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A Rectangular-Waveguide Filter Using Trapped-Mode Resonators

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Abstract—A two-resonator, narrow-band waveguide filter with a very wide stop band is described. Each resonator cavity has one side wall which is entirely open except for a bifurcating *E*-plane septum. Energy in most modes tends to radiate freely out of the open end of each resonator to absorbing material; however, energy in the fundamental TE_{101}-mode is trapped in the resonator structures to give high-Q resonances such as are typical of conventional solid-wall resonators. Thus, a primary pass band is obtained similar to that of filters using conventional cavity resonators, but the many higher-order pass bands usually found in cavity-resonator filters are largely eliminated because the higher-order-mode cavity resonances are damped out. This type of filter attenuates unwanted signals mainly by reflection. For applications where a low-input VSWR is desired in the pass band, a bifurcated section of guide backed by absorbing material is also used in the input waveguide so as to tend to absorb the input energy at frequencies above that of the pass band.

GENERAL

A MAJOR DISADVANTAGE of narrow-band cavity-resonator filters is that they have many unwanted (or "spurious") pass bands. These spurious responses occur for higher-order longitudinal resonances of the dominant mode, and for undesired higher-order modes of propagation that are often strongly excited in narrow-band filters. In particular, for high-power systems where insertion loss must be minimal and where arcing in waveguide is always a danger, the problem is compounded because design techniques that improve power handling and reduce pass-band insertion loss tend to increase the number of spurious responses. The reason for this is that high-power handling capability and high unloaded Q (for low dissipation loss) are obtained by using cavities of large volume, which can then support many spurious resonances unless selective damping is applied. Our purpose here is to describe a new type of filter that uses resonators that damp out undesirable spurious resonances, with little or no effect on the fundamental resonance. A cross section of this new rectangular-waveguide filter is shown in Fig. 1. Filters similar in principle but which utilize the circular TE_{01}-mode are discussed elsewhere [1].

Attenuation in the stop band is due largely to reflection at the coupling apertures, and partly to selective absorption created by the loss mechanism, which is provided by absorbing material behind reduced-width waveguides opening into a wall of each cavity.[1] There

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[1] Thorn and Straiton discussed somewhat similar resonators which were open-ended for the purpose of passing gas through the resonators. See: D. C. Thorn and A. W. Straiton, "Design of open-ended microwave resonant cavities," *IRE Trans. on Microwave Theory and Techniques*, vol. 7, pp. 389–390, July 1959.

are three coupling apertures: from the input waveguide to Resonator No. 1; from Resonator No. 1 to Resonator No. 2; and from Resonator No. 2 to the output waveguide. The condition for a pass band to occur is that the reflections from these three couplings cancel one another. In particular, they are designed to cancel in the fundamental pass band.[2] Partial cancellation would be possible at certain higher frequencies, and would cause spurious pass bands, were it not for the open walls created by the septums (Fig. 1), which at frequencies somewhat above the pass band begin to introduce absorptive attenuation. This is the loss mechanism just referred to, which prevents the cancellation of reflections from the coupling apertures at higher frequencies and, thus, prevents spurious modes from arising.[3] To reduce the power reflected back to the source, the input waveguide is extended, and divided into two half-width cutoff waveguides as shown in Fig. 1. (Sidewall coupling is used to couple power to Resonator 1.) The half-width waveguides in line with the input absorb power above their cutoff frequency (which is above the pass-band of the filter). As frequency increases, the "beam effect" of the incident microwave power becomes more pronounced and reflection at the input decreases with increasing frequency.

Description of a Trial Filter

The trial filter consists of two trapped-mode waveguide cavities, resonant near 2.9 Gc/s. The cavities are shunt-inductively coupled to each other and to the terminating waveguides. The filter structure is symmetrical, and the irises were experimentally adjusted to yield a pass band with about 0.6 percent bandwidth. Minimum insertion loss was a design goal. One wall of each resonator cavity and the short-circuit end walls of the input and output waveguides (Fig. 1) have been replaced by short-circuiting H-plane septums that divide the waveguide into two narrower (approximately one-half standard-width) waveguides. These are below-cutoff waveguides for the pass-band frequency (2.9 Gc/s). Above the cutoff frequency of the half-width waveguides (nominally 4 Gc/s), the cavities are either nonresonant or have very low Q because of the loading by the half standard-width waveguides (which are filled with power-absorbing material). The absorbing loads are made of oblong pieces of commercially available foam-type absorbing material with graded absorptivity; this material has a low reflection coefficient for L band and higher frequencies. This material fills the cutoff waveguide cross section (in the region where the fields at the signal frequency are negligible) and, therefore, is not mode-selective. The two external coupling apertures in the side wall of the waveguide are rectangular holes 0.964 inch wide by 1.340 inches high (full waveguide height), and the internal coupling aperture is a similar hole between two groups of posts (the clear distance of 0.491 inch between the two center posts is the effective coupling aperture). The diameters of the posts are $\frac{1}{4}$ inch nominally. The inner septums, acting as cavity walls, are 1/16-inch brass plates set in grooves, while those in the terminating waveguides are 3/16 inch thick with threaded holes on the edges. The resonator cavities are slightly higher than standard S-band waveguide. Additional details are seen in the photograph of the filter with a cover plate removed, as shown in Fig. 2.

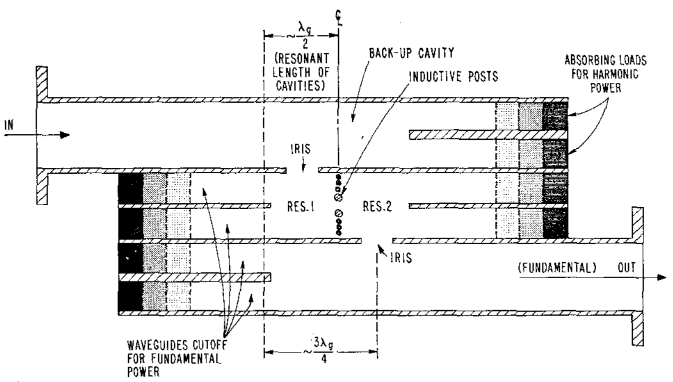

Fig. 1. Cross section of experimental trapped-mode resonator filter.

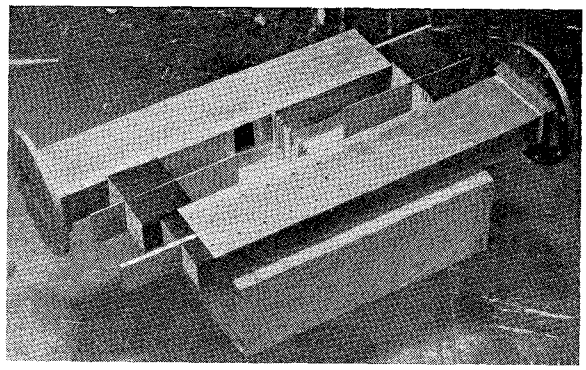

Fig. 2. Trapped mode resonator filter.

Measured Performance of the Filter

Figure 3 shows the attenuation from 2.4 to 15.5 Gc/s for the TE_{10} mode. Except for the portion of the curve below 4 Gc/s, the measurements were taken with long, smooth waveguide tapers at the filter input and output, to transform from standard waveguide for the higher stop-band frequencies to S-band waveguide (WR-284). The S-band-size end of the tapers contained bulk padding material to dampen resonances that would other-

[2] From the resonator point of view, this implies that Resonators 1 and 2 are both resonant.

[3] From the resonator point of view, this means that higher-order resonances are heavily damped by the open side walls and absorptive material.

wise be caused by the tapers. (The cause of these resonances is the excitation of higher-order modes, such as the TE_{20} mode, at the filter input iris; these modes are then reflected and may resonate between the filter input and the narrow end of the taper.) Since the bulk padding dampened any such resonances, the measured response is essentially that of the filter alone. The attenuation measurements were made by a continuous recording method and the curve in Fig. 3 is an envelope of minimum attenuation points, omitting the many high peaks of attenuation that were actually recorded. The attenuation curve shows no spurious pass bands.

In those portions of the stop band that are below 4 Gc/s, the filter attenuates by reflection only. The pass-band response, illustrated in Fig. 4, shows point-by-point attenuation measurements (circles) and a superimposed theoretical maximally flat curve [2] of the same 3-dB measured bandwidth (17.5 Mc/s) and band-center dissipation loss (0.5 dB). The reason for choosing the maximally flat curve as a basis for comparison with the measured points is that the filter was finally adjusted experimentally to have the widest pass band without a ripple. (The maximally flat two-resonator filter is an equal-element filter and, therefore, has close to the minimum dissipation loss [3].) The attenuation measurements fit the theoretical curve well. Likewise, the VSWR measurements in the pass band (shown by the circles in Fig. 5) fit the computed VSWR curve (the solid line in Fig. 5).[4]

The mechanical construction of the filter (Figs. 1 and 2) leaves something to be desired. It is felt that the dissipation losses could be reduced by a more "permanent" construction than is possible with an experimental model requiring experimental adjustment. Thus, it should be possible to raise the unloaded cavity Q to approach the theoretical unloaded Q of a copper S-band waveguide cavity ($Q_u = 7500$). The actual Q_u of the filter cavities were computed from an approximate formula [3],

$$L_0 = 4.343 \frac{\omega_1'}{w} \sum_{i=1}^{n} \frac{g_i}{Q_{ui}} \text{ dB} \qquad (1)$$

where

L_0 = Center frequency attenuation
ω_1' = Cutoff frequency of the low-pass prototype
w = Fractional bandwidth of the band-pass filter
g_i = Prototype element values (here $i = 1, 2$)
Q_{ui} = Unloaded Q of ith resonator.

Equal Q_u's are assumed for each resonator and the g_i values are assumed to be those of the maximally flat prototype, $g_1 = g_2 = 1.414$ with $\omega_1' = 1$. Fairly consistent results were obtained with this Q_u calculation when comparing measured and computed attenuation during the course of adjusting the filter. Some of the results of these adjustments may be seen in Fig. 6, which shows midband dissipation loss plotted against inverse fractional bandwidth $(1/w)$. Equation (1) is linear in $(1/w)$, hence the straight line through the origin yields a mean value of the resonator unloaded Q, in this case 3700, by (1). However, the last point representing the final adjustment of the filter indicates a Q_u of 4100. In each case for points 1 through 4 (in Fig. 6) the filter was adjusted for near minimum loss, hence the quoted maximally flat response g_i values of 1.414 were used in all calculations of Q_u.

The narrow waveguides that absorb power in the stop band are approximately square in cross section, and they should therefore absorb power in the stop band about equally well for modes of propagation that are cross polarized but otherwise similar to each other. In Fig. 7 is shown the attenuation of the filter for such a cross-polarized mode, the TE_{01} mode. The attenuation for this mode is weak at the low end of the stop band, unlike the (predominantly reactive) attenuation for the TE_{10} mode, shown in Fig. 3, which cuts off sharply. This difference could, in part, be attributed to dissimilar coupling coefficients of the irises for the two modes, which are strong series couplings for TE_{01} mode and are weak shunt couplings for the TE_{10} mode. Also, the use of metal-plate irises between the resonators, instead of posts, would have been helpful in increasing the attenuation of the TE_{01} mode.

The attenuation characteristics of the narrow-band mode-trap filter in the stop band, as shown in Figs. 3 and 7, demonstrate the inherent capability of the filter under conditions of reasonably good terminations at each end. Such conditions may not actually occur in practice. That is, the transmitting tube source impedance and the load impedance of an actual antenna may each produce a much more severe mismatch than does the impedance of the bulk padding material that was placed in the wide ends of the waveguide for test purposes. To test the filter in a perhaps more realistic manner, the bulk pads in the wide ends of the tapered waveguides were removed and a 0-dB coupler pad was placed between the filter input and tapered waveguide.[5] The attenuation measurements with the 0-dB coupler pad are shown in Fig. 8. The filter is seen to have almost

[4] The solid line in Fig. 5 was also computed for a maximally flat filter with 0.5 dB midband dissipation loss (the same model used for calculating the solid curve in Fig. 4).

[5] The 0-dB coupler consisted of two waveguide forward-coupling, side-wall 3-dB couplers connected in cascade so that the two output arms of the first 3-dB coupler fed directly into two adjacent (input) arms of the second 3-dB coupler. The couplers were designed to operate at S band, and in this band there was almost complete power transfer from the input port of the first coupler to the diagonally opposite output port of the second coupler (the port at which the filter was connected). The remaining two ports were terminated in matched loads. At higher frequencies the couplers tended to dump the input power into the loads, instead of sending the power to the filter (and in the same way, power reflected from the filter was largely sent to the loads). In this way the desired padding effect was achieved.

as good attenuation characteristics in this test condition as when tested with the bulk padding at each end (Fig. 3). Also, it is definitely superior to the case of no padding, shown in Fig. 9. The spurious responses in Fig. 9 are due to higher-mode resonances in the tapered waveguides that are excited at the filter input. Tapered waveguides, which are used here to test the filter over a very broad band, would not, of course, be part of a transmitter system. However, the comparative tests (without padding, and with bulk padding materials in one case and a 0-dB coupler pad in another case) have significance in the design of transmission systems because any source (transmitter tube) and any load (antenna) might have impedance properties that for certain mode and frequency combinations could cause waveguide system resonances in the same manner as the narrow ends of the tapered waveguides. If there were no loss elements in the filter, as would be the case in a conventional filter, then the degradation of the stop-band performance would undoubtedly be more severe than recorded in Fig. 9.

The reflection coefficient of the TE_{10} mode was measured in the stop band, for the case of no padding in the tapered input waveguide (see Fig. 10) and for the case of a 0-dB coupler pad between tapered input waveguide and filter (see Fig. 11). The 0-dB coupler pad is seen to reduce reflections in the 6 to 8 Gc/s range. The reflection coefficient for the TE_{01} mode was measured over a portion of the stop band and the results are shown in Fig. 12. No 0-dB coupler pad was used here. The filter is apparently much better matched in its stop band for the TE_{01} mode than for the TE_{10} mode. A probable reason for this characteristic is that the septum in the input guide is at right angles to the E field for the TE_{01} mode, hence, power absorption tends to be relatively efficient.

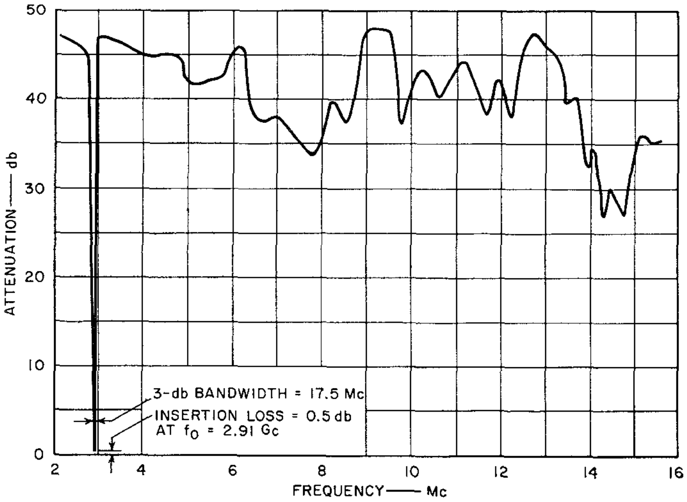

Fig. 3. Attenuation vs. frequency of filter of Fig. 2 for the TE_{10} mode with bulk pads in the input and output waveguides.

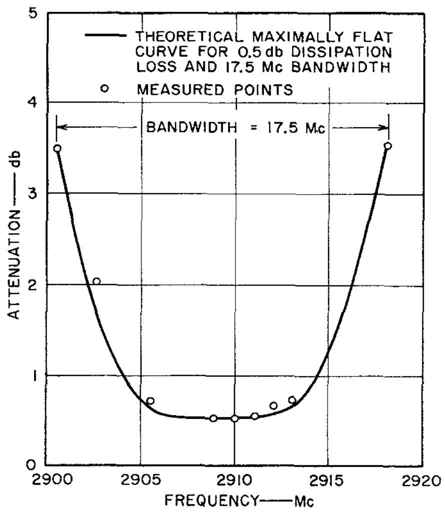

Fig. 4. Attenuation vs. frequency of filter of Fig. 2 in the pass band for the TE_{10} mode.

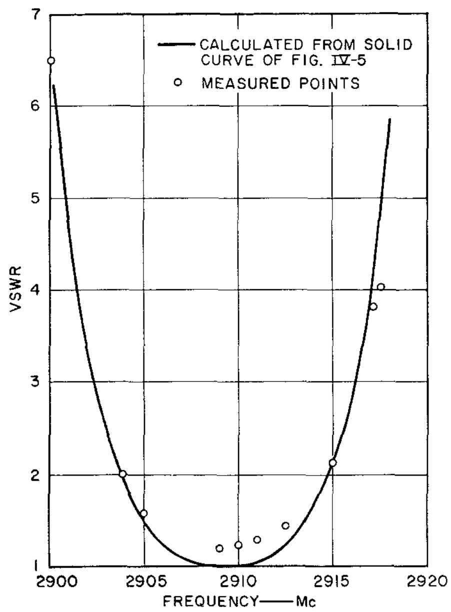

Fig. 5. VSWR of the filter of Fig. 2 in the pass band for the TE_{10} mode

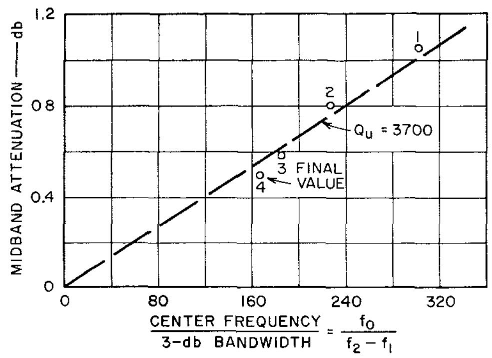

Fig. 6. Midband attenuation as a function of bandwidth of filter on Fig. 2 for the TE_{10} mode.

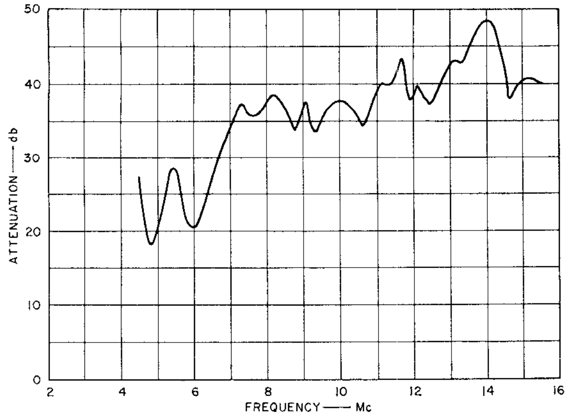

Fig. 7. Attenuation of filter of Fig. 2, for the TE_{10} mode in the stop band, with bulk pads in the tapered input and output waveguides.

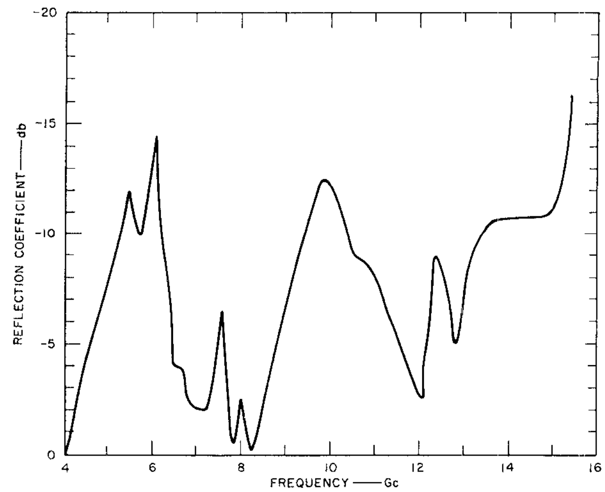

Fig. 10. Reflection coefficient of filter of Fig. 2, for the TE_{10} mode without padding between filter and tapered waveguides.

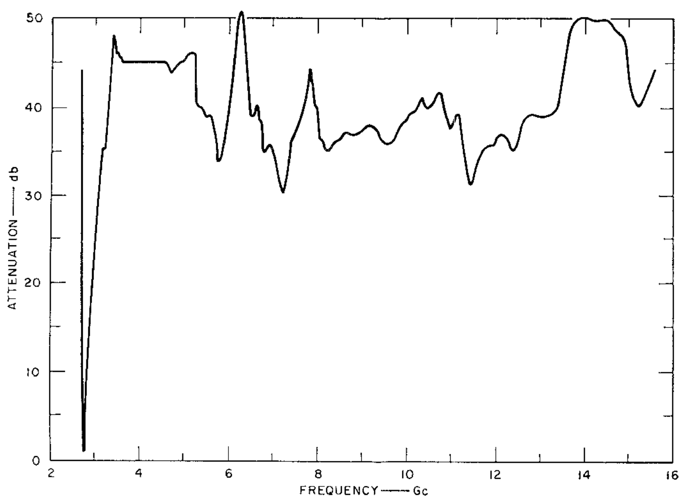

Fig. 8. Attenuation of filter of Fig. 2, for the TE_{01} mode, with 0-db coupler pad between filter and tapered input waveguide.

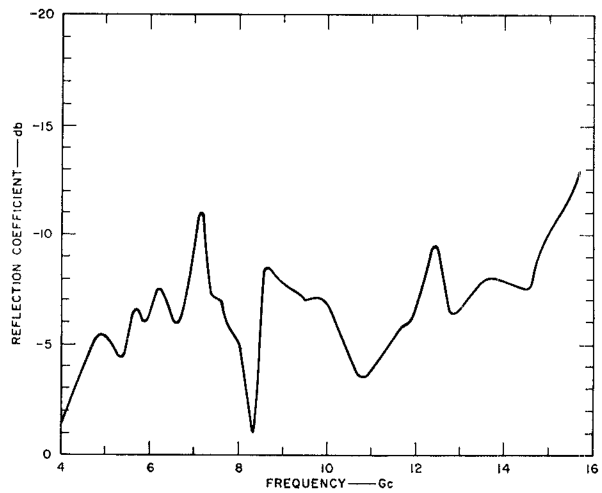

Fig. 11. Reflection coefficient of filter of Fig. 2, for the TE_{10} mode, with 0-db coupler pad between filter and tapered input waveguide.

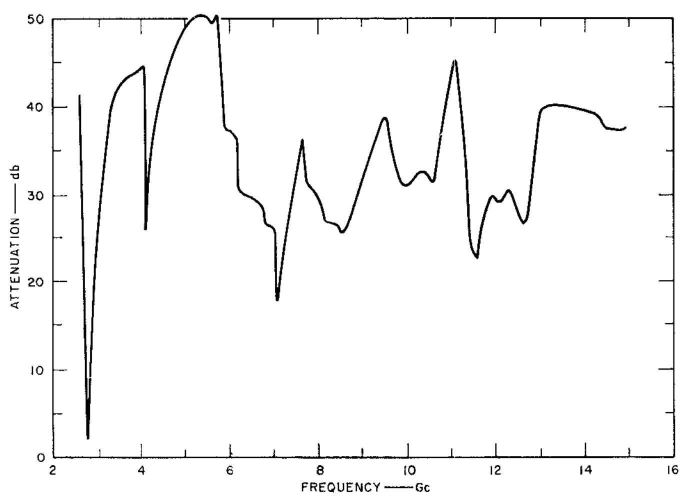

Fig. 9. Attenuation of filter of Fig. 2, for the TE_{10} mode, without padding between filter and tapered waveguides.

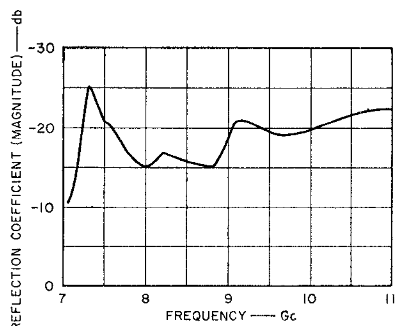

Fig. 12. Reflection coefficient of filter of Fig. 3, for the TE_{01} mode over a portion of the stop band, without padding between filter and tapered input waveguide.

Pulse Power Capacity of Filter

The midband pulse-power capacity of a direct-coupled resonator filter with inductive iris coupling, can be estimated from a formula given by Cohn [4]. This formula is based on the electric-field strength in the center of a waveguide resonator (Cohn considers resonators that are any number of half-wavelengths long, and of arbitrary height. Our concern here, however, is for the simple case of a half-wavelength waveguide resonator). The field in the resonator, rather than the field at the iris, limits power, as is clearly proved for a single inductive iris in waveguide by Hart, Stevenson and Tannenbaum [5]. Their result can be directly applied to the case of a single resonator with equal irises for which the standing wave in the resonator is analogous to the standing wave in a waveguide with one iris. Still further, it may be expected that their result is still valid for the two-coupled-resonators case, since the field in the center iris of a two-cavity filter differs from the fields in the irises of a single-cavity filter only in that a standing wave exists on both sides of such a center iris rather than on one side only. Therefore, the E field in the center iris is probably only moderately greater than that of a single-resonator-filter iris, if it is greater at all, and the limiting factor is then still the resonator peak field. On that basis, the relative power capacity R of the ith cavity of an n-cavity filter compared with that of a plain rectangular waveguide is [4]

$$R = \frac{\pi w}{2 g_i \omega_1'} \left(\frac{\lambda_{g0}}{\lambda_0} \right)^2 \qquad (2)$$

where

λ_{g0} = Guide wavelength at center frequency
λ_0 = Free-space wavelength at center frequency.

The fractional bandwidth of the filter is $w = 17.5/2910 = 0.006$, the element values are $g_1 = g_2 = 1.41$, and $\omega_1' = 1$. Now using the equivalence $(\lambda_0/\lambda_{g0})^2 = 1 - (f_c/f_0)^2$, we obtain $R = 1.4$ per cent. This low value of relative pulse power capacity is the price paid for the narrow pass band, and can be increased significantly only by increasing the filter bandwidth. A moderate increase can be obtained by increasing the resonator cavity height. The pulse power capacity of S-band waveguide at 2.9 Gc/s is about 2.5 MW and that of the filter is computed to be 35 kW. (The pulse power could of course be increased substantially by pressurization, evacuation, changing to special gases, or other conventional means.)

Conclusions

The rectangular trapped-mode resonators used in the trial two-resonator filter were found to give the desired broad stop bands with reasonably high-Q performance in the pass band.

It appears probable that by use of such concepts, a band-pass filter having a narrow, high-Q pass band at a desired frequency can be designed with high attenuation at all other frequencies. Using more than two resonators, the off-pass-band attenuation will be even higher, and the possibility of some appreciable spurious response at some high frequency will be even more remote. Filters with wide stops bands of this sort should be very valuable for dealing with radio-frequency interference problems.

The power-handling ability of this type of filter is nominally the same as that of corresponding filters using conventional cavity resonators. The same measures used to increase the power handling ability of filters with conventional resonators also apply here. These measures include using as large a waveguide as is feasible, rounding off of all sharp edges of apertures, etc., pressurizing the structure, or filling the structure with a gas such as sulfur hexafluoride.

Acknowledgment

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