

A Compact Phase Shifter with Wide Phase Range Using Loaded Transmission Line

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Abstract—This paper presents a 90° broadband compact phase shifter which employs loaded $\lambda/2$ transmission line. By adding an H-shaped open stub loaded transmission line, the bandwidth of the phase shifter is broadened. Detailed theoretical analysis and circuit configuration are presented to explain the mechanism. The proposed phase shifter is fabricated and measured to validate the design principle. The simulated and measured results show that the proposed phase shifter achieves 6.6 to 19.4 GHz bandwidth with low phase instability $\pm 5^\circ$, very low insertion loss (0.3 dB in 7.5–15.2 GHz), high return loss (10 dB), and a compact size ($12.8 \text{ mm} \times 22 \text{ mm}$). Good agreements are observed between the measured and simulated results with small phase deviation. Moreover, the configuration of the proposed phase shifter is simple in both design and fabrication which makes the design suitable for actual applications.

1. INTRODUCTION

Phase shifter is a two-port device used to produce a fixed or adjustable time delay in a transmitting (or reflecting) signal. It plays an important role in microwave beam formers found in phase-array antenna systems, phase modulation communication systems, and emerging intelligent antenna systems for broadband wireless mobile communications [1, 2]. With the increasing application of phase shifters, various structures have been designed [3–6]. In order to achieve a broad bandwidth, an extremely tight coupling is required, thus resulting in narrow microstrip lines and very narrow coupling gaps. In [7], a phase shifter using stub structure is designed. To reduce phase error, a phase correcting structure which shows small phase error of 2.54° with 82% frequency bandwidths (FBW) is proposed in [8].

As the pin counts increase in integrated circuits and the bandwidth requirement grows in wireless communication systems, the phase shifter with broadband operation may be more useful for the phased arrays [9, 10]. A wideband phase shifter is introduced by combining delay line and “equal length unequal width” techniques [11]. In [12], a new phase shifter consisting of several phase channels made by substrate integrated waveguide (SIW) resonators loaded with extra metallic posts is proposed. In [13], a multilayer broadside-coupled structure was utilized to build ultra-wideband (UWB) phase shifters with excellent performance. This multilayer phase shifter has recently been utilized to build UWB Butler matrix for a switched beam antenna array that operates across the range 3.1 to 10.6 GHz [14]. In [15], a 4-bit phase shifter with a maximum phase shift degree of 75° based on packaged metal-contact single-pole double-throw (SPDT) radio frequency microelectromechanical system (RF MEMS) is proposed. As can be seen from the literature surveyed, it is difficult to get all the characteristics, such as wideband, low phase instability, low insertion loss, high return loss, and compact size, in a single structure. Noting that an array antenna may require numerous phase shifters highlights the importance of developing phase shifters with small size and light weight that are also in low cost [16]. A complex structure is relatively difficult to fabricate.

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In this letter, a broadband compact phase shifter using a loaded transmission line is proposed. By adding an H-shaped open stub loaded transmission line, the bandwidth of the phase shifter is greatly improved. Compared with a conventional coupled line phase shifter, the design shows good performance with simplicity in both design and fabrication. Detailed geometry configuration and experimental results of the proposed phase shifter are demonstrated in the following parts. The paper is divided in four parts. In Section 2, we discuss the design and mechanism of the proposed phase shifter. Then, the fabrication and measurement results are presented in Section 3. At last, the work is concluded in Section 4.

2. STRUCTURE DESIGN AND ANALYSIS

2.1. Design and Simulation of the Proposed Phase Shifter

The configuration of the proposed phase shifter is shown in Figure 1. We can see that two pairs of open-circuit and short-circuit stubs are added at the head and tail of the phase shifter. The annulus is grounded, and the rectangle is open-circuit. By changing the width of transmission line W_2 , we can adjust the impedance matching, and the length of the stub L_3 can adjust the phase angle. So we can design the length of the stub L_3 according to the actual phase angle requirement. The proposed phase shifter is designed on an Arlon AD255A substrate with a thickness of 0.6 mm, relative permittivity of $\epsilon_r = 2.55$, and loss tangent of 0.0015. Obviously, the structure of the proposed phase shifter is remarkably simple which means low cost and is suitable for wide application.

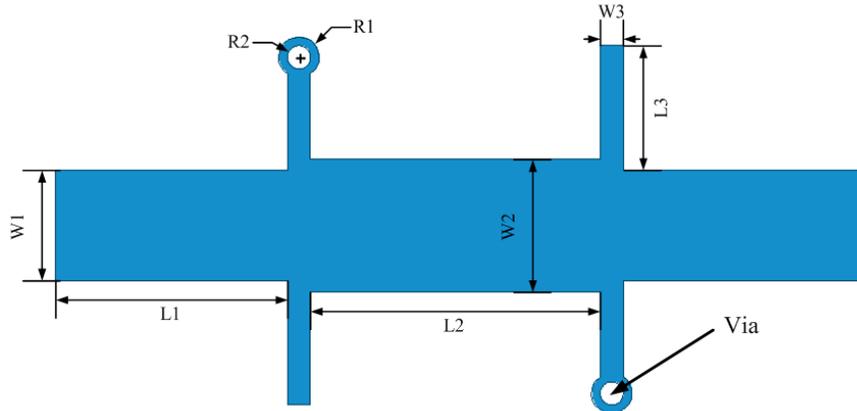


Figure 1. The structure of the proposed phase shifter.

Open-circuit and short-circuit stubs are added to broaden the bandwidth. To better show the performance of the stubs, the evolution process of the proposed phase shifter is given in Figure 2. Firstly, structure 1 is obtained by adding an open-circuit stub. It can be seen that $S_{11} \leq 10$ dB in 6–13 GHz with phase shifting. Then, one terminal of the open-circuit is connected to the ground to obtain structure 2. S_{11} and phase shift function are improved, and the insertion loss is decreased. The phase shifter can work at 8–14 GHz. Finally, by employing the open-circuit and short-circuit stubs, the designed phase shifter is proposed. As shown in Figure 2(b), the bandwidth is broadened. Figure 2(c) shows that the phase difference is decreased in high operating band which reaches the design requirement. As stated above, using the open-circuit and short-circuit stubs can greatly improve the bandwidth and performance.

For better understand the design structure, the circuit configuration of the proposed phase shifter using a loaded transmission line is shown in Figure 3. An open stub is loaded at the middle of a half-wavelength transmission line with characteristic impedance Z_m . Characteristic impedances of the input, output, and reference line are the same Z_0 , and for the stub it is Z_s . The microstrip line is assumed to be nondispersive, and hence, its characteristic impedance is assumed to be frequency independent. The numerical analysis and geometry refinement of the proposed antenna are performed by using ANSYS HFSS 13.0 simulation software.

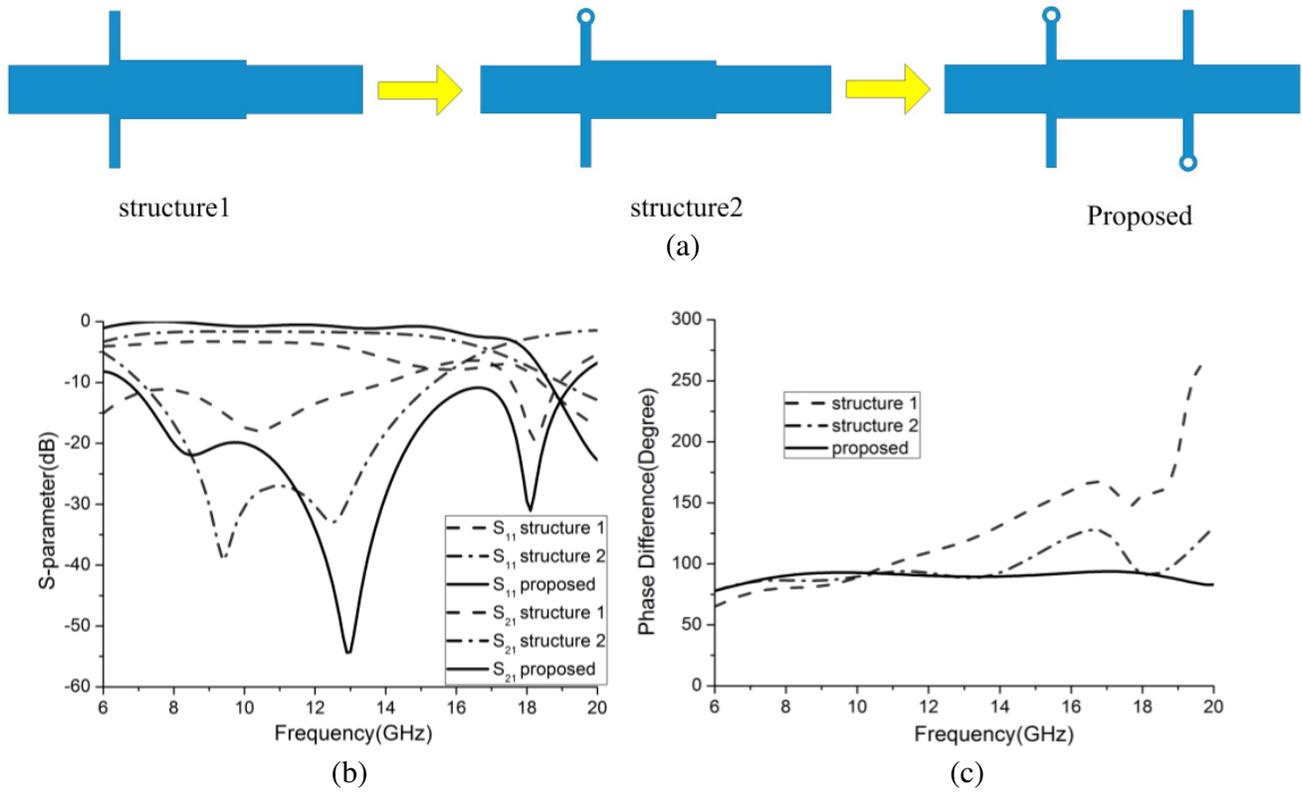


Figure 2. The evolution process of the proposed phase shifter, (a) the structures with different elements, (b) the simulated S -parameters of the three structure, (c) the simulated phase difference of different structures.

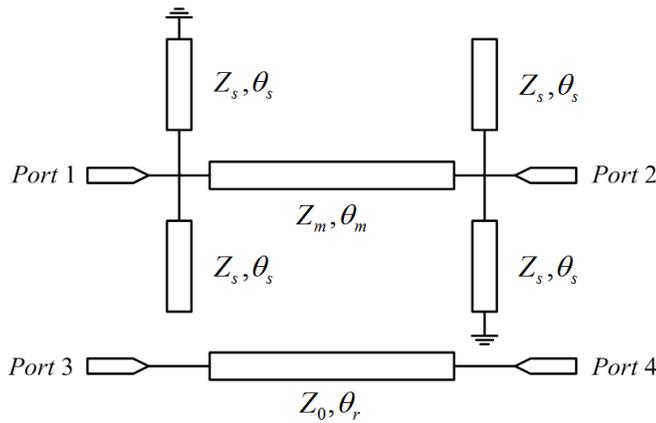


Figure 3. The circuit configuration of the proposed phase shifter.

2.2. Theoretical Analysis of the Phase Shifter

The phase shift of the proposed structure is the difference of the main line and reference line. Assume that the characteristic impedance and electrical angle of the main line are Z_m and θ_m , respectively, while those for the reference line are Z_r and θ_r . The characteristic admittance of the added open-circuit stub is jY . Then, the electrical length of the main line and the electrical angle of the reference line are:

$$\theta_m = \theta_{m0} \frac{f}{f_0} \quad \theta_r = \theta_{r0} \frac{f}{f_0} \quad (1)$$

Thus, the transmission matrix of the main line can be defined as:

$$\begin{aligned} & \begin{bmatrix} 1 & 0 \\ jY & 1 \end{bmatrix} \begin{bmatrix} \cos \theta_m & jZ_m \sin \theta_m \\ j\frac{1}{Z_m} \sin \theta_m & \cos \theta_m \end{bmatrix} \begin{bmatrix} 1 & 0 \\ jY & 1 \end{bmatrix} \\ = & \begin{bmatrix} \cos \theta_m - Z_m Y \sin \theta_m & jZ_m \sin \theta_m \\ 2jY \cos \theta_m + j\frac{1}{Z_m} \sin \theta_m - jY^2 Z_m \sin \theta_m & \cos \theta_m - Z_m Y \sin \theta_m \end{bmatrix} \end{aligned} \quad (2)$$

where

$$\begin{aligned} A &= D = \cos \theta_m - Z_m Y \sin \theta_m \\ B &= \cos \theta_m - Z_m Y \sin \theta_m \\ C &= 2jY \cos \theta_m + j\frac{1}{Z_m} \sin \theta_m - jY^2 Z_m \sin \theta_m \end{aligned} \quad (3)$$

$$S_{11} = S_{22} = \frac{A + \frac{B}{Z_m} - CZ_m - D}{A + \frac{B}{Z_m} + CZ_m + D} = \frac{\frac{B}{Z_m} - CZ_m}{2A\frac{B}{Z_m} + CZ_m} \quad (4)$$

$$S_{12} = S_{21} = \frac{2}{A + \frac{B}{Z_m} + CZ_m + D} = \frac{2}{2A + \frac{B}{Z_m} + CZ_m} \quad (5)$$

$$\Delta\phi = \theta_r - \tan^{-1} \left(\frac{\frac{B}{Z_m} + CZ_m}{2A} \right) \quad (6)$$

In order to ensure the accurate phase shift at the center frequency $\Delta\phi$ and good match, $S_{11} = 0$ and $S_{21} = 1$ are chosen. We plug Equation (3) into Equations (4), (5), and (6), respectively. $\theta_{m0} = \pi$ can be calculated. Assume that the characteristic impedance of the main line Z_m is equal to the port impedance, the electrical angle of the reference line can be calculated:

$$\theta_{r0} = \Delta\phi + \theta_{m0} = \Delta\phi + \pi \quad (7)$$

We plug Equation (3) into Equation (6), and $\Delta\phi$ can be defined as:

$$\Delta\phi = \theta_r - \tan^{-1} \left(\frac{2 \sin \theta_m + 2Z_m Y \cos \theta_m - Y^2 Z_m^2 \sin \theta_m}{2 \cos \theta_m - 2Z_m Y \sin \theta_m} \right) \quad (8)$$

We plug Equation (3) into Equation (4), and the return loss of the main line can be calculated:

$$S_{11} = \frac{jY^2 Z_m^2 \sin \theta_m - 2jY Z_m \cos \theta_m}{2 \cos \theta_m + 2j \sin \theta_m - 2Y Z_m \sin \theta_m + jY Z_m (2 \cos \theta_m - Y Z \sin \theta_m)} \quad (9)$$

Figure 4 shows the return loss and phase difference of the phase shifter for differential phase shifts of 60° , 75° , 90° , 105° , and 120° . This configuration provides a simple topology for the implementation of a broadband phase shifter. Some parameters have great influence on the performance of the proposed phase shifter, such as the width of transmission line W_2 , the length of stub L_3 , and the width of stub W_3 . Therefore, parametric studies have been carried out to investigate the effects. In the following discussion, we change one parameter with the other parameters unchanged. By this way, we can study the influence of different parameters and find approximate solution for choosing the optimized parameter.

The simulated phase difference against the frequency of the phase shifter with different values of W_2 is shown in Figure 5. We can see that by increasing the length of W_2 , the phase difference of the higher operating band especially the 10 GHz–19 GHz is decreased. So an appropriate value $W_2 = 2.3$ mm is chosen. As shown in Figure 6, the variation of L_3 has great influence on the phase difference. The phase difference is increased as L_3 increases. Meanwhile, the performance of the high frequency band

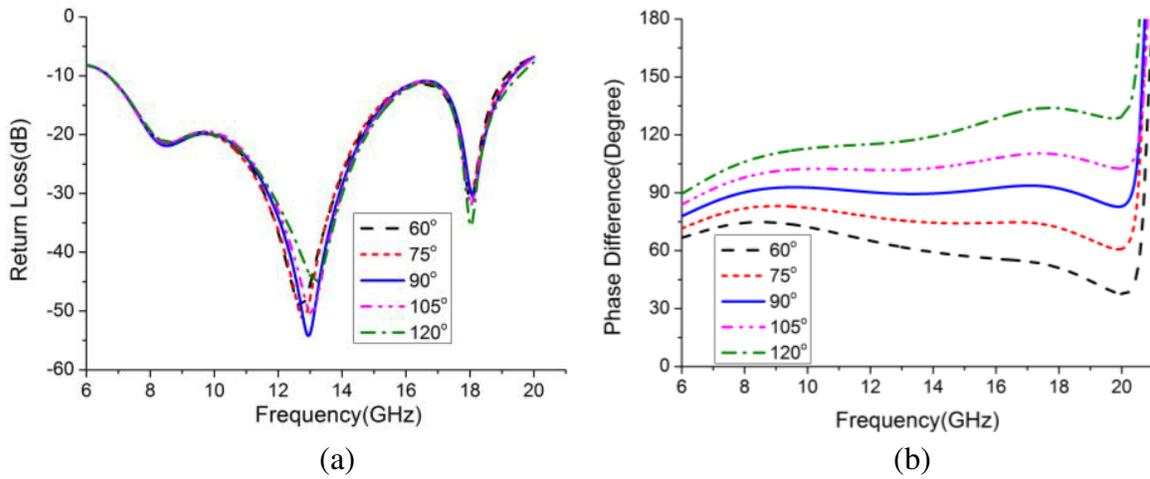


Figure 4. Theoretical responses of phase shifters using transmission line for different phase shifts.

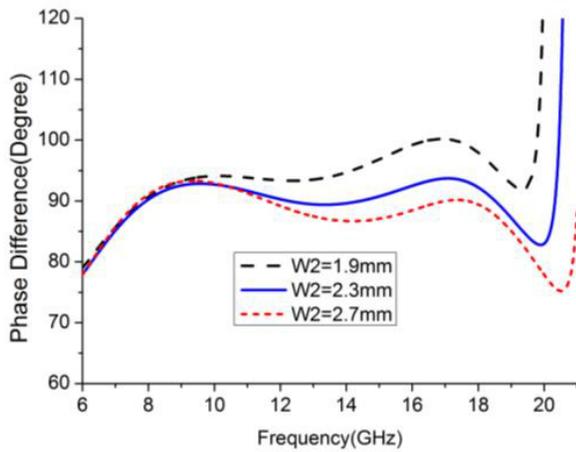


Figure 5. Simulated phase difference of different values of W_2 .

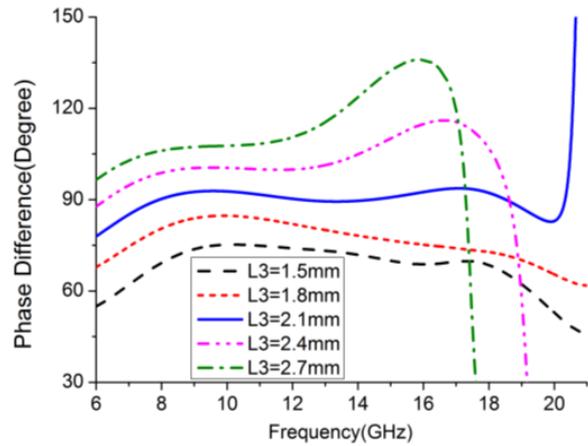


Figure 6. Simulated phase difference of different values of L_3 .

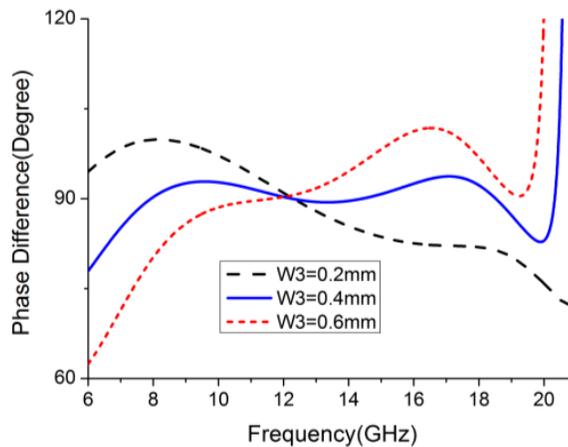


Figure 7. Simulated phase difference of different values of W_3 .

is affected. For balance, we choose $L_3 = 2.1$ mm. The influence of W_3 on the proposed phase shifter is shown in Figure 7. It can be observed that with the increase of W_3 , the low frequency band is decreased while the high band is increased. So we choose an appropriate value $W_3 = 0.4$ mm. By carefully adjusting the dimensions according to the laws above, the proposed phase shifter can exhibit good performance. The operating band of the phase shifter is 6.6 to 19.4 GHz which covers C-, X-, and Ku-bands. The final optimized dimensions are listed in Table 1.

Table 1. Parameters for the proposed absorber (unit: mm).

L_1	L_2	L_3	W_1	W_2	W_3	R_1	R_2
4	5	2.1	1.9	2.3	0.4	0.35	0.2

3. FABRICATION AND MEASUREMENT RESULTS

The proposed phase shifter is fabricated to validate the design. A photograph of the proposed phase shifter is shown in Figure 8. It can be seen that the proposed phase shifter is simple, and the phase shifter is fabricated on a $13.8 \text{ mm} \times 22 \text{ mm}$ Arlon AD255A substrate with a thickness of 0.6 mm, relative permittivity $\epsilon_r = 2.55$, and loss tangent of 0.0015. We use an AV3672B vector network analyzer (VNA) to measure the reflection coefficient in free space. The simulated and measured responses of the phase shifter are depicted in Figure 9. A good agreement between measurement and simulation can be found. The proposed phase shifter achieves 6.6 to 19.4 GHz bandwidth with low phase instability $\pm 5^\circ$, very

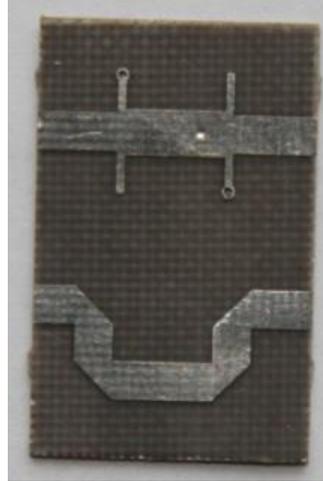


Figure 8. Photograph of the proposed phase shifter.

Table 2. A comparison of other high gain antenna.

Reference	Operating BW (GHz)	Phase instability	Thickness (mm)
[1]	2.3–5.5	$\pm 6.4^\circ$	0.508
[3]	4.2–7.385	$\pm 3^\circ$	3
[5]	9–18.1	$\pm 5^\circ$	0.787
[9]	4.7–6.5	$\pm 6^\circ$	0.813
[13]	3.1–10.6	$\pm 3^\circ$	0.508
This work	6.6–19.4	$\pm 5^\circ$	0.6

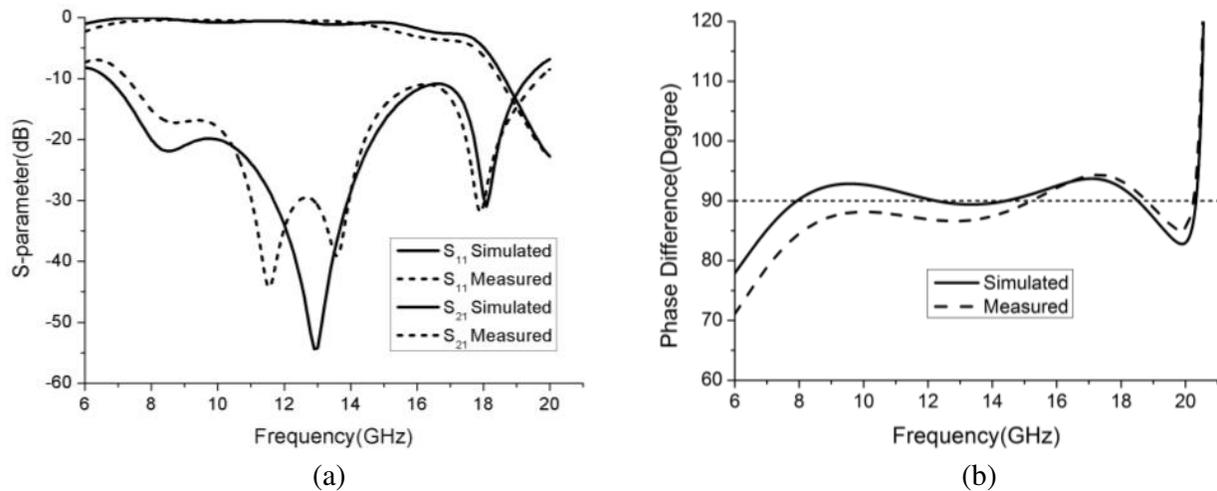


Figure 9. Simulated and measured amplitude and phase responses of the phase shifter using transmission line.

low insertion loss (0.3 dB in 7.5–15.2 GHz), high return loss (10 dB), especially in 7.5–15.2 GHz. The phase instability is low with $\pm 2.5^\circ$ and has low insertion loss with 0.3 dB and high return loss with 15 dB. Good agreement between the simulated and measured results can be observed. The discrepancy between them can be mostly attributed to the tolerance in the manufacturing process. In order to show a better performance of the proposed phase shifter, a comparison of various phase shifter designs is carried out in Table 2. We can see that a broadband phase shifter is obtained. Compared with phase shifters designed in [1, 5, 13], the bandwidth of the proposed structure is greatly broadened. Compared with [3, 9], the proposed structure has low profile.

4. CONCLUSION

A broadband phase shifter for C-, X-, and Ku-band applications is proposed in this letter. Two pairs of open-circuit and short-circuit stubs are added at the head and tail of the phase shifter to broaden the bandwidth. The results show that the proposed phase shifter achieves 6.6 to 19.4 GHz bandwidth with low phase instability, very low insertion loss (0.3 dB in 7.5–15.2 GHz), high return loss (10 dB), and a compact size (13.8 mm \times 22 mm). For better understanding the design processes, the contribution of individual element is studied, and the circuit configuration is given. Various design parameters have also been optimized for selecting the suitable band of operation and desired application. The simulated and measured results demonstrate that the proposed structure is feasible for actual use. Moreover, the proposed structure is simple in both design and fabrication which manifests its suitability for applications.

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