Conductor Loaded Resonator Filters with Wide Spurious-Free Stopbands

Chi Wang, Kawthar A. Zaki, *Fellow, IEEE*, Ali E. Atia, *Fellow, IEEE*, and Tim G. Dolan, *Member, IEEE*

***Abstract*—A new configuration of conductor loaded resonator filters using two different size conductor loaded resonators and enclosures with significantly improved spurious performance is presented. A rigorous mode-matching method is used to compute the resonant frequencies, unloaded *Q*, and the fields of the resonant modes of the conductor (solid or ring) loaded resonators. The coupling coefficients between two resonators are computed using small aperture coupling theory. The stopband characteristics of the filter are investigated. An eight-pole elliptic-function filter was designed, constructed, and tested. Extremely wide spurious-free stopband filter response was obtained which verified the theory.**

***Index Terms*—Filters, miniature filters, mode matching, multiplexers, waveguide components.**

I. Introduction

THE NEWLY opened personal-communication-system (PCS) market demands a large number of base-station filters with extraordinarily strict requirements on both in-band and out-of-band performances. High selectivity, high rejection, low loss, and extremely wide spurious-free performance are required for both transmitter and receiver channels. Furthermore, the filters are desired to have small size and low cost.

Resonators with high unloaded *Q* and the elliptic-function response of the filter have to be used to satisfy the loss and the high rejection requirements [2]. Furthermore, resonators with good spurious-free performance are needed to meet the out-of-band requirements.

Tremendous progress has been achieved on improving the size, in-band, and out-of-band performance of the filters in the past three decades. Dual-mode filters greatly decrease the volume of the filters and open a way of realization of elliptic-function responses [2]. The use of dielectric loaded resonators greatly improves the in-band performance, size, and thermal stability of the filters [3]–[9]. Although dielectric loaded resonators have higher unloaded *Q*, they have spurious responses [6], [7], [11], [12] which are too close. To satisfy the out-of-band requirements using the dielectric loaded resonator filter, a low-pass filter with very high rejection response is needed to be connected with the dielectric loaded filter. Thus, the size, loss, cost, and complexity of the filter assembly will significantly increase. While coaxial and combline filters have very good spurious performance, lower price, and can be very small in size [1], they cannot achieve very high unloaded *Q*'s [1], [10], [17] to satisfy the loss requirement of the systems. The conductor loaded resonator filter, which has both high unloaded *Q* and relatively good spurious performance, is the desired filter type for the systems [19], [20]. Further improvement on the spurious performance of the conductor loaded resonator filters is extremely desirable.

In this paper, a new configuration of a conductor loaded resonator filter is proposed. By using two different size conductor loaded resonators, the resonant frequencies of the spurious modes of two coupled resonators are shifted apart; thus, the spurious responses close to the filter's cutoff frequency are completely suppressed. A rigorous mode-matching method is used to compute the resonant frequencies, unloaded *Q*, and the fields of the desired resonant mode as well as the spurious higher order modes of the conductor (solid or ring) loaded resonators. The coupling coefficients between two resonators are efficiently computed using the small aperture coupling theory [13]–[16]. The stopband characteristics of the filter are investigated. The mode charts and the unloaded *Q* of the resonators are presented. An eight-pole elliptic-function filter was designed, constructed, and tested. Extremely wide spurious-free stopband filter response was obtained which verified the theory.

II. Configuration and Analysis of the Filter

The configuration of an eight-pole dual-mode elliptic-function conductor loaded resonator filter is shown in Fig. 1(a). Two different size cavities with two different size metallic loadings are used. The dimensions of both resonators are chosen such that both resonate at the same frequency for the HE_{11} mode, but at different frequencies for other spurious modes. Because the spurious modes of the resonators have different resonant frequencies, the spurious response of the filter near the cutoff frequency will be significantly suppressed. Thus, better spurious performance of the filter can be achieved.

A. Method of Analysis

To be able to successfully design the proposed type of filters, the dimensions of the resonators have to be accurately determined by simulation. The configuration of the conductor loaded resonators (both solid and ring types) are given in Fig. 1(b). A rigorous mode-matching method is used to compute the resonant frequencies, unloaded *Q*, and the fields of the resonant modes. In this method [19], the resonators are divided

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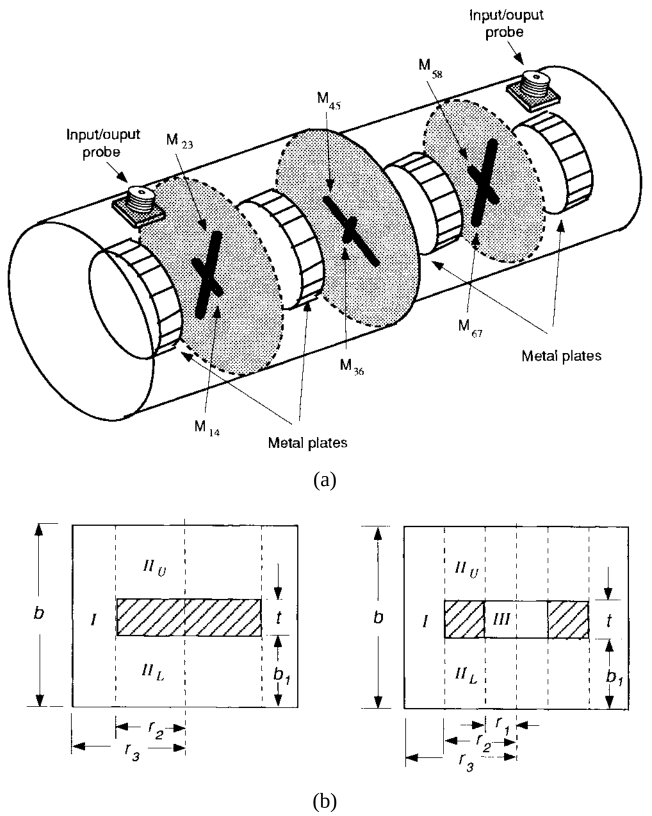

Fig. 1. (a) Configuration of an eight-pole different sized conductor loaded resonator filter. (b) Solid and ring loaded resonators.

into several regions in radial direction, as shown in Fig. 1(b), where the solid-case resonator can be considered as a special case of the ring resonator. The mode fields in each region are expressed as the summations of their own waveguide eigenmodes. Then the tangential electric and magnetic fields are forced to be continuous at the interfaces between regions I and II, and between regions II and III if the resonator is the ring case, respectively. By taking the proper inner products, a characteristic equation for resonant frequency can be obtained as follows:

$$\det[X] = 0. \tag{1}$$

Searching for the frequencies which give the roots of (1), the resonant frequencies and the field coefficients of the resonant modes can be obtained.

Once the field expansion coefficients in each region are obtained, the unloaded Q of the cavity can be analytically computed by integrating the superposition of the eigenmode fields as follows:

$$Q_u = \omega_o \frac{W_s}{P_{l,c}} = \omega_o \frac{\frac{1}{2}\mu_o \int_V |H|^2 dV}{\frac{1}{2} R_s \oint_S |H_t|^2 dS} \tag{2}$$

where W_s is the stored energy in the cavity at the resonant frequency ω_o, $P_{l,c}$ is the power loss on the structure, and R_s is the surface resistance of the enclosure.

The coupling coefficient between two identical cavities can be obtained by small aperture approximation [13]–[16], using the following equation:

$$k = \mathbf{c}_l \mathbf{c}_t M \frac{\int_{S_a} |H_t|^2 dS}{S_a \int_V |H|^2 dV} \tag{3}$$

where M is the magnetic polarizability of the aperture, c_l is the large aperture correction factor, and c_t is the thickness correction factor.

The coupling coefficient between two different sized cavities is obtained from the coupling coefficients between two identical cavities as [12] as follows:

$$k_{12} = \frac{M_{12}}{\sqrt{L_1 L_2}} = \sqrt{k_1 k_2}. \tag{4}$$

B. Effect of Iris Dimensions and Spurious Resonances

The stopband characteristics of the filter are determined by the mode separation, coupling strength of the spurious modes, the arrangement of the resonators, and the order of the filter. To be able to sufficiently suppress the response of a spurious mode, the mode separation between this mode and the nearby modes has to be large enough so that the spurious modes will not interact with each other. It is desirable that the dimension of an iris is chosen to provide the correct coupling of the desired mode, i.e., HE_{11} mode, and at the same time minimizes the couplings of all the spurious modes at their resonant frequencies. Good spurious performance of the filter can be achieved by large mode separations [10].

The spurious-free frequency response of a filter is determined not only by the spurious-mode separation, but also by the coupling structure of the filter. Above a certain frequency, all the coupling irises become propagating waveguides, and the whole filter is a propagating waveguide structure. That frequency is then the maximum achievable spurious-free frequency of the filter, and it can be estimated from the length of the iris at which the iris becomes a propagating waveguide as follows:

$$f_c \approx \frac{v_c}{2l} \tag{5}$$

where v_c is the speed of light and l is the length of the iris.

III. Numerical Results

A computer program has been developed to compute the resonant frequencies, unloaded Q, field distribution, and coupling coefficients of the conductor loaded resonators for the design of the presented dual-mode filter. Fig. 2 shows the mode charts of both solid and ring resonators versus the height of the enclosure. Fig. 3 gives the resonant frequencies of solid and ring resonators versus the radius of the enclosure. It is shown that the resonant frequencies of the first several modes, except the TM_{02} mode, are not very sensitive to the height of the enclosure for both types of resonators. Most of the modes, except HE_{11} and HE_{21}, are very sensitive to the radius of the enclosure. The resonant frequencies of the HE_{11} and HE_{12} modes are very close to each other for solid and ring resonators. The resonant frequencies of the HE_{21} and TM_{02} modes are quite different for both types of the resonators. The

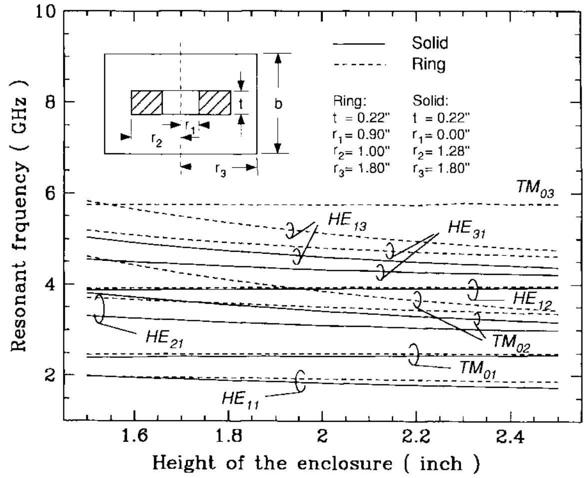

Fig. 2. Mode chart of the conductor loaded resonators versus the height of the enclosure.

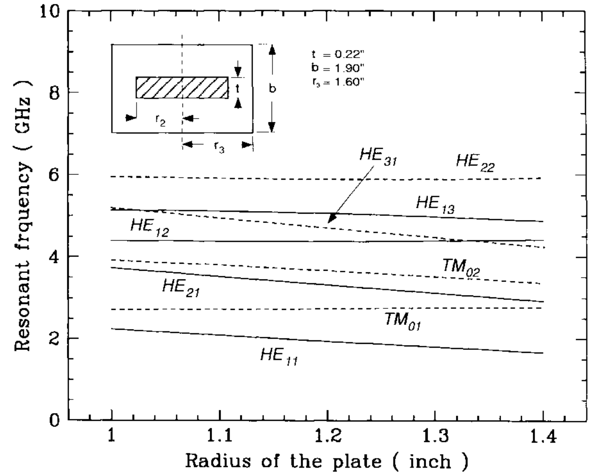

Fig. 4. Resonant frequencies of a solid loaded resonator versus the radius of the conductor.

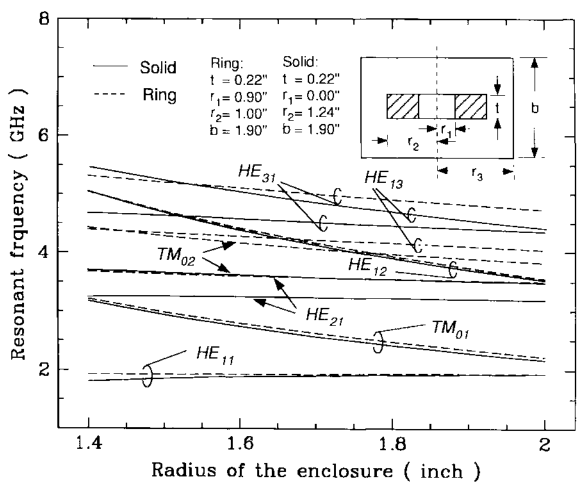

Fig. 3. Mode chart of the conductor loaded resonators versus the radius of the enclosure.

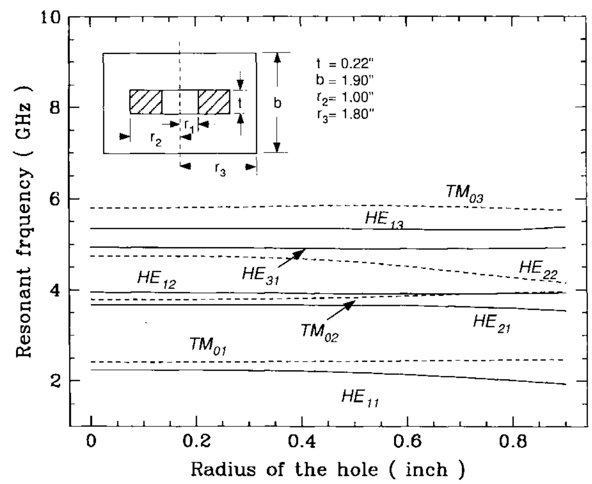

Fig. 5. Resonant frequencies of a conductor loaded resonator versus the radius of the hole.

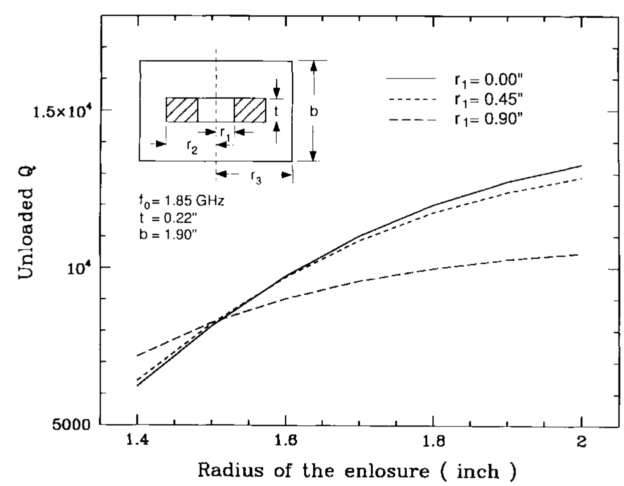

Fig. 6. Unloaded Q of HE_{11} mode for the solid and ring resonators versus the radius of the enclosure (silver plated).

resonant frequency of the operating mode (HE_{11} mode) is nearly constant to the radius of the enclosure.

Fig. 4 shows the resonant frequencies of a solid resonator versus the radius of the inner conductor. It is seen that the resonant frequencies of the HE_{n1} mode is more sensitive to the radius of the inner conductor than other modes. Fig. 5 gives the resonant frequencies of a ring resonator versus the radius of the hole. It is seen that the resonant frequencies of the resonator are not sensitive to the radius of the hole, especially when the hole is not large. The unloaded Q of the HE_{11} mode in conductor loaded resonators versus the radius of the enclosure is given in Fig. 6. It is shown that the unloaded Q of the HE_{11}-mode ring resonator is very close to that of the solid one when the hole is small. The unloaded Q of the ring resonator with the large hole is smaller than the solid resonator when the enclosure is large, but is larger than the solid one when the enclosure is small.

Fig. 7 shows the magnetic-field distributions of the first six resonant modes of a conductor loaded resonator at the top or the bottom plate. The vector plots show both the magnitude and the direction of the tangential magnetic fields, and the mesh plots show the tangential magnetic field H_x which has the same direction as the iris and has the major effect on the coupling between two resonators. It is shown that the HE_{11}

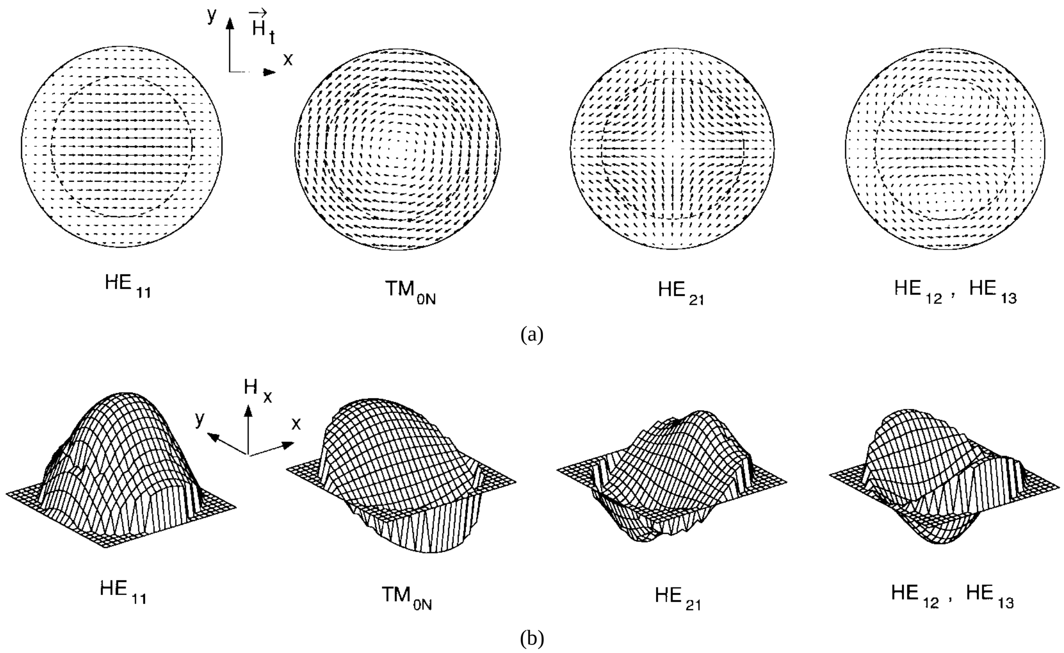

Fig. 7. Magnetic-field distributions of the first six resonance modes at top or bottom plate. (a) Vector plot of H_t. (b) Mesh plot of H_x.

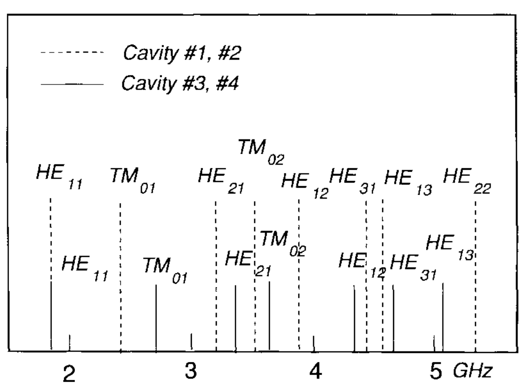

Fig. 8. Spectrum of the designed two conductor loaded resonators for the eight-pole test filter.

mode can be coupled by iris effectively in the middle region. The coupling of the HE_{21} mode is not very sensitive to the position of the iris. The field distributions of the HE_{12} and HE_{13} modes are similar to those of the HE_{11} mode. These modes (HE_{12} and HE_{13}) will have a strong effect on the spurious response of the filters. The off-center iris can decrease the coupling of the HE_{12} and HE_{13} modes, while it has a small effect on the coupling of the HE_{11} mode. However, it will significantly increase the unwanted spurious coupling of TM_{0N} modes.

IV. Filter Realization

An eight-pole elliptic-function filter for PCS base-station application with center frequency of 1.8575 GHz and bandwidth of 15.5 MHz was designed, constructed, and tested. The dimensions of the cavities were determined from the previous analysis and computer simulations. Solid conductors of different radius were loaded into the cavities of different radius in order to separate the spurious resonances and obtain

TABLE I
Computed Resonant Frequencies (GHz) and Coupling Coefficients (MHz) of Various Modes

	Cavity 1, 2	Iris M_{23}	Cavity 3, 4	Iris M_{67}
Mode	f_0	Coupling	f_0	Coupling
HE_{11}	1.86	13.1	1.86	13.1
TM_{01}	2.42	0.0	2.74	0.0
HE_{21}	3.13	2.9	3.21	3.5
TM_{02}	3.48	0.0	3.58	0.0
HE_{12}	3.90	88.7	4.38	242.2
HE_{31}	4.36	1.1	4.53	2.4
HE_{13}	4.66	193.2	5.02	—

higher unloaded Q. The input/output resistances and the coupling matrix elements of the filter are $R_1 = R_2 = 1.2101$, $M_{12} = M_{78} = 0.8153$, $M_{23} = M_{67} = 0.8465$, $M_{34} = M_{56} = 0.4292$, $M_{45} = 0.5408$, $M_{14} = M_{58} = -0.4119$, $M_{36} = -0.0109$. The unloaded Q of the designed cavities are 9500 and 12 000 with both the inner conductor and enclosure silver plated. Fig. 8 shows the spectrum of the two designed resonators. As seen, the resonant frequencies of all the spurious modes are separated up to 5 GHz.

Table I gives the resonant frequencies of the first seven modes in cavities one and two and cavities three and four. Table I also shows the coupling coefficients of iris M_{23} and M_{67} for these modes. The mode separations among TM_{01}, HE_{21}, and TM_{02} modes are much larger than the corresponding computed couplings of these modes. Therefore, it is expected that the spurious responses of these modes can be significantly suppressed. The cutoff frequencies of irises M_{23} and M_{67} are 5.1 and 4.98 GHz, respectively.

Due to the uneven loadings on the resonant frequencies of the two resonators in each cavity by the couplings, one of the tuning screws with less loading will be deeper into the cavity. Thus, the power handling of the filter will decrease. This problem can be solved by partially flattening the side of

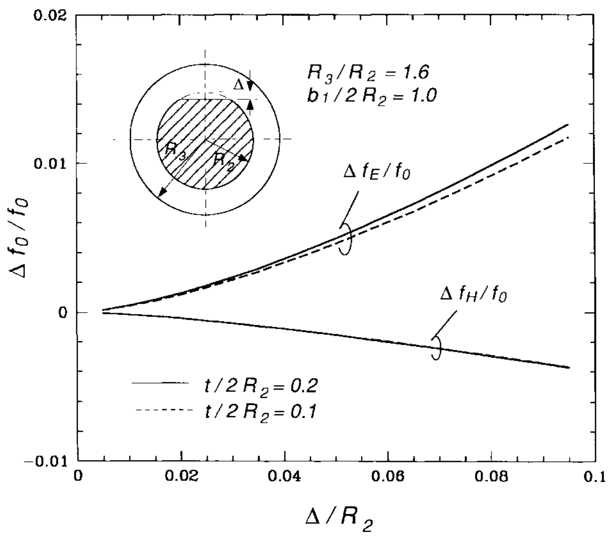

Fig. 9. Resonant frequency shift of a partially side-flattened conductor loaded resonator.

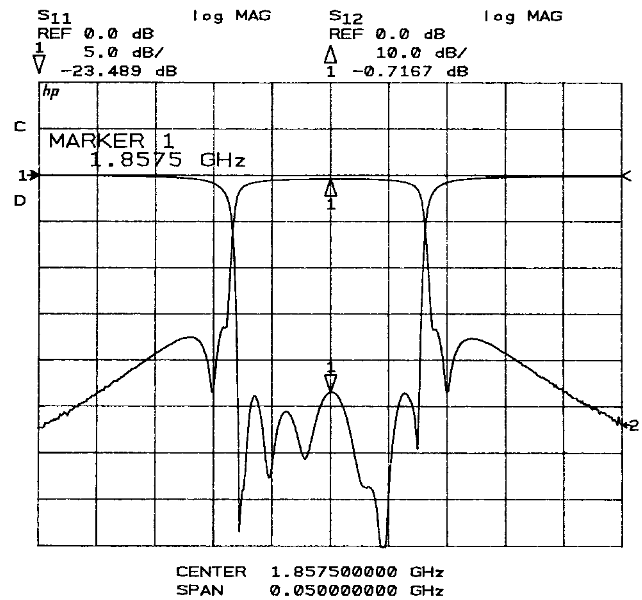

Fig. 10. Measured frequency responses of the test eight-pole filter.

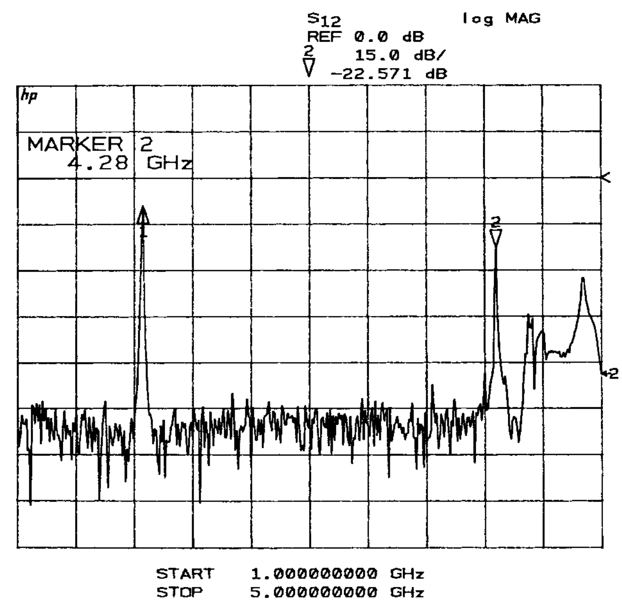

Fig. 11. Measured spurious response of the eight-pole filter.

the inner conductor (see inset of Fig. 9) where the electric field of the resonator with larger loading is maximum to increase the resonant frequency of that resonator [18]. The change in resonant frequencies of the two resonators can be approximated by perturbation theory and can be obtained as

$$\frac{\Delta f}{f_0} = \frac{\int_\tau \epsilon_o |E|^2 d\tau - \int_\tau \mu_o |H|^2 d\tau}{4W_o} \tag{6}$$

where E and H are the electric and magnetic fields in the perturbed volume τ of the cut resonator. The unknown E and H can be approximated from the fields near the conductor of the unflattened resonator.

The computed frequency shift versus the depth of the flat is shown in Fig. 9. The flat increases the resonant frequency of the resonator where the flat is perpendicular to the direction of maximum electric field, and at the same time decreases the resonant frequency of the orthogonal mode. The inner conductors of the input/output cavities are flattened at the input/output probe side to eliminate the effect of the uneven loadings on the depth of the tuning screws.

Fig. 10 shows the measured frequency responses of the test filter. The insertion loss of the filter at the center frequency is 0.72 dB. The corresponding realized unloaded Q of the filter is larger than 6000. Fig. 11 gives the wide-band frequency response of the eight-pole filter. The first spurious response results from the HE_{12} mode of the smaller cavities and the HE_{31} mode of the larger cavities. The spurious-free performance of the filter is up to 4.2 GHz or $2.26f_0$, which is much better than that of the HE_{11} mode dielectric resonator (DR) filter of $1.2f_0$, TE_{01} mode DR filter of $1.5f_0$, and the same size conductor loaded resonator filter of $1.76f_0$ [18].

V. Conclusion

A new configuration of dual-mode filters using different size conductor loaded resonators and enclosures is presented. By differentiating the resonant frequencies of the two different size resonators, the spurious level of the nearby modes is significantly suppressed. Rigorous mode-matching techniques are used to compute the resonant frequencies, unloaded Q, and the fields of the resonant modes. An eight-pole test filter was designed, constructed, and tested. Measured results show that the spurious-free stopband of the filter is widened such that the first spurious level occurs at about $2.26f_0$.

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