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DESIGN OF WIDEBAND SUBSTRATE INTEGRATED CIRCULAR CAVITY (SICC) FILTER USING $\mathbf{TM_{01}}$ MODE COUPLING

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Abstract—A novel type of wideband SICC filter using TM_{01} mode coupling by the circular hole between the SICCs is proposed. Of circular symmetry, the TM_{01} mode in SICC demonstrates the advantages of compact and high flexibility of the filter's input and output setting. In order to validate the new proposed topology, three filter prototypes with different included angle between input and output have been designed and manufactured. The filters exhibit a low insertion loss of -1 dB in the 12.8 to 20 GHz, a wide relative bandwidth of 54.5% at -3 dB, high flexibility and very good agreement with simulation data.

1. INTRODUCTION

In microwave and wireless communication systems, such as ultra-wideband (UWB), wireless-LANs, multimedia wireless systems and automotive sensors, various filters with stringent selective, broad bandpass, low insertion, easy manufacture and potential integration into active circuits are required. The standard waveguide filters possess good performance, but they are bulky, heavy, narrowband, and not suitable for integration or assembling. On the other hand, using microstrip technology can easily get wide bandpass filters, yet having high radiation losses, especially at high frequencies. Currently the substrate integration waveguide (SIW) has attracted wide interest in microwave application because of its ease of fabrication by standard printed circuit board (PCB) or low temperature cofired ceramic (LTCC) process, and its compact size is to useful integration or

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assembling in RF circuits [1, 2]. SIW filters have high-performance, small size and high Q factor. Most of the publications in SIW are mainly focused on SIW resonator filters and dual mode SIW filters, both of which have narrow bandpass and fixed input and output settings. Some applications of filter using SIW resonator and dual mode method are presented [2–4], with a bandwidth in 5–28%. In [5], SICC filters implemented new aperture coupling technology is proposed, with 1.5–5% fractional bandwidth. Bandwidths upon 60% are fabricated in [7] by mixing period structure in the SIW with a fixed input and output structure also.

In this paper, a new wideband bandpass filter with 54.5% bandwidth at K-band is demonstrated. The filter is based on SICC technology and TM_{01} mode coupling by the coupling circular hole between the two SICCs. The filter operating in circular symmetrical TM_{01} mode has the advantages of broadband, size miniaturization, low insertion loss and flexibility structure. Furthermore, the structure is scalable to other frequencies and other setting needs easily.

2. WIDEBAND SICC FILTER DESIGN USING TM_{01} MODE COUPLING

An SICC is shown in Fig. 1. Dielectric filled structure of the conventional cylindrical waveguide resonators can be readily implemented in LTCC by replacing the vertical metallic walls by closely spaced via posts and covering the bottom and top metal layers. The current lines of TM mode waveguide are along the waveguide. Because the via holes are along current lines, TM mode is selected as the operating mode in SICC only [5]. The resonant frequency (unloaded) of SICC can be computed by [8],

$$f_{mnl} = \begin{cases} \dfrac{c}{2\pi\sqrt{\mu_r\varepsilon_r}}\sqrt{\left(\dfrac{p'_{nm}}{R}\right)^2 + \left(\dfrac{l\pi}{h}\right)^2} & \text{TE}_{mnl} \text{ mode} \\ \dfrac{c}{2\pi\sqrt{\mu_r\varepsilon_r}}\sqrt{\left(\dfrac{p_{nm}}{R}\right)^2 + \left(\dfrac{l\pi}{h}\right)^2} & \text{TM}_{mnl} \text{ mode} \end{cases} \tag{1}$$

where μ_r and ε_r are relative permeability and permittivity of substrate respectively, c is the speed of light in free space, p'_{mn} and p_{mn} are the nth roots of the mth Bessel function of the first kind and its derivative, and R is the SICC radius, h is the length of the SICC along the z axis.

The TM_{010} is the dominant mode in one SICC resonator provided $h < 2.1R$, Of course, this constraint should be compatible with the filter's size miniaturization, as discussed in [5] and [6]. One filter be synthesized by the SICC with one resonant cavity has a narrow

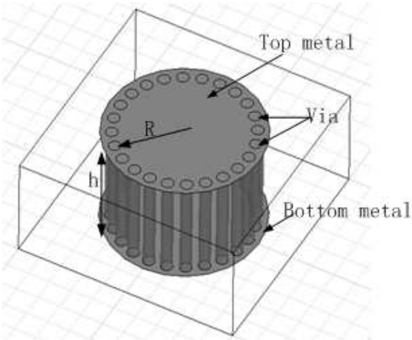


Figure 1. SICC construction.

bandwidth due to the resonating in the dominant mode. To get broadband filter, more resonators and coupling between the resonators would be employed to provide more transmission poles in the passband. One coupling circular hole is placed between the circular cavities to obtain the coupling. The coupling structure is circular, it is different from rectangle and metal circular cavity using aperture or iris to couple the TE and TM [9], because the TM_{01} mode existing in the SICC resonator is circular symmetrical. The circular symmetrical TM_{01} mode brings on more flexibility in structure. The proposed filter is designed as the Fig. 2, its top and side views are shown in Fig. 2(a) and Fig. 2(b), respectively. The filter consists of a pair of SICCs between with one coupling circular hole, a input microstrip line is centrally located on the filter's bottomlevel layer, another output microstrip line is located on the toplevel layer with an arbitrary angle of θ (as shown in Fig. 2(a)). Two crosses at right angles with corresponding apertures for the input and output are located in first SICC's metal top and second's metal bottom layers. All apertures are designed to have equivalent radial distance, width and length.

Shown in Fig. 3 is an equivalent lumped-element circuit model for the coupled resonator structures. Where L and C are the self-inductance and self-capacitance, L_m represents the mutual inductance, L_1 and C_1 are coupling inductance and capacitance of the aperture at the input and output. The resonator structure's coupling coefficient K can be find by (2)

$$K = \frac{f_e^2 - f_m^2}{f_e^2 + f_m^2} \tag{2}$$

$$f_e = \frac{1}{2\pi\sqrt{(L - L_m + L_1)C}} \tag{3}$$

$$f_m = \frac{1}{2\pi\sqrt{(L + L_m + L_1)C}} \tag{4}$$

where f_e is the resonant frequency of the equivalent single resonant circuit using the an electric wall to replace the symmetry plane $T-T'$, f_m is the resonant frequency of the equivalent single resonant circuit using the an magnetic wall to replace the symmetry plane $T-T'$.

Equations (2), (3) and (4) describe the relationship of the coupling coefficient and the resonant frequency. Where the central frequency f_0 equals to $(f_e + f_m)/2$ approximately, to get a wideband passband for the proposed filter, a increasing of the difference between the f_e and f_m is effective [10]. The difference of the two resonant frequencies can be controlled by a mutual inductance, namely by the radius of the coupling circular hole between the SICCs. The coupling coefficient K through various radius of the coupling circular hole is obtained by a 3D EM simulated tool Ansoft HFSS as shown in Fig. 4. The central frequency of the filter is computed by the Equation (1) and the L and C can be estimated by the equation $f_0 = \frac{1}{2\pi\sqrt{LC}} = f_{mnl}$, where $m = 1$, $n = 0$, $l = 0$, TM_{010} mode in SICC. The L_m can be expected by

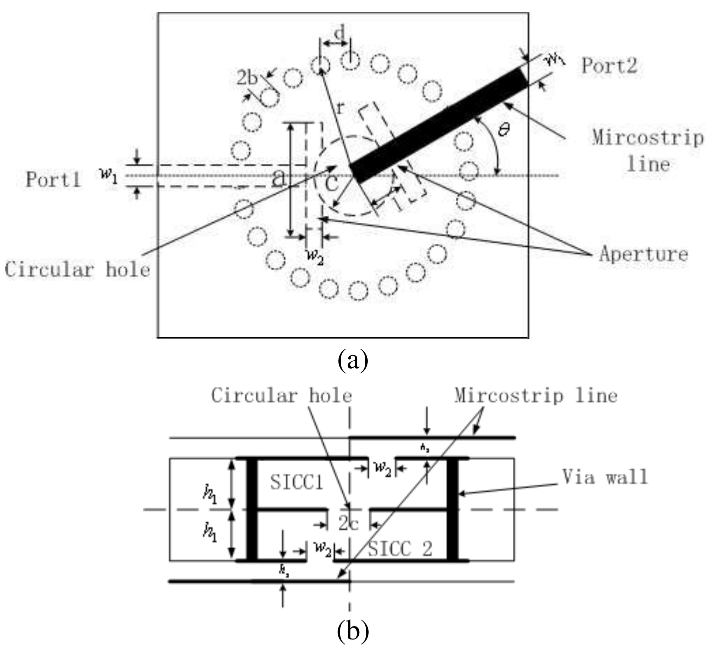


Figure 2. Structure of the SICC filter. (a) Top view of the SICC filter. (b) Side view of the SICC filter.

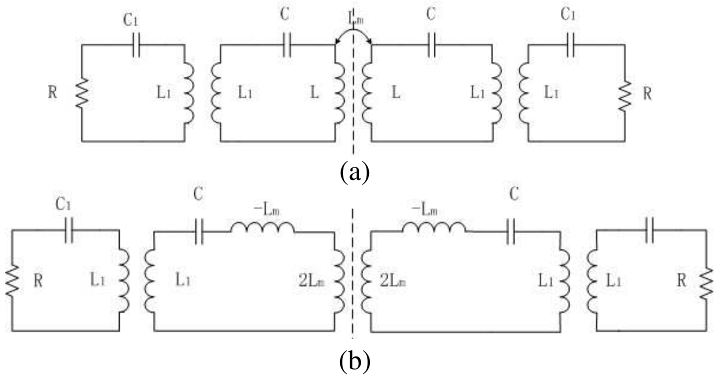


Figure 3. (a) An equivalent lumped-element circuit model for the coupled resonator structure. (b) An alternative form of the equivalent circuit.

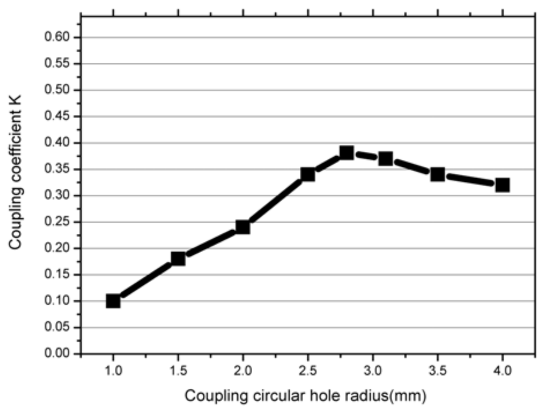


Figure 4. Coupling coefficient K vs. coupling circular hole radius for the SICCs resonator.

using appropriate coupling coefficient K and the Equations (2), (3), (4). The simulation tool can be used for estimating the sizes of the aperture also.

3. VALIDATION AND EXPERIMENTAL RESULTS

In compliance with the principle description in 2, a broadband filter is synthesized basing on a pair of SICCs with circular hole coupling structure as displayed in Fig. 2. The design parameters of the a, c, R,

h_1 and w_2 are initialized by the Equations (1)–(4). The w_1 is width of the microstrip line at the central frequency 16.5 GHz. The b, d is same as the suggestions in [1]. Table 1 shows the final optimum results of the broadband filter by ansoft HFSS (ver.11). Three prototypes of the filter have been manufactured in order to validate the simulated results shown in Fig. 5. The filters are fabricated on Taconic RF-35 substrate with relative permittivity $\varepsilon_r = 3.5$ and loss tangent $\sigma = 0.0018$ by the LTCC process.

Table 1. Dimensions of the filter structure (UNIT: mm).

a	b	c	d	h_1
4.22	0.26	2.61	0.34	0.25
l	R	w_2	h_2	w_1
1.12	3.98	1.12	0.25	0.48

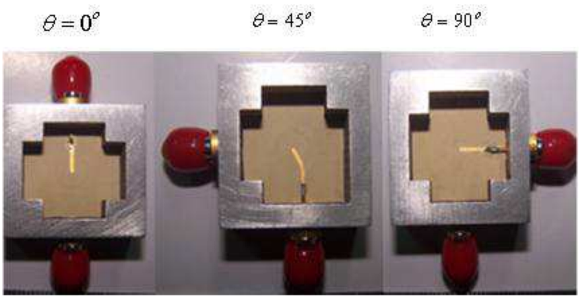
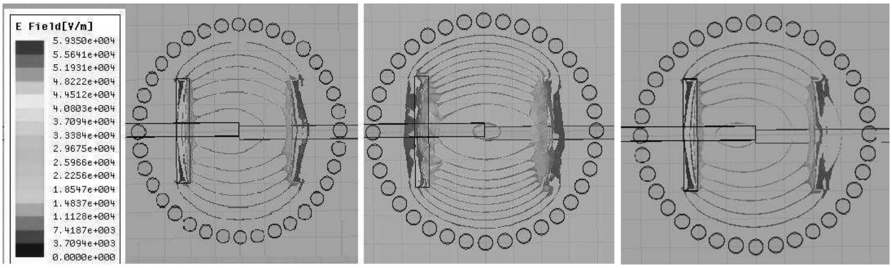


Figure 5. Photograph of the fabricated SICC filters.



(a) (b) (c)

Figure 6. Electric field equipotential surface in the SICCs filter with different frequencies on the xy-plane. (a) 13 GHz, (b) 15 GHz, (c) 20 GHz.

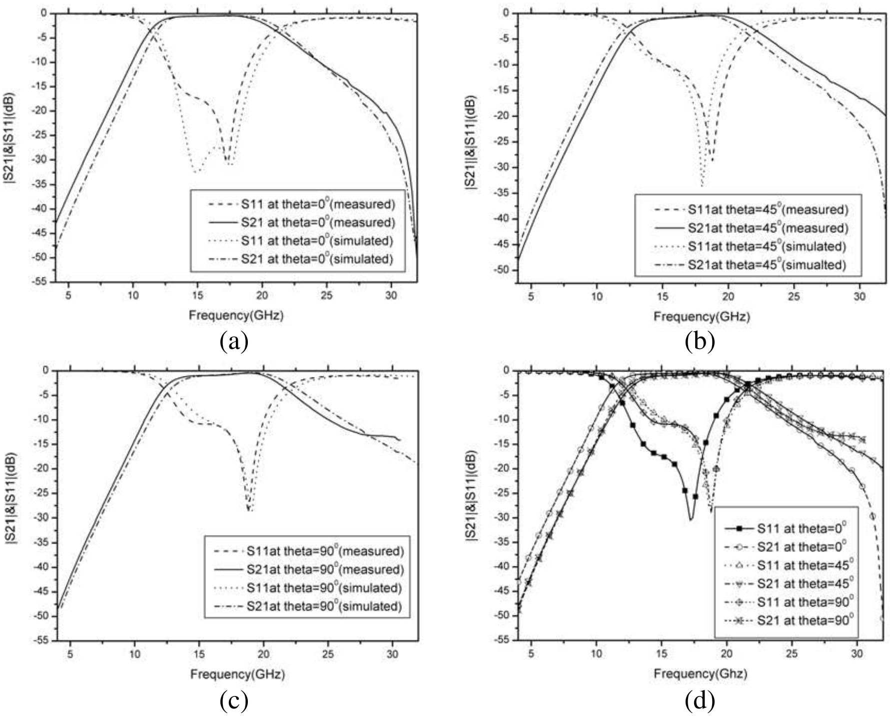


Figure 7. Simulation and measurement results of the proposed filters. (a) $\theta = 0°$, (b) $\theta = 45°$, (c) $\theta = 90°$, (d) measurement results of the three designed filters.

Plots of the simulated electric field equipotential surface in the designed filter with different frequencies show in Fig. 6. The results demonstrate the TM_{01} mode is dominant mode in the SICC filter. The S-parameter simulation and measurement results of the filters for $\theta = 0°$, $\theta = 45°$ and $\theta = 90°$ are shown in Figs. 7(a), (b), (c) and (d), respectively. It is seen that the measured and simulated performance are in good agreement. The filter's relative bandwidth is 54.5% (from 12 to 21 GHz, -3 dB) with the center frequency of 16.5 GHz. It has an excellent selectivity performance and a small return loss lower than -13 dB in the passband. The insertion loss is -1.3 dB at 12.8 GHz and -1.6 dB at 20.0 GHz, which include the insertion loss of two SMA connectors. Compare with the experimental results, the SMA connector insertion loss is -0.6 dB. Removing the connector losses, the complete filter (including the microstrip to SICC transitions) has an insertion loss level of -1 dB in bandpass. The measured results corresponding to $\theta = 0°$, $\theta = 45°$ and $\theta = 90°$ show good agreement between each other as shown in Fig. 7(d). The transmission S_{21} spectrum has barely changes with the varying the angle theta, but the S_{11} shifts. Because the input and output microstrip come near to with the varying the angle theta, the increase of reflection effect between the input and output leads to the S_{11} a little rising and shifting in the pass band, not to S_{21}. So the predicted flexibility characteristic of the filter structure using TM_{01} mode is validated. Utilizing such structure, the different I/O setting filters can be obtained easily.

4. CONCLUSION

A new SICC structure using TM_{01} mode coupling by circular hole has been proposed for the design of a wideband filter. Three filter prototypes with different angles between input and output have been fabricated using LTCC technology. The measured results show that the filter has a 54.5% fractional bandwidth, low insertion loss of -1 dB in pass band, and good agreement with simulated data. The design method for flexibility using TM_{01} is validated by good measured results acquired from different θ value. This broadband filter is characterized by very low insertion loss, compact size and flexibility structure. It can thus be easily embedded in compact RF and microwave multi-layer integrated circuits for exceptional needs using LTCC and multilayer PCB technologies.

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