Low-cost high-performance frequency-tunable substrate-integrated waveguide filter structure and fabrication method

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Abstract: This paper presents a new frequency-tunable substrate-integrated waveguide (SIW) filter structure and its fabrication method. The center frequency of the filter is adjusted by moving the membrane structure in each resonator, and the presented fabrication method mainly focuses on how to minimize the number of fabrication steps for constructing the flexible membrane. Due to the simplified process, the filter has advantages of low cost and low risk fabrication. The comparison between a conventional fabrication procedure and the new proposed method is described. For verifying the presented filter structure and fabrication method, two frequency-tunable SIW bandpass filters of the presented structure have been implemented using the presented fabrication method. It is shown that the measured response agrees well with the simulated one. The minimum insertion loss is 0.85 dB, demonstrating that high quality factor can be achieved.

Keywords: substrate integrated waveguide (SIW), filter, high Q, copper membrane

Classification: Microwave and millimeter-wave devices, circuits, and modules

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1 Introduction
As the demand on communications systems that use multiple operating frequencies
increases, design of frequency-tunable RF/microwave filters and multi-band filters
has been of a great interest in the field of microwave engineering [1, 2, 3, 4, 5, 6, 7,
8, 9, 10, 11, 12, 13, 14]. Particularly, study on frequency-tunable filters has been
mainly motivated by increased necessity of frequency agility in next-generation
communications systems and electronic-warfare systems. Tremendous amount of
effort has been devoted to developing various types of frequency tunable filters.
For practical application to frequency-agile systems, having a simple fabrication
process and good electric performances is important.

Planar structure filters such as microstrip line filter usually adopt varactors for
the purpose of adjusting the center frequency or the coupling coefficients [2, 3].
Although planar filters can be fabricated at low cost with ease, they have moderate
performance in terms of, for example, insertion loss due to inherent low Q-factor of
the planar type resonator.

On the other hand, waveguide cavity resonator filters have excellent electrical
performance by virtue of the unbeatable Q-factor [4, 5, 6]. Tuning devices such as
tuning plunger and tuning screws are usually used in adjusting the resonant
frequency of each resonator, but only small frequency tuning ranges can be obtained.
It has been claimed that a tunable SIW cavity resonator filter can be a
compromise between a planar filter and a waveguide cavity filter. Tunable SIW
cavity resonator filters have shown large frequency tuning ranges and high-Q performances [7, 8, 9, 10, 11, 12, 13]. Fig. 1 shows the layer-by-layer view of a typical 2-pole SIW cavity resonator filter structure. The SIW tunable cavity resonator has a conductive post at the center and this allows for achieving a large frequency tuning range due to confinement of the electric field between the post and the membrane. In short, frequency tuning can be carried out by adjusting the membrane. Hence, having large deflection of the copper membrane is key parameter for obtaining a wide frequency tuning range. Typically circular shape piezo actuators have been widely used in adjusting the position of the copper membrane. In addition, many research works have shown that the tunable SIW filters can have wide frequency tuning ranges. Fabricating the tunable SIW filters involves milling, laminating, and copper plating processes. In general, the post-loaded SIW filter fabrication procedure includes two copper plating processes. The second copper plating process is the high-risk task and requires pretreatment causing fabrication complexity.

This paper presents a new frequency-tunable SIW resonator filter structure and its fabrication method. The presented structure can be fabricated by a more simplified fabrication process compared to the conventional structure. For verifying the presented filter structure, we have designed and fabricated two 2-pole frequency-tunable SIW filters. It is shown that the presented filter structure and fabrication method can reduce the fabrication complexity adding practicality to the filter.

In Chapter II, the new SIW filter structure, brief design procedure, and the fabrication method are described. In addition, benefits of using the new filter structure and fabrication method are highlighted comparing the new filter structure
and fabrication method with the conventional ones. In Chapter III, the measured results of the new filter structure are shown for verifying the new structure and fabrication method. Also, in Appendix, conventional SIW filter fabrication method is presented for the comparison.

2 Filter design and fabrication

2.1 Filter design

Fig. 2(a) shows the layer-by-layer view of the presented filter and Fig. 2(b) shows physical dimensions of the filter. The filter consists of two different substrates. One (0.508 mm-thick Rogers 5880) has microstrip line structures. Two microstrip lines are connected to the input and output ports individually. One end of each of these lines is connected to the ground plane via a capacitor (or varactor) and a via hole. The other microstrip line in the middle of the substrate constitutes an inter-resonator coupling structure, along with the inductive iris, between two resonators. Each end of the line are connected to the ground plane via a capacitor (or varactor) and a via hole. The value of the capacitor (or varactor) along with the size of the coupling aperture on the ground plane determines the external coupling coefficient and the internal coupling coefficient.

The other substrate (3.175 mm-thick Rogers TMM3) contains two frequency-tunable SIW resonators. The resonators have the via-holes on the outer boundary for defining the side walls. As shown in [14], the resonant frequency, $f_r$, of the post-loaded cavity resonator can be approximated as

$$f_r = \frac{c}{2\pi} \sqrt{\frac{\varepsilon_r}{	ext{height}}}$$
\[ f_r = \frac{c_0}{\pi \sqrt{\frac{g^2}{2p} \ln \left(\frac{f}{g}\right)}} \]  

(1)

where \( c_0 \) is the speed of light in free space, \( g \) is the diameter of the post, \( l \) is the height of the post, \( p \) is the air gap between the center post and the membrane and \( f \) is the diameter of the resonator. For having the frequency tuning range from 2.7 GHz to 3.7 GHz, 22 mm and 6 mm have been chosen for the diameter of the resonator and the post, respectively. A thin copper foil is laminated to the TMM3 substrate having a prepreg layer between them. Due to the cylindrical holes in the prepreg, an air gap can be formed between the TMM3 substrate and the copper foil. Hence the copper foil can deflect and can be used as a membrane. The capacitance between the post and membrane can be varied by moving the membrane in vertical direction, and this leads to the variation of the resonant frequency of each resonator. It is worth noting that solder paste is used between the membrane and the via-holes on the outer boundary for electrical connection between them. On the other hand, the conventional filter structure \([7, 8, 9, 10, 11, 12]\) has copper-plated via-holes running from the TMM3 substrate to the membrane. This via-hole structure increases fabrication complexity, and the details will be discussed later.

Physical dimensions of the filter can be determined by target performances. For demonstration, the filter is designed to have Butterworth response at 2.9 GHz with 3.5% fractional bandwidth. The normalized coupling coefficients for the second-order Butterworth response can be found by using the well-known filter synthesis methods \([15, 16]\), and they are

\[ M_{01} = M_{23} = 0.8409, \quad M_{12} = 0.7071, \]  

(2)

where 0 and 3 denote the source and load, respectively, and 1 and 2 denote the resonators. The external coupling coefficient can be denormalized and is given by \([17]\)

\[ k_{01} = \sqrt{\Delta f} \cdot M_{01}, \]  

(3)

where \( \Delta f \) is the fractional bandwidth. As mentioned before, the coupling coefficient of the external coupling structure is determined by the capacitance of the capacitor (or varactor) and the size of the coupling aperture. In this work, the method for extracting the external coupling coefficient presented in \([18]\) has been used, and Fig. 3(a) shows the relationship between the external coupling coefficient and the angle of the coupling aperture for various capacitor values. It is shown that the coefficient increases as the angle of the coupling aperture increases. The required external coupling coefficient is 0.157 and there are a number of options in choosing the capacitor value and the aperture angle to obtain the desired coupling value. However, we took into account two factors and made a compromise between them.

The first one we considered is the \( k_{01} \) variation with respect to the capacitor value. Fig. 3(a) shows that \( k_{01} \) decreases as the capacitor value increases but it rarely decreases when the capacitor value is larger than 2.2 pF. This implies that using a higher capacitor value is favorable for designing the external coupling
structure that is insensitive to the variation of the capacitor value and can tolerate the tolerance of commercially available capacitors.

The second one we considered is the dissipative loss (Q-factor) of capacitors. In general, a commercially available capacitor has a smaller loss with a smaller capacitor value. This indicates that using a smaller capacitor value is favorable for designing the low-loss external coupling structure. Hence, considering the two factors mentioned above, 2.2 pF has been chosen for the capacitor value and this requires the slot angle of 80 degrees for obtaining $k_{01} = 0.157$.

The inter-resonator coupling structure in this work consists of the inductive iris and the aperture-coupled microstrip line between the two resonators. The coupling value can be controlled by the iris width, the coupling aperture dimensions, and the internal capacitor value. The denormalized inter-resonator coupling coefficient, $k_{12}$, is given by

$$k_{12} = \Delta f \cdot M_{12}. \quad (4)$$

Extracting the inter-resonator coupling value is described in [16], and Fig. 3(b) shows the relationship between $k_{12}$, the iris width, and the internal capacitor value. According to (4), the required coupling value is 0.0249, and we considered two factors in determining the capacitor value and the iris width.

The first one we considered is the dissipative loss (Q-factor) of capacitors. Again, using a smaller capacitor value is favorable for designing the low-loss external coupling structure.

The second one we considered is the resonance in the iris structure. Fig. 3(b) indicates that, for obtaining a required $k_{12}$ value, a larger iris width is required as the capacitor value increases. It is more likely that an unwanted resonance takes place in the iris structure with a larger width. Hence, using a smaller capacitor value is favorable for designing the non-resonating iris. Consequently, 0.1 pF has been chosen for the capacitor value and this requires the iris width of 14.6 mm for obtaining the required coupling value, $k_{12} = 0.0249$.

### 2.2 Fabrication method

In this section, we describe the fabrication process for the presented filter structure. Implementing the presented filter structure requires less process steps and effort.
Although the fabrication process for the typical filter structure shown in Fig. 1 can be found in [12], it is given in Appendix for convenient comparison with that for the presented filter structure. Fig. 4(a) shows the cross-section of one of the resonators of the presented filter structure for each step of the fabrication process. Since the microstrip line structure can be fabricated by using a typical etching process, we only show the cross-section of the resonator. The first step is to create via-holes for the post and side wall. These via-holes are then copper-plated (Step 2). The post at the center of the resonator can be defined by milling one side the substrate (Step 3). Fig. 4(b) shows the bottom-view of the substrate after Step 3. The last step is the membrane lamination procedure (Step 4). The solder paste is used to electrically connect the via holes on the outer boundary and the copper membrane. Since the solder paste is applied to the region external to the via holes, it does not leak into the resonator. A 0.06 mm-thick prepreg is used as an adhesive so that the membrane is firmly attached to the TMM3 substrate. Since the prepreg has a dumbbell-shaped hole, the air gap can be created between the membrane and the post in each resonator, and the air-gap thickness is mainly determined by the thickness of the prepreg.

It is shown that the presented filter structure can be implemented with less process steps and effort compared with the conventional filter structure. In the traditional fabrication method, as details are presented in Appendix, two copper plating steps are needed. The first one is for plating the via holes forming the post at the center of each resonator, and the second one is for plating the via holes on the outer boundary forming the side wall of each resonator.

The second copper plating requires a pretreatment and is a high risk process, since this must be carried out after laminating the membrane to the TMM3 substrate. More specifically, the copper plating liquid leaks into the resonators.
through the via holes forming the posts and ruins them when there is no pretreatment. Hence, the via holes forming the holes must be blocked by using an adhesive material that can endure the copper plating process. It is a high-risk process since there is a chance that the adhesive is detached from the substrate. In addition, this second plating process adds more copper to the membrane deteriorating the flexibility of the membrane. The newly presented method can reduce the fabrication steps and can avoid having the serious unwanted problems that could take place if the conventional method were employed.

3 Measurement

In this work, we have fabricated two 2-pole SIW resonator filters. First, based on the design result described in the previous section, we have implemented a filter using commercially available static capacitors in the external and inter-resonator coupling structures. Fig. 5 shows the fabricated filter and Fig. 6(a) shows the measured response centered at 2.9 GHz. The Butterworth response with 3.5% fractional bandwidth has been obtained and it agrees well with the simulated response. Since the filter consists of frequency-tunable SIW resonators, the center frequency of the filter can be tuned. In this design, for frequency tuning, tiny ultrasonic linear actuators (Piezo Electric Technology TULA70) with large move-

![Fig. 5](image1)

(a) Top-view of the fabricated filter with static capacitors in the external and internal coupling structures. (b) Bottom-view of the fabricated filter before attaching tuning elements for frequency tuning

![Fig. 6](image2)

Fig. 6. Measured results of the fabricated filter shown in Fig. 5. (a) Comparison between measurement and simulation at 2.9 GHz. (b) Frequency tuning characteristic.
ment range have been used to adjust the copper membrane. Fig. 6(b) shows the measured results when the filter is tuned at different center frequencies. The center frequency is tuned from 2.7 GHz to 3.7 GHz with low insertion loss (<1.8 dB).

The minimum measured insertion loss is 0.85 dB at 2.9 GHz including the one of SMA connectors for measurement. This indicates that the Q-factor of the fabricated resonators is 670 which is comparable to the resonator fabricated using the conventional fabrication process [8, 10]. It is shown in the measured results that the return loss performance varies as the center frequency of the filter is adjusted. This is because the external coupling value and the inter-resonator coupling value change as the operating frequency varies. Excellent return loss performance can be obtained by having variable external and/or inter-resonator coupling structures. In this work, we only use variable external coupling structures for demonstration.

Fig. 7(a) shows the fabricated filter with varactors in the external coupling structures. This filter has the same resonator structure as the previous one. Skyworks SMV1265-011LF varactors are used for this filter and placed in the microstrip line. The capacitance of the varactors can be tuned from 0.71 pF to 22.47 pF. Fig. 7(b) shows the measured result of the filter shown in Fig. 7(a). The external coupling coefficients can be tuned by adjusting DC supply voltage for the varactors and Butterworth responses can be achieved over the entire frequency tuning range. The large DC voltage decreases the capacitance of varactor diodes and increases the external coupling coefficient. The center frequency varies from 2.6 GHz to 4 GHz. The high return loss can be obtained by using varactors. However, varactors and DC blocks add the insertion loss, and the minimum measured insertion loss is 1.7 dB at 2.6 GHz. It is a difficult task to measure the deflection range of the membrane physically. However, by comparing the measured responses to the simulated one, the deflection range of the copper membrane can be estimated. From that comparison, it has been concluded that the deflection range of the membrane is approximately 0.28 mm. This movement range of the membrane is crucial for acquiring frequency tuning capability.

Fig. 7. (a) Top-view of the fabricated filter with varactor diodes in the external coupling structures. (b) Measurement of the fabricated filter shown in Fig. 7(a).
4 Conclusion

A new frequency-tunable SIW filter structure and its fabrication method are presented in this paper. This manufacturing process can be conducted in a facility equipped with machines for drilling (milling), copper plating, and substrate laminating at low cost. The presented filter structure and fabrication method can enhance the practicality of frequency-tunable SIW filters.

Also, this filter fabrication procedure can be applied to any SIW cavity resonator filter types. Besides, the filter which is fabricated by the presented method has comparable electrical performance as the conventional filter has. The proposed filter fabrication method is a promising alternative to the conventional procedure.

5 Appendix

For convenient comparison between the new and conventional fabrication methods, we provide the cross-sectional view of the resonator for each step of the conventional fabrication process in this Appendix (Fig. 8). The detailed fabrication steps are as follows:

Step 1: Drill via holes for the post.
Step 2: Copper-plate the via holes for the post.
Step 3: Mill one side of the substrate to define the post.
Step 4: Laminate the copper membrane to the substrate.
Step 5: Drill via holes for the side walls.
Step 6: Block the via holes for the post using, for example, high temperature resistance tape. This is the pretreatment for the second copper plating for the side walls. Without this pretreatment, the copper plating liquid leaks into the resonators and ruins them.
Step 7: Copper-plate the via holes for the side walls. This step adds more copper to the membrane deteriorating its flexibility.

Fig. 8. Cross-sectional view of the resonator for each step of the conventional fabrication process.
Step 8: Detach the high temperature resistant tape used in Step 6 from the TMM3 substrate.

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