

# Inset Resonators and Their Applications in Fixed/Reconfigurable Microwave Filters

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**Abstract**— This paper introduces a new so-called “inset” resonator configuration for fixed and tunable microwave filter applications. The proposed configuration has many attractive advantages in comparison with conventional structures, including miniaturized size, enhanced spurious performance, and wide tuning capabilities with the least deterioration in unloaded quality factor throughout the tuning window. For proof of concept purposes, a single inset resonator and a two-pole filter are designed, manufactured, and measured. The measurements agree very well with simulations. The measured prototypes demonstrate a wide spurious-free band, volume saving up to 50%, a wide tuning range > 41%, and a high  $Q_u$  of  $4004 \pm 2.4\%$  with minimum variation throughout the tuning range.

**Keywords**—Filter, inset, passive components, resonator, tunable filters.

## I. INTRODUCTION

The introduction of high-power, low-loss, compact, and lightweight RF front-end components, including filters, has become very essential to meet the ever-stringent requirements of the evolving high-performance wireless communication systems. Considering these challenging requirements, coaxial and dielectric-loaded waveguide bandpass filters are getting an increasing amount of attention in research and industry due to their ability to handle high-power levels and high- $Q_u$ , with the additional benefit of miniaturized size when compared to air-filled waveguide structures. These types of filters are commonly realized using the conventional half-wavelength dielectric and combline resonators as in [1], [2]. Nevertheless, the introduction of more volume-saving, high- $Q_u$  resonator topologies is still highly appreciated, especially that filtering components occupy the largest space of the RF front-end units.

Similarly, high- $Q_u$  tunable filters are a key part of future flexible RF and satellite payloads. A 2.5 GHz tunable  $\lambda/2$  coaxial filter was presented in [3] with a 20% tuning range using a common tuning rod. However, the bulky, large size and degraded spurious responses limit the proposed structure and have been shown to have a deterioration in the  $Q_u$  ( $\approx 20\%$ ). In [4], a compact 2.6 GHz  $\lambda/4$  tunable coaxial combline filter was introduced using metallic tuning discs with a very small tuning range of 70 MHz. This mechanism suffers from severe deterioration in the  $Q_u$  (even over a very small tuning window), and also the possible appearance of unwanted spurious resonances. Recently, we presented tuning concepts based on TM-mode resonators featuring compact structures and wide tuning capabilities > 90% [5], [6]. Unfortunately, they also experience noticeable deterioration in the  $Q_u$  with the tuning process. All these drawbacks of the aforementioned state-of-

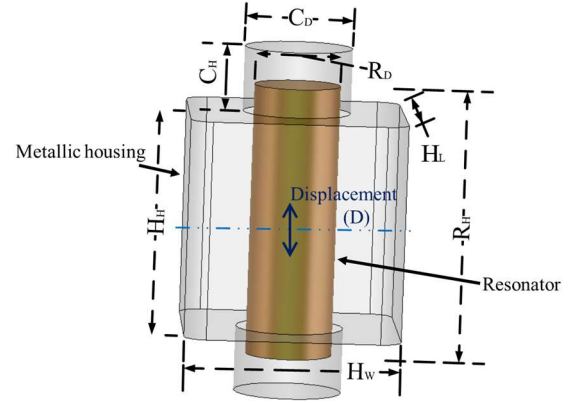


Fig. 1. 3D view of the proposed inset resonator configuration. The inner resonator (R) can be either metallic or dielectric. The original metallic housing height ( $H_H$ ) is set < the resonator height ( $R_H$ ). The resonator is inserted partially in sidewall caps (C), where the cap's diameter ( $C_D$ ) > the resonator diameter ( $R_D$ ). For fixed configurations, the inner resonator is centered in the housing with no displacement ( $D=0$ ). For tunable configurations, the resonator is displaced ( $|D|>0$ ) up-shifting the frequency.

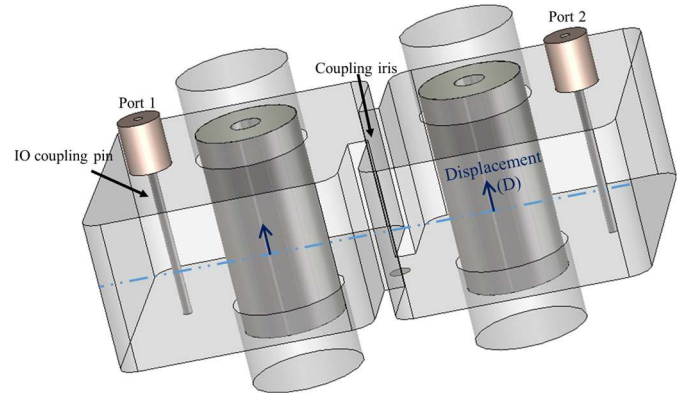


Fig. 2. 3D view of the proposed two-pole inset BPF. The displacement = 0 for the fixed configuration, and changes from 0 to 5 mm for the tunable responses.

the-art designs strongly motivate the introduction of more compact tunable filter designs that cover wider frequency ranges with enhanced spurious performance, and less variation in the  $Q_u$ .

A new so-called “inset” resonator configuration is preliminarily introduced in this paper for fixed and tunable filters applications for the first time. The proposed inset topology can advantageously provide substantial volume-saving, better spurious performance, and comparably high  $Q_u$  in comparison with the conventional structures. Additionally, tunable inset filters and components can be designed

effectively to maintain high  $Q_u$  with minimal degradation and without the need for any auxiliary tuning elements.

## II. CONCEPT AND DESIGN

### A. Inset Resonator

The proposed inset resonator configuration is depicted in Fig. 1. The concept is based on properly modifying the top and bottom sidewalls of the cavity and inserting the resonator inside them to obtain smaller volumes than conventional structures at the same operating frequencies with similar  $Q_u$ . Firstly, the height of the original cavity ( $H_H$ ) is reduced to be less than the resonator height ( $R_H$ ). Then, both the height and diameter of the modified side walls ( $C_H$ ,  $C_D$ ) are carefully chosen to obtain the same operating frequency with similar  $Q_u$  (or as desired, for example, more size reduction at the cost of lower unloaded  $Q$ ). The resonator is positioned in the center of the cavity with equal insertion inside the modified wall caps. Any sort of low-loss support can be used under the condition that there is no electrical contact between the resonator and the cavity. The resonator can be either metallic or dielectric (for instance, the TM mode dielectric resonator [7]). The operation mode of the proposed inset resonator structure is the fundamental TM mode and the fields are distributed similarly as in conventional  $\lambda/2$  structures. Table 1 provides a comparison example between the proposed inset-type, conventional half-wavelength and combline resonators (reported in [2]) operating at 2.5 GHz. The length of the resonator ( $R_H$ ) in the  $\lambda/2$  structure is 50 mm, and 25 mm in the combline and inset configurations ( $\approx \lambda/4$ ). As can be seen, the inset resonator structures offer the highest volume-saving (up to 63% of miniaturization), best  $Q_u$ /volume ratio, and better spurious performance ( $f_{spur.}=8.0$  GHz) with a negligible change in the  $Q_u$  ( $<5\%$ ). The sidewall caps are designed to contain the lowest field intensities, and therefore, the cap heights ( $C_H$ ) can be decreased for more compactness without causing any change to the resonant frequency. This effect can be seen in the second inset-type example ( $C_H$  is 8 mm in the first inset example and 4 mm in the second example providing more volume-saving, while the resonant frequency ( $f_r$ ) is kept fixed at 2.5 GHz).

Similarly, tunable frequency responses can be ideally obtained through the proposed inset resonator topology. The tuning concept is based on the displacement of the resonator to change the resonant frequency while keeping high  $Q_u$  without the need for any additional tuning means. As mentioned, the sidewall caps are designed to have the lowest field densities. When considering the rapid decay of the EM fields, this allows designers to increase the cap heights with enough room for the movement of the resonators (more tuning can be obtained) without causing any change in the reference resonant frequency. When the resonator is centered: this is the reference (fixed) case where the frequency is the lowest. Moving the resonator up or down will move it away from one sidewall and closer to the other one. This means that the resonant frequency will shift up with reference to the first cap sidewall and also, simultaneously want to shift down with reference to the second side. In general, this is correct, but due

TABLE 1 Comparison between the conventional half-wavelength and combline resonators, and the proposed inset resonators at 2.5 GHz.

Structure	Half-wavelength	Comblne	Inset-1	Inset-2
$f_r$ (GHz)	2.5	2.5	2.5	2.5
$f_{spur.}$ (GHz)	5.0	7.4	8.0	8.0
$Q_u$	4733	3712	3623	3536
Volume (cm <sup>3</sup> )	24	12	9.41	8.9
$Q_u$ / Volume (cm <sup>3</sup> )	197.2	309.3	385	397.3

Dimensions (in mm): Half-wavelength:  $H_W = 20$ ,  $H_L = 20$ ,  $H_H = 60$ ,  $R_H = 50$ ,  $R_D = 8$ . Comblne:  $H_W = 20$ ,  $H_L = 20$ ,  $H_H = 30$ ,  $R_H = 25$ ,  $R_D = 8$ . Inset-1:  $H_W = 20$ ,  $H_L = 20$ ,  $H_H = 21$ ,  $R_H = 25$ ,  $R_D = 8$ ,  $C_H = 8$ ,  $C_D = 9$ . Inset-2:  $H_W = 20$ ,  $H_L = 20$ ,  $H_H = 21$ ,  $R_H = 25$ ,  $R_D = 8$ ,  $C_H = 4$ ,  $C_D = 9$ .

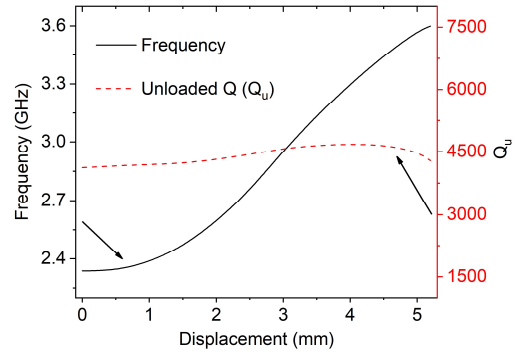


Fig. 3. Simulated frequency and unloaded  $Q$ -factor ( $Q_u$ ) as a function of the inset resonator displacement.

to the fact that the contained EM fields in the caps are minimal, the up-shift in the frequency caused by the displacement away from the cap is larger than the frequency down-shift caused by the displacement towards the opposite side. Therefore, the net result is that the frequency is always shifted up. This also means that the  $Q_u$  will not be affected by the tuning process, unlike most of the conventional tuning concepts.

To validate the inset-type tuning concept, a single inset resonator example is investigated using the Eigen-mode solver in CST Microwave Studio considering copper for the metallic housing and resonator. The corresponding dimensions in mm are:  $H_H = 15$ ,  $H_W = 30$ ,  $H_L = 30$ ,  $R_H = 20$ ,  $R_D = 10$ ,  $R_{Di} = 3$ ,  $C_H = 8$ ,  $C_D = 11$ . Fig. 3 demonstrates the simulated frequency and  $Q_u$  in relation to the resonator displacement. As shown, the frequency is reconfigured from 2.3 GHz ( $D=0$ ) to 3.6 GHz ( $D=5.2$  mm) providing a wide tunability of 44%. Also, the resonator has maintained a high  $Q_u$  of  $4400 \pm 6.5\%$  with minimum variation throughout the tuning window.

### B. Inset Bandpass Filter

Fig. 2 illustrates a 3D schematic of a two-pole bandpass filter using the proposed inset resonator. The filter is designed to have a Chebyshev response and operates at a center frequency of 2.45 GHz with an absolute bandwidth of 50 MHz. Firstly, the corresponding coupling matrix is extracted and optimized following the standard synthesis process in [8].

Then, the required physical coupling coefficients ( $K_{12}$ ) and external quality factor ( $Q_{ext}$ ) are calculated and realized. The simulated S-parameter responses of the proposed 2nd-order inset BPF are depicted in Fig. 4(a). The extracted Q factor is 3000 when considering copper metal ( $\sigma = 5.8 \times 10^7 \text{ S/m}$ ).

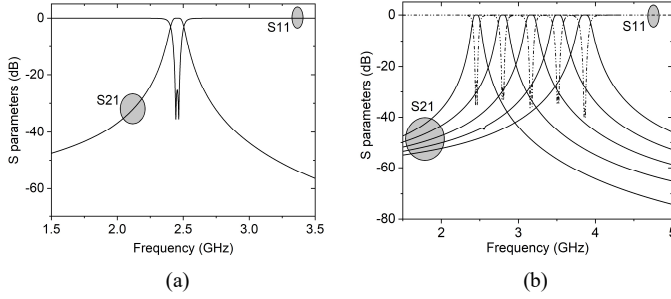


Fig. 4. Simulated S-parameter responses of the fixed and tunable configurations of the proposed inset BPF: (a) Fixed response. (b) Tunable responses.

Also, the tuning capabilities of the introduced filter are demonstrated in Fig. 4(b). In tunable filters, it's important to maintain a constant bandwidth across the whole tuning range satisfying the following equation extracted from [8]:

$$T_d \times K_{12} \times f_r = \text{constant} = \frac{2 \times m_{12}}{\pi \times m_{s1}^2} \quad (1)$$

Where  $m_{12}$ ,  $m_{s1}$  can be obtained from the extracted coupling matrix, and they are fixed regardless of the corresponding frequency. When the resonant frequency ( $f_r$ ) increases, the peak group delay ( $T_d$ ) (corresponds to the physical IO coupling) and the inter-resonator coupling ( $K_{12}$ ) decrease with a similar amount in order to maintain a constant bandwidth.

A wide 1.41 GHz tuning band is obtained from 2.45 GHz to 3.86 GHz with constant bandwidth of  $52 \text{ MHz} \pm 5\%$ . Similarly, a high unloaded quality factor is obtained with small variation ( $3200 \pm 7\%$ ).

### III. EXPERIMENTAL RESULTS

A single inset resonator and a 2nd-order BPF are manufactured, assembled, and measured to validate the above-presented designs. Photographs and measured S parameters of the implemented resonator and filter are depicted in Fig. 5 to Fig. 7, respectively. Measurements agree very well with simulations. These prototypes were manufactured out of brass metal and then silver-plated to get higher  $Q_u$ . The resonator dimensions are similar to those of the provided example in the above section in mm: ( $H_H = 15$ ,  $H_W = 30$ ,  $H_L = 30$ ,  $R_H = 20$ ,  $R_D = 10$ ,  $R_{Di} = 3$ ,  $C_H = 8$ ,  $C_D = 11$ ). The measured resonant frequency of the fixed resonator configuration is 2.32 GHz with a high extracted  $Q_u$  of 3909. For the tunable version, the frequency is tuned from 2.32 GHz to 3.59 GHz offering a 43% tunability and a high, stable  $Q_u$  of  $4004 \pm 2.4\%$ . The fabricated inset resonator offers 25% volume-saving in comparison with the conventional combline structure and 50% with the half-wavelength one. The measured responses of the proposed two-pole inset filter are shown in Fig. 6(c), (d). The filter operates at a frequency of 2.51 GHz with 53 MHz bandwidth and

extracted  $Q_u$  of  $\approx 2000$ . The filter has a wide spurious-free band up to 8.63 GHz as can be seen in Fig 6(d). The measured reconfigurable inset filter has a wide 1.36 GHz frequency tuning window from 2.51 GHz – 3.87 GHz with a constant BW of  $54 \text{ MHz} \pm 1 \text{ MHz}$  and a high  $Q_u$  of  $1950 \pm 2.5\%$  throughout the tuning window.

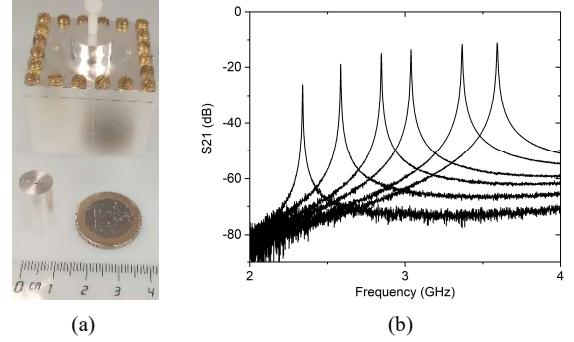


Fig. 5. Photograph and measured transmission responses (S21) of the proposed inset resonator: (a) Photograph. (b) Measured S21 (dB).

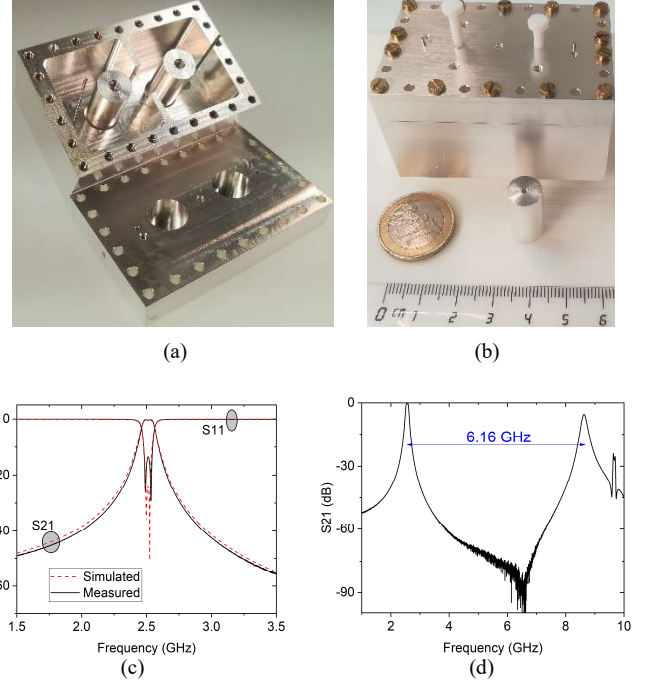


Fig. 6. Photographs and measured results of the two-pole inset bandpass filter: (a) Photograph, disassembled. (b) Photograph, assembled. (c) Measured responses of the fixed configuration versus simulations (dB). (d) Measured wideband response (dB).

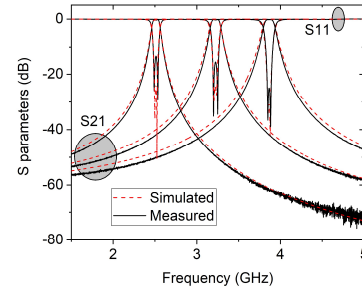


Fig. 7. Measured S parameters of the proposed tunable inset bandpass filter.

#### IV. CONCLUSION

A novel inset resonator configuration was presented for applications of fixed/reconfigurable microwave filters and components. The proposed concept brings many highly desirable advantages in comparison with the conventional structures, including more compact size and enhanced spurious performance. Also, the inset configuration is designed to be tuned efficiently without the need for any auxiliary tuning components. A wide tuning range can be effectively obtained with the least variation in the  $Q_u$  when compared with all available state-of-the-art designs.

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