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A Novel Wideband Phase Shifter Using T- and Pi-Networks

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Abstract—In this paper, a wideband differential phase shifter based on modified T- and Pi-networks is proposed. Invoking the even-odd mode analysis in this symmetric phase shifter, closed-form equations of its S-parameters are derived. The derived equations enable a generic design scheme of the phase shifter, that is, ideally the phase shifter can be designed for any differential phase requirements. To illustrate the proposed idea, design parameters for differential phases of 45°, 60°, 75°, 90°, 105° and 120° are evaluated and tabulated considering a center frequency of 3 GHz. Simulation of these examples using the Keysight ADS exhibits the intended performance. For validation, a 90° phase shifter has been fabricated and tested. The measurement results show a return loss better that 10 dB, an insertion loss of less than 1 dB, and a ±7° of phase deviation from 1.18 GHz to 5.44 GHz, which is equivalent to a fractional bandwidth of 142%.

1. INTRODUCTION

Differential phase shifters are commonly employed in wideband phase-array antennas, mobile satellite systems and measuring instruments, etc. Schiffman [1] introduced a phase shifter which has a main line built around a shorted coupled line and a simple transmission line serves as the reference line. However, it was based on a strip line that for specific bandwidth requirement, often necessitated very tight coupling. Various improvements over the Schiffman phase shifter using cascade and parallel combination of shorted coupled line have been introduced [2–4], but again, tight coupling is still required. The implementation of a phase shifter using selectively etching the underneath of the coupled lines and placing a material of different permittivity to change the even and odd mode impedance values is an interesting idea [5]. A return loss better than 10 dB and a bandwidth up to 70% have been achieved by doing so, but this phase shifter requires extra process step. Phase shifters reported in [6, 7] provide wide bandwidth but these designs also require multilayer fabrication process which increases their fabrication cost and may not be compatible with other part of the circuit. A design using stub loaded line reported in [8] has relatively smaller insertion loss and could provide a bandwidth up to 82%. Some other interesting designs have been reported in literature as well [9–12] and their performance are given at the end of this paper in the comparison section; majority of them rely on multilayer processing. A technique to utilize single reference line and multiple main lines to achieve different phase shifts was reported in [13], and can provide 45% bandwidth with a phase deviation of 5° and with an insertion loss up to 0.9 dB. While in [14] the main line is formed by changing the position of the stubs and could attain a bandwidth of 55.6% with a return loss up to 0.7 dB considering a phase deviation of 8°, the multilayer technique reported in [15] achieves a bandwidth of 112%. A modified version of the Shiffman phase shifter with the reference line also comprising of a coupled line was reported in [16], while [17] is limited to providing only 180° phase shift.

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In this paper, we propose a differential phase shifter in which a Pi-network serves as the main line, and a T-network is used as the reference line. The design offers an excellent fractional bandwidth of 142% considering a phase deviation of $\pm 7°$, is fully planar and does not require any extra processing step in the underneath ground plane and therefore, is highly suitable for microstrip implementation.

2. THE PROPOSED PHASE SHIFTER: THEORY AND DESIGN

The schematic of the proposed phase shifter is depicted in Fig. 1. To illustrate how we arrive at the proposed phase shifter configuration, it is pertinent to recall that there are normally two lines in a differential phase shifter — the main line and the reference line. For example, in [9] a Pi-network is used as the main line, and a simple transmission line (TL) serves as the reference line. In contrast, a T-network is used in [8] as the main line. It implies that the T- and Pi-networks have similar phase responses. Though a simple transmission line is utilized as the reference line in these reports, theoretically any two-port network can be chosen as the reference line. The important requirement is that both, the main two-port network and the reference two-port network, must have the same phase slope ($d\angle S_{21}/df$) [14]. We, therefore, present a novel phase shifter that uses a Pi-network as the main line and a T-network as the reference line. In addition, since coupled lines give extra degrees of design freedom due to their even and odd mode characteristic impedance parameters, the middle transmission line section in the Pi-network is replaced with shorted coupled lines. The coupled lines have even and odd mode impedances z_{ev} and z_{od}, respectively, and an electrical length of θ_c. The arms of Pi-network has a characteristic impedance z_5 and electrical length θ_5. An extra TL section having characteristic impedance z_2 and length θ_2 has been added in the T-network to compensate for any small imbalances in the phase response, return loss or transmission coefficient by varying its parameters. The open stub of T-network having characteristic impedance z_3 and electrical length θ_3 provides an extra degree of freedom, where θ_3 independently makes the design procedure more flexible. The terminating TL sections at the ports have characteristic impedance z_0 and the electrical lengths θ_1 and θ_4 in the reference and the main line, respectively.

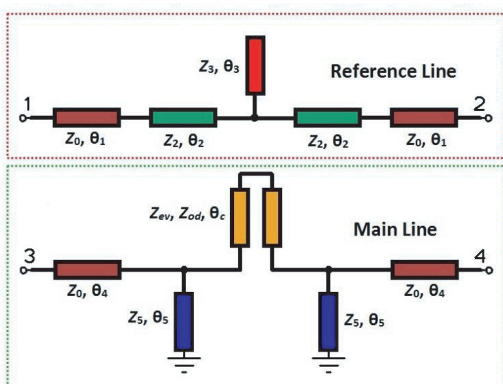

Figure 1. Schematic diagram of the proposed phase shifter.

The required differential phase is the difference between the phases of the main and the reference networks:

$$\Delta\phi = \angle s_{43} - \angle s_{21} \tag{1}$$

In addition, it is required that there must no insertion loss in both the paths and all the four ports must be matched, and therefore, the following conditions exist:

$$|s_{21}| = |s_{12}| = |s_{43}| = |s_{34}| = 1 \tag{2}$$

$$|s_{11}| = |s_{22}| = |s_{33}| = |s_{44}| = 0 \tag{3}$$

$$s_{11} = s_{22} = \frac{(j + \tan\theta_1)\left(z_2^3 \tan^2\theta_2 + 2\left(z_0^2 - z_2^2\right) z_3 \tan\theta_2 \cot\theta_3 + z_0^2 z_2\right)}{(\tan\theta_1 - j)\,(z_0 + jz_2\tan\theta_2)\,(z_0\,(2z_3\tan\theta_2\cot\theta_3 + z_2) + jz_2\,(z_2\tan\theta_2 - 2z_3\cot\theta_3))} \tag{4}$$

$$s_{21} = s_{12} = \frac{j2z_0z_2z_3\left(j+\tan\theta_1\right)\cot\theta_3\sec^2\theta_2}{\left(\tan\theta_1-j\right)\left(z_0+jz_2\tan\theta_2\right)\left(z_0\left(2z_3\tan\theta_2\cot\theta_3+z_2\right)+jz_2\left(z_2\tan\theta_2-2z_3\cot\theta_3\right)\right)} \tag{5}$$

$$s_{33} = s_{44} = -\frac{\left(\tan\theta_4+j\right)\left\{z_0^2\left(z_{ev}\cot\theta_5\cot\theta_c-z_5\right)\left(z_5\cot\theta_c+z_{od}\cot\theta_5\right)+z_5^2z_{ev}z_{od}\cot\theta_c\right\}}{\left(\tan\theta_4-j\right)\left\{z_0z_5-z_{ev}\cot\theta_c\left(z_0\cot\theta_5+jz_5\right)\right\}\left\{z_0\left(z_5\cot\theta_c+z_{od}\cot\theta_5\right)+jz_5z_{od}\right\}} \tag{6}$$

$$s_{43} = s_{34} = \frac{jz_0z_5^2\left(\tan\theta_4+j\right)\left(z_{ev}\cot^2\theta_c+z_{od}\right)}{\left(\tan\theta_4-j\right)\left(z_0z_5-z_{ev}\cot\theta_c\left(z_0\cot\theta_5+jz_5\right)\right)\left(z_0\left(z_5\cot\theta_c+z_{od}\cot\theta_5\right)+jz_5z_{od}\right)} \tag{7}$$

$$\begin{aligned}\angle s_{21} = {} & \tan^{-1}\left(\frac{\tan\theta_1\cot\theta_3\sec^2\theta_2}{-\cot\theta_3\sec^2\theta_2}\right)\\ & -\tan^{-1}\left(\frac{\begin{array}{l}\tan\theta_1\left\{z_2\tan\theta_2+z_3\cot\theta_3\left(\tan^2\theta_2-1\right)\right\}-2z_0^2\left(2z_3\tan\theta_2\cot\theta_3+z_2\right)\\ +2z_2^2\tan\theta_2\left(z_2\tan\theta_2-2z_3\cot\theta_3\right)\end{array}}{\begin{array}{l}z_2\tan\theta_2+z_3\cot\theta_3\left(\tan^2\theta_2-1\right)+2z_0^2\tan\theta_1\left(2z_3\tan\theta_2\cot\theta_3+z_2\right)\\ -2z_2^2\tan\theta_1\tan\theta_2\left(z_2\tan\theta_2-2z_3\cot\theta_3\right)\end{array}}\right)\end{aligned} \tag{8}$$

$$\begin{aligned}\angle s_{43} = {} & \tan^{-1}\left\{\frac{z_0z_5^2\tan\theta_4\left(z_{ev}\cot^2\theta_c+z_{od}\right)}{-z_0z_5^2\left(z_{ev}\cot^2\theta_c+z_{od}\right)}\right\}\\ & -\tan^{-1}\left\{\frac{\begin{array}{c}z_0^2\left(z_{ev}\cot\theta_5\cot\theta_c-z_5\right)\left(z_5\cot\theta_c+z_{od}\cot\theta_5\right)-z_5^2z_{ev}z_{od}\cot\theta_c\\ +z_5z_0\tan\theta_4\left\{z_5\left(z_{od}-z_{ev}\cot^2\theta_c\right)-2z_{ev}z_{od}\cot\theta_5\cot\theta_c\right\}\end{array}}{\begin{array}{l}z_5z_0\left\{z_5\left(z_{od}-z_{ev}\cot^2\theta_c\right)-2z_{ev}z_{od}\cot\theta_5\cot\theta_c\right\}\\ +z_0^2\tan\theta_4(z_5-z_{ev}\cot\theta_4\cot\theta_c)(z_5\cot\theta_c+z_{od}\cot\theta_5)+z_5^2z_{ev}z_{od}\tan\theta_4\cot\theta_c\end{array}}\right\}\end{aligned} \tag{9}$$

Since both the lines are symmetric and thus the even-odd mode analysis is invoked and the resulting S-parameters are obtained as mentioned in Eqs. (4)–(9).

In order that both the networks' phase variations are similar with frequency, an additional condition on the phase slope of both the networks holds true [14]:

$$\frac{d\angle s_{43}}{df} = \frac{d\angle s_{21}}{df} \tag{10}$$

For a required differential phase, Eqs. (1), (2), (3) and (10) are solved using MATLAB with the help of the closed-form S-parameters obtained in Eqs. (4)–(9). It is noted that some of the design parameters can be chosen independently. It is also important to note that for a required differential phase, there could be overwhelming computational burden while enforcing the conditions set by Eqs. (2), (3), and (10), and we may even get some unrealizable design parameters. Since, normally achieving 10–20 dB return loss is adequate for all practical purposes, it is justified to relax $|S_{11}|$ requirement (from its ideal value of ∞ dB) to enhance the computational speed. Similarly, 0.5 dB–1 dB insertion loss is common over a wide bandwidth, relaxing $|S_{21}|$ form its ideal value of 0 dB a bit helps speed up the computation. Thus, it is recommended that rather than solving for the ideal return and insertion losses, we can, for example, allow a VSWR of 1.1 to 1.3 and a transmission loss of 0.04 to 0.06 to obtain a realistic solution with considerable ease. Yet another constraint is placed on the characteristic impedances of various microstrip lines in the proposed phase shifter as for a physically realizable design these values must line between 20 Ω and 140 Ω. Finally, since in a design incorporating coupled lines their gap may constrain the fabrication; the minimum coupled lines gap in this paper is assumed to be 0.25 mm, which further helps the choice of z_{od}. Following these guidelines, variation of the design parameters with the required phase shift is obtained. Fig. 2 shows this variation for the differential phase ranging from 45° to 120°. It must be noted that this curve is not unique as z_{od}, z_2, and θ_3 are independent variables and they can assume any value as far as the design constraints are satisfied. The current plot is obtained considering these parameters to be 36 Ω, 50.5 Ω, and 7.5°, respectively. This choice is motivated noting that z_2 cannot be much far from 50 Ω and length of its stub should be as small as possible considering that ports 1 and 2 of the reference T-network are to be matched. Furthermore, z_{od} is considered on a lower side to achieve a practically realizable design as it has a relationship with z_{ev} in terms of $\rho = z_{ev}/z_{od}$, and typically for ease of fabrication ρ lies between 1 and 4 [18].

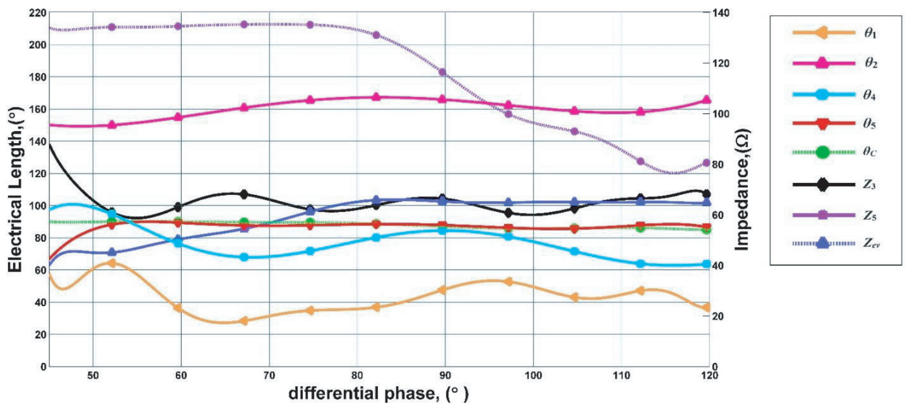

Figure 2. Design parameters of the proposed phase shifter for different phase shifts.

The values of various design parameters can easily be read from Fig. 2 and the Table 1, for example, list these parameters for the phase variation from 45° to 120° at an interval of 15°. The design examples listed in Table 1 are simulated using the Keysight Advanced Design System (ADS) and the results are depicted in Figs. 3 and 4. Fig. 3 shows the variation of differential phase shifts with the frequency for different simulation examples. The wideband characteristic of the proposed phase shifter for all the mentioned phase shifts is clearly evident. The simulation results of return and insertion losses of these examples are depicted in Fig. 4, which reflects remarkable performance of the proposed phase shifter. It is to be noted that these near ideal results are obtained due to the application of ideal transmission line elements during the simulations.

Table 1. The design parameters of the proposed phase shifter (θ_i in degrees and Z_i in ohms).

Phase Shift / Parameters	120°	105°	90°	75°	60°	45°
θ_1	37.2	42	48	32.4	30.2	58
θ_2	167	158	164	168	154	150
Z_3	67	65	64	63.5	66	132
θ_4	63.3	65	84.4	75.8	65.9	97.4
θ_5	86.8	87	86.8	88.7	88.3	88
Z_5	80.8	94	118	135	135	134
θ_C	85.1	86.1	86.1	89.1	90.2	90
Z_{ev}	65	65	40	62	50	40

3. DESIGN PROTOTYPE, MEASUREMENT AND COMPARISON

The momentum electromagnetic (EM) simulation engine of the Keysight ADS is used to verify and optimize the formulated design. The substrate used is the Rogers RT/Duroid 5880 with $\in_r = 2.2$, loss tangent 0.0009 and substrate thickness of 1.575 mm and 35 µm copper on both sides.

To validate the proposed idea, a 90-degree phase shifter at 3 GHz is designed, simulated, fabricated and measured. The ideal design parameters are given in Table 1. Since there are multiple bends and junctions emanating during the layout of the phase shifter, the final design is obtained after optimization to compensate for their effects. Since reducing the coupled lines gap normally improves the bandwidth performance, the initial gap of 0.33 millimeter (mm) was optimized to a final value of 0.25 mm due to

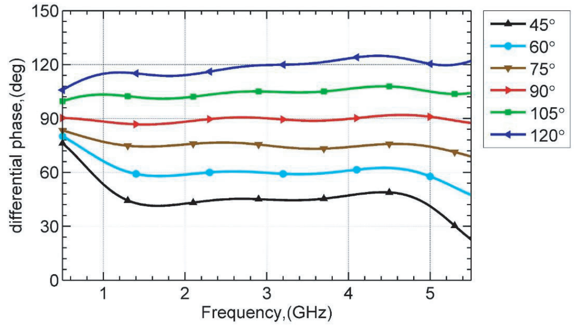

Figure 3. Differential phase shift corresponding to the Table 1.

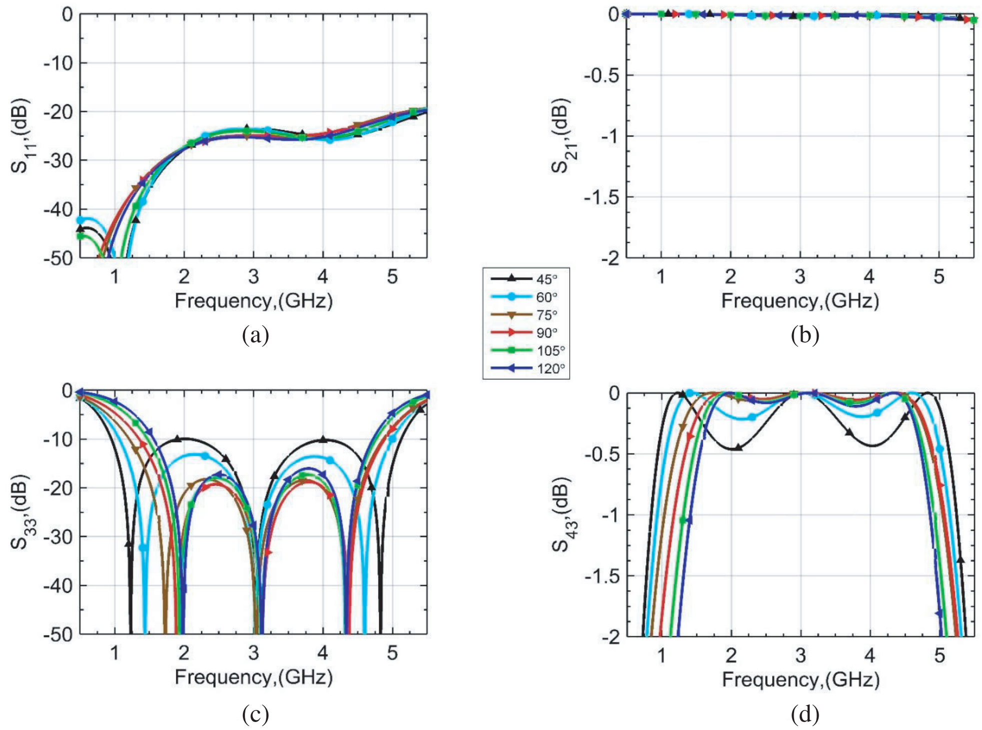

Figure 4. Simulated S-parameters of design cases listed in Table 1 (a) S_{11} (dB), (b) S_{21} (dB), (c) S_{33} (dB), and (d) S_{43} (dB).

the availability of a good fabrication facility. Fig. 5 shows the implemented prototype and measurement setup along with the dimensions marked in mm. The measurement of the prototype is carried out using an E5063A vector network analyzer (VNA) from the Keysight Technologies. The comparison of EM simulated and the measured S-parameters are depicted in Fig. 6. The EM simulated and the measured differential phase are also shown in Fig. 7. It is apparent that there is a good agreement between the EM simulated and the measured results. It is apparent from Fig. 6 that both the networks have better that 10 dB return losses and better than 1 dB insertion losses over a wide frequency span. Specifically, if we consider a phase error up to ± 7 degree in Fig. 7, a return loss better than 10 dB, and an insertion loss less than 1 dB as the performance indicators, the minimum fractional bandwidth (FBW) is for S_{33}, which is around 142% at the centre frequency of 3 GHz. An anomaly between the EM simulated and measured results can potentially be due to the higher losses associated with the real substrate as well as fabrication and measurement tolerances. In addition, junction discontinuities also contribute to the

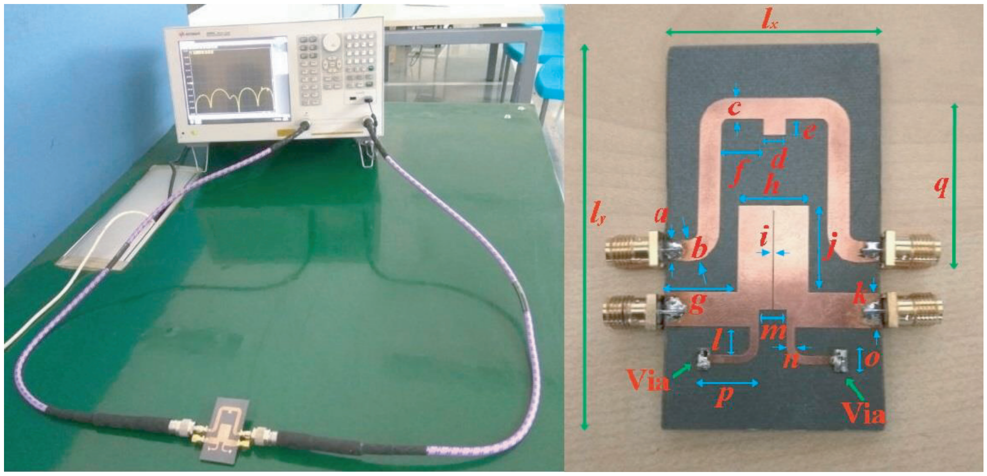

Figure 5. The measurement setup and the prototype. An E5063A vector network analyzer from Keysight Technologies is used for the measurement. The proposed prototype has the following dimensions (in mm): $a = 3.55$, $b = 4.19$, $c = 3.94$, $d = 3.94$, $e = 3.05$, $f = 8.01$, $g = 13.2$, $h = 12.7$, $i = 0.255$, $j = 16.25$, $k = 6.35$, $l = 5.08$, $m = 5.08$, $n = 1.53$, $o = 4.06$, $p = 11.17$, $q = 31.11$, $l_x = 39.75$, and $l_y = 86.21$.

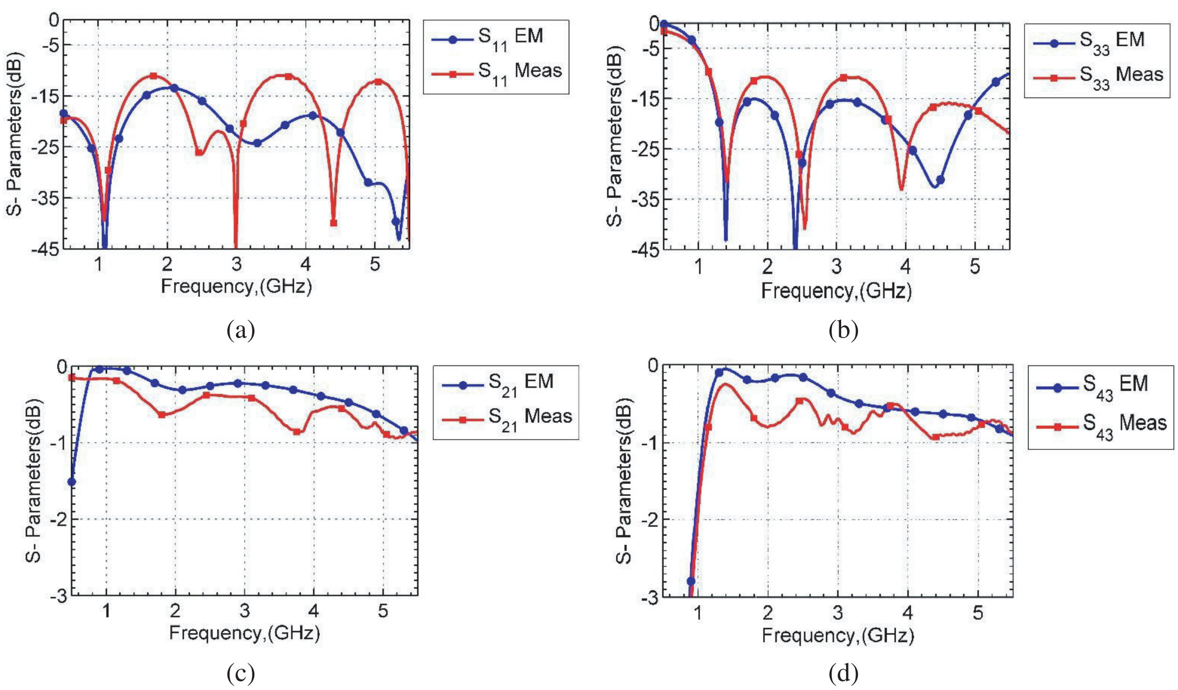

Figure 6. S-parameters of the designed phase shifter (a) S_{11}, (b)S_{33}, (c) S_{21}, (d) S_{43}.

parasitics, which might not have been exactly represented during the EM simulation. Nevertheless, the measurement results clearly show the outstanding performance of the fabricated prototype.

A comparison between the proposed design and some of the previously reported phase shifter is made in Table 2. It is apparent that the proposed design is a single layer implementation (that is, a pattern exists only on the top side of microstrip) and provides an excellent FBW of 142%.

Table 2. Comparison with previous reported Phase Shifters.

Reference	Publication	Frequency (GHz)	Differential Phase (deg)	Phase Deviation (deg)	Insertion Loss (dB)	Return Loss (dB)	FBW (%)	Layers
[5]	TMTT	1.5–3.1	90	5	0.5	12	70	2
[6]	TMTT	3.1–10.6	45	3	1	10	109	3
[7]	MWCL	3.1–10.6	180	7	1.4	10	109	3
[8]	MWCL	2.3–5.5	90	6.4	0.6	10	82	1
[9]	IMS	3.1–10.6	45	4.5	0.3	13.4	109	1
[10]	MWCL	3.1–10.6	90	9.02	0.96	10	109	1
[11]	EL	2.2–9.8	90	6	1.8	10	126.7	3
[12]	MWCL	3–11	90	3	0.4	15	114	2
[13]	MWCL	2.24–3.55	135	5	0.9	10	45	1
[14]	TCPMT	2.6–4.6	135	7.8	0.7	10	55.6	1
[15]	MWCL	3.1–11	90	8	1.8	14	112	2
This Wor		**1.18–5.44**	**90**	**7**	**0.97**	**10.4**	**142**	**1**

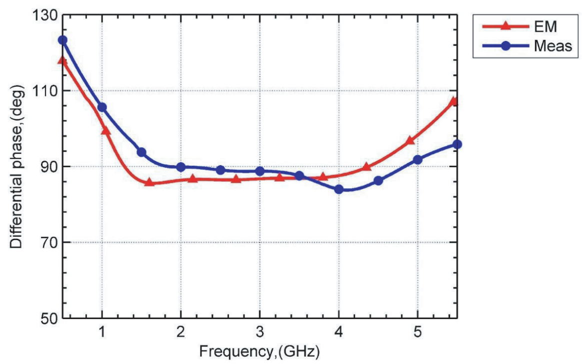

Figure 7. The EM Simulated and the measured differential phase shift.

4. CONCLUSION

A fully planar wideband phase shifter is demonstrated in this paper. The Pi- and T-types of lines having similar phase characteristics serve as the main and reference lines, respectively, and are the key to wideband performance of the proposed phase shifter. The derived closed-form S-parameters are solved in conjunction with the various constraints to obtain the design parameters. For design validation, a prototype was fabricated to achieve wideband 90° phase shift at a center frequency of 3 GHz. The measured results exhibited close resemblance with the EM simulated results. A differential phase shift of 90° with a phase deviation of ±7°, a return loss better than 10 dB, an insertion loss within 1 dB, and an excellent fractional bandwidth of 142% were achieved.

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