# Mixed Modes Cylindrical Planar Dielectric Resonator Filters with Rectangular Enclosure

Chi Wang, Hui-Wen Yao, Kawthar A. Zaki, *Fellow, IEEE*, and Raafat R. Mansour, *Senior Member, IEEE*

***Abstract*—A compact mixed modes cylindrical planar dielectric resonator filter in a rectangular enclosure is presented. Space coupling between the resonators excited in different modes and iris coupling between the identical resonators are realized in the filter. All the couplings and resonant frequencies of the DR cavities are computed by a rigorous full wave mode matching method and a cascading procedure using generalized scattering matrices. A 6-pole elliptic function filter is designed and constructed, and the measured filter frequency responses verify the theory.**

## I. Introduction

Dielectric resonator loaded filters play an important role in mobile and satellite communications. Significant development efforts have been spent and great progress has been achieved in DR filter technology since the end of the 1960's [1–6], [9–13]. Two types of the filters are most commonly used. One type is the dual-mode dielectric resonator filter, operating in the $HE_{11}$ mode, providing low loss, smaller volume and elliptic function realizations. The draw-back of the dual-mode dielectric resonator filters is their inferior spurious characteristics. The other type is the single mode dielectric resonator loaded filter with all resonators operating in the $TE_{01}$ mode, providing low loss and good spurious free performance. An elliptic function response can also be realized by this type of the filter to further reduce the loss and the volume. To achieve negative coupling between the TE mode resonators, coupling probes are usually used, and this makes the construction and adjustment of the filter more difficult. A recent paper [8] reports the application of mixing the $TE_{01}$ mode and the $HE_{11}$ dual-mode ring dielectric loaded cavity resonators in a quasi-elliptic function filter. The filter has some single $TE_{01}$ mode dielectric resonators and some dual $HE_{11}$ modes resonators. The structure can achieve good spurious performance.

In the above realizations, the dielectric resonators are usually loaded axially in cylindrical enclosures, and the couplings between the resonators are realized by irises at the enclosure's end planes and calculated by the small aperture approximation [16]–[20]. In such structures, it is difficult to physically support the resonators [7]. Planar structures, in which the cylindrical dielectric resonators are held perpendicular to either the top or the bottom plane of a rectangular enclosure, have good mechanical stability.

In this paper, a new configuration of a single mode dielectric resonator loaded cavity filter with planar structure is proposed to provide an elliptic function response (Fig. 1). Mixed $TE_{01}$ and $HE_{11}$ single mode planar dielectric resonators in rectangu-

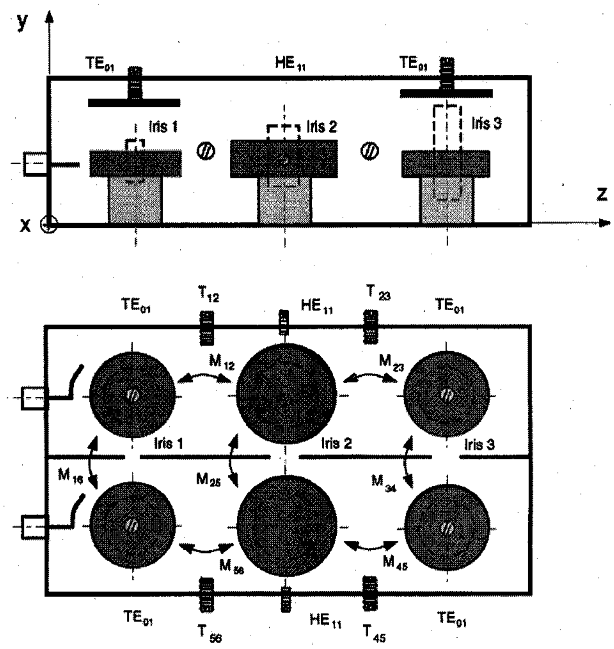


Fig. 1. The structure of the 6-pole elliptic function filter.

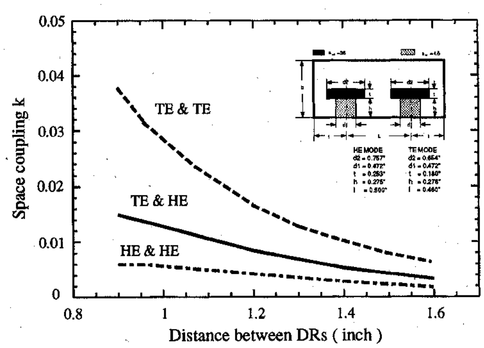


Fig. 2. Comparison of the coupling coefficients between two identical $TE_{01}$ mode DR cavities and two mixed $TE_{01}$ and $HE_{11}$ mode DR cavities versus the distance between the DR's.

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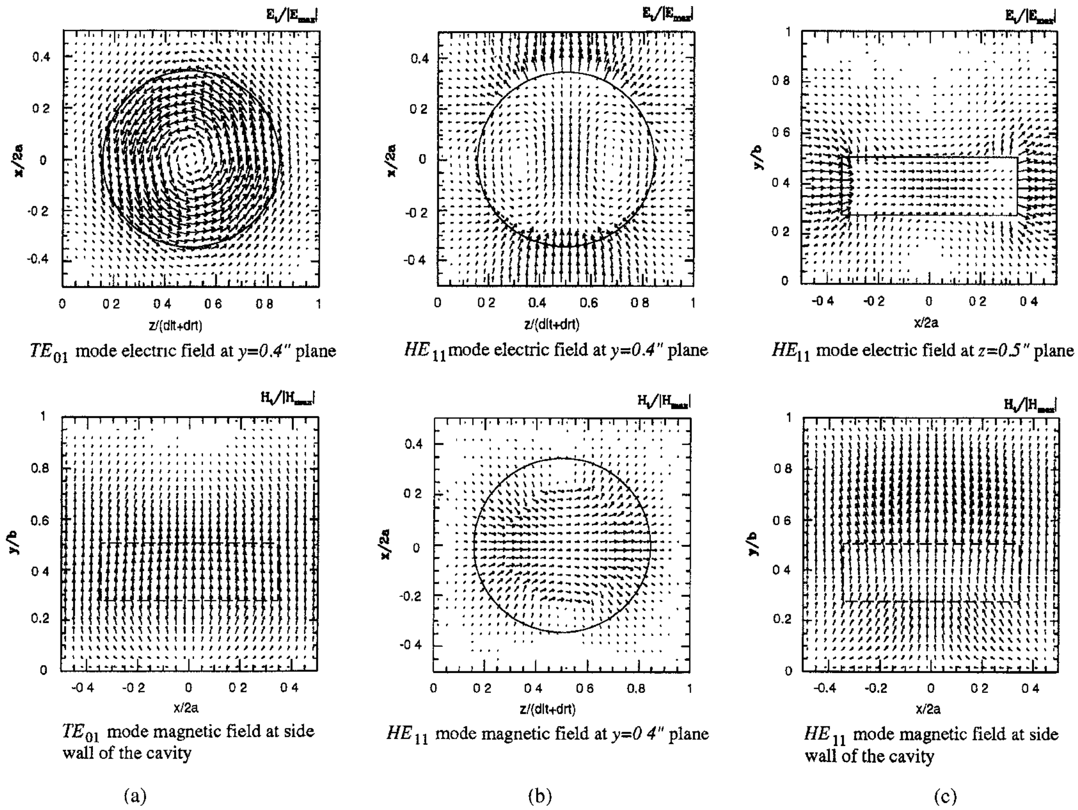


Fig. 3. Typical field distributions of the $TE_{01}$ and $HE_{11}$ mode dielectric resonator with $2a = 1''$, $b = 1''$, $d2 = 0.689''$, $h = 0.275''$, $t = 0.23''$, $L = 1''$, $\epsilon_r = 38$. (a) Field distributions for the $TE_{01}$ mode, (b) top view of the field distributions for the $HE_{11}$ mode, (c) field distributions of the $HE_{11}$ mode at cross section.

lar enclosures are used. Space coupling between the dielectric resonators excited in different modes and iris coupling between the identical dielectric resonators are realized in the filter. Instead of using a coupling probe between the $TE_{01}$ mode resonators, an iris between the $HE_{11}$ mode resonators is used to provide the required negative coupling. Accurate computation of the resonant frequency and coupling of the dielectric resonators is vital to the design of this kind of filter. A computer program has been developed to perform these calculations using a rigorous full wave mode matching method with the cascading procedure of generalized scattering matrices [7].

## II. Filter Configuration and Coupling Mechanism

The proposed structure of a 6-pole canonical elliptic function planar dielectric resonator filter in a rectangular enclosure is shown in Fig. 1. The high permittivity dielectric is supported by a low dielectric constant material. In this configuration, DR 1, 3, 4, and 6 are operating in the $TE_{01}$ mode, while DR 2 and 5 are operating in the $HE_{11}$ mode. The coupling between dielectric resonators operating in the same mode are achieved by irises. Direct space couplings are used in the filter between the $TE_{01}$ and the $HE_{11}$ mode resonators to simplify the structure. By direct computations and experimental verification, it is found that the spacing between the $TE_{01}$ and the $HE_{11}$ resonators to achieve a certain coupling is much less than that between two $TE_{01}$ mode dielectric resonators to achieve the same coupling (Fig. 2). This property makes the structure of the filter compact, very simple and easy to be built. To realize an elliptic function response, electric coupling for $M_{25}$ is required. This coupling is provided by the two $HE_{11}$ mode DR's.

Fig. 3 shows the field distributions of the $TE_{01}$ mode and $HE_{11}$ mode of a cylindrical dielectric resonator in a cubic cavity $(-0.5 \leq x \leq 0.5, 0 \leq y \leq 1.0, 0 \leq z \leq 1.0)$. Fig. 3(a) gives the electric field distribution in the $x$-$z$ plane cut at the middle of the DR and the magnetic field distribution at the side wall of the cavity for the $TE_{01}$ mode. The magnetic field is dominant in the $y$ direction at the side wall. Fig. 3(b) presents the electric field and magnetic field distribution of a $HE_{11}$ mode in the $x$-$z$ plane. Fig. 3(c) shows the electric field distribution in the $x$-$y$ plane at $z = 0.5$ and magnetic field distribution at the side wall of the cavity for the same $HE_{11}$ mode. The electric field is dominant in the region between the DR and the cavity walls of the $y$-$z$ plane in the $x$ direction. The magnetic field at the cavity walls of the $x$-$y$ plane is mostly in the $y$ direction.

The coupling mechanism of the filter is shown in Fig. 4. The desired $HE_{11}$ mode is coupled to the $TE_{01}$ mode by the $H_y$ field of the dielectric resonators. Two $TE_{01}$ mode dielectric resonators are also coupled together by the $H_y$ fields. The coupling between the $HE_{11}$ mode dielectric resonators is dominanted by $E_x$, so that negative coupling can be obtained, and an elliptic function response can be realized.

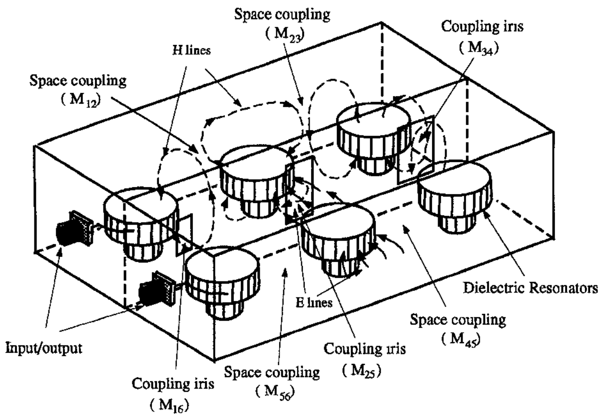


Fig. 4. Coupling mechanism of the 6-pole elliptic function filter.

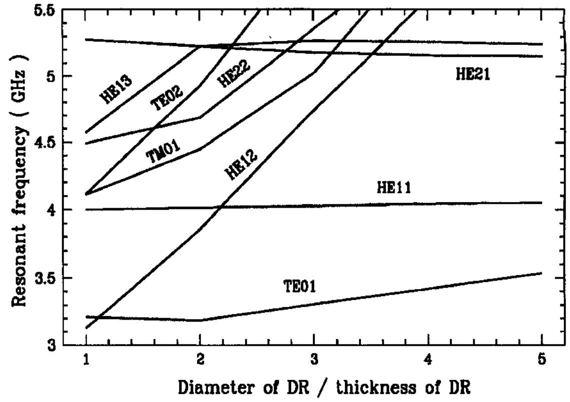


Fig. 5. Typical mode chart of acylindrical dielectric resonator with resonant frequency of $HE_{11}$ mode approximately equal to 4 GHz, in the center of a 1.0″ cubic cavity as a function of aspect ratio (diameter of DR/thickness of DR).

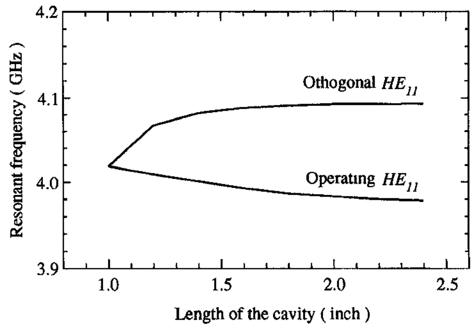


Fig. 6. The resonant frequencies of the two orthogonal $HE_{11}$ modes of the dielectric resonator with $2a = 1''$, $b = 1''$, $d1 = 0.472''$, $d2 = 0.708''$, $h = 0.275''$, $t = 0.234''$, $\epsilon_r = 38$ and $\epsilon_r$ of the support = 4.5 versus the length of the cavity.

In order to make the spurious free region as wide as possible, DR's have to be designed carefully. Fig. 5 shows the typical mode chart of a cylindrical resonator in a rectangular cavity as a function of aspect ratio (diameter of DR/thickness of DR). By proper selection of the diameter to the thickness ratio of the DR, good spurious performance can be achieved. Since the filter is designed to work at the single mode, the effect of the degenerate $HE_{11}^0$ mode, which is orthogonal to the operating $HE_{11}$ mode, has to be examined. As shown in Fig. 1 the distance of the metallic walls in the two orthogonal directions of the enclosure are different for the DR of $HE_{11}$ mode. This will split the degeneracy of the two orthogonal modes. Fig. 6 shows how the resonant frequencies of the two orthogonal $HE_{11}$ modes change when the length of the cavity changes while the width is kept fixed. The two resonant frequencies of the orthogonal $HE_{11}$ modes are separated, thus enabling single mode operation of the $HE_{11}$ mode.

The space coupling between the $TE_{01}$ and the $HE_{11}$ mode dielectric resonators can be changed by tuning the screws $T_{12}$, $T_{23}$, $T_{45}$, and $T_{56}$ at the side walls as shown in Fig. 1. The metal plungers over the $TE_{01}$ mode resonators are used to tune their resonant frequencies. The tuning screws at the side of the $HE_{11}$ mode dielectric resonators are used to change their resonant frequencies.

## III. Computation of Resonant Frequencies and Couplings

The rigorous mode matching method reported in [7] is applied to compute the resonant frequencies and the coupling coefficients of the dielectric resonators.

The results of the analysis in [7] yield the generalized scattering matrix $[S_{\rm DR}]$ of a cylindrical dielectric resonator in a rectangular waveguide. The resonant frequency of the cavity is obtained from the generalized scattering matrix by putting two perfect electric conductor (PEC) walls at the end of the cavity as

$$\det[\mathbf{S}_{\rm DR} + \mathbf{I}] = 0. \qquad (1)$$

For a coupling structure consisting of two identical cavities with a rectangular iris inserted in between, the iris creates an evanescent mode waveguide with two waveguide discontinuities at the ends. By cascading the generalized scattering matrix of the dielectric resonator loaded rectangular waveguide junction and waveguide discontinuities, the generalized scattering matrix of the whole structure is obtained.

The coupling coefficients between two DR cavities can be modeled from the equivalent circuit of the coupled structure. For the case of two identical cavities, the equivalent circuit is given in Fig. 7(a). A short-circuit and an open-circuit condition, which are equivalent to a perfect electric conductor (PEC) and a perfect magnetic conductor (PMC) wall in the physical structure, are applied at the symmetrical plane $A$-$A$ to acquire two resonant frequencies $f_e$ and $f_m$, respectively. Then the coupling coefficient is obtained as [15]

$$k = \frac{M}{L} = \frac{f_e^2 - f_m^2}{f_e^2 + f_m^2}. \qquad (2)$$

If the two coupled cavities are different, such as a $TE_{01}$ mode cavity coupled with a $HE_{11}$ mode cavity, a different approach must be used. The equivalent circuit in this case is given in Fig. 7(b). For this circuit, there exists two natural frequencies $f_{01}$ and $f_{02}$ which make the input impedance $Z_{\rm in}(f) = 0$, and one natural frequency $f_p$ which makes

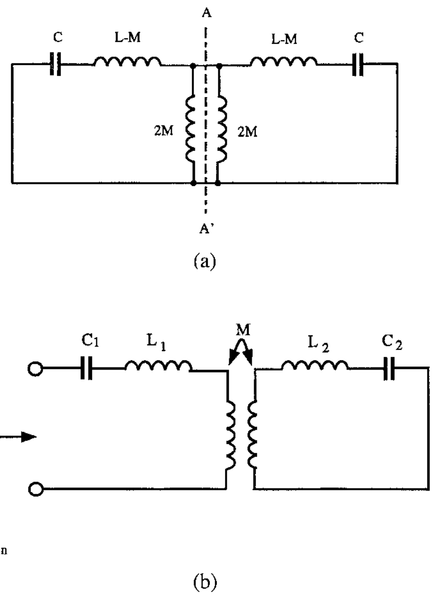


Fig. 7. The equivalent circuits of two coupled DR cavities (a) two identical cavities (b) two general cavities.

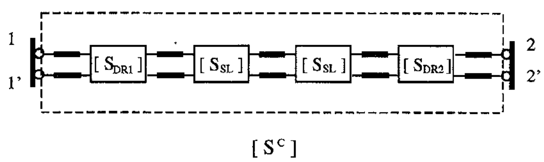


Fig. 8. Equivalent scattering matrix network of two different mode DR's through a slot.

$Z_{\text{in}}(f) = \infty$. The coupling coefficient is derived from the equivalent circuit containing these three natural frequencies

$$k^2 = \frac{M}{\sqrt{L_1 L_2}} = 1 - \frac{\hat{f}^2 + f_p^2}{f_{01}^2 + f_{02}^2} \tag{3}$$

where

$$\hat{f}^2 = \frac{f_p^2 f_{01}^2 f_{02}^2}{f_p^2(f_{01}^2 + f_{02}^2) - f_{01}^2 f_{02}^2}. \tag{4}$$

In the physical structure, the condition $Z_{\text{in}}(f) = 0$ can be realized by placing the PEC at the both ends. The two natural frequencies are found by solving the characteristic equation formed by the $S$-matrix $[S^c]$ of the over all structure (Fig. 8) and the PEC terminating condition

$$\det \begin{bmatrix} [S_{11}^c] + [I] & [S_{12}^c] \\ [S_{21}^c] & [S_{22}^c] + [I] \end{bmatrix} = 0. \tag{5}$$

However, the condition $Z_{\text{in}}(f) = \infty$ can not be realized exactly in the physical structure. One can only approximate this condition by detuning the first cavity off resonance, i.e. removing the first DR and placing the (PMC) at the 1-1′ plane. Under this condition, $f_p$ is found from

$$\det \begin{bmatrix} [S_{11}^{c'}] - [I] & [S_{12}^{c'}] \\ [S_{21}^{c'}] & [S_{22}^{c'}] + [I] \end{bmatrix} = 0 \tag{6}$$

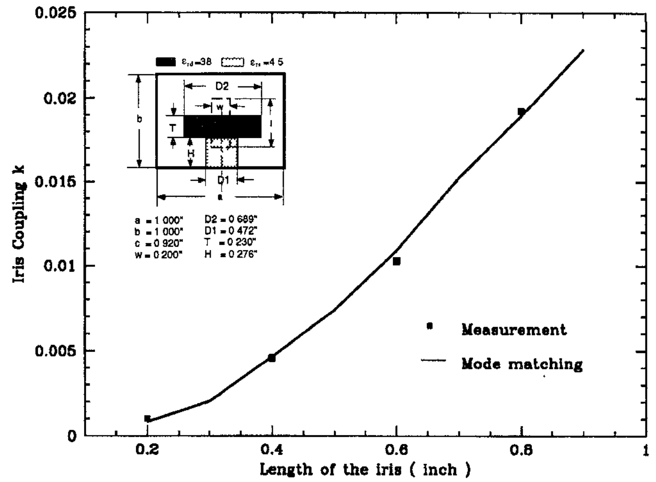


Fig. 9. Coupling coefficients of two identical $TE_{01}$ mode cavities versus the length of a vertical iris.

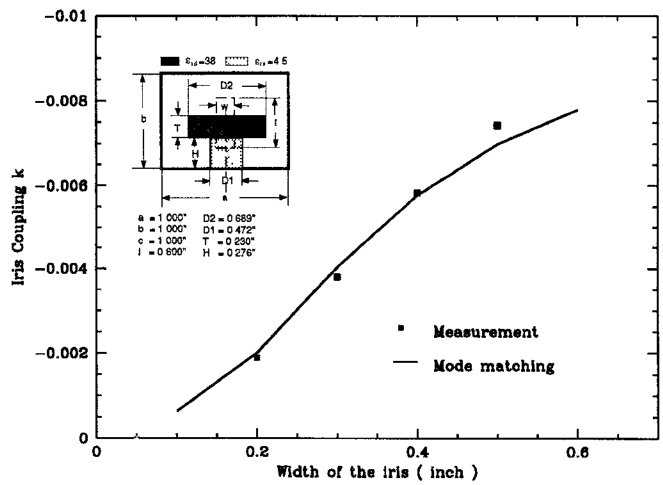


Fig. 10. Negative coupling coefficients of two identical $HE_{11}$ mode cavities versus the width of a vertical iris.

where $[S_{ij}^{c'}]$ is obtained from the cascaded structure shown in Fig. 8 by replacing the $[S_{\text{DR1}}]$ with an identity matrix.

Fig. 9 shows the coupling coefficient between two $TE_{01}$ mode dielectric resonators by a vertical iris versus the length of the iris. This coupling is achieved through the magnetic fields $H_y$ of the respective modes. Thus only positive coupling can be realized. Fig. 10 shows the negative coupling coefficient between two $HE_{11}$ mode resonators by a vertical iris as a function of the width of the iris. Negative coupling can be achieved between the $HE_{11}$ mode resonators through their radial electric fileds ($E_r$). The iris is rectangular in shape and located at the center of the cross section plane. Fig. 11 shows the space coupling coefficient between the $TE_{01}$ and the $HE_{11}$ mode dielectric resonators versus the distance between the two resonators. It is seen that the numerical solutions are in good agreement with the experimental results. The computed results are also shown in Fig. 11 as obtained by the geometrical mean $k^2 = k_{\text{TE}} k_{\text{HE}}$—[8], where $k_{\text{TE}}$ and $k_{\text{HE}}$ represent the coupling coefficients of two identical $TE_{01}$ mode and two identical $HE_{11}$ mode resonators respectively. The results of the

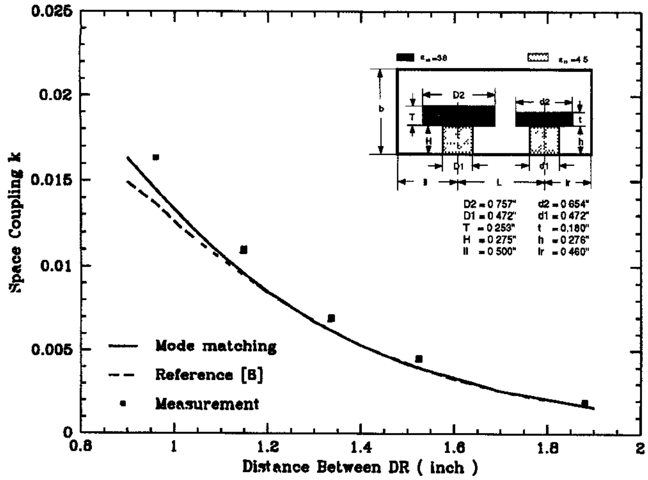


Fig. 11. Spacing coupling between $HE_{11}$ and $TE_{01}$ mode DR's.

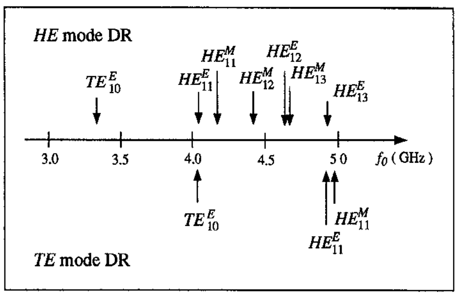


Fig. 12. The resonances of the designed $TE_{01}$ and $HE_{11}$ mode dielectric resonators with $D/t = 3$.

approximation provide acceptable accuracy for small coupling values.

## IV. Results and Discussions

A 6-pole elliptic function filter with a center frequency 4.05 GHz and bandwidth of 50 MHz is designed, built and tested. The normalized input/output resistances and coupling matrix elements of the filter as obtained from synthesis are

$$M = \begin{bmatrix} 0 & 0.9415 & 0 & 0 & 0 & 0.0566 \\ 0.9415 & 0 & 0.5909 & 0 & -0.2690 & 0 \\ 0 & 0.5909 & 0 & 0.7953 & 0 & 0 \\ 0 & 0 & 0.7953 & 0 & 0.5909 & 0 \\ 0 & -0.269 & 0 & 0.5909 & 0 & 0.9415 \\ 0.0566 & 0 & 0 & 0 & 0.9415 & 0 \end{bmatrix}$$

$$R_A = R_B = 1.2475. \tag{7}$$

The resonances of various modes of the two kinds of the designed DR's are given in Fig. 12, where superscripts $E$ and $M$ represent resonant frequencies obtained by putting the PEC and the PMC plane at the $x = 0$ plane, respectively. It is shown that the resonant frequencies of the $HE_{12}$ and $HE_{13}$ modes of the HE mode DR are moving closer to the center frequency of the filter than that in the cubic cavity. The

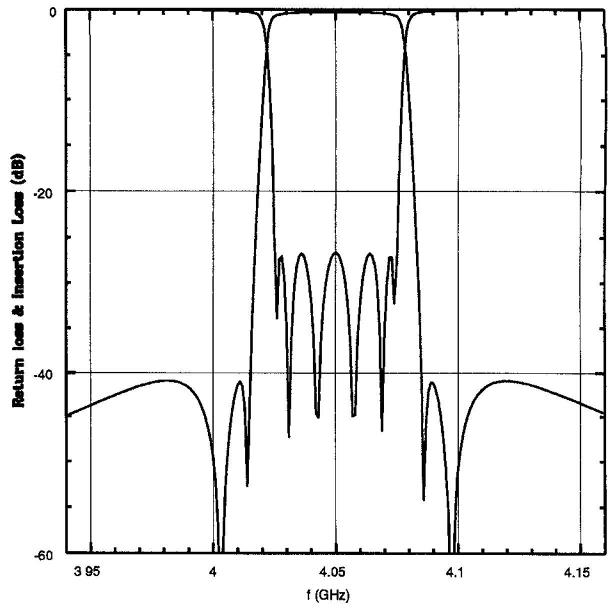


Fig. 13. Theoretical (ideal) frequency responses of the 6-pole elliptic function filter.

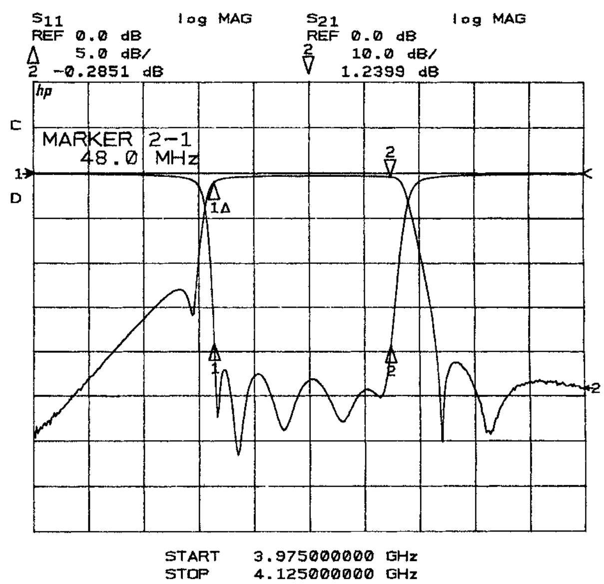


Fig. 14. Frequency responses of the 6-pole experimental filter.

resonant frequency of the orthogonal $HE^M_{11}$ mode is about 120 MHz higher than the operating $HE_{11}$ mode. Fig. 13 shows the theoretical frequency response of this filter. The corresponding measured frequency response of the filter with aluminum cavities after tuning according to the procedure described in [14] is shown in Fig. 14. The filter has 22 dB return loss and 0.40 dB insertion loss at the center frequency.

It is observed that the tuning ability of the tuning screw is to lower the resonant frequency of the $HE^E_{11}$ mode by several hundred MHz. If wider separation of the orthogonal $HE^M_{11}$ mode is needed, the resonant frequency of the operating $HE^E_{11}$ mode can be designed 100 MHz–200 MHz higher, and tuned back to the center frequency of the filter by the tuning screw,

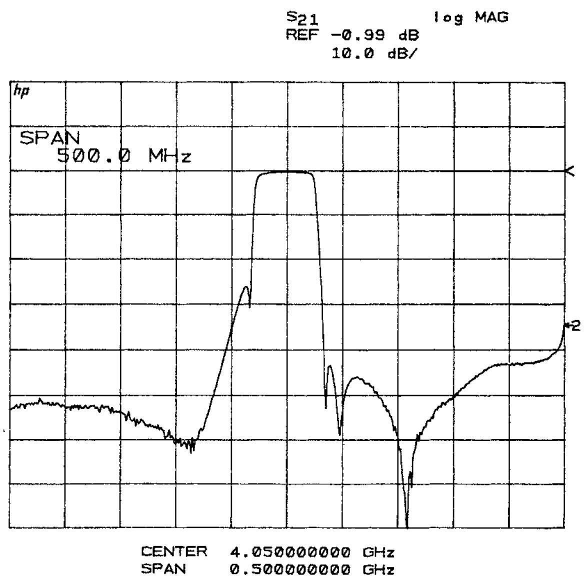


Fig. 15. Wide band frequency response of the 6-pole experimental filter.

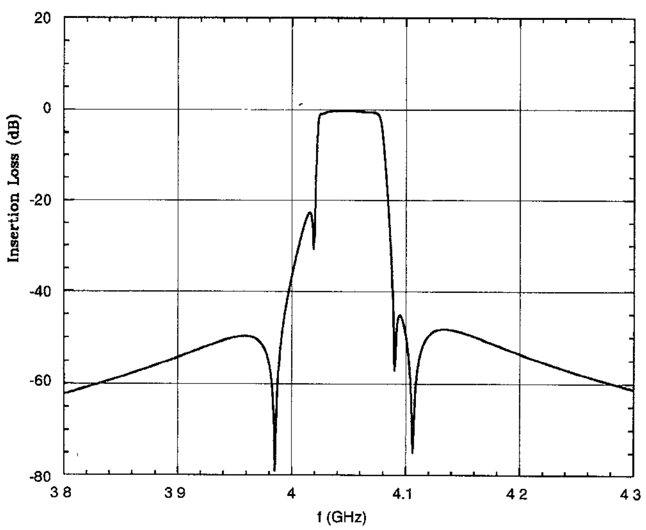


Fig. 16. Computed frequency response of the filter when nonadjacent coupling is considered.

the degenerate $HE_{11}^{M}$ mode will be much higher than the center frequency of the filter.

Another way to move the resonant frequencies of the orthogonal $HE^{M}$ mode is cutting some portions of the $HE_{11}$ mode dielectric resonator by perturbation the stored electrical energy of the resonator [21]. Fig. 15 shows the wide band frequency responses of the filter. A 500 MHz spurious free performance has been achieved after moving the resonant frequency of the orthogonal $HE_{11}^{M}$ mode.

Figs. 14 and 15 show that the response of $S_{12}$ is unsymmetrical. The level of the left side peak is about 20 dB higher than right side one. This is mostly caused by the nonadjacent coupling $M_{13}$ and $M_{46}$. The computed nonadjacent couplings $M_{13}$ and $M_{46}$ of the filter was determined using the cascading procedure to be about 0.089. Fig. 16 shows the computed frequency response when these nonadjacent couplings are considered, and coupling $M_{16}$ is changed to 0.0354, respectively. It is shown that the simulated frequency response of $S_{12}$ is very close to the measured response.

## V. Conclusion

A new type of mixed modes planar dielectric resonator filter in a rectangular enclosure with a simple structure is presented. A rigorous analysis method is used to compute the coupling coefficient of the resonators. The computed coupling coefficients are in fair agreement with the measured results. A 6-pole elliptic function filter is designed, constructed and tested. The measured filter frequency responses verify the theory.

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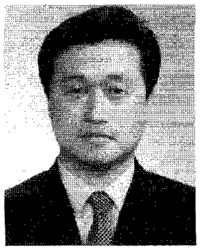

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