Design of a tunable center frequency and small size cavity bandpass filter by separating capacitor-loaded resonators

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ABSTRACT

This paper presents a tunable center frequency and small size cavity bandpass filter design method. In this method, a capacitor-loaded open terminal coaxial resonator is employed to reduce the size of cavity filters. The resonator is designed and fabricated separately into two parts to achieve the flexible operating frequency purpose. The first part is called the base of the resonator which is simply a pillar and directly fabricated integrally with the cavity housing. The second part called the hat of the resonator is the main part causing the load capacitance in cavity filters. By using different heights of the base part or/and different shapes and sizes of the hat, the operating frequency of cavity filters can be changed flexibly. This method not only reduces the difficulty and cost of cavity filter processing but also makes cavity filters reconfigurable. To demonstrate the effectiveness of the method, a cavity filter sample with a center frequency of 3.45 GHz and a bandwidth of 80 MHz was designed, fabricated, and measured. The measured results show that the insertion loss was smaller than 1.33 dB in the whole bandwidth, one zero-point at 3.350 GHz reaching -68 dB, the rejection at 3.550 GHz was -41 dB, unloaded Q was 5,898, and the dimension of the filter was 128 mm×86 mm×23 mm.

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1. INTRODUCTION

With the increasing development of modern communication technology and electronic countermeasures, the electromagnetic spectrum is becoming more and more crowded. However, the resource of the electromagnetic spectrum is limited, thus the electromagnetic spectrum is needed to allocate reasonably according to applications. Microwave filters, which are regarded as band selection devices, are an indispensable part of modern communication systems. They have become the center of many design issues in radio technology and play an extremely important part in modern microwave and millimeter wave communication technologies. Their performance directly affects the quality of the entire communication system.

Many types of microwave filters have been proposed, such as waveguide [1]–[3], microstrip [4], stripline [5], [6] substrate integrated waveguide [7], and dielectric cavity [8], [9]. Among them, stripline filters have the advantages of small size, can be processed by photolithography technology, and can be integrated with other active circuit components [10], [11]. However, when the filter is required to withstand high power, have low insertion loss, high out-of-band rejection, and narrow bandwidth, a cavity filter is the best choice [12]–[14].

However, cavity filters have the disadvantage of large size and they are hard to meet the development requirements of miniaturization and portability of electronic systems. Therefore, cavity filters are required to be designed in the direction of miniaturization. There are many methods for miniaturizing cavity filters such as cross-coupling [15], capacitive-load [12], [16], multi-mode [17], dielectric-metal hybrid technology [18], low-temperature co-fired ceramic (LTCC) technology [19], and so on. Among the above miniaturization methods, since the coaxial capacitor-loaded resonator is relatively simple, it only needs to add capacitive metal in the empty cavity to reduce the resonant frequency of the filter, thereby reducing the size of the filter, this method has been widely used. Zhang *et al.* [15] presented a cross-coupling technology to design a filter with the actual size to be 25 mm×25 mm×5 mm at the center frequency of 3.5 GHz with the insertion return loss is more than 14 dB. Yu and Li [12] designed a small size C-band cavity bandpass filter by adopting a capacitor-loaded open terminal coaxial resonant cavity. The dimension of their designed filter is 79 mm×60 mm×25 mm. Jelodar *et al.* [16] used substrate-integrated waveguide and split rings capacitive load post to design a compact high Q bandpass filter at 4.6 GHz with the dimension is $0.97\lambda_g \times 0.5\lambda_g$, where λ_g is the guided wavelength at the center frequency. Wang *et al.* [20] designed a capacitive load cross-coupled cavity filter working in a range of 2,040 MHz to 2,120 MHz with a return loss larger than 20 dB and the filter dimension is $0.84\lambda_g \times 0.32\lambda_g$.

Modern microwave communication systems, such as aircraft airborne communication equipment, and communication satellites, include hundreds of microwave filters. These filters need to be highly stable and consistent. If the designing and fabricating cost of filters is high, the product cost will become very high since each filter is very expensive. Therefore, it is very important to find a cavity filter design solution that is reliable, easy to process, low-cost, structurally reconfigurable, and mass-produced. Until now, most of the literature focuses more on how to achieve miniaturization [21] and is less focused on the specific implementation of the miniaturized filter and its consistency in mass production. These capacitor-loaded resonator-based designs are generally fabricated by using computer numerical control (CNC) machine tools to process the capacitor-loaded resonator together with the cavity housing. This fabricating style will increase the difficulty of processing. Especially when the structure of the capacitor-loaded resonator is relatively complex (such as hollow and disc shape), the processing becomes very difficult and the cost of processing is very high.

Moreover, usually in the traditional approach, once a cavity filter is processed, its center operating frequency is fixed. However, if you desire to tune the operating frequency of the filter while keeping other parts of the system unchanged, including the dimension of the filter, you need to re-design and re-process a new filter, the existing cavity filter can not be reconfigurable. This results in longer design cycles and higher costs. Schuster *et al.* [22] proposed a filter working at the center frequency range from 1.5 GHz to 1.75 GHz with a constant bandwidth of 100 MHz and a tunable bandwidth between 70 MHz and 180 MHz at a fixed center frequency of 1.625 GHz by using a cross-coupled open-loop resonator. Wong *et al.* [13] proposed a design of a single-/dual-band triple-mode cavity filters with a wide tunable frequency range which the tunable passband is from 0.8 to 3.2 GHz. Liu *et al.* [23] employed dual-capacitively-loaded cavity resonators to implement a dual-band microwave filter. This filter works at 2.4 GHz with a bandwidth of 24.8 MHz, a high unloaded quality factor, and a low insertion loss.

Although using microstrip structures can achieve small size, mass production, consistent performance, and the function of tunable center frequency [24], their Q value is small and cannot meet certain applications. Therefore, cavity filters that use the coaxial capacitor-loaded resonator method have emerged to achieve these demands. Vallerotonda *et al.* [3] developed a high unloaded Q-factor value (> 4,500) dielectric-loaded Ku-band cavity filter. Soi *et al.* [25] designed a high Q value single cavity filter, which can be switched/reconfigured between two bands, i.e., band I from 4.4 GHz to 4.6 GHz and band II from 4.8 GHz to 5.0 GHz, by manually tuning the coupling and tuning screws. Pelliccia *et al.* [9] designed a high power (up to 900 W) bandpass cavity filter by using a dielectric-loaded diplexer working at L-band.

To sum up, the biggest difficulty and challenge encountered by current miniaturized cavity filters are mainly reflected in the consistency of mass production. Especially as the operating frequency increases, the size of the filter will gradually become smaller. The internal components (e.g., coaxial capacitor-loaded resonators and cross-coupling elements) of the cavity filters are also increasingly sensitive. The specific areas requiring improvement encountered in the current miniaturized filter design are reflected in: i) the structure of filters is complex and difficult to implement; ii) the internal components are difficult to configure and highly sensitive; iii) the performance stability is poor; iv) the debugging margin is small and the adjustability is low; and v) it is not reconfigurable and the cost is high.

The main contributions of our work are concluded as follows: firstly, a flexible and easy-to-process miniaturized cavity filter design method is proposed. This approach would resolve the issues raised in the above. First, to achieve the purpose of miniaturization, we use a coaxial resonator at the open end of a hat-shaped capacitive load. Second, in order to reduce the difficulty and cost of fabrication, we process the capacitive-load resonator separately. The resonator is partitioned into two parts. The first part is called the base of the resonator. This part is simply a pillar, which is directly fabricated integrally with the cavity housing and its material is the same as the cavity housing. The second part is called the hat of the resonator. Because the material of the cavity housing has little impact on the overall filter performance, the main impact is the plating material used on the surface of the cavity. While the open-end terminal of the capacitive load resonator has a greater impact on the performance of the filter. By processing the capacitive load resonator body separately, the simple part (called base) can be processed directly with the cavity housing, while the part (called hat) that affects the performance can be processed separately. The hat part is individually fabricated and made of better materials such as copper refining for better performance. This can reduce the difficulty of processing and greatly reduce the cost.

Secondly, an easy way to turn the center frequency of filters is provided. The filters that are designed and processed by the proposed design style can be effortlessly reconfigured. When we desire to change the operating frequency of a cavity filter or reconstruct an existing filter, we can change the length of the base part to the resonator to change the center frequency of the filter or change the diameter of the hat. Filters with different performances can be achieved by designing and processing different shapes of the hat (such as disc and donut). The cavity does not need to be refabricated, so the cost can be greatly reduced.

Thirdly, a method for mass production and low-cost cavity filters is recommended. Because the cavity structure is relatively simple and the capacitive load resonator is processed separately, the processing consistency is not only high but also the cost of fabrication is relatively cheaper. Thus, it is suitable for industrial mass production.

To demonstrate the effectiveness of the proposed method, we verified this method by designing, fabricating, and measuring a cavity filter with a center frequency of 3.45 GHz and a bandwidth of 80 MHz. The measured results show that the insertion loss was smaller than 1.33 dB in the whole bandwidth, one zero-point at 3.350 GHz reaching -68 dB, the rejection at 3.550 GHz was -41 dB, unloaded Q was 5898, and the dimension of the filter was 128 mm×86 mm×23 mm. Comparing with some other existing filter design methods such as traditional cavity band pass filter [26], Iris coupled cavity bandpass filter [25], gap waveguide coupled-resonator filter [27], and high-permittivity ceramic substrates-based SIW filter [28], the result show that the proposed method is effective and it can achieve good performance filters for industrial applications.

This paper is organized as follows: first, in section 2, the proposed method of designing cavity bandpass filters with separating housing and resonators for flexible operating frequency is described in detail. Then, in section 3, the results of the simulation and measurement of the designed cavity filter are exhibited and a brief discussion is given. Finally, in section 4, the conclusion of our work is drawn.

2. METHOD

2.1. Capacitive load resonator for reducing the size of cavity filers

Displayed in Figure 1 is the typical structure of a capacitive load resonator (seen in Figure 1(a)), along with its corresponding equivalent circuit representation (illustrated in Figure 1(b)) [29]. This is a traditional quarter-wavelength coaxial resonant cavity, in which the bottom short-circuit end is equivalent to the total inductance while the top open-end conductor is equivalent to the total capacitance. The relationship between the magnitude of the equivalent capacitance at the top open-end conductor of the resonator (C) and the resonant frequency (ω_0) can be computed as [12]:

$$\frac{cos(\beta\, l)}{Z_0} - \omega_0 C = 0 \quad (1)$$

where Z_0 is the characteristic impedance, β is the phase constant, and l is the height of the resonator.

In (1) can be transformed in the form:

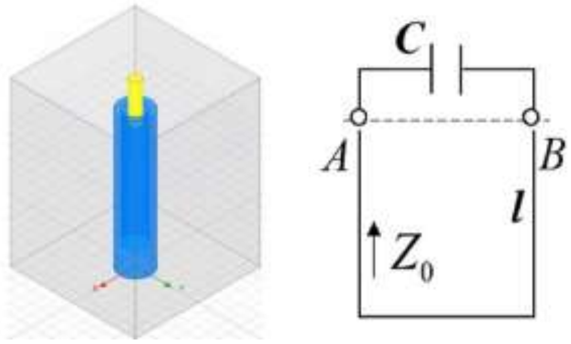
$$l = \frac{arctan\left(\frac{1}{Z_0 \omega_0 C}\right)}{\beta} = \frac{\lambda}{2\pi} arctan\left(\frac{1}{Z_0 \omega_0 C}\right) \quad (2)$$

Since $0 < arctan\left(\frac{1}{Z_0\omega_0 C}\right) < \frac{\pi}{2}$ and $0 < l < \frac{\lambda_0}{4}$, the presence of the equivalent capacitance affects the height of the resonator, i.e., the height of the resonant cavity is shorter than that of a quarter-wavelength coaxial resonant cavity without capacitive load. From (2), we can see that the larger the equivalent capacitance, the smaller the height of the cavity. Therefore, if the height of the cavity remains unchangeable, the resonant frequency of the resonator can be adjusted by changing the capacitance at the top open end of the resonator.

Moreover, the value of the equivalent capacitance of the top open end of the resonator is a function of the area of the top end and can be computed as [20]:

$$C = \frac{\varepsilon_r \varepsilon_0 d^2}{4\alpha} \quad (3)$$

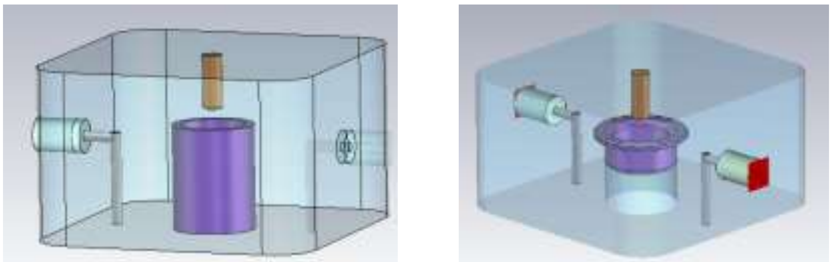
where d is the diameter of the resonator and a is the length of the gap between the top open end to the top of the cavity. It can be seen that when the diameter (area) of the top open-end conductor is increased, the equivalent capacitance can be increased, and this make to reducing the size of the resonant cavity.



(a) (b)

Figure 1. The structure of (a) the common capacitor-loaded resonator and (b) the equivalent circuit diagram

To demonstrate the effect of the area of the top open-end conductor on the size of the cavity. Figure 2 shows different configurations of resonators. Table 1 lists the size of the cavity when the resonant frequency is fixed at 3.45 GHz and the area of the top open-end conductor is changed by using the different structures of resonators, namely, direct [12], [23], [29] as shown in Figure 2(a) and the proposed structure that is shown in Figure 2(b). From Figure 2 and Table 1, it can be seen that our method is effective in reducing the size of the cavity filter.



(a) (b)

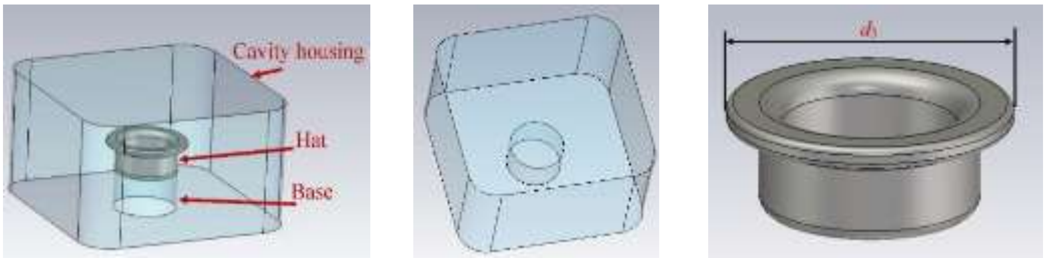
Figure 2. The configurations of resonator (a) direct resonator and (b) the proposed resonator

Table 1. The size of the cavity filter when using different capacitive load structures

Type of capacitive load structures	Direct	The proposed
Cavity filter dimension (mm^3)	35×35×21	35×35×19
Height of resonator (mm)	12.6	11.56

2.2. Separating housing and resonator for flexible frequency

The overall structure of proposed resonant cavity is described in Figure 3. Figure 3(a) shows the cavity housing, hat and base parts. We divide the resonator into two parts. The base part will be processed together with the cavity housing and its material is the same as the cavity housing as shown in Figure 3(b). The hat part as shown in Figure 3(c) is designed and fabricated separately. It can use other better materials such as refined copper, and silver. The base and hat parts are connected by screws. This structure of the resonator reduces the difficulty of processing in reality. Most of the filter parts (cavity housing and the base of the resonator) can be made of low-priced materials, while the complex and influential part (the hat) can be processed separately and can use other good materials to achieve better performance of the filter.



(a) (b) (c)

Figure 3. The overall structure of proposed resonant cavity; (a) the structure of the resonator, (b) the base and cavity housing, and (c) the hat structure

The designed resonator structure allows the cavity filter to be easily reconfigurable. According to (3), it can be seen that the frequency of the filter is affected by the loaded capacitance. The main influence part is the diameter (area) of the top open-end conductor. Therefore, when we desire to change the operating frequency of the filter, we only need to change the hat part, while the housing can remain unchanged. In addition, according to (3), one method is to keep the hat structure unchanged, we change the height of the base and the operating frequency of the filter is also changed. In this case, we only need to process the base part (shorten or lengthen it) and the cavity housing and the hat part do not need to be re-fabricated. This method can greatly reduce the cost of cavity filters and achieve filter reconfigurable function at the same time.

Figure 4 plots the operating frequency center of the cavity filter under different hat sizes (its diameter d_3). It can be seen that different operating frequencies can be obtained by using different sizes of the hat part. The larger the diameter of the hat, the smaller the operating frequency. This is consistent with what (1) to (3) reflects.

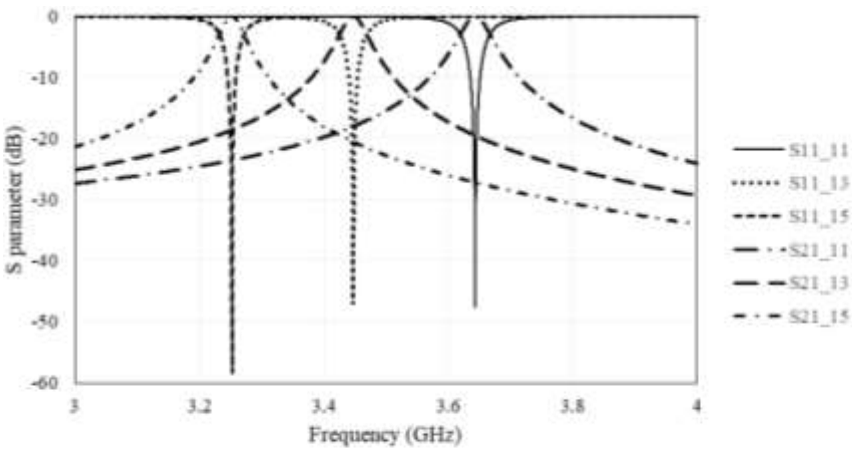


Figure 4. The operating frequency of the cavity filter with different sizes of the hat (d_3 in mm)

2.3. The configuration of the designed filter

To demonstrate the effect of the proposed design method, a 6th-pole prototype filter at 3.44 GHz with BW=70 MHz and -30 dB rejection at ±100 MHz is designed, optimized, and fabricated for verification. The design of this cavity filter is based on Chebyshev prototype element values for lowpass filters, which are used in calculating the normalized capacitances per unit length between adjacent resonators and resonator to ground. The design of the cavity filter is performed in the following steps.

In the first step, a single-cavity resonator is designed: a small size single-cavity resonator is the base of the miniaturization design of the filter. However, the smaller the cavity, the smaller the unloaded Q factor. Therefore, it needs to find a balance between a high Q factor and miniaturization. The size of the designed single-cavity resonator is shown in Figure 5. Normally, the height of a single-cavity resonator is taken by the quarter-wavelength (21.7 mm) of the center frequency (3.45 GHz). By introducing the proposed capative load structure, the height of the single-cavity becomes smaller (only 19 mm, a reduction of 12.4%). With the structure of the cavity as coaxial cable, the height of the resonator (l_1+l_2) is chosen between 50%-80% of the quarter-wavelength. In our structure, the height is 10.66 mm, that is, the gap between the open-end terminal of the capacitive load resonator with the top surface of the cavity is large, the loaded capacitance is not easily broken down, the filter can achieve a higher Q value.

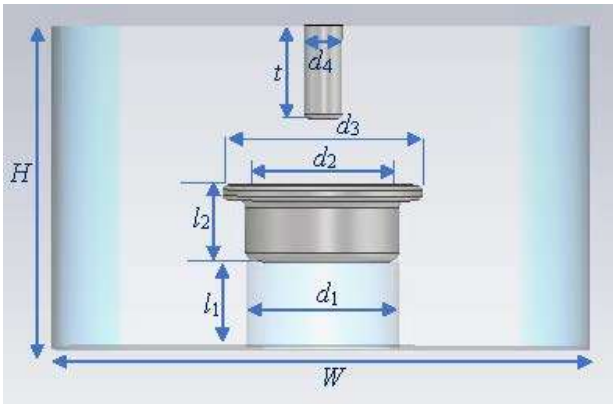


Figure 5. The schematic diagram and the dimension of the proposed single-cavity resonator.
(In mm: l_1=5.66, d_1=10, l_2=5, d_2=8, d_3=12.4, d_4=2.5, t=6, W=35, H=19)

In the second step, the order and the structure of the cavity filter are determined: assuming that the normalized frequency of the cavity filter is Ω_s, the stopband rejection, and the in-band ripple are L_{As} and L_{Ar}, respectively. It is easy to determine the order n of the filter by [30]:

$$n \geq \frac{\cos h^{-1}\sqrt{\frac{10^{0.1L_{As-1}}}{10^{0.1L_{Ar-1}}}}}{\cos h^{-1}\Omega_s} \quad (4)$$

According to the parameters required by the design, it is easy to calculate that at least a 6th-order filter is required. In this sample, we design a small size cavity filter with 6 cavities. How to arrange these cavities, i.e., designing the filter topology is very important. Different topologies of cavities will produce completely different numbers and structures of transmission zeros, thus, the performance of filters varies greatly. Figure 6 provides the topology and inside structures of the propose filter. Figure 6(a) shows the structure of the designed cavity filter, in which the main path for direct coupling is 1-2-3-4-5-6 and an auxiliary path for cross-coupling is 2-5.

In the third step, the coupling coefficient is computed: the direct coupling (inter-coupling) coefficient between two resonant cavities *i-th* and *j-th* is calculated as (5):

$$k_{ij} = m_{ij} \times FBW = \frac{FBW}{\sqrt{g_i g_j}} \quad (5)$$

where FBW is the relative bandwidth, g_i and g_j are the normalized low-pass prototype values of the resonant cavities. Figure 6(b) shows the designed structure of the direct coupling in this work. The direct coupling coefficient is tuned by changing the length of a coupling crew entering between two cavities [31].

The fourth step, cross-coupling is determined: two non-adjacent resonant cavities are electromagnetically coupled together called cross-coupling [22], [32]. It is used to bring transmission zeroes into the stopband domain to increase filter selectivity. Figure 6(c) shows the structure of the cross-coupling used in our design which is a quadrilateral capacitive cross-coupling. By adopting this cross-coupling path, one transmission zero is created at the outside of the pass band to improve the out-of-band selectivity of filters.

Moreover, the coupling, that connects the filter to the outside world, is called the external coupling, it is often expressed as the external quality factor Q_{ext}, and it is calculated by (6).

$$Q_{ext} = \frac{1}{(m_{s1} \times FBW)^2} = \frac{g_s g_1}{FBW} \tag{6}$$

The external quality factor Q_{ext} is also calculated based on the group delay t_d.

$$Q_{ext} = \frac{2\pi f_0 t_d}{4} \tag{7}$$

The structure of the external quality factor Q used in our design is shown in Figure 6(d). In the final step, the single-cavity resonator, the topology, the structures of inter-coupling, cross-coupling, and the external quality factor are combined to construct a cavity filter: in this design, the five above computed factors are combined to arrange a 6th-order compact cavity filter that is shown in Figure 7. Figure 8 shows the layout of our designed cavity filter.

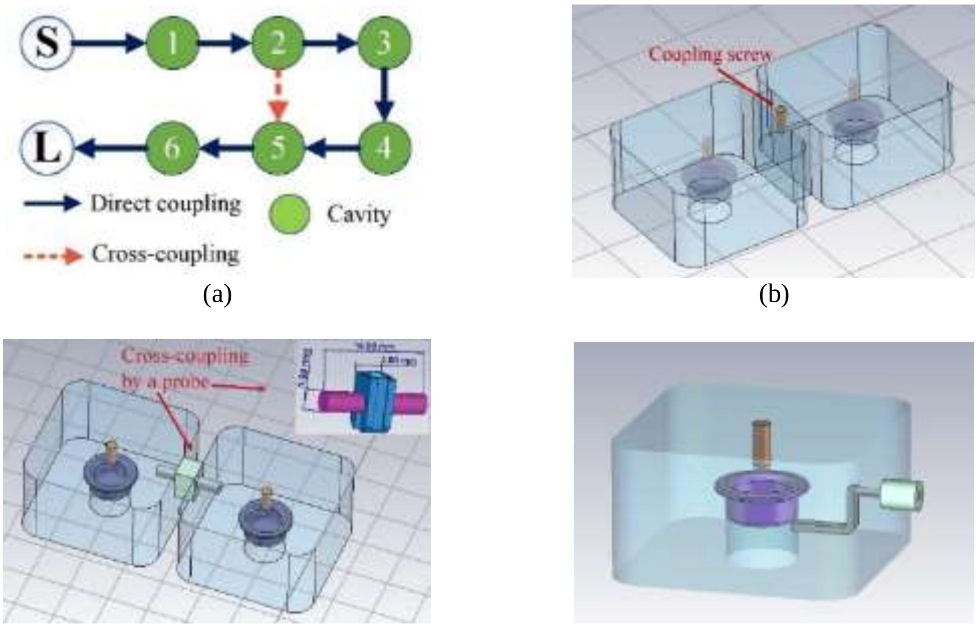
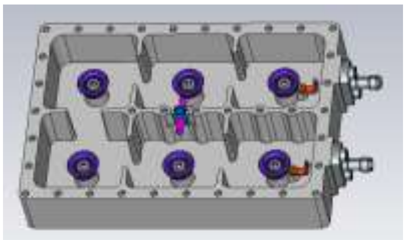
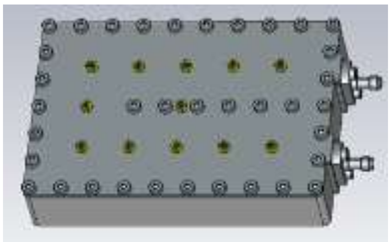


Figure 6. The topology of the proposed filter; (a) the structures of, (b) inter-coupling, (c) cross-coupling, and (d) external quality factor Q_{ext}

Figure 7. Schematic diagram of the proposed cavity filter

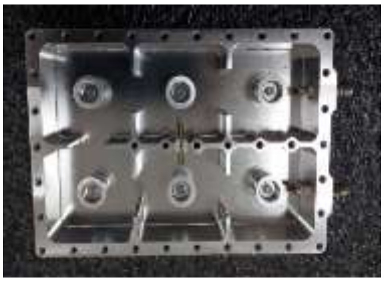



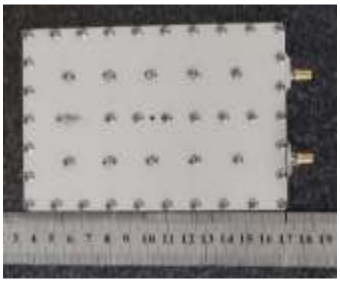
(a) (b)

Figure 8. The layout (in 3D) of the proposed cavity filter (a) without cover layer and (b) complete filter

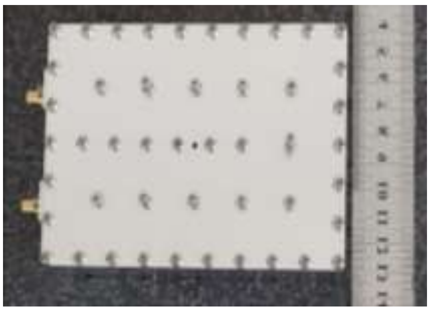
3. RESULTS AND DISCUSSION

In this section, the results of the simulation and measurement of the designed cavity filter are exhibited to verify the effectiveness of the proposed design method. First, based on the results of the above simulation, the designed cavity filter is fabricated and measured. Figure 9 shows the physical photo of the fabricated bandpass filter in which Figures 9(a) to 9(e) are the cavity body without cover layer, the resonator, the top view of the filter with length, the top view of the filter with width, and the view of the filter with thickness, respectively. Since the fund for this project is limited and we also desire to test the performance of the proposed design method when the processing cost is the cheapest. Thus, our cavity filter is made of aluminum without a silver-plated layer on the inner surface, the hat part is also made of aluminum the same as the cavity housing, and the ports are connected by SMA connectors. As can be seen in Figure 9, the size of the filter is determined as 128 mm×86 mm×23 mm.





(a) (b) (c)




(d) (e)

Figure 9. Physical view of the fabricated cavity filter; (a) without cover layer, (b) the hat part and probe, (c) the size of the filter, (d), the size of the filter, and (e) the size of the filter

Figure 10 depicts the measured results interface. Figure 11 draws the comparison of the S-parameter frequency response of the filter between the simulation and the post-fabricating test. As can be seen, the fabricated cavity filter achieves a good agreement. The insertion loss was smaller than 1.33 dB in the whole bandwidth, with one zero-point at 3.350 GHz reaching 68 dB, and the rejection at 3.550 GHz was 41 dB. The performance indicators of this cavity filter meet general engineering application requirements. To check the performance of the designed cavity filter, we compare our filter with some different types of related resonators such as waveguide, SIW, and cavity.

The results of measuring the fabricated cavity filter show that although in the simulation, the filter has a zero point at 3.65 GHz, the actual measurement of the fabricated filter does not have this zero point. This may be because the cross-coupling effect is not very good. Therefore, the cross-coupling needs to be further optimized and fine tuned to achieve the zero point. A comparison of our design with some existing works is listed in Table 2 in detail. It can be seen that although our filter size is not the smallest, it can achieve a higher Q value and has good out-of-band rejection.

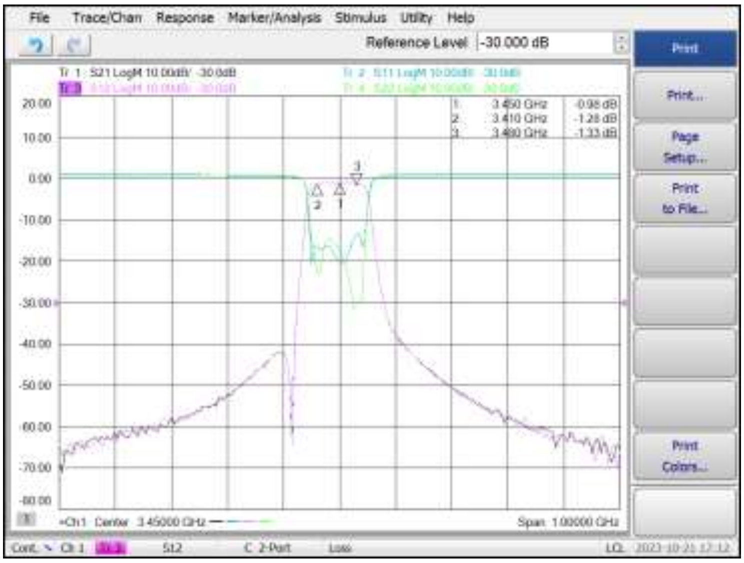


Figure 10. The interface of measurement

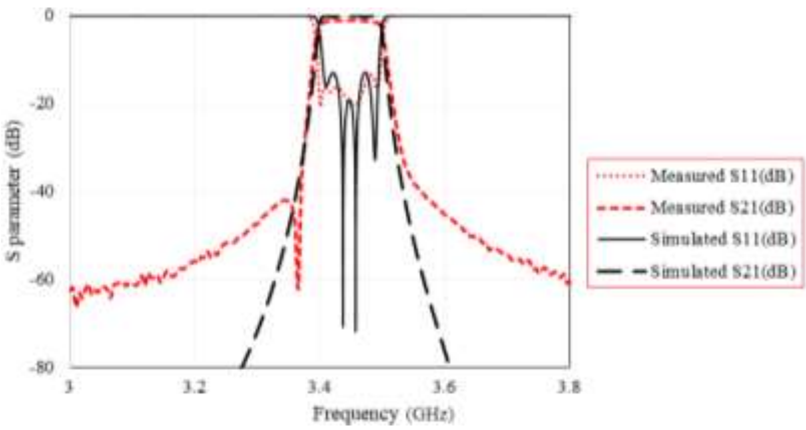


Figure 11. The comparison of the simulation and measurement results

Table 2. A comparison of the performances of the designed cavity filter with some related published works

Reference	f_0 (GHz)	Related BW (%)	Insertion loss (dB)	Unloaded quality factor	Size (λ_g)	Type of resonators	Stop band rejection
[27]	37.23	1.5	1.3	3365	4.88×2.1	Waveguide	≥70 dB@3.5 GHz ≥70 dB@4.5 GHz
[28]	4.0	6.25	2.48	260	1.4×0.28	SIW	≥40 dB@3.5 GHz ≥30 dB@4.5 GHz
[26]	3.45	8.7	1.5	-	2.07×0.31	Cavity	≥55dB@ 3.68GHz ≥50dB@ 3.22GHz
[25]	4.5	4.4	1.5	2500	0.7×0.53	Cavity	≥50 dB@4.2 GHz ≥50 dB@4.8 GHz
This work	3.45	2.32	1.33	5898	1.47×0.99	Cavity	≥68 dB@3.350 GHz ≥41 dB@3.550 GHz

4. CONCLUSION

In this paper, a tunable center frequency and small size cavity bandpass filter design method is proposed. This method employs a capacitor-loaded open terminal coaxial resonator to reduce the size of cavity filters. The resonator is designed and fabricated separately into two parts, i.e., base part and hat part, to archive the tunable operating frequency purpose. By changing the size of the hat part, the center frequency of the filter is easy to tune. This method not only makes the cavity filter reconfigurable but also reduces the difficulty and cost of cavity filter processing. A cavity filter sample with a center frequency of 3.45 GHz and 80 MHz bandwidth was designed, fabricated, and measured to demonstrate the effectiveness of our method. This cavity filter has an insertion loss smaller than 1.33 dB in the whole bandwidth, one zero-point at 3.350 GHz reaching -68 dB, the rejection at 3.550 GHz was -41 dB, unloaded Q was 5898, and the dimension of the filter was $1.47\lambda_g \times 0.99\lambda_g$. The designed and processed filters are not only cheap but also meet engineering requirements.

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