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INDUSTRIAL AND ENGINEERING PAPER

Miniaturized Bagley Polygon power divider by using composite right-/left-handed transmission lines

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A miniaturized Bagley Polygon power divider based on composite right/left-handed transmission line is presented. The composite right/left-handed transmission line and conventional microstrip transmission line are utilized to realize the 0° phase shift transmission line, which is used to replace the 180° transmission line of the conventional Bagley Polygon power divider. As a result, miniaturization is realized, without deteriorating the isolation between the output ports. The design equations are presented. This power divider shows advantages compared with other miniaturized ones. For verification, a miniaturized Bagley Polygon power divider is designed and fabricated. The 58.2% length reduction of the counterpart is realized. The measurement and simulation results show good agreement.

Keywords: Polygon power divider, Miniaturized, Composite, Right-/left-handed transmission lines

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I. INTRODUCTION

With the rapid development of radio frequency (RF) and microwave systems, various types of power dividers have been developed to realize the power divider/combing [1–27]. The waveguide-based power dividers have been widely investigated and used in microwave and millimeter-wave systems because of their low insertion loss, high-power capability, and wide bandwidth [2–13]. While the substrate integrated waveguide (SIW) and planar power dividers have advantages of easy integration with monolithic microwave integrated circuit (MMIC), good impedance matches at all ports and high isolation among the output ports [14–27]. Among the planar power dividers, the Bagley Polygon power divider is an input impedance match N-way (N is odd) circuit. Compared with the Wilkinson power divider, the Bagley Polygon power divider does not use lumped elements and can be easily extended to arbitrary odd number of output ports. Therefore, this kind of power divider is suitable for antenna feeding networks, power combing networks, and multiplexers, etc.

However, the disadvantage of the Bagley Polygon power divider is its large size. In order to solve this problem, a five-way miniaturized power divider was proposed in [25]. The length of the transmission line (TL) between the output ports can be tuned according to the requirement, but the isolation performance has been ignored. Moreover, the realizable N is limited by the high-impedance TL. In [26], the defected ground structure (DGS) technology is utilized for miniaturization. However, this circuit suffers from the difficulty in assembling. In [27], a miniaturized three-way Bagley Polygon power divider was proposed by using the dual TLs, but it also ignores the isolation performance. Moreover, the high-impedance TL used in the circuit will lead to the same problem that occurs in [25]. In addition, more analysis is needed when the number of output port N is changed.

In this paper, a three-way miniaturized Bagley Polygon power divider is implemented based on the composite right/left-handed (CRLH) TL. The proposed power divider not only realizes the size reduction, but also maintains the isolation between the output ports. It is observed that simulated and measured results show a good agreement.

II. ANALYSIS AND DESIGN OF THE POWER DIVIDER

Figure 1 shows the circuit layout of the conventional Bagley Polygon power divider, which is composed of two $\lambda/2$ length TLs and two $\lambda/4$ length TLs. Based on the theory in [25], $Z_a = 2Z_0/\sqrt{3}$, while Z_b is arbitrary. The output of the power divider is equal in amplitude. The phase of port 2 and port 3 is same and out-of-phase with port 4. The power divider shows 10-dB isolation performance between the three output ports [23]. In this paper, the two $\lambda/2$ length TLs are replaced by 0° TLs.

The 0° phase shift TL is realized by the CRLH and conventional microstrip TL. The CRLH TL provides the positive phase shift, and the latter provides the negative phase shift. Figure 2(a) shows the structure of the CRLH part. Figure 2(b) is the equivalent circuit of the CRLH TL. Interdigital capacitor provides the left-handed capacitor C_L.

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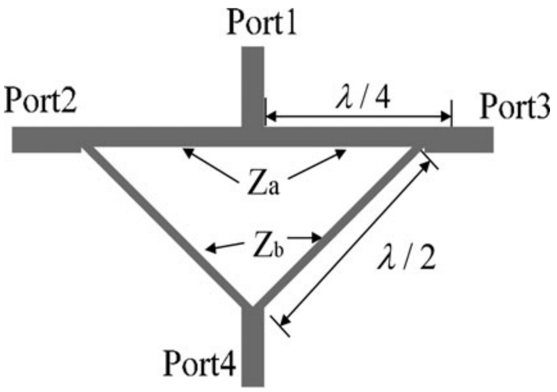


Fig. 1. The circuit of conventional Bagley Polygon power divider.

The short-ended stubs provide the left-handed inductors L_L. Based on the theory in [22], the phase response of the CRLH TL can be calculated by equation (1):

$$\varphi = \pm n \times \arccos[1 - (\omega^2 L_R C_R + 1/\omega^2 C_L L_L) + (C_R/C_L + L_R/L_L)], \tag{1}$$

where the "±" sign denotes that the phase shift is negative in the left-handed band and positive in the right-handed band, n is the number of the CRLH cells; ω is the angular frequency. In order to apply this structure into the circuit, the impedance must be equal to Z_b. The impedance of the CRLH TL can be calculated by equation (2):

$$Z_B = \frac{\pm\left(j\omega L_R + 1/j\omega C_L\right)}{\sqrt{\left[1 + \left(1/j\omega L_L + j\omega C_R\right)\left(1/j\omega C_L + j\omega L_R\right)\right]^2 - 1}}, \tag{2}$$

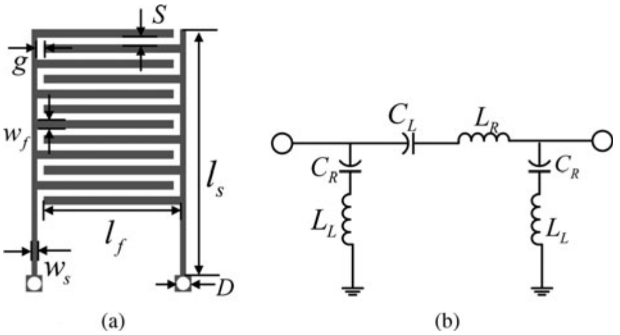
where Z_B indicates the Bloch impedance. Based on the CRLH TL theory, the balance condition is

$$L_R C_L = L_L C_R = 1/\omega_0^2, \tag{3}$$

where the ω_0 is the center angular frequency. Based on the balance condition, the equation (2) can be simplified to

$$\sqrt{L_L/C_L} = \sqrt{L_R/C_R} = Z_B. \tag{4}$$

The Z_B should be equal to Z_b. In reality, the phase response of the CRLH TL (φ) should be set bigger than 0. The CRLH structure should connect with other part of the power divider through the microstrip TL, which will introduce some negative phase shift. The structures of the miniaturized Bagley Polygon power divider and the 0° TL are shown in Fig. 3. The dimensions of CRLH TL in Fig. 3 are as same as in Fig. 2.



(a) (b)

Fig. 2. (a) The structure of the CRLH TL. (b) Equivalent circuit of the CRLH TL.

If the φ and C_L are given, the parameters C_R, L_L, and L_R can be calculated based on the equations (1), (3), and (4). The other part of the power divider is same as the conventional type as shown in Fig. 1. The C_L can be implemented based on the empirical equation [28]:

$$C_L \approx (\varepsilon_r + 1)l[(N - 3)A_1 + A_2]. \tag{5}$$

Here,

$$A_1 = 4.409\ \tanh\left[0.55\left(\frac{h}{\omega_f}\right)^{0.45}\right](pF/\mu\text{m}) \tag{6}$$

$$A_2 = 9.92\ \tanh\left[0.52\left(\frac{h}{\omega_f}\right)^{05}\right](pF/\mu\text{m}), \tag{7}$$

where, ε_r is the dielectric constant of the substrate; l, N, and ω_f denote the length (l_f), number, and width of the interdigital line, respectively; h is the height of the substrate.

III. EXPERIMENT AND RESULTS

For experimental demonstration, the proposed miniaturized Bagley Polygon power divider is designed and fabricated on substrate Taconic RF-35 with dielectric constant of 3.5, thickness of 0.508 mm, and loss tangent of 0.0018. The center frequency is 3.5 GHz. According to above design procedure, the initial dimensions of the proposed power divider can be obtained firstly. Then the HFSS (high frequency structural simulator, a commercial finite element method solver for electromagnetic structures from Ansys) is utilized to simulate and optimize. After optimization, the final sizes of the power divider are: $L_1 = 16.9$ mm, $L_2 = 4$ mm, $L_3 = 3.4$ mm, $W_1 = 0.87$ mm, $W_2 = 0.6$ mm, $l_s = 5.4$ mm, $w_s = 0.2$ mm, $g = 0.15$ mm, $S =$

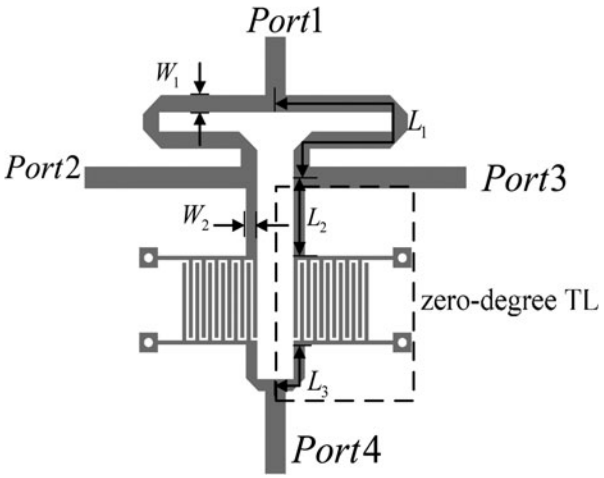


Fig. 3. Circuit layout of the miniaturized Bagley Polygon power divider.

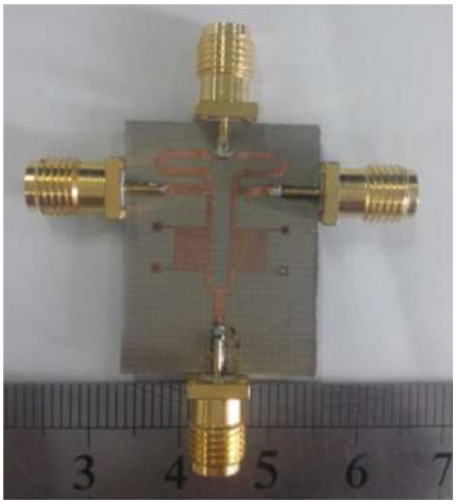


Fig. 4. Photograph of the fabricated Bagley Polygon power divider.

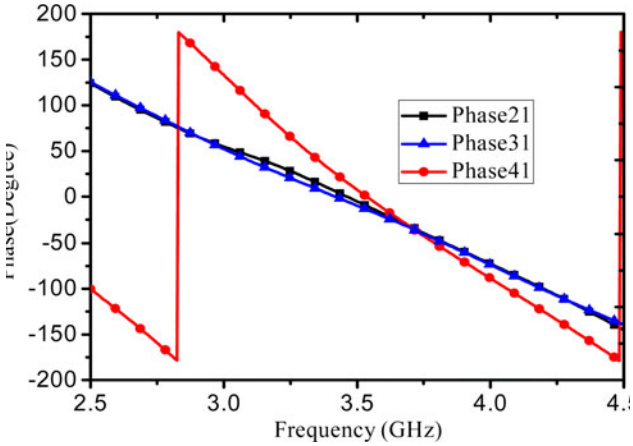


Fig. 6. Measured phase response of the miniaturized Bagley Polygon power divider.

0.15 mm, $l_f = 4$ mm, $w_f = 0.2$ mm, $D = 0.5$ mm. The $\lambda/4$ sections are bended to further reduce the total size. The fabricated Bagley Polygon power divider is shown in Fig. 4.

The simulated and measured results of the fabricated Bagley Polygon power divider are shown in Fig. 5. It can be seen that the measured results show a reasonable agreement with the simulated ones. The input return loss is >15 dB in the center frequency. The maximum insertion loss between the three output ports is 4.89 dB (4.77 + 0.12 dB). Figure 5(a) shows the good amplitude imbalance at the center frequency. Figure 5(b) shows that the S_{23}, S_{24}, and S_{34} are 10.12, 9.27, and 10.14 dB, respectively, which demonstrates that the miniaturization does not deteriorate the isolation performance of this type of power divider. In this design, the 0° phase shift TL is utilized to replace the 180° TL. Based on the TL theory, the output ports should be in-phase instead of out-of-phase. Figure 6 demonstrates the success of the design method, although there is some imbalance between the three output ports. As for imbalance at 3.5 GHz between the fourth and the other output ports, some measurement error may cause it and make the in-phase frequency deviate from the 3.5 GHz. To the point, it has no effect on the performance of the power divider.

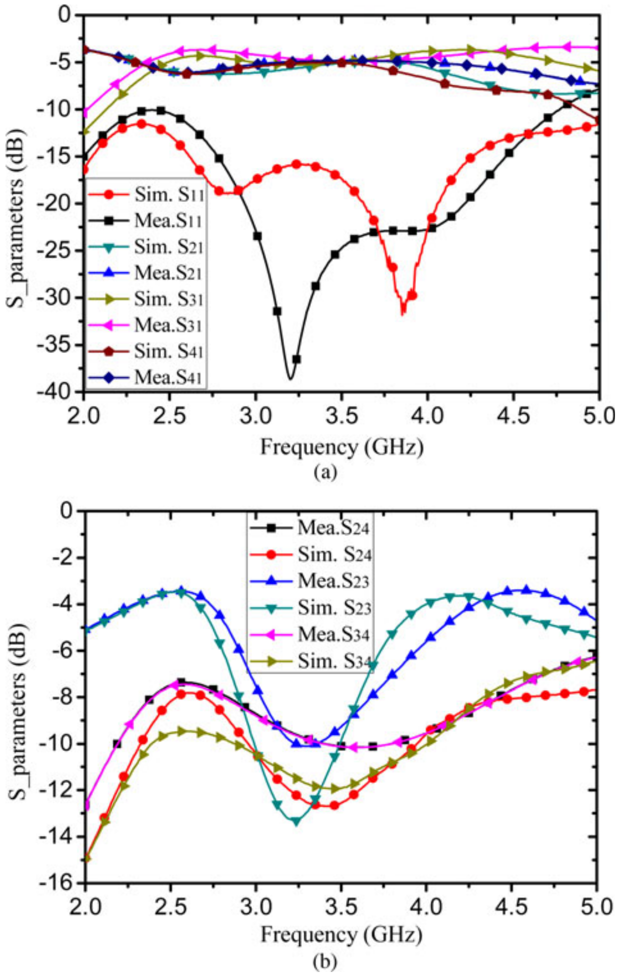


Fig. 5. Simulated and measured results of the fabricated power divider. (a) Insertion loss and return loss; (b) isolation.

In addition, the number of the output ports can be added by simply inserting the 0° phase shift TL between the two arbitrarily adjacent output ports without other calculation or extra analysis. It also avoids the limitation of the realizable impedance during the fabrication. Table 1 compares the performance of the proposed design and other miniaturized Bagley Polygon power dividers reported in recent years. It demonstrates that the proposed power divider has realized the significant size reduction and maintained its isolation performance. Although the size of the proposed power divider is larger than that in [27], our work features easier assembly and isolation maintained.

Table 1. Comparison with some prior miniaturized Bagley polygon power divider.

Ref.	f (GHz)	Size*	IL (dB)	Isolation	Technology
[25]	1	30%	0.5	No	High-impedance TLs
[26]	1.62	50%	1	No	DGS
[27]	2	23%	≈0.3	No	Dual TLs
This work	3.5	37%	0.12	>8 dB	CRLH TLs

*The ratio of the size of proposed power divider and the size of the conventional Bagley Polygon PD ($\lambda g/2^*\lambda_g/4$); IL, insertion loss.

IV. CONCLUSION

In this paper, a miniaturized Bagley Polygon power divider by using the CRLH TLs has been proposed. The working mechanism about the power divider and the function about the CRLH TLs have been presented and analyzed. The design equations have been presented. The major advantages of the proposed Bagley Polygon power divider are its compact size, the preservation of its intrinsic isolation performance, and the simple design method. Good agreement between the simulated and measured results has been observed.

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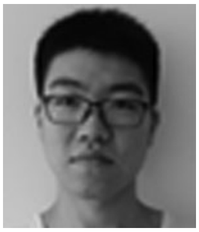

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