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VERTICAL TRANSITION IN MULTILAYER MILLIMETER WAVE MODULE USING CIRCULAR CAVITY

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Abstract—A novel transition structure based on Substrate Integrated Circular Cavity (SICC) is proposed in this paper. The design approach of the transition structure can also be used in other operating frequency. Good performance of flexibility and S-parameters were observed for the new transition structure. Different design tools were used to validate the design method.

1. INTRODUCTION

The development of wireless communication system promotes miniaturization of front-end modules, more and more components were arranged in a given space simultaneously for dimension restriction. In these systems, planar transmission lines in different layers were used to reduce system size or develop new circuit components. For instance, in LTCC (Low temperature co-fired ceramic) systems, low insertion loss transitions were needed between the same/different transmission lines in different layers. It is well known that line loss will deteriorate in millimeter wave band especially for planar transmission lines, which makes troubles for the design of good performance transition in millimeter wave band. Several new structures of planar transmission line transition in different layers have been demonstrated in [1, 2] although which performed in frequencies under millimeter wave band. In [1] and [2] transitions between microstrip/CB-CPW and CB-CPW (conductor backed coplanar waveguide) were constructed through a slot located in ground plane of middle layer. Insertion loss less than 2 dB was obtained in the operating frequency up to 16 GHz.

Recently, SIW (substrate integrated waveguide) components have been widely used in microwave and millimeter-wave integrated circuits and systems. Fundamental design principles can be found in [3], the related principles and examples of transition between microstrip and SIW or other kind of transmission lines were proposed in [4], [5] and [6], and low insertion loss was observed at the frequency up to 30 GHz. Both the slot coupled structure and the via-probe transition structure can hardly perform well in millimetre wave band when fabricated with microstrip substrate for the affecting of parasitical inductive and capacitive. In [7], a SIW rectangular cavity was employed to couple energy from top layer to bottom layer without any auxiliary components in middle layers. The Via-walled cavity structure might perform well in higher frequency band for its high Q-value cavity and low parasitical inductive and capacitive structure. However, flexibility of the structure is not good enough, planar transmission lines in different layers of the transition in [7] can not spread out with arbitrary directions for the rectangular cavitys non-revolution-invariant structure, which restrict the flexibility of application. In this paper, we present a novel transition which based on SICC (Substrate Integrated Circular Cavities) structure. This SICC transition takes the advantages of high flexibility, low insertion loss, simple structure, etc, and can easily be integrated into microwave and millimeter-wave integrated circuits.

2. DESIGN OF THE SICC TRANSITION

Figure 1 depicts the structure of SICC, it is constructed with top and bottom wall (conducting traces), vias array which connected the top and bottom wall. On the other hand, the operating mode of SICC should have vertical direction surface current as that of TE_{101} mode in SIW rectangular cavity for the microstrip exciting structure, so TM_{010}

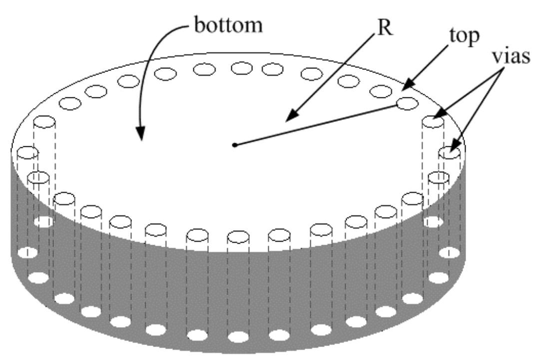

Figure 1. Photograph of the SICC.

mode was selected as the working mode for its special field distribution. The TM_{010} mode in SICC was characterized with revolution invariant and z-axis irrespective if $z < 2.1R$, it may have more flexibility than rectangular cavity in application.

It is well known that the resonant frequency (unloaded) of Circular Cavities with solid wall can be calculated by:

$$f_{mnp} = \begin{cases} \dfrac{c}{2\pi\sqrt{\mu_r\varepsilon_r}}\sqrt{\left(\dfrac{\mu'_{mn}}{R}\right)^2 + \left(\dfrac{p\pi}{z}\right)^2} & TM_{mnp} \text{ mode} \\ \dfrac{c}{2\pi\sqrt{\mu_r\varepsilon_r}}\sqrt{\left(\dfrac{\mu_{mn}}{R}\right)^2 + \left(\dfrac{p\pi}{z}\right)^2} & TE_{mnp} \text{ mode} \end{cases} \tag{1}$$

So the corresponding resonant frequency of TM_{010} is:

$$f_{010} = \frac{c}{2\pi\sqrt{\mu_r\varepsilon_r}} \cdot \frac{2.405}{R} = \frac{0.383c}{R\sqrt{\mu_r\varepsilon_r}} \tag{2}$$

where μ_r and ε_r are relative permeability and permittivity of the filling material used in SICC, μ'_{mn} and μ_{mn} are the nth roots of mth Bessel function of the first kind and it's derivative, the conductor conductivity is $\sigma = 5.8 \times 10^7\,\mathrm{S/m}$ and the loss tangent of the dielectric material is $\tan\delta = 0.002\,(30\,\mathrm{GHz})$, R is the radius of the SICC with solid wall, c is the speed of light in free space.

Once the resonant frequency was given, the radius of the SICC (solid wall) can be calculated by:

$$R = \frac{0.383c}{f_{010}\sqrt{\mu_r\varepsilon_r}} \tag{3}$$

The operating frequency was selected to be 30GHz; the permittivity of the filling material in this paper is $\varepsilon_r = 5.7$. So the corresponding radius of the material filled SICC with solid wall can be calculated by (3), that is:

$$R = \frac{0.383c}{30 \times 10^9\sqrt{5.7}} = 1.6\,\mathrm{mm} \tag{4}$$

Figure 2 shows the proposed transition structure based on SICC, which consists of a SICC, a pair of identical microstrip located on top and bottom layer with an arbitrary angle of θ and two identical coupled apertures which cross at right angles with corresponding microstrip in middle layer.

The distance between centre line of the aperture and circle centre d; the length of the stub l (calculated from centre line of the aperture);

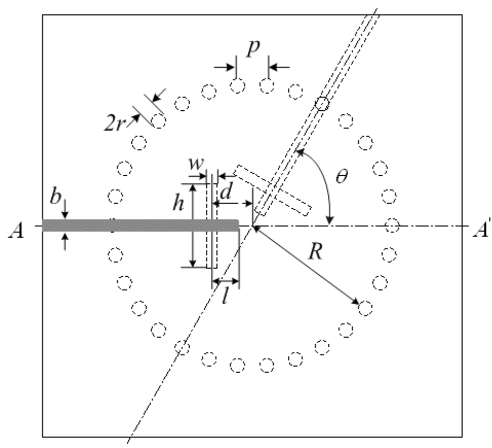

Figure 2. Top view of SICC transition.

the radius of the SICC R; the length and width of aperture h, w; the radius and pitch of the via were optimized when $\theta = 0$ with 3D Full-wave simulation tool. The initial values of above parameters were, $d_0 = 1\,\text{mm}$, $l_0 = 1\,\text{mm}$ (approximately $\lambda_g/4$), $h_0 = 2\,\text{mm}$, $w_0 = 0.2\,\text{mm}$, $R_0 = 1.6\,\text{mm}$, the transition structure was modeled with solid wall firstly and then the solid wall was replaced by vias-array under the guidelines of references [8–11], Some applications of SICC can be found in references [12–14], some important design guidelines can be found in [15–19]. The radius of the cavity R and the gap location d were two key parameters in designing of the transition structure; the R can be calculated with (3), and the parameter d was approximately $\lambda_g/4$; the width of the microstrip lines were calculated to guarantee a $50\,\Omega$ impedance.

Flexibility is an important aspect should be considered in design of transition structure, the SICC based structure performed well in an arbitrary direction in different layers for the revolution-invariant field pattern distribution of the operating TM_{010} mode. In order to validate the flexibility of the structure, the angle θ was set as variable parameter, simulated results about S_11 and $S21$ when $\theta = 30°$, $\theta = 60°$, $\theta = 90°$, $\theta = 120°$ and $\theta = 150°$ are presented in Fig. 3, Fig. 4, Fig. 5 and Fig. 6 with other parameters fixed.

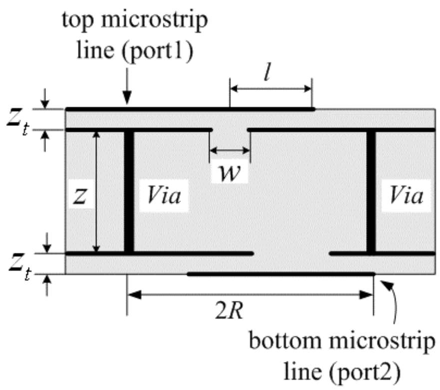

Figure 3. Lateral view of SICC transition.

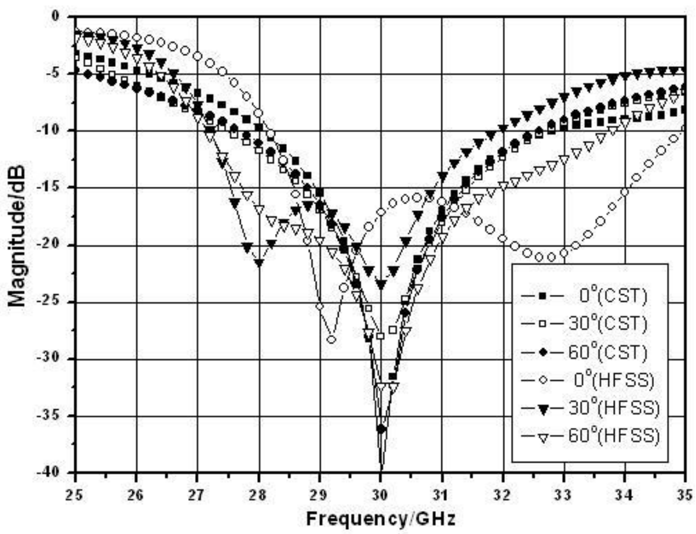

Figure 4. Simulated return loss for $\theta < 90°$.

3. SIMULATION AND RESULTS

Two different 3D Full-wave simulation tools based on different algorithms CST MICROWAVE STUDIO and ANSOFT HFSS were used to validate the design method and transition structure in the absence of measured results. Table 1 shows the final optimum results of the transition dimensions, the vias were arranged with an equivalent

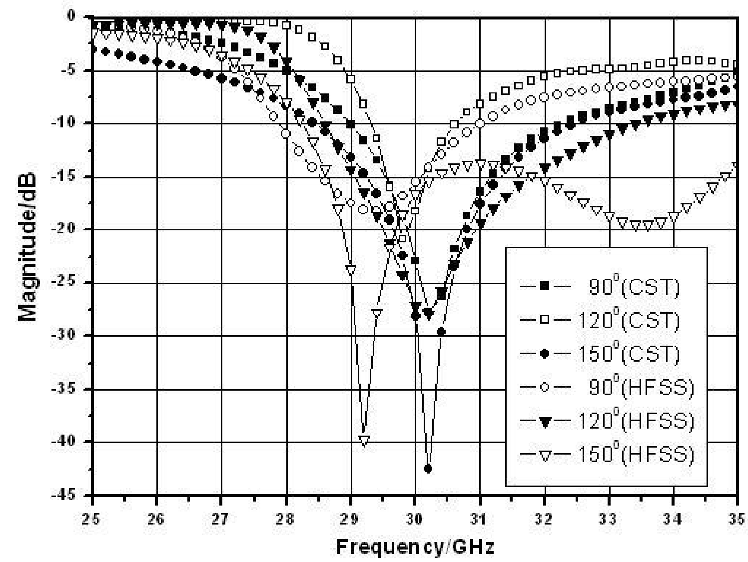

Figure 5. Simulated return loss for $\theta \geq 90°$.

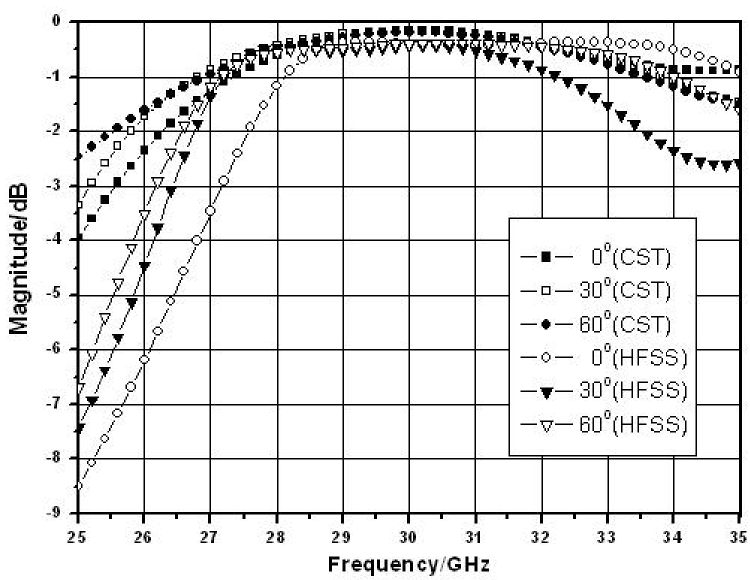

Figure 6. Simulated insertion loss for $\theta < 90°$.

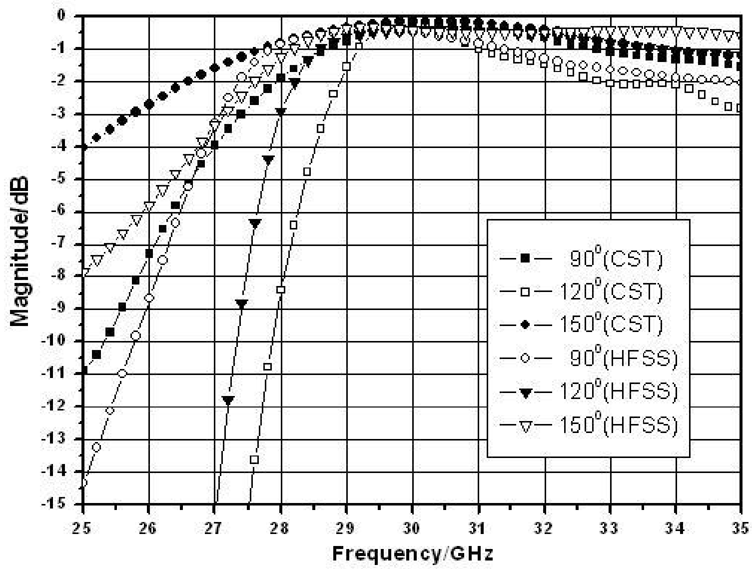

Figure 7. Simulated insertion loss for $\theta \geq 90°$.

angle of 36 degrees between two adjacent ones and the corresponding pitch is about 0.93 mm, if the radius of via was selected to be 0.2 mm.

So, we have:

$$2r/p \simeq 0.5 \tag{5}$$

The condition for decreasing leakage of via walls effectively, that is

$$2r/p = 0.5 \tag{6}$$

which mentioned in [11] can be satisfied. Return loss for different θ values of $\theta < 90°$ and $\theta \geq 90°$ were shown in Fig. 3 and Fig. 4; the corresponding insertion loss for different θ values of $\theta < 90°$ and

Table 1. Dimensions of the transition structure.

d	l	h	w	R
0.6 mm	0.6 mm	2 mm	0.2 mm	1.5 mm
p	r	b	z_t	z
0.93 mm	0.2 mm	0.4 mm	0.26 mm	0.26 mm

$\theta \geq 90°$ were shown in Fig. 5 and Fig. 6. Return loss and insertion loss of the transition structure when $\theta = 0°$ were found to be better than -35 dB and less than 0.5 dB at the operating frequency. Return loss better than 15 dB and Insertion loss less than 0.5 dB can be observed for all the other θ values at the operating frequency 30 GHz. The simulated 10-dB return loss bandwidth was found to be approximately 2.5 GHz. Simulation results corresponding to two different simulation tools both show good performance between each other for the same angle of θ in Fig. 3, Fig. 4 (return loss) and Fig. 5, Fig. 6 (insertion loss), so the predicted flexibility of the transition structure was validated.

4. CONCLUSIONS

A novel transition based on SICC (Substrate Integrated Circular Cavities) was proposed in this paper. Design method was presented for design and optimization of this transition structure. Good performance between simulated results acquire from different simulation tools was found for the proposed novel structure. Flexibility of the transition was validated by good simulation results acquired from different parameter θ values and different simulation tools. The special transition structure was characterized with high flexibility, low insertion loss, compact structure. Some disadvantages for using of the structure, such as narrow 3-dB bandwidth and bulky dimension in a certain extent were also observed. It's suitable for using in microwave and millimeter-wave multi-layer circuits such as LTCC module.

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