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A Broadband Half-Mode Substrate Integrated Waveguide Quadrature Wilkinson Power Divider Using Composite Right/Left-Handed Transmission Line

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Abstract

In this work, a broadband composite right/left-handed (CRLH) half-mode substrate integrated waveguide (HMSIW) quadrature Wilkinson power divider is proposed. The proposed CRLH-HMSIW quadrature power divider includes a microstrip Wilkinson power divider on the transition structure between the microstrip and HMSIW, and two thru transmission lines for the HMSIW and the CRLH-HMSIW. The measured amplitude, phase difference and isolation between the two output ports of the proposed structure have 1 dB, ±5° and less than −15 dB in a wide frequency range of 4.1–6.68 GHz with 47.9% bandwidth, respectively.

Key Words: Composite Right/Left-Handed (CRLH), Half-Mode Substrate Integrated Waveguide (HMSIW), Quadrature Power Divider.

I. INTRODUCTION

Quadrature Wilkinson power dividers have typically been adopted to realize balanced amplifiers and as image-rejection mixers in microwave circuit design. Structurally, quadrature Wilkinson power dividers are designed to integrated the Wilkinson power divider with a 90° phase-adjusting circuit. Numerous studies have been devoted to the design of these 90° phase-adjusting circuits [1–5]. Low-pass and high-pass filters were implemented with Wilkinson power divider to obtain a 90° phase difference between output ports [1]. The phase compensated transmission lines [2] or the all-pass active filters [3] were introduced for achieving wideband 90° phase difference. The metamaterial-based quadrature power divider has also been reported for realizing broad-bandwidth [4]. On the other hand, a substrate integrated waveguide (SIW)-based quadrature power divider using lumped elements has also been described [5].

The SIW is one of the planar waveguides, constructed with two parallel via fences or bar vias between metal layers at the top and the bottom of the printed circuit board (PCB). The SIW has two distinct merits: it enables the taking of traditional waveguide components to PCB-based planar components, and reduces the hollow waveguide size by using the dielectric constant of the PCB [5–7]. However, the reported SIW quadrature power divider [5] has a narrow band with a 90° phase difference because the lumped elements on the transition structure have

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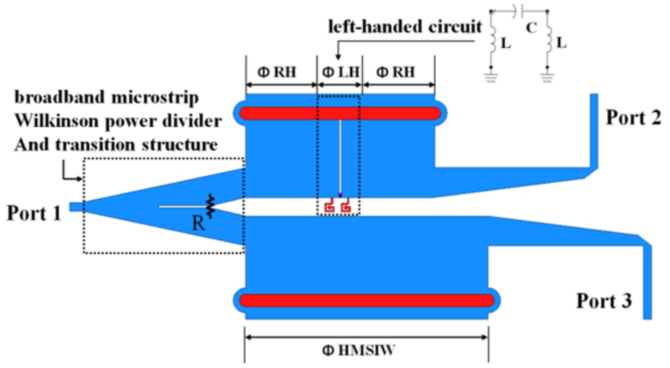


Fig. 1. Proposed HMSIW quadrature power divider using CRLH-HMSIW.

limitations with respect to their ability to achieve the broadband 90° phase difference.

In this paper, we propose a broadband half-mode SIW (HMSIW) quadrature Wilkinson power divider using composite right and left-handed (CRLH) transmission line (TL). The HMSIW is one of the SIW, and is half size of the SIW. The proposed CRLH-HMSIW is conducted with two lumped shunt inductors and a surface mount technology (SMT) series capacitor on the edge of the HMSIW, and the broadband Wilkinson power divider [8] is integrated with the transition structure.

Ⅱ. DESIGN PROCEDURE

Fig. 1 presents the proposed HMSIW quadrature power divider using CRLH-HMSIW. The SIW or HMSIW requires a transition circuit for use with other planar circuit devices based on microstrip (MS) or coplanar waveguide (CPW) [5, 6]. The broadband MS Wilkinson power divider was designed and integrated with the transition structure between MS and HMSIW for achieving a highly integrated SIW circuit. To obtain broad-bandwidth, a tapered line was adopted for input/output matching of the power divider [9]. The fundamental mode of SIW is the $TE_{1,0}$ mode and its higher order mode starts with the $TE_{2,0}$ mode. However, the fundamental mode of the HMSIW is the $TE_{0.5,0}$ mode, with the first higher order being the $TE_{1.5,0}$ mode. The $TE_{1.5,0}$ mode has a frequency range that is three times that of the fundamental mode; therefore, the bandwidth for HMSIW is wider than that of SIW [9].

The proposed power divider splits the power to the phase adjust circuit, the proposed CRLH-HMSIW and the HMSIW. Fig. 2 shows the phase responses of the proposed CRLH-HMSIW and the HMSIW. The proposed CRLH-HMSIW phase response was designed to have 90° synchronization with the HMSIW from f_1 to f_2, since CRLH TLs lead the phase compared with right-handed (RH) TLs. The power divider was designed at f_0.

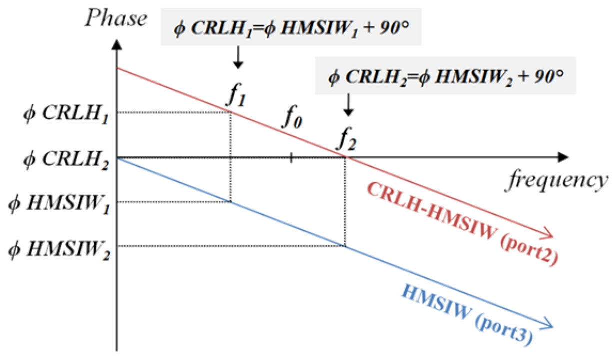


Fig. 2. Phase responses of the proposed CRLH-HMSIW and the HMSIW.

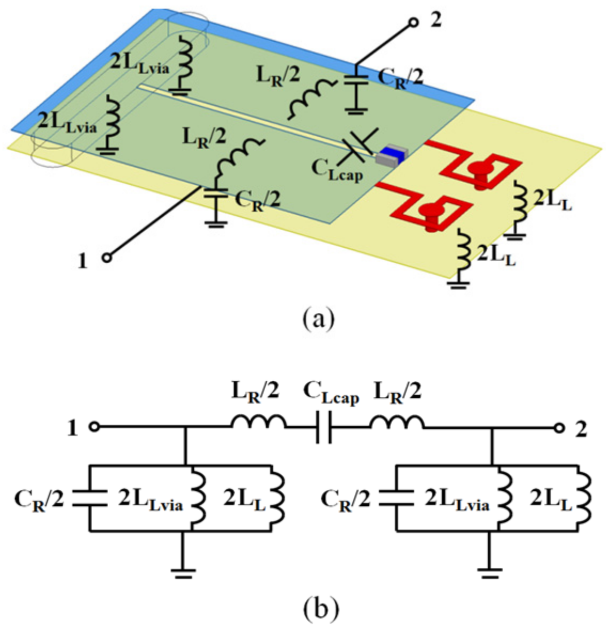


Fig. 3. (a) The unit cell of the proposed CRLH-HMSIW. (b) Equivalent circuit model of the unit cell.

To design the proposed structure, the phase response between $\phi HMSIW_1$ and $\phi HMSIW_2$ should be selected appropriately by the length of the HMSIW. The left-handed (LH) and RH phases of the CRLH-HMSIW should be calculated according to previously described methods [4, 10].

$$\emptyset CRLH_1 = \emptyset RH_1 + \emptyset LH_1 = -P \cdot f_1 + Q/f_1 \tag{1}$$

$$\emptyset CRLH_2 = \emptyset RH_2 + \emptyset LH_2 = -P \cdot f_2 + Q/f_2 \tag{2}$$

where $P = -\emptyset RH_i / f_i$ and $Q = \emptyset LH_i \cdot f_i$.

Fig. 3(a) and (b) refer to the unit cell of the proposed CRLH-HMSIW and the equivalent circuit model of the unit cell. The LH section of the proposed CRLH-HMSIW has a controllable shunt inductor, L_L for L_{Lvia} inductance. The L_{Lvia}, L_L and C_{Lcap} values are concerned with Q from the formula (1) and (2). The Q is derived as in [4].

$$Q = \frac{N}{2\pi\sqrt{LC}} \tag{3}$$

where N is the number of the LH unit cell.

After solving the formulas (1) and (2), the P and Q are obtained as shown in [4].

$$P = \frac{f_1\phi CRLH_1 - f_2\phi CRLH_2}{f_2^2 - f_1^2} \tag{4}$$

$$Q = \frac{f_1 f_2^2\phi CRLH_1 - f_1^2 f_2\phi CRLH_2}{f_2^2 - f_1^2} \tag{5}$$

The design procedures can be summarized as follows:

1) Design of the broadband MS Wilkinson power divider at f_0.
2) Choice of the frequency range, f_1 to f_2, and calculation of the $\phi CRLH_1$ and $\phi CRLH_2$ by using

$$\emptyset CRLH_1 = \emptyset HMSIW_1 + 90° \tag{6}$$

$$\emptyset CRLH_2 = \emptyset HMSIW_2 + 90° \tag{7}$$

3) Solve formulas (4) and (5) using the parameters of the f_1, f_2, $\phi CRLH_1$ and $\phi CRLH_2$
4) Calculate the $P = -\emptyset RH_i / f_i$ for obtaining HMSIW length
5) Extract the L and C with LC product by using formula (3) and formula (8), as in [10]

$$L = Z_0\sqrt{(LC)} \quad C = \frac{\sqrt{(LC)}}{Z_0} \tag{8}$$

where Z_0 is the characteristic impedance.

6) Solve formula (9) to obtain f_c^{LH} as in [10]. If $f_c^{LH} < f_0$, the design is completed. If it is not satisfied, choose a larger N and proceed again from step 5.

$$f_c^{LH} = \frac{1}{4\pi\sqrt{(LC)}} \tag{9}$$

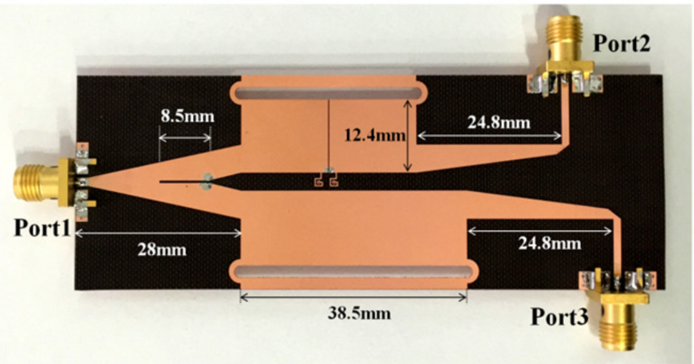


Fig. 4. Demonstration of the proposed HMSIW quadrature power divider.

Ⅲ. EXPERIMENTAL RESULTS

The demonstrated HMSIW quadrature power divider is shown in Fig. 4. Three target frequencies, $f_1 = 4.5$ GHz, $f_0 = 5.5$ GHz, and $f_2 = 6.5$ GHz are chosen to achieve broad bandwidth.

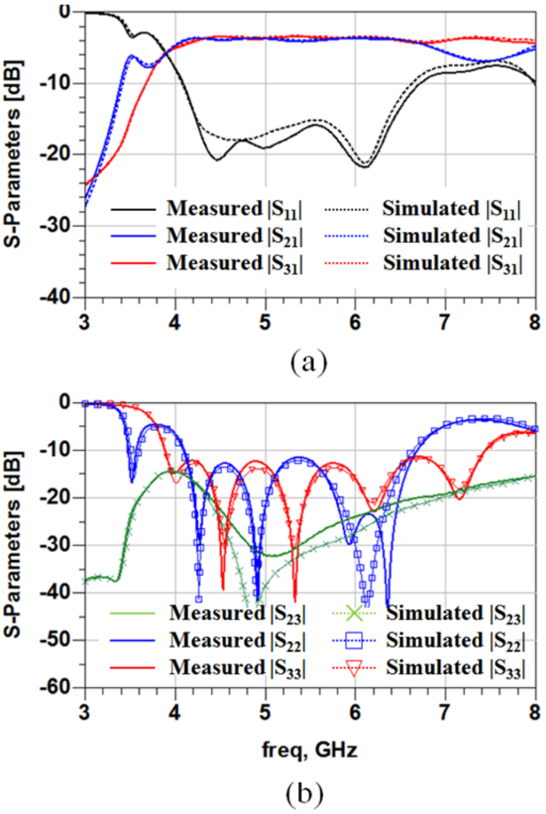
The demonstration was designed on a Taconic TLX-8 substrate (dielectric constant = 2.55, height = 0.508 mm). The HMSIW in the proposed structure has characteristic impedance (Z_0) of the power-current (Z_{PI}) definition of 13 Ω, which was calculated by using ANSYS HFSS ver. 14 simulation. Note that the traditional CRLH TLs can be analyzed by using the TL theory on the strip-like lines [11]. In the example provided here, the characteristic impedance of the Z_{PI} definition is most appropriate for the strip-like lines [12]. Therefore, the Z_{PI} definition is used for calculating the L and C values in the proposed structure.

To realize the CRLH-HMSIW, two PCB-embedded inductors and a Murata 0201-sized SMT capacitor are utilized. This demonstration implements the calculated design parameters from Section II with the LH section parameters being N = 1, $C_{Lcap} = 0.8$ pF and $L_L = 1.3$ nH. Note that total inductor value (sum of $2L_L$ and $2L_{Lvia}$) of the LH section needs 0.13 nH through the formula (8). However, the value calculated from the simulation tool was $L_{Lvia} = 0.07$ nH. Therefore, $L_L = 1.3$ nH is necessary to meet the target, 0.13 nH inductance of the LH section.

The 50-Ω chip resistor on the input transition structure was attached for obtaining isolation between the output ports [8].

For measurement, the transition structures between HMSIW and MS were utilized, and the SMA connectors were soldered on the edge of the MS line. The measured S-parameters were carried out by using a vector network analyzer, Agilent N5230A. Fig. 5(a) and (b) show the simulated and measured S-parameters of the insertion losses ($|S_{21}|$, $|S_{31}|$), in and out return loss ($|S_{11}|$, $|S_{22}|$, and $|S_{33}|$), and isolation ($|S_{23}|$). The measured $|S_{21}|$, $|S_{31}|$ show -4 ± 0.5 dB on the frequency range from 4.14 to 6.74 GHz, and the measured $|S_{11}|$, $|S_{22}|$, and $|S_{33}|$ are better than -10 dB from 4.1 to 6.68 GHz. The $|S_{23}|$ is less than -20 dB between output ports from 4.39 to 6.68 GHz. In Fig. 6(a), the measured amplitude imbalance is within 1 dB from 4.23 to 6.82 GHz, except that it reaches 0.56 dB at 5.39 GHz, and the measured phase difference shows 90° ± 5° from 3.84 to 6.68 GHz.

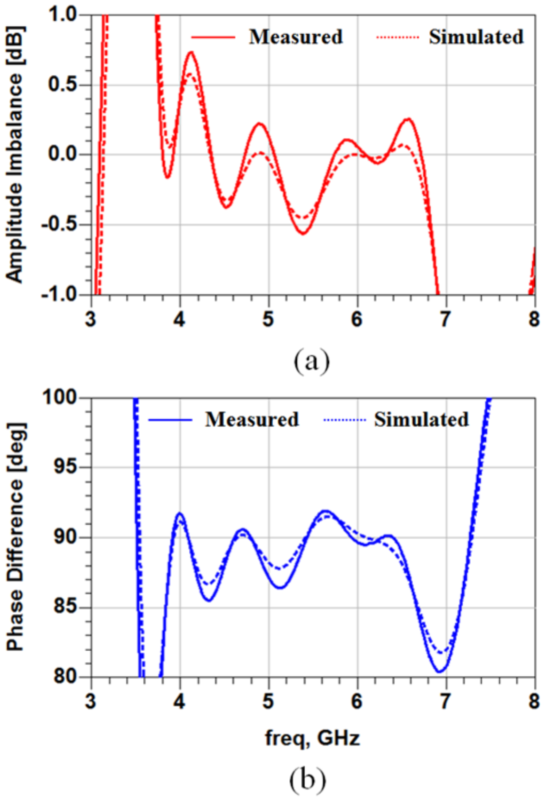
The performance comparison between the conventional SIW quadrature power divider [5] and the proposed HMSIW quadrature power divider is shown in Table 1. The proposed structure has more wide-bandwidth than [5], with better isolation performance.



(a)

(b)

Fig. 5. (a) Simulated and measured insertion losses and input return loss of the proposed HMSIW quadrature power divider. (b) Simulated and measured output return losses and isolation.



(a)

(b)

Fig. 6. (a) Simulated and measured amplitude imbalance of the proposed HMSIW quadrature power divider. (b) Simulated and measured phase difference.

Table 1. Performance comparison

	Relative bandwidth (%)	Phase error (°)	Amplitude imbalance (dB)	Isolation (dB)
[5]	18.4	±5	1	−15
This work	47.9	±5	1	−20

* Relative bandwidth = (frequency range/center frequency) × 100%.

IV. CONCLUSION

In this paper, a broadband HMSIW quadrature Wilkinson power divider using CRLH TL is presented. The proposed structure shows good amplitude imbalance, within 1 dB, 90° phase difference, and excellent isolation performance between output ports. The measurement results show good agreements with the simulation.

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