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Research Article

A Multilayer Substrate Integrated Circular Cavity (SICC) Dual-mode Filter Using a Novel Topology of Coupling

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Abstract: A compact multilayer dual-mode filter is developed using a new topology of coupling in this study. The filter is constructed with three Substrate Integrated waveguide Circular Cavities (SICC) and each cavity supports two degenerate modes, which is generated by the double arc-shaped slots located between layers. With multilayer topology, the structures can exhibit vertical coupling between vertically stacked dual-mode cavities. This coupling is achieved by double arc-shaped slots with same center, which are etched in the metal layers of cavities. The novel topology is used to improve the stop-band rejection, and suppress some undesirable response spur in transition band. Good agreement is obtained between the simulated and measured results of the proposed structure.

Keywords: Double coupling slots, dual mode filter, high selectivity, multilayer, microwave and millimeter wave, Substrate Integrated Circular Cavities (SICC)

INTRODUCTION

The rapid development of modern wireless communication systems brings the general requirements for good performance filters with compact size. So, Substrate Integrated Waveguides (SIW) have been proposed to develop many high-quality components (Chen and Wu, 2009; Shen *et al*., 2011; Deslandes and Wu, 2003; Potelon *et al*., 2006; Wei *et al*., 2009; Tang *et al*., 2007; Ahn and Yom, 2008). Compared with rectangular cavities, the Substrate Integrated Circular Cavity (SICC) is also a good choice for good performance filters design (Wei *et al*., 2009; Tang *et al*., 2007; Ahn and Yom, 2008). It not only has the same attractiveness as classical SIW filters, but also presents higher quality factor, lower loss. However, the dimension of SIW circuits may be too large for certain applications. In (Chen and Wu, 2009), cross-coupling was provided by higher order modes in cavities. Due to the transmission zeros far away from the passband, steep transition band was hard to realize. In addition, the oversized SIW cavities took up too much area. Accordingly, the dual-mode technology (Tang *et al*., 2007; Ahn and Yom, 2008) has been introduced in the SIW filter design to meet the requirements of size reduction. Based on the dual-mode SICCs, a planar diplexer was developed in (Tang *et al*., 2007). But, these filters still require too much area since of the planar structure designs.

On the other hand, in a 3-D multilayer substrate, more SIW circuits are synthesized and accommodated into different layers. Therefore, the dual-mode and multilayer techniques can be combined together to achieve more compact SIW filters. In (Ahn and Yom, 2008), a Ka-band 4-pole band pass filter was proposed. A coupling via placed in the cavities was used to perturb the two degenerate modes. But, the via located in SICCs also decreased the quality factor of cavities, and the four layers circuit demonstrated an insertion loss of 2.95 dB and the stop-band rejection below 25 dB. There is still several aspects need to be improved, i.e., the lower side band rejection and some response spur.

In this study, a novel multilayer dual mode filter with higher selectivity has been realized by the double arc-shaped coupling slots etched between layers. The topology of coupling can effectively improve the stop-band rejection, and suppress some undesirable response spur in transition band. Meanwhile, it is possible to control the bandwidth and the rejection level by adjusting parameters of the two arc-shaped slots. The filter is not only very compact, but also has the advantages of return loss, low insertion loss (<2.35 dB), and high selectivity (rejection >58 dB).

Filter analysis and design:

Multilayer dual-mode SICC filter: Figure 1 shows the structure of a multilayer dual-mode SICC filter.

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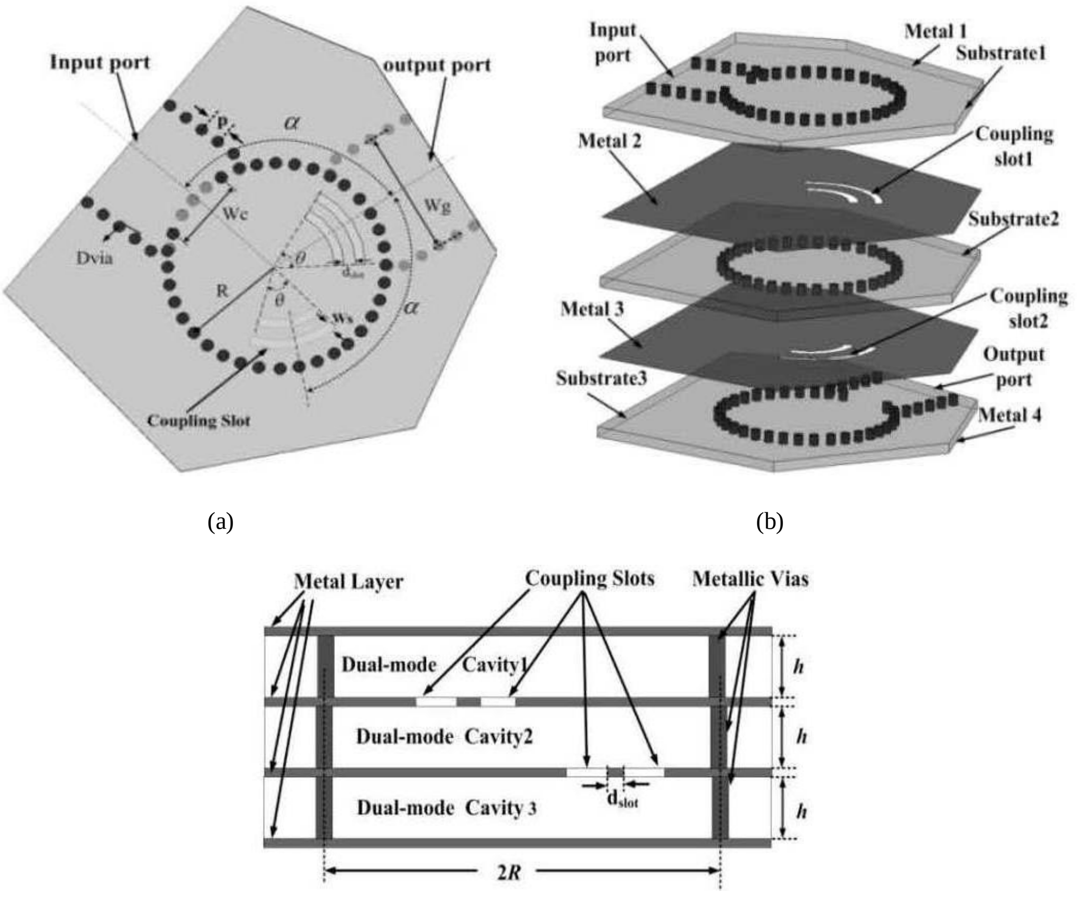

Input port
output port
α
p
Wc
Wg
Dvia
R
θ
d_slot
Ws
Coupling Slot
Input port
Metal 1
Substrate1
Metal 2
Coupling slot1
Substrate2
Metal 3
Coupling slot2
Output port
Substrate3
Metal 4
Metal Layer
Coupling Slots
Metallic Vias
Dual-mode Cavity1
Dual-mode Cavity2
Dual-mode Cavity 3
h
d_slot
2R

(a)

(b)

(c)

Fig. 1: Proposed dual - mode SICC filter with three layers: (a): Top view; (b): Anatomy view; (c): Side view

First and last layer are used as input and output ports respectively. Three vertically stacked cavities are coupled through arc-shaped coupling slot in metal layer 2 or 3. In particular, double concentric coupling slots are introduced in order to improve the stop band performance.

In these figures, α is the angle between the coupling slots and input/output port, R is the radius of the SICC, W_S is the width of the coupling slot, θ is the central angle of the coupling slot, W_C is the width of the coupling aperture.

Dual mode SICC principle: It is well known that the dual-mode phenomenon exists in a SICC. Compared to the traditional SIW cavities, the SICCs are more suitable to be used as dual-mode resonators. The resonant frequency of mode for circular cavity with solid wall can be calculated by (Pozar, 1998):

$$\mathrm{fmnp} = \begin{cases} \frac{c}{2\pi\sqrt{\mu_r\varepsilon_r}}\sqrt{\left(\frac{\mu'_{mn}}{R}\right)^2+\left(\frac{p\pi}{\Delta h}\right)^2} & TE_{mnp} \\ \frac{c}{2\pi\sqrt{\mu_r\varepsilon_r}}\sqrt{\left(\frac{\mu_{mn}}{R}\right)^2+\left(\frac{p\pi}{\Delta h}\right)^2} & TM_{mnp} \end{cases} \tag{1}$$

where, μ_r and ε_r are relative permeability and permittivity of the filling material, μ_{mn} and μ'_{mn} are the n^{th} roots of m^{th} Bessel function of the first kind and its derivative, R is the radius of circular cavity, Δh is the height of the of circular cavity and c is the speed of light in free space. For $m>0$, each m represents a pair of degenerate TM and TE modes ($\cos m\varphi$ or $\sin m\varphi$ variation). In circular cavity, TM_{110}, the second order mode, is selected as the working mode. Different directions represent different TM_{110} modes. μ_{mn} is 3.832 for the TM_{110} mode. Therefore, the corresponding resonant frequency is:

$$f_{110} = \frac{c}{2\pi\sqrt{\mu_r\varepsilon_r}}\cdot\frac{3.832}{R} = \frac{0.61c}{R\sqrt{\mu_r\varepsilon_r}} \tag{2}$$

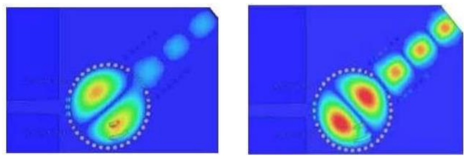
Then, the radius of the SICC can be obtained:

$$R = \frac{0.61c}{f_{110}\sqrt{\mu_r\varepsilon_r}} \tag{3}$$

Under the guideline of (Wei *et al*., 2009; Tang *et al*., 2007), the solid wall is replaced by metallic vias in a SICC. Furthermore, the size and spacing of metallic

Table 1: Relative bandwidth change with θ and W_s, d_{slot}

θ(deg)	δ_{p1z1}/f_0	$\Delta f/f_0$ (%)	W_S (mm)	d_{slot} (mm)	δ_{p1z1}/f_0	$\Delta f/f_0$ (%)
30	0.028	3.15	0.3	0.5	0.029	2.95
40	0.041	3.62	0.7	0.6	0.043	3.43
60	0.083	3.83	0.8	0.7	0.046	3.52



(a) (b)

Fig. 2: The E-field distribution of the degenerate TM_{110} modes (Setting output along horizontal direction); (a): Verticale mode; (b): Horizontal mode

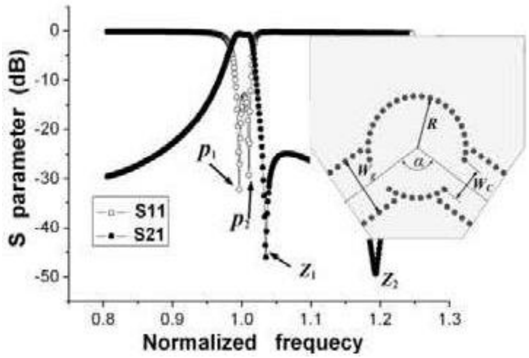


Fig. 3: Response of dual-mode filter with single circular cavity

vias are chosen to prevent electromagnetic field leakage (Xu and Wu, 2005). Consequently, using formula (3), the initial dimension of a SICC is determined for a desired resonant frequency with the TM_{110} mode.

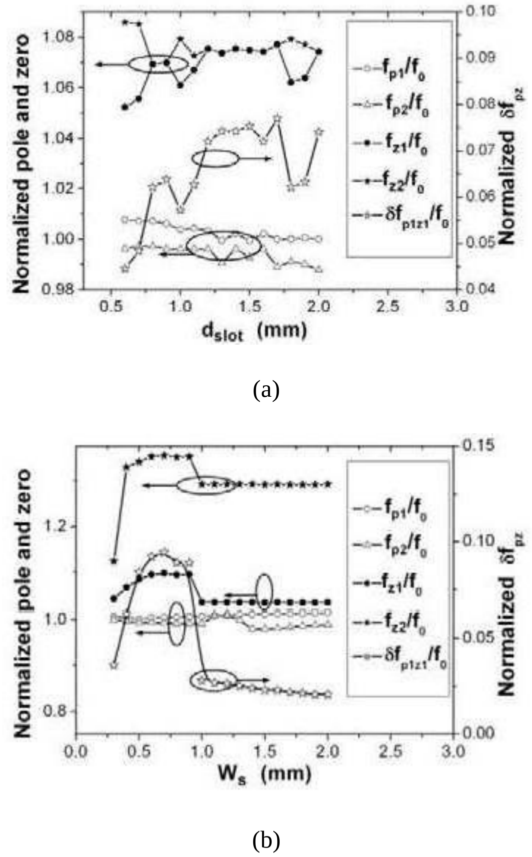
Figure 2 depicts the electrical fields of TM_{110} modes in a SICC. Obviously, they are two orthogonal degenerate modes, which co-exist in the same cavity, and have the same resonant frequency.

Double coupling slots: As shown in Fig. 3, two poles and two Transmission Zeros (TZs) can be found in the response of a dual-mode SICC filter. Two poles below the zero Z_1 are denoted as P_1 and P_2, respectively, which can be used to control the bandwidth.

The coupling slot size determines the position of the first zero and then decides the slope of the upper side response. Figure 4 illustrates variation of poles, zero for the TM_{110} mode when the coupling slot size W_S and the spacing d_{slot} are changed.

The distance between the zero Z_1 and pole P_1 is decreased evidently with the width of coupling slots W_S or the spacing d_{slot} decreased. Meanwhile, small change can be found in the frequency of pole P_1, P_2.

Table 1 evidences the bandwidth increased as the slot size increased. When the slot size is changed, the position of P_1, P_2 and Z_1 is also modified in frequency. In addition, the distance between the zero Z_1 and pole P_2 is decreased evidently with the central angle of coupling slots θ decreased.



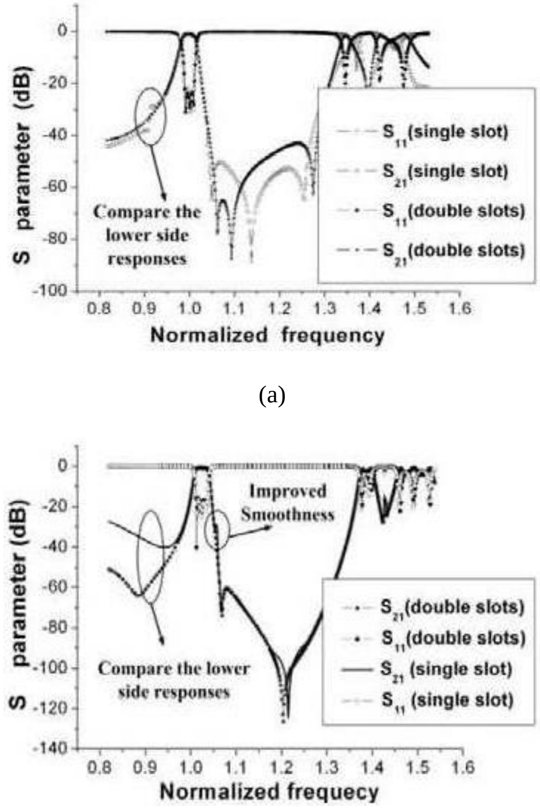
(a)

(b)

Fig. 4: Variation of poles, zero, distance between pole and zero with *Ws* or d_{slot}, Where, $\delta f_{plsI} = f_{z1} - f_{p1}$, f_0 is the eigenfrequency of mode TM_{110}. (a) Variation of P_1, Z_1 and δf_{pc} with respect to W_s, d_{slot} = 0.7 mm (b) Variation of P_1, Z_1 and δf_{ps} with d_{slot}, W_s = 0.4 mm

As observed in Fig. 5, compared with single slot, the double coupling slots can not only improve the stop-band rejection remarkably, but increase smoothness of the upper and lower side response to a certain extent. On the other hand, better return loss can be achieved by adjusting the parameters of the slots. It is concluded that the novel topology can contribute to improve the response performance of multilayer SIW circuits.

The angle α also affects the bandwidth, as illustrated in Table 2. A large value of α should be chosen for a broadband filter, while a small α may be proper for a narrowband filter. In addition, as depicted in Fig. 6, α determines the second zero Z_2, which is in



(a)

(b)

Fig. 5: Responses of dual-mode SICC filter with single or double coupling slots. (a) Two layers SICC filter. (b) Three layer SICC filter. Here, the frequency is normalized f_0

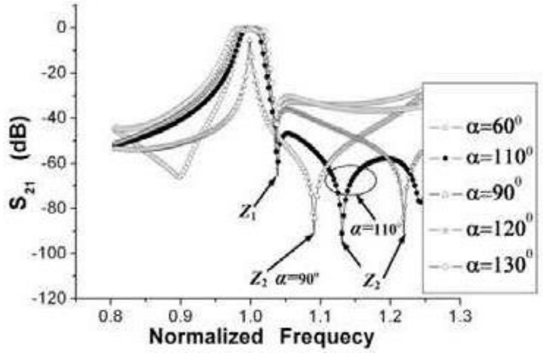


Fig. 6: Relation between zero Z2 and *a* in the dual-mode SICC filter

Table 2: $\Delta f/f_0$ change with α

W_c/R	α (deg)	$\Delta f/f_0$ (%)
0.7	110	3.53
0.7	120	3.65
0.7	130	3.90

the stop band and close to the adjacent TM_{210} mode. Smaller distance between Z_2 and the center frequency f_0 leads to better stop band rejection.

Table 3: $\Delta f/f_0$ change with W_c/R

W_c/R	α (deg)	$\Delta f/f_0$ (%)	W_c/R	α (deg)	$\Delta f/f_0$ (%)
0.60	110	3.15	0.60	130	3.61
0.65	110	3.32	0.78	130	4.12
0.75	110	3.63	0.85	130	4.53

External feeding structure: The SICC filter is excited by tapered microstrip lines, which is located at the input/output ports. Energy travels from the microstrip line into the SICC resonators and then is magnetically coupled into the adjacent SICC by means of double concentric coupling slots. Figure 1 depicts the waveguides located in input/output port, which are helpful to suppress the fundamental mode of the cavities.

Moreover, the bandwidth and rolloff slope in the transition band are affected by W_c/R for a given angle α, as shown in Table 3. In general, smaller W_c/R leads to narrower bandwidth and steeper rolloff slope in the transition band.

Design example: The dual-mode filter is designed to meet the following specifications: the center frequency and bandwidth are 10 GHz and 350 MHz, respectively. The substrate used for the filter is Rogers 5880 with relative permittivity of 2.2 and height of 0.508 mm. Firstly, the dimensions of the cavities should be decided. According to the Formulas (2) and (3), the initial values for the radius of these SICC cavities (R) should be 12.3 mm.

The second step is to calculate the coupling coefficients and external quality factor. Figure 7 depicts the coupling scheme of the proposed dual-mode complementary filter.

Then, external quality factor Q of such a filter meeting these requirements can be extracted by the certain technique in (Cameron, 1999), and given by

$$Q_{ei} = Q_{eo} = 38.91 \tag{4}$$

As shown in Fig. 1a and b, the dual-mode cavities 1, 2 and 3 are well coupled by introducing double arc slots in the common wall. The coupling strength between the two cavities depends on the geometrical parameters of the filter, which is described by the coupling coefficient calculated by (Hong and Lancaster, 2001):

$$\mathrm{M}_{\mathrm{i,j}} = \pm \frac{f_e^2 - f_m^2}{f_e^2 + f_m^2} \tag{5}$$

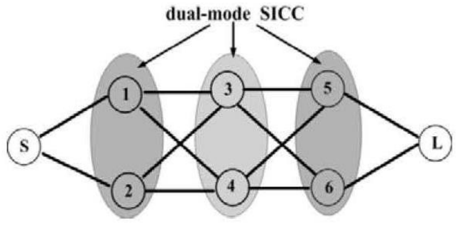


Fig. 7: Coupling scheme of sixth-order dual-mode filter (gray areas show dual-mode cavities)

Table 4: Parameters of the fabricated filter

*D*via (mm)	0.8	*W*strip (mm)	1.580
p (mm)	1.5	W_g (mm)	13.000
ε_r	2.2	W_C (mm)	8.200
*W*s (mm)	0.7	*h* (mm)	0.508
(deg)	110.0	*R* (mm)	12.000
θ (deg)	37.0	d_{slot}	0.700

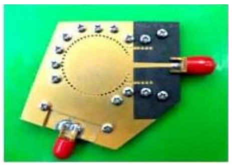


Fig. 8: Photograph of the fabricated filter

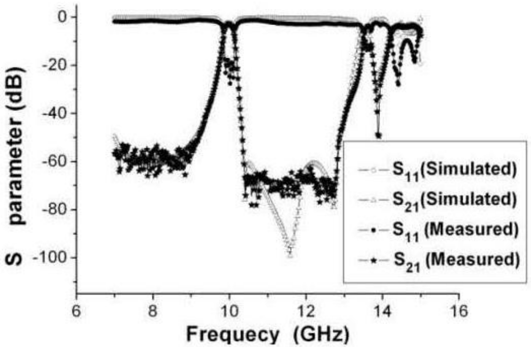


Fig. 9: Simulated and measured results of the dual-mode

Where f_e and f_m are the resonant frequencies of two coupling cavities corresponding to its symmetrical plane replaced by an electric wall and a magnetic wall, respectively.

The third step is to realize the coupling coefficients and external quality factor by suitably choosing the sizes and locations of the coupling slots. Based on above discussion, the initial parameters will be determined as flowing:

- On the one hand, the angle α is the key factor to realize the TM_{110} degenerate modes in multilayer SICCs. As shown in Fig. 1, the angle between the coupling slot 1 and input port is set to α in order to realize dual-mode character in cavity 1. And then, the angle between the coupling slot 1 and slot 2 is also equal to α so that degenerate modes can exist in cavity 2. Similarly, the angle between the coupling slot 2 and output port must be kept as α in cavity 3. So, the dual-mode phenomenon can be easily excited by setting the angle α between 100 and 130 degrees. Based on the specification, the proper value of α is 110º.
- The bandwidth and rolloff slope in the lower transition band are affected by W_c/R. As observed in Table 3, the width of the coupling aperture will be determined as $W_c/R = 0.75$.
- The coupling slot size determines the position of the first zero Z_1. According to Fig. 4 and Table 1, the initial geometrical parameters of slots will be determined to meet the specification. Thus, one can choose the width of the coupling slot with $W_S = 0.8$ mm, the central angle $\theta = 36º$, the spacing between slots $d_{slot} = 0.7$ mm.

EXPERIMENTAL RESULTS

Based on the above discussion, the multilayer dual-mode SICC filter with double arc-shaped slots is designed and fabricated with PCB process. Figure 8 is the photograph of the fabricated dual-mode filter with three layers.

After optimization implemented by Ansoft HFSS, the geometry parameters of the proposed filter are listed in Table 4. The transition tapers from the SIWs to microstrips are the same with a length of 8 mm and widths of 3 and 1.58 mm at two ends.

As observed in Fig. 9, the fabricated filter has a center frequency of 9.98 GHz with a bandwidth of 345.3 MHz. The maximum return loss of the filter is 19 dB within the pass band and the insertion loss is about 2.35 dB. It is demonstrated that measured results agree very well with simulated ones except for a little frequency offset. Compared with multilayer dual-mode filter based on double SICCs, the proposed structure has higher selectivity and better response performance. It demonstrates that this study has realized miniaturization and improved selectivity.

CONCLUSION

A compact multilayer dual-mode SICC filter using a novel topology of coupling has been designed, fabricated, and measured in this study. The bandwidth and restraint outside the band can be controlled by adjusting the size of the double arc-shaped slots. The measured maximum return loss is 19 dB over pass band while the insertion loss is about 2.35 dB. Its stop band is from 7.1 to 9.06 GHz and 10.36 to 12.8 GHz with the rejection more than 58 dB. Obviously, the topology of coupling can effectively improve the stop-band rejection, and suppress some undesirable response spur in transition band. Good agreement is obtained between the simulated and measured results of the proposed structure. This structure is very compact and well suited for the microwave and millimeter wave applications.

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