A TM_{11} Dual-Mode Dielectric Resonator Filter With Planar Coupling Configuration

Hai Hu, *Student Member, IEEE*, and Ke-Li Wu, *Fellow, IEEE*

***Abstract*—This paper presents a novel dielectric resonator filter exploiting dual TM_{11} degenerate modes. The dielectric rod resonators are short circuited on the top and bottom surfaces to the metallic cavity. The dual-mode cavities can be conveniently arranged in many practical coupling configurations. Through-holes in height direction are made in each of the dielectric rods for the frequency tuning and coupling screws. All the coupling elements, including inter-cavity coupling elements, are accessible from the top of the filter cavity. This planar coupling configuration is very attractive for composing a diplexer or a parallel multifilter assembly using the proposed filter structure. To demonstrate the new filter technology, two eight-pole filters with cross-couplings for UMTS band are prototyped and tested. It has been experimentally shown that as compared to a coaxial combline filter with a similar unloaded Q, the proposed dual-mode filter can save filter volume by more than 50%. Moreover, a simple method that can effectively suppress the lower band spurious mode is also presented.**

***Index Terms*—Bandpass filter, dielectric filter, dual-mode filter, TM mode.**

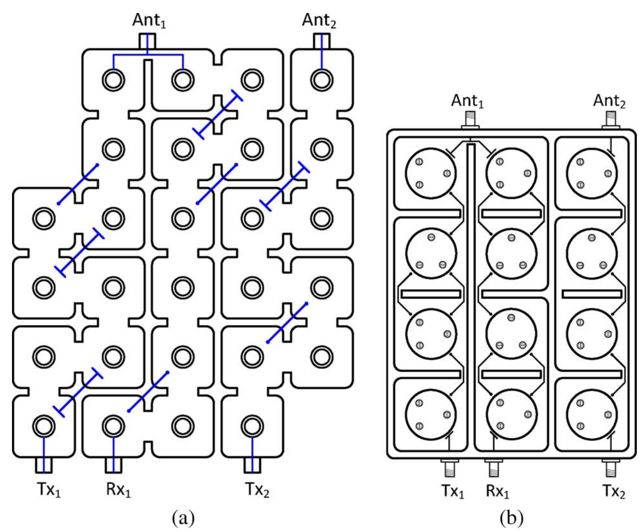

Fig. 1. Planar-coupled filter/diplexer configuration: (a) by conventional single mode coaxial resonators and (b) by the proposed dual-mode TM_{11} dielectric resonators.

I. Introduction

The dielectric resonator filter has been widely employed in space payloads and cellular base-station equipment due to their relatively compact size, good thermal stability, and high-Q performance. Since Cohn first theoretically and experimentally showed the possibility of making high-Q bandpass filters using the fundamental $TE_{01\delta}$ or $TM_{01\delta}$ mode of a cylindrical dielectric resonator [1] in 1968, some practical implementations of dielectric resonator filters have been used in space applications [2]–[4] in the 1980s. In these applications, the hybrid HEH_{11} mode, whose electromagnetic (EM) field resembles the TE_{11} mode in a hollow circular waveguide, was employed. In recent years, single-mode dielectric resonator filters, which have an obvious advantage in manufacturability and filter coupling configurations, have been widely used in wireless industry [5]–[9]. A comprehensive survey of single-mode dielectric filters for wireless application can be found in [10].

Multiple degenerate mode resonances in a dielectric resonator have also been explored by many researchers utilizing either the same type of modes with certain spatial symmetries or different types of modes resonating at the same frequency since the 1980s [11]–[18]. In the existing dual-mode dielectric resonator structures, the tuning element for the degenerate modes is neither in the same plane as other tuning elements [15]–[18], nor on a wall of the housing cavity [11]–[14]. The former introduces the nonconformity problem when a complex coupling layout is needed, and thus not feasible for a planar-oriented filter/diplexer unit in a wireless base station. An example of such a planar unit is illustrated in Fig. 1(a), where the planar-coupled filter/diplexer is realized by coaxial cavities. The latter causes difficulties in independent tuning of both self and mutual couplings. One of the reported planar-coupled dielectric resonator filters using TM_{11}-like degenerated modes was done by Hunter *et al.* [15], in which the conductor loaded dielectric resonator is situated in a large metal cavity in order to shift the resonance frequency to be the lowest mode. To effectively perturb the modes in such a resonator, the tuning metal plungers have to be intruded from the sidewalls of the cavity. Such tuning element arrangement is neither convenient for some practical filter and diplexer configurations, nor favorable for size reduction.

To develop a highly compact dielectric resonator filter for base-station application with moderate electric performance and a friendly tuning configuration, a novel TM_{11} dual-mode dielectric resonator filter is proposed in this paper. The proposed filter configuration can save filter volume by more than 50% as compared to a traditional coaxial filter with similar Q value. Both the resonators and all the coupling elements of the new

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The authors are with the Department of Electronic Engineering, The Chinese University of Hong Kong, Shatin, NT, Hong Kong (e-mail: hhu@ee.cuhk.edu.hk; klwu@ee.cuhk.edu.hk).

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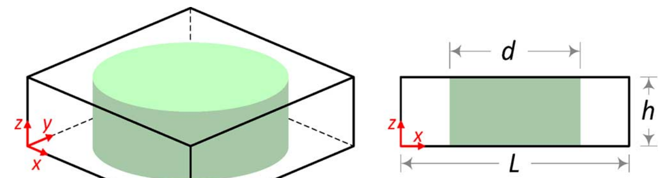
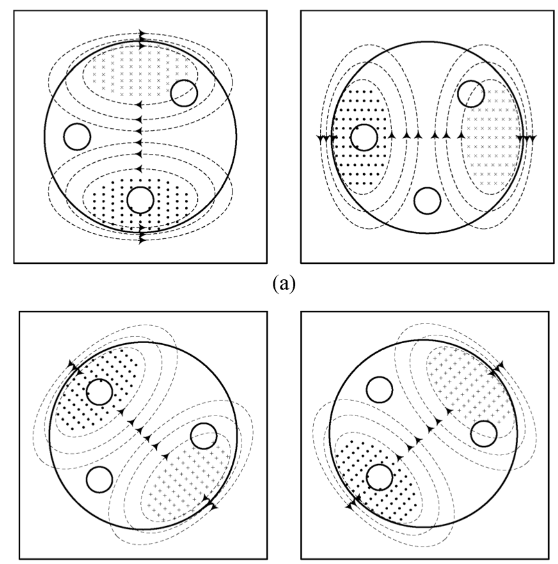
TM_{11} dual-mode filter are arranged in a planar manner. Each cylindrical dielectric rod is short circuited to the top and the bottom walls of the metal cavity. The inter-mode coupling and the self-coupling of each degenerate mode are realized through tuning screws penetrating into the through-holes pre-made in the rod along the axis. It can also be expected that the direct contact of the dielectric resonator with the cavity walls will help in heat dissipation and improvement of temperature stability. Being a dual degenerate modes used in one physical resonator, the proposed filter reduces the number of physical resonators by half. Another attractive attribute of the filter is that it allows all the couplings and their associated tuning elements to be accessible on the top lid of the filter cavity. Such a true planar coupling configuration provides the advantages in: 1) enabling the use of a dual-mode dielectric resonator filter in constructing a diplexer or filter/diplexer combined module in a planar layout, as is illustrated in Fig. 1(b); 2) creating a great flexibility of realizing various filter coupling topologies with both symmetric and asymmetric responses; and 3) significantly facilitating the filter assembling and tuning processes in mass production.

In this paper, the basic configuration and features of the proposed dual-mode dielectric resonator structure are given first. The electric field distribution and the achievable tuning and coupling range of the degenerate modes are provided. The details for the input/output (I/O) coupling, as well as the inter-cavity coupling structures are then presented. Finally, two examples of the proposed dual-mode filter for realizing symmetric and asymmetric general Chebyshev characteristics are demonstrated. A method that can effectively suppress the lower frequency spurious mode is also discussed in Section IV.



(a) (b)

Fig. 2. Resonator with dielectric rod short-circuited to the metallic cavity walls. (a) 3-D view and (b) cross-section view with dimension parameters.



(a)

(b)

Fig. 3. EM field modal plot (top view) of the TM_{11} degenerate modes in a resonator with the: (a) coupling hole on the cavity diagonal and (b) coupling hole on the horizontal axis. (*left*) v mode. (*right*) h mode. Dashed lines: H-field. Dots and crosses: E-field.

II. TM_{11} Dual-Mode Dielectric Resonator

In this section, the resonance modes of a short-circuited dielectric resonator is analyzed so as to select the proper dimensions of the dielectric rod, as well as the housing cavity for the best tradeoff between the resonator's Q factor and spurious behavior. Since the intended application of the proposed filter is in UMTS band, the resonance frequency f_0 is set to 1.95 GHz. In a prototype filter, the dielectric material with the relative permittivity $\varepsilon_r = 20.5$ and loss tangent $\tan\delta = 2.5 \times 10^{-5}$ will be used in the analysis and design. Metal conductivity $\sigma = 2 \times 10^7$ S/m is set to imitate the silver plated imperfect cavity in the Q-factor analysis.

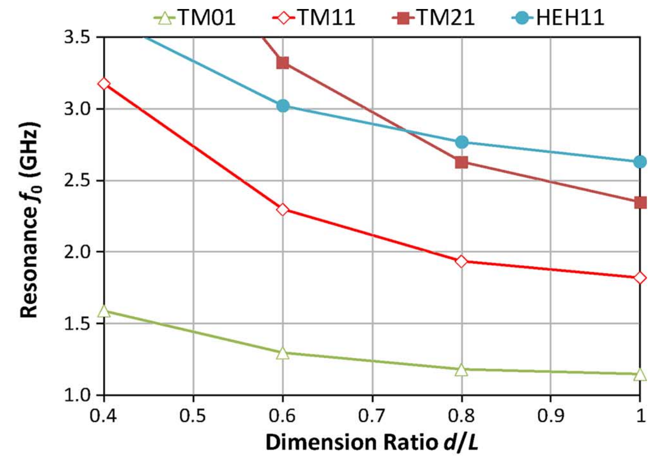
A. Resonator Structure and Its Resonance Modes

The TM_{11} mode resonator is constructed by a full height cylindrical dielectric rod situating in a metal cavity. It means that the dielectric rod is short circuited at both top and bottom surface by the metallic housing cavity, as shown in Fig. 2, where d is the diameter of the dielectric rod, L is the side length of the square cavity, and h is the height of the cavity. The side length, as well as the height of the cavity is chosen by trading off the spurious mode locations and the Q value of the resonator.

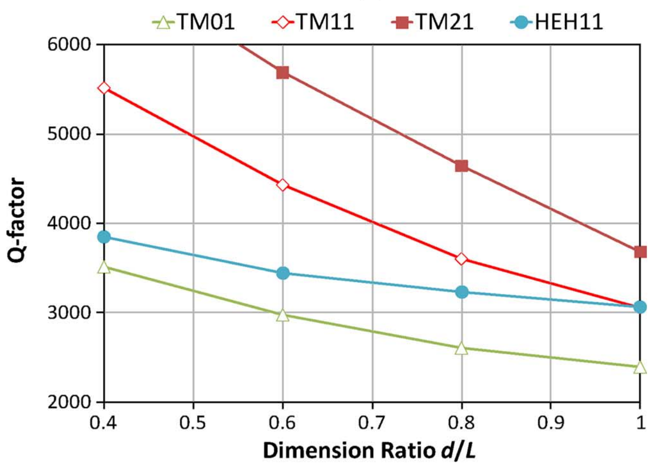
The first four resonance modes in the resonator are TM_{01}, TM_{11}, TM_{21}, and HEH_{11}. The first three modes are named according to the resemblance of their EM fields to the TM_{010}, TM_{110} and TM_{210} modes existed in a hollow cylindrical cavity, respectively. The fourth mode is a hybrid mode and is named HEH_{11} according to the traditional dielectric mode naming convention [19].

The TM_{01} mode is a single mode, which is widely used for building TM single-mode filters [6]–[9]. The TM_{11} mode is the first degenerate mode in the short-circuited dielectric resonator for an appropriate aspect ratio of d/h, and will be exploited in this paper for creating a TM_{11} dual-mode dielectric filter. A pair of orthogonal degenerate TM_{11} modes is shown in Fig. 3, where the electric field lines going out of and into the paper and the dashed lines are the magnetic field lines. If one of the modes is called the vertically polarized mode (v mode), then the other is the horizontally polarized mode (h mode). The location of the tuning elements can affect the polarizations of the dual modes as can be observed from Fig. 3(a) and (b).

The cavity size needs to be designed by trading off the filter's Q factor and the spurious-free frequency window. Taking a dielectric resonator with $L = 41$ mm, $h = 14$ mm dielectric resonator as an example, the variation of the resonance frequency and the Q factor of the first four modes versus the diameter d is

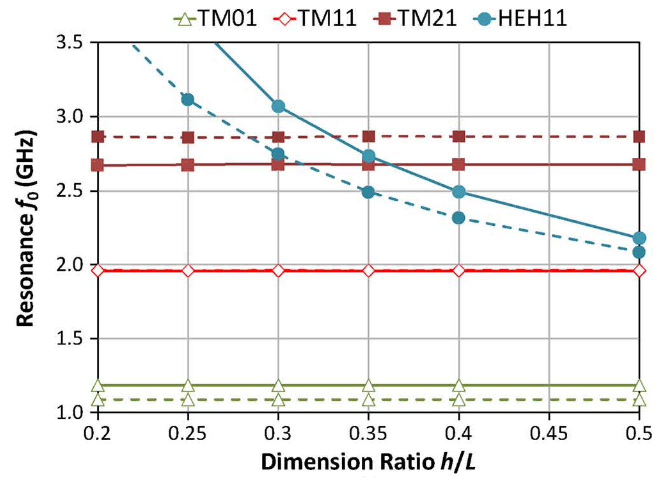


(a)

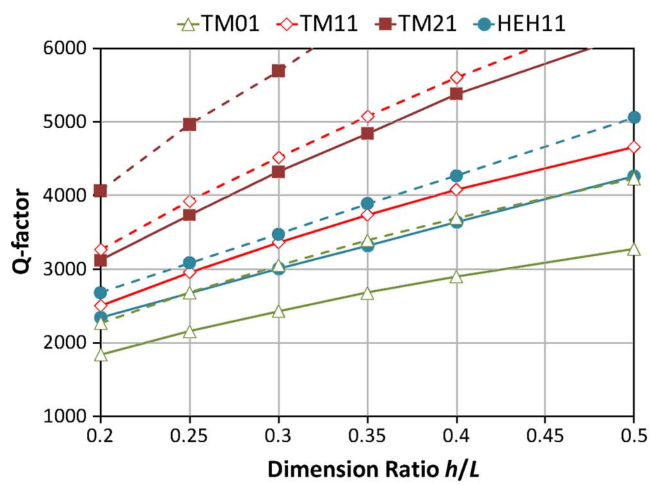


(b)

Fig. 4. First four modes of a short-circuited dielectric rod in a fixed L = 41 mm, h = 14 mm cavity with the change of d. (a) Resonance frequencies. (b) Q factors.



(a)



(b)

Fig. 5. First four modes of a short-circuited dielectric resonator with d and L fixed, h varies: (a) resonance frequencies and (b) Q factors. The solid lines are for the resonator with $d = 32.4$ mm, $L = 41$ mm, and the dashed lines are for the resonator with $d = 28.8$ mm, $L = 50$ mm.

shown in Fig. 4. It can be seen that as ratio $d/L = 0.8$, the TM_{11} mode resonance is near 1.95 GHz with a Q factor of 3600.

As revealed by Fig. 5, the cavity height h affects the Q factor and the spurious-free window of the resonator. In Fig. 5, two different-sized dielectric resonators are compared while retaining TM_{11} mode resonance frequency at 1.95 GHz: the dashed lines refer to the resonator with $d = 32.4$ mm, $L = 41$ mm, and the solid lines refer to the resonator with $d = 28.8$ mm, $L = 50$ mm.

After intensive parametric studies, several useful design rules for choosing the TM_{11} mode dielectric resonator dimensions can then be drawn:

1) with fixed h and L, a larger d gives lower f_0 and poorer Q;
2) with fixed d and L, increasing h within a certain range increases Q while f_0 and spurious resonances nearly unchanged;
3) with fixed f_0, a larger L and h gives better Q;
4) with fixed f_0, increasing L decreases d/L ratio.

B. Coupling Method of Degenerate Modes

A dual-mode resonator works by coupling energy from one mode to its degenerate mode in the same resonator. Therefore, the tuning and coupling structure is crucial to a dual-mode filter design. A good tuning structure should not only provide the required couplings independently, but also should be accessible in a convenient way. Traditionally, tuning screws or tuning disks are employed to perturb the EM fields near the dielectric rod [3], [4], [15]–[17]. Such perturbation easily reaches its maximum when tuning elements are inserted from a sidewall. In a dielectric resonator of the proposed filter configuration, three through-holes are pre-made at strategic locations, as shown in Fig. 6: two for adjusting the resonance frequencies of the two degenerate modes (self couplings) and one for adjusting the coupling between the two modes, where a is the distance from the center of a through-hole to the axis of the rod; c and c_0 are the diameters for the screws and the through-holes, respectively; t_f, t_v, and t_h are the penetration depths of the screws for the dual-mode coupling, v-mode frequency tuning, and h-mode tuning, respectively.

The distance a and the screw penetration depth t_f are the two main factors that influence the coupling coefficient M_{12} between the two degenerate TM_{11} modes. To quantify the coupling by the two parameters, a set of representative coupling values can be obtained using a commercial EM simulation software, e.g., HFSS, and sweeping parameter a with three different

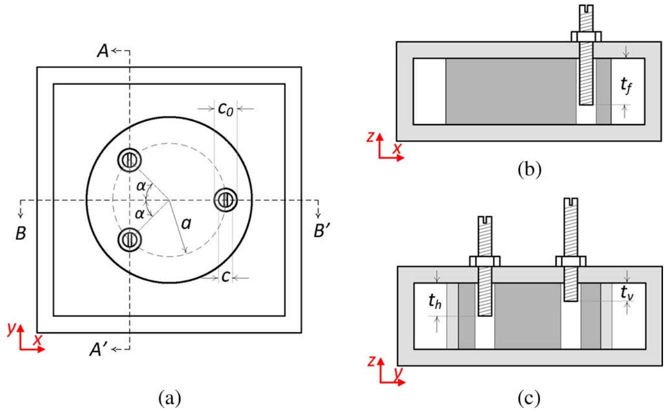


Fig. 6. TM dual-mode resonator degenerate mode tuning and coupling structure with key dimension parameters. (a) Top view. (b) BB' cross-section view. (c) AA' cross-section view.

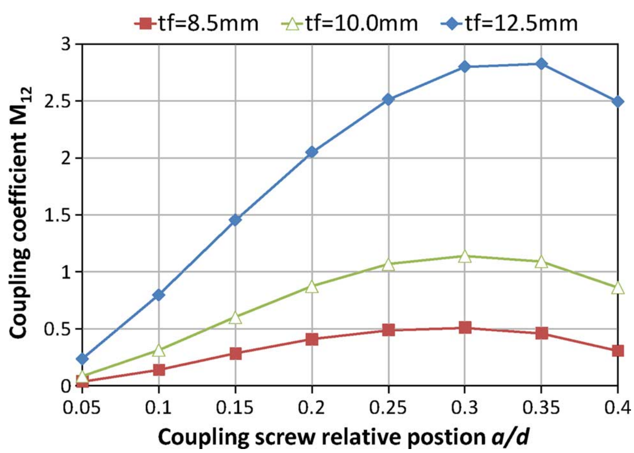


Fig. 7. TM_{11} degenerate mode coupling coefficient M_{12} change with the screw relative positions and penetration depths.

penetration depths t_f. The other dimensions of the resonator are $L = 41$ mm, $h = 14$ mm, $d = 32.4$ mm, $c = 3$ mm, and $c_0 = 4$ mm. For simplicity, the other two tuning screws and through-holes are omitted in the calculation of the coupling value. The coupling coefficient M_{12} is calculated by [19]

$$M_{12} = \frac{f_1^2 - f_2^2}{f_1^2 + f_2^2} \cdot \frac{f_0}{\mathrm{BW}} \tag{1}$$

where f_1 and f_2 are resonance frequencies of the two modes, and f_0 and BW are the center frequency and bandwidth (BW) of the filter, which are 1.95 GHz and 60 MHz in this case, respectively. The resultant M_{12} curves are shown in Fig. 7, where the ratio a/d around 0.3 gives the best location for the screw. At this location, the screw penetration depth between 8.5–10.0 mm can provide sufficiently large coupling coefficient.

To realize a filter with the proposed dual-mode resonators, in addition to the degenerate mode coupling, the I/O coupling, as well as the inter-cavity couplings must also be effectively created. In other words, convenient coupling configurations need to be designed for accommodating most of practical layouts of filters and diplexers for wireless base stations.

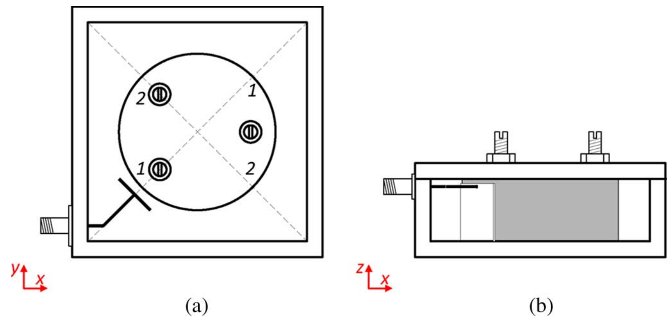


Fig. 8. Grounded strip loop structure for I/O coupling of a dual TM_{11} mode filter. (a) Top view of an end cavity. (b) Side view of the I/O coupling structure.

C. Coupling Method of I/O Coupling

Since the transversal magnetic field dominates the space near the dielectric rod in the TM_{11} mode, a grounded strip loop positioned with its area perpendicular to the magnetic field of the end resonator, as depicted in Fig. 8, is used to realize the I/O coupling. In the I/O coupling structure, one end of the loop is soldered to the SMA probe, while the other end is grounded to the lower floor of the cavity. By adjusting the distance between the loop and dielectric rod, the required I/O coupling can be achieved. It should be mentioned that a similar I/O structure has been used for a conventional TM single mode filter [9]. Special attention needs to be paid to the relative location of the input loop and the frequency tuning screw of the first (last) mode to which the energy is coupled.

As illustrated by Fig. 8, in order to maximally use the space of the metal cavity for realizing the couplings between two dielectric resonators and minimize the stray coupling between two metal cavities, the two frequency tuning screws are placed along the two diagonal lines.

D. Coupling Method of Inter-Cavity Coupling

An effective inter-cavity coupling structure for a dual-mode TM_{11} dielectric resonator filter can be realized by a conductor loop. The detailed structure is illustrated in Fig. 9, where the loop is formed by a metal wire with two ends short circuited to the upper conductor lid of the cavities. The metal wire is folded in a trapezoid shape in the horizontal lower side and vertical straight in the upper side. Fig. 9(a) shows the loops for the couplings between the resonance modes 2 and 3 and 1 and 4, respectively. Since the degenerate mode coupling screws of the adjacent dielectric rods excite two pairs of oppositely polarized v and h modes in each individual cavity, the inter-cavity couplings M_{23} and M_{14} realized by the two loops are in opposite signs, which may result in a pair of symmetric transmission zeroes on both sides of the passband.

The proposed inter-cavity coupling structure can be easily controlled by adjusting the height of the loop H, which is marked in Fig. 9(b). By pulling up or pushing down the pair of straight wires forming the coupling loop outside of the cavity lid, one can reduce or increase the coupling accordingly. It is worth mentioning that using the coupling loops, instead of irises, can effectively suppress the stray couplings.

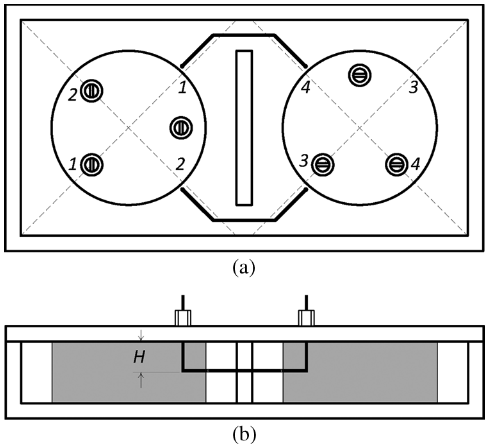


Fig. 9. TM_{11} dielectric resonator filter with V-shape inter-cavity coupling loops. (a) Top view. (b) Side view.

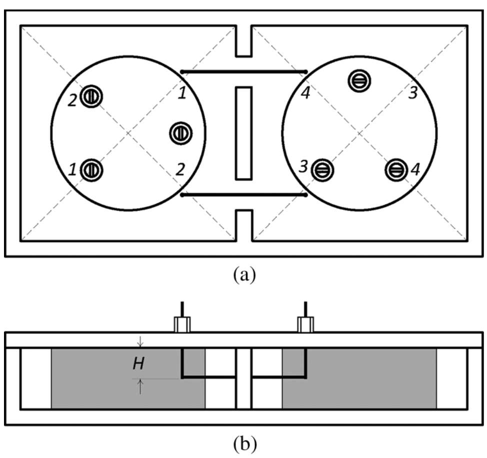


Fig. 10. TM_{11} dielectric resonator filter with the alternative inter-cavity coupling loops. (a) Top view. (b) Side view.

An alternative inter-cavity coupling structure uses a simple rectangular loop, as shown in Fig. 10. This structure provides a more convenient means for volume manufacturing and tuning than that shown in Fig. 9 without noticeable stray couplings.

Having studied all the required coupling structures, it has been demonstrated that all the coupling structures can be realized by mechanical elements adjustable on the top lid of a proposed dual-mode filter. Since there are no tuning elements to be accessed from the sidewalls, the planar coupling configuration is very suitable for constructing an integrated multiplexer or filter/multiplexer module.

III. Possible Filter Coupling Configurations

With the proposed TM_{11} dual-mode dielectric resonator cavity and the established coupling structures, many practical filter coupling configurations with symmetric and asymmetric characteristics can then be realized. In addition to the filter characteristics, the layout of dielectric resonators is also critical to a filter realization and applications in constructing a diplexer or a multiplexer.

Taking an eight-pole symmetric filter as an example, several practical layout schemes using the proposed dual-mode filter for realizing two or four symmetric transmission zeroes are studied in this paper. The filters illustrated in Fig. 11(a) and (b) are in a straight line layout while those in Fig. 11(c) and (d) are in a folded layout. The filters in Fig. 11(a) and (c) are in *folded* coupling topology [19], whereas those in Fig. 11(b) and (d) are in *cascaded-quartet (CQ)* coupling topology [19].

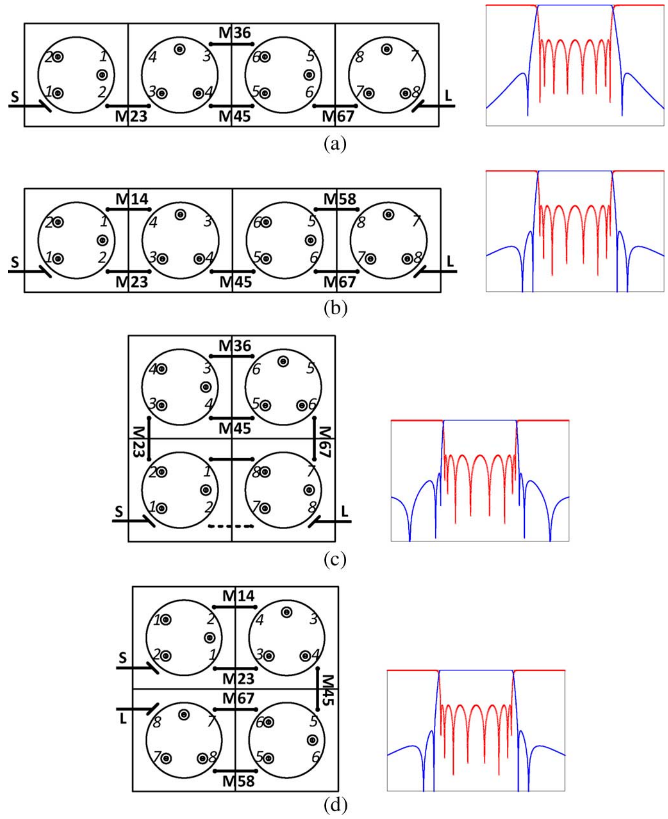


Fig. 11. Eighth-order symmetric filter coupling configurations and their ideal responses with the proposed TM_{11} dual-mode dielectric resonators. (a) *Folded* in straight-line layout. (b) *CQ* in straight-line layout. (c) *Folded* in folded-line layout. (d) *CQ* in folded-line layout.

When the TM_{11} dual-mode dielectric resonators are used for channel filters of a diplexer, a filter characteristics with independently controllable asymmetric transmission zeroes are usually required. Several possible practical layout schemes for such requirement are demonstrated in Fig. 12 for a typical eighth-order filter. The filters in Fig. 12(a) and (b) are in *box* and *extended-box* [19] coupling topologies, and are capable of generating two and three independent transmission zeroes, respectively. The filters in Fig. 12(c) and (d) are in *cul-de-sac* and *further cul-de-sac* [19] coupling topologies, and can generate five and three independent transmission zeroes, respectively.

IV. Design Examples

In designing a bandpass filter, a coupling matrix with an appropriate coupling topology to yield the desired BW and filter characteristic should be synthesized first. The dielectric resonator size and the minimum size of the metal cavity are designed by trading off the spurious-free frequency window and the unloaded Q value. The initial dimension designs of the resonators and the required coupling structures can be done using a full-wave EM software. In this study, Ansoft HFSS is used. The final full-wave design of a filter relies on

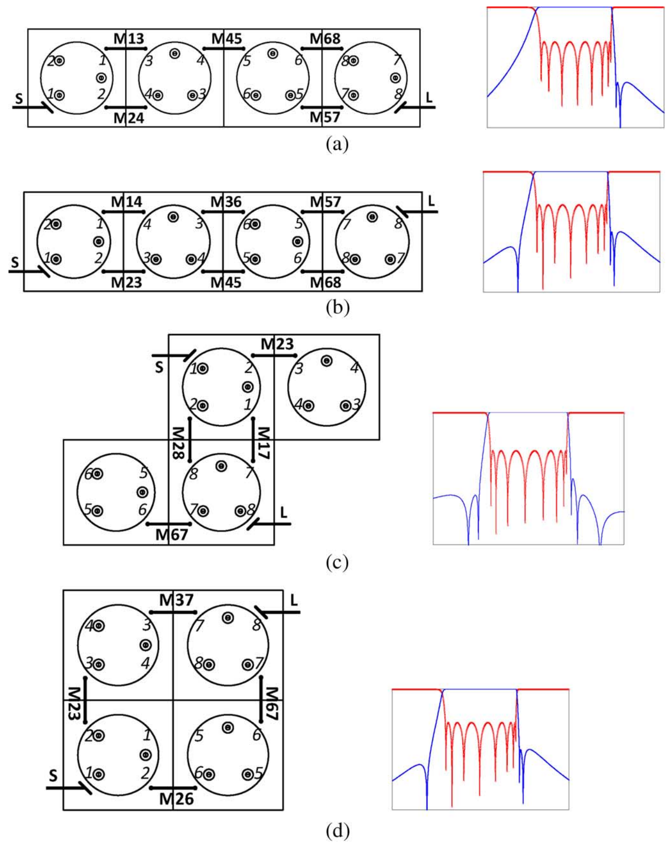


Fig. 12. Eighth-order asymmetric filter coupling configurations and their ideal responses for the proposed TM_{11} dielectric resonators. (a) *Box*. (b) *Extended-box*. (c) *Cul-de-Sac*. (d) *Further Cul-de-Sac*.

TABLE I
COUPLING MATRIX FOR THE EIGHT-POLE FOLDED-COUPLED FILTER

M_{01}	0.9882	M_{36}	-0.1014	M_{78}	0.8178
M_{12}	0.8178	M_{45}	0.6376	M_{89}	0.9882
M_{23}	0.5877	M_{56}	0.5393		
M_{34}	0.5393	M_{67}	0.5877		

the computer-aided tuning technique proposed in [20]. In this section, two design examples are shown to validate the concept of the proposed TM_{11} dual-mode dielectric resonator and to demonstrate the attractive features of the proposed bandpass filter.

A. Eight-Pole Symmetric Filter in a Folded Topology

In this example, the center frequency f_0 and BW for the prototyped filter is 1.948 GHz and 67 MHz, respectively. Four dielectric resonators with radius $R = 16.2$ mm, relative permittivity $\varepsilon_r = 20.5$, and loss tangent 2.5×10^{-5} are used. For each metal cavity the inner size is $41 \times 41 \times 14$ mm^3. The *folded* coupling topology with straight line layout, as is shown in Fig. 11(a), is adopted in this design example. The coupling matrix which gives 20-dB return loss and two 60-dB sidelobe filter characteristic is synthesized with a standard procedure [19] and is given in Table I.

The designed filter is prototyped and measured. A photograph of the filter hardware is shown in Fig. 13, where both the top and the bottom surfaces of the dielectric rods were silver plated for a better contact with the housing. A proprietary technique was employed to create mechanical stress to minimize any possible air gap between the dielectric rods and the housing. The measured and the circuit model (with $Q_u = 3000$) S-parameters of the prototype filter are superimposed in Fig. 14. It can be seen that the measured insertion loss at f_0 is less than 0.5 dB, and the extracted unloaded Q factor from the measured data is slightly more than 3000. A slight asymmetry of the sidelobes is caused by a weak stray coupling between the dielectric resonator 2 and 3. It is worth mentioning that the overall volume of the prototype filter is less than half of that of a conventional coaxial cavity filter of the same order with a comparable unloaded Q value.

Fig. 13. Photograph of the prototyped eight-pole TM_{11} dual-mode dielectric resonator filter hardware with upper lid removed.

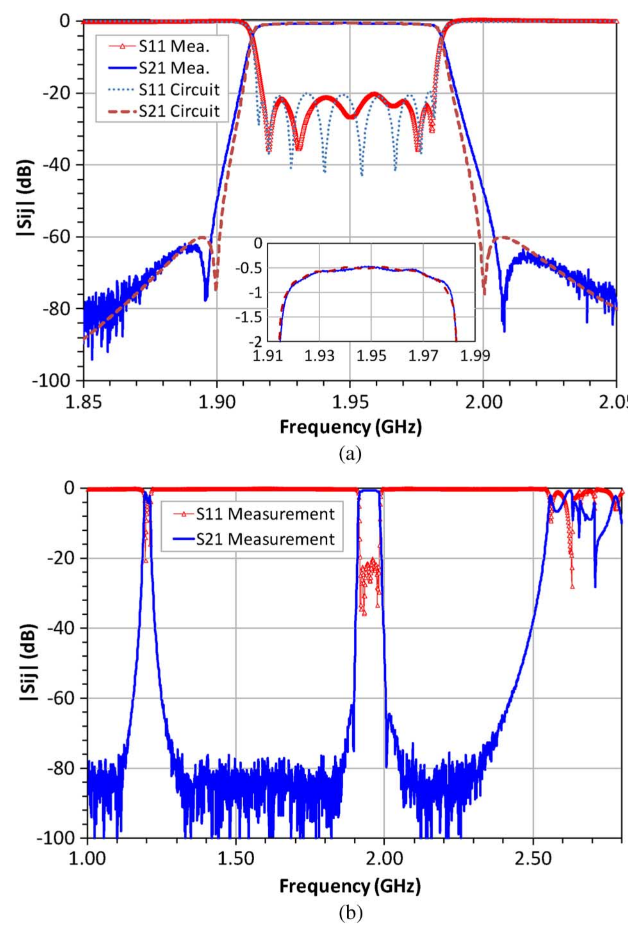


Fig. 14. Measured result of the eight-pole TM_{11} dual-mode dielectric resonator filter. (a) In-band S-parameters responses. (b) Broadband S-parameters responses.

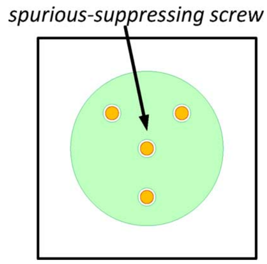


Fig. 15. Top view of the TM_{11} dielectric resonator with TM_{01} spurious mode suppression screw in the center.

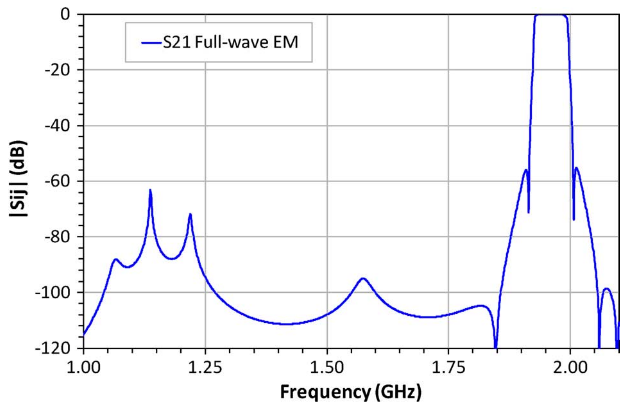


Fig. 16. S_{21} curve of the TM_{11} dielectric resonator filter with lower spurious TM_{01} mode suppressed.

From the broadband response of the prototype filter shown in Fig. 14(b), it can be observed that the lower spurious mode TM_{01} is below 1.25 GHz and the higher spurious mode TM_{21} is above 2.55 GHz. These two spurious modes can be easily suppressed by cascading a wideband bandpass filter.

The TM_{01} spurious mode can also be suppressed by a self-contained method. To illustrate the simple suppression method, the same filter is redesigned. With the proposed method, the spurious mode can be suppressed by introducing an additional through-hole at the center of each dielectric resonator and a metal tuning screw inserted into the hole, as is shown in Fig. 15. By adjusting penetration of the central tuning screws to different depths for the four resonators, the TM_{01} resonance frequencies in each dielectric resonator will be different and will be spread in a broad frequency range so that very weak signal carried by the mode can pass through the filter. The suppression effect by this method has been very well demonstrated in Fig. 16, where the spurious resonance has been suppressed to below -60 dB. Since the spurious mode suppression is not a major concern of this paper, only the result by full-wave EM simulation is given here.

B. Eight-Pole Asymmetric Filter in a Box Coupling Topology

In the second example, a bandpass filter with $f_0 = 1.955$ GHz and $\text{BW} = 65$ MHz is EM designed. The size and the number of the TM_{11} dielectric resonators used in this example are the same as those in example 1. The only difference is that a *box* coupling configuration is adopted to realize two transmission zeroes all located on the upper rejection band so that a very sharp selective band-edge on the higher frequency end of the filter passband can be achieved. The coupling matrix for this design example is listed in Table II.

TABLE II
COUPLING MATRIX FOR THE EIGHT-POLE BOX-COUPLED FILTER

M_{01}	1.0291	M_{68}	-0.2515	M_{44}	0.0586
M_{12}	0.4027	M_{57}	0.7296	M_{55}	0.0564
M_{13}	-0.7539	M_{78}	0.4452	M_{66}	0.3399
M_{24}	0.2143	M_{89}	1.0291	M_{77}	-0.8397
M_{34}	0.5187	M_{11}	0.0176	M_{88}	0.0176
M_{45}	0.5485	M_{22}	-0.8884		
M_{56}	0.4998	M_{33}	0.2790		

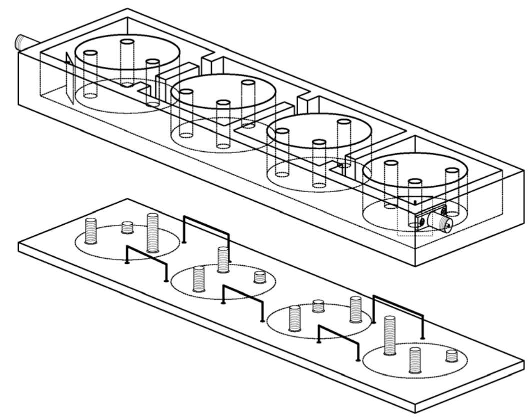


Fig. 17. Full-wave EM model of the eight-pole TM_{11} dielectric resonator filter in *box* coupling topology.

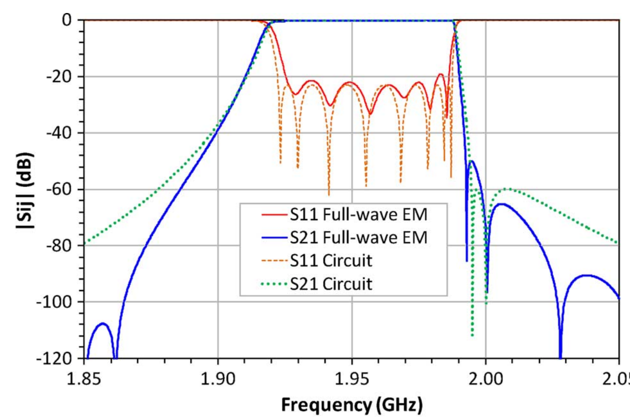


Fig. 18. S-parameters comparison between the full-wave EM model and the circuit model of the eight-pole asymmetric filter in *box* coupling topology.

The perspective view of the filter realization is shown in Fig. 17. The designed filter responses from the full-wave EM analysis are compared with those from a circuit model of the coupling matrix and are shown in Fig. 18. It can be observed that the two major finite transmission zeroes on the upper rejection band have been realized. The other minor transmission zeroes are caused by some inevitable stray cross couplings, which, in this example, happen to help sharpen the rejection response.

V. CONCLUSION

A compact TM_{11} dual-mode dielectric resonator has been proposed in this paper. The proposed resonator is very suitable for a planar coupling configuration and effective heat dissipation. High-Q dielectric resonator filters with versatile coupling schemes can be achieved using the proposed dual-mode resonators and coupling mechanism. The tuning screws inserted into the through-holes in dielectric resonators can effectively control the required coupling of the two degenerate modes and the frequency offsets. Moreover, some practical coupling schemes and resonator structure layouts using the proposed resonator and coupling configuration for realizing symmetric and asymmetric filter characteristics are also discussed in the paper. Two design examples with full-wave EM software and the experiment results of one hardware prototyped filter are presented to validate the proposed resonator concept. Excellent agreement between the theoretical and the measured results is obtained, demonstrating the superior features of the proposed dielectric dual-mode resonator filter.

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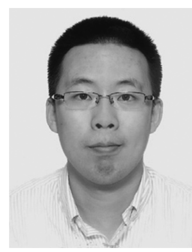

Hai Hu (S'10) received the B.Sc. degree from Nanjing University, Nanjing, China, in 2004, the M.Phil. degree from The Chinese University of Hong Kong, Shatin, NT, Hong Kong, in 2006, both in electronic engineering, and is currently working toward the Ph.D. degree at The Chinese University of Hong Kong.

From 2006 to 2010, he was a Research Assistant with the Department of Electronic Engineering, The Chinese University of Hong Kong, where he was involved with numerical modeling of low-temperature co-fired ceramic (LTCC) layouts and passive integrated circuit components, automatic design of dual-mode waveguide filters, and manifold multiplexers for payload systems. His research include nonplanar filter, such as dielectric filter and compact multimode filter design and application for next-generation wireless base-station systems, analytical computer-aided tuning (CAT) techniques, computational EM algorithms for modeling of waveguide structures, and frequency- and time-domain numerical modeling and analysis of multilayered high-speed RF circuits.

Ke-Li Wu (M'90–SM'96–F'11) received the B.S. and M.Eng. degrees from the Nanjing University of Science and Technology, Nanjing, China, in 1982 and 1985, respectively, and the Ph.D. degree from Laval University, Quebec, QC, Canada, in 1989.

From 1989 to 1993, he was with the Communications Research Laboratory, McMaster University, as a Research Engineer and a Group Manager. In March 1993, he joined the Corporate Research and Development Division, COM DEV International (the largest Canadian space equipment manufacturer), where he was a Principal Member of Technical Staff. Since October 1999, he has been with The Chinese University of Hong Kong, Shatin, HT, Hong Kong, where he is currently a Professor and the Director of the Radio Frequency Radiation Research Laboratory (R3L). He has authored or coauthored numerous publications in the areas of electromagnetic (EM) modeling and microwave passive components, microwave filters, and antenna engineering. His current research interests include partial element equivalent circuit (PEEC) and derived physically expressive circuit (DPEC) EM modeling of high-speed circuits, RF and microwave passive circuits and systems, synthesis theory and practices of microwave filters, antennas for wireless terminals, LTCC-based multichip modules (MCMs), and RF identification (RFID) technologies. His research group is the main workforce in various active RFID research and applications in Hong Kong.

Prof. Wu is a member of the IEEE MTT-8 Subcommittee (Filters and Passive Components). He is a Technical Program Committee (TPC) member for many prestigious international conferences including the IEEE Microwave Theory and Techniques Society (IEEE MTT-S) International Microwave Symposium (IMS). He was an associate editor for the IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES (2006–2009). He was the recipient of the 1998 COM DEV Achievement Award for the development of exact EM design software of microwave filters and multiplexers and the 2008 Asia–Pacific Microwave Conference Prize.