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RESEARCH PAPER

Compact power divider based on half mode substrate integrated waveguide (HMSIW) with arbitrary power dividing ratio

ALI-REZA MOZNEBI AND KAMBIZ AFROOZ

Design and realisation of a compact power divider based on half mode substrate integrated waveguide (HMSIW) with an arbitrary power dividing ratio is presented. This design consists of a substrate integrated waveguide (SIW) transition, two bisected HMSIW transitions by a gap, an SIW-to-microstrip transition, and two microstrip feed lines. In addition, a resistor is attached between two HMSIW transitions. To adjust the power division ratio, four parameters are introduced. Furthermore, four graphs are plotted using a three-dimensional electronmagnetic (3D EM) simulator to graphically determine the introduced parameters. In this study, three circuits with power division ratios of 1:1, 1:4, and 1:8 are simulated using the 3D EM simulator and fabricated on a Rogers RO4003C substrate. The results show a good agreement between the simulated and measured results. The measured results display these circuits (1:1, 1:4, and 1:8) have the bandwidths of 70, 36, and 40%, respectively. Moreover, the proposed structures (1:1, 1:4, and 1:8) are compact and their overall sizes are $1.13 \times 1.04\lambda_g^2$, $0.96 \times 0.91\lambda_g^2$, *and* $0.81 \times 0.78\lambda_g^2$, *respectively. These structures have the advantages of the compactness in size, wide bandwidth, high power division ratio (from 1:1 to 1:16), and compatibility with planar circuits.*

Keywords: Power divider, Arbitrary power division, Half mode substrate integrated waveguide (HMSIW), Compact size

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I. INTRODUCTION

Power divider is one of the fundamental devices in microwave and millimeter-wave circuits such as mixers, power amplifiers, and phase-array antennas [1–3]. Microstrip transmission lines have been widely used in power dividers because of compatibility with planar circuits and simple manufacturing process. But in these structures, the electromagnetic leakage and coupling are serious problems at high frequencies that limit their applications.

Conventional waveguide power dividers have the advantages of high Q-factor and low loss capacity [4, 5]. But, these structures suffer from problems of high cost, bulky volume, and difficult integration with planar circuits [6]. Recently, substrate integrated waveguide (SIW) structure is introduced [7, 8]. The SIW is configured by metallic via holes, as shown in Fig. 1. This structure has the benefits of the low loss, low cost, high Q-factor, and easy integration with planar circuits [9]. The size of the SIW is relatively large. The half mode substrate integrated waveguide (HMSIW) can be considered by separating the SIW along the propagation direction, which is an equivalent magnetic wall [10]. By this work, compared with the SIW, the size of the structure is reduced by nearly 50%.

Several power dividers based on SIW and HMSIW have been investigated [11–20]. In [14], a Y-junction four-way power divider was reported. This power divider had the large insertion loss. The reported circuit in [16] had the large insertion loss and large phase imbalance. Among these SIW/HMSIW power dividers, two T-junction SIW power dividers with arbitrary power division ratio were introduced in [19] and [20]. But these power dividers had the disadvantages of the large insertion loss and big size because the T-junction nature is comparatively large size.

In this paper, a compact power divider based on HMSIW with an arbitrary power dividing ratio is proposed. Three circuits with power division ratios of 1:1, 1:4, and 1:8 are presented. These structures consist of an SIW transition, two bisected HMSIW transitions by a gap, an SIW-to-microstrip transition in the input port at the left side, two microstrip feed lines in the output ports at the right side, and a resistor between the two HMSIW transitions. In the circuit of the equal power divider, this resistor is just added to achieve the isolation between the output ports. But their value and location, the angle of the gap with the propagation direction, and the length of the gap are the parameters of the power management in the two other circuits. Four graphs are plotted using a three-dimensional electromagnetic (3D EM) simulator to graphically determine the introduced parameters. Figure 2 shows the configuration of these circuits. Moreover, the used SIW-to-microstrip transition is introduced in [21].

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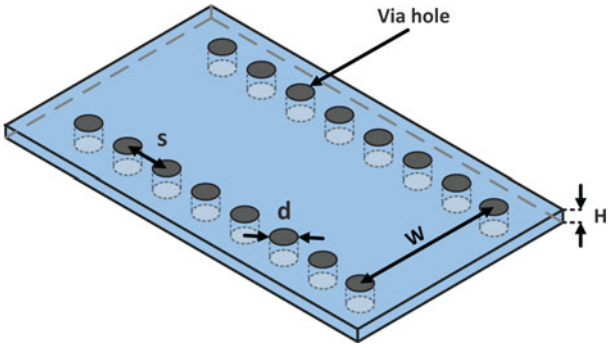

Fig. 1. Configuration of a SIW structure.

It features two vias, which have the same diameter as the SIW vias and are located symmetrically at both sides of the microstrip taper. These designs are simulated using the 3D EM simulator and fabricated on a Rogers RO4003C substrate. The results show a good agreement between the simulated and measured results. The measured results display these circuits (1:1, 1:4, and 1:8) have the bandwidths of 70, 36, and 40%, respectively.

II. DESIGN PROCEDURE

A) SIW and HMSIW design

As shown in Fig. 2(a), one SIW transition is used and two HMSIW transitions are separated with a gap between them. The TE_{10} is the dominant mode of the SIW structure. The cutoff frequency is obtained by [3]:

$$f_{cmn} = \frac{c}{2\pi\sqrt{\mu_r \varepsilon_r}}\sqrt{\left(\frac{m\pi}{W_{eff}}\right)^2 + \left(\frac{n\pi}{h}\right)^2}. \quad (1)$$

In this case, the cutoff frequency is the same as conventional rectangular waveguide. In (1), m and n are the mode indexes, c is the velocity of light in the free space, ε_r is the relative permittivity of the substrate, μ_r is the relative permeability of the substrate, h refers to the height, and W_{eff} refers to the equivalent width of the SIW, which is equal to [22]:

$$W_{eff} = W - 1.08.\frac{d^2}{s} + 0.1.\frac{d^2}{W}. \quad (2)$$

In (2), d refers to the diameter of the vias, s is their longitudinal spacing, and W displays the transverse spacing of the two vias that are located at both sides of the SIW. In this structure, the transverse magnetic (TM) modes cannot be guided due to the dielectric gaps created by the via separations [23]. For the better performance of the circuit, d and s are limited as follows [24]:

$$\frac{s}{d} \leq 2. \quad (3)$$

B) SIW-to-microstrip transition and microstrip feed lines design

In the input, a microstrip-to-SIW transition is used based on [21]. After designing the microstrip and SIW parameters, the

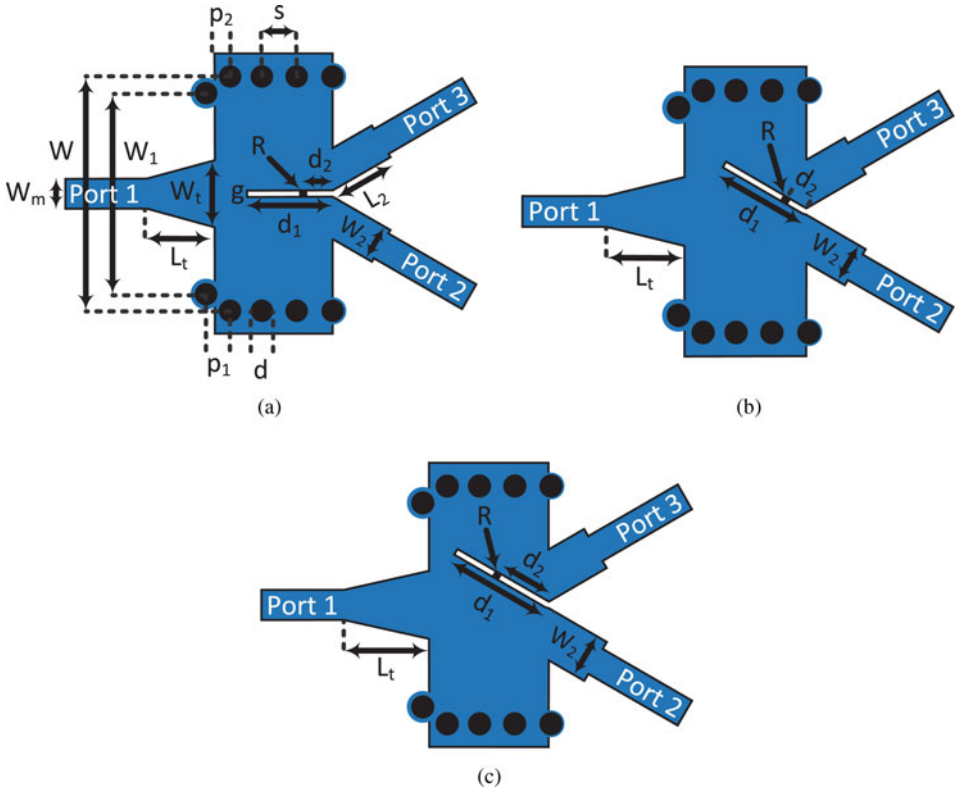

Fig. 2. Configuration of the proposed structures: (a) $\Delta out = 0$ dB, (b) $\Delta out = 6$ dB, and (c) $\Delta out = 9$ dB.

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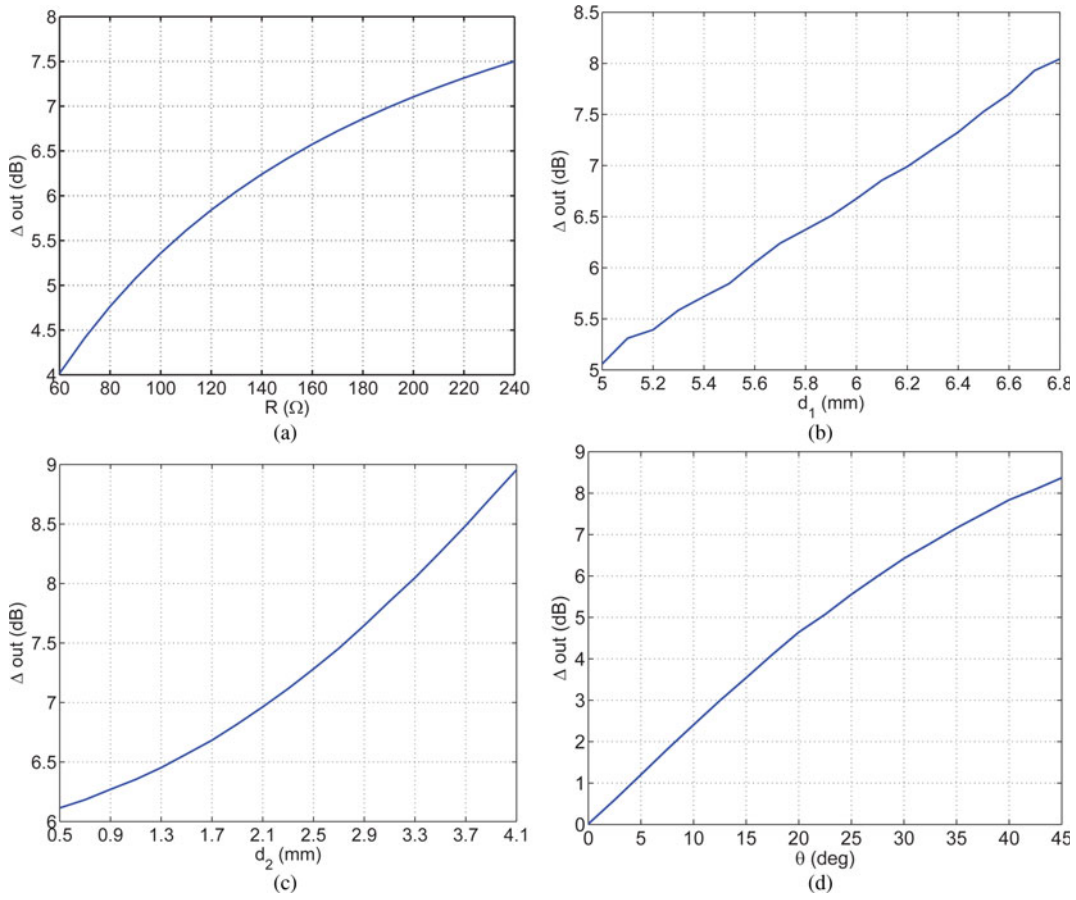

Fig. 3. Values of Δout versus different: (a) R when $\theta = 30^{\circ}$, $d_1 = 5.83$ mm, and $d_2 = 1.21$ mm, (b) d_1 when $R = 150\ \Omega$, $\theta = 30^{\circ}$, and $d_2 = 1.21$ mm, (c) d_2 when $R = 150\ \Omega$, $\theta = 30^{\circ}$, and $d_1 = 5.83$ mm, (d) θ when $R = 150\ \Omega$, $d_1 = 5.83$ mm, and $d_2 = 1.21$ mm.

taper-via transition parameters can be calculated as [21]:

$$L_t = 0.2368\lambda_{g_{MS}}, \tag{4}$$

$$W_t = W_m + 0.1547W, \tag{5}$$

$$p_1 = 0.6561s, \tag{6}$$

$$W_1 = 0.8556W. \tag{7}$$

λ_{gMS} is the guided wavelength of the microstrip line calculated at the center frequency

$$\lambda_{g_{MS}} = \frac{\lambda_{go}}{\sqrt{\varepsilon_{reff}}}. \tag{8}$$

In (8), ε_{reff} refers to the effective dielectric constant of the microstrip line and λ_{go} refers to the wavelength in free space. In the output, two microstrip feed lines are used. After designing the structure with 50 Ω microstrip lines, by tuning the parameters of the microstrip feed lines (W_2 and L_2), excellent impedance matching can be achieved.

C) Determining R, θ, d_1, and d_2

In this paper, the power management is realized by varying the value (R) and location of the resistor (d_2), the angle of the gap with the propagation direction (θ), and the length of the gap (d_1). To adjust the power division ratio, the value of θ is main parameter. If this parameter is equal to zero, then $\Delta out = 0$ dB, and the parameters of R, d_1, and d_2 have no effect on the power management. In the presented equal

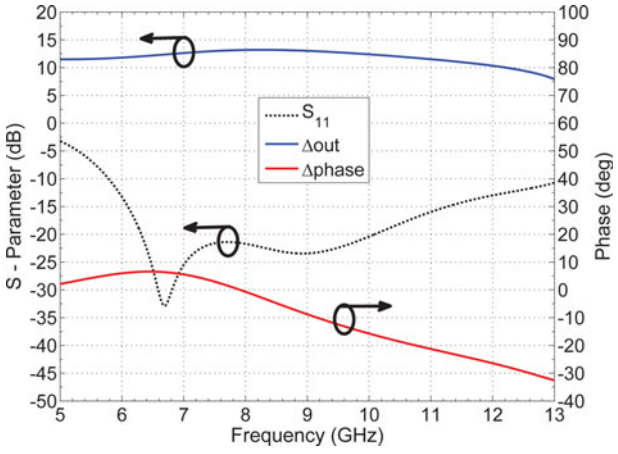

Fig. 4. Results of the compact HMSIW power divider with $\Delta out = 12$ dB ($\theta = 45^{\circ}$, $R = 156\ \Omega$, $d_1 = 6.75$ mm, and $d_2 = 3.57$ mm).

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Table 1. Parameters of the proposed structures.

$\Delta out = 0$ dB	W	14.65 (mm)	L_t	4.24 (mm)	p_2	1.11 (mm)
	W_1	12.56 (mm)	d	1.45 (mm)	s	2.18 (mm)
	W_2	2.28 (mm)	d_1	5.35 (mm)	g	0.4 (mm)
	W_t	4.19 (mm)	d_2	1.85 (mm)	R	47 (Ω)
	L_2	4.15 (mm)	p_1	1.5 (mm)	θ	0 (°)
$\Delta out = 6$ dB	W_2	2.54 (mm)	d_1	5.83 (mm)	R	150 (Ω)
	L_t	4.74 (mm)	d_2	1.21 (mm)	θ	30 (°)
$\Delta out = 9$ dB	W_2	2.79 (mm)	d_1	6.67 (mm)	R	150 (Ω)
	L_t	5.25 (mm)	d_2	3.23 (mm)	θ	30 (°)

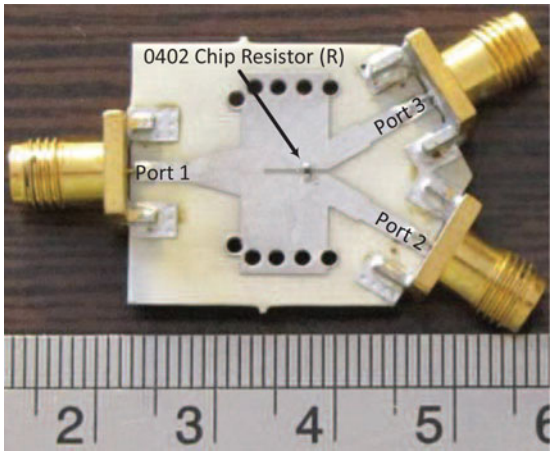

Fig. 5. Photograph of the compact HMSIW power divider with $\Delta out = 0$ dB.

power divider, the used resistor is attached between two HMSIW transitions to improve the isolation and return loss of the output ports. The parameters of R, d_1, and d_2 are arisen by increasing the value of θ. Figure 3 shows the values of Δout versus different R, θ, d_1, and d_2. This figure is obtained by changing the values of the introduced parameters. As shown in Fig. 3, the power difference between the output ports can be increased by increasing R, θ, d_1, and d_2. From Fig. 3(d), it can be concluded that the proposed structure can obtain the high power division ratio.

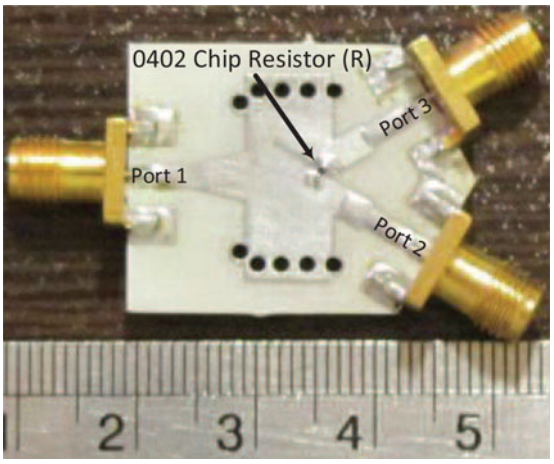

Fig. 7. Photograph of the compact HMSIW power divider with $\Delta out = 6$ dB.

Furthermore, by increasing the values of R, d_1, and d_2, the value of Δout can vary in a wider range (from 1:1 to 1:16). In order to prove it, an unequal power divider with $\Delta out = 12$ dB is designed. Figure 4 shows the simulated results of the unequal power divider with $\Delta out = 12$ dB.

Moreover, Table 1 displays the parameters of the proposed structures shown in Fig. 2.

III. SIMULATED AND MEASURED RESULTS

Three compact HMSIW power dividers with power division ratios of 1:1, 1:4, and 1:8 have been designed and fabricated on a single layer Rogers RO4003C substrate with a thickness, relative permittivity, and loss tangent of 0.8128 mm, 3.55, and 0.0027, respectively.

A) Compact HMSIW power divider with $\Delta out = 0$ dB

In the equal power divider, the measured results illustrate the return loss is >12.5 dB for the fractional bandwidth of 70%

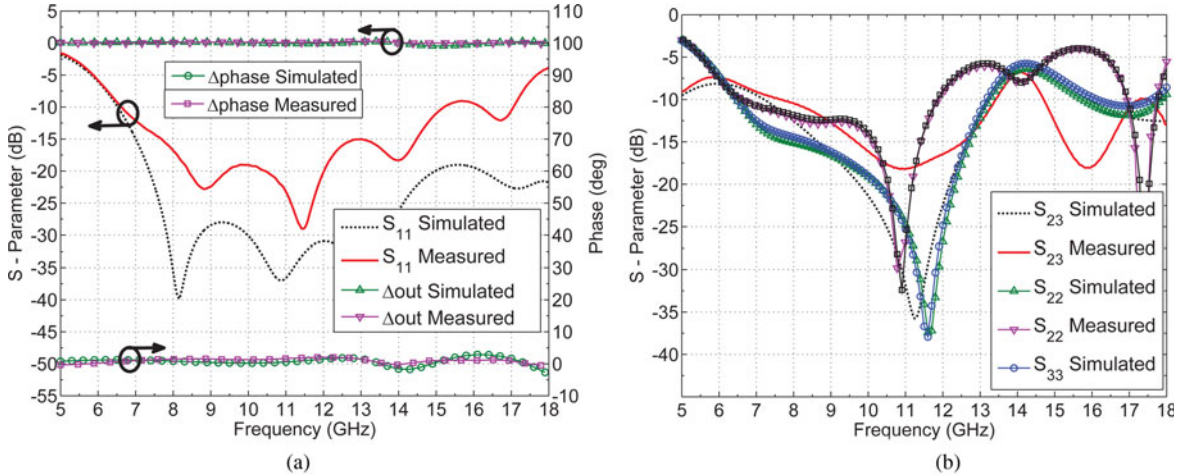

Fig. 6. Simulated and measured results of the compact HMSIW power divider with $\Delta out = 0$ dB: (a) S_{11}, Δout, and $\Delta phase$, (b) isolation (S_{23}) and the return loss of the output ports (S_{22} and S_{33}).

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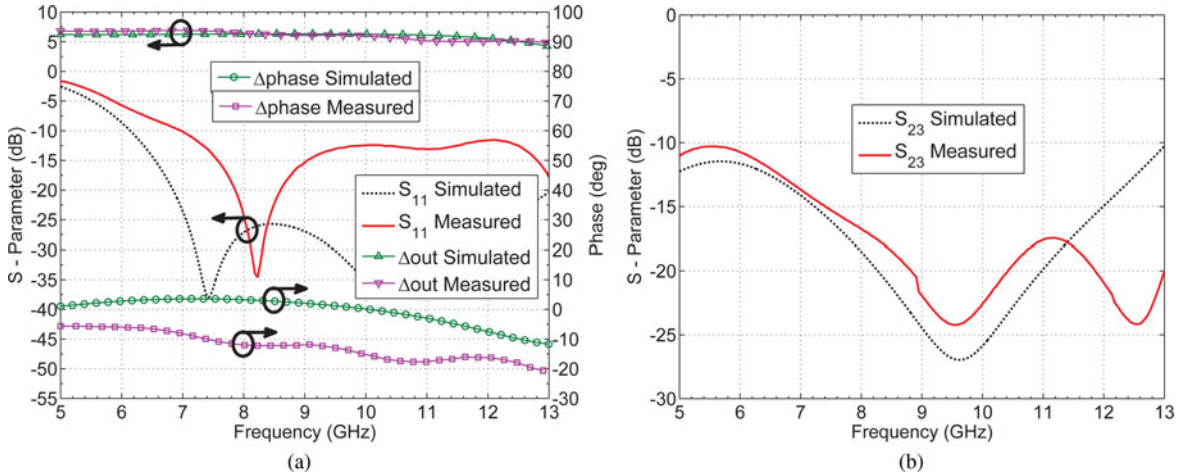

Fig. 8. Simulated and measured results of the compact HMSIW power divider with $\Delta out = 6$ dB: (a) S_{11}, Δout, and $\Delta phase$, (b) isolation (S_{23}).

(7.08–14.77 GHz). Moreover, Δout is <0.3 dB and $\Delta phase$ is $<2^{\circ}$. But the isolation between output ports and the return loss of the output ports are >10 dB for the fractional bandwidth of 43% (7.67–11.87 GHz). The photograph of the fabricated equal power divider is shown in Fig. 5. Figures 6(a) and 6(b) depict the simulated and measured results of the proposed structure.

B) Compact HMSIW power divider with $\Delta out = 6$ dB

In the unequal power divider with $\Delta out = 6$ dB, the measured fractional bandwidth is 36% (7.59–10.88 GHz), Δout is $<\Delta out \pm 12\%$, and $\Delta phase$ is $<18^{\circ}$ when the return loss is better than 12.5 dB. The photograph of the fabricated unequal power divider with $\Delta out = 6$ dB is shown in Fig. 7. Figures 8(a) and 8(b) depict the simulated and measured results of the proposed structure.

C) Compact HMSIW power divider with $\Delta out = 9$ dB

In the unequal power divider with $\Delta out = 9$ dB, the measured fractional bandwidth is 40% (6.18–9.25 GHz), Δout is $<\Delta out \pm 10\%$, and $\Delta phase$ is $<10^{\circ}$ when the return loss is better than 12.5 dB. The photograph of the fabricated unequal power divider with $\Delta out = 9$ dB is shown in Fig. 9. Figures 10(a) and 10(b) depict the simulated and measured results of the proposed structure. It should be noted here

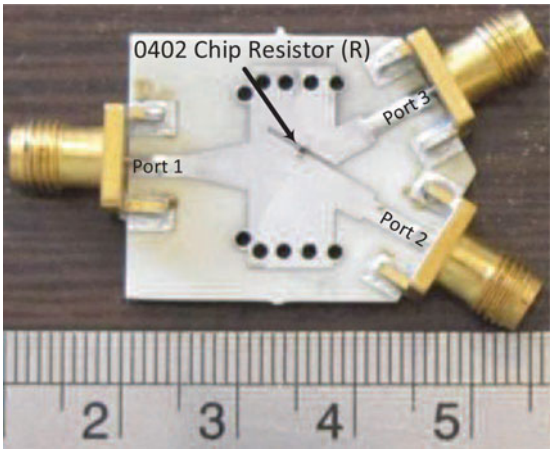

Fig. 9. Photograph of the compact HMSIW power divider with $\Delta out = 9$ dB.

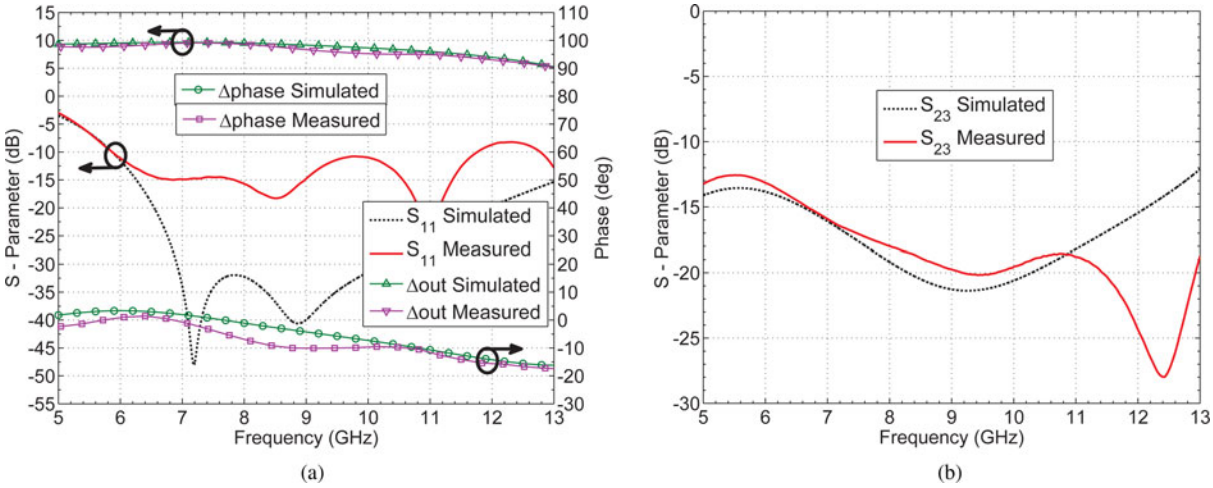

Fig. 10. Simulated and measured results of the compact HMSIW power divider with $\Delta out = 9$ dB: (a) S_{11}, Δout, and $\Delta phase$, (b) isolation (S_{23}).

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Table 2. Comparison with other works.

$\lvert dB(S_{21}) - dB(S_{31})\rvert \leq \Delta out \pm 12\%$, $dB(S_{11}) \leq -12.5$ dB				
Reference	**Δout (dB)**	**FBW (%)**	**Size (λ_g^2)**	**Structure**
[17]	0	10.9	3.91 × 1.64	SIW Y-junction
[18]	0	23.5	1.5 × 0.95	Ring-shaped SIW
This Work	0	70	1.13 × 1.04	HMSIW
[19]	6	12.2	4.42 × 2.3	SIW T-junction
This Work	6	36	0.96 × 0.91	HMSIW
[25]	9	18	0.9 × 0.49	Microstrip
This Work	9	40	0.81 × 0.78	HMSIW

FBW: fractional bandwidth.

that the bandwidth is limited by both input matching and Δout variations.

The proposed structures (1:1, 1:4, and 1:8) are compact and have the overall sizes of $1.13 \times 1.04\lambda_g^2$, $0.96 \times 0.91\lambda_g^2$, and $0.81 \times 0.78\lambda_g^2$, respectively. This indicates that the proposed structures are a good candidate for compact HMSIW power divider with arbitrary power dividing ratio. Some slight differences between the measured and simulated results is mainly caused by the insertion loss of sub-miniature-A (SMA) connectors, fabrication errors, and the tolerance of the dielectric constant. In Table 2, a comparison between this work and other works is summarized.

IV. CONCLUSION

In this paper, a compact HMSIW power divider with an arbitrary power dividing ratio has been presented. Compared with the previously introduced structure, this unequal power divider can be widely used in millimeter-wave systems and microwave because of its simple and compactness in size.

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