# Four-way SIW Filtering Power Divider with In- and Out-of-phase Characteristics and Large Power Division Ratio

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***Abstract –*** A novel four-way substrate integrated waveguide (SIW) filtering power divider (FPD) with in-phase and out-of-phase characteristics and a large power division ratio (PDR) is presented in this work. The frequency selection and power division functions are effectively realized by employing SIW resonators at the bottom layer and at microstrip sections at the top layer, respectively. Four microstrip lines coupled with SIW cavity through a slotline realize in-phase and two out-of-phase output characteristics and a large PDR of 7:1. To verify the design method, a four-way prototype with PDR of 7:7:1:1 is designed, fabricated, and measured. Results exhibit good filtering performance, large power division ratio, and in-phase and out-of-phase characteristics.

***Index Terms –*** Four-way, filtering power divider (FPD), in-phase - out-of-phase, power division ratio (PDR), substrate integrated waveguide (SIW).

## I. INTRODUCTION

In modern wireless system, as two key passive components in wireless communication system, power dividers and filters are usually used in a cascaded way. This undoubtedly increases the circuit size and loss. In recent years, a high-integration design method, namely filtering power divider (FPD), has been widely developed. It can not only achieve the frequency selection function of the filter but also realize the power division of the power divider. According to its response type, it can be divided into in-phase FPD [1–4] and out-of-phase FPD [5–8]. In addition, unequal FPDs also become particularly important because their specific unequal power division ratio (PDR) can enable the array to obtain better directional performance in beamforming systems [9].

On the other hand, as an important part of substrate integrated circuits (SICs), substrate integrated waveguide (SIW) has attracted extensive attention from scholars due to its low cost, low loss, high integration, high power capacity, and so on [10]. A series of SIW-based FPDs is proposed, such as dual-band FPD on SIW triangular cavities [11], wideband four-way design based on SIW loaded square patch resonator [12], three-way FPD with adjustable PDR [13], and so on. Nevertheless, very few designs can realize in-phase and out-of-phase output at the same time and with a large PDR.

In this work, a novel four-way SIW FPD with large PDR of 7:7:1:1 is presented. Specifically, two ways are in-phase output while other two ways are out-of-phase phase output, with a 7:1 PDR of in-phase and out-of-phase output. The frequency selection and power division functions are effectively realized by employing SIW resonators and microstrip sections, respectively. Four microstrip lines coupled with SIW cavity through a slotline realize two in-phase and two out-of-phase output characteristics and a large PDR of 7:1. To verify the method, a prototype is designed, fabricated, and measured. The results show good filtering performance, large power division ratio, and in-phase and out-of-phase characteristics.

## II. DESIGN AND ANALYSIS

The physical structure of proposed four-way SIW FPD is shown in Fig. 1. It consists of two coupled SIW resonators at the bottom layer, a slotline at the middle layer, and four microstrip lines at the top layer. Specifically, the two SIW cavities resonate at $TE_{101}$ mode and are coupled through a coupling window to realize second-order filtering performance. Then, the energy is transmitted to the top layer through the slotline and output through four microstrip lines. The slotline is set at the strong magnetic field of the SIW cavity to realize the transmission from the bottom layer to the top layer. Figure 2 shows the coupling diagram of proposed four-way SIW FPD.

According to the above design concept, a four-way SIW FPD operating at 13 GHz with PDR of 7:7:1:1 is designed. Firstly, the size of the SIW cavity can be

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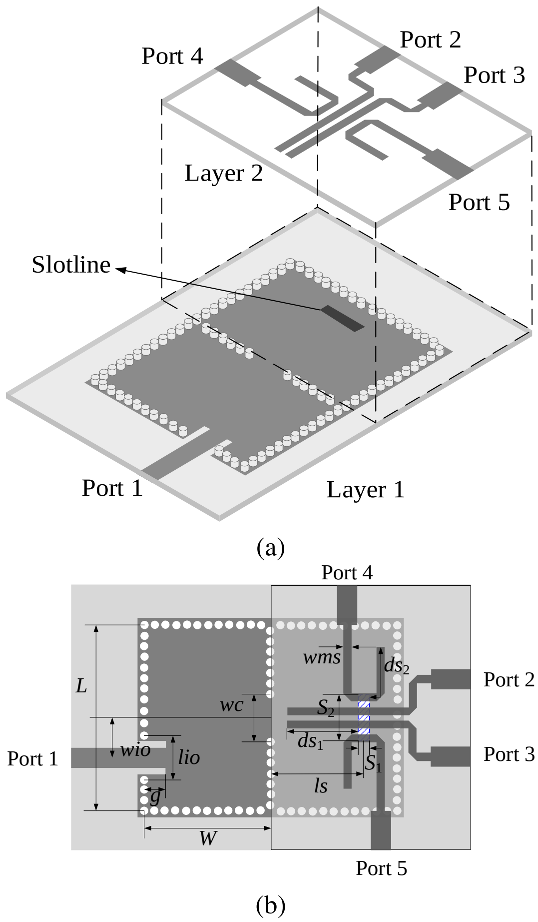



Fig. 1. Structures of proposed four-way SIW FPD: (a) Three-dimension view and (b) planar layout.

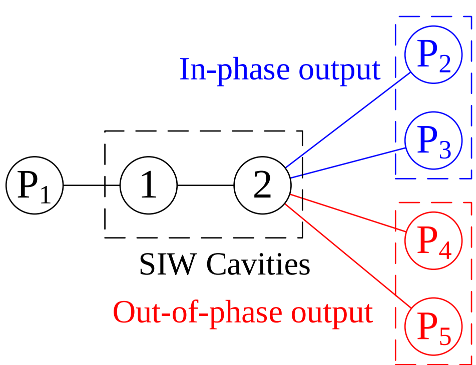



Fig. 2. Coupling diagram of proposed four-way SIW FPD.

calculated according to the formulas

$$f_{TEm0q} = \frac{c}{2\sqrt{\varepsilon_r \mu_r}} \sqrt{\left(\frac{m}{w_{\text{eff}}}\right)^2 + \left(\frac{q}{l_{\text{eff}}}\right)^2}, \tag{1}$$

$$w_{\text{eff}} = w_1 - \frac{d^2}{0.95p}, \quad l_{\text{eff}} = l_1 - \frac{d^2}{0.95p}, \tag{2}$$

where $w_1$ and $l_1$ represent the design width and length of the SIW cavity and $w_{eff}$ and $l_{eff}$ represent the effective width and length, respectively. $d$ is the diameter of the vias, $p$ is the distance between the adjacent vias, $c$ is the speed of light in vacuum, and $\varepsilon_r$ is the relative permittivity of substrate.

The external quality factor of the input port and the coupling coefficient between the SIW resonators can be calculated according to the formulas

$$Q_{es} = \pi f_i \cdot \tau_{S_{11}}(f_i)/2\,, \tag{3}$$

$$K = \frac{f_1^2 - f_2^2}{f_1^2 + f_2^2}, \tag{4}$$

where $\tau_{S11}(f_i)$ is the group delay of $|S_{11}|$ at resonance $f_i$, and $f_1$ and $f_2$ denote the higher and lower resonant frequencies of two coupled, respectively. Figure 3 shows the graphs of the external quality factor $Q_{es}$ and the coupling coefficient $K$ as a function of different parameters.

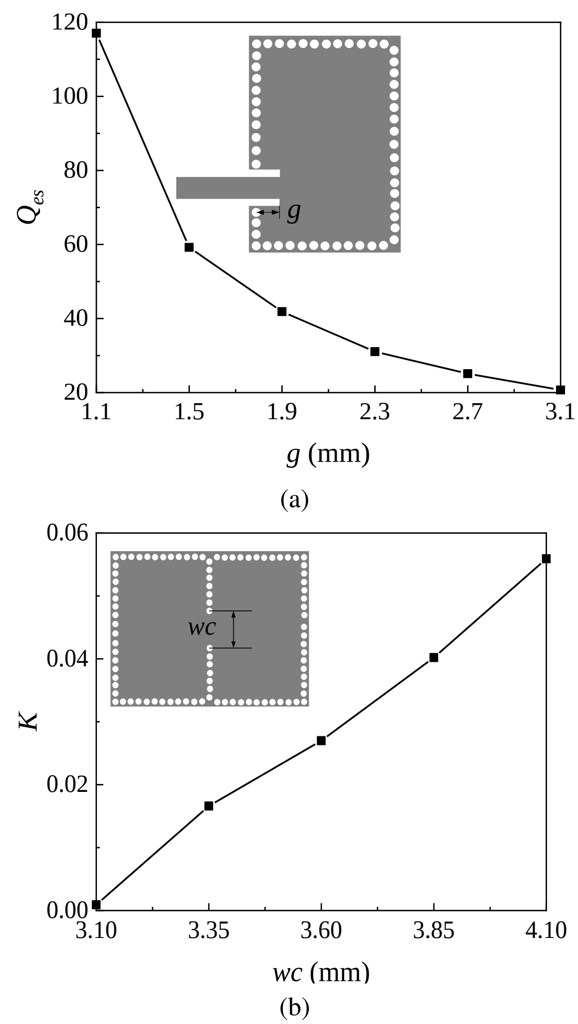
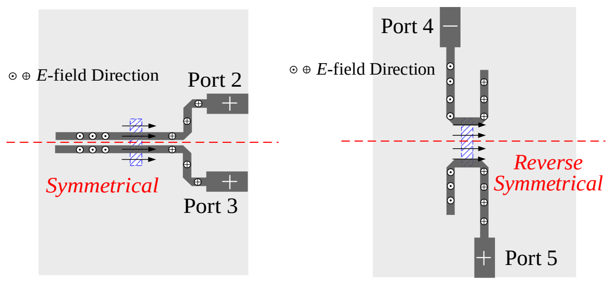



Fig. 3. Extracted external quality factor: (a) $Q_{es}$ and coupling coefficient and (b) $K$.




(a) (b)

Fig. 4. Analysis of phase characteristic of output ports: (a) In-phase output and (b) out-of-phase output.

The phase characteristics of the output ports can be analyzed as follows. As shown in Fig. 4 (a), microstrip lines connected to output ports 2 and 3 are symmetrical about the slotline, so the in-phase characteristic can be obtained at output ports 2 and 3, while microstrip lines connected to output ports 4 and 5 are reverse symmetrical about the slotline, shown in Fig. 4 (b), so the out-of-phase characteristic can be obtained at output ports 4 and 5 [14]. It is worth noting that by adjusting $Q_{eL}$, that is, the parameter $ds_1$ and $ds_2$, the PDR of in-phase output and out-of-phase output can be controlled. The $Q_{eL}$ of each output port can be obtained as [15]

$$Q_{eLi} = \frac{\alpha_1 + \alpha_2 + \ldots + \alpha_N}{\alpha_i} Q_s, \tag{5}$$

where $N = 4$, and $\alpha_1$, $\alpha_2$, $\alpha_3$, and $\alpha_4$ represent the dissipated power of each output port. The division ratio can be adjusted by tuning the $Q_{eL}$ ratio of the four output ports. In order to more clearly demonstrate the adjustment process of the PDR, Fig. 5 depicts the PDR changes under different $Q_{eL}$, that is, different parameters $ds_1$, of output ports.

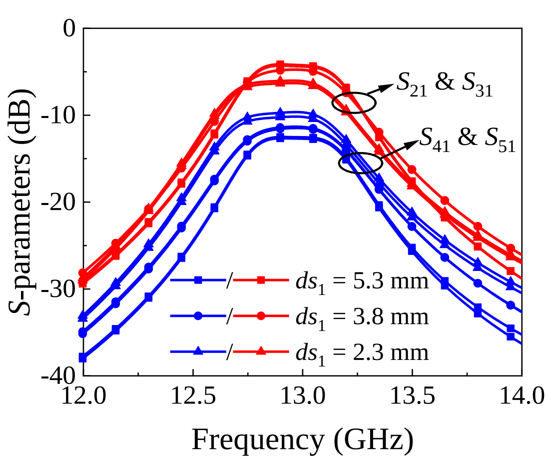
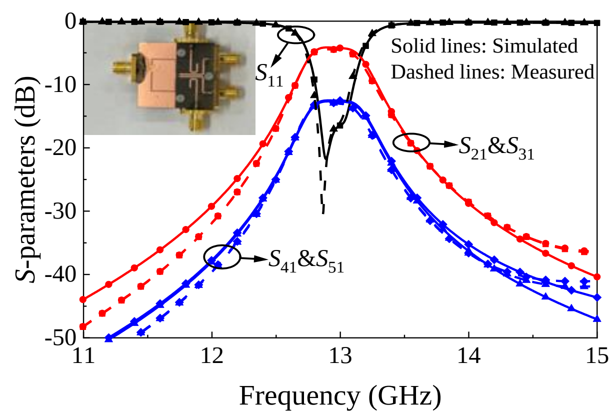



Fig. 5. The PDR changes under different parameters $d_{s1}$.

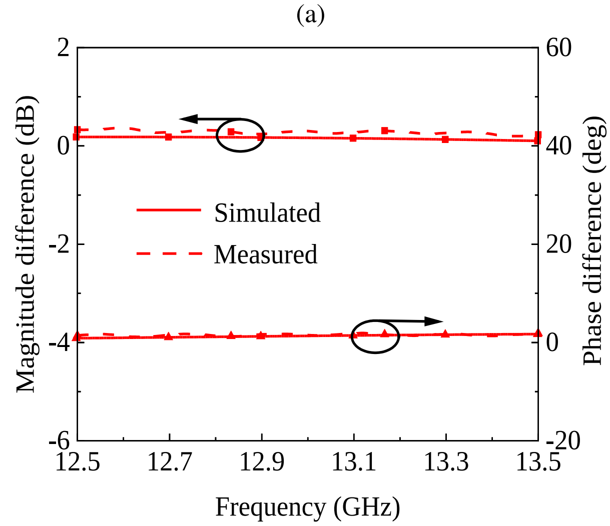
## III. SIMULATED AND MEASURED RESULTS

To verify the design method, a prototype operating at 12.96 GHz with PDR of 7:7:1:1 is fabricated on Rogers 5880 substrate with the relative dielectric constant of 2.2 and thickness h = 0.508 mm. The final dimension of the proposed four-way SIW FPD is determined as follows: $L = 14$, $W = 9.5$, $wio = 3$, $lio = 2.55$, $g = 1.6$, $wc = 3.6$, $wms = 0.6$, $ls = 7$, $S_1 = 0.8$, $S_2 = 3.3$, $ds_1 = 5.3$, $ds_2 = 5.05$ (all units: mm). The whole area of fabricated FPD is around 1.2 $\lambda_g \times 0.9\ \lambda_g$, where $\lambda_g$ is the guided wavelength at 13 GHz.

According to the PDR of 7:7:1:1, $S_{21}$, $S_{31}$, $S_{41}$, and $S_{51}$ are -3.6 dB, -3.6 dB, -12.04 dB, and -12.04 dB. As shown in Fig. 6 (a), we can see that in the machining model the input port is off center, this is mainly to achieve impedance matching of the input port, so as to adjust the return loss of $S_{11}$. And the measured return loss (RL) is better than 16.6 dB, and the minimum insertion loss (IL) is 0.8 dB (not including 7:7:1:1 power




(a)

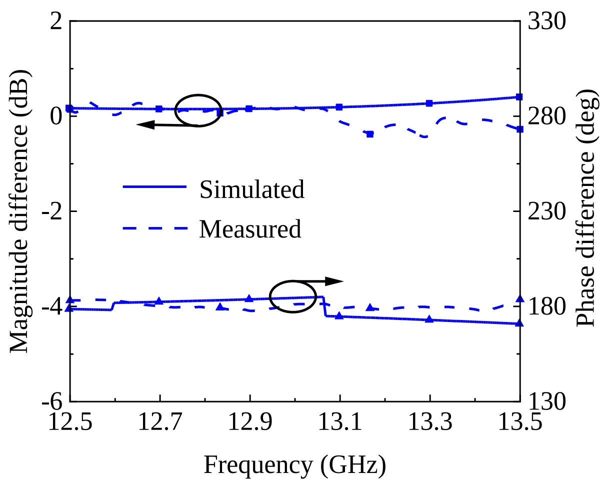



(b)

Fig. 6. *Continued*

Table 1: Comparisons with other reported works

| Refs. | CF (GHz) | 3-dB FBW (%) | Size ($\lambda$g2) | IL (dB) | Order | Number of Ways | Power Division Ratio | Phase |
|---|---|---|---|---|---|---|---|---|
| [4] | 4.82 | 11.6 | 0.469 | 2.0 | 2 | 2 | 1:1 | In-phase |
| [11] | 8.3 | 9.6 | 1.91 | 1.5 | 2 | 2 | 1:1 | In-phase |
| [12] | 3.55 | 21.3 | 1.3 | 2.0 | 2 | 4 | 1:1:1:1 | In-phase |
| [13] | 11.8 | 5.9 | 1.28 | 1.0 | 2 | 3 | 1:1:1.5 | In-phase |
| This work | 12.96 | 3.96 | 1.08 | 0.8 | 2 | 4 | 7:7:1:1 | In-phase & Out-of-phase |




(c)

Fig. 6. Simulated and measured results of proposed four-way SIW FPD: (a) *S*-parameters, (b) magnitude difference and phase difference of in-phase case, and (c) magnitude difference and phase difference of out-of-phase case.

division loss). The measured center frequency (CF) is 12.96 GHz, and the 3 dB fractional bandwidth (FBW) is 3.96%. As shown in Figs. 6 (b) and (c), the magnitude difference between in-phase output ports is 0.3 dB, while between out-of-phase output ports is 0.45 dB. The phase difference between in-phase output ports is 1.8 degrees, while between out-of-phase output ports is 4.9 degrees. The simulated results show most consistency with the measured results, but there are some differences between the measured and simulated results in our article, mainly because there are certain errors in the processing process, and the SMA plug has a certain degree of wear during testing, both of which lead to the difference.

In addition, in order to highlight the advantages of our design, Table 1 lists the comparisons between this work and other reported works. It is clear that the proposals in this work achieves a larger PDR and both in-phase and out-of-phase response.

## IV. CONCLUSION

In this work, a four-way SIW FPD with in-phase and out-of-phase characteristics and large PDR is presented. A prototype with PDR of 7:7:1:1 is designed, fabricated, and measured. The results show good filtering performance, phase characteristic, and large PDR. It is believed that the proposal has a good prospect in beamforming systems.

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