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RESEARCH ARTICLE

# Design of Tunable Coaxial Bandpass Filter Based on Embedded Stepped Impedance Resonators

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**ABSTRACT** This paper describes a method for designing tunable coaxial bandpass filters based on an inserted coaxial stepped impedance resonator (SIR). The miniaturization of the coaxial resonator is realized by the shape of the stepped impedance structure. In addition, an extended tuning range can be achieved by utilizing the SIR. A third-order tunable bandpass filter with constant absolute bandwidth is designed and fabricated for verification. The fabricated filter exhibits a wide tuning range from 2.13 GHz to 3.54 GHz (52.4%), over which the absolute bandwidth (ABW) varies within 97.5 ± 5.5 MHz (±5.6%).

**INDEX TERMS** Coaxial resonator, constant bandwidth, wide tuning range, tunable filter.

## I. INTRODUCTION

With the development of modern wireless communication technology, the demand for multi-channel capabilities and reconfigurable RF front-ends is increasing. As a key component of RF systems, tunable filters have the characteristics of low cost and flexible passband adjustment. At the same time, it has good development potential in reducing the size, weight, and complexity of the system [1], [2], [3], [4].

The currently studied tunable filters can be realized in two-dimensional and three-dimensional structures by means of electrical, and mechanical tuning. With the development of the application of tunable filters, higher requirements are put forward for filters. When the filter is required to maintain the performance of low loss and narrow bandwidth at high power operation, cavity filters are a better choice. However, cavity filters have a large volume, and miniaturized filters also have difficulties in batch production consistency. Therefore, the use of compact waveguide filters is a classic topic in the field of microwave technology.

In [5], [6], and [7] it was proposed to mount resonators in series on a common tuning column using metal or dielectric elements of horizontal sliding and rotating or one of these structures. The structure in [5] uses a forming CAM on the rotating resonator column to change the loading capacitance of the resonator to achieve frequency adjustment. Work by using the structure design of the filter in L-band 0.95 GHz to 2.05 GHz, return loss is better than 11 dB, but change with frequency bandwidth. The structure in [6] adopts the rotating elliptical metal load fixed quarter-wave resonant cavity, achieved 10.5±0.7 MHz bandwidth range and 11.6% of the tuning range, return loss is better than that of 15 dB. The downside of this approach is due to perturbations of the electromagnetic fields are not sufficient, frequency tuning window is very narrow.

Another tuning method is to use the tuning element to move vertically between the resonator and the cavity to adjust [8], [9], [10], [11], [12]. In [8], the tunable filter made of in-line double-column resonators adjusts the coupling characteristics though the height of the columns and height difference of the columns, achieving a bandwidth variation range of 230 ± 9 MHz, a tuning range of 17.2%, and a return loss of better than 12 dB. However, the vertically movable tuning element reduces the $Q$-factor because the tuning element is close to the resonator. Based on the tuning concept of TM mode resonator, it is compact and has >90% wide tuning capability [13], [14]. Unfortunately, they also experience noticeable deterioration in $Q_u$ with the tuning process.

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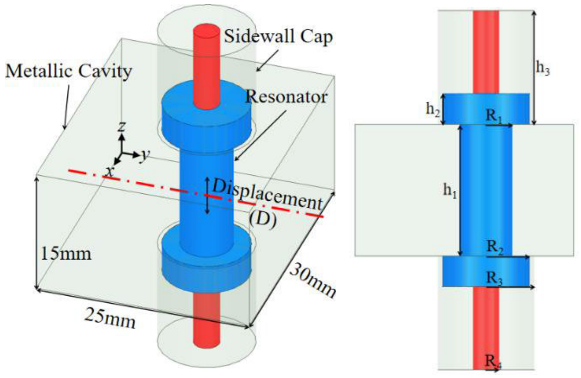
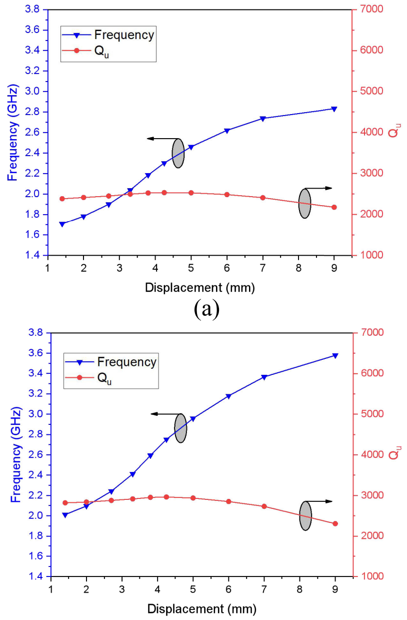


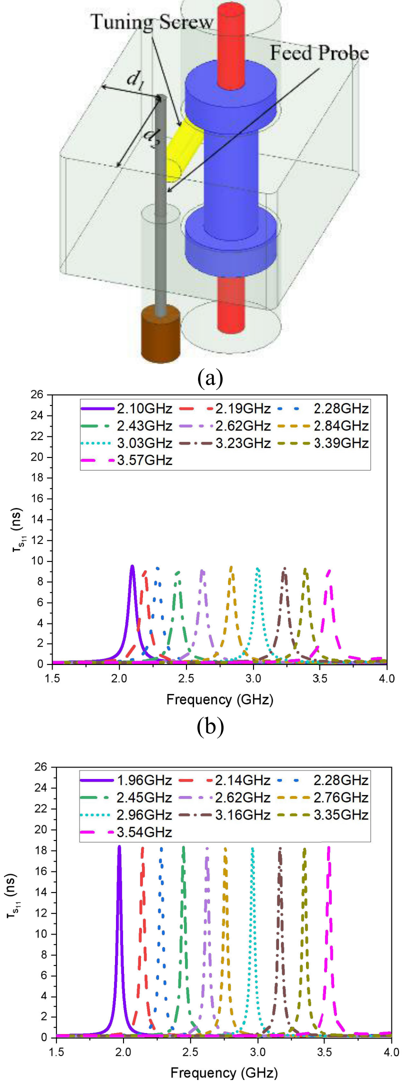
(a) (b)

**FIGURE 1. Resonator structure. (a) 3D model. (b) Front view. Dimensions: R1=3 mm, R2=5 mm, R3=5.5 mm, h2=15 mm, h2=3.5 mm, h3=13 mm.**



(b)

**FIGURE 2. Resonant frequency and unloaded Q. (a) R1=1.6 mm, R2=5 mm. (b) R1=3 mm, R2=5 mm.**



(c)

**FIGURE 3. Feeding structure. (a) Structure. (b) Simulated reflection group delay when $d_1 = 6.9$ mm, $d_2 = 15$ mm. (c) Simulated reflection group delay when $d_1 = 5$ mm, $d_2 = 15$ mm.**

The inset resonator configuration proposed in [15], [16], and [17] is a new structure that can effectively save a lot of volume and solve the problem of large cavity filter size. The structure in [15] can be in the case of no tuning elements in the process of tuning maintaining high $Q$-factor. The structure in [16] uses a half-wavelength coaxial resonator to change the loaded capacitance by shifting up and down to realize frequency tuning. The third-order filter with this structure can realize the tuning range of 1.3 GHz is 2.54 GHz-3.96 GHz, the relative tuning range is 43.6%, the stable insertion loss is less than 0.35 dB, the return loss is better than 15dB. Compared to similar load waveguide designs, the tuning technique and associated components presented in their paper represent the current optimal tuning range and stable high-$Q$ with minimal variation.

The filter based on the step impedance resonator (SIR) can shorten the length of the resonator without significantly reducing the $Q$-factor, while having higher selectivity, better out-of-band suppression, and further parasitic mode. SIR can be widely applied to the cavity structure of the filter to realize the cavity filter miniaturization. In order to further extend the tuning range and realize filter miniaturization, the inset coaxial SIR structure is employed to design a tuning bandpass filter in this paper. An experimental prototype has been designed and fabricated for demonstration, which shows a wide tuning range from 2.07 GHz to 3.54 GHz (52.4%), with BW varying within 83±3 MHz (±3.6%).

## II. DESIGN OF TUNABLE FILTER

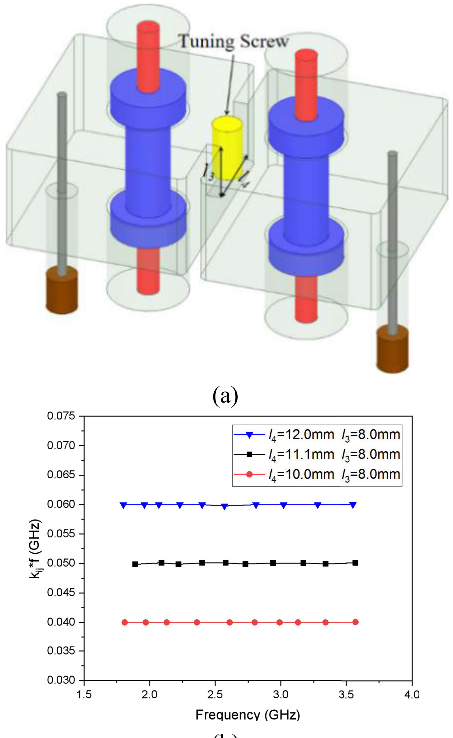
### A. TUNABLE COAXIAL RESONATOR

As described in Fig. 1(a) and (b), this is the structure of the resonant cavity proposed in this paper. A coaxial stepped impedance resonator (SIR, blue cylinder in Fig.1 (a)) is

**TABLE 1.** Comparison with the previous works.

| Ref. | Freq. (GHz) | Tuning Range | IL(dB) | Tuning elements | Oder | Size($\lambda_0^3$) | Size($\lambda_0^3$) / Order | BW and Variation |
|---|---|---|---|---|---|---|---|---|
| [6] | 0.68-0.76 | 80 MHz (11.1 %) | 0.8-0.9 | 1 | 4 | 0.0308 | 0.0077 | 10.5 MHz ±6.6% |
| [8] | 9.15-10.87 | 1.72 GHz (17.2%) | <0.6 | 2N | 4 | NA | NA | 230 MHz ±3.9% |
| [9] | 1.81-2.17 | 0.36 GHz (18.1%) | <1.8 | 1 | 5 | NA | NA | 25 MHz |
| [10] | 15.6-16 | 0.4 GHz (18.1%) | 1.5-4.5 | N | 3 | NA | NA | 150MHz |
| [11] | 2.565-2.634 | 69 MHz (2.7 %) | 0.9-2.3 | N | 6 | NA | NA | NA |
| [12] | 4.97-5.22 | 0.25 GHz (4.9 %) | 3.9-4.4 | N | 4 | NA | NA | 66 MHz ±1.5% |
| [16] | 2.66-3.96 | 1.3 GHz (39.4%) | 0.39-0.44 | N+2 | 4 | 0.0662 | 0.0165 | 116 MHz ±6% |
| This work | 2.13-3.54 | 1.41 GHz (49.7%) | 0.65-1.35 | N+1 | 3 | 0.0331 | 0.0110 | 97.5 MHz ±5.6% |

Freq.: Frequency. N: The filter's order.



(a)

(b)

**FIGURE 4.** Tuning structure of inter-resonator coupling. (a) Structure. (b) Product of coupling coefficient and resonant frequency with different width of the iris.

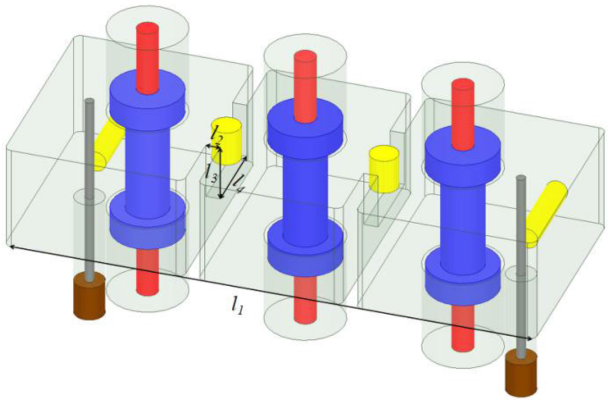


**FIGURE 5.** Third-order filter structure. Dimensions: l1=70 mm, l2=2 mm, l3=8 mm, l4=11.1 mm.

adopted, consisting of a middle cylinder and two end cylinders into dumbbell structure. The SIR is positioned within the cavity using a low loss dielectric (red cylinder in Fig. 1(a)). As shown in Fig. 2, when the radius of the cylinder changes, the resonant frequency varies accordingly, which also affects the $Q$-factor, the effect of tuning screws, and the relative tuning range. The displacement $D$ in Fig. 1(a) is used to describe the deviation of the resonator from the center of the cavity, which affects the resonant frequency. When the SIR is placed at the middle of the cavity, the displacement $D$ is defined as 0 mm. As shown in the comparison of Fig. 2(a) and (b), the resonant frequency of the SIR can be tuned over a wide range when $D$ varies. It should be noted that the unloaded quality factor ($Q_u$) deteriorates as $D$ increases. When $R_1 = 3$ mm and $R_2 = 5$ mm are selected, the resonator has a wide tuning range (55.9%) and $Q_u$(>2300) performance.

### B. INPUT/OUTPUT COUPLING

In frequency tunable filter, the tuning range of all the different frequency constant absolute bandwidth (CABW) is very important. According to the filter synthesis theory, CABW tunable filters should satisfy two requirements: the reflection group delay ($\tau_{S11}$) and $k_{ij}f_r$ are constant over the tuned frequency range [18], [19], where $\tau_{S11}$ is the reflection group delay. As shown in Fig. 3(a), a feeding probe is adopted as the feeding structure. However, the group delay obtained utilizing only the probe cannot remain constant. Therefore, M3 Teflon screws (yellow cylinder in Fig. 3(a)) were added to keep the group delay constant. In Fig. 3(a), the dark silver

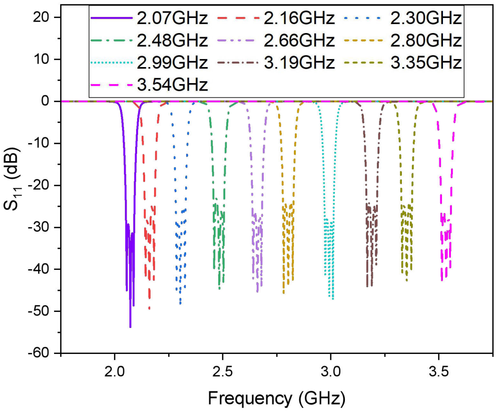


**FIGURE 6.** Simulated reflection coefficients of the tunable filter.

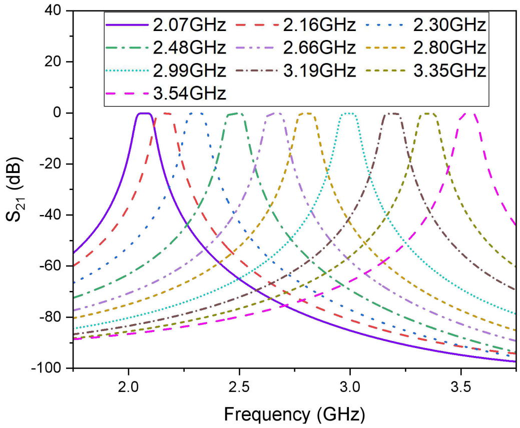


**FIGURE 7.** Simulated transmission coefficients of the tunable filter.

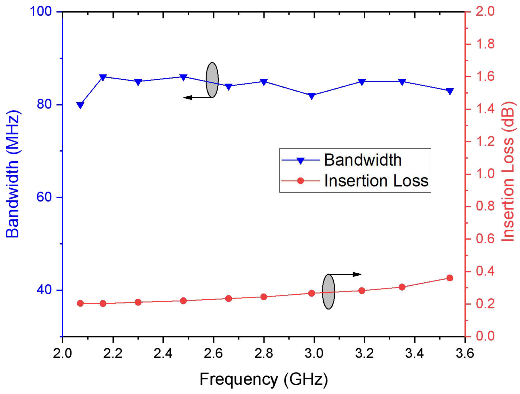
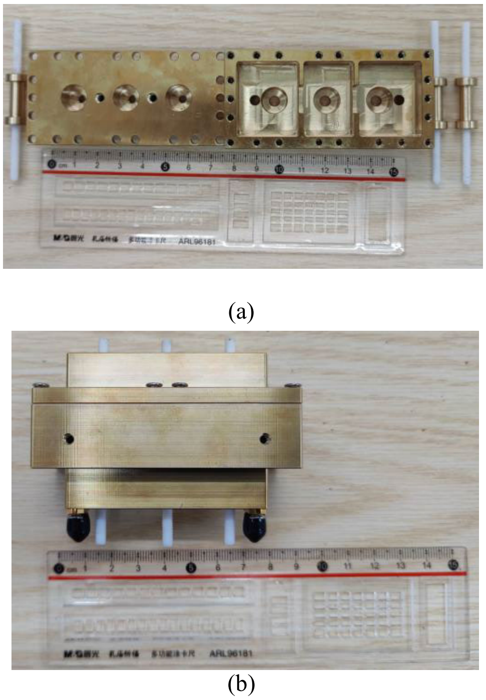


**FIGURE 8.** Simulated bandwidth and insertion loss.

part of the fed probe is the inner conductor, the brown part is the outer conductor. The group delay can be obtained using

$$\tau_{S_{11}} = \frac{4Q_e}{\omega_0} \tag{1}$$

where $Q_e$ denotes the external coupling. Fig. 3(b) and (c) shows the simulated reflection group delay under different position of the coupling probe, indicating that the group delay can be adjusted flexibly by tuning $x$ and $y$.


(a)

(b)

**FIGURE 9.** Fabricated filter. (a) Before assembly. (b) After assembly.

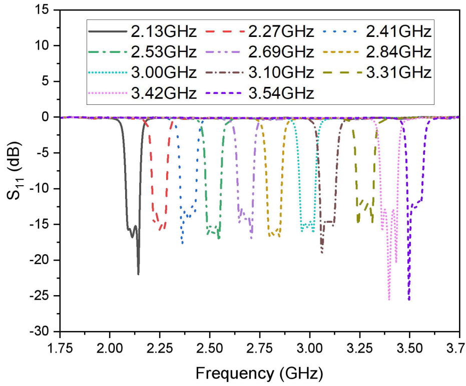


**FIGURE 10.** Measured reflection coefficients.

### C. INTER-RESONATOR COUPLING

Similarly, it is difficult to realize that $k_{ij}f_r$ is constant over the tuning frequency range using coupled windows with openings above the design, where $k$ is the coupling between resonators and $f_r$ is the resonant frequency. Fig. 4(a) depicts the tuned structure of inter-cavity coupling. We also introduce M4 screws in the coupling window to keep $k_{ij}f_r$ constant:

$$k_{ij} \times f_r = \text{constant} \tag{2}$$

where $k_{ij}$ is the coupling coefficients between the adjacent resonators and can be calculated as

$$k_{ij} = \frac{f_2^2 - f_1^2}{f_2^2 + f_1^2} \tag{3}$$

Fig. 4(b) shows that different $k_{ij}f_r$ values can be adjusted by tuning screws under different width of the iris. As shown in

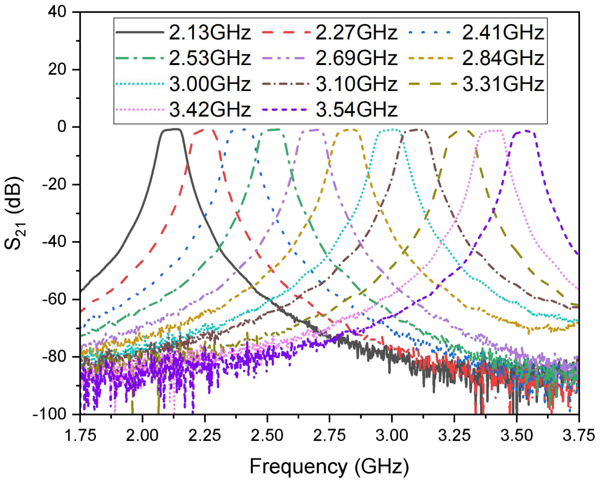


**FIGURE 11.** **Measured transmission coefficients.**

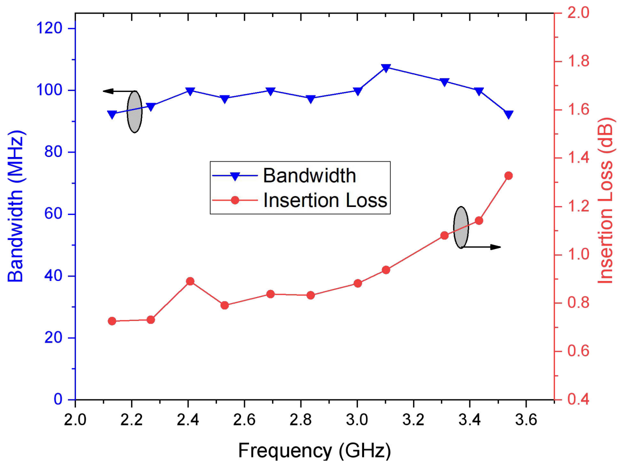


**FIGURE 12.** **Measured bandwidth and insertion loss.**

Fig. 4(b), the value of $k_{ij}f_r$ meets the requirements of the CABW bandpass filter when the physical dimensions of the iris are fixed.

### D. FILTER DESIGN

As shown in Fig. 5, a third-order bandpass filter is designed using the SIRs and coupling structures above. It is important to note that, due to the input/output coupling, second the size of the resonator and the first and third the size of the resonator is slightly different. Fig. 6 and Fig. 7 show S parameters simulated by ANSYS High frequency structure simulator (HFSS). The frequency tuning range is 2.07 GHz-3.54 GHz, the 3-dB BW variation range is 83±3 MHz (±3.6%), and the insertion loss (*IL*) range is 0.28±0.07 dB, as shown in Fig. 8. Note that the insertion loss becomes larger with the increase of frequency as the relative bandwidth becomes smaller.

## III. FABRICATED FILTER AND MEASUREMENT

The fabricated tunable filter is shown in Fig. 9. White dielectric rods are used to hold the resonator in place and to move it up and down. Fig. 10, Fig. 11, and Fig. 12 show the measurement results of $S_{11}$ and $S_{21}$ and the variation of bandwidth and insertion loss (*IL*), respectively. The frequency tuning range was 2.13 GHz to 3.54 GHz (49.7%), the BW range was 97.5±5.5 MHz (±5.6%), and the measured *IL* range was 1±0.35 dB. Compared with the simulation results, the measured result has a wider bandwidth, which is due to the stronger inter-cavity coupling and the instability of input/output coupling caused by machining errors.

Table 1 shows a comparison of our work with other similar CABW tunable load waveguide filters, showing that the proposed filter has a wide tuning range and a miniaturized size.

## IV. CONCLUSION

This paper presents a design method of a wide tuning range and miniaturized tunable filter based on embedded SIR Structure. The tunable coaxial resonators and their coupling structures are introduced in detail. A third-order filter prototype is designed and manufactured for demonstration. The proposed method realizes further miniaturization of the inset resonator structure effectively.

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