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A NOVEL 3-D TRANSITION AND POWER DIVIDER BASED ON HALF-MODE SICC STRUCTURE

J. Gu, Y. Fan, Y. Zhang, and D. Wu

EHF Key Laboratory of Fundamental Science
University of Electronic Science and Technology of China (UESTC)
Chengdu, Sichuan 610054, China

Abstract—In this paper, a new kind of 3D transition and power divider based on half mode substrate integrated circular cavity (HSICC) is proposed. This novel HSICC transition and power divider can be easily integrated into microwave and millimeter-wave multilayer circuits using LTCC technology. What is more, it can reduce nearly half size of normal SICC resonator and has the advantages of high flexibility, low insertion loss and amplitude imbalance. Two different 3D simulation tools are employed to validate the design method of this novel structure.

1. INTRODUCTION

In modern microwave and millimeter-wave applications, front-end modules are required to have compact size and high integration. Multilayer circuits using low-temperature co-fired ceramic (LTCC) technology are very attractive candidates to satisfy these requirements. In these 3D multilayer circuits, different components and transmission lines are often placed in different layers due to space restriction. So vertical transition and power divider with compact size and highly flexibility will serve as important interconnect structures. Various kinds of substrate integrated cavities are suitable to be vertical transition and power divider. Numerous publications have dealt with these cavities, including rectangular substrate integrated waveguide (SIW) [1–5], substrate integrated circular cavity (SICC) [6, 7] and half mode substrate integrated waveguide (HMSIW) [8, 9]. However, although SIW and SICC have small sizes and excellent performances, they are still too large for some applications which have higher requirement for small sizes. Compared with SIW, HMSIW structures

Corresponding author: J. Gu (gujian_jeff@163.com).

can minimize the size. But, in both SIW and HMSIW structures, the transition is sensitive to the orientation of the microstrip lines, thus it is not easy to adjust the input and output ports freely in different directions.

In this paper, a vertical transition and power divider based on a novel half mode SICC (HSICC) structure is developed. This new kind of compact transition and power divider can save about half of the area compared with normal SICC structure, and has high flexibility in designing of input and output ports at the same time. To verify the design method of this structure, two different 3D simulation tools are used.

2. DESIGN OF HSICC STRUCTURE

The concept of the proposed half mode SICC is based on the traditional full size SICC resonator. Thus we should first briefly introduce the related concepts of SICC. The resonant frequency (unloaded) of SICC can be calculated by the following formula [10].

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

where p_{mn} and p'_{mn} are the nth roots of mth Bessel function of the first kind and its derivative respectively, and R is the radius of SICC resonator.

We suppose that H is the height of SICC. Then TM_{010} mode will be the dominant mode in SICC when the height satisfies $H < 2.1R$, and it is selected to be the operating mode for HSICC in this paper. The electric field of TM_{010} mode is the strongest in the center of SICC. Its field distribution is axisymmetrical, and the current of this mode has vertical direction [10].

Once the resonant frequency of TM_{010} mode is calculated, the radius of the SICC can be obtained according to the formula (2).

$$R = \frac{c}{2\pi\sqrt{\mu_r\varepsilon_r}} \cdot \frac{p_{01}}{f_{010}} \tag{2}$$

Because TM_{010} mode has axisymmetrical field distribution in SICC, there is a chance to keep almost the same field distribution by cutting down half of the size of SICC resonator. Thus we can realize HSICC resonator in this way.

The geometrical structure of the HSICC resonator is shown in Fig. 1. It is constructed with top and bottom metal layers, and hemicycle metal via arrays which connect these two layers. An additional row of metal via fence is used to avoid possible field radiation. These two metal layers are both hemicycle and have about half the size of metal layers in SICC. A-A' is the axis line which crosses the center point of HSICC resonator and D is the distance between via fence and A-A'.

According to the theoretic analysis above, HSICC should have similar field distribution of SICC after half the circular cavity is cut down. HSICC can also support the dominant mode TM_{010} when the condition of $H < 2.1R$ is satisfied. This means that the radius and resonant frequency of HSICC should be calculated by the same formulas which are used for SICC and described in formulas (1) and (2).

To prove that the fields of HSICC resonators are almost the same as those of SICC resonators, a HSICC resonator and a SICC resonator both using slot excitation with $\lambda/4$ open stub are designed with the help of HFSS simulator. LTCC multilayer substrate Dupont943-C2 is supposed to be used here. The relative dielectric constant (ε_r) of the LTCC material is 7.4, and its loss tangent ($\tan\delta$) is 0.0009. The metal thickness is 10 μm. The dielectric layer thickness per layer is 50 μm, and there are six substrate layers to build the HSICC cavities of these two resonators. Most structure parameters of these two resonators are almost the same.

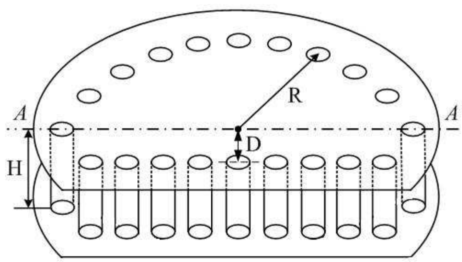

Figure 1. Structure of HSICC resonator.

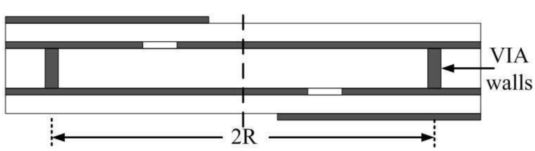

Figure 2. Side view of HSICC and SICC resonators.

The side views of these two resonators are the same and they can be both shown by Fig. 2. The input and output microstrip lines are placed on the upside and downside of HSICC cavities.

The electric fields of SICC resonator and HSICC resonator are shown in Fig. 3 and Fig. 4. We can see that the electric fields are almost the same and the hypothesis above thus gets proven.

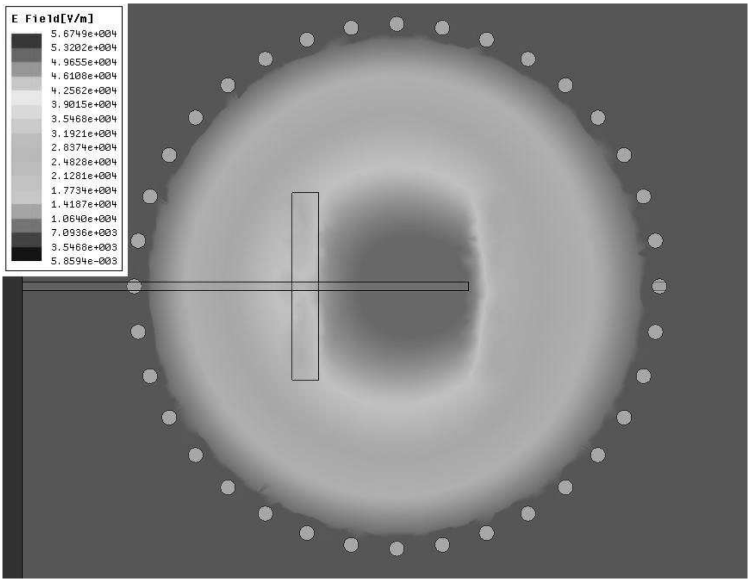

Figure 3. E-field of SICC resonator.

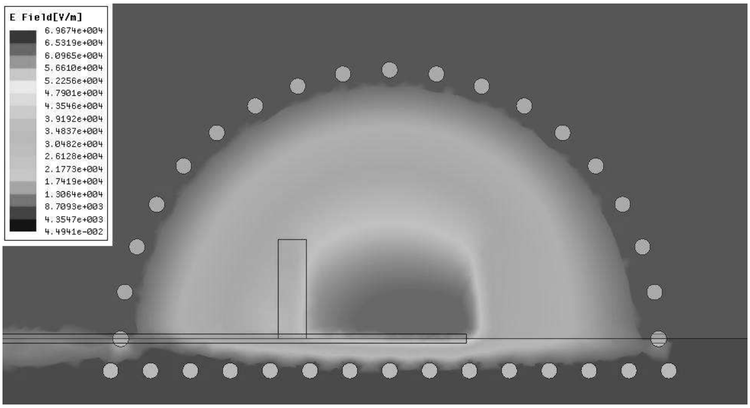

Figure 4. E-field of HSICC resonator.

3. HSICC TRANSITION AND POWER DIVIDER

A vertical transition and power divider based on HSICC structure is designed here, and its operating frequency is set to be 9.64 GHz.

LTCC multilayer substrate Dupont943-C2 is supposed to be used in the design of the power divider. The dielectric layer thickness per layer is 50 μm, and there are six substrate layers to build HSICC cavity of the transition and power divider.

The top view of this structure is described in Fig. 5. Port 1 is the input port, and port 2 and port 3 are two output ports. The input microstrip line and one output microstrip line of port 2 are placed along the axes A-A', and another output microstrip line of port 3 is designed to rotate around the center of the HSICC to verify the flexibility of this kind of 3D transition and power divider. The angle β between two output transmission lines is set to be a variable parameter, and three typical angles of $\beta = 45°$, $\beta = 90°$, $\beta = 135°$ are chosen.

The side view of the feeding structure is shown in Fig. 6. Probes are used to feed the transition and power divider based on HSICC. Considering the feasibility of manufacturing, exciting probes descend

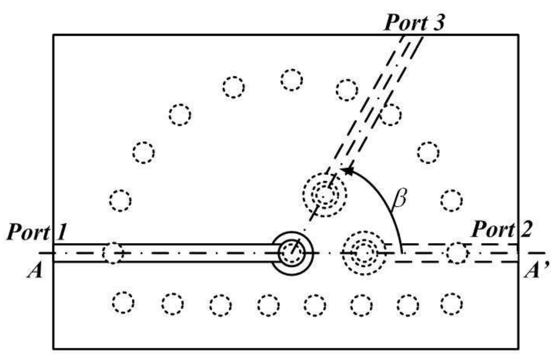

Figure 5. Top view of HSICC transition and power divider.

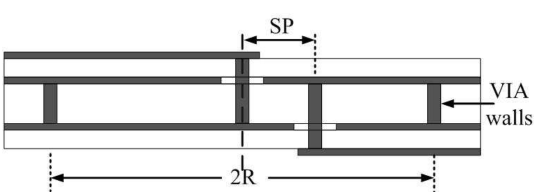

Figure 6. Side view of feeding structure using probes excitation.

into all of the six substrate layers (300 μm) of HSICC cavity through circular apertures etched in the top and bottom metal layers of cavity respectively. The input probe is placed in the center of HSICC, and the distances between the center and two output probes are set up to be SP. During the process of simulation, the probe position is found to be the important factors to adjust insertion loss.

The working frequency will shift down because of the probe perturbation, and this perturbation can be characterized with induced dipole moments [11]. Output probes with different angles will also cause small variation to the center frequency of HSICC structure. According to the formulas (1) and (2), the initial values of radius of the HSICC structures should be 4.38 mm.

4. VALIDATION AND SIMULATION RESULTS

With the structures in Fig. 5 and Fig. 6, vertical transitions and power dividers with different output ports corresponding to $\beta = 45°$, $\beta = 90°$, $\beta = 135°$ are designed.

The physical parameters of these power dividers are optimized in HFSS simulator to get the operating frequencies of 9.64 GHz. The radius of HSICC (R) is 4.32 mm and the position of probes (SP) is 1.85 mm. The sizes of these transition and power divider are all $4.33 \times 8.66 \times 0.54$ mm without pad. They can save about half the size compared with those based on normal SICC structure.

We can see that the final design values of center frequency and cavity radius are accordant with the initial values based on the theoretical expectation in formula (1) and formula (2).

Simulation results of transmission coefficients S_{21} and S_{31} for different angles are got from HFSS and shown in Fig. 7. All transmission coefficients are from -2.89 dB to -3.53 dB at the operating frequency.

The reflection coefficients of input port for all angles are found to be better than -29.51 dB at the operating frequency and the bandwidths for S_{11} less than -10 dB are found to be wider than 1.1 GHz. As shown in Fig. 7, we can see that these novel power dividers have the advantages of low amplitude imbalances and insensitivity to the orientation of the ports. The amplitude imbalances between two output ports are all lower than 1 dB in the bandwidth for different angles β.

Another simulation tool CST is used here to further validate the correctness of this design, and the results are shown in Fig. 8.

We can see that both the simulation results got from CST and HFSS show highly consistency for all models with different β values.

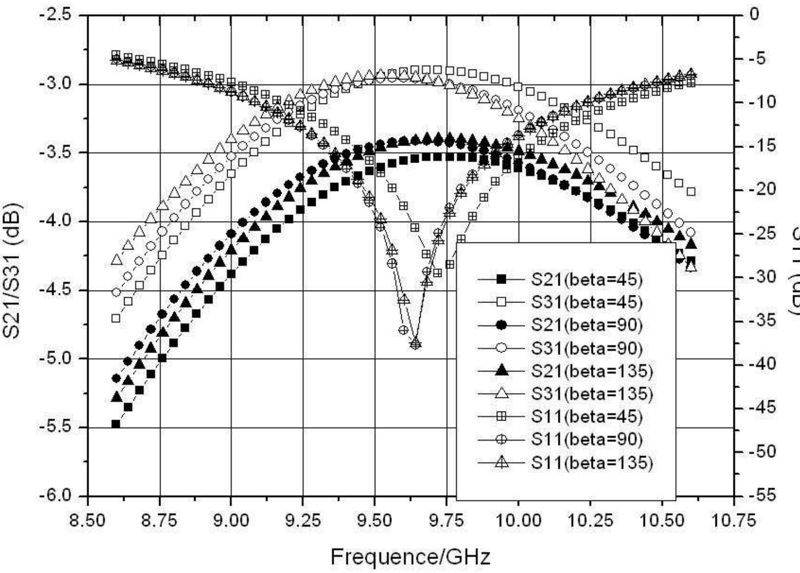

Figure 7. S parameters got from HFSS.

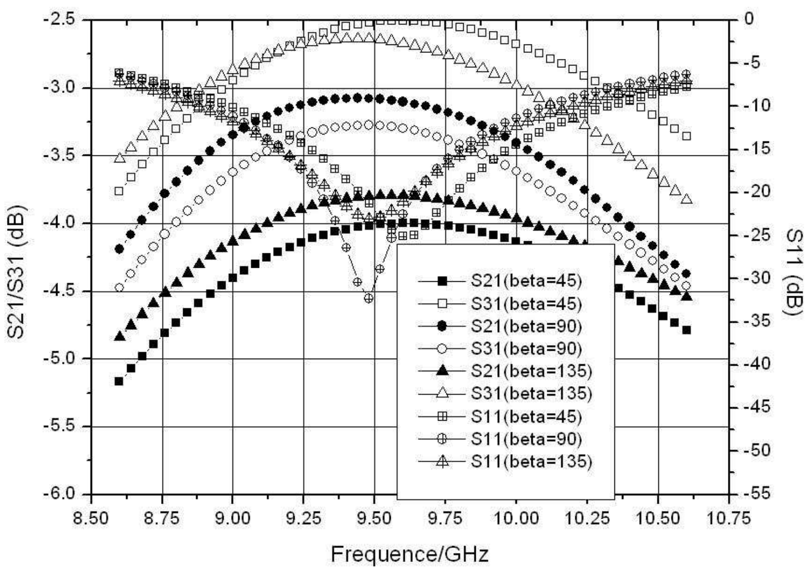

Figure 8. S parameters got from CST.

So the flexibility characteristic of this kind of transition and power divider is validated.

5. CONCLUSION

It is the first time that a novel kind of 3D transition and power divider based on HSICC structure is proposed. Feasibility of this kind of vertical transition and power divider is validated by simulated results got from different simulation tools, and they are suitable to be integrated into compact multi-layer circuits and modules for microwave and millimeter-wave applications. It can be seen from the proposed designing that HSICC is a useful supplement to integrated substrate cavity.

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