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A SEMI-ELLIPTICAL WIDEBAND PHASE SHIFTER

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Abstract—A new microstrip structure for realization of wideband phase shifter has been designed and fabricated. The proposed design uses edge-coupled semi-elliptical structure and an elliptical defected ground plane to increase the coupling coefficient and operating bandwidth. Simulation performed using CST Microwave Studio and measured results confirm the good performance of the proposed design. The phase deviation is better than $\pm 4^\circ$, insertion loss less than 0.6 dB and return loss better than 10 dB over a wide frequency range. The achievable bandwidth is more than 2.3 : 1.

1. INTRODUCTION

Phase shifters are commonly used in many modern microwave systems such as electronic beam-scanning phased arrays, modulators, microwave measurement and instrumentation systems, and many other industrial applications. In addition to constant phase shift, the other important parameters to achieve include low insertion loss, low amplitude and phase ripple, and compact size.

The main drawback to the use of edge-coupled quarter-wave sections is that an extremely tight coupling is required in order to achieve the desired performance. This required narrow space-width which is very difficult to fabricate and reproduce. Some researchers have proposed the use of cascaded multiple coupled section [1, 2]. The design by Meschanov et al. [1] consists of a cascade of coupled line pairs of varying length and coupling coefficient, and each connected at one end. Good phase ripple over wide bandwidth is achieved for 4-elements design. The phase shifter is able to work at lower coupling

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coefficients. However, the requirement of a large number of coupled line pairs increases the size of the design. A double parallel Schiffman phase shifter introduced in [2] is able to achieve equivalent phase response as the standard Schiffman phase shifter at weaker coupling coefficient. However, the design shows high phase variations near the lower and upper frequency band, thus indicating a narrowband performance.

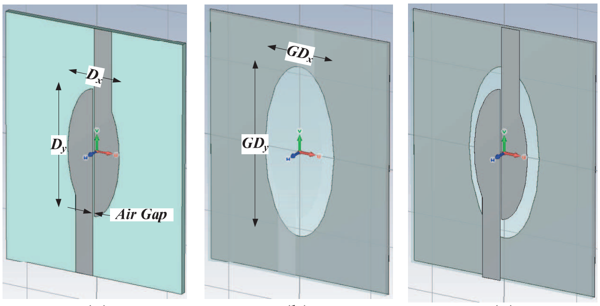
A compact and cost effective version of the Schiffman phase shifter was introduced by Chai et al. [3]. The design uses Teflon as substrate and comprises either 1 or 2 coupling sections. Higher phase stability is achieved with two coupling sections design, but the useful frequency range is limited to just few hundreds MHz. Minnaar et al. used tapered coupled method consisting of a nine-section structure and several impedance transformers [4]. It is a multilayer design where a 5 mil substrate consisting the coupler is sandwiched between two 32-mil substrates. The insertion loss is higher than 2 dB and phase ripple is $\pm 10^\circ$ for the 90° phase shifter.

Ahn and Wolff presented several asymmetric ring-hybrid phase shifters [5]. The phase shift of the design is tuned by the terminating impedances. However, the bandwidth was limited to 1.6 : 1. Compensation techniques were introduced to improve the return loss and insertion loss of the Schiffman phase shifter [6]. Compensating capacitors are used at various locations to compensate the parasitic reactance at the transition regions between coupled and signal lines. However, the technique is unable to increase the bandwidth of the phase shifter. The usable bandwidth is 2 to 3 GHz.

Guo et al. introduced an improved version of Schiffman Phase Shifter by removing the ground plane under the coupled lines to increase the even-mode impedance [7]. A floating rectangular patch is also introduced to decrease the odd-mode impedance. The proposed method also allows wider separation between coupled lines. The achieved bandwidth was about 2 : 1. Abbosh and Bialkowski introduced a three-layer broadside coupled phase shifter [8]. It comprises two elliptical microstrip patches at the top and bottom layer, and a ground plane with elliptical slot in the middle layer. The phase shifter shows a broadband performance from 3.3–10.6 GHz. However, the useful phase shift range is limited to 25°–48° with a phase deviation of $\pm 3^\circ$.

2. DESIGN

Defected ground structure has been widely used recently in microwave circuit design [9–11]. In this paper, an edge-coupled semi-elliptical structure with an elliptical defected ground plane is used to construct



(a) (b) (c)

Figure 1. Configuration of the proposed phase shifter. (a) Top layer. (b) Bottom layer and (c) complete structure.

a phase shifter, as shown in Figure 1. Coupling coefficient of edge-coupled structures can be increased by introducing an aperture in the ground plane as demonstrated in [12, 13]. The use of elliptical structure provides an almost constant coupling coefficient over a wider bandwidth.

The phase shifter is modeled as a four port device where two of its ports are open circuited. Port 1 and port 2 are the input and output ports, respectively, as shown in Figure 2. The performance is defined by its insertion loss, return loss, and the deviation of the differential phase shift.

CST Microwave Studio is used to analyze the performance of the phase shifter. Rogers RT/duroid 5880 with $\varepsilon_r = 2.2$ and thickness = 1.575 mm is chosen as the substrate. The differential phase shift can be adjusted by varying the gap between the two semi-elliptical patches. Figure 3 shows the simulated differential phase shift with varying gap width. It is observed that phase shift increases with increasing gap width (decreasing coupling coefficient).

The simulation results of the insertion loss and the return loss of the proposed phase shifter are shown in Figures 4 and 5. From the figures, higher return loss and lower insertion loss is achieved with smaller gap width, and bandwidth of the phase shifter degrades as the gap width increases. This is because the coupling coefficient of an edge-coupled structure depends largely on the gap width between the coupled lines. Higher coupling coefficient is achieved with smaller gap width, thus results in improved performance of the phase shifter.

The dimension of the major axis, D_y of the semi-elliptical patch, is equal to a quarter wavelength at the center frequency:

$$D_y = \frac{\lambda}{4} \tag{1}$$

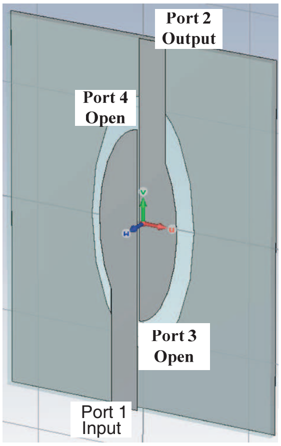


Figure 2. The proposed phase shifter is modelled as a four-port device, with two of the ports open circuited.

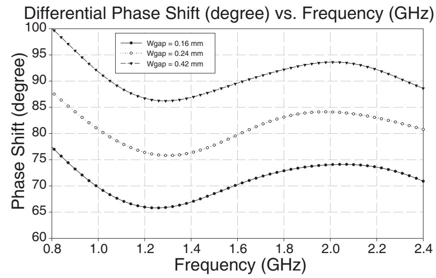


Figure 3. Simulated differential phase shift for varying gap width.

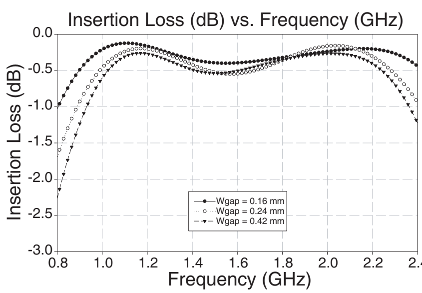


Figure 4. Simulated insertion loss for varying gap width.

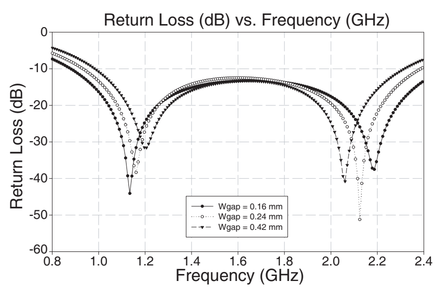


Figure 5. Simulated return loss for varying gap width.

where $\lambda = \frac{\lambda_{\text{free space}}}{\sqrt{\varepsilon_{\text{eff}}}}$ and ε_{eff} is the effective dielectric constant.

The optimum ratio of $\frac{D_x}{D_y}$ and the gap width between the semi-elliptical patches vary slightly with the desired center frequency, f_c and the required amount of phase shift. For Rogers RT/duroid 5880, these values can be obtained graphically from Figures 6 and 7, respectively. Generally greater gap width is required for higher phase shift.

The surface current distribution is also analyzed in the simulation. Figure 8 shows the surface current at 0.95 GHz and 2.35 GHz, for the phase shifter designed to operate at $f_c = 1.65$ GHz. It can be

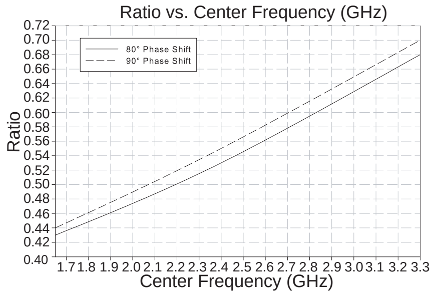


Figure 6. Ratio varies with center frequency for a certain amount of phase shift.

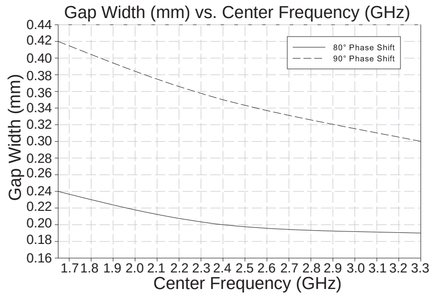
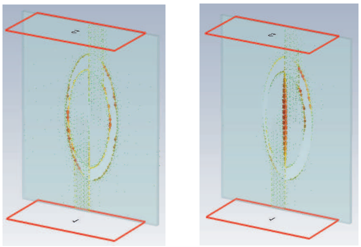


Figure 7. Gap width varies with center frequency for a certain amount of phase shift.



(a) (b)

Figure 8. Surface current distribution (a) $f = 0.95$ GHz and (b) $f = 2.35$ GHz.

observed that the surface current takes an elliptical path at lower frequencies and a straighter path at high frequencies. The semi-elliptical patch can be viewed as a resonator. When it resonates, at the fundamental longitudinal mode, the electrical length is equal to a quarter-wavelength. At lower frequencies, this required quarter-wavelength can only be satisfied by a curved path. The elliptical shaped edge gives optimum support for this curved path over wide bandwidth.

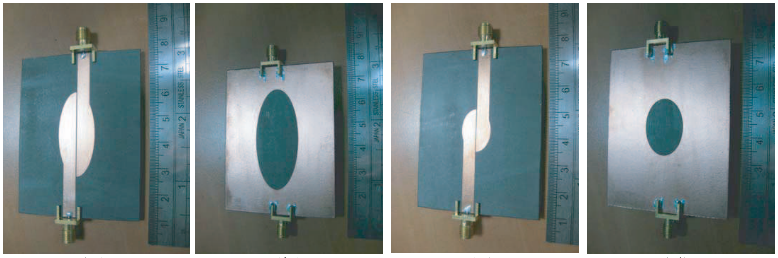
3. RESULTS AND DISCUSSION

The proposed phase shifter is fabricated on Rogers RT/duriod 5880 with a substrate thickness of 1.575 mm based on the dimension given in Table 1:

The value of D_y is obtained using Equation (1). The dimension of D_x can be obtained from the graph in Figure 6, while the gap

Table 1. Design parameters of phase shifter.

Center Frequency, (GHz) f_c	Phase Shift (°)	Parameters				
		D_y (mm)	D_x (mm)	GD_y (mm)	GD_x (mm)	W_{gap} (mm)
1.65	80	33.24	14.29	43.21	18.58	0.24
1.65	90	33.24	14.63	43.88	19.31	0.42
3.30	90	16.62	11.63	21.94	15.36	0.30



(a) (b) (c) (d)

Figure 9. Photographs of the fabricated phase shifters. (a) Top layer, $f_c = 1.65$ GHz. (b) Bottom layer, $f_c = 1.65$ GHz. (c) Top layer, $f_c = 3.3$ GHz and (d) Bottom layer, $f_c = 3.3$ GHz.

width, W_{gap} can be obtained from Figure 7. For optimum bandwidth, the dimension of the defected ground plane, GD_x and GD_y should be between 1.30–1.32 times the dimension of the top patches.

Figure 9 shows the photographs of some of the fabricated phase shifter with $f_c = 1.65$ GHz and $f_c = 3.3$ GHz. Both of the phase shifters are fabricated on a board with dimension of 65 mm × 50 mm.

The phase shift, return loss and insertion loss of the phase shifter is measured using the Agilent 8722ES Vector Network Analyzer. A full two-port SOLT calibration is performed, and port extension for port 1 is activated to move the measurement reference plane to a reference length. The measurement results are shown from Figure 10 to Figure 12.

Figure 10 shows the measured and simulated phase shifts for the proposed phase shifters. A phase deviation of ±4° can be obtained in the 0.95 GHz to 2.35 GHz band. The results in Figure 10 also shows that the measured phase shifts are in good agreement with the simulated values.

Figures 11 and 12 show the simulated and the measured return losses and insertion losses, respectively, for the 80° and 90° phase

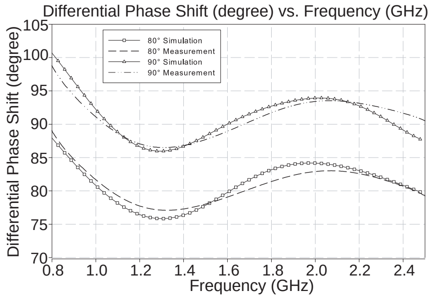


Figure 10. Simulated and measured differential phase shift, $f_c = 1.65\,\mathrm{GHz}$.

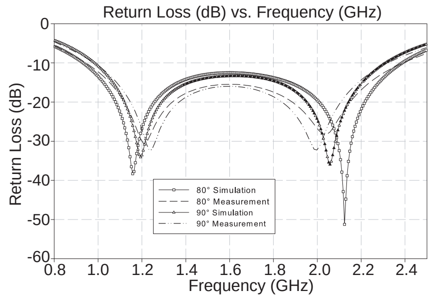


Figure 11. Simulated and measured return loss, $f_c = 1.65\,\mathrm{GHz}$.

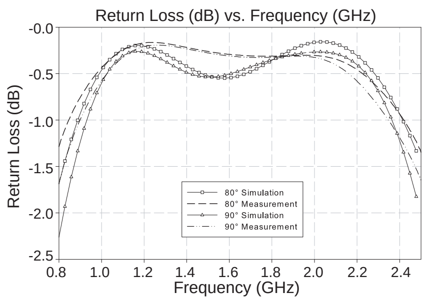


Figure 12. Simulated and measured insertion loss, $f_c = 1.65\,\mathrm{GHz}$.

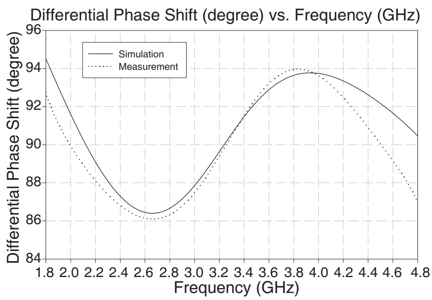


Figure 13. Simulated and measured differential phase shift, $f_c = 3.3\,\mathrm{GHz}$.

shifters. Both the results show return losses better than 10 dB and insertion losses better than 0.6 dB for the targeted frequency range. The measured results for both of the phase shifters are once again in good agreement with the simulation results.

Figure 13 to Figure 15 show the measurement and simulation results of the phase shifter at $f_c = 3.3\,\mathrm{GHz}$. A phase deviation of $\pm 4^\circ$ can be obtained by both simulation and measurement in the 2 GHz to 4.6 GHz range. The measured return loss is better than 10 dB and the measured insertion loss is less than 0.7 dB at the targeted frequency. There is a little difference between the measured return loss and insertion loss for this phase shifter. The lower return loss and higher insertion loss in the measurement are due to the slight mismatch between the SMA end-launcher connectors and the fabricated microstrip line, which is not taken into account during the simulation. The effect of this mismatch is more apparent for the phase shifter operating at higher frequency.

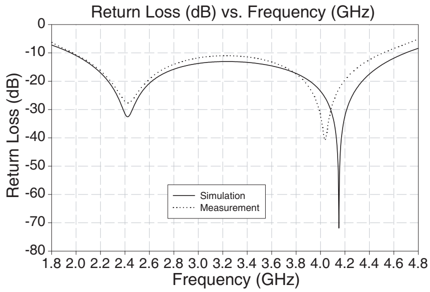


Figure 14. Simulated and measured return loss, $f_c = 3.3\,\mathrm{GHz}$.

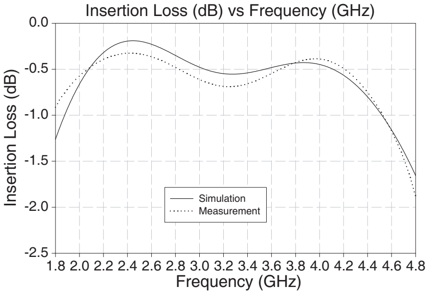


Figure 15. Simulated and measured insertion loss, $f_c = 3.3\,\mathrm{GHz}$.

4. CONCLUSION

A new microstrip structure for the realization of wideband phase shifter is presented. The proposed design uses semi-elliptical edge-coupled structures at the top layer and an elliptical defected ground plane at the bottom layer. This structure is simple, compact, low cost and easy to fabricate. Both the simulation and measurement results show that the proposed phase shifter has a phase deviation better than $\pm 4^\circ$, a return loss better than 10 dB, and an insertion loss better than 0.6 dB for both the 80° and 90° phase shifters in the 0.95 GHz to 2.35 GHz band. A bandwidth of more than 2.3 : 1 is achieved using the proposed design.

REFERENCES

1. Meschanov, V., I. Metelnikova, V. Tupikin, and G. Chumaevskaya, "A new structure of microwave ultrawide-band differential phase shifter," *IEEE Trans. on Microw. Theory and Tech.*, Vol. 42, No. 5, 762–765, May 1994.
2. Quirarte, J. and J. Starski, "Novel Schiffman phase shifters," *IEEE Trans. on Microw. Theory and Tech.*, Vol. 41, No. 1, 9–14, Jan. 1993.
3. Chai, D., M. Linh, M. Yim, and G. Yoon, "Asymmetric teflon-based Schiffman phase shifter," *Electron. Lett.*, Vol. 39, No. 6, 529–530, 2003.
4. Minnaar, F., J. Coetzee, and J. Joubert, "A novel ultrawideband microwave differential phase shifter," *IEEE Trans. on Microw. Theory and Tech.*, Vol. 45, No. 8, 1249–1252, Aug. 1997.

5. Ahn, H. and I. Wolff, "Asymmetric ring-hybrid phase shifters and attenuators," *IEEE Trans. on Microw. Theory and Tech.*, Vol. 50, No. 4, 1146–1155, Apr. 2002.
6. Gruszczynski, S., K. Wincza, and K. Sachse, "Design of compensated coupled-stripline 3-dB directional couplers, phase shifters, and magic-T's — Part I: Single-section coupled-line circuits," *IEEE Trans. on Microw. Theory and Tech.*, Vol. 54, No. 11, 3986–3994, Nov. 2006.
7. Guo, Y., Z. Zhang, and L. Ong, "Improved wideband Schiffman phase shifter," *IEEE Trans. on Microw. Theory and Tech.*, Vol. 54, No. 3, 1196–1200, Mar. 2006.
8. Abbosh, A. and M. Bialkowski, "Design of compact directional couplers for UWB applications," *IEEE Trans. on Microw. Theory and Tech.*, Vol. 55, No. 2, 189–194, Feb. 2007.
9. Chen, X.-Q., X.-W. Shi, Y.-C. Guo, and M.-X. Xiao, "A novel dual band transmitter using microstrip defected ground structure," *Progress In Electromagnetics Research*, Vol. 83, 1–11, 2008.
10. Chen, W. N., W. K. Chia, M. Cheung, and C. F. Yang, "Compact etched ground structure ultra-wideband bandpass filter with adjustable bandwidth," *Journal of Electromagnetic Waves and Applications*, Vol. 24, No. 10, 1375–1386, 2010.
11. Weng, L. H., Y.-C. Guo, X.-W. Shi, and X.-Q. Chen, "An overview on defected ground structure," *Progress In Electromagnetics Research B*, Vol. 7, 173–189, 2008.
12. Massot, F., F. Medina, and M. Horno, "Theoritical and experimental study of modified coupled strip coupler," *Electron. Lett.*, Vol. 28, No. 4, 347–348, 1992.
13. Velazquez-Ahumada, M. C., J. Martel, and F. Madina, "Parallel coupled microstrip filters with ground-plane aperture for spurious band suppression and enhanced coupling," *IEEE Trans. on Microw. Theory and Tech.*, Vol. 52, No. 3, 1082–1086, Mar. 2004.