# High-$Q$ TE01 Mode DR Filters for PCS Wireless Base Stations

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***Abstract*—This paper presents the state-of-the-art of high-$Q$ TE01 mode DR cavity filters for PCS wireless base station applications. In order to have TE01 mode filter to be competitive with other high-$Q$ cavity technologies, employment of nonadjacent coupling to implement advanced filter features and easy filter machining and integration are essential. The quadruplet and trisections are regarded as basic blocks to implement symmetric and asymmetric transmission zeros in filter stop band. The relative alignment of the magnetic mode field across the coupled adjacent cavities is analyzed to identify the sign of nonadjacent coupling. A direct cascading of a wide band combline filter to a TE01 mode dielectric resonator (DR) filter is proposed to suppress the spurious response of the DR cavity filter. This approach simplfies the integration between the DR filter and the spurious suppression device and has been proved to be very cost effective. Experimental eight- and six-pole quasi-elliptic function filters show the typical performances. To take advantage of the special property of magnetic mode field alignment across the adjacent cavities, a five-pole canonical asymmetric filter with three transmission zeros in low side is implemented. We believe this filter is a new design for high-$Q$ cavity filter, while a three-pole elliptic function filter is new for DR filter technology.**

***Index Terms*—Cross coupling, dielectric resonator, filter.**

## I. Introduction

DIELECTRIC resonator (DR) cavity filters have been used for satellite communications since the early 1980's due to their high-$Q$ ($>$10 000) and compact size. The temperature stability [1]–[3] and the employment of HEH11 dual-mode are regarded as major breakthroughs for DR cavity filters [4], [5]. The single TE01 mode cavities did not attract much attention for satellite applications, due to the fact that they provided no significant advantage over an air-filled cylindrical dual-mode cavity [6] if transmission zeros could not be implemented in the stop band.

However, the TE01 mode filter with planar layout, as in Fig. 1, offers many advantages over an in-line configuration. The overall performance requirements for filters and multiplexer networks for wireless base stations and satellite applications are quite different. The cost of each individual filter and the issue of mass production are much more crucial than volume and weight in wireless base station applications. In the authors' opinion, the electrical performance of the state-of-the-art TE01 mode DR filter almost can match the performance of the HE11 dual-mode DR filter because the cross-coupling techniques have been developed for quasi-elliptic function filters. Also, asymmetric filter response with multiple transmission zeros in stop band have been successfully implemented. TE01 single-mode filters offer the advantages of design simplicity, flexibility in layout options, and low-cost manufacturing over HE11 dual-mode filters; the corresponding drawbacks are greater size and weight.

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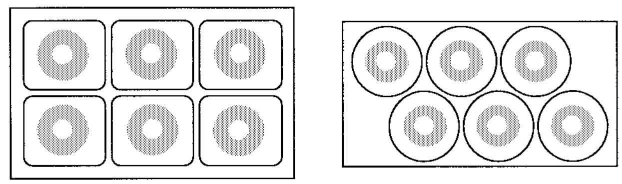


Fig. 1. Planar filter layouts for high-$Q$ TE01 mode DR cavity filter.

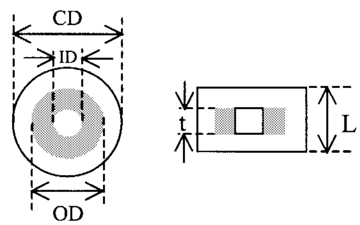



Fig. 2. Configuration of TE01 mode DR cavity.

The interest of this paper is to present the technology innovation of TE01 mode DR cavity filter for PCS wireless base station applications. In Section II, the aspects of the cavity performances and design are presented. The coupling designs, include nonadjacent coupling, are described in Section III. A direct cascading of a wide-band combline filter is suggested to provide spurious suppression and the advantage is analyzed in Section IV. In Section V, several design examples are presented. The conclusions are summarized in Section VI.

## II. Cavity Performance and Design

### A. Cavity Performance

For high-$Q$ microwave filters, the cavity electrical performances and size/weight should be assessed simultaneously. This is due to the fact that the high-$Q$ microwave filters always occupy a significant amount of space in a transceiver subsystem, especially in $L$-band.

Fig. 2 shows a basic configuration of a TE01 mode DR cavity. The conductive enclosure can be a circular or rectangular cavity. In order to limit the loss from conductive enclosure, the cavity diameter $(CD)$ usually is greater than 1.5 times the DR diameter $(OD)$, and the height of the cavity $(L)$ is

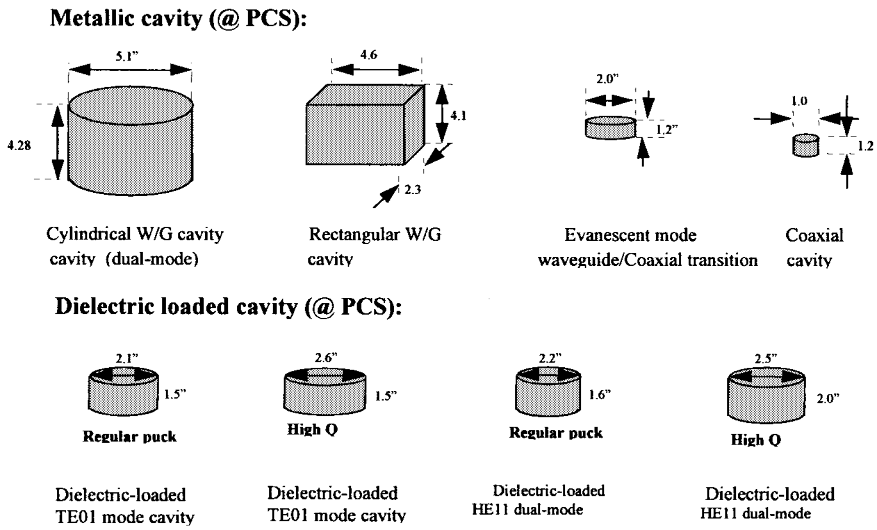



Fig. 3. Typical cavity sizes for metallic and DR cavities at PCS frequencies.

TABLE I
VOLUME AND CAVITY UNLOADED $Q$ FOR SOME HIGH $Q$ CAVITIES AT PCS FREQUENCIES

| Cavity Type | Volume (in$^3$) | CavityQu | Qu/Volume |
|---|---|---|---|
| Cylindrical TE11 dual-mode cavity (air) | 87.2/2 | 29,500[1] | 676 |
| Rectangular TE01 mode cavity (air) | 43.3 | 19,200[1] | 443 |
| Coaxial cavity (air) | 1.4 | 3,000[2] | 2,142 |
| Combline /Evanescent mode cavity (air) | 3.8 | 6,000[2] | 1,428 |
| DR TE01 mode cavity # 1 ( $\varepsilon_r = 44.0$) | 5.2 | 18,500[3] | 3,653 |
| DR TE01 mode cavity # 2 ( $\varepsilon_r = 29.5$) | 7.9 | 30,700[3] | 3,987 |
| DR HE11mode cavity # 1 ( $\varepsilon_r = 44.0$) | 6.1/2 | 20,000[3] | 6,721 |
| DR HE11mode cavity # 2 ( $\varepsilon_r = 29.5$) | 9.8/2 | 29,500[3] | 6,938 |

1: theory; 2: estimated; 3: measured (with puck supported by low desity form support)

TABLE II
MEASURED DIELECTRIC $Q$ OF SOME COMMERCIAL MATERIALS

| | $\varepsilon_r$ | $Q_d$ (measured) | Measured fo (MHz) | Measured $Q_d f$ |
|---|---|---|---|---|
| A | 44.0 | 22,000 | 1800 | 39.6K |
| B | 36.3 | 16,800 | 1943 | 32,6 K |
| C | 34.0 | 23,800 | 1900 | 45.2 K |
| D | 29.5 | 47,600 | 1778 | 84.6 K |
| E | 21.0 | 52,000 | 1944 | 102.2 K |

*: f in GHz

about three times that of DR thickness $(t)$. Fig. 3 shows the relative cavity size/volume for several typical designs of high-$Q$ cavity resonators at PCS frequencies. The cavity volume and unloaded $Q$, $Q_u$ (theoretical or measured) are summarized in Table I. The last column of the Table I shows the cavity $Q$ to volume (in$^3$) ratio. This value can be used to assess how efficiently the volume is used to produce cavity $Q$ for each cavity. The results in this table indicate that the coaxial cavity is very efficient in cavity miniaturization (compared to waveguide cavity), while the maximum achievable $Q$ is limited. In order to increase the maximum achievable cavity $Q$, the cross section of the coaxial resonator can be increased. The resonator is working within the transition region between TEM and evanescent mode waveguide [7], but the efficiency in volume utilization is reduced. The DR loaded cavity not only has the best efficiency in volume utilization to produce cavity $Q$, but also has maximum achievable $Q$ (a slightly better than cylindrical dual-mode cavity). For a DR cavity, the TE01 mode is the fundamental mode and has the smallest size. The HEH11 mode can be the first high-order mode and its volume is about 20–30% larger than the fundamental one. One physical HEH11 mode cavity can be used twice electrically and thus result in a smaller filter size. Table II summarizes the measured resonator dielectric $Q$ (i.e., 1/loss tangent), $Q_d$, for some commercially available materials. Table II is obtained by subtracting the enclosed conductor loss from measured TE01 DR cavity $Q$. The DR puck is supported by low density form in order to have minimum effect by supporting. The enclosure $Q$ is computed by rigorous mode-matching technique. The materials A and D in Table II are used for the computations of DR cavity size and $Q_u$ (theory) in Fig. 3 and Table I.

### B. Cavity Design

The design of a TE01 mode DR cavity should include cavity $Q_u$, size, and spurious responses. In this paper, they are computed by a rigorous radial mode-matching technique [8], [9]. The cavity $Q_u$, size, and spurious responses are dictated by the DR aspect ratio, which is defined as the ratio of DR diameter $(OD)$ to DR thickness $(t)$, as shown in Fig. 2. The aspect ratio of the DR cavity should be properly chosen, otherwise the high-order modes may be too close to the working mode. Mode charts [8], [9] have been proposed to design DR cavities. The mode chart of a solid DR with dielectric constant of 44 is shown in Fig. 4(a). It is also well known that to open a hole in the center of TE01 mode DR [8], [9] can increase the spurious free region of the cavity, as shown in Fig. 4(b). This is due to the fact that the TE01 mode DR cavity has a minimum electric field at the DR center, while all the closer spurious regions have maximum electric fields. The results in Fig. 4 suggest that the aspect ratio of the TE01 mode DR $(\varepsilon_r = 44.0)$ cavity can be chosen around 2.5 and the diameter of the center hole can be opened up to 35% of the DR diameter. The relative mode locations in the frequency spectrum are not a strong function of the conductive enclosure.

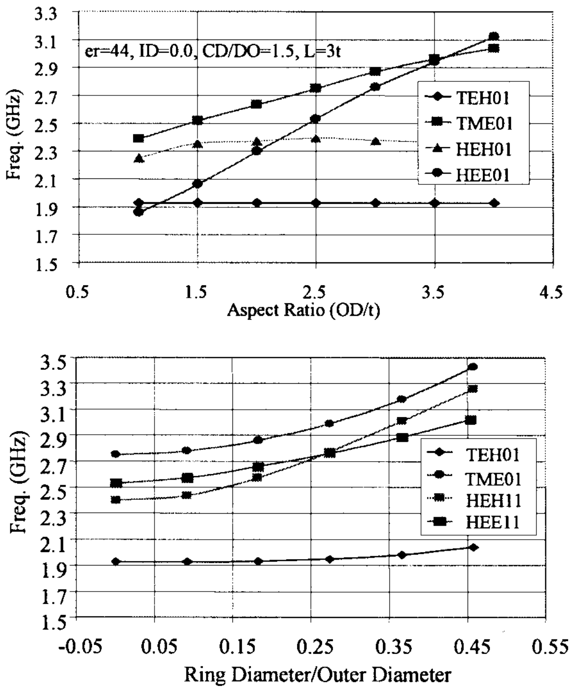



Fig. 4. Mode chart of a TE01 mode DR solid and ring resonator ($\varepsilon_r = 44.0$).

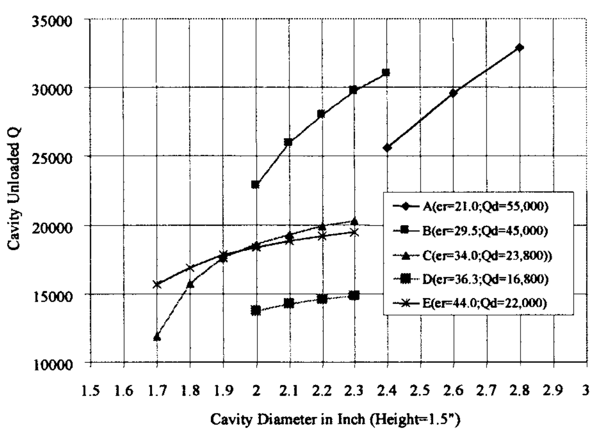



Fig. 5. TE01 mode DR cavity $Q$ as a function of enclosure diameter.

The mode charts in Fig. 4 suggest that HE11 (HEH11) and HE12 (HEE11) modes are the closer spurious frequencies, but TM01 mode is usually the one that causes interference in pass-band [10], [11]. This is due to the fact that the TM01 mode has much stronger coupling through coupling iris and is more sensitive in frequency tuning than other modes. Either bigger coupling iris or excess frequency tuning can move the coupled TM01 mode down to close the working mode. Too small an enclosure will degrade the cavity $Q_u$ significantly. The simulated cavity $Q_u$ as a function of enclosure diameter is shown in Fig. 5.

### C. Cavity $Q$ That Can Be Recovered for Filter Realization

The results in Fig. 5 do not show the effects of the supporting structure. The cavity $Q_u$ that can be achieved for a filter implementation is a function of supporting structure design [12], coupling iris size [13], and tuning of the cavity resonant frequency [14]. The supporting structure design and material choice has always been a challenge for both design and manufacturing. The achieved filter $Q$, $Q_{u,f}$ can be related to DR dielectric $Q$ and cavity $Q$, $Q_{\mathrm{cty}}$ by

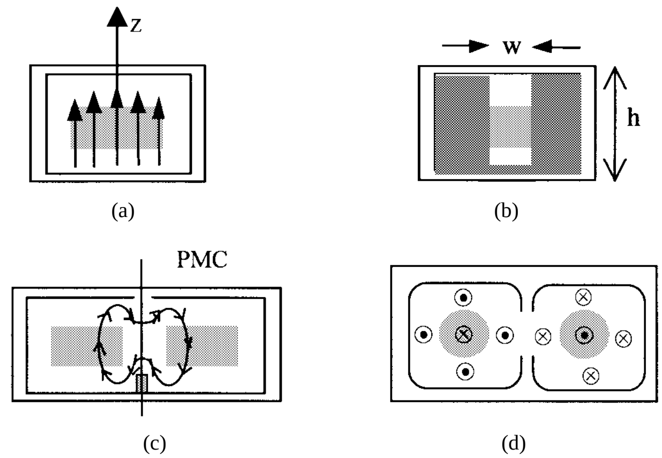



Fig. 6. (a) Magnetic field on the sidewall. (b) Suggested coupling iris structure. (c) Magnetic fields between two coupled cavities with PMC at center. (d) Magnetic mode fields from top view of the coupled cavities in (c).

$$\frac{1}{Q_{u,f}} = \frac{1}{Q_{\mathrm{cty}}} + \frac{1}{Q_{k,t}} = \frac{1}{Q_d} + \frac{1}{Q_{\mathrm{sup}}} + \frac{1}{Q_c} + \frac{1}{Q_{k,t}} \tag{1}$$

where $Q_{\mathrm{sup}}$ represents the cavity $Q$ degradation by supporting, $Q_c$ is for conductive enclosure, while $Q_{k,t}$ is for coupling and tuning. One can choose a large cavity diameter in order to reduce cavity $Q$ degradation by $Q_c$. Practically, $Q_c$ cannot be increased infinitely because substantial field strength on the cavity wall is necessary to produce intercavity coupling. Spurious can also move down to close the TE01 mode. It may cause pass-band interference or a better spurious suppression device is required to clear the spurious. Those effects can offset the advantage of the increasing of cavity $Q$ by increasing the cavity size. From our experiences, the recovered rate of $Q_{u,f}$ can be as high as 85% from $Q_{\mathrm{cty}}$ and 70% from $Q_d$.

## III. Coupling Design

### A. Adjacent Coupling Through Iris

The iris structure design for coupled cavities should consider the electromagnetic field alignment. The iris should be open at the location of maximum magnetic field and also parallel to its direction. For planar structure of TE01 mode cavity filters, as shown in Fig. 1, the iris is opened along the $z$-direction, as shown in Fig. 6(a). The suggested coupling structure is depicted in Fig. 6(b). It is found that the iris width $\boldsymbol{w}$ should not be too wide in order to keep the frequency of the coupled TM01 mode away from that of the TE01 mode. The TM01 mode has much stronger coupling than the TE01 mode, and the width of the iris is the direction that the magnetic fields align. There are two eigen modes for a pair of symmetric coupled cavities. One corresponds to inserting a perfect electric wall between them, the other one is by a perfect magnetic wall. The actual field distribution is a linear superposition of those two eigen modes. For magnetic coupling, the mode field with

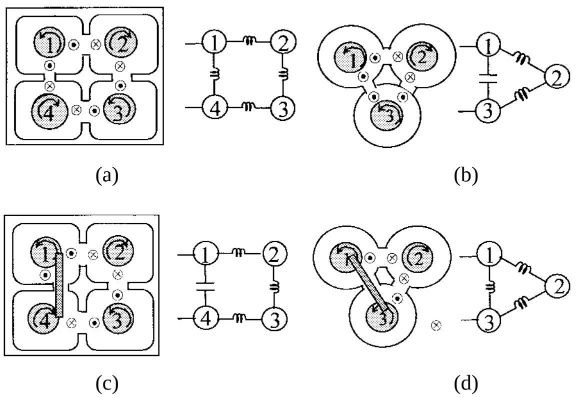



Fig. 7. (a) A quadruplet section with positive cross coupling between cavities 1 and 4. (b) A quadruplet section with negative cross coupling between cavities 1 and 4. (c) A tri-section with negative cross coupling between cavities 1 and 3. (d) A tri-section with positive cross coupling between cavities 1 and 3.

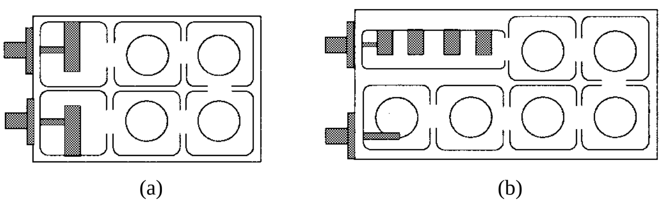



Fig. 8. (a) Approach I and (b) approach II to improve DR cavity spurious performance.

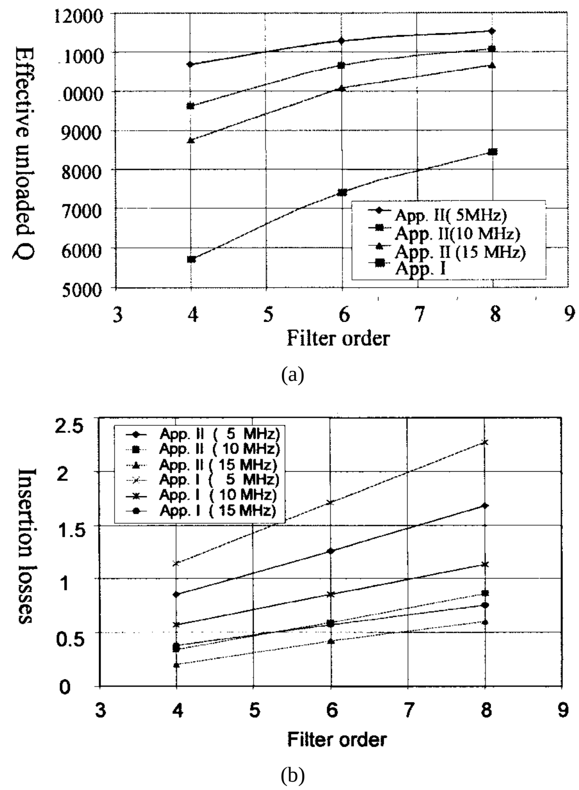



Fig. 9. Effective unloaded $Q$ and insertion losses of Chebyshev filters of approaches I and II in Fig. 8.

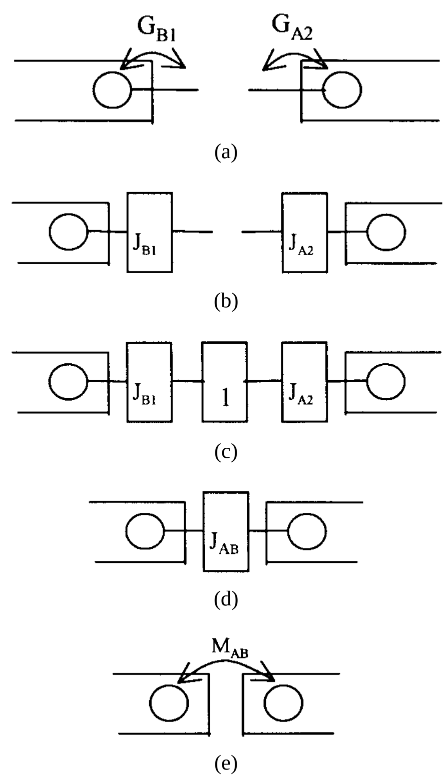



Fig. 10. The design of coupling between the output resonator and the input resonator of two filters with the same center frequency and different bandwidths.

magnetic wall at center dominates because major disturbed energy around the coupling region is the magnetic one. This principle is true for coupling through small aperture [15], [16], large aperture, or asymmetric cavities [17], [18]. The side and top view of the magnetic fields of two coupled DR TE01 mode cavities are shown in Fig. 6(c) and (d). The tangential magnetic fields across the iris seem to have discontinuity because the magnetic field of the working mode changes sign (or direction) across the iris. But the localized fields (i.e., high-order modes) will dominate the fields around the iris and make sure the total tangential fields are continuous across the boundary. The relative magnetic field orientation of the working mode across the adjacent cavities is very important in determining the sign of nonadjacent coupling, which we will discuss later on. Rigorous mode-matching technique [19] or an empirical approach can be used to obtain the dimensions of the iris.

### B. Nonadjacent Coupling

Nonadjacent coupling can be used to realize advanced filter features, such as quasi-elliptic function, constant delay, and asymmetric responses. A negative nonadjacent coupling for a quadruplet section had been realized with stacked cavity configuration (cavity 1 and 2 on low level; 3 and 4 on high level) and offsetting the DR's (1 and 4) that produce negative coupling [20], [21]. Here, we are not only interested on quasi-elliptic function realization, but also the filter with asymmetric response. Quadruplet and tri-sections can be regarded as basic function blocks to generate symmetric and asymmetric transmission zeros. Quadruplet [22], [23] and tri-sections [24] for TE01 mode cavities and their equivalent coupled-resonator model are shown in Fig. 7. In Fig. 7, magnetic coupling is

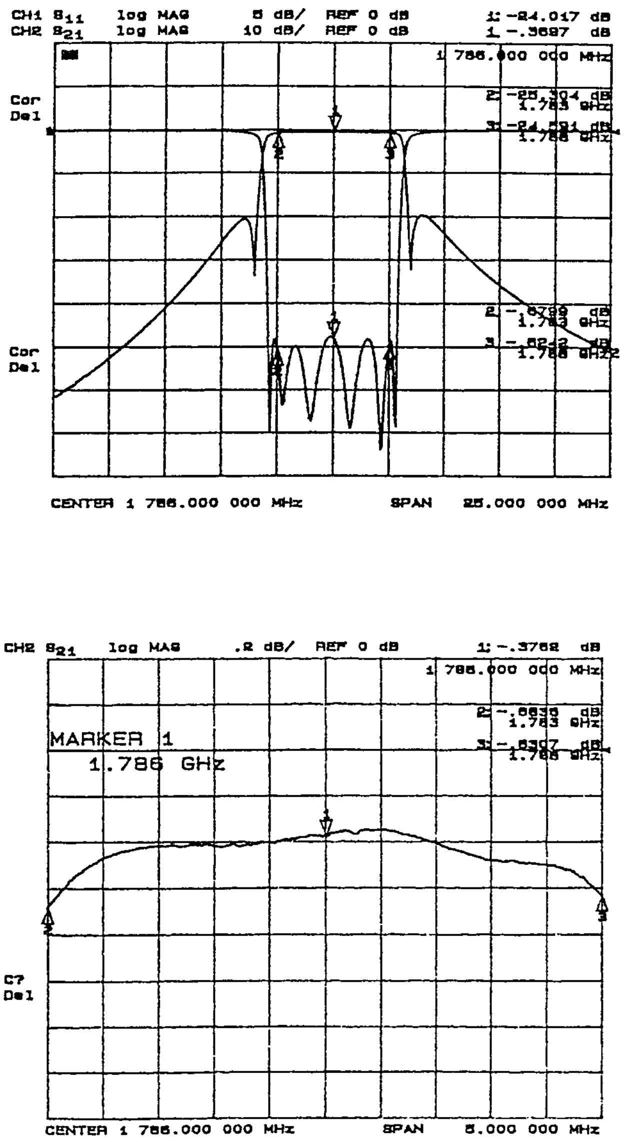



Fig. 11. Measured response of a six-pole quasi-elliptic function filter, the filter unloaded $Q$ is 24 500.

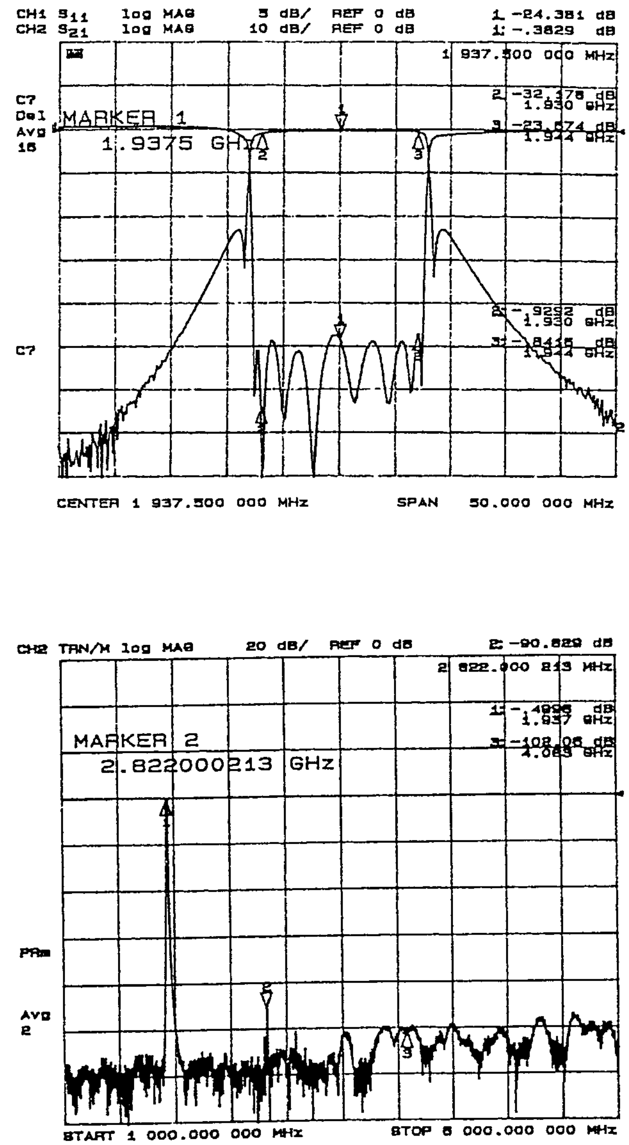



Fig. 12. Measured response of an eight-pole quasi-elliptic function filter and its wide-band response up to 6 GHz.

regarded as positive coupling and denoted by an inductor. The nonadjacent coupling, which has opposite sign with adjacent coupling, is regarded as negative coupling and denoted by a capacitor. It is very interesting to note that relative signs of the cross coupling realized by an iris in a planar quadruplet and tri-sections are different, as is the cross-coupling by probe. This property may not be true for other types of cavities, such as waveguide and combline cavities, because the field distributions of working modes are different.

## IV. Spurious Suppression Devices

### A. Spurious Suppression Devices

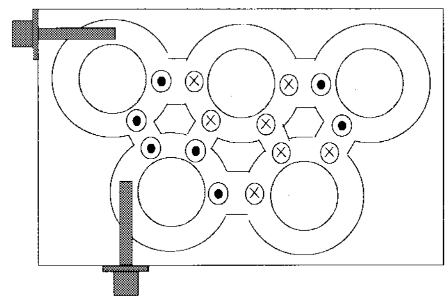
As the results show in Section II, the spurious free region of the TE01 mode DR cavity can be about 1.4 times the operating frequency. A spurious-free region up to the second or third harmonics is usually required for communication systems, i.e., about 6 GHz for PCS frequencies. A low-pass filter can be used to suppress the spurious response. Alternately, mixing metallic resonators with DR resonators [25], [26] can improve the spurious performance significantly with the cost of degradation of overall filter $Q$. Here, we propose to cascade a four-pole wide-band (140–180 MHz) combline filter with the DR filter to eliminate the spurious response. The advantage of the second approach is that no additional volume/space is required. The insertion losses of the two different approaches, as shown in Fig. 8, for Chebyshev filtering are shown as follows:

$$(IL)_1 = 4.343 \sum_{k=2}^{n-1} g_{k,m} \frac{w_n}{Q_{u,DR}} + 4.343 \times (g_{1,n} + g_{n,n}) \frac{w_n}{Q_{u,M}} \tag{2}$$

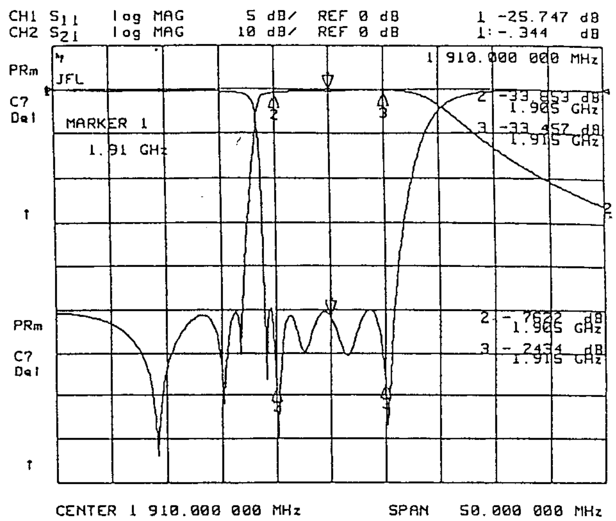
$R_A = R_B = 1.3000$

$$\begin{bmatrix} -0.0108 & 1.0120 & 0 & 0 & -0.1093 \\ 1.0120 & -0.0114 & 0.3328 & -0.4933 & 0.4608 \\ 0 & 0.3327 & -0.5362 & 0.2042 & 0 \\ 0 & -0.4933 & 0.2042 & -0.2641 & 0.9011 \\ -0.1093 & 0.4608 & 0 & 0.90110 & -0.0140 \end{bmatrix}$$

(a)



(b)




(c)

Fig. 13. (a) Coupling matrix of the five-pole filter. (b) Physical layout of the filter. (c) Measured response.

$$(IL)_2 = 4.343 \sum_{k=1}^{n} g_{k,n} \frac{w_n}{Q_{u,DR}} + 4.343 \sum_{k=1}^{4} g_{k,w} \frac{w_w}{Q_{u,M}} \tag{3}$$

where $w_n$, $g_{kn}$, and $Q_{uDR}$ are the fractional bandwidth, low-pass prototype parameter, and cavity $Q$ for the narrow-band DR cavity filter, while $w_w$, $g_{kw}$, and $Q_{uM}$ are for the wide-band combline filter. The effective filter $Q$ and insertion loss at the center frequency of these two approaches are calculated and shown in Fig. 9. Assume that the resonator unloaded $Q$ is 12 000 for the DR cavity and 3000 for the metallic cavity. The major advantage of the DR loaded cavity over the waveguide cavity is the size reduction with a factor of 8–12. It offers three to five times cavity $Q$ over metallic resonator but its volume is about 1.5 times bigger at PCS. For spurious performance assessment, the overall effective cavity $Q$ and cavity size should be included for overall performance evaluation. The results in Fig. 9(a) show that the degradation of the filter $Q$ at filter center frequency by approach I could be from 30% to 50% for typical applications, while approach II is 5% to 25%. The insertion losses of typical applications for these two approaches show that approach I can reduce filter size significantly with a slight increase in insertion loss for a low-order filter. For high-order filters, the cavity $Q$ is much more important, and thus approach II is a much better choice. The extra loss from the wide-band four-pole combline filter can be less than 0.15 dB with dimension of 1.0 in $\times$ 1.0 in $\times$ 4.0 in. This loss can match that of a low-pass filter, while the simple integration makes it very cost effective.

### *B. Direct Cascading of a DR and Combline Filters*

A direct cascading of a narrow-band DR filter with a wide-band combline filter is to combine two filters' external $Q$ as one intercavity coupling. As shown in Fig. 10(a), the output coupling admittance of the first filter and input coupling admittance of the second filter are $G_{B1}$ and $G_{A2}$. Admittance inverters $J_{B1}$ and $J_{A2}$ can realize them, as in Fig. 10(b). In order to construct the proper phase relationship between these two resonators, an admittance inverter with admittance of unity is inserted. One equivalent inverter, as shown in Fig. 10(e), can replace the three cascading inverters. It is straightforward that the equivalent inverter $(J_{AB})$ is equal to the multiplication of the other two inverters and the effective coupling $(M_{AB})$, as in Fig. 10(d), is equal to the geometry average of the input–output coupling of the individual filter, as follows:

$$J_{AB} = J_{B1} \cdot J_{A2} \tag{4}$$

$$M_{AB} = \sqrt{G_{B1} \cdot G_{A2}}. \tag{5}$$

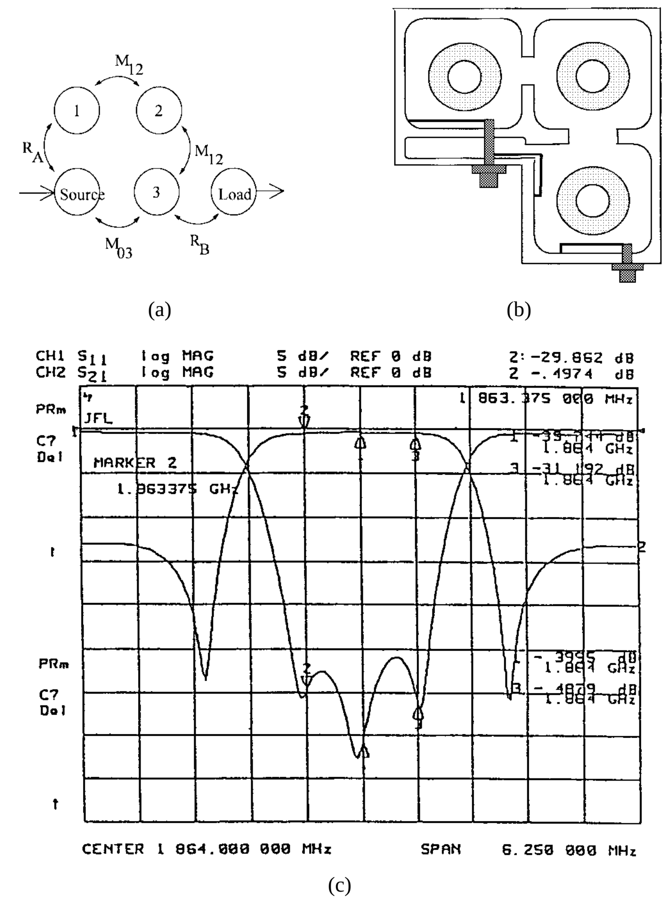



Fig. 14. (a) A three-pole elliptic function filter. (b) Physical layout of the filter. (c) Measured response.

## V. Design Examples

### *Example I. Six- and Eight-Pole Quasi-Elliptic Function Filters*

The results of a six-pole, 5-MHz bandwidth and eight-pole 15-MHz bandwidth quasi-elliptic function filters at PCS frequencies are shown in Figs. 11 and 12. The six-pole filter has one 2–5 cross coupling, while the eight-pole filter has 3–6 cross coupling. The six-pole filter is realized by high-$Q$ DR puck, and the effective filter unloaded $Q$ is 24 500. A four-pole 160-MHz combline filter is directly coupled to the 15-MHz DR filter to suppress the spurious of the DR cavity.

### *Example II. Five-Pole Canonical Asymmetric Filter*

The synthesis of the canonical asymmetric filter with asymmetric response has been demonstrated in [24] and [27]. But, to the authors' knowledge, the realized filter in the public domain is limited to the case of one transmission zero. The coupling matrix and practical filter layout of a five-pole canonical asymmetric filter are shown in Fig. 13(a) and (b). The orientation of the magnetic field of the cavity sidewall is also shown in Fig. 13(b) to justify that $M_{24}(-)$, $M_{25}(+)$, and $M_{15}(-)$ are all implemented by coupling irises. The measured results are shown in Fig. 13(c).

### *Example III. Three-Pole Elliptic Function Filter*

A true odd-order elliptic function filter requires nonadjacent coupling between the source or load to an internal resonator. Three-pole elliptic function filters had been realized with waveguide cavities [28], [29], but have not been realized in DR filter yet. The schematic of a three-pole elliptic function filter is shown in Fig. 14(a), the physical layout in Fig. 14(b), and the measured response in Fig. 14(c). The nonadjacent coupling $M_{03}$ and input coupling $R_A$ are realized by inductive loops to construct proper phase between cavities 1 and 3.

## VI. Conclusion

This paper presents the technology innovations and performances of high-$Q$ TE01 mode cavity filters for PCS base station applications. DR material, DR cavity, and coupling design are described. The nonadjacent coupling is analyzed through quadruplet and tri-section coupled resonator models. Those models can be regarded as basic building blocks to implement symmetric and asymmetric transmission zeros in filter stop band. A direct cascading of a four-pole wide-band combline filter to the DR filter is suggested for spurious suppression and its advantage is analyzed. Design examples with excellent measured performance are presented. The examples of six- and eight-pole quasi-elliptic function filters show typical performances. The five-pole canonical asymmetric filter with asymmetric response and a three-pole elliptic function filter highlight the effort and progress of the high-$Q$ TE01 mode cavity filter for PCS wireless applications.

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