

Metal-Dielectric Coaxial Dual-mode Resonator for Compact Inline Bandpass Filters

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Abstract—A novel dual-mode resonator called metal-dielectric coaxial (MDC) resonator for compact inline bandpass filters is proposed. The dual-mode resonator occupies the same size as that of a conventional metallic coaxial resonator but co-supports the TEM and a HE_{11} modes. Among various applications of the new dual-mode resonator for inline filters, a possible use in a cascade quadruplet (CQ) section that produces one transmission zero (TZ) on each side of the passband is discussed in detail. To demonstrate the applicability of the MDC dual-mode resonator, a 6-pole inline bandpass filter with an asymmetric response is designed, fabricated, and tuned. Experimental results show that the MDC dual-mode resonator filter can achieve a favorable RF performance while having a compact inline physical structure.

Keywords—Metal-Dielectric Coaxial (MDC) dual-mode resonator, bandpass filter, inline layout, transmission zero (TZ).

I. INTRODUCTION

The demands for high-performance microwave filters with compact size and simple layout configuration for base station radio frond-end applications has become more and more prominent in the fifth generation (5G) and future wireless communication systems [1]. Two effective ways to make filter size compact are to use dual-mode resonator and to use dielectric resonator (DR). Therefore, a favorable configuration would be a dual-mode resonator filter with an inline layout.

Using degenerate modes is a popular mindset for constructing a dual-mode or triple-mode DR resonator [2]–[5]. Its disadvantages are obvious, one of which is the poor spurious performance as compared to that of single-mode DR resonators. In recent years, utilizing two dissimilar fundamental modes to form a dual-mode resonator is found to be promising to realize compact filters [6] [7]. In such a resonator, since both modes are fundamental modes, the size reduction can be maximized.

Owing to its relatively high unloaded Q , flexibility in realizing cross-couplings, and a good spurious-free band, the metallic coaxial resonator filter still dominates the market of bandpass filters for wireless base stations. However, other than reducing the cavity height by using the ‘mushroom’ conductor post, there are no effective solutions to reduce the overall size of the filters. On the other hand, to realize various cross-couplings for creating transmission zeros (TZs), it is difficult to layout coaxial resonators in the inline configuration, which is undesirable to composite a channel filter array affixing to a massive multi-input multi-output (M-MIMO) array antenna.

In this work, a new kind of dual-mode resonator is proposed. The resonator is composed of a metallic hollow cylinder coaxially mounted on top of a grounded dielectric resonator, which co-supports the TEM mode with the metallic

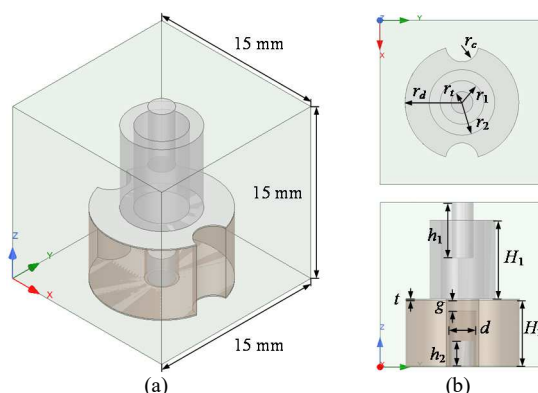


Fig. 1. (a) Isometric view of the proposed MDC dual-mode resonator with outer dimensions; (b) top view and side view of the MDC dual-mode resonator with dimensional parameters.

cylinder and independently supports a dielectric HE_{11} modes. The two dissimilar fundamental modes construct a compact dual-mode resonators in a cavity of the same size as that for a conventional metallic coaxial resonator. The new dual-mode resonator is conceived from an attempt of replacing the lower part of the grounded conductor post of a conventional metallic coaxial resonator by a dielectric resonator. It is surprisingly discovered that the dielectric resonator not only plays the role of the replaced portion of the conducting post, supporting the TEM mode, but also supports two dielectric HE_{11} modes. To create a dual-mode resonator that is suitable for an inline coupling configuration, only the HE_{11} mode whose magnetic field is aligned in the inline direction is retained. By appropriately creating the inter-cavity magnetic coupling between the HE_{11} modes and electric coupling between two TEM modes in two adjacent dual-mode resonators, a typical cascaded quadruplet (CQ) section can be directly constructed with a true inline configuration. To demonstrate the concept of the proposed dual-mode resonator, a 6-pole inline bandpass filter operating at 3.6 GHz band with one TZ on each side of the passband is designed and experimentally verified. It shows that the MDC dual-mode resonator inherits the compactness and convenience on coupling control of a metallic coaxial resonator and also exhibits certain flexibilities in realizing cross-couplings with an inline structure, leading to a promising solution to a compact, high Q and inline bandpass filter for base station radio frond-end applications of wireless communication systems.

II. THE MDC DUAL-MODE RESONATOR

The basic structure of the proposed MDC dual-mode resonator is depicted in Fig. 1(a). The dimensions of the

metallic cavity are $15 \times 15 \times 15 \text{ mm}^3$, which is the same as that of a conventional single-mode metallic coaxial resonator. A grounded cylindrical dielectric puck, whose top surface is optionally metalized, is located at the center of the bottom of the cavity. A metallic hollow cylinder is coaxially mounted on the top of the dielectric resonator. In the EM model of the demonstration example, the dielectric material is with a relative permittivity $\epsilon_r = 39.5$ and a loss tangent $\tan \delta = 5 \times 10^{-5}$, the metal conductivity of its silver-plated top surface and the metallic cavity housing is set to $\sigma = 2 \times 10^7 \text{ S/m}$.

A. The Dual-mode Resonator

To analyze the two resonant modes quantitatively, an HFSS EM model is built. The dimensional parameters labeled in Fig. 1(b) are set initially as $r_1 = 2 \text{ mm}$, $r_2 = 3 \text{ mm}$, $r_d = 5.2 \text{ mm}$, $H_1 = 7.15 \text{ mm}$, $H_2 = 6 \text{ mm}$, $d = 2.5 \text{ mm}$, and $g = 1 \text{ mm}$. The thickness of the silver plated layer is set to $t = 0.1 \text{ mm}$, the radius of both tuning screws is $r_t = 1 \text{ mm}$, and their depths are chosen as h_1 and h_2 , respectively.

Having conducted eigenmode analysis for resonant modes, the TEM mode (called mode 1) is still reserved. When the penetration depth of the tuning screw $h_1 = 4 \text{ mm}$, the resonant frequency of mode 1 is $f_1 = 3.6 \text{ GHz}$, and its unloaded Q is 1900. It can be observed that the magnetic field distribution of mode 1 is very similar to that of an ordinary metallic coaxial resonator, justifying that the displacement current of the mode in the dielectric puck maintains the continuity of the current of mode 1 on the upper metallic cylinder.

By choosing appropriate dimensions, the resonant frequencies of two degenerate HE_{11} modes can be observed near the TEM mode. To create a dual-mode resonator with inline coupling feature, one of the degenerate modes, namely HE_{11b} mode, is pushed away by cutting two semicircle grooves vertically on two sides of the dielectric puck with radius of r_c . With $r_c = 1.5 \text{ mm}$ and $h_2 = 2.5 \text{ mm}$, a parametric study by varying radius of dielectric puck r_d is presented in Fig. 2. It can be seen that the resonant frequencies of both HE_{11} modes and the 1st higher-order spurious mode decrease as radius r_d increases. The unloaded Q of the retained HE_{11} mode (mode 2), or HE_{11a} mode, is almost unchanged. When $r_d = 5.2 \text{ mm}$, the resonant frequency of mode 2 is $f_2 = 3.6 \text{ GHz}$ with an unloaded Q = 1550 while the frequency of HE_{11b} mode is being pushed to 3.91 GHz .

B. A CQ Coupling Section

For high-order filter applications, cascading two or more MDC dual-mode resonators to create required TZs is a favorable option to reduce the size and to straighten the layout. Fig. 3(a) shows a possible coupling configuration for realizing a CQ section consisting of two MDC dual-mode resonators. In the physical realization of the CQ section, the coupling M_{23} is realized by a partial-width window and a grounded loop between the dielectric pucks 2 and 3, thus the magnetic fields of two HE_{11} modes can be coupled. Furthermore, the capacitive cross-coupling M_{14} is realized by a dumbbell shaped probe between two metallic coaxial resonators 1 and 4. Therefore, with the inductive mainline coupling M_{23} and

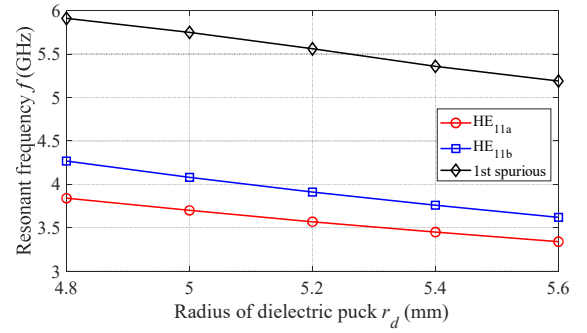


Fig. 2. Resonant frequencies of HE_{11} modes and the 1st higher-order spurious mode versus different radius r_d for $r_c = 1.5 \text{ mm}$ and $h_2 = 2.5 \text{ mm}$.

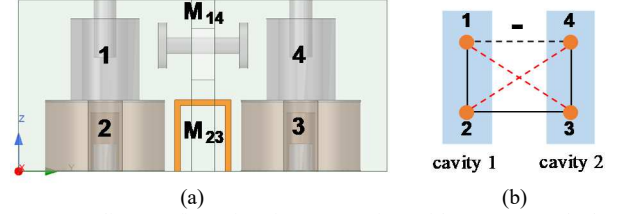


Fig. 3. Coupling configuration for CQ section with two MDC dual-mode resonators: (a) physical structure (side view); (b) coupling diagram.

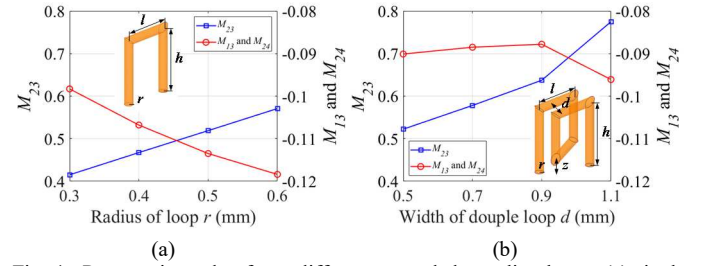


Fig. 4. Parametric study of two different grounded coupling loops: (a) single loop for mainline/diagonal coupling versus radius of loop r for $h = 6 \text{ mm}$ and $l = 4.2 \text{ mm}$; (b) double loop for mainline/diagonal coupling versus width of double loop d for $h = 6 \text{ mm}$, $l = 4.2 \text{ mm}$, $r = 0.3 \text{ mm}$, and $z = 1.5 \text{ mm}$.

capacitive cross-coupling M_{14} , two TZs, one on each side of the passband can be created.

As depicted in Fig. 3(a), the coupling structure between two dual-mode resonators perturbs the original dual-mode resonators, causing a certain amount of parasitic couplings (M_{13} and M_{24}) between mode 1 and mode 2. The actual coupling diagram of the quadruplet section is shown in Fig. 3(b). Due to the symmetry of the structure, the diagonal parasitic couplings M_{13} and M_{24} can be assumed to be equal.

C. The Grounded Coupling Loop

A parametric study of the grounded single coupling loop is presented in Fig. 4(a). The coupling coefficient is extracted at the center frequency of 3.6 GHz and the bandwidth is 125 MHz . It can be seen that, with fixed height h and length l of the loop, both the mainline coupling M_{23} and parasitic diagonal couplings M_{13} and M_{24} become stronger as the radius r increases. It indicates that the diagonal coupling might be too strong when the desired M_{23} is obtained.

To alleviate this contradiction, a double coupling loop is introduced. Its structure and parametric study with fixed h , l , r ,

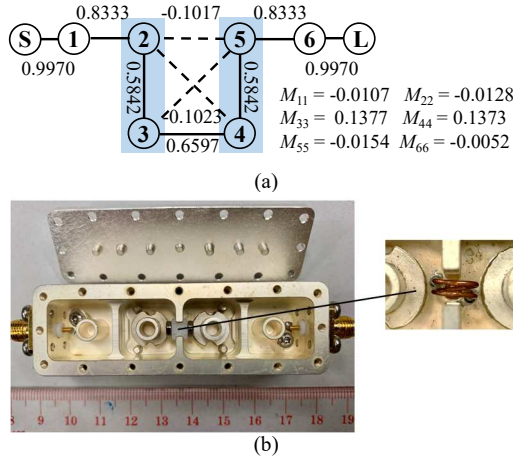


Fig. 5. (a) Target coupling diagram with synthesized coupling coefficients of the 6-2 inline bandpass filter. (b) Photograph of the fabricated 6-2 inline bandpass filter and the detailed structure of the double coupling loop (underneath the removed dumbbell probe).

and z are shown in Fig. 4(b). It can be found that the coupling M_{23} is stronger as the width d increases, whereas M_{13} and M_{24} maintain at a relatively lower level as compared to those of the single coupling loop. A sufficiently large M_{23} is critical to achieve a large fractional bandwidth and to provide more design freedoms.

III. A DESIGN EXAMPLE

For proof of concept, a 6-pole 2-TZ (6-2) inline bandpass filter with an asymmetric response is designed and prototyped at center frequency $f_0 = 3.6$ GHz with bandwidth $BW = 125$ MHz and return loss level of 20 dB. The two TZs are at $\Omega = -1.3$ and 2.2 rad/s in the low-pass frequency domain to ensure the rejection level of -30 dB at the lower side and -60 dB at the upper side of the passband. The coupling topology with the synthesized coupling coefficients is given in Fig. 5(a), in which the quadruplet 2-3-4-5 is realized by two dual-mode resonators, whereas resonators 1 and 6 are two single-mode conventional coaxial resonators.

The designed 6-2 filter is fabricated and tuned with the aid of the model-based vector fitting technique [8]. The photograph of the prototyped hardware is shown in Fig. 5(b). The filter consists of two MDC dual-mode resonators and two single-mode coaxial resonators. The coupling between a single-mode resonator and the adjacent dual-mode resonator is realized by a partial-height coupling window. The total inner dimension of the filter is $66 \times 15 \times 15$ mm³. The size of the dual-mode resonator is the same as that of the single-mode cavity, thus a 33% volume saving is achieved. The measured filter responses are plotted in Fig. 6, superposed by the EM simulated responses for comparison. It can be seen that the prototyped filter realizes a return loss under 20 dB within the prescribed passband, and the measured insertion loss at f_0 is 0.67 dB, which is slightly lower than that of the EM simulated response due to the contaminated inner surface caused by the rough assembling. The symmetry of TZs is not very satisfactory due to the limited tunability of the grounded loop. Moreover, it can be noticed that a spurious resonance occurs

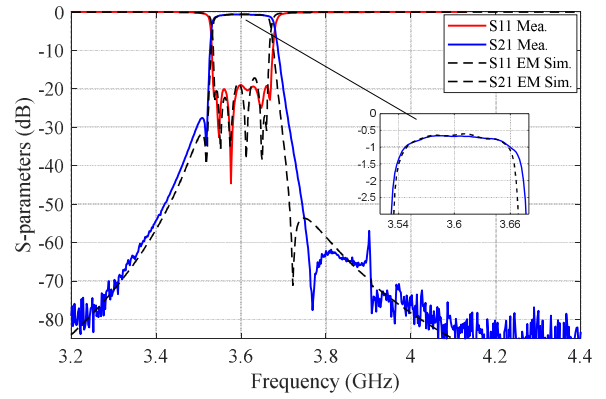


Fig. 6. Measured and EM simulated responses of the fabricated 6-2 inline bandpass filter with zoomed insertion loss.

near 3.9 GHz due to the pushed away HE_{11b} mode, which can be further suppressed in a higher-order filter application.

IV. CONCLUSION

In this paper, a novel dual-mode resonator utilizing two dissimilar fundamental modes, namely metal-dielectric coaxial dual-mode resonator, is proposed and put into practical use for the first time. The dual-mode resonator occupies the same volume and exhibits similar unloaded Q as those of a conventional metallic coaxial resonator. The basic property of the resonator is analyzed, and a possible inter-cavity coupling configuration is investigated. A 6-2 inline filter with asymmetric TZs realized by a CQ section that consists of two MDC dual-mode resonators is designed and experimentally validated, showing that the MDC dual-mode resonator is easy to fabricate and is fully compatible with conventional coaxial resonator. It is expected that the new dual-mode resonator is a promising option for designing compact and inline bandpass filters for 5G and future wireless communication systems.

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