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MODIFIED BROADBAND SCHIFFMAN PHASE SHIFTER USING DENTATE MICROSTRIP AND PATTERNED GROUND PLANE

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Abstract—In this letter, a modified broadband 90° phase shifter is proposed. By using a dentate microstrip and a patterned ground plane, an extremely tight coupling can be obtained, and consequently a constant phase shift over a wide bandwidth can be achieved. To verify the proposed idea, a topology is implemented, the measured results of a phase difference of $90 \pm 5°$ in 79.5% bandwidth, better than 10 dB return loss across the whole operating band, are also given. The measurement results agree well with the full-wave electromagnetic simulated responses.

1. INTRODUCTION

Phase shifters are fundamental components extensively used in microwave and millimeter-wave circuits, such as phase-array antenna systems and phase modulation communication systems [1–11]. The original Schiffman phase shifter is the most attractive one of all the phase shifters. It consists of a transmission lines and a coupled section and has a bandwidth of about 80% with a phase ripple of 10 degrees [1]. In order to broaden the bandwidth with an acceptable phase ripple, some phase shifters have been developed [2–5] based on the Schiffman differential phase shifter, like using a multisection coupling line and a transmission line [2, 3], and two coupled lines [4]. However, the broad bandwidth may need an extremely tight coupling, thus resulting in very narrow coupling gaps, which is difficult to implement. Recently, an improved broadband Schiffman phase shifter with patterned ground plane underneath the coupled line has been

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proposed [6]. The manufacturing problem can be alleviated somewhat, however, it only has a 70% bandwidth with a phase ripple of 5 degrees. Abbosh recently proposed a method to realize ultra wide band (UWB) phase shifters by using broadside coupling structures [7]. Although it has high performance and compact size, the multilayer technology is difficult to be fabricated and it can only provide a phase shift range from 25° to 48°.

In this letter, a 90° phase shifter employing a modified ground plane and a dentate microstrip for broadband operations is presented. By properly arranging the ground pattern and the size of the dentate microstrip, a bandwidth of around 80% with a phase ripple of 5 degrees could be achieved, which is much wider than the 70% provided by the phase shifter proposed in [6]. Details of the phase shifter design and both the theoretical and experimental results are given and discussed.

2. PHASE SHIFTER DESIGN

Figure 1 shows a standard Schiffman phase shifter structure. From equations mentioned in [12], the phase shift $\Delta\varphi$ is obtained by (1)

$$\Delta\varphi = K\theta - \cos^{-1}\left(\frac{\rho - \tan^2\theta}{\rho + \tan^2\theta}\right) \tag{1}$$

where θ is the electrical length of the coupled section and ρ is its impedance ratio defined as

$$\rho = \frac{Z_{0e}}{Z_{0o}} \tag{2}$$

Z_{0e} and Z_{0o} are the even and odd mode impedances of the coupled lines respectively. For a 90° Schiffman phase shifter, substitute $\theta_0 = \Delta\varphi_0 = 90°$ in (1), we get $K = 3$. And for a phase deviation $\varepsilon = \pm 5°$, by using (3), $\Delta\varphi_{\max} = 95°$ and $\Delta\varphi_{\min} = 85°$ can be obtained, respectively.

$$\varepsilon = \Delta\varphi_{\max} - \Delta\varphi_0 = \Delta\varphi_0 - \Delta\varphi_{\min} \tag{3}$$

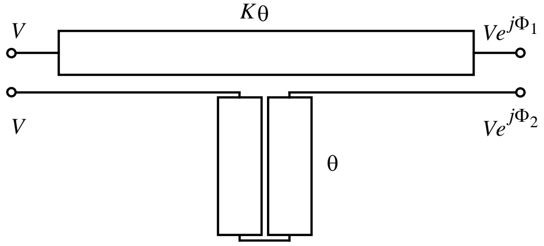

Figure 1. Structure of a standard Schiffman phase shifter.

Consequently, the impedance ratio $\rho = 3.023$ can be achieved by (4).

$$\Delta\varphi_{\max} = K \tan^{-1}\sqrt{\frac{K\rho - 2\sqrt{\rho}}{2\sqrt{\rho} - K}} - \cos^{-1}\left(\frac{\rho + 1 - K\sqrt{\rho}}{\rho - 1}\right) \quad (4)$$

Accordingly, the even and odd mode impedances of the coupled lines could be determined as $Z_{0e} = 50 \times \sqrt{\rho} = 86.93\,\Omega$ and $Z_{0o} = 50/\sqrt{\rho} = 28.76\,\Omega$. And the coupling factor of the coupled line section $C = -20\log_{10}\frac{\rho-1}{\rho+1} = 5.97\,\text{dB}$. For achieving such even and odd mode impedances, the width of the coupled lines and the space gap between coupled lines could be determined as 1.69 mm and 0.01 mm on a substrate with a relative dielectric constant of 2.65, thickness of 1 mm and loss tangent of 0.003. In fact, the coupled microstrip line with 0.01 mm gap is difficult to fabricate because of the manufacture limits.

In order to avoid the difficult fabrication, set the coupled microstrip line with 0.2 mm in gap and 10 mm in width, then the even and odd mode impedances of the coupled microstrip line can be determined as $Z_{0e} = 19.914\,\Omega$ and $Z_{0o} = 15.665\,\Omega$. However, these two low impedances cannot meet the demand. Nevertheless, the use of patterned ground plane can increase the even mode impedance while decrease the odd mode impedance [6], which makes it possible to realize

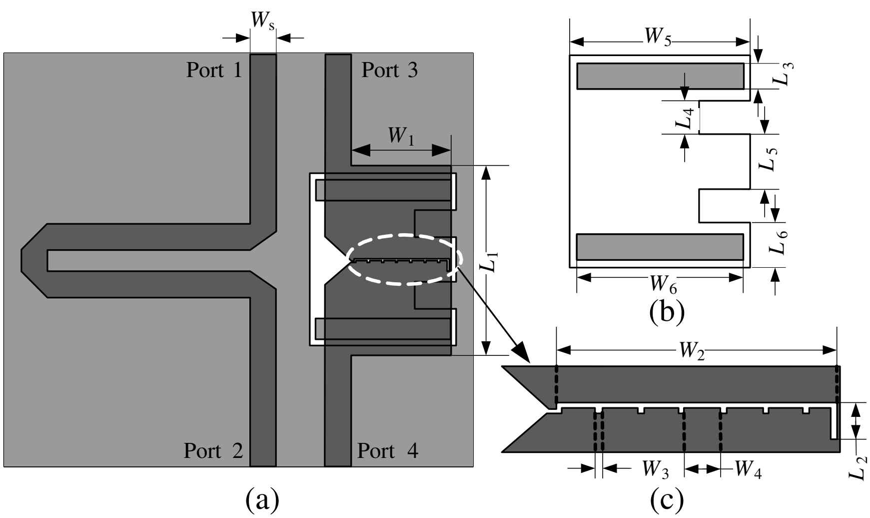

Figure 2. Configuration of the proposed modified broadband 90° Schiffman phase shifter.

the coupled microstrip line with a realizable gap and satisfy the even and odd mode impedances.

Configuration of the proposed phase shifter is presented in Fig. 2. Fig. 2(b) shows the simple details of the patterned ground plane with marked variables. Moreover, a dentate microstrip is used here to obtain a further tight couple between the two branches of the coupled lines, with the details are shown in Fig. 2(c). Since W_3, L_2 and L_4 are clearly the limiting factors to be considered for the implementation, a series of parametric studies were also carried out to achieve desired phase shifter performance.

For the phase difference is the more concerned factor, Figs. 3–5 illustrate the simulated phase differences for diverse values of W_3, L_2 and L_4 only. Fig. 3 plots the simulated phase differences with various dentate widths $W_3 = 0.2$, 0.6, and 0.85 mm. It should be noted that the microstrip became a beeline for the 0.85 mm case. The length L_2 case (varies from 1.1 mm to 1.5 mm with an interval 0.2 mm) presented in Fig. 4 shows that the phase difference increases as L_2 increases. In order to obtain a desired 90° phase difference with wider operating bandwidth, we chose 0.2 mm for W_3 and 1.3 mm for L_2 finally. Fig. 5 displays the phase difference of the proposed modified broadband 90° Schiffman phase shifter patterned ground plane. From the parameter analysis above, it can be found that the tuning of dimensions of the dentate microstrip and the patterned ground plane can wider the operating bandwidth with a 90° phase difference.

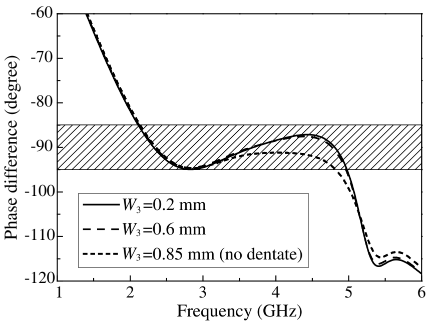

Figure 3. Simulated phase responses for different values of W_3 (other dimensions are the same as given in Fig. 2).

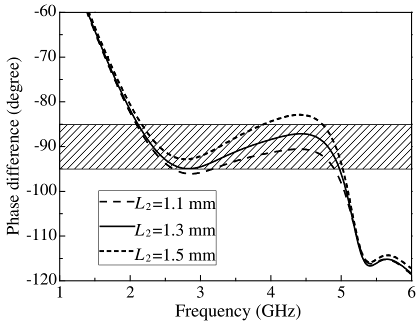

Figure 4. Simulated phase responses for different values of L_2 (other dimensions are the same as given in Fig. 2).

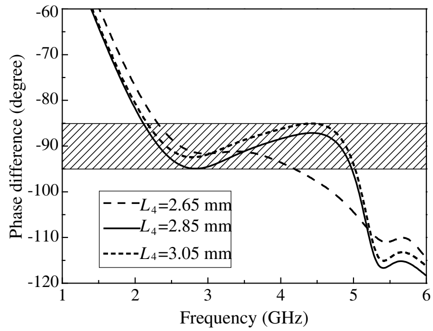

Figure 5. Simulated phase responses for different values of L_4 (other dimensions are the same as given in Fig. 2).

3. EXPERIMENTAL RESULTS

The optimum performance of the proposed phase shifter is achieved by the parametric studies carried out by Zeland IE3D software, and the final dimensions are as follows: $L_1 = 20\,\text{mm}$, $L_2 = 1.3\,\text{mm}$, $L_3 = 2.1\,\text{mm}$, $L_4 = 2.85\,\text{mm}$, $L_5 = 4.7\,\text{mm}$, $L_6 = 3.8\,\text{mm}$, $W_1 = 10.6\,\text{mm}$, $W_2 = 10\,\text{mm}$, $W_3 = 0.2\,\text{mm}$, $W_4 = 1.3\,\text{mm}$, $W_5 = 15.35\,\text{mm}$, $W_6 = 14.25\,\text{mm}$ and $W_s = 2.73\,\text{mm}$.

With the optimal parameters, the prototype of the proposed modified broadband 90° Schiffman phase shifter was constructed and measured with the photograph presented in Fig. 6. The phase shifter was fabricated on a 1 mm-thick substrate, which has a relative permittivity of 2.65 and whole dimensions of 48 mm × 42 mm. The measurement is carried out with a WILTRON 37269A vector network analyzer after manufactured. Measured and simulated S-parameter amplitude and phase difference of the proposed modified broadband 90° Schiffman phase shifter are displayed in Figs. 7–8, respectively. It can be distinctly found that the simulated and measured results are in basic agreement. The deviation between them may be caused by the nonuniformity of the relative permittivity of the substrate, also the SMA connectors and the manufacture limits somewhat result in the differences, which were not included in the simulation at all. As seen in Fig. 7, over the whole 2.18 to 5.05 GHz impedance matching band, the measured return loss is better than 10 dB, and the insertion loss is less than 1.5 dB. Additionally, the measured phase difference between the two branches is $90° \pm 5°$ from 2.18 to 5.05 GHz covering around 80% relative bandwidth, which can be observed from Fig. 8. It is much wider than the 70% achieved in [6].

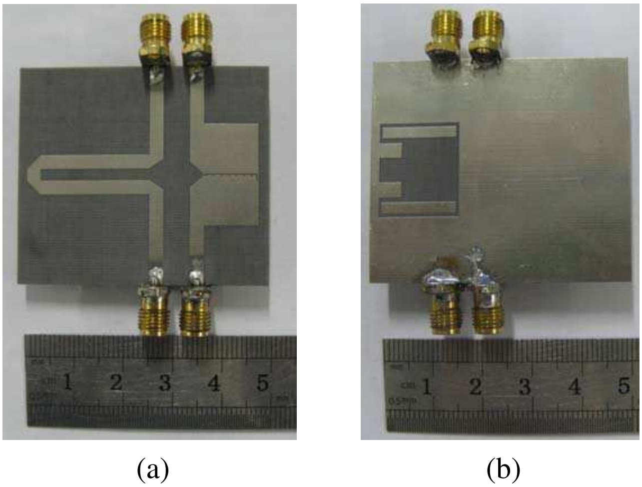

Figure 6. Photograph of the proposed modified broadband 90° Schiffman phase shifter. (a) Top view. (b) Bottom view.

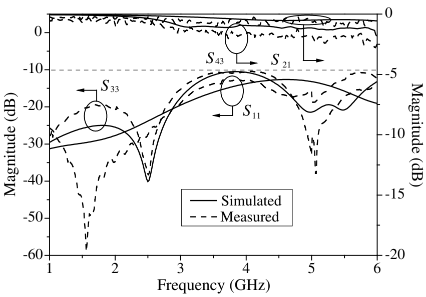

Figure 7. Simulated and measured amplitude responses of the proposed modified broadband 90° Schiffman phase shifter.

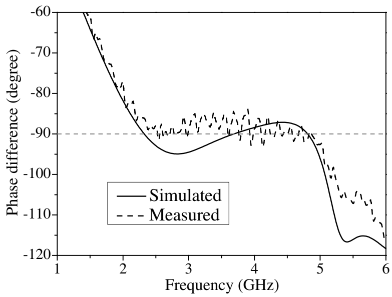

Figure 8. Simulated and measured phase responses of the proposed modified broadband 90° Schiffman phase shifter.

The proposed phase shifter is compared with shifters in [5–9], their respective performances are tabulated in Table 1. The normalized circuit size (NCS) is given by:

$$\text{NCS} = \frac{\text{physical size (width} \times \text{length)}}{\lambda_g \times \lambda_g}$$

where λ_g is the guided wavelength at the designed center frequency. As can be observed seen from the table, the proposed shifter exhibits a much broad operating band with the smallest size among the quoted phase shifter.

Table 1. Comparison with other designs.

Ref.	Implementation methods	Phase responses		NCS
		FBW	phase difference	
[5]	common ground-plane incorporates a slot-line terminated with two rectangular slots	114%	$22.5° \pm 2.5°$	1.1×0.6
[6]	Schiffman phase shifter with DGS	70%	$90° \pm 5°$	not given
[7]	common ground-plane incorporates a elliptical slot terminated with two elliptical microstrip patches	109%	30°45°	1.1×0.9
[8]	shifter using microstrip -CPW-microstrip transition	103%	180°	not given
[9]	shifter consists of four bits realized as periodically loaded-line and two bits based on novel switched-line with loaded-line	1.3%	$5.625° \pm 3.4°$, $22.5° \pm 3.4°$, $45° \pm 3.4°$, $11.25° \pm 3.4°$, $90° \pm 3.4°$, $180° \pm 3.4°$	not given
This work	Modified Schiffman shifter using a dentate microstrip and a patterned ground plane	80%	$90° \pm 5°$	0.35×0.3

4. CONCLUSION

In this letter, a 90° phase shifter utilizing a dentate microstrip and a patterned ground plane for broadband applications has been designed and successfully implemented, with experimental and numerical results. By using the dentate microstrip and patterned ground, a much tight coupling can be obtained, and consequently a constant phase shift over 2.18 GHz–5.05 GHz (79.5% bandwidth with a phase ripple of 5 degrees) can be achieved, which is much wider than the 70% realized in [6]. Good agreement between the measured and simulated results is obtained. The measured results have also presented that the designed phase shifter has less than 1.5 dB insertion loss, and better than 10 dB return loss across the operating band.

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