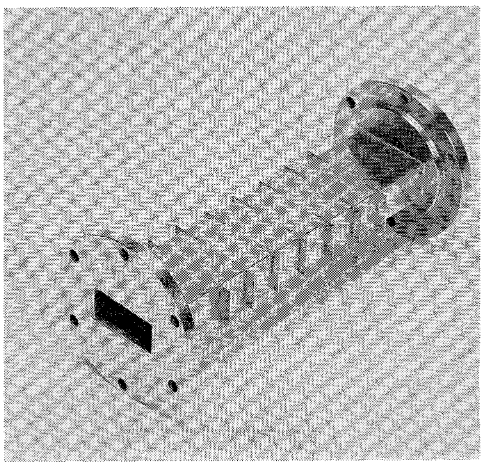


Fig. 9. A *C*-band six-resonator direct-coupled-cavity filter in waveguide [57].

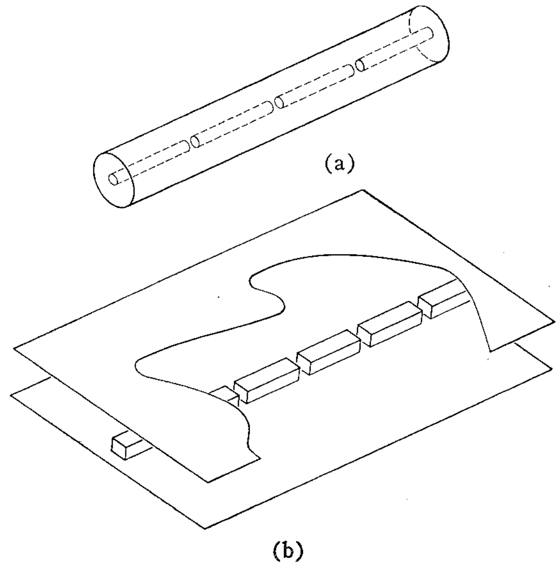


Fig. 10. Direct-coupled-resonator filters in coaxial and strip lines.

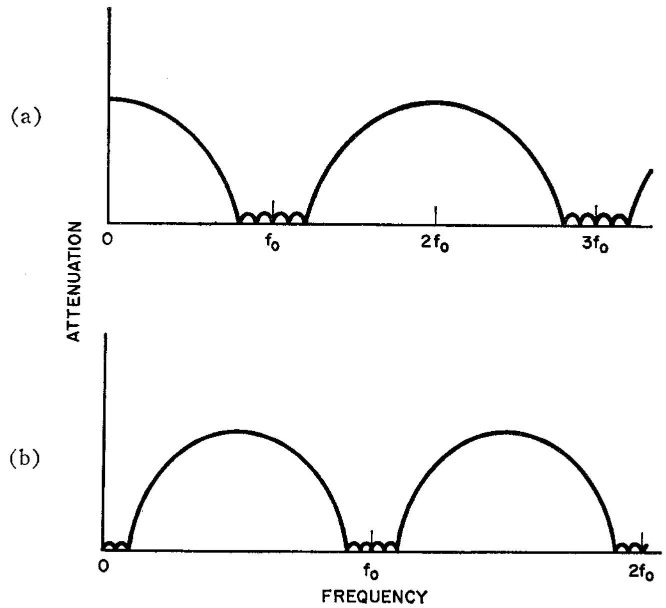


Fig. 11. The periodic nature of the frequency response of transmission-line filters; (a) quarter-wave transformer, and (b) half-wave filter [20].

III. Filters with Cascaded Lines or Cavities [19]–[25]

A periodic structure, such as a waveguide or coaxial line loaded periodically with posts or irises, has filter properties. However, the pass bands and stop bands are clearly defined only for an infinite length of line, whereas in practice the input and output lines must usually be in uniform waveguide or transmission line. In a sense, the problem is not how to design the filter (the periodic structure) but how to match between unloaded and loaded lines. For an optimum match, a gradual loading is required, starting with light loading at the ends and increasing to the greatest loading at the center. The structure is now only approximately periodic—it is a filter.

We have just described the wave (or physicist's) view of a direct-coupled-resonator filter, consisting of end-coupled transmission-line resonators or cavities. The network engineer would start with a lumped-constant filter and approximately transform the *LC* resonators into transmission-line form. Cohn's paper [19] is the most useful on this subject, having served as the basis for much subsequent work. It generally applies to microwave filters with fractional bandwidths up to around 30 percent, provided that the pass-band VSWR is not too low.

Returning to the idea of the periodically loaded line, we should like to know if at least one type of periodic loading can be designed exactly, so that others may be designed from it by suitable approximations. The quarter-wave transformer, for which a complete synthesis procedure was first given by Riblet [19a], is such a prototype [20], the periodic loading being obtained by impedance steps. The impedance ratios at the steps in a typical quarter-wave transformer are on the order of 20 percent from unity, and are seldom greater than 2-to-1, as can be seen from Fig. 8. The corresponding impedance ratios at the steps of the quarter-wave transformer prototype are frequently on the order of 100-to-1, and may be as high as 10,000-to-1 or even higher. Clearly, such a transformer is not practical, but the mathematical theory is the same for any impedance ratio, and exact solutions are possible for the ideal transformer [13], [20]–[22]. The impedance steps are then replaced by other more realizable discontinuities, such as shunt inductances (irises, posts) or series capacitances, each having a discontinuity VSWR equal to the corresponding step impedance ratio [23]. Two filters of this type are shown in Figs. 9 and 10, and also in circles (Q), (R), and (S) in Fig. 7.

The lumped-constant low-pass prototype [19] is easier to use, but the quarter-wave transformer prototype [20] enables one to predict the filter performance more accurately, especially when the bandwidth is large or the pass-band VSWR is particularly low, or both.

The step-twist filter of DeLoach [25] has equal line lengths between junctions, and is a good example of a filter that could more efficiently be designed from a stepped-impedance prototype [20], [22].

The frequency response of a quarter-wave transformer (Fig. 8) or a direct-coupled-resonator filter (Figs. 9 and 10) is periodic, or approximately periodic, in frequency. (For waveguides, substitute reciprocal guide wavelength in place of frequency.) This periodicity is indicated in Fig. 11 for an ideal quarter-wave transformer and an ideal half-wave filter [20], [22]. The response of actual filters [23], [24] will be modified by the frequency sensitivity of the couplings and eventually by the generation of higher-order modes.

IV. TEM-Mode Band-Pass Filters with Parallel-Line Coupling [26]–[34]

Consider the filter shown in Fig. 10. To obtain large bandwidths, adjacent resonators have to be coupled tightly, which requires large series capacitances at the gaps and therefore small, critical gaps. If the resonators could be coupled on their sides instead of at their ends, then wider, less critical gaps would be possible. Such an arrangement is indicated in circle (L) of Fig. 7, showing a parallel-coupled resonator filter [26]. Since the facing areas are larger, the gaps are also wider and less critical. However, the coupling is no longer purely capacitive (with equi-phase surfaces), since the overlapping lengths are one-quarter-wave long at band center and the phase varies along them. The design of these filters [26], [27] is based on other concepts [13], [26], developed by Jones and Bolljahn, which we shall not discuss here.

The interdigital-line filter [28]–[33] was first built by Bolljahn and Matthaei. Filters using circular rods have been constructed by Cristal [30] (Fig. 12). Each resonator is one-quarter-wave long at band center, when the ends of the rods are open-circuited. As in the parallel-coupled filter, the resonator spacings are not very critical. In addition, the resonator commends itself for many applications by its compact form. An exact design theory for interdigital filters and related structures is given by Wenzel in this issue [33]. Fractional pass-band bandwidths in excess of one octave have been obtained.

The digital resonators of the interdigital filter can be made shorter than one-quarter wavelength at band center, and the filter becomes even more compact by capacitively loading the ends of the rods [32], as shown in Robinson's filter (Fig. 13). Also, the first spurious pass band is thereby moved further away from the design center frequency.

Another very compact structure is the comb-line filter developed by Matthaei [34] (Fig. 14), which is similar in many ways to the capacitively loaded interdigital-line filter. In the comb-line filter the capacitances are all on the same side. They are necessary to the functioning of the filter, since there is no coupling between quarter-wave digital resonators when they are all grounded on one side, and all open-circuited on the other. The rods are typically one-eighth of a wavelength long at midband. The first spurious pass band then does not occur till past the fourth harmonic frequency. The comb-line filter is more compact than an (unloaded) interdigital line filter. Current design procedures are suitable only for up to relatively narrow bandwidths, on the order of 10 per cent. The comb-line filter is likely to find most application at VHF, UHF, and the lower microwave frequencies.

The parallel-coupled, interdigital, and comb-line filters are indicated in circles (L), (M) and (Y) in Fig. 7.

V. Band-Stop Filters [35]–[45]

Various band-stop filters have been developed at Stanford Research Institute [35]–[40]. Many of them [35], [36], [39] consist of a length of transmission line and either series, short-circuited stubs—or shunt, open-circuited stubs—or both, as indicated in circles (B) and (C) in Fig. 7. They are a good illustration of the application of Richards' transformation [18] to the low-pass prototype. Richards' transformation is illustrated in Fig. 15, showing how the transformation (A) into (B) is accomplished in Fig. 7. Note the periodic nature of the band-stop filter response. To realize the required cluster of stubs on a single junction is usually not mechanically convenient; in coaxial line it could be constructed as shown in Fig. 16. It is often more convenient to separate the stubs, one to a junction, and this can be accomplished by means of the Kuroda identities (a) or (b) in Fig. 17. Kuroda's identity makes it possible to spread out the stubs; moreover, each stub is of the

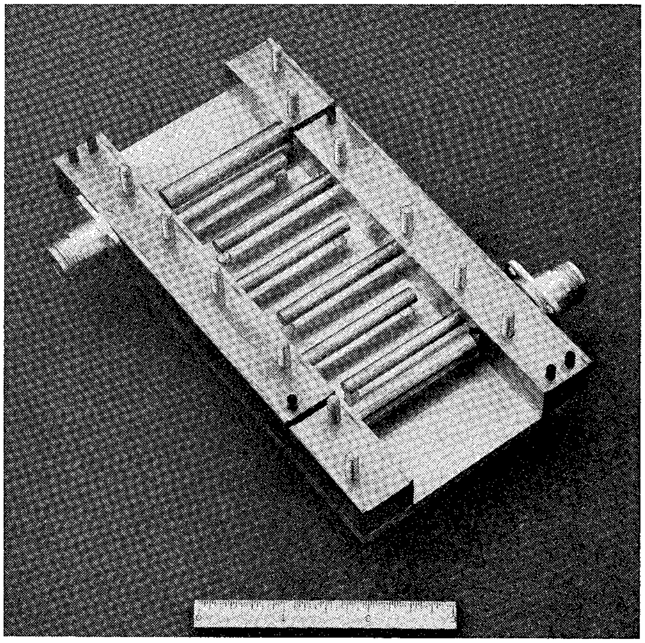


Fig. 12. An L-band interdigital filter with round rods [30].

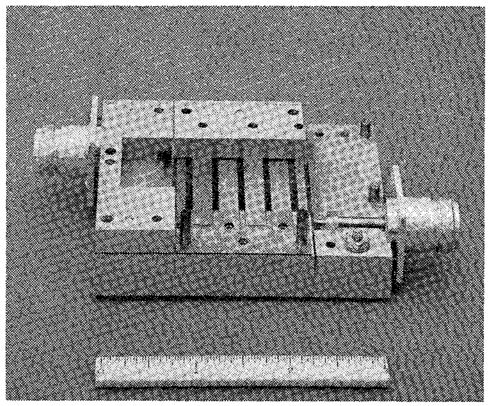


Fig. 13. An L-band capacitively loaded interdigital filter [32].

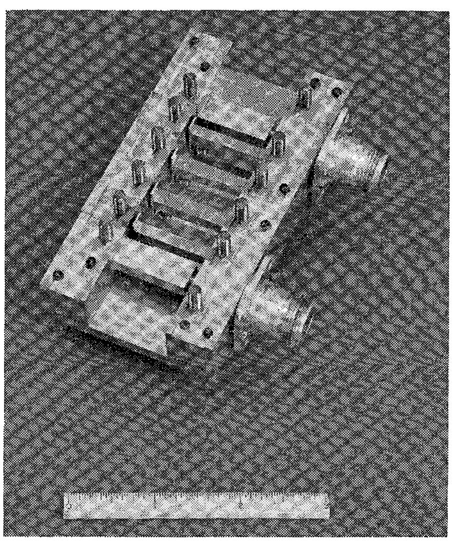


Fig. 14. An L-band comb-line filter [34].

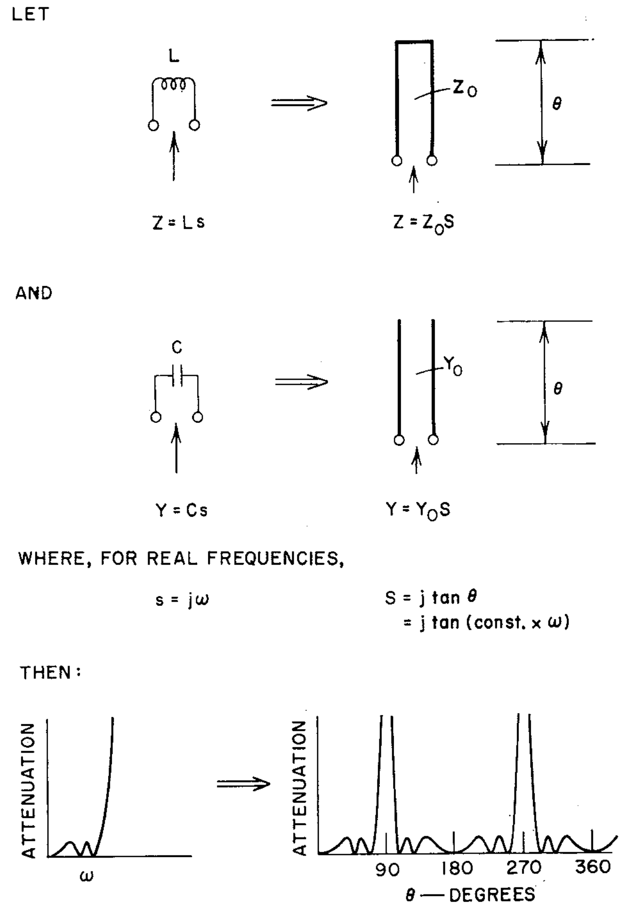


Fig. 15. Element substitutions (corresponding to Richards' transformation) to turn a lumped-constant low-pass filter into a commensurable-line-length band-stop filter. The periodic nature of the new frequency response is also indicated.

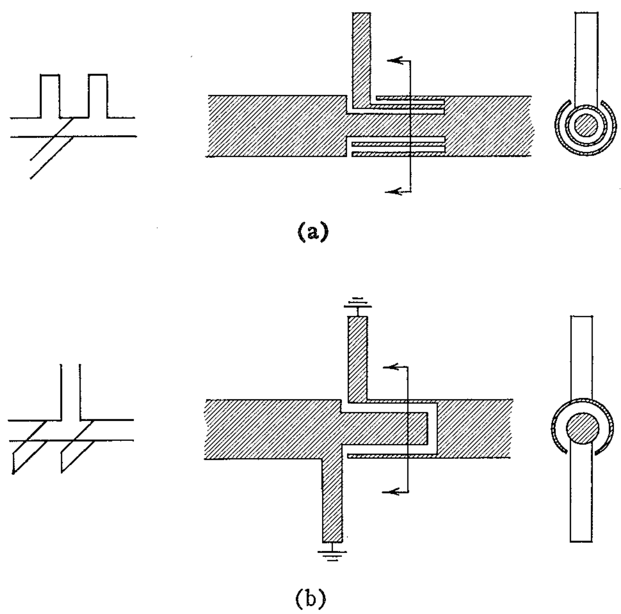
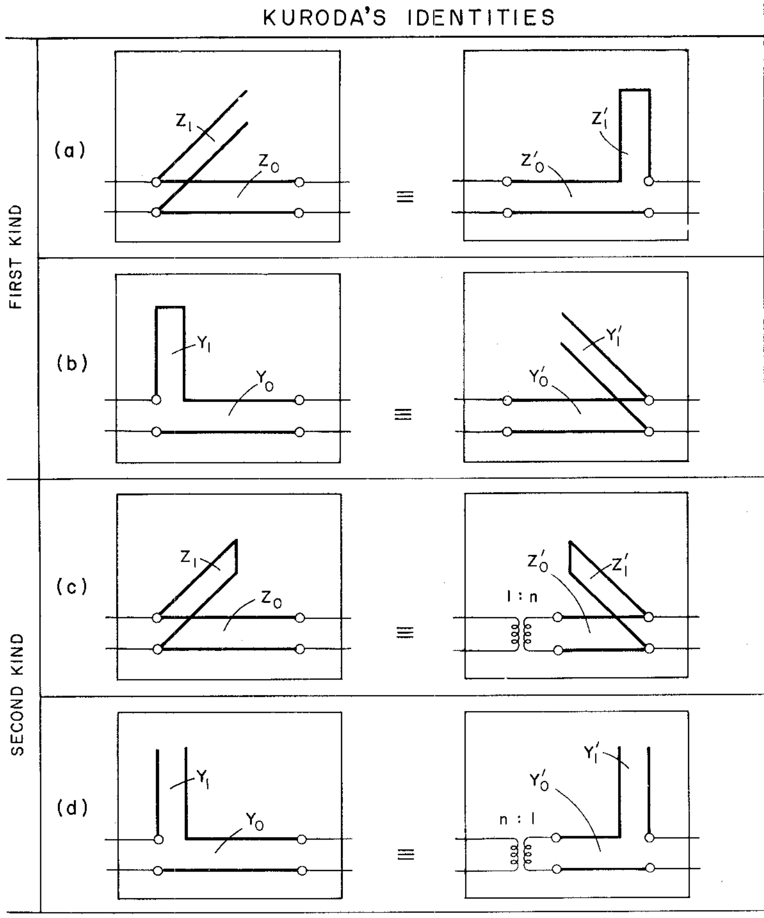


Fig. 16. Physical realization of several stubs at one junction in coaxial line.



	Z_0' or Y_0'	Z_1' or Y_1'	n and m	CHECK
(a)	$Z_0' = \frac{Z_0}{n} = \frac{Z_0 Z_1}{Z_0 + Z_1}$	$Z_1' = \frac{Z_0}{m} = \frac{Z_0^2}{Z_1 + Z_0}$	$n = 1 + \frac{Z_0}{Z_1}$, $m = 1 + \frac{Z_1}{Z_0}$	$\frac{Z_1'}{Z_0'} = \frac{Y_1}{Y_0} = \frac{n}{m}$
(b)	$Y_0' = \frac{Y_0}{n} = \frac{Y_0 Y_1}{Y_0 + Y_1}$	$Y_1' = \frac{Y_0}{m} = \frac{Y_0^2}{Y_1 + Y_0}$	$n = 1 + \frac{Y_0}{Y_1}$, $m = 1 + \frac{Y_1}{Y_0}$	$\frac{Y_1'}{Y_0'} = \frac{Z_1}{Z_0} = \frac{n}{m}$
(c)	$Z_0' = nZ_0$	$Z_1' = Z_1 + Z_0$	$n = 1 + \frac{Z_0}{Z_1}$	$\frac{Z_1'}{Z_0'} = \frac{Z_1}{Z_0}$
(d)	$Y_0' = nY_0$	$Y_1' = Y_1 + Y_0$	$n = 1 + \frac{Y_0}{Y_1}$	$\frac{Y_1'}{Y_0'} = \frac{Y_1}{Y_0}$

Fig. 17. Kuroda's identities [46]. (Heavy lines represent transmission lines, or "unit elements," all of the same length θ.)

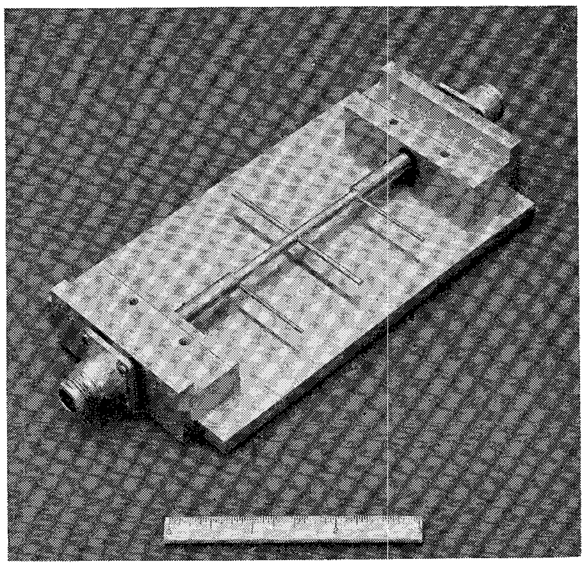


Fig. 18. An L-band band-stop filter with stubs [36].

same type. For instance, the stubs in Fig. 18 are all shunt, open-circuited. The four band-stop filters [35], [38], [40] in Figs. 19 through 22 are more suitable for narrower stop bands. The spur-line filter may be considered to be obtainable from the stub filter (Fig. 18) by laying the stubs parallel to the main line; the parallel-line coupling opposes the junction coupling, weakening it and making the filter more suitable for narrower stop bands. These band-stop filters are indicated in circles (B) through (F) in Fig. 7.

A more general kind of band-stop filter [37] can be designed which has three separate, but symmetrically placed, poles of attenuation. This filter is based on the low-pass prototypes of Saal and Ulbrich [6], as in circle (G) of Fig. 7. It uses one double stub, as in circle (H) of Fig. 7; it has not been possible so far to accommodate more than one double stub, when all the stubs are separated (no more than one to a junction), because Kuroda's identity does not apply to a double stub. (However, concerning a generalization of Kuroda's identity, see the end of Section VI.)

VI. Filters with Stubs: General Theory [46]–[53]

We shall begin with some general remarks about Kuroda's identities: The two Kuroda identities of the first kind in Fig. 17 are the same, except that both boxes have been turned around. In each identity a series, short-circuited stub is exchanged for a shunt, open-circuited stub. (Note that no impedance transformer is required.) Also, each circuit transmits at dc.

The two Kuroda identities of the second kind interchange two *like* stubs; furthermore, an impedance

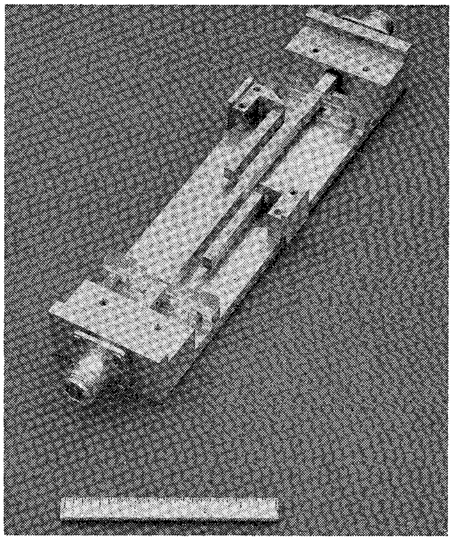


Fig. 19. An *L*-band parallel-coupled-line band-stop filter [35].

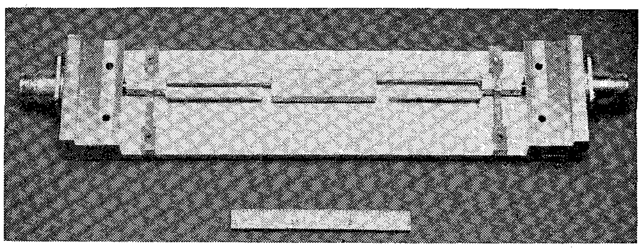


Fig. 20. An *L*-band spur-line band-stop filter [35].

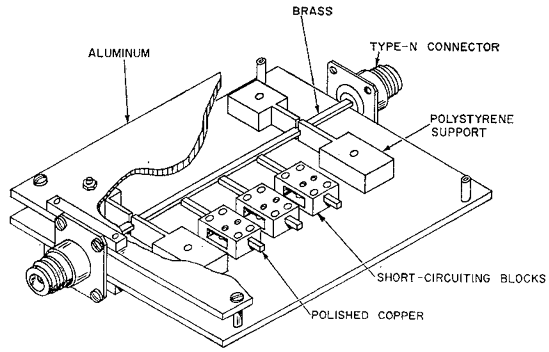


Fig. 21. A *C*-band narrow-band band-stop filter [40].

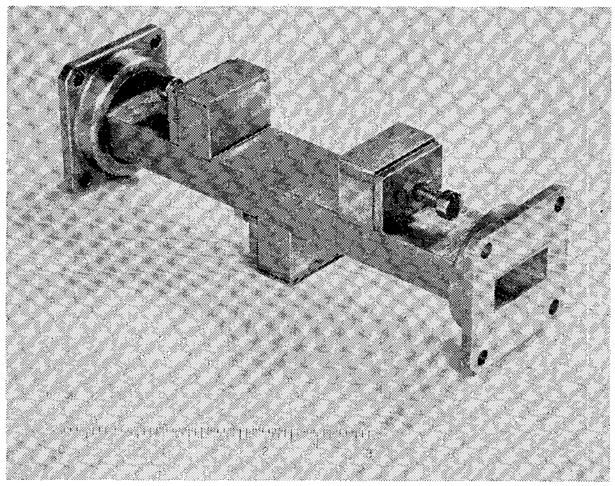


Fig. 22. An *X*-band narrow-band band-stop filter in waveguide [40].

transformer is required. Each circuit is totally reflecting at dc. It is not possible to separate the stubs in Fig. 16(b) and obtain stubs all of one kind, as can be done for the stubs in Fig. 16(a) to obtain a filter like that shown in Fig. 18. The reason is that the two Kuroda identities of the second kind do not change the stub type. Thus, it is not possible in Fig. 7 to make an exact transformation from (*I*) to (*J*), as was possible from (*B*) to (*C*). The appearance of a transformer in the last two identities is a further complication, which however disappears for *symmetrical* filters, since then the transformers can be passed through the circuit, changing the impedance levels of the elements passed over and, finally, the symmetrical series of transformers from each half of the filter combine at the center into two transformers that cancel. For unsymmetrical band-pass filters, application of a Kuroda identity of the second kind leaves a transformer in the circuit.

A filter [13] which could be (but was not) designed by making use of a succession of Kuroda identities of the second kind is shown in Fig. 23, and schematically in circle (*J*) of Fig. 7. The filter is highly redundant since the thirteen stubs have only a single pole of attenuation at zero frequency. Thus, the same performance could be obtained (in principle) by a filter with twelve line sections in cascade and but a single stub. Of course, the impedance of the single stub might turn out to be so low as to make it impractical to realize. One could use any number of stubs between one and thirteen (preferably an odd number to avoid a transformer), compromising between the impedance level and the number of the stubs. Filters of this type are also the subject of a recent paper by Riblet [52].

To avoid redundancy, or in other words, to obtain "optimum filters" (filters having the fewest number of elements to meet a specified frequency characteristic), one cannot use only shunt, short-circuited stubs, as in Fig. 23, or only series, open-circuited stubs, since they could all be reduced to a single stub. One must alternate between the two stub types, as indicated in circle (*N*) of Fig. 7. Filters of this general design have recently been treated by Horton and Wenzel [49], and by Carlin and Kohler [51]. They make use of the connecting lines between stubs, as well as the stubs themselves, to contribute to the filter performance. In contrast, designs based on the low-pass prototype [circle (*A*) in Fig. 7], after separation of one or more stubs by one of Kuroda's identities, do not give "optimum filters"; the connecting lines between stubs are redundant since they do not contribute to the filter performance (but only toward a simpler mechanical design).

An important practical consideration is the value of the impedances of the stubs and connecting lines. The spread between realizable impedance values is limited in practice; for instance, in coaxial line, between 15 ohms and 150 ohms is usually considered reasonable. A 5-ohm stub would have an inconveniently low impedance. This situation can always be remedied by introducing redundancy. For instance, a 5-ohm shunt stub could be replaced by three 15-ohm shunt stubs in parallel, then separated by Kuroda's identity. However, the filter is then no longer "optimum" according to our definition. (It would be useful to have some kind of new "optimum" synthesis procedure, in which upper and lower bounds for the impedances are specified as an *additional* constraint to the problem.)

For illustration of this point, consider four numerical examples, including two of the examples given by Horton and Wenzel [49]. They all have a 3-to-1 pass band with a ripple of 0.1 dB. Let m be the minimum number of stubs (either shunt, short-circuited, or series, open-circuited), and n the minimum number of connecting lines between stubs. One would expect m to contribute much more to the stop-band attenuation than n. This is borne out on comparing, say, the ($m=5$, $n=2$) filter with the ($m=1$, $n=8$) filter. The latter corresponds to the type of filter shown in Fig. 23 (with all but one stub redundant). Two additional curves are plotted in Fig. 24, both for filters with $n=0$ and derived from the low-pass prototype circuit, Fig. 6 or circle (A) in Fig. 7. One filter is ($m=5$, $n=0$), and is inferior to the ($m=5$, $n=2$) filter; the other is ($m=7$, $n=0$), and is the best of the four filters considered. This, of course, was to be expected since a nonredundant stub would contribute more to the stop-band attenuation than a connecting line. However, it was not possible to predict how the impedances would turn out. It was found that the ($m=5$, $n=2$) filter was realized with two redundant stubs so as to make all impedances nearly equal [49], and thus it ended up with seven rather than five stubs. The ($m=7$, $n=0$) filter could not be realized as such because seven stubs could not be crowded at one junction; however, it could be realized with two redundant connecting lines introduced by Kuroda's identity from outside the filter. Thus the final *practical* structures for the ($m=7$, $n=0$) filter would be very similar to those for the ($m=5$, $n=2$) filter, and both would contain the same number of elements of each kind.

Band-pass filters with stubs that create poles of attenuation close to the pass band have been described by Matthaei [13], pp. 605–614. They use stubs that are one-half wavelength long at band center, as indicated in circle (K) of Fig. 7.

Recently, Kuroda's identity has been extended by Levy [47]. In particular, this generalization can be applied to removal of the limitation on transmission-line elliptic-function [6] filters, mentioned in Section V. It should be possible to design such filters with several double stubs, requiring no more than one stub per junction, spread out along the main line.

VII. Low-Pass and High-Pass Filters [54]–[60]

The low-pass prototype filter of Fig. 6, or circle (A) in Fig. 7, can be turned into a transmission-line filter by replacing each series inductance by a short high-impedance line, and each shunt capacitance by a low-impedance line, as indicated in circle (X) of Fig. 7. A coaxial line filter of this type [13] is shown in Fig. 25. In waveguide, it can lead to the waffle-iron filter [54]–[56] developed by Cohn and others at Stanford Research Institute. The waffle-iron filter can be designed to have a wide pass band (on the order of a waveguide band) [55], [56], as well as a very wide stop band (almost three octaves for the composite filter shown in Fig. 26). It will handle moderately high power levels, and makes a very compact unit.

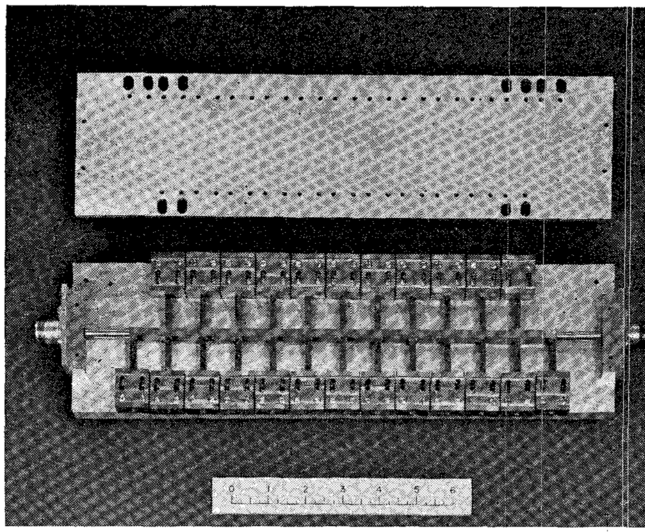


Fig. 23. A wideband band-pass filter centered at 3.6 Gc [13].

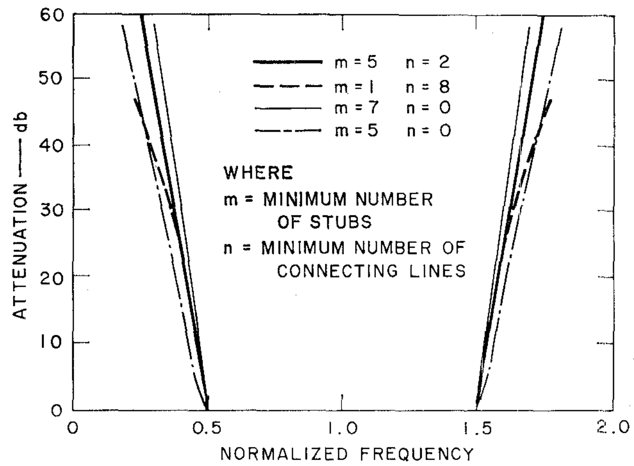


Fig. 24. Attenuation characteristics of optimum band-pass filters with stubs, showing the effect of the number of stubs and the number of internal connecting lines (taken partly from Reference [49]).

Low-impedance, high-impedance short-line low-pass filters can also be designed from a stepped-impedance prototype [20], [22]. The effect of the corner shunt-capacitances at the steps must be allowed for in any practical filter.

High-pass filters in coaxial or strip line may take the form shown in Fig. 10 [57]. Waveguide is a natural high-pass filter. As is apparent from Fig. 27, the problem reduces to the design of a good inhomogeneous transformer [13], [60] that is, a transformer in which the guide wavelength changes along the transformer. It

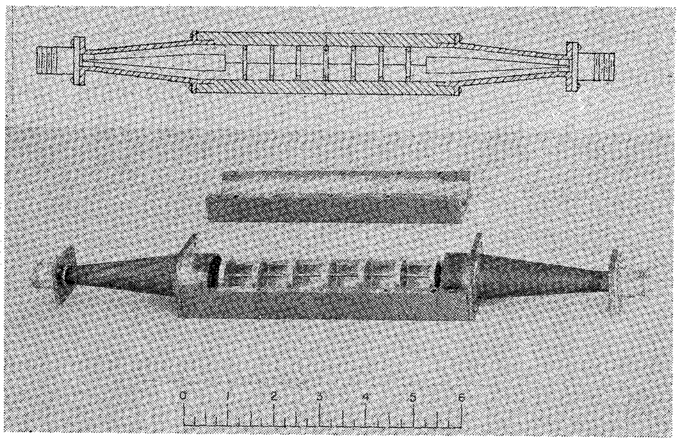


Fig. 25. A coaxial low-pass filter [13].

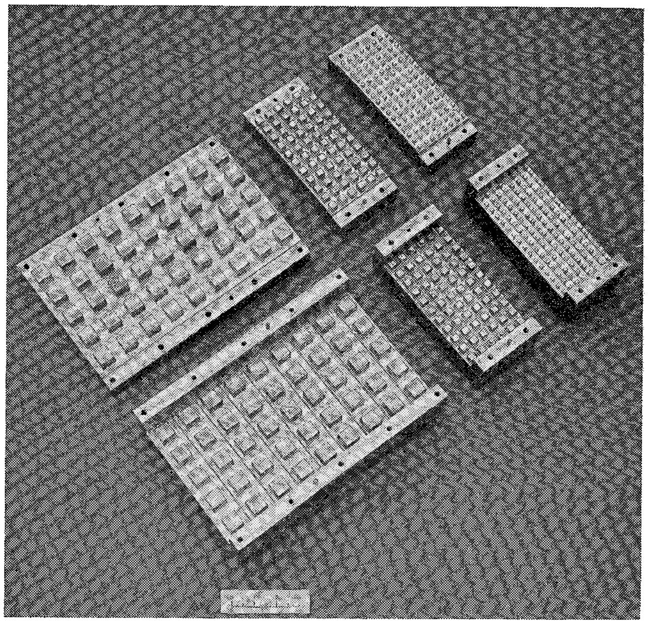


Fig. 26. An L-band waffle-iron filter with stop band up to 13.7 Gc [56].

is usually necessary to obtain a good match relatively close to the cutoff frequency, where the impedance of the near-cutoff waveguide is still high and changing fast. (Another application of inhomogeneous transformers has nothing directly to do with filtering, but concerns making a transition piece between two different waveguide sizes, as in Riblet's paper [60] in this issue.)

VIII. Dissipation Loss, Group Delay, and Power-Handling Capacity [61]–[69]

Filters are usually designed by first neglecting dissipation loss, and then allowing for the dissipation loss on the assumption that it is small. A remarkably accurate formula for the midband dissipation loss of band-pass filters has been given by Cohn [61] for well-matched filters that are designed from a low-pass prototype. The formula can readily be modified [68] for filters that are appreciably mismatched, and then continues to hold quite accurately for filters with up to several decibels of reflection loss. It can also be extended to band-stop filters [40]. The midband dissipa-

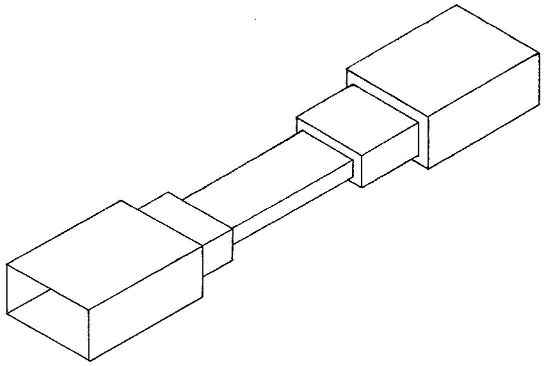


Fig. 27. A high-pass filter in waveguide using two inhomogeneous quarter-wave transformers.

tion loss of a stepped-impedance filter can also be calculated quite accurately [62]. Taub [63]–[65] has given numerical curves for the insertion loss of lossy equal-element filters as a function of frequency, both for band-pass and band-stop filters.

The dissipation loss is closely related to the group delay [13], [68] and is nearly proportional to it over most of the pass band. This is intuitively acceptable, since the longer the energy remains inside the filter, the greater should be the amount of its dissipation in the filter.

Figure 28 shows some typical curves. Curve (a) is the general shape of either the dissipation loss vs. frequency, or the group delay vs. frequency characteristic. Notice the two sharp peaks which usually occur just outside the pass band. The effect of the dissipation loss on the overall insertion loss is to produce "dimples," as indicated in curve (b).

The power-handling capacity is also related to the group delay. The equivalent power ratio [13] is nearly proportional to the ratio of the gross power flow (the sum of the powers in the forward and backward waves) to the net power flow (their difference), and is inversely proportional to the power-handling capacity. The equivalent power ratio vs. frequency curve varies from cavity to cavity, as can be seen from Fig. 29, plotted for a six-cavity filter of 10 percent bandwidth. The shape of the group delay or dissipation loss vs. frequency curve (Fig. 28) represents a sort of averaging of all the curves in Fig. 29.

Some considerations in the design of waveguide filters [66] indicate that both the dissipation loss and the power-handling capacity of a rectangular-waveguide filter stay constant to within a few percent for a wide range of waveguide shapes.

IX. Delay Equalization [70]–[75]

Delay distortion arises from dispersive structure, such as a filter or a length of rectangular waveguide. Torgow [71] has compensated for delay distortion by using a circulator and a section of tapered waveguide, the shape of which is controlled to nearly equalize the delay in a long section of waveguide over a band of frequencies (Fig. 30). A similar taper has been described by Tang [70].

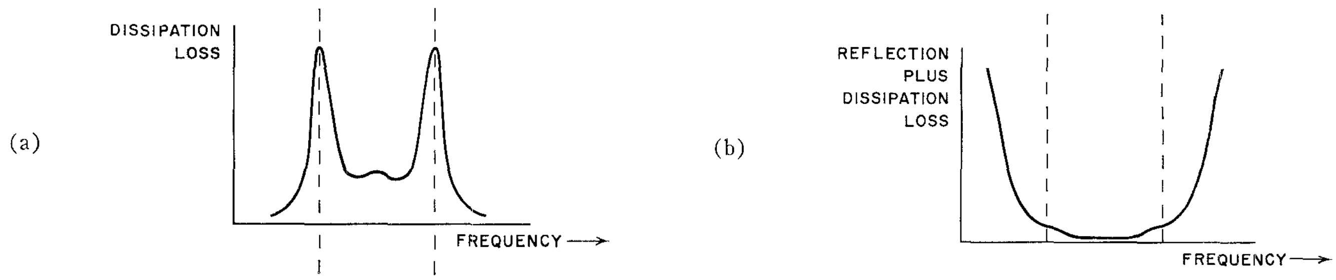


Fig. 28. Dissipation loss characteristic and effect on overall insertion loss for typical band-pass filters [13].

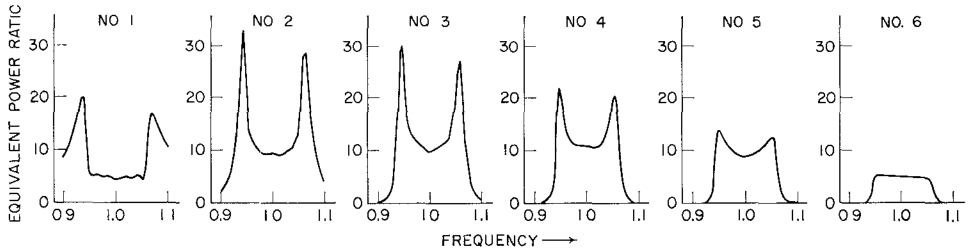


Fig. 29. Equivalent power ratios in the six cavities of a direct-coupled-resonator filter of 10-percent bandwidth [13].

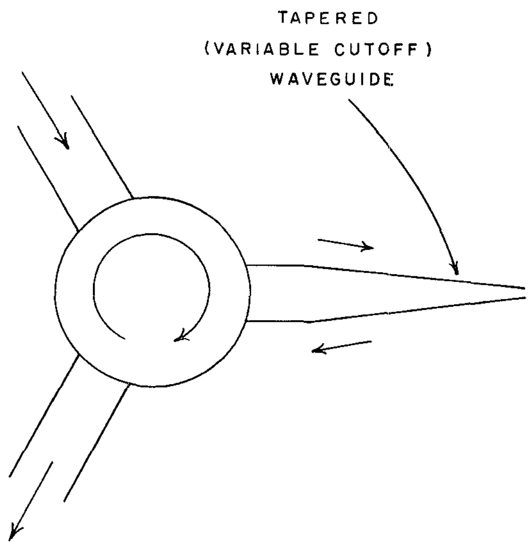


Fig. 30. Delay equalizer using a circulator and a tapered waveguide [71].

X. Diplexers and Multiplexers [76]–[81]

A diplexer separates power entering a common input into two frequency bands; or conversely, it combines two frequency bands arriving separately into a common output. A multiplexer extends this principle from two to many channels. Frequently, a multiplexer is made up of a cascade of diplexers because of the mechanical problems that arise in connecting many filters close to a single junction.

Diplexers in which there are adequate guard bands between channels may be designed by suitably connecting two separate, doubly terminated filters onto a T-junction. The design procedure is not so simple when the bands are contiguous [76–79], that is, when they cross over at the 3-dB points (and thus have no guard bands to separate them). This case is illustrated in Fig. 31 for the case of a band-pass and a band-stop filter. It is possible to maintain perfect match at the common port, provided that the two filters are designed as singly terminated, maximally flat filters [1], [76].

Two filters having contiguous pass bands are shown in Figs. 32 and 33. The filter in Fig. 32 was built by Matthaei and Cristal [79], and it has a relatively narrow pass band of about 5 per cent at L-band. The filter in Fig. 33 was built by Matthaei and Schiffman, and it has a relatively wide pass band of one octave (4 to 8 Gc).

XI. Directional Filters [82]–84]

Directional filters [13] can be constructed in waveguide and in strip line, as indicated in Fig. 34. Craven, Stopp, and Thomas [82] and Williams [82a] describe filters such as that shown in Fig. 34(a). Standley [83], [84] reports on filters such as that shown in Fig. 34(d); he analyzes discontinuity effects, which often set a practical limit on the performance of such filters.

Directional filters can also be realized in a straightforward manner by joining two quadrature hybrids in cascade through a pair of identical filters. For example, in the polarization filter of Fig. 34(a), the two hybrids are the two junctions at top and bottom, and the single circular tube represents two waveguides by vitrue of the two independent circularly polarized waves that propagate in it.

Directional filters can be used as channel-dropping filters, or as matched diplexers with contiguous channels (compare Fig. 31). However, the isolation in one channel will generally not be very good in practice because of the small (but not negligible) reflection in the pass band of the filter pair.

XII. Tunable Filters [85]–[94]

Filters can be tuned mechanically [85]–[87] or electronically. They have been tuned electronically by a magnetic field [88]–[92], by a varactor [93], and by means of a plasma [94].

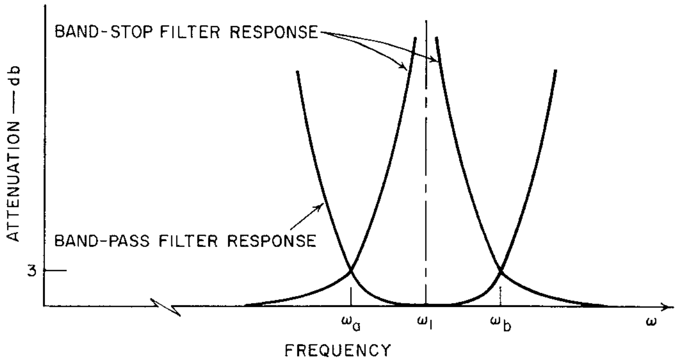


Fig. 31. Characteristics of complementary band-pass and band-stop filters.

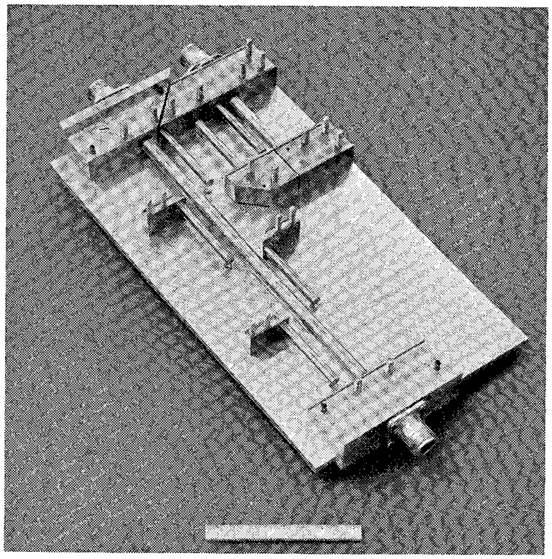


Fig. 32. An L-band diplexer composed of an interdigital filter and a parallel-coupled-line band-stop filter [79].

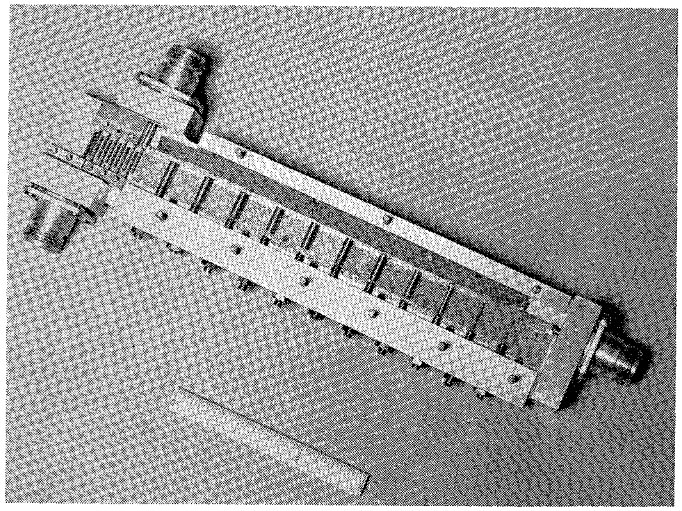


Fig. 33. A wideband diplexer (pass band of interdigital filter = stop band of band-stop filter = 4 to 8 Gc).

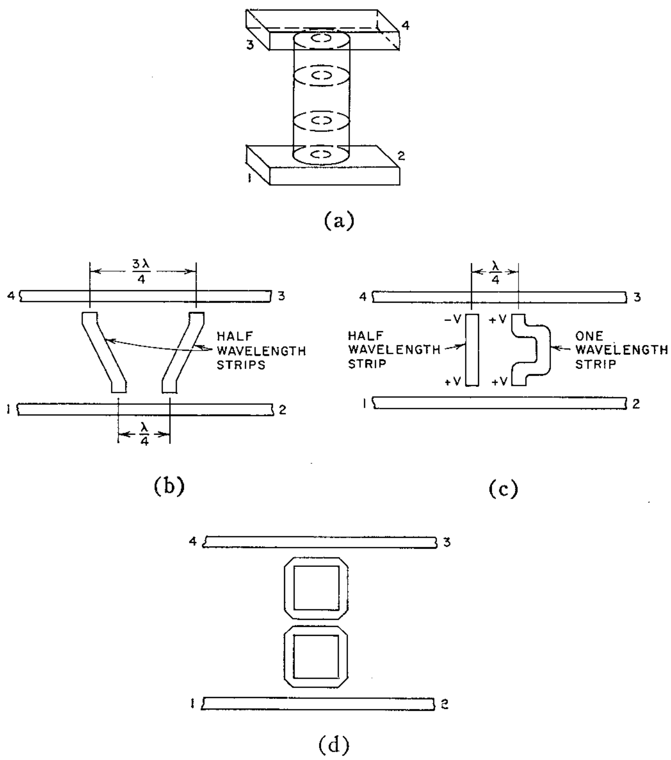


Fig. 34. Some directional filters; (a) in waveguide, and (b) in strip line [13].

Magnetically tunable filters using single-crystal ferrimagnetic resonators of yttrium iron garnet (YIG) have proved very successful at microwave frequencies. They attain high unloaded Q, and it is therefore possible to build band-pass filters with relatively low insertion loss (typically 1–2 dB per resonator), and band-stop filters with relatively high attenuation [88]. The filter is tuned by adjusting the applied (static) magnetic field; the resonant frequency in megacycles is approximately equal to 2.8 times the applied magnetic field in oersteds. The lowest frequency at which a ferrimagnetic resonator can be operated depends on the sample shape and material. For example, a pure YIG sphere can be resonated down to about 2 Gc, but it rapidly loses unloaded Q as this frequency is approached. A pure YIG disk can be tuned to much lower frequencies —for example, down to about 500 Mc for a diameter-to-thickness ratio of 10-to-1. (An infinitely thin disk theoretically has no lower-frequency limit.) A disk also tends to have fewer spurious-mode resonances than a sphere. On the debit side, disks are difficult to machine, expensive, fragile, and more temperature-sensitive than spheres. For this reason, where a pure YIG sphere will not do (below about 2 Gc), it is generally preferred to dope the YIG—for instance, by gallium substititution. Doping reduces the saturation magnetization and thus the internal demagnetizing field, and it permits filter operation down to a few hundred megacycles. Doping has several undesirable effects. It reduces the unloaded Q (increases filter losses), and makes it more difficult to couple to the doped YIG resonator. In addition, since it is difficult to control the uniformity of the doping, there will be appreciable inhomogeneities within one crystal, and there is likely to be a relatively large spread in resonant frequencies between doped resonators.

The first single-resonator YIG filter was reported by DeGrasse, and the first multiresonator filter was reported by Carter [13]. Two magnetically tunable

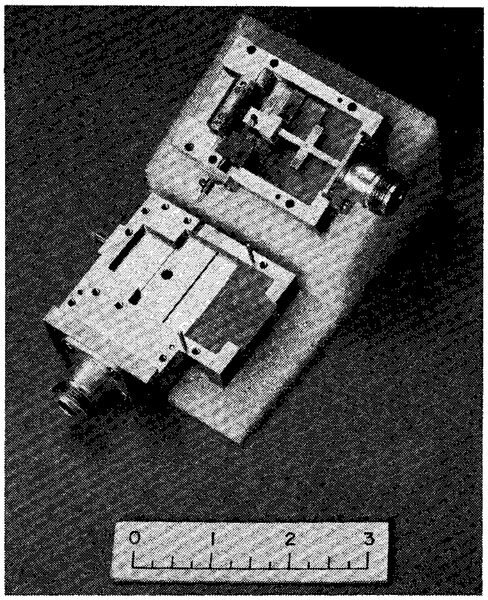


Fig. 35. Magnetically tunable band-pass filter, using two gallium-YIG spheres and low-pass matching transformers [7], tunable from 1.3 to 2.7 Gc.

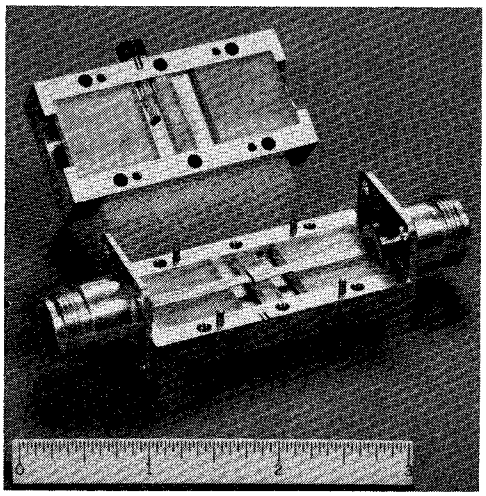


Fig. 36. Magnetically tunable band-stop filter, using two YIG spheres (one has been removed), tunable from 2.2 to 6 Gc [88].

filters built recently by Matthaei [88] are shown in Figs. 35 and 36. They use YIG spheres as the resonators. One sphere mounted at the end of a dielectric rod can be seen in each photograph.

Blau [92a] has lowered the saturation magnetization of a gallium YIG resonator by heating it, and has operated it down to 50 Mc. However, heating also lowers the unloaded Q of the resonator, thus increasing filter insertion loss.

Each ferrimagnetic sphere may be treated as a resonator from the circuit point of view, and one has to devise means for coupling into and out of it. The coupling is through the RF magnetic field, which should therefore be made as strong as possible over a wide frequency band (the tuning range of the filter). This result implies that the ferrimagnetic resonator should be placed at a low impedance point, which can be accomplished either by dielectric loading or by an impedance transformer.

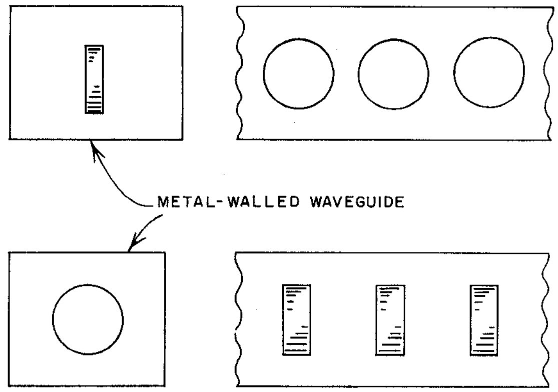


Fig. 37. Dielectric-resonator filters using TiO_2 disks [96].

YIG resonators saturate at relatively low power levels (typically below one milliwatt), and they are therefore also used as limiters [91].

XIII. Dielectric-Resonator and Dielectric-Loaded Filters [95]–[100]

Okaya and Barash [95] showed that high unloaded Q (on the order of 10^4) can be obtained with materials having high dielectric constant (on the order of 80). This phenomenon makes it possible to use small volumes of such materials as dielectric resonators [96]–[99a]. Theoretically, no metal walls would be required, but it is necessary in practice to provide shielding. Filters can then be constructed from these resonators, and can be made very compact. Such a filter is sketched in Fig. 37, adapted from Cohn [96]. The filters can be tuned, for instance, by adjusting the spacing between resonators. If the material is ferroelectric, the possibility exists of tuning the resonance electrically, by the application of a high electric field.

The chief drawback of high-dielectric-constant resonators is the excessive dependence of the resonant frequence on temperature, at least with present-day materials.

XIV. Filter Techniques Applied to Semiconductor Devices [101]–[109]

Rapid strides in the semiconductor art and the progress toward ever-higher frequencies have led to the application of microwave filter techniques to various semiconductor devices. They include frequency multipliers [101], [102], frequency converters [103], and amplifiers [104]–[106a], as well as diode phase shifters [107] and switches [108]. Circuits have become more "integrated" [109], and this trend is likely to continue.

XV. Stepped-Impedance Filters as Directional Couplers [110–120]

From the design point of view, there is a strong resemblance between filters and certain types of directional coupler. Nowhere is this more apparent, perhaps, than with the TEM-mode coupled-transmission-line directional coupler, pioneered by Jones, Bolljahn, and Shimizu [13]. (There are at least two papers on this subject in this filter issue [117], [118].) The correspondence reduces to the stepped-impedance filter prototype shown in Fig. 38. The design of the TEM-mode backward-wave coupler reduces to the design of a stepped-impedance filter, with the reflected wave becoming the coupled component. The input and output impedances of the prototype must be the same (Z_0 in Fig. 38). The design problem is to maintain nearly constant (equal-ripple) reflection over a specified stop band.

Two kinds of coupler are of practical importance, the asymmetrical coupler [110]–[114] of Fig. 38(a) and the symmetrical coupler [115]–[120] of Fig. 38(b). The former requires fewer sections, while only the latter maintains phase quadrature between the two outputs, which is usually of importance for 3-dB couplers. An asymmetrical coupler realization in strip transmission line is sketched in Fig. 39.

We make a final comment on the asymmetrical coupler prototype [Fig. 38(a)], illustrating its resemblance to and difference from a band-pass filter. The problem of constant coupling reduces to one of constant reflection coefficient magnitude for the prototype. Now the junction of two lines of different characteristic impedances gives a perfectly constant reflection coefficient. It may therefore be expected that the coupler of Fig. 38(a) should be designed as a quarter-wave transformer from Z_0 to some impedance Z_0'; the ratio Z_0'/Z_0 would then be nearly constant and would determine the coupling. This approach is indicated on a Smith chart in Fig. 40(a). The difference between the coupler and the transformer is that it is only the variation in the *magnitude* of the reflection coefficient that interests us in the coupler, whereas the transformer approach has minimized the variation in the *vectorial* change of the reflection coefficient. Thus, an optimum design allows the tip of the reflection coefficient vector to lie anywhere inside the annulus shown in Fig. 40(b), the radial width of which can be made appreciably less than the diameter of the circle in Fig. 40(a), for a given number of sections. The author has analyzed the performance of couplers based on quarter-wave transformers [20], and that of couplers based on Levy's tables [111], and has found the latter to give appreciably better performance.

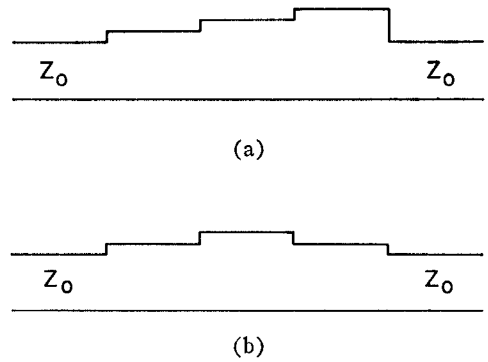


Fig. 38. Stepped-impedance filters that serve as prototypes for TEM-mode backward-wave directional couplers; (a) asymmetrical, and (b) symmetrical.

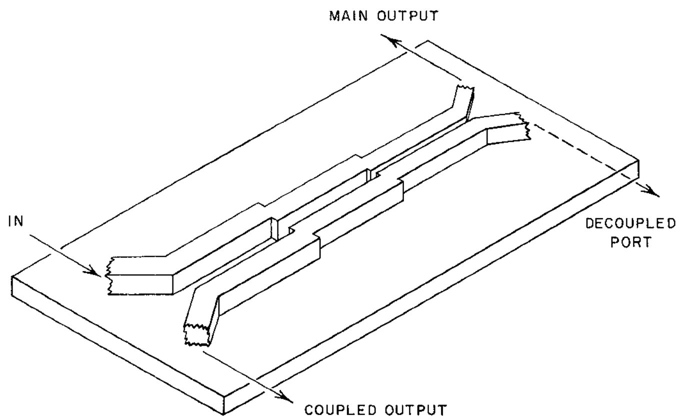


Fig. 39. Typical TEM-mode backward-wave directional coupler in strip line.

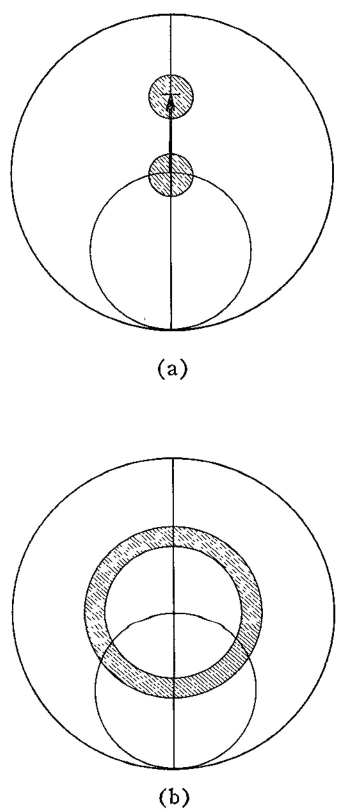


Fig. 40. Diagram showing why the optimum prototype in Fig. 38(a) is not based on a quarter-wave transformer.

XVI. Couplers from Filters and Filters from Couplers [121]–[125]

The connection between couplers and filters is further exemplified by the branch guide coupler [121] shown in Fig. 41, which can be designed to a close approximation from a quarter-wave-transformer prototype.

Directional couplers can also serve as filters [123]. This principle depends on the fact that complete transfer of power can occur only between two transmission lines having the same phase velocity [124]. If one line is made dispersive with respect to the other, 100-percent coupling occurs over only a narrow frequency band, where the two phase velocity curves cross.

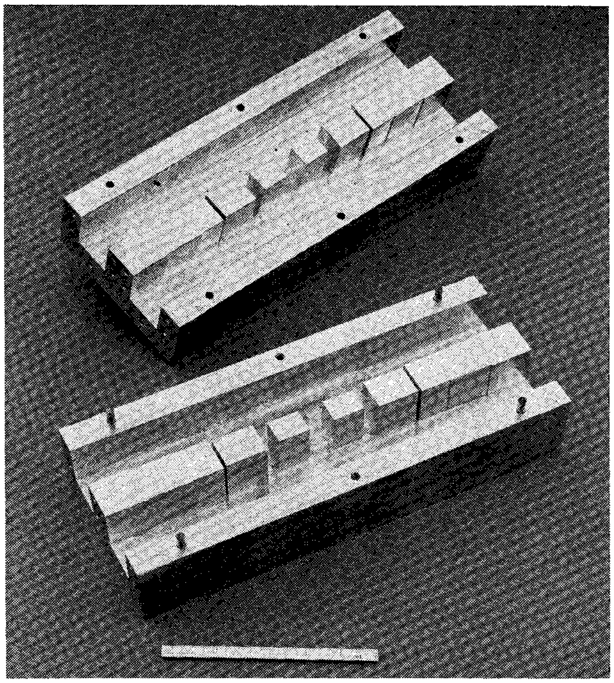


Fig. 41. An S-band branch-guide directional coupler [121].

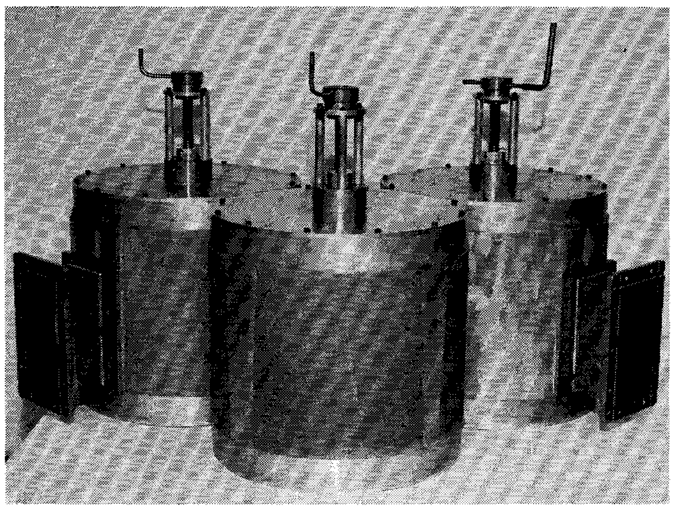


Fig. 42. An L-band circular-waveguide TE_{01}-mode high-power tunable filter [13].

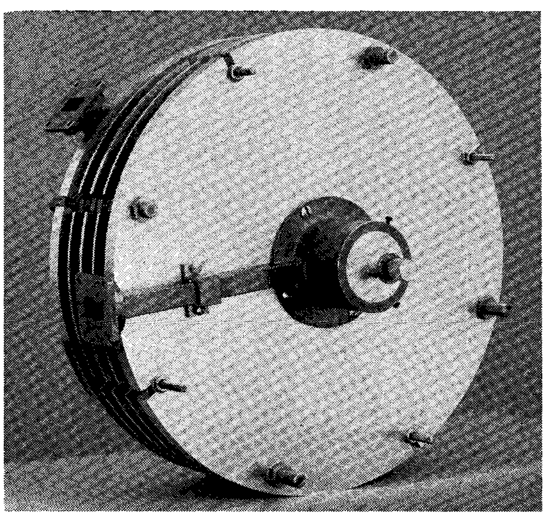


Fig. 43. An X-band circular-waveguide TE_{01}-mode "trapped-mode" filter using open-wall construction [129].

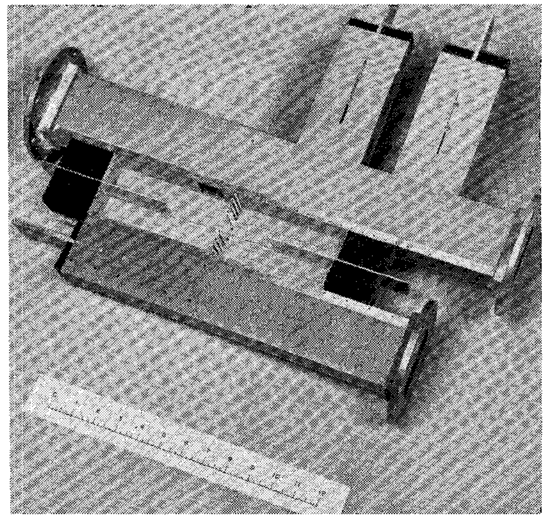


Fig. 44. An S-band diplexer in rectangular waveguide using open-wall construction [131].

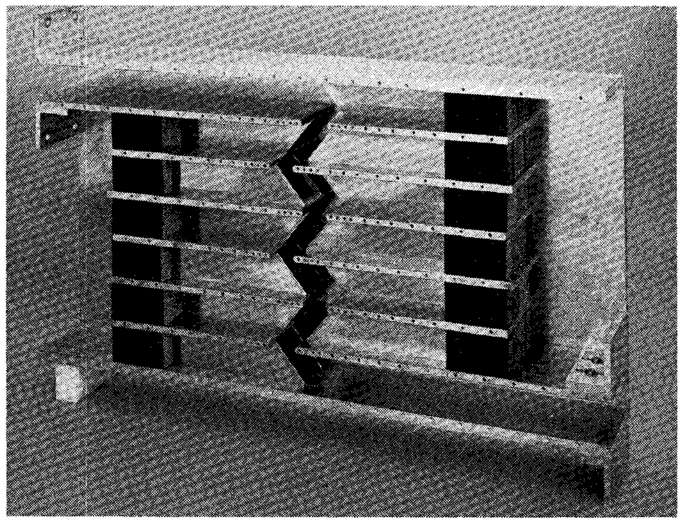


Fig. 45. A low-pass leaky-waveguide filter using open-wall construction [133].

XVII. Filters with Open Walls [126]–[133]

Microwave filters that are to operate at high power or with very low insertion loss are usually constructed in waveguide, and sometimes in overmoded guide, such as the circular TE_{01}-mode. Figure 42 shows a three-cavity tunable filter constructed by Jones [13]. Waveguide filters, especially when in overmoded guide, suffer from spurious frequency responses; that is, in the stop band there will be occasional resonances and the attenuation drops sharply over a very narrow band. To damp out these spurious resonances, a number of filters have recently been tested at Stanford Research Institute, using an open-wall construction, reminiscent of leaky-wave filters [126]–[128]. However, in this case, a filter is first designed as a band-pass filter and then selected walls are removed. An open-wall TE_{01}-mode filter [129] is shown in Fig. 43, and an open-wall rectangular waveguide filter is described in another paper [130] in this issue. An open-wall waveguide diplexer [131] is shown in Fig. 44, and an open-wall low-pass filter [133] is shown in Fig. 45.

XVIII. Filters for Millimeter Waves and Higher Frequencies [134]–[143]

Filters at millimeter wavelengths have been built in TE_{01} circular waveguides [134]–[137]. The Fabry-Perot resonator [137]–[139] and other filter types and directional couplers [140]–[142] have been adapted from optics. There are many points of similarity between microwave and optical filters [141].

A stack of separated dielectric plates makes a good reflector when the thicknesses of the plates and the separations between them are equal to or close to one-quarter wavelength. Two such stacks, spaced an integral number of half-wavelengths apart, as indicated in Fig. 46, form a Fabry-Perot resonator.

When the diameter of this system does not equal many wavelengths, there is appreciable outward radiation, causing a drop in the unloaded Q. Such a drop can be remedied to a large extent by placing spherical mirrors at or near confocal spacing. If coupling losses are to be kept low, some sophistication is necessary in coupling to the confocal resonator. A system devised by the author and B. M. Schiffman is shown in Fig. 47. The thin dielectric sheets determine the maximum possible coupling; the coupling and bandwidth are then controlled by moving the mirrors C and D in unison.

There has recently been renewed interest in millimeter and submillimeter waves [137]. The main problem today is still a lack of reliable inexpensive power sources, especially above 150 Gc. New types of transmission line are also being developed. With sufficient progress in these developments, we may expect to see more activity in the area of submillimeter wave filters.

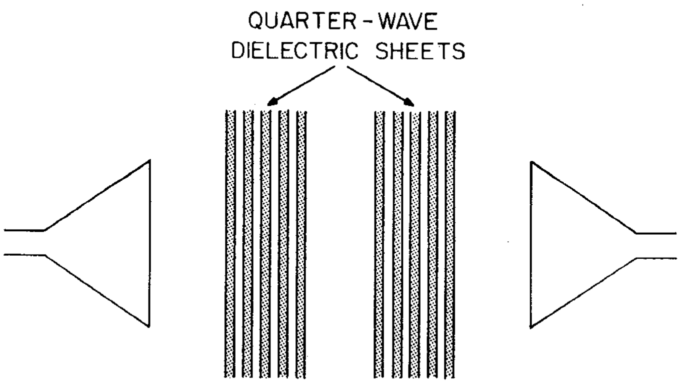


Fig. 46. Millimeter-wave Fabry-Perot interferometer using dielectric stacks.

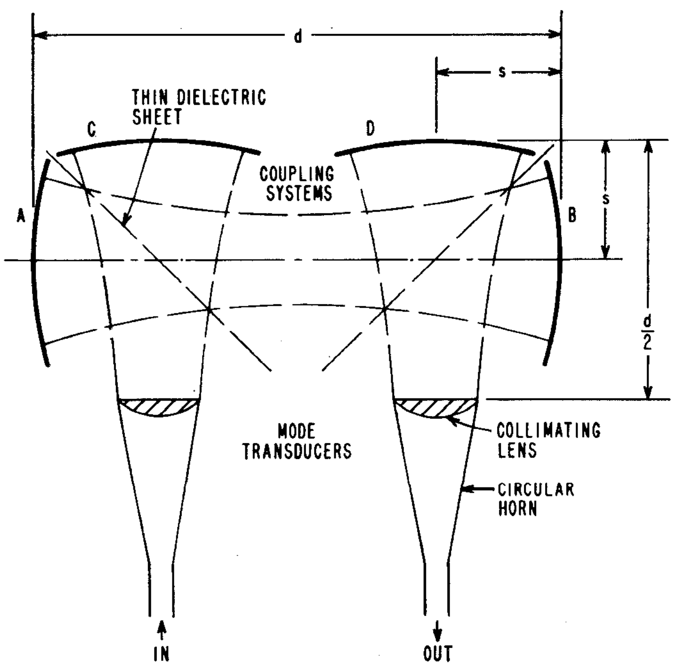


Fig. 47. A band-pass confocal resonator filter showing low-loss coupling mechanism.

XIX. Miscellaneous Filters [144]–[153]

A few filters have escaped classification. Torgow and Lubell [144] have described a combination of band-pass and band-stop filter to obtain steep skirt selectivity. They make the interesting observation that, with properly spaced filters, very sharp spurious resonances (the two stop bands almost canceling one another) are prevented by the damping due to the small amount of dissipation.

Log-periodic structures [146]–[148], described by DuHamel and others, offer the possibility of components with very wide bandwidths.

An interesting type of band-pass filter [13] is shown in Fig. 48 and in circle (W) of Fig. 7. Resonators are capacitively coupled in such a way to suppress the first spurious resonance so that the filter has a wide stop band.

A differential phase shifter is not a filter, but the Schiffman phase shifter [152] of Fig. 49 has been widely

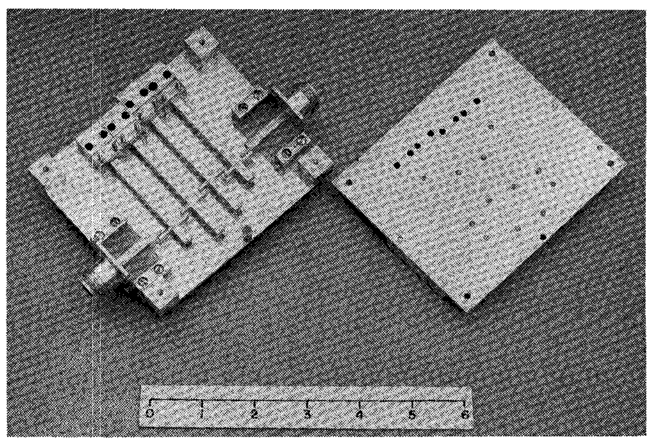


Fig. 48. A band-pass filter with wide stop band [13].

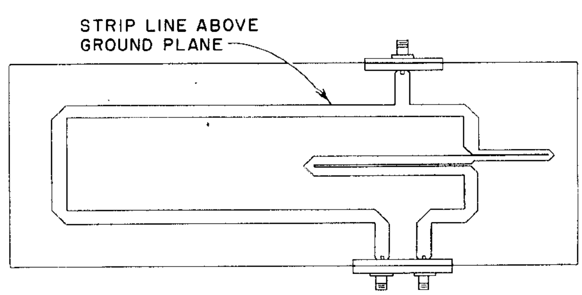


Fig. 49. A wideband 90-degree differential phase shifter [152].

used and depends on the theory of parallel-coupled lines, as do certain types of filter (Section IV).

We have not discussed experimental procedures in the alignment of filters. For this material we direct the reader's attention to References [13] and [153].

XX. Conclusion

We are at the end of our journey. We have attempted to conduct the reader past the principal types of filters of interest today. We have relied on photographs and diagrams, rather than on mathematics, to convey an impression of the needs felt and the ideas generated. The reader will find a fuller description of many of the filters in Reference [13], which reports developments up to early 1963, whereas the present paper covers the work undertaken since late 1962.

The presentation has been colored by the author's particular interests, and some omissions were inevitable. No attempt was made to scan every relevant journal.[1] We apologize in advance to any author whose work may not have been given proper credit, whether through ignorance or oversight.

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References

Lumped-Constant Filters and Prototypes

[1] E. A. Guillemin, *Synthesis of Passive Networks.* New York: Wiley, 1957.
[2] D. F. Tuttle, Jr., *Network Synthesis*, vol. 1. New York: Wiley, 1958.
[3] M. E. Van Valkenburg, *Introduction to Modern Network Synthesis.* New York: Wiley, 1960.
[4] L. Weinberg, *Network Analysis and Synthesis.* New York: McGraw-Hill, 1962.
[5] H. W. Bode, *Network Analysis and Feedback Amplifier Design.* Princeton, N. J.: Van Nostrand, 1945.
[6] R. Saal, *The Design of Filters Using the Catalogue of Normalized Low-Pass Filters.* Backang, West Germany: Telefunken, G.m.b.H., 1961.
See also R. Saal and E. Ulbrich, "On the design of filters by synthesis," *IRE Trans. on Circuit Theory*, vol. CT-5, pp. 284–327, December 1958.
[7] G. L. Matthaei, "Tables of Chebyshev impedance-transforming networks of low-pass filter form," *Proc. IEEE*, vol. 52, pp. 939–963, August 1964.

[1] This is especially true of many fine Japanese contributions. The author wishes there had been more time to investigate and reference them.

[8] G. Szentirmai, "Band-pass matching filter in the form of polynomial low-pass filter," *IEEE Trans. on Circuit Theory*, vol. CT-11, pp. 177–178, March 1964.
[9] E. G. Cristal, "Tables of maximally flat impedance transforming networks of low-pass filter form," this issue, page 693.
[10] R. Levy, "Explicit formulas for Chebyshev impedance-matching networks, filters and interstages," *Proc. IEE (London)*, vol. 111, pp. 1099–1105, June 1964.
[11] H. J. Hindin, "Bandwidth transform curves speed Chebyshev filter design," *Microwaves*, vol. 3, pp. 68–69, October 1964.
[12] A. G. J. Holt, "A comparison of five methods of low-pass passive filter design," *The Radio and Electronic Engineer*, vol. 27, pp. 167–180, March 1964.

Microwave Filters (General)

[13] G. L. Matthaei, Leo Young, and E. M. T. Jones, *Microwave Filters, Impedance Matching Networks, and Coupling Structures.* New York: McGraw-Hill, 1964.
[14] L. Young, "Progress in circuit theory—1960–1963: Microwave filters," *IEEE Trans. on Circuit Theory*, vol. CT-11, pp. 10–12, March 1964.
[15] E. N. Torgow, "Microwave filters," *Electro-Technology*, vol. 67, pp. 90–96, April 1961.
[16] R. E. Wells, "Microwave bandpass filter design," *Microwave J.*, vol. 5, pp. 92–98, November 1962; pp. 82–88, December 1962.
[17] R. M. Kurzrok, "Couplings in direct-coupled waveguide band-pass filters," *IEEE Trans. on Microwave Theory and Techniques (Correspondence)*, vol. MTT-10, pp. 389–390, September 1962.
[18] P. I. Richards, "Resistor-transmission-line circuits," *Proc. IRE*, vol. 36, pp. 217–220, February 1948.

Filters with Cascaded Lines or Cavities

[19] S. B. Cohn, "Direct-coupled-resonator filters," *Proc. IRE*, vol. 45, pp. 187–196, February 1957.
[19a] 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.
[20] L. Young, "Stepped impedance transformers and filter prototypes," *IRE Trans. on Microwave Theory and Techniques*, vol. MTT-10, pp. 339–359, September 1962.
[21] H. J. Carlin, "Cascaded transmission line synthesis," Polytechnic Institute of Brooklyn, Brooklyn, N. Y., Rept. PIBMRI 889-61, April 1961.
[22] R. Levy, "Tables of element values for the distributed low-pass prototype filter," this issue, page 514.
[23] L. Young, "Direct-coupled cavity filters for wide and narrow bandwidths," *IRE Trans. on Microwave Theory and Techniques*, vol. MTT-11, pp. 162–178, May 1963.
[24] K. Whiting, "The effect of increased design bandwidth upon direct-coupled-resonator filters," *IEEE Trans. on Microwave Theory and Techniques*, vol. MTT-11, pp. 557–560, November 1963.
[25] B. C. DeLoach, "Direct- and quarter-wave-coupled microwave band-pass filters with adjustable transmission characteristics and fixed center frequencies," *IEEE Trans. on Microwave Theory and Techniques*, vol. MTT-12, pp. 73–77, January 1964.

TEM-Mode Filters with Parallel-Line Coupling

[26] S. B. Cohn, "Parallel-coupled transmission-line-resonator filters," *IRE Trans. on Microwave Theory and Techniques*, vol. MTT-6, pp. 223–231, April 1958.
[27] H. Smith, "Computer-generated tables for filter design," *Electronic Design*, vol. 11, pp. 54–57, May 10, 1963.
[28] G. L. Matthaei, "Interdigital band-pass filters," *IRE Trans. on Microwave Theory and Techniques*, vol. MTT-10, pp. 479–491, November 1962.
[29] J. R. Pyle, "Design curves for interdigital band-pass filters," *IEEE Trans. on Microwave Theory and Techniques*, vol. MTT-12, pp. 559–567, September 1964.
[30] E. G. Cristal, "Coupled circular cylindrical rods between parallel ground planes," *IEEE Trans. on Microwave Theory and Techniques*, vol. MTT-12, pp. 428–439, July 1964.
[31] P. Vadopalas and E. G. Cristal, "Coupled rods between ground planes," *IEEE Trans. on Microwave Theory and Techniques (Correspondence)*, vol. MTT-13, pp. 254–255, March 1965.
[32] L. A. Robinson, "Wideband interdigital filters with capacitively loaded resonators," *1965 G-MTT Symposium Digest*, pp. 33–37.
[33] R. J. Wenzel, "Exact theory of interdigital band-pass filters and related coupled structures," this issue, page 559.
[34] G. L. Matthaei, "Comb-line band-pass filters of narrow or moderate bandwidth," *Microwave J.*, vol. 6, pp. 82–91, August 1963.

Band-Stop Filters

[35] B. M. Schiffman and G. L. Matthaei, "Exact design of band-stop microwave filters," *IEEE Trans. on Microwave Theory and Techniques*, vol. MTT-12, pp. 6–15, January 1964.
[36] B. M. Schiffman, "A harmonic rejection filter designed by an exact method," *IEEE Trans. on Microwave Theory and Techniques*, vol. MTT-12, pp. 58–60, January 1964.
[37] B. M. Schiffman, "A multiharmonic rejection filter designed by an exact method," *IEEE Trans. on Microwave Theory and Techniques*, vol. MTT-12, pp. 512–516, September 1964.
[38] B. M. Schiffman, "Capacitively-coupled stub filter," *IEEE Trans. on Microwave Theory and Techniques* (*Correspondence*), vol. MTT-13, pp. 253–254, March 1964.
[39] E. G. Cristal, "Addendum to an exact method for synthesis of microwave band-stop filters," *IEEE Trans. on Microwave Theory and Techniques*, vol. MTT-12, pp. 369–382, May 1964.
[40] L. Young, G. L. Matthaei, and E. M. T. Jones, "Microwave band-stop filters with narrow stop bands," *IRE Trans. on Microwave Theory and Techniques*, vol. MTT-10, pp. 416–427, November 1962.
[41] P. D. Lubell, "A simple relation between cavity Q and maximum rejection for narrow-band microwave band-stop filters," *IEEE Trans. on Microwave Theory and Techniques* (*Correspondence*), vol. MTT-12, p. 145, January 1964.
[42] R. D. Standley and A. C. Todd, "A note on strip-line band-stop filters with narrow stop bands," *IEEE Trans. on Microwave Theory and Techniques* (*Correspondence*), vol. MTT-11, pp. 548–549, November 1963.
[43] W. T. Flannery, A. Fox, L. N. Engel, and F. J. Morris, "Microwave rejection networks," *IEEE Trans. on Electromagnetic Compatibility*, vol. EMC-7, pp. 25–30, March 1965.
[44] B. C. DeLoach, "Radial-line coaxial filters in the microwave region," *IEEE Trans. on Microwave Theory and Techniques*, vol. MTT-11, pp. 50–55, January 1963.
[45] J. H. Vogelman, "Design of high-order-mode resonant filters," *Microwaves*, vol. 4, pp. 20–24, April 1965.

Filters with Stubs (General)

[46] N. Ozaki and J. Ishii, "Synthesis of a class of strip-line filters," *IRE Trans. on Circuit Theory*, vol. CT-5, pp. 104–109, June 1958.
[47] R. Levy, "A general equivalent circuit transformation for distributed networks," *IEEE Trans. on Circuit Theory* (*Correspondence*), vol. CT-12, pp. 457–458, September 1965.
[48] R. J. Wenzel, "Exact design of TEM microwave networks using quarter-wave lines," *IEEE Trans. on Microwave Theory and Techniques*, vol. MTT-12, pp. 94–111, January 1964.
[49] M. C. Horton and R. J. Wenzel, "General theory and design of optimum quarter-wave TEM filters," *IEEE Trans. on Microwave Theory and Techniques*, vol. MTT-13, pp. 316–327, May 1965.
[50] M. C. Horton and R. J. Wenzel, "Exact design of filters by network techniques," *Microwaves*, vol. 3, pp. 16–21, April 1964.
[51] H. J. Carlin and W. Kohler, "Direct synthesis of band-pass transmission line structures," *IEEE Trans. on Microwave Theory and Techniques*, vol. MTT-13, pp. 283–297, May 1965.
[52] H. J. Riblet, "The application of a new class of equal-ripple functions to some familiar transmission-line problems," *IEEE Trans. on Microwave Theory and Techniques*, vol. MTT-12, pp. 415–421, July 1964.
[53] W. W. Mumford, "An exact design technique for a type of maximally flat quarter-wave-coupled band-pass filter," *1963 PTGMTT Symposium Digest*, pp. 57–61.

Low-Pass and High-Pass Filters

[54] E. Sharp, "A high-power wide-band waffle-iron filter," *IEEE Trans. on Microwave Theory and Techniques*, vol. MTT-11, pp. 111–116, March 1963.
[55] L. Young and B. M. Schiffman, "New and improved types of waffle-iron filters," *Proc. IEE* (*London*), vol. 110, pp. 1191–1198, July 1963.
[56] L. Young, "Postscript to two papers on waffle-iron filters," *IEEE Trans. on Microwave Theory and Techniques*, vol. MTT-11, pp. 555–557, November 1963.
[57] L. Young and B. M. Schiffman, "A useful high-pass filter design," *Microwave J.*, vol. 6, pp. 78–80, February 1963.
[58] G. Oltman, "Sharp cutoff microwave filters," *IRE Trans. on Microwave Theory and Techniques*, vol. MTT-11, pp. 30–35, January 1963.
[59] C. C. H. Tang, "Nonuniform waveguide high-pass filters with extremely steep cutoff," *IEEE Trans. on Microwave Theory and Techniques*, vol. MTT-12, pp. 300–309, May 1964.
[60] H. J. Riblet, "A general design procedure for quarter-wavelength inhomogeneous impedance transformers having approximately equal-ripple performance," this issue, page 622.

Dissipation Loss, Group Delay, and Power-Handling Capacity

[61] S. B. Cohn, "Dissipation loss in multiple-coupled-resonator filters," *Proc. IRE*, vol. 47, pp. 1342–1348, August 1959.
[62] L. Young, "Prediction of absorption loss in multilayer interference filters," *J. Opt. Soc. Am.*, vol. 52, pp. 753–761, July 1962.
[63] J. J. Taub, "Design of minimum loss band-pass filters," *Microwave J.*, vol. 6, pp. 67–76, November 1963.
[64] J. J. Taub and H. J. Hindin, "Minimum insertion loss microwave filters," *Microwave J.*, vol. 7, pp. 41–45, August 1964.
[65] J. J. Taub and R. L. Sleven, "Design of band-stop filters in the presence of dissipation," this issue, page 589.
[66] L. Young, "Some considerations in the design of narrow-band waveguide filters," *IEEE Trans. on Microwave Theory and Techniques*, vol. MTT-11, pp. 522–527, November 1963.
[67] H. J. Riblet, "The coupling coefficients of an unsymmetrical high-Q lossy waveguide resonator," *IEEE Trans. on Microwave Theory and Techniques*, vol. MTT-11, pp. 78–83, January 1963.
[68] L. Young, "Group delay and dissipation loss in transmission-line filters," *IEEE Trans. on Microwave Theory and Techniques* (*Correspondence*), vol. MTT-11, pp. 215–217, May 1963.
[69] H. H. Schreiber, "Phase and time delay of Butterworth and Chebyshev filters," *Microwaves*, vol. 4, pp. 14–21, March 1965.

Delay Equalization

[70] C. H. Tang, "Delay equalization by tapered cutoff waveguides," *IEEE Trans. on Microwave Theory and Techniques*, vol. MTT-12, pp. 608–615, November 1964.
[71] E. N. Torgow, "Equalization of waveguide delay distortion," *1965 G-MTT Symposium Digest*, pp. 39–43.
[72] D. Merlo, "Development of group-delay equalizers for 4 Gc/s," *Proc. IEE* (*London*), vol. 112, pp. 289–295, February 1965.
[73] K. Woo, "An adjustable microwave delay equalizer," *IEEE Trans. on Microwave Theory and Techniques*, vol. MTT-13, pp. 224–232, March 1965.
[74] J. P. Bobis, "Symmetrical-antimetrical filters with maximally flat group delay," *Microwaves*, vol. 3, pp. 20–27, February 1964.
[75] W. J. D. Steenart, "The synthesis of coupled transmission line all-pass networks in cascades of 1 to n," *IEEE Trans. on Microwave Theory and Techniques*, vol. MTT-11, pp. 23–29, January 1963.

Diplexers and Multiplexers

[76] E. G. Cristal and G. L. Matthaei, "A technique for the design of multiplexers having contiguous channels," *IEEE Trans. on Microwave Theory and Techniques*, vol. MTT-12, pp. 83–93, January 1964.
[77] R. G. Veltrop and R. B. Wilds, "Modified tables for the design of optimum diplexers," *Microwave J.*, vol. 7, pp. 76–80, June 1964.
[78] R. J. Wenzel, "Application of exact synthesis methods of multichannel filter design," *IEEE Trans. on Microwave Theory and Techniques*, vol. MTT-13, pp. 5–15, January 1965.
[79] G. L. Matthaei and E. G. Cristal, "Multiplexer channel-separating units using interdigital and parallel-coupled filters," *IEEE Trans. on Microwave Theory and Techniques*, vol. MTT-13, pp. 328–334, May 1965.
[80] L. v.d. Kint and E. Schanda, "A microwave quadruplexer," *IEEE Trans. on Microwave Theory and Techniques* (*Correspondence*), vol. MTT-11, pp. 90–92, January 1963.
[81] G. L. Matthaei and E. G. Cristal, "Theory and design of diplexers and multiplexers" in *Advances in Microwaves*. L. Young, Ed., New York: Academic Press, to be published.

Directional Filters

[82] G. Craven, D. W. Stopp, and R. R. Thomas, "Resonant-slot hybrid junctions and channel-dropping filters," *Proc. IEE* (*London*), vol. 112, pp. 669–680, April 1965.
[82a] R. L. Williams, "A three-cavity circularly polarized waveguide directional filter yielding a maximally flat response," *IRE Trans. on Microwave Theory and Techniques*, vol. MTT-10, pp. 321–328, September 1962.
[83] R. D. Standley, "Frequency response of strip-line traveling wave directional filters," *IEEE Trans. on Microwave Theory and Techniques*, vol. MTT-11, pp. 264–265, July 1963.
[84] R. D. Standley and A. C. Todd, "Discontinuity effects in single traveling wave filters," *IEEE Trans. on Microwave Theory and Techniques* (*Correspondence*), vol. MTT-11, pp. 551–552, November 1963.

Tunable Filters

[85] H. L. Schumacher, "Direct coupled ganged tuned bandpass filters," *Microwave J.*, vol. 7, pp. 48–52, July 1964.
[86] R. Wilds, G. Wheeler, and E. Cota, "Compact tunable filters," *Microwave J.*, vol. 7, pp 60–65, May 1964.
[87] M. H. N. Potok, "Capacitive-iris-type mechanically tunable waveguide filters for the *X*-band," *Proc. IEE* (*London*), vol. 109, pp. 505–510, November 1962.
[88] G. L. Matthaei, "Magnetically tunable band-stop filters," *IEEE Trans. on Microwave Theory and Techniques*, vol. MTT-13, pp. 203–212, March 1965.
[89] G. H. Thiess, "Theory and design of tunable YIG filters," *Microwaves*, vol. 3, pp. 14–31, September 1964.
[90] F. Reggia, "Magnetically tunable microwave bandpass filter," *Microwave J.*, vol. 6, pp. 72–84, January 1963.
[91] R. C. Cumming and D. W. Howell, "YIG filters as envelope limiters," this issue, page 616.
[92] R. L. Comstock, "Synthesis of filter-limiters using ferrimagnetic resonators," *IEEE Trans. on Microwave Theory and Techniques*, vol. MTT-12, pp. 599–607, November 1964.
[92a] R. Blau, "YIG filters in the 50–500 Mc range," *Proc. IEEE*, vol. 52, pp. 1074–1075, September 1964.
[92b] P. S. Carter, "Side-wall, coupled, strip-transmission-line magnetically tunable filters employing terrimagnetic YIG resonators," *IEEE Trans. on Microwave Theory and Techniques*, vol. MTT-13, pp. 306–315, May 1965.
[93] A. P. Benguerel and N. S. Nahman, "A varactor tuned UHF coaxial filter," *IEEE Trans. on Microwave Theory and Techniques* (*Correspondence*), vol. MTT-12, pp. 468–469, July 1964.
[94] I. Kaufman and W. H. Steier, "A plasma-column band-pass microwave filter," *IEEE Trans. on Microwave Theory and Techniques*, vol. MTT-10, pp. 431–439, November 1962.

Dielectric-Resonator and Dielectric-Loaded Filters

[95] A. Okaya and L. F. Barash, "The dielectric microwave resonator," *Proc. IRE*, vol. 50, pp. 2081–2092, October 1962.
[96] S. B. Cohn, "Microwave filters containing high-*Q* dielectric resonators," *1965 G-MTT Symposium Digest*, pp. 49–53.
[97] H. J. Shaw, A. Karp, and D. K. Winslow, "Circuit properties of dielectric resonators," Stanford University, Stanford, Calif., Microwave Lab. Rept. (in preparation).
[98] H. Y. Lee, "Natural resonant frequencies of microwave dielectric resonators," *IEEE Trans. on Microwave Theory and Techniques* (*Correspondence*), vol. MTT-13, p. 256, March 1965.
[99] R. V. D'Aiello and A. J. Prager, "Dielectric resonators for microwave applications," *IEEE Trans. on Microwave Theory and Techniques*, vol. MTT-12, pp. 549–550, September 1964.
[99a] D. L. Rebsch, D. C. Webb, R. A. Moore, and J. D. Cowlishaw, "A mode chart for accurate design of cylindrical dielectric resonators," *IEEE Trans. on Microwave Theory and Techniques*, vol. MTT-13, pp. 468–469, July 1965.
[100] E. O. Ammann and R. J. Morris, "Tunable, dielectric-loaded microwave cavities capable of high *Q* and high filling factor," *IEEE Trans. on Microwave Theory and Techniques*, vol. MTT-11, pp. 528–542, November 1963.

Filter Techniques Applied to Semiconductor Devices

[101] C. L. Cuccia, "Broad-band multiplier chains with interdigital filters," *Microwaves*, vol. 3, pp. 22–25, June 1964.
[102] R. J. Wenzel, "Wideband varactor harmonic multipliers," *1965 G-MTT Symposium Digest*, pp. 61–65.
[103] F. S. Coale and P. M. LaTourrette, "Filter-diode integration," *1965 G-MTT Symposium Digest*, pp. 67–71.
[104] B. L. Humphreys, "Characteristics of broadband parametric amplifiers using filter networks," *Proc. IEE* (*London*), vol. 111, pp. 264–274, February 1964.
[105] W. J. Getsinger and G. L. Matthaei, "Some aspects of the design of wide-band up-converters and nondegenerate parametric amplifiers," *IEEE Trans. on Microwave Theory and Techniques*, vol. MTT-12, pp. 77–87, January 1964.
[106] W. J. Getsinger "Prototypes for use in broadbanding reflection amplifiers," *IEEE Trans. on Microwave Theory and Techniques*, vol. MTT-11, pp. 486–497, November 1963.
[106a] J H. Lepoff and G. J. Wheeler, "Octave bandwidth tunnel-diode amplifier," *IEEE Trans. on Microwave Theory and Techniques*, vol. MTT-12, pp. 21–26, January 1964.
[107] J. F. White, "High power, *p-i-n* diode controlled, microwave transmission phase shifters," *IEEE Trans. on Microwave Theory and Techniques*, vol. MTT-13, pp. 233–242, March 1965.
[108] H. J. Peppiatt, A. V. McDaniel, Jr., and J. B. Linker, Jr., "A 7-Gc/s narrow-band waveguide switch using *p-i-n* junction diodes," *IEEE Trans. on Microwave Theory and Techniques*, vol. MTT-13, pp. 44–47, January 1965.
[109] A. Uhlir, "Microwave application of integrated-circuit techniques, *Proc. IEEE*, vol. 52, pp. 1617–1623, December 1964.

Stepped-Impedance Filters as Directional Couplers

[110] R. Levy, "General synthesis of asymmetric multi-element coupled-transmission-line directional couplers," *IEEE Trans. on Microwave Theory and Techniques*, vol. MTT-11, pp. 226–237, July 1963.
[111] R. Levy, "Tables for asymmetric multi-element coupled-transmission-line directional couplers," *IEEE Trans. on Microwave Theory and Techniques*, vol. MTT-12, pp. 275–279, May 1964.
[112] R. J. Mohr and J. E. McFarland, "Exact analysis of asymmetric couplers," *Microwaves*, vol. 2, pp. 90–93, March 1963.
[113] L. Sweet, "A method of improving the response of waveguide directional couplers," *IEEE Trans. on Microwave Theory and Techniques* (*Correspondence*), vol. MTT-11, p. 554, November 1963.
[114] R. Levy, "Transmission-line directional couplers for very broadband operation," *Proc. IEE* (*London*), vol. 112, pp. 469–476, April 1965.
[115] L. Young, "The analytical equivalence of TEM-mode directional couplers and transmission-line stepped-impedance filters," *Proc. IEE* (*London*), vol. 110, pp. 275–281, February 1963.
[116] H. Seidel and J. Rosen, "Multiplicity in cascade transmission-line synthesis—Parts I and II," *IEEE Trans. on Microwave Theory and Techniques*, vol. MTT-13, pp. 257–283, May 1965; pp. 398–407, July 1965.
[117] E. G. Cristal and L. Young, "Tables of optimum symmetrical TEM-mode coupled-transmission-line directional couplers," this issue, page 544.
[118] P. P. Toulios and A. C. Todd, "Synthesis of symmetric TEM-mode directional couplers," *IEEE Trans. on Microwave Theory and Techniques*, this issue, page 586.
[119] S. B. Cohn, "The re-entrant cross section and wide-band 3-db hybrid couplers," *IEEE Trans. on Microwave Theory and Techniques*, vol. MTT-11, pp. 254–258, July 1963.
[120] J. P. Shelton, J. Wolfe, and R. C. Van Wagoner, "Tandem couplers and phase shifters for multi-octave bandwidth," *Microwaves*, vol. 4, pp. 14–19, April 1965. (Further details will be found in the *Proceedings of the Fourteenth Annual Symposium*, USAF Antenna Research and Development Program, sponsored by the Air Force Avionics Laboratory, Wright-Patterson AFB, Ohio; Monticello, Ill., October, 1964.)

Couplers from Filters and Filters from Couplers

[121] L. Young, "Synchronous branch guide directional couplers for low and high power applications," *IRE Trans. on Microwave Theory and Techniques*, vol. MTT-10, pp. 459–475, November 1962.
[122] H. Smith, "Tables for the design of aperture type waveguide couplers," *Microwave J.*, vol. 6, pp. 91–94, June 1963.
[123] L. R. Whicker and A. K. Kamal, "Designing coupled-wave nonreflective filters," *Microwaves*, vol. 4, pp. 34–40, January 1965.
[124] J. S. Cook, A. G. Fox and W. H. Louisell, "Broadband directional couplers employing non-constant propagation in coupling coefficients," Bell Monograph 2460, 1955. Also *Bell Sys. Tech. J.*, vol. 34, pp. 807–870, July 1955.
[125] R. Levy, "Directional couplers," in *Advances in Microwaves*. L. Young, Ed. New York: Academic Press, to be published.

Filters with Open Walls

[126] E. G. Cristal, "A $1\frac{5}{8}$ inch coaxial leaky-wave filter for the suppression of spurious energy," *Microwave J.*, vol. 6, pp. 72–76, September 1963.
[127] E. G. Cristal, "Analytical solution to a waveguide leaky-wave structure," *IEEE Trans. on Microwave Theory and Techniques*, vol. MTT-11, pp. 182–190, May 1963.
[128] E. Wantuch and R. Maines, "A novel high-power harmonic suppressor," *IEEE Trans. on Microwave Theory and Techniques*, vol. MTT-10, pp. 428–431, November 1962.
[129] G. L. Matthaei and D. B. Weller, "Circular TE_{011}-mode, trapped-mode bandpass filters," this issue, page 581.
[130] B. M. Schiffman, L. Young, and G. Matthaei, "A rectangular waveguide filter using trapped-mode resonators," this issue, page 575.
[131] E. G. Cristal, "A method for the design of non-reflecting high-power microwave band-pass filters," *Microwave J.*, vol. 8, to be published.
[132] C. K. Birdsall and R. M. White, "Experiments with the forbidden regions of open periodic structures: Application to absorptive filters," *IEEE Trans. on Microwave Theory and Techniques*, vol. MTT-12, pp. 197–202, March 1964.
[133] B. M. Schiffman, L. Young, and G. L. Matthaei, "A new type of low-pass filter that attenuates by dissipation," this issue, page 699.

Filters for Millimeter Waves and Higher Frequencies

[134] E. A. Marcatili, "A circular-electric hybrid junction and some channel-dropping filters," *Bell Sys. Tech. J.*, vol. 40, pp. 185–196, January 1961.
[135] E. A. Marcatili and D. A. Bisbee, "Band-splitting filter," *Bell Sys. Tech. J.*, vol. 40, pp. 197–213, January 1961.
[136] E. A. Marcatili, "Mode-conversion filters," *Bell Sys. Tech. J.*, vol. 40, pp. 149–184, January 1961.
[137] The Millimeter and Submillimeter Conference Papers, *IEEE Trans. on Microwave Theory and Techniques*, vol. MTT-11, September 1963.
[138] R. W. Zimmerer, M. V. Anderson, G. L. Strine, and Y. Beers, "Millimeter wavelength resonant structures," *IEEE Trans. on Microwave Theory and Techniques*, vol. MTT-11, pp. 142–149, March 1963.
[139] P. D. Clark, "A self-consistent field analysis of spherical mirror Fabry-Perot resonators," *Proc. IEEE*, vol. 53, pp. 36–41, January 1965.
[140] J. J. Taub, H. J. Hindin, and G. P. Kurpis, "Quasi-optical waveguide filters," *IEEE Trans. on Microwave Theory and Techniques* (*Correspondence*), vol. MTT-12, pp. 618–619, November 1964.
[141] L. Young and P. W. Baumeister, "Microwave and optical interference filters: Some similarities and differences," *NEREM Record*, vol. 5, pp. 8–9, November 1963.
[142] L. Young and E. G. Cristal, "Stacked dielectric low-pass and high-pass filters," Stanford Research Institute, Menlo Park, Calif., Sec. IX, Final Rept., SRI Project 4657, Contract AF 30(602)-3174, September 1964.
[143] W. L. Wolfe and S. S. Ballard, "Optical materials, films, and filters for infrared instrumentation," *Proc. IRE*, vol. 47, pp. 1540–1546, September 1959.

Miscellaneous

[144] E. N. Torgow and P. D. Lubell, "Band-pass filters with steep skirt selectivity," *IEEE Trans. on Microwave Theory and Techniques* (*Correspondence*), vol. MTT-13, pp. 124–126, January 1965.
[145] J. F. Lally and R. R. Ciehoski, "A wide stop band UHF coaxial band-pass filter," *IEEE Trans. on Microwave Theory and Techniques* (*Correspondence*), vol. MTT-11, p. 452, September 1963.
[146] R. H. Duhamel and M. E. Armstrong, "Characteristics of log-periodic transmission line circuits," *1964 G-MTT Symposium Digest*, pp. 9–20.
[147] J. W. Duncan, "Characteristic impedances of multiconductor strip transmission lines," *IEEE Trans. on Microwave Theory and Techniques*, vol. MTT-13, pp. 107–118, January 1965.
[148] R. M. Bevensee, "Nonuniform TEM transmission line. Part 1: Lossless and log-periodic properties," *Proc. IEE* (*London*), vol. 112, pp. 644–654, April 1965.
[149] M. McDermott and R. Levy, "Very broadband coaxial dc returns derived by microwave filter synthesis," *Microwave J.*, vol. 8, pp. 33–36, February 1965.
[150] L. Young, "Practical design of a wide-band quarter-wave transformer in waveguide," *Microwave J.*, vol. 6, pp. 76–79, October 1963
[151] L. Young, "Waveguide 0-db and 3-db directional couplers as harmonic pads," *Microwave J.*, vol. 7, pp. 79–87, March 1964.
[152] B. M. Schiffman, "A new class of broad-band microwave 90-degree phase shifters," *IRE Trans. on Microwave Theory and Techniques*, vol. MTT-6, pp. 232–237, April 1958.
[153] E. L. Ginzton, *Microwave Measurements*. New York: McGraw-Hill, 1957, pp. 417–424.

Band-Stop Filters for High-Power Applications

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***Abstract*—There are several advantages to the use of band-stop filters, rather than band-pass filters, in many systems. This is shown to be particularly true when signals at high-power levels must be transmitted or rejected.**

A formula has been derived which expresses the external Q of each resonator in a band-stop filter in terms of the element values of the normalized low-pass prototype and the parameters of the frequency transformation. The peak power capacity of iris-coupled waveguide cavity filters and TEM filters using capacitively coupled inductive stubs is then determined in terms of the external Q of the first resonator and the dimensions of the resonator. Experimental results given for a waveguide band-stop filter show good agreement with theory.

I. Introduction

In THE recent literature a number of articles have appeared expounding the virtues of band-stop filters in lieu of band-pass filters for many applications [1], [2]. In cases where a high rejection loss is required over a relatively narrow frequency band, and where low insertion loss is needed at a frequency close to this rejection band, the band-stop filter is the more efficient device. The band-stop filter can also be more easily aligned to exhibit its prescribed response. Each resonator can be independently adjusted so that the coupling from the main transmission line to that resonator yields the specified external Q. This is accomplished by detuning all other resonators. When all of the couplings are properly set, the band-stop filter is then aligned by adjusting the individual cavity resonators in turn until peak rejection is obtained. In practice, very little additional trimming is required beyond this point. In Section II of this paper, a simple expression is derived which enables the design engineer to determine the external Q of each resonator directly in terms of the required performance and the element values of a normalized low-pass prototype filter [3].

The band-stop filter offers advantages when considered as part of a diplexer or multiplexer. A combination of band-pass and band-stop filters can be designed to approximate a true complementary pair, presenting a matched input over a very wide band of frequencies [4]. Band-stop filters can also be used in cascade connection with other filters to provide more complex rejection characteristics [5]. This is a particular advan-

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