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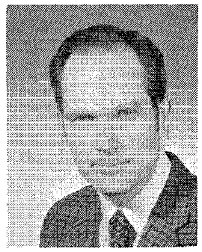

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Microwave Filter Loss Mechanisms and Effects

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***Abstract*—The losses in coupled cavity filters due to coupling apertures, tuning screws, and surface roughness have been determined experimentally. The results show, for example, that the shapes of the coupling apertures have a significant effect on filter losses. They may be used to estimate how the effective unloaded Q of a filter, and thus its insertion loss, varies as a function of bandwidth, configuration (e.g., single- or dual-mode), and response type (e.g., Chebyshev or elliptic). Also, they may be used to predict other effects such as response skewing and spatial distribution of dissipated power.**

I. Aperture Losses

FIG. 1 SHOWS one of the solid copper test structures used for the investigation of aperture losses [1]. The aperture being tested is shown in the center; machined on each side is a 0.861-in diameter cylindrical waveguide section, which is one-half wavelength for the TE_{11} mode. The small excitation aperture shown at the right has a half-wavelength section on the near side and WR75 waveguide flange on the back side. A shorting plate is shown at the left. Thus, when the parts are stacked, a TE_{111}-mode cavity is formed between the test and excitation apertures, and a half-length, nonresonant cavity between the test aperture and the short. The irises are 0.020-in thick. The test procedure consisted of measuring the unloaded Q, Q_u, and the TE_{111}-mode resonant frequency of a cavity without a test aperture and then repeating these measurements on the same cavity for a series of progressively larger apertures. The accuracy required for this study was achieved by using an automatic network analyzer with direct computer reduction of the data to resonant frequency and Q values.

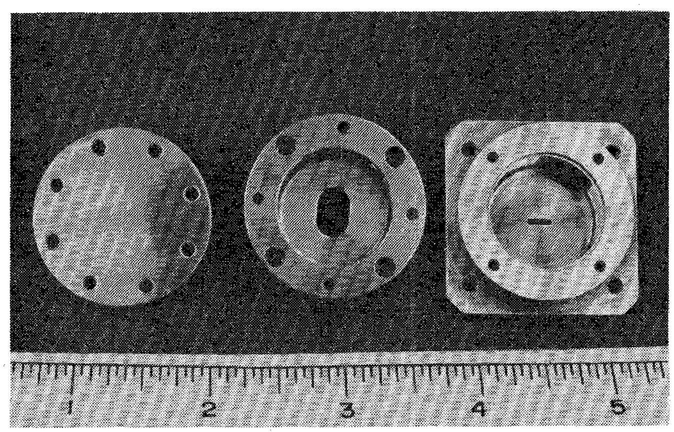

Fig. 1. Copper test structure, scale in inches.

Fig. 2 gives an equivalent circuit for the experimental configuration. The unperturbed cavity is represented by the series resonant circuit L, C, R. The test aperture and

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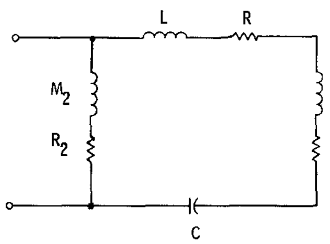


Fig. 2. Equivalent circuit of resonant cavity with lossy apertures.

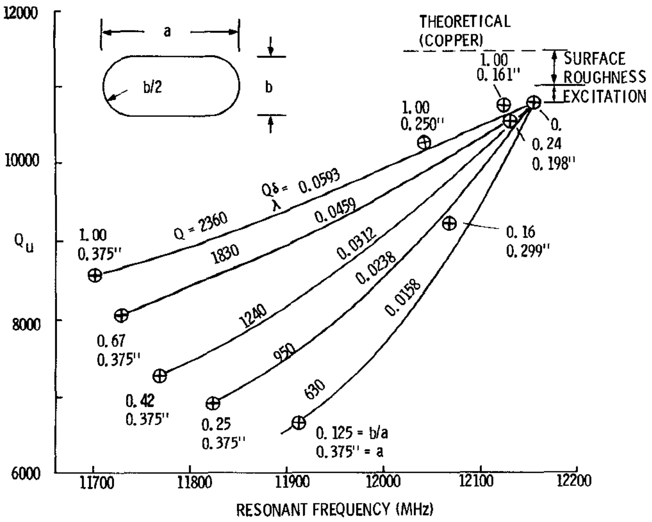


Fig. 3. Effect of apertures in 0.861-in diameter cavity on resonant frequency and unloaded Q.

associated losses are represented by M_1 and R_1, and the excitation aperture by M_2 and R_2. Increasing the physical size of the aperture increases M_1 and shifts the frequency downward. It also increases R_1 and thus lowers the unloaded cavity Q. The resonant frequency ω_0 and unloaded Q of the unperturbed cavity are defined by

$$\omega_0 = \frac{1}{\sqrt{LC}} = 2\pi f_0 \tag{1}$$

$$Q_0 = \frac{\omega_0 L}{R}. \tag{2}$$

Let the Q of each iris be defined by

$$Q_n = \frac{\omega_0 M_n}{R_n} \tag{3}$$

which represents the Q that would be achieved with this iris if it were resonated by a pure capacitance. For the perturbed cavity the resonant frequency and unloaded Q become

$$\omega_r = \frac{1}{\sqrt{(L+M_1+M_2)C}} \tag{4}$$

$$Q_u = \frac{\omega_r(L+M_1+M_2)}{R+R_1+R_2}. \tag{5}$$

Fig. 3 gives experimental values of Q_u as a function of f_0 for different aperture configurations. The value of Q_u decreases as frequency decreases from its unperturbed

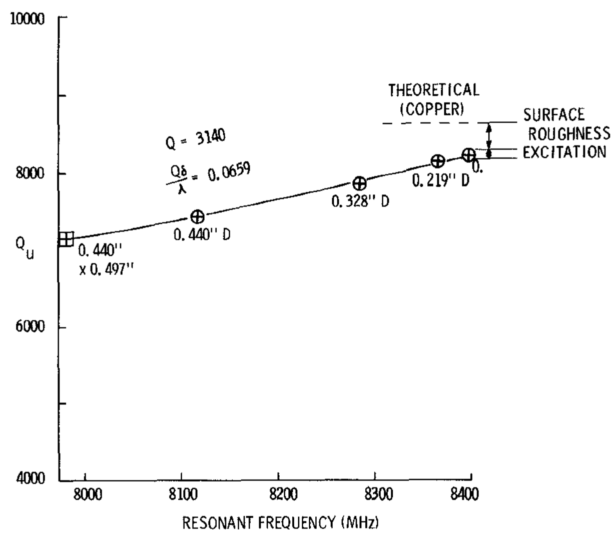


Fig. 4. Effect of apertures in 1.122-in$\times$0.497-in$\times$0.896-in cavity on resonant frequency and unloaded Q.

value. The significance of presenting the results in this manner is that all filter performance can ultimately be related to frequency shifting (or splitting) [2], [3]. That is, apertures which shift the resonant frequency by the same amount yield essentially the same coupling regardless of the physical configuration, but the unloaded Q degradation is much more severe for a thin slot than for a circular aperture that gives the same frequency shift. Extrapolating out the Q reduction due to the excitation aperture leaves an unloaded Q which is four percent below the theoretical value; this discrepancy is apparently due to surface roughness (8-μin nominal finish) [4], [5]. For fixed aspect ratio (b/a), the frequency shift is approximately proportional to the length (a) cubed.

Superimposed on the experimental points in Fig. 3 are theoretical curves based on the equivalent circuit. Note that all of the circular aperture points (aspect ratio of 1.00) lie approximately on the same curve, and the other small aperture points are near to the interpolated curve corresponding to their aspect ratios so that reasonable circuit modeling may be achieved by assuming that the normalized aperture Q is a function only of the shape factor. These Q's drop from 2360 for the circular aperture to 630 for the 0.125 aspect slot; they become 0.0593 and 0.0158 in terms of the normalized parameter $Q\delta/\lambda$, where δ is the skin depth and λ the wavelength. (For comparison, the unperturbed cavity has $Q\delta/\lambda = 0.276$.) Although they are not shown, points obtained with a slot rotated by 90° to orient its major axis in the E-field direction fall essentially on the circular aperture curve; of course thin slots yield much less frequency shift in this orientation.

Similar experiments were performed using a rectangular cavity 1.122-in wide $\times$0.497-in high $\times$0.896-in long with circular apertures; a 0.440-in-wide full height slot was also measured. The results are shown in Fig. 4. An aperture Q of 3140 fits the experimental points well. The normalized $(Q\delta/\lambda)$ value is 0.0659 which is only eleven percent different from the value obtained in the cylindrical cavity experiment. The unperturbed rectangular cavity has $Q\delta/\lambda = 0.175$.

II. Tuning Screw Losses

Tuning screws at the midplane of the cavity may be used to compensate for mechanical variations or to provide cross-coupling in dual-mode operation by splitting the frequencies of the two degenerate cavity modes having electric field parallel and perpendicular to the screw. The mechanism of interest is still the reduction in unloaded Q as a function of frequency shift. When the screw is located at the maximum electric field point, it is equivalent to a lossy capacitance in parallel with the resonator C; increasing screw penetration decreases the resonant frequency. When the location is rotated by 90° to the maximum magnetic field point, the equivalent circuit element becomes a lossy inductance in parallel with the resonator L; the resonant frequency increases with screw penetration.

Fig. 5 shows results obtained with 0.072-in diameter silver-plated tuning plungers (Johannson #6924). The capacitive and inductive orientations yield tuning Q's of 1000 and 520, respectively; the normalized values are 0.0252 and 0.0130. For dual-mode operation where the same screw may appear both inductively and capacitively, it is necessary to relate the resonant frequencies to the penetration h. The following empirical tuning equations provide this relation:

$$\Delta f_c = -[2Ah + Bh^3] \tag{6}$$

$$\Delta f_L = Ah \tag{7}$$

where $A = 170$ MHz/in and $B = 1.39 \times 10^5$ MHz/in^3. Combinations of screws encountered in typical dual-mode designs were measured to verify that the process is essentially linear; i.e., the net frequency and Q shifts are the sum of those obtained with the screws separately.

III. Single Mode Filter

Consider the impact of these mechanisms on the insertion loss of a 0.05-dB ripple eight-pole single-mode 1.2-in diameter cylindrical waveguide filter with circular apertures and 0.125-in diameter tuning plungers. The synchronous frequency is 8002 MHz, and the theoretical silver-plated cavity unloaded Q is 14 300. Surface roughness reduces it to 13 800. The tuning curve (Fig. 5) may be scaled by multiplying the frequency scale by $8002/12120 = 0.66$ and dividing the Q scale by the square root of this factor. Thus, the nominal tuning allowance of 70 MHz decreases the Q by 1900 to a value of 11 900. It is assumed that Fig. 5 may be applied even though the tuning plungers of this filter are somewhat larger relative to a wavelength.

The circular aperture Q scales to 2900 at this frequency but the aperture losses enter in a more complicated manner than the tuner losses. First, the coupling values vary within the filter from a maximum at the ends to a minimum at the center of the filter. Second, the voltage across each internal aperture varies from a maximum at the low-frequency end of the band where the phase shift between cavities is close to zero to a minimum at the high end where the phase shift

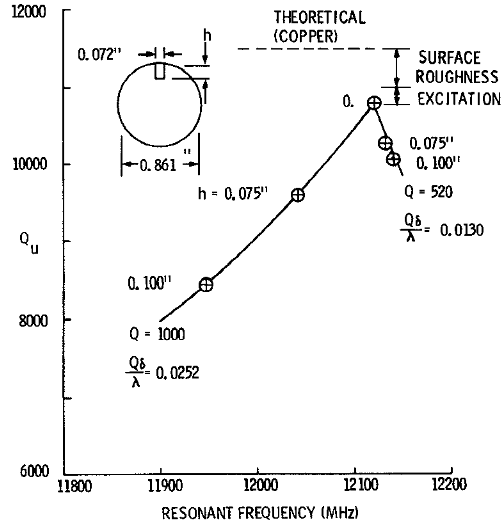


Fig. 5. Effect of silver-plated tuning screws on cylindrical cavity resonant frequency and unloaded Q.

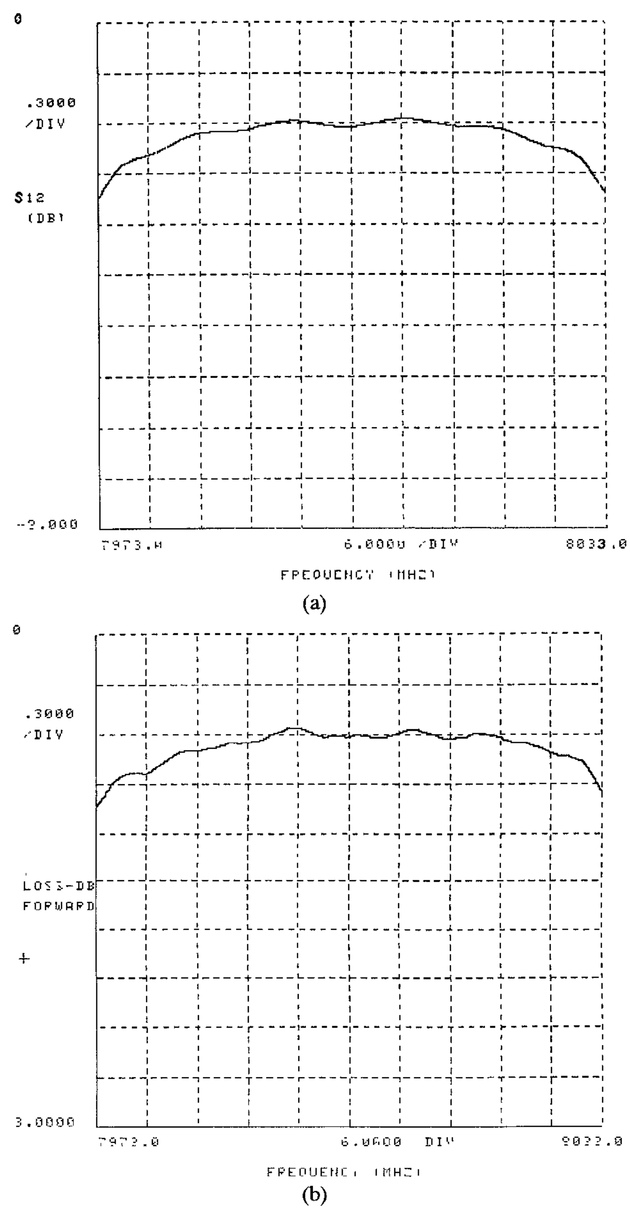


Fig. 6. (a) Computed response of 8-pole filter. (b) Measured response.

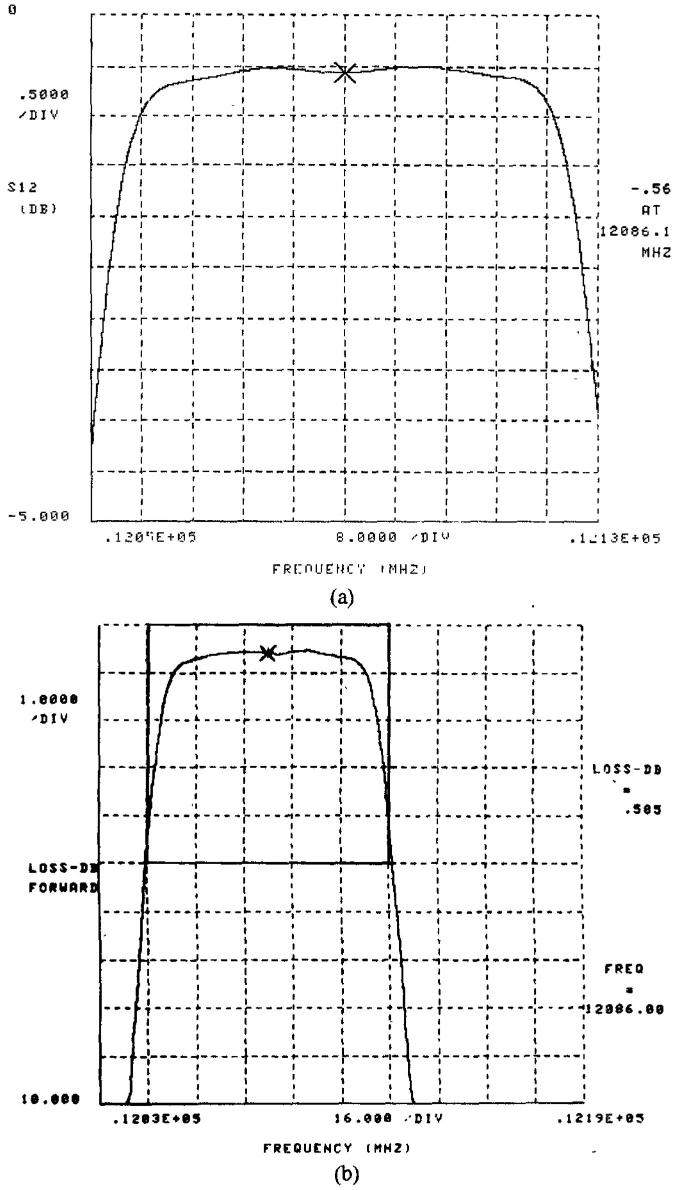
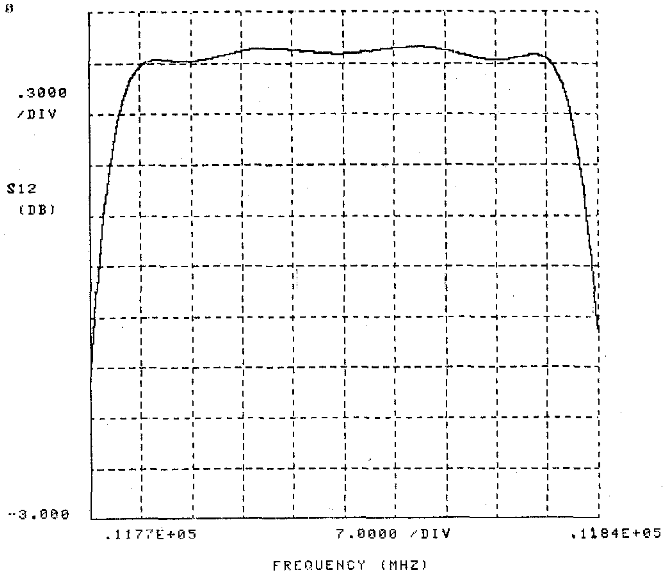


Fig. 7. (a) Computed response of 4-pole dual-mode filter. (b) Measured response from [1, Fig. 5] with region of (a) shown in box.

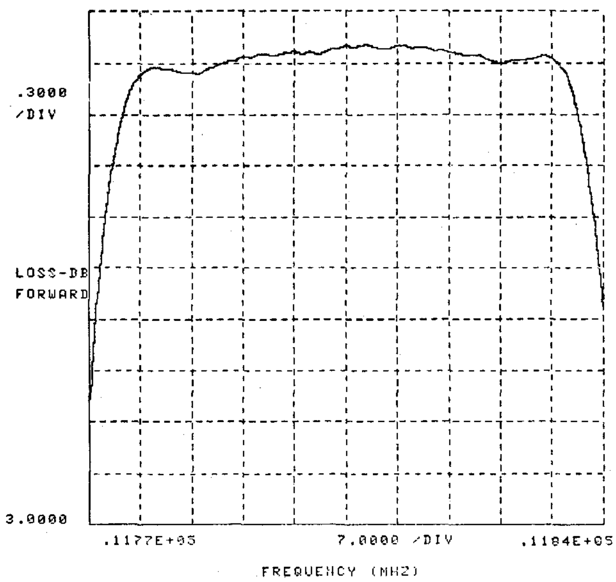
approaches 180°; this mechanism contributes a tilt to the in-band insertion loss. Thus, the aperture losses are evaluated by assuming lossy coupling inductances between cavities and computing the response as shown in Fig. 6(a). The effective midband filter Q has been reduced to 11 300 which is 0.79 times the unperturbed cavity Q. The computed loss agrees well with the measured response of Fig. 6(b). For this loss comparison the coupling values used in the analytical model were derived from the experimental scattering parameters [3]. The additional power lost due to the tuning screws and apertures is presumably dissipated in their immediate vicinity; this fact could be important in the thermal design of high-power filters.

IV. Dual Mode Filter

A copper four-pole 0.05-dB ripple dual-mode [6] filter is used as a second example [1]. The cavities have a diameter of 0.861-in and a theoretical unloaded Q of 11 440. The output coupling apertures are 0.309-in in diameter, the internal one is a 0.212-in by 0.047-in slot, and the tuning and coupling screws are 0.072-in in diameter. Each tuning screw appears capacitive to one mode and inductive to the orthogonal mode in the same cavity; for 50-MHz net tuning, the Q reduction of each resonance is 875 due to the capacitive screw and 300 from the inductive one. The surface roughness loss is 440. Furthermore, the output aperture causes a parasitic loss of 1100 (from Fig. 3) to the end-cavity mode that is not coupled through it. Thus, the net Q values before coupling effects are introduced are 9825 for the end resonances and 8725 for the internal ones. The coupling Q values are 2360 for the circular output apertures, 860 for the coupling screws (including both capacitive and inductive effects), and 880 for the center slot ($b/a = 0.22$). The computed response is shown in Fig. 7(a); it is in good agreement with the experimental results of Fig. 7(b). The effective filter Q is 8200 which is 0.72



(a)



(b)

Fig. 8. (a) Computed response of 4-pole TE_{011}-mode filter. (b) Measured response from [7, fig. 5(b)].

times the theoretical cavity Q. The internal coupling elements contribute a loss slope of approximately 0.06 dB across the passband.

V. Higher Order Mode Filter

The response of a higher order filter was computed as another example. This filter is comprised of four modified TE_{011} cavities with circular coupling apertures in the cylindrical walls [7]. The extrapolated Q of the unperturbed cavity is 29 700, which is assumed to be reduced to 28 500 by surface roughness. The tuning losses are negligible in this configuration. A circular aperture Q of 2400 scaled from Fig. 3 predicts somewhat too low a loss; however a Q of 1600 used to compute the response of Fig. 8(a) gives excellent agreement with the experimental results in Fig. 8(b). This Q corresponds to an interpolated aspect ratio of 0.57 from Fig. 3. Although the apertures are circular, the curvature of the cylindrical walls may make them appear to be somewhat elongated. The aperture losses reduce the effective midband Q to 20 300 which is 0.68 times theoretical and they contribute a slight tilt to the response.

Acknowledgment

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