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Broadband Eight-Way Substrate Integrated Waveguide Radial Power Divider/Combiner With High-Isolation

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ABSTRACT A broadband eight-way substrate integrated waveguide (SIW) radial power divider/combiner with high-isolation is presented. The step probes are utilized to achieve broadband impedance matching and improve the return loss. What's more, the star structure based on microstrip circuit is employed to improve the isolation performance. A two-layer SIW radial power divider/combiner is designed, fabricated and measured. Good agreement between simulated and measured results is achieved for the proposed power divider/combiner. The measured results show that both bandwidths of the input and output port are 25% and 20% when their return loss are lower than −15 dB. The measured output isolation is greater than 17.5 dB from 5.75 GHz to 7.85 GHz and greater than 20 dB from 6.8 GHz to 7.9 GHz. The presented eight-way SIW power divider/combiner has the advantage of wider bandwidth, lower return loss and insertion loss, and higher isolation between the outputs.

INDEX TERMS Power divider/combiner, broadband, substrate integrated waveguide, high-isolation.

I. INTRODUCTION

With the rapid development of radio frequency (RF) and microwave systems, high power and small size have become major development trends. Power divider is an important component to realize high power. Over the years, a variety of power dividers/combiners have been developed to meet the requirements of RF systems [1]–[20]. The microstrip-based power dividers/combiners have been widely investigated and used in microwave system because of their compact size, low cost and easy to be fabricated [1]–[4]. However, it also has some disadvantages such as low power capacity and high insertion loss. In addition, the waveguide-based power dividers/combiners have been used in microwave systems due to their low insertion loss and high-power capability [5], [6]. However, waveguide structure is large in size and high in cost. The substrate integrated waveguide (SIW) structure came into being [7]–[14]. The SIW structure makes a compromise between the advantages and disadvantages of the microstrip and waveguide structure, and is characterized by lower cost and smaller size than the waveguide structure and higher power than the microstrip structure.

Radial power divider/combiner is a kind of the structures of power divider/combiner. The amplitude and phase of the radial power divider/combiner are well balanced due to the inherent symmetry. There are a lot of researches on radial power divider [10]–[20]. In [10], an eight-way radial SIW power divider is proposed, but it only works as a power divider and ignores the isolation performance. In [11], [12], an eight-way radial SIW power divider using novel probe transition is proposed. Good input matching is achieved by using novel probe transition, but output matching and isolation performance are ignored. In [13], an eight-way differential SIW power divider with bandpass-filtering response is proposed. It uses hybrid multiple-via probe to achieve broadband impedance matching and multiple radial slots to improve the out-of-band rejection level. Similarly, its ports are poorly isolated. In [14], a SIW differential radial power combiner design is presented based on changing the electric field polarity of selected probes. It greatly simplifies the design and modelling, and has good phase and amplitude balance. But its bandwidth is narrow and isolation is poor.

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In [15], a 14-way power combiner with a two-octave bandwidth (1.5 GHz - 6 GHz) is designed and fabricated on a three-layer PCB. The manufacturing process is simplified, and the manufactured device has good amplitude and phase balance, but the input and output return and the isolation of each port are not good. In [16], an eight-way radial power divider with ring-shape isolation network is proposed. It has a certain isolation, but its matching performance between the output ports of the radial power divider is poor and insertion loss is relatively high.

To sum up, the existing radial power divider has poor isolation due to its lack of isolation network. In this paper, an eight-way SIW radial power divider/combiner with isolation network is designed. The isolation network is realized by microstrip structure. The proposed power divider/combiner adopts the step plated holes to improve the impedance matching of the input port and the output ports, while the star structure based on microstrip circuit is employed to improve the isolation performance between the outputs and miniaturize the dimension. Ultimately, the proposed power divider/combiner not only realizes the miniaturized size, but also has a high isolation performance and a good matching performance between the output ports.

II. ANALYSIS AND DESIGN

The structure of the proposed eight-way multilayer radial SIW power divider/combiner is shown in Fig. 1. The power divider/combiner consists of a radial SIW cavity and a microstrip isolation circuit. The port2-port9 are placed on the top layer and connected to the slotted SMA connector. The port1 is placed on the center of the bottom layer. To get broadband ports impedance matching, the step plated holes have been used in both central and eight peripheral probes. In Fig. 1(b), d_1 and d_2 denote the diameter of the central hole and peripheral hole. The a_1, a_2 and c_1, c_2 denote the external diameter and inner diameter of the coupling window of the ports respectively. The characteristic impedance of the radial waveguide is given by [3]

$$Z_0 = \frac{h}{2\pi r}\sqrt{\frac{\mu_0}{\varepsilon_0 \varepsilon_r}} \tag{1}$$

where r is the radius of the radial waveguide and h is the thickness of the substrate. The μ_0 and the ε_0 is permeability of vacuum and vacuum dielectric constant respectively. The ε_r is relative dielectric constant. According to formula (1), the characteristic impedance of the radial waveguide is related to the radius of the radial waveguide. The size of r can be designed to match the input/output ports to the 50 Ω SMA connectors. Therefore, it is not necessary to add additional matching circuits along the radial waveguide. Without any additional circuits, the impedance matching of the proposed power divider/combiner is achieved by step plated holes. Formula (1) works in radial waveguide with relatively large radius. In this paper, the radius of the radial waveguide is small, so the imaginary part cannot be ignored. In order to offset the imaginary part of the port impedance and make the output impedance match to 50 Ω, a coupling window is introduced. The coupling window can produce a capacitive imaginary part, which is used to offset the inductive imaginary part of the port impedance, so that the output impedance is a pure real number of 50 Ω. Therefore, the impedance matching of input and output ports can be realized by introducing step plated hole and coupling window. By adjusting radii of step plated holes and coupling windows, the input/output ports can be matched to 50 Ω SMA connectors. Fig. 2 illustrated the return loss with varied d_1 and d_2. As can be seen from Fig. 2, d_1 has a greater impact on the input return, while d_2 has a smaller impact on the output return. Therefore, d_1 is mainly adjusted, while d_2 is adjusted as an auxiliary parameter to achieve broadband port impedance matching.

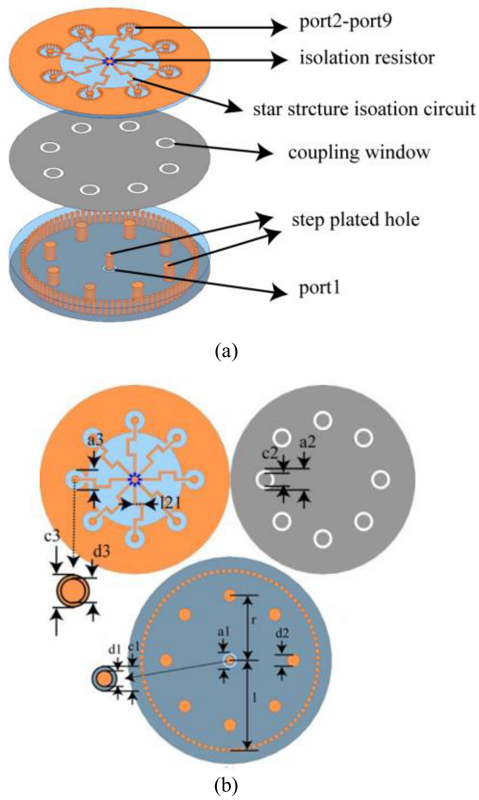

FIGURE 1. Layout of the proposed SIW power divider/combiner (a) 3-D view (b) 2-D view.

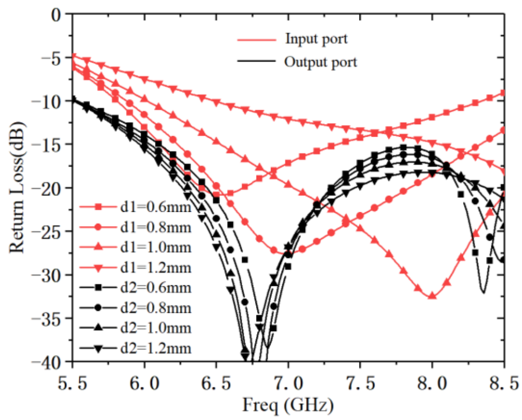

FIGURE 2. Return Loss with varied d_1 and d_2.

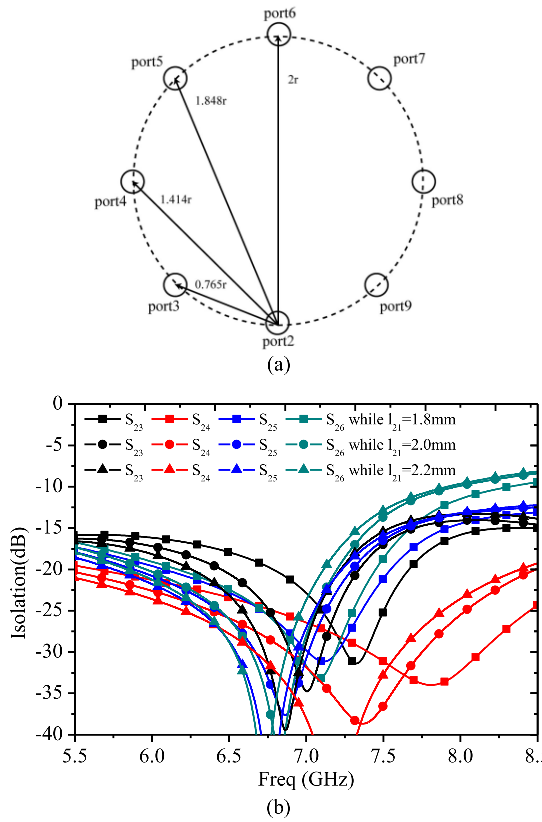

FIGURE 3. (a) Isolation of the SIW cavity between port2-port9 (b) Isolation with varied l_{21}.

A star structure based on microstrip circuit is employed to achieve the isolation among the port2 to port9. This isolation circuit is evolved from the N-way Wilkinson circuit, which is very suitable for radial circuit isolation network due to its rotational symmetry. The signal is input from output port, then passes both the SIW cavity and the microstrip circuit, and finally arrives at other output ports. Two path signals will be cancelled out when there is a 180° phase difference between them, thus achieving good isolation performance. As shown in Fig. 3(a), there are four ways from one port to another port along the port2-port9 in the SIW cavity due to symmetry, where port2-to-port3/4/5 is symmetric with port2-to-port9/8/7. Same as Wilkinson power divider, the electrical length of the SIW cavity transmission θ_{SIW} has the effect of impedance transformation in the circuit, so it must satisfy formula:

$$\theta_{SIW} = \frac{\pi}{2}(2m+1) \tag{2}$$

where m = 0, 1, 2, ... In order to improve isolation, the electrical length of the additional isolation circuit transmissions $\theta_{isolation}$ must satisfy formula:

$$|\theta_{isolation} - \theta_{SIW}| = \frac{\pi}{2}(2n+1) \tag{3}$$

where n = 0, 1, 2, ... When formula (2) and (3) are satisfied at the same time, the phase difference between the two path signals reaching the output ports is 180°, thus achieving the isolation between the two ports, and the eight-way radial SIW power divider will obtain good isolation performance. The phase difference between the SIW cavity transmission and the isolation circuit transmission can be adjusted by l_{21}. Fig. 3(b) illustrated the isolation with varied l_{21}. There are eight resistors in the isolation circuit. The isolation resistors balance the eight output ports and play an isolation role.

In summary, the overall design approach of the proposed eight-way SIW radial power divider/combiner is as follows. Firstly, the position of the output port is determined according to formula (1), and then the step plated hole from coaxial to radial cavity can be designed. Secondly, the size of the coupling window is adjusted to offset the imaginary part of the port impedance and make the output impedance match to 50 Ω. Finally, according to formula (2) and formula (3), the size of the microstrip line in the isolation network is designed, and the design result of the whole circuit is obtained.

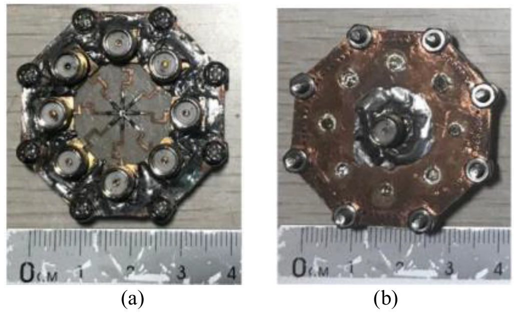

FIGURE 4. Both layers of the power divider/combiner (a) top layer (b) bottom layer.

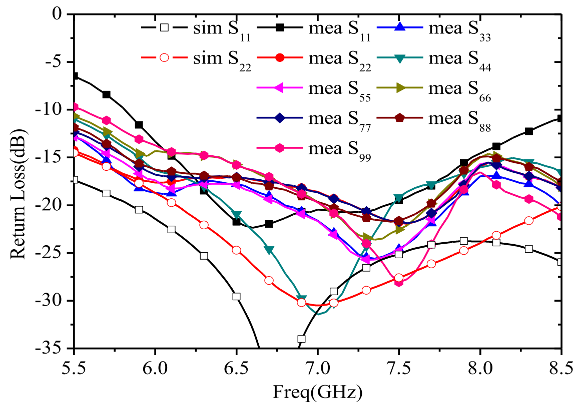

FIGURE 5. Return Loss of input and output.

III. SIMULATION AND MEASURED RESULTS

The SIW cavity is based on the substrate Rogers 5870 substrate (bottom layer) with dielectric ε_r of 2.33 and thickness h of 3.17 mm. The isolation microstrip circuit is based on Arlon AD300C substrate (top layer) with dielectric ε_r of 3.1 and thickness h of 0.762 mm. The package of the resistor in the isolation circuit is 0402. An eight-way SIW power divider/combiner is designed, optimized and fabricated. Fig.4 shows the top and bottom layers of the power divider/combiner. Ansoft HFSS is applied to optimize the eight-way SIW power divider/combiner with high-isolation. The final dimensions of the SIW power divider/combiner are shown in Table 1.

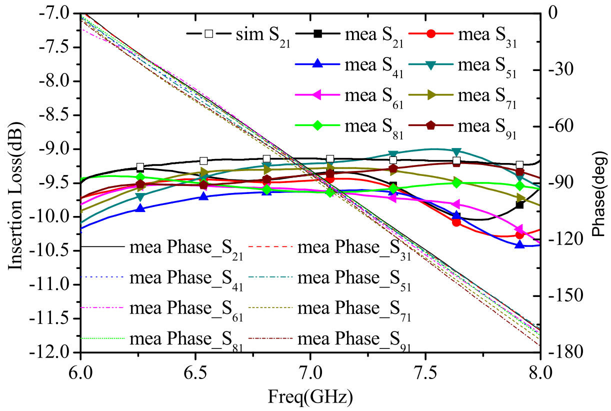

FIGURE 6. **Insertion loss and Phase balance.**

TABLE 1. **Dimensions of the SIW power divider/combiner (unit: mm).**

d_1	d_2	a_1	a_2	c_1	c_2	l_{21}	r	l
0.8	1.2	1.5	2.1	1	1.4	2	12.5	17.3

TABLE 2. **Comparison with other radial power dividers/combiners.**

	Input/Output 15dB-FBW (%)	Input/Output RL (dB)	No. of Ways	IL (dB)	ISO (dB)	Size (λ_g^2)
[10]	9.5/-	-/12	8	0.2	>15	1
[13]	84.3/-	15/-	8	0.3	-	2.82
[14]	5/-	20/-	4	0.15	>15	-
[15]	-/28.5	10/15	14	1	>8.6	-
[16]	15/16	17/18	8	1.1	>15	0.72
This work	**25/20**	**20/20**	**8**	**0.5**	**>20**	**1.96**

FBW: Fractional Bandwidth, RL: Return Loss, IL: Insertion Loss, ISO: Isolation

Fig. 5 shows the results of the return loss of the all ports. It can be seen that the simulated and measured results are in reasonable agreement at 15 dB. It is observed that the measured return loss of input port is greater than 15 dB in the frequency range from 6.2 GHz to 8 GHz (25% fractional bandwidth). The measured return loss of output port is greater than 15 dB in the frequency range from 6.5 GHz to 8 GHz (20% fractional bandwidth).

The results of the insertion loss and the phase balance of the all transmissions are shown in Fig. 6. The measured insertion loss is within 9.5 ± 0.3dB in a range from 6.5 GHz to 7.5 GHz (14.3% fractional bandwidth), while the insertion loss should ideally be 9 dB for an eight-way power divider. The amplitude balance is approximately ± 0.3dB and the phase balance is approximately $\pm 4°$, which is theoretically consistent with the amplitude and phase balance of the radial power divider due to its symmetry.

Fig. 7 shows the simulated and measured results of isolation between output ports. Since the coupling between the output ports is not exactly the same, the shape of each isolation curve is not consistent, but it can be seen from the Fig. 7 that the isolation performance is generally good. The measured output isolation is greater than 17.5 dB from 5.75 GHz to 7.85 GHz (30.8% fractional bandwidth) and

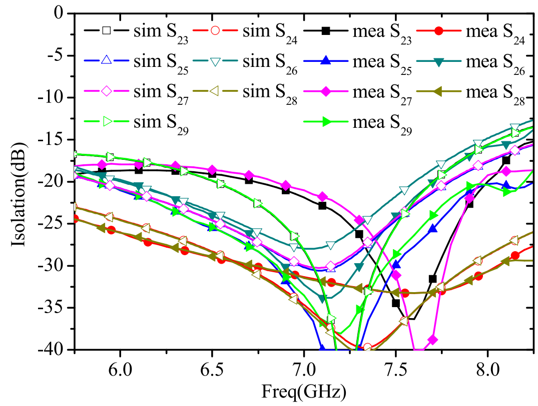

FIGURE 7. **Simulated and measured output isolation.**

greater than 20 dB from 6.8 GHz to 7.9 GHz (15% fractional bandwidth).

Table 2 shows the comparison with other radial power dividers/combiners. Compared with the references, the presented eight-way SIW divider power divider/combiner shows the advantage of wider bandwidth, lower return loss and insertion loss, higher isolation between the outputs, and smaller size.

IV. CONCLUSION

A broadband eight-way SIW radial power divider/combiner with isolation network has been presented and investigated. The isolation network is realized by microstrip structure. The proposed power divider/combiner adopts the step plated holes to improve the impedance matching of the input port and the output ports, while the star structure based on microstrip circuit is employed to improve the isolation performance between the outputs. The presented power divider has been designed, fabricated and measured. The measured and simulated results show reasonable agreement with each other over the operating frequency range. The presented eight-way SIW radial power divider/combiner has the advantage of wider bandwidth, lower return loss and insertion loss, and higher isolation between the outputs.

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