Canonical and Longitudinal Dual-Mode Dielectric Resonator Filters Without Iris

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Abstract —Two bandpass filter realizations using dual-mode dielectric resonators in simple tubular enclosures are described. The new configurations do not require iris to achieve the couplings among the resonators. This eliminates the need for the most expensive machined parts of the filters, which require tight tolerances. The realizations also achieve lower midband insertion losses than comparable filters with iris, because conduction currents on the metallic cavity ends are eliminated. Measured results on two four-pole elliptic function experimental filters realized in the new structures agreed closely with theory.

I. Introduction

DUAL-MODE band pass filters [1], [2] possess considerable performance advantages over conventional waveguide realizations [3], especially for applications where mass and volume are critical. Further dramatic reduction in filter size and mass could be achieved using dielectric loading of the cavities [4], with high-dielectric, low-loss, temperature-stable materials. Both types of air-filled and dielectric-loaded dual-mode filters reported previously in the literature require that physically adjacent resonators be coupled to each other through iris slots or holes. Generally, the iris must be produced (i.e., machined and silver plated) to a high degree of precision to provide the required accuracy for achievement of the desired exacting filter response. Extremely tight tolerances on iris dimensions constitute a major cost factor in producing these types of filters. This high cost restricts the use of these filters to applications where the performance, mass, and size are more critical factors (e.g., space applications in communication satellites) and precludes their use in areas where cost is the major driver (e.g., extremely large numbers of filters for use in phased arrays).

This paper presents two novel realizations of dual-mode dielectric resonator filters in simple structures, which completely eliminate the need for iris. The first realization is analogous to the canonical dual-mode form [2] and the second is analogous to the longitudinal dual-mode form [1]. Both realizations provide the same optimum high-quality performance achievable from multiple coupled cavities [5], and the miniaturized size advantage of dielectric loading, and they can be inexpensively manufactured due to the elimination of the iris. Further, the new filters have lower midband insertion loss than the corresponding realizations with iris, because the conduction currents on the iris are eliminated.

Section II of this paper describes the canonical realization and some interesting characteristics not reported before. In section III, the longitudinal dual-mode realization is presented. Two experimental filters (one of each type) have been constructed and tested to verify the theory. Measured test results obtained from these filters as well as the computed results are compared in Section IV. Finally, Section V contains conclusions and discussions.

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II. Canonical Realization

It is known [5] that the most general bandpass transfer function realizable by a multiple coupled cavity structure can be reduced to a canonical form containing the minimum number of coupling elements. An equivalent circuit of this canonical form is shown in Fig. 1. It consists of two halves, each of which has a number of identical resonant circuits coupled in cascade by frequency-invariant coupling elements having the same sign. Each resonant circuit in one half is coupled to the corresponding circuit in the other half by means of a specified sign (either positive or negative) cross-coupling element. Realization of the canonical form using dielectric-loaded resonators excited in hybrid (HEH_{11} modes) [6] is shown in Fig. 2. This realization is similar to the realization of the circular waveguide form excited in TE_{111} modes described in [2]. In Fig. 2, the cascade couplings are provided by circular iris separating the dielectric resonators. The magnitudes of the cascade couplings are controlled by the iris size (radius). The cross couplings are realized by coupling screws located at a 45° angle to the directions of the degenerate dual modes. The relative signs of any two cross couplings are determined by the relative directions of the corresponding coupling screws (same sign for parallel screws and opposite signs for perpendicular screws).

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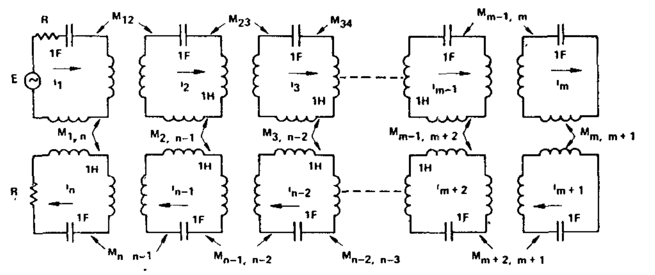


Fig. 1. Canonical form of the equivalent circuit of $n = 2m$ coupled cavities.

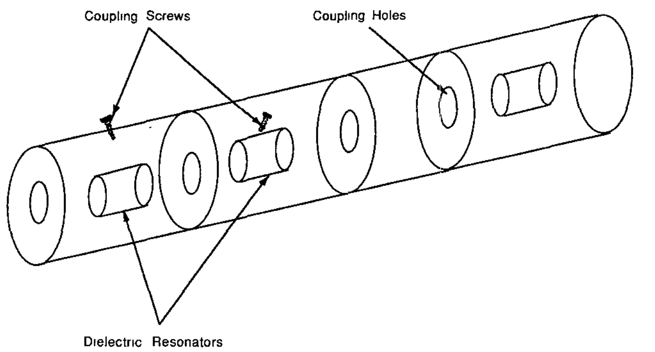


Fig. 2. Dielectric-loaded circular waveguide canonical dual-mode filter with coupling holes.

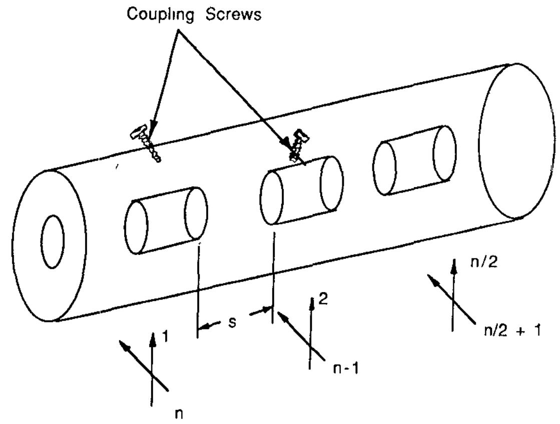


Fig. 3. Dielectric-loaded canonical dual-mode filter with no coupling holes.

The same canonical form can also be realized by the new structure shown in Fig. 3, which has no iris. Proper cascade coupling values between any two adjacent dual-mode resonators excited in the hybrid modes are obtained by adjusting the spacing S between the resonators. The input and output ports of the filter are located in the same physical cavity and can be realized in a number of ways [2], two of which are shown in Fig. 4. The coaxial probes in Fig. 4(a) couple the radial electric fields of each of the two orthogonal dual modes of the resonators. The amount of coupling (or external Q) is controlled by the depth of penetration and the probe's thickness (diameter). The maximum isolation achievable between the input and output ports in this case is partly limited by the ability to maintain the probes mechanically at right angles with respect to each other and partly by the spurious mode couplings. As shown later, in Section IV, only about 30 dB isolation can be achieved by the two orthogonal probes coupling.

The coupling $M_{1,n}$ between the input and output cavities can be realized by either of the two orientations A or B shown in Fig. 4(a). Experimentally, it was found that if orientation A is used, two additional transmission zeros are created in the stopband of the filter. These zeros tend to improve the filters selectivity. Orientation B, on the other hand, does not introduce these real frequency transmission zeros, and the filter becomes less selective than orientation A. Experimental data which illustrate these observations are included in Section IV. A theoretical model that could possibly predict the existence of these two extra transmission zeros was reported in [7].

The configuration shown in Fig. 4(b) has one coaxial probe port (as in Fig. 4(a)). The other port is a dipole or a loop [8] that couples to the magnetic field of the mode near the end wall of the resonator. The configuration of 4(b) should provide better isolation between the input and output ports than the two orthogonal probes of Fig. 4(a), since it is less susceptible to spurious couplings. However, the dipole or the loop are more difficult to realize than the simple coaxial probe, and are also more sensitive to dimensional tolerances.

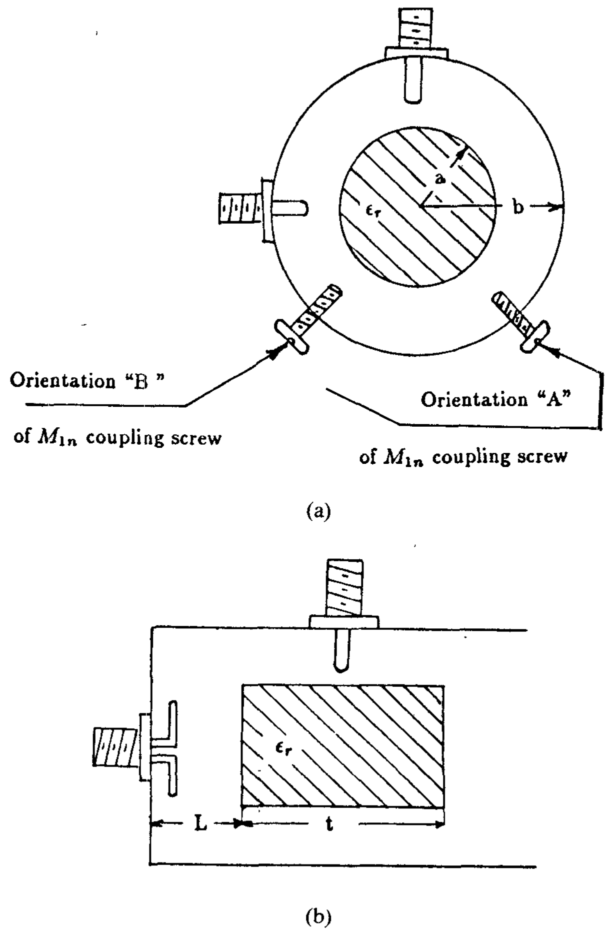


Fig 4. Input/output couplings. (a) Two coaxial probes with two possible orientations of coupling screw M_{1n}. (b) Coaxial input and dipole (or loop) output.

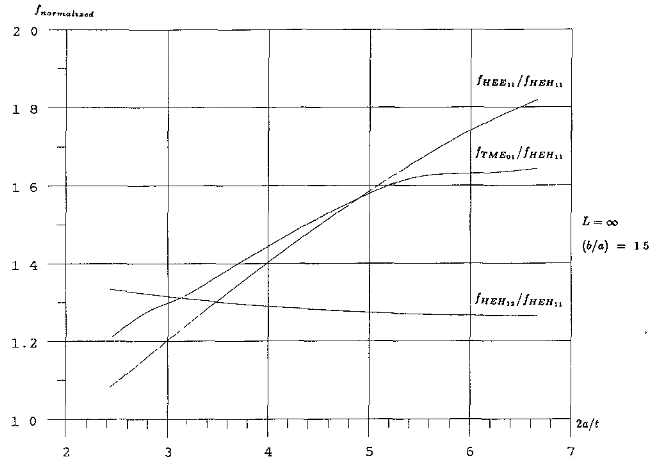


Fig. 5. Variation of $(f_{\text{spurious}}/f_0)$ for a resonator in an infinite guide (f_0 is HEH_{11} mode).

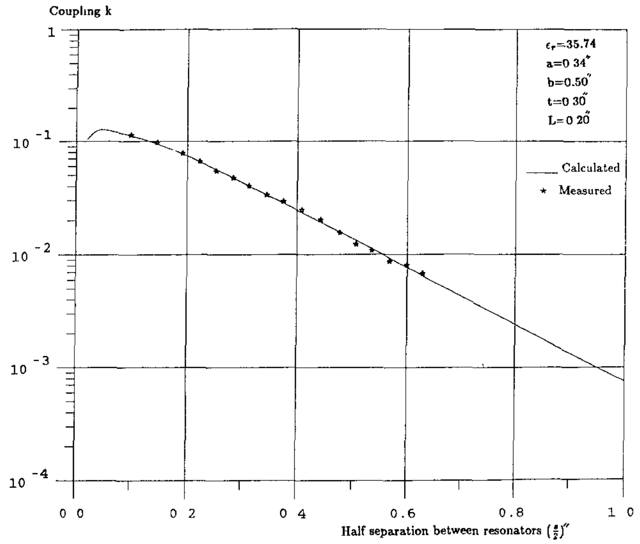


Fig. 6. Measured coupling between two resonators for the hybrid HEH_{11} mode.

Parameters required for the design of this type of filters are resonant frequency of the dual-hybrid-mode dielectric resonators in the cylindrical tube, coupling between two adjacent resonators and the external Q of the probe, dipole, or coupling loop. Theoretical calculation of the resonant frequency can be performed using the methods described in [6]. Selection of optimum resonator dimensions which results in the widest spurious-free stopband can be made based on mode charts of the resonators [6]. A more convenient form of these charts for the resonator design is shown in Fig. 5, which shows the variation of the ratio between the closest spurious modes to the desired mode (f_{sp}/f_0) of a resonator in an infinitely long waveguide with the diameter to length ratio $(2a/t)$. In this figure, both the desired mode frequency f_0 (the HEH_{11} mode) and the ratio (b/a) were held constant. The optimum choice of the ratio $(2a/t)$ for this mode is about 3.5, which results in a spurious-free region approximately 30 percent of the resonant frequency. The optimum diameter of the dielectric resonator for this case is approximately given by

$$(2a)_{\text{optimum}} = (c/f_0)\sqrt{\frac{2.24}{\epsilon_r}}$$

where c is the speed of light.

Methods for the coupling calculations between the hybrid modes are described in [9]. Computed and experimentally measured data showing the variation of the coupling coefficient between two resonators as a function of their separation are shown in Fig. 6

III. Longitudinal Dual-Mode Realizations

The maximum out-of-band isolation achievable with the dual-mode canonical realization described above is limited due to the incidental coupling between the input and output ports which always exist in the same cavity. Although it may be possible to improve this isolation by using a dipole, loop, or waveguide slot [10] in one of the ports, such improvement involves complicating the structure to a certain extent. To achieve close to the theoretically possible isolation in the out-of-band insertion loss of the filters, the input and output ports must be located in two different physical resonators. Although this is not possible with the symmetrical canonical form described above, there are realizations that either achieve the same response with asymmetric coupling structure [11] or achieve the required isolation without the maximum number of realizable finite transmission zeros (e.g., longitudinal dual-mode filters [1], [4]). To realize such filters, however, requires a means to provide unequal couplings between any two corresponding modes of adjacent dual-mode resonators. Since in the structure described in Section II above these couplings are always equal due to the circular symmetry, a modification is needed to achieve these more desirable realizations.

Consider the coupling configuration shown in Fig. 7. It consists of two dielectric resonators separated by a distance S. Screws for coupling adjustment are placed midway between the resonators parallel to the maximum of the radial electric fields of the two hybrid modes. By changing the penetration of these screws, the coupling between the two pairs of hybrid modes can be changed independently of each other. Thus in Fig. 7, the coupling $M_{k,k+3}$ between the two modes $(k, k+3)$ can be changed by adjusting the penetration of screws A–A without affecting the coupling between modes $(k+1, k+2)$. Similarly, the coupling $M_{k+1,k+2}$ between the two modes $(k+1, k+2)$ can be adjusted by changing the penetration of the screws B–B without affecting the coupling $M_{k,k+3}$. Therefore unequal coupling between each of the two pairs of hybrid modes can be realized without the need for an iris. Furthermore, these couplings can be simply and independently controlled by means of coupling screws. It is important to note that increasing the depth of penetration of

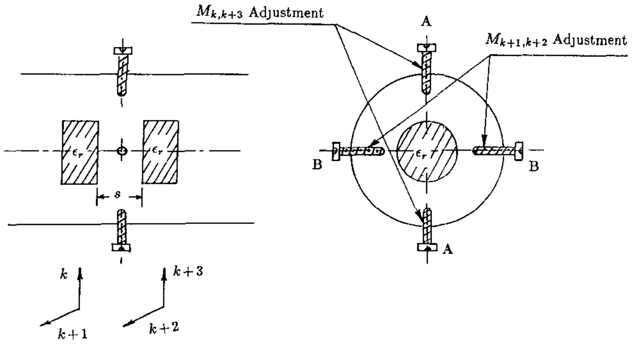
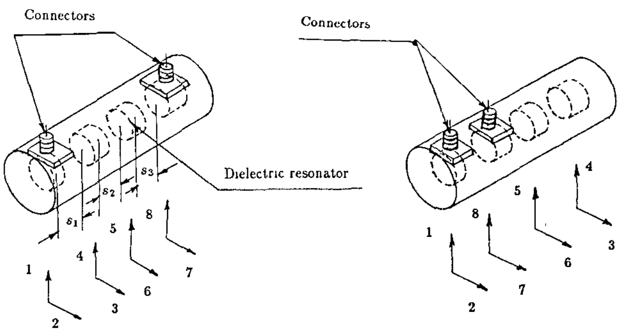


Fig. 7. Coupling adjustment between two hybrid-mode dielectric resonators.



(a) (b)

Fig. 8. Examples of eight-pole filter realizations. (a) Dual-mode longitudinal (two pairs of finite transmission zeros). (b) Dual-mode nonsymmetric canonical (three pairs of finite transmission zeros).

the screws increases the corresponding coupling between the mode pair [9]. Thus in the design of filters, the spacing S (see Fig. 7) between the two resonators should be chosen to correspond to a coupling value which is slightly less than the minimum required of the two couplings $M_{k,k+3}$ and $M_{k+1,k+2}$. The screws A–A and B–B could then be used to adjust the coupling to achieve the precise desired values of these unequal couplings.

Filter realizations employing these principles are illustrated by the examples shown in Fig. 8. The eight-pole dual-mode longitudinal filter realization [1], [4] shown in Fig. 8(a) can achieve two pairs of finite transmission zeros. To design this filter the dimensions of the dielectric resonators are determined so that their resonant frequency in the HEH_{11} mode [6] corresponds to the desired center frequency of the filter with the other spurious modes separated as far as possible, as discussed in Section II. The distances S_1, S_2, and S_3 are then computed to yield couplings slightly less than the $\min(M_{14}, M_{23})$, $\min(M_{36}, M_{45})$, and $\min(M_{58}, M_{67})$ respectively. The rest of the coupling matrix elements, i.e., M_{12}, M_{34}, M_{56}, and $M_{7,8}$ are realized by means of 45° screws appropriately located in the planes bisecting the lengths of the corresponding resonators.

The eight-pole filter shown in Fig. 8(b) can realize the optimum transfer function which could be realized by the

TABLE I
FILTER PARAMETERS

Parameter	Canonical Filter	Longitudinal Filter
Center Frequency (GHz)	3 9145	3 920
Bandwidth (MHz)	21.0	47.0
Normalized input impedance R_1	1.300	1.150
Normalized output impedance R_2	1.300	1.150
Coupling Matrix M	$\begin{bmatrix} 0 & .98 & 0 & -.21 \\ .98 & 0 & .84 & 0 \\ 0 & .84 & 0 & .98 \\ -.21 & 0 & .98 & 0 \end{bmatrix}$	$\begin{bmatrix} 0. & .86 & 0 & -0\ 26 \\ .86 & 0. & .80 & 0 \\ 0 & .80 & .0 & .86 \\ -0.26 & 0 & .86 & 0 \end{bmatrix}$

symmetric canonical form described in Section II (i.e., three pairs of finite frequency transmission zeros). However, this realization allows the input and output ports to be located in two different resonators, thus eliminating the limitation imposed on the maximum out-of-band isolation that exists in the canonical form. Synthesis procedure for this type of filters is very similar to the procedures described in [5], [11], and [12]. Design of this filter can be made following the same steps that are outlined above for the dual-mode longitudinal filter.

IV. EXPERIMENTAL RESULTS

To verify the theory, three experimental four-pole elliptic function filters were designed, constructed, and tested. Parameters of the filters are given in Table I. Two of the experimental filters (filters A and B) are of the canonical dual-mode type described in Section II. The difference between these two filters is in the location of the M_{14} coupling screw. In one filter (filter A) the M_{14} coupling screw is chosen to have orientation A shown in Fig. 4(a), while in the other filter (filter B) the M_{14} coupling screw has the orientation B shown in Fig. 4(a). The distance S between the resonators (see Fig. 3) determines the couplings M_{12} and M_{34} (which are equal, as indicated by the coupling matrix M above). The couplings M_{23} are realized by screws located at a 90° angle from the respective M_{14} screws. Measured and computed insertion and return loss responses of filter B are shown in Fig. 9. Fig. 10 shows the measured insertion loss responses of the two filters (A and B) over a wider frequency band. It is clear from Fig. 10 that in the case of filter A two additional transmission zeros are present in the response. The out-of-band isolation for both filters is, however, limited to about 30 dB. The third filter was designed to have the input and output ports in separate resonators, as described in Section III. Computed and measured insertion loss responses of this filter are shown in Fig. 11. The improvement in the out-of-band isolation is due to locating the input and output ports in two different resonators. Typical expanded in-band insertion loss response is shown in Fig. 12. The center frequency insertion loss is about 0.4 dB, which corresponds to an unloaded Q of approximately 6000. Finally, Fig 13 is a photograph of a typical experimental filter.

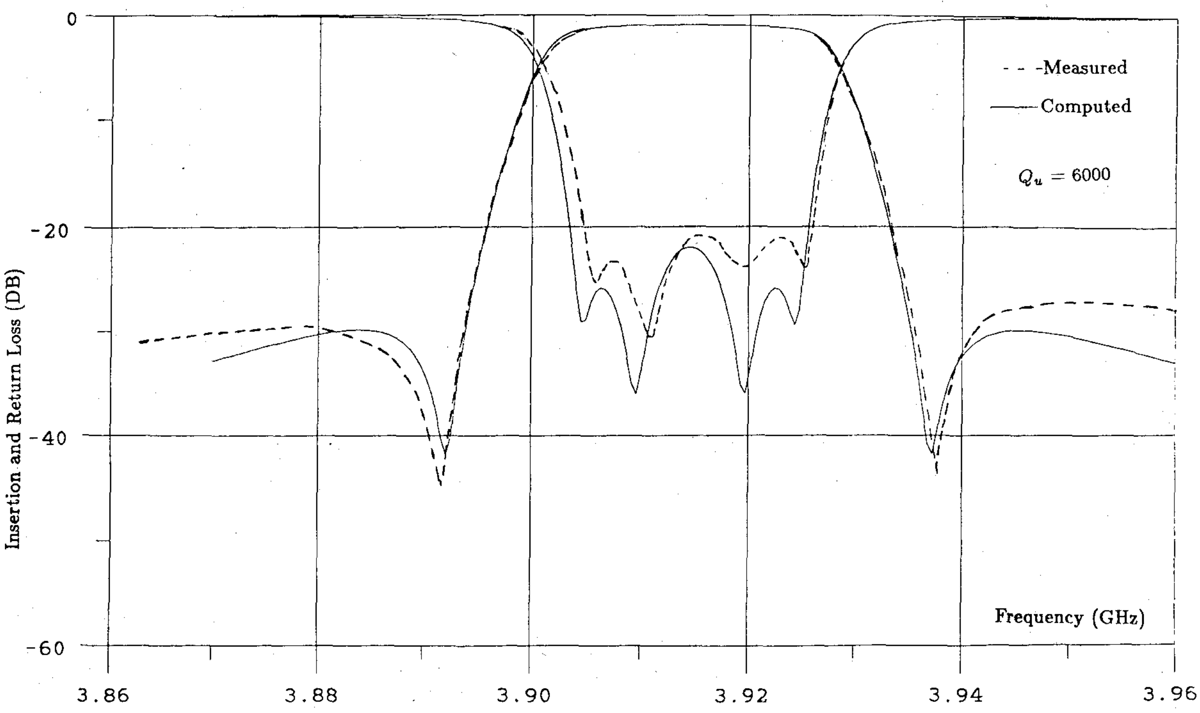


Fig. 9. Measured and computed insertion and return loss responses of a canonical dual-mode four-pole filter without iris.

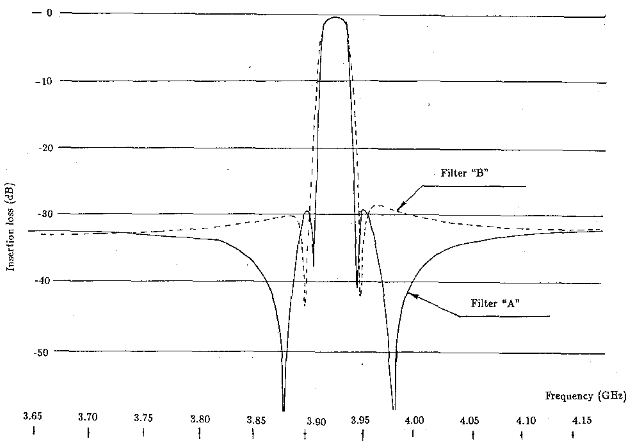


Fig. 10. Measured wide-band insertion loss responses of two four-pole canonical dual-mode filters.

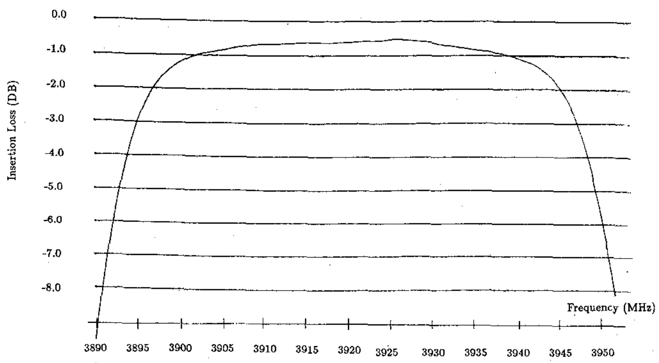


Fig. 12. Measured expanded insertion loss response of a four-pole dual-mode dielectric resonator filter without iris.

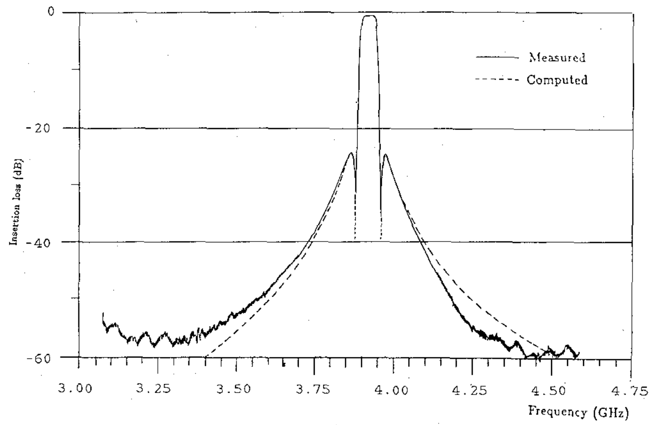


Fig. 11. Measured insertion loss response of a four-pole longitudinal dual-mode dielectric resonator filter.

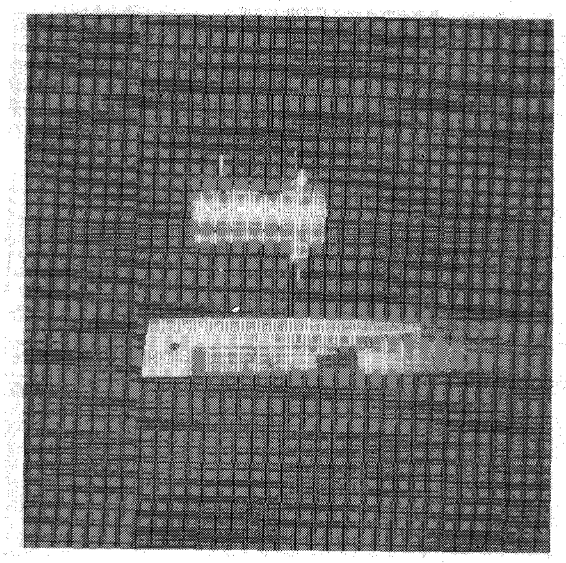


Fig. 13. A photograph of the experimental filter.

V. Conclusions

The novel realizations of the dual-hybrid-mode dielectric resonator filters described achieve the optimum response in simple inexpensive structures that do not require any iris. Measured results on three four-pole elliptic function filters are in excellent agreement with the theoretical calculations. Locating the coupling screw in a canonical dual-mode filter's first resonator symmetrically at a 45° orientation with respect to the input and output coaxial probes produces an additional pair of finite transmission zeros, which improves the filter selectivity. If out-of-band isolation of more than 30 dB is required, then the dual-mode longitudinal realization should be used. This realization, although equally simple, requires additional coupling screws and may result in an overall longer filter than the corresponding canonical realization.

The filter realizations described in this paper can open the door for using these high-quality microwave filters in applications previously not possible because of the high manufacturing and production costs of the earlier known realizations.

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