UWB 90° phase shifter based on broadside coupler and T-shaped stub

Jun Wang, Zhongxiang Shen✉ and Lei Zhao

An UWB 90° phase shifter based on broadside coupler and T-shaped stub is proposed. Its operation mechanism is explained by the equivalent circuit. The measured results exhibit that the bandwidth is 126.7% with phase deviation within ±6°, and the insertion loss is <1.8 dB over the frequency band from 2.2 to 9.8 GHz. Comparison shows that the proposed design not only achieves the widest bandwidth, but also has low insertion loss and small phase difference. This design is a good candidate for UWB applications due to its low cost, planar structure, and convenient installation.

Introduction: Broadband phase shifters are extensively used in many wideband phased-array antennas and microwave control modules systems. Several structures were employed to achieve 90° phase shifters such as Schiffman [1], lumped-elements [2], and other planar structures [3–7]. However, there exist some disadvantages for practical applications. Schiffman structures have limited bandwidth and are not suitable for wideband applications. The coupled-line configurations with lumped-elements [2] can improve the bandwidth effectively. However, such designs maybe unsuitable for high-frequency applications and cannot be easily integrated with other circuits due to their parasitic effects, high cost, and inconvenient installation. In contrast, planar structures including loaded transmission lines [3–5] and broadside-coupled-lines [6, 7] are easy to fabricate with low cost. However, their bandwidths are still not sufficient to meet the rapid growing requirements of UWB applications.

In this Letter, an UWB 90° phase shifter with the bandwidth of 126.7% is proposed, which consists of two parts: phase shifting line and 'L' shaped reference line. Different from the edge-coupled structure [1], the elliptical broadside coupler is a good candidate for wideband applications because of its potentials for achieving an almost constant coupling factor over the desired UWB range [6]. The proposed phase shifting line contains two elliptical broadside couplers in parallel, which are combined by T-shaped stubs. For further bandwidth enhancement, an improved quasi-rectangular slotted ground is employed for decreasing the loaded quality factor Q. Additionally, to gain an insight into the proposed design, an equivalent circuit model and mathematical descriptions of the proposed phase shifter are given. Measured results demonstrate that the widest bandwidth of 126.7% with phase deviation within ±6° and insertion loss below 1.8 dB can be obtained from 2.2 to 9.8 GHz.

Phase shifter design and analysis: The configuration of our proposed UWB 90° phase shifter is shown in Fig. 1. Two opposite T-shaped stubs are printed on the top and bottom substrates. Each of them connects to double broadside elliptical coupled patches loaded with open-ended stubs which are used for phase difference handling. Moreover, an improved quasi-rectangular slot is etched on the ground plane as the middle layer between two substrates. To obtain a certain phase difference, a comparison is made with a reference transmission line of 50 Ω locating on the top substrate. A slotted ground between the top and bottom coupling layers is formed for realising coupling between the elliptical patches on the top and bottom layers, and the coupling factor can be accurately controlled by the shape and dimension of the elliptical patch and quasi-rectangular slot. The typical physical length of the elliptical coupled structure should be a quarter effective wavelength at the centre frequency.

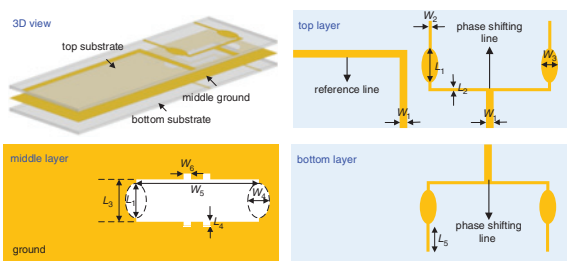

Fig. 1 *Structure of proposed phase shifter*

The simplified model and corresponding equivalent circuit of the proposed design are given in Figs. 2*a* and *b*, respectively. Owing to the almost stable coupling performance, the coupling factor C_f is assumed for the elliptical patches with the electrical length of θ_c at the centre frequency. The characteristic impedance of part 1 is $Z_1 = \sqrt{Z_{1e}Z_{1o}}$, where Z_{1e} and Z_{1o} are even- and odd-mode characteristic impedances of part 2, respectively. Applying these assumptions and even–odd-mode analysis, the reflection and transmission coefficients of part 2 can be expressed as [6]

$$S_{11} = \Gamma \frac{1 - C_f^2[1 + \sin^2(\theta_c)]}{\left[\sqrt{1 - C_f^2}\cos(\theta_c) + j\sin(\theta_c)\right]^2} \quad (1)$$

$$S_{21} = \Gamma \frac{j2C_f\sqrt{1 - C_f^2}\sin(\theta_c)}{\left[\sqrt{1 - C_f^2}\cos(\theta_c) + j\sin(\theta_c)\right]^2} \quad (2)$$

$$\Gamma = \frac{jZ_s\cot(\theta_s) + Z_{cl}}{jZ_s\cot(\theta_s) - Z_{cl}} \quad (3)$$

where Z_s and θ_s are the characteristic impedance and electrical length of the open-ended stub in part 2, respectively. Z_{cl} is the characteristic impedance of the coupled line in part 2, which is dependent on the required coupling factor. According to the equivalent circuit, conversions between two-port network parameters and ***ABCD*** matrices of the T-shaped stub can be realised. Then, using cascaded and parallel connections, we can obtain the ***ABCD*** matrix of the entire equivalent circuit. Thereby, reflection (S'_{11}) and transmission (S'_{21}) coefficients of the proposed phase shifter can be derived. The phase difference between the phase shifting line and the reference line is $\Delta\phi = \phi_1 - \phi_2$. Here, ϕ_1 is the output phase for the phase shifting line, which can be obtained from S'_{21}, and ϕ_2 denotes the output phase of the reference line.

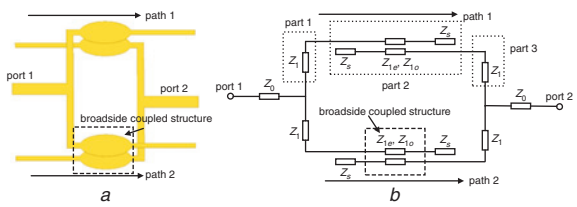

Fig. 2 *Schematic diagram of proposed phase shifter*

a Simplified model of phase shifter
b Equivalent circuit of phase shifter

To make a further understanding on the proposed structure, we carry out a parametric study on the coupling factor C_f and electrical length θ_c of the elliptical patch. The results show that C_f and θ_c should be 0.78 and 90°, respectively, for achieving the following design requirements: the operating frequency is from 2.2 to 9.8 GHz, insertion loss is <1.8 dB, return loss is more than 10 dB, and the phase difference is 90° with a deviation within ±6°.

According to the above analysis on C_f and a comprehensive consideration on the return loss and phase information, we can determine Z_{1e} and Z_{1o} from the relationship of $C_f = (Z_{1e} - Z_{1o})/(Z_{1e} + Z_{1o})$. In physical, Z_{1e} and Z_{1o} can be controlled by the dimensions of elliptical coupled patches and the improved quasi-rectangular slot in the ground plane [8].

Results and discussion: A prototype of the proposed broadband 90° phase shifter is fabricated on Rogers RO3003 with a permittivity of 3, thickness of 0.76 mm, and tan $\delta = 0.001$. Fig. 3 illustrates the photograph of the fabricated phase shifter. Physical dimensions of the proposed phase shifter are as follows: $W_1 = 2$ mm, $W_2 = 0.2$ mm, $W_3 = 3.9$ mm, $W_4 = 6.9$ mm, $W_5 = 19.2$ mm, $W_6 = 1$ mm, $L_1 = 7.6$ mm, $L_2 = 1$ mm, $L_3 = 10$ mm, $L_4 = 0.7$ mm, and $L_5 = 9.4$ mm.

Fig. 3 *Photograph of fabricated 90° phase shifter*

To validate the presented design concept and corresponding structure, the reflection and transmission coefficients and phase difference of the

designed phase shifter are measured and plotted in Figs. 4*a* and *b*, respectively. Good agreements can be observed between simulated and measured results. It is seen in Fig. 4*a* that the frequency range for return loss better than 10 dB and insertion loss lower than 1.8 dB is from 2.2 to 9.8 GHz, representing a fractional bandwidth (FBW) of 126.7% at the centre frequency of 6 GHz. Moreover, the measured and simulated phase difference of the designed 90° phase shifter is shown in Fig. 4*b*. It is clear that the phase shifter presents a phase deviation of <±6° over the same operating frequency band. A performance comparison of our proposed design with existing 90° phase shifters is listed in Table 1. It is clear that our proposed planar phase shifter has the widest FBW of 126.7%. In addition, the phase deviation and insertion loss are also quite good and suitable for many wideband microwave applications.

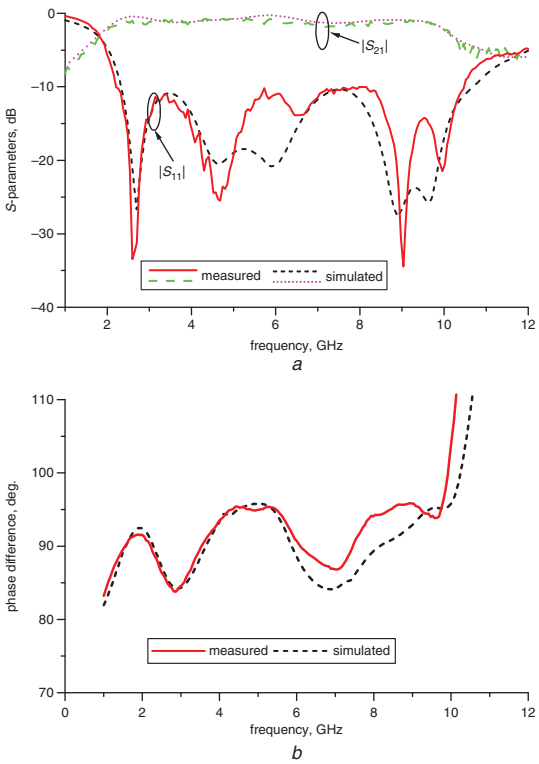

Fig. 4 *Measured and simulated scattering parameters and phase difference of our proposed 90° phase shifter*

a Scattering parameters
b Phase difference

Table 1: Performance comparison of various 90° phase shifters

Reference	Frequency (GHz)	Phase deviation (deg)	Insertion loss (dB)	FBW (%)
[3]	3.1–10.6	±9.02	0.96	109
[4]	2.3–5.5	±6.4	0.6	82.1
[5]	2.5–7.5	±8	2.3	100
[6]	3.1–10.6	±7	1.4	109
[7]	2.3–5.43	±2.54	0.8	81
This work	2.2–9.8	±6	1.8	126.7

Conclusion: In this Letter, an UWB 90° phase shifter has been presented. The proposed configuration consists of two broadside elliptical couplers combined by T-shaped stubs, with an improved quasi-rectangular slot in the middle ground plane for bandwidth enhancement. The performance of the structure has been interpreted by an equivalent circuit model. Measured results are in good agreement with simulated ones. It has been demonstrated that its return loss is better than 10 dB and insertion loss is <1.8 dB from 2.2 to 9.8 GHz. The corresponding FBW is 126.7% with phase deviation within ±6°.

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One or more of the Figures in this Letter are available in colour online.

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