Novel UWB Trapezoidal and Butterfly Shaped Microstrip Phase Shifters Using Multilayered PCB Technology

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Abstract ─ In this paper, design of two different aperture-coupled phase shifters for ultra-wideband (UWB) multilayer microwave circuits are introduced. The proposed phase shifters use broadside coupling between microstrip patches at the top and the bottom layers via a rectangular-shaped slot in the common ground plane (mid-layer). The proposed patch shapes are trapezoidal and butterfly shapes which are capable of achieving broadband characteristics for UWB operation. The reference transmission line is installed on the top layer. The numerical calculated results using two simulation programs using two different numerical techniques show that the proposed phase shifters have good phase characteristics with high return losses and good insertion losses over most of the 3.1–10.6 GHz frequency band. The phase characteristics for the proposed phase shifters can be easily controlled by proper adjusting the physical dimensions. Two 45° phase shifters prototypes are fabricated and then tested experimentally using Agilent E8364B PNA Network Analyzer. Experimental results are in good agreement with the calculated ones.

Index Terms ─ Beam-forming, microstrip phase shifters, microstrip printed circuit board (PCB) technology, multi-layer technology, ultra-wideband (UWB).

I. INTRODUCTION

There is a big need for phase shifters due to their consideration as important microwave devices widely used in different applications such as electronic beam scanning phased arrays, phase modulators, etc. Conventional phase shifters have narrowband characteristics and the phase changes linearly with increasing the frequency. For wideband applications, phase shifters should be implemented using printed circuit board (PCB) technology because of the non-dispersive characteristic and broadband propagation properties of microstrip PCB. The original Schiffman phase shifter [1] which is considered one of the early designs based on using sections of coupled-strip transmission lines operating in the transverse electromagnetic (TEM) mode and a reference transmission line. The constant broadband phase difference between these lines can be achieved by controlling the degree of coupling between lines and the length of those coupled lines. However, the bandwidth of the original Schiffman phase shifter does not cover the desired UWB frequency range. Recently, researchers have tried to improve the original Schiffman phase shifter to achieve the desired broadband phase response [2]-[6]. This can be achieved by using cascade of multiple coupled parallel transmission line sections connected to each other as in [4]. These designs have large size and some limitations in PCB manufacturing because of narrow gaps for tight coupling. Another approach is achieved by using dumb-bell-shaped phase shifter using multi-section stubs, but the bandwidth achieved does not cover the whole UWB frequency range [2]. In [3], an improved wideband Schiffman phase shifter is proposed by modifying the ground plane underneath the microstrip coupled lines to form a defected ground structure (DGS), while the achieved bandwidth is from 1 GHz to 3.5 GHz which is not enough for UWB operation. Another approach to design a broadband phase shifter in multi-layer PCB technology is achieved by using the multi-layer vertical elliptical transition and a microstrip reference line as in [5].

The problem with the conventional narrowband phase shifters that the phase changes linearly with the frequency. To design a broadband phase shifter where the phase is almost constant with frequency, we exploit the broadband characteristics of the designed trapezoidal and butterfly shaped transitions and the conventional transmission lines. In this paper, two aperture-coupled microstrip 45° phase shifters with different patch shapes

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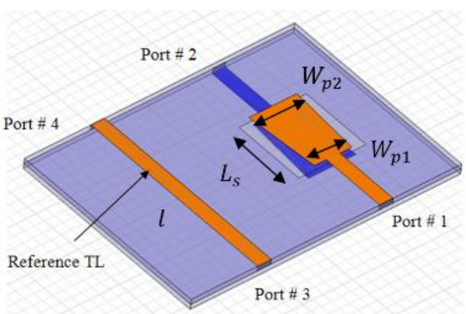
are presented. In the first design, the microstrip coupling patches have trapezoidal structure while the coupling slot has rectangular structure. The second proposed transition has butterfly shaped microstrip coupling patches with rectangular coupling slot. The trapezoidal-shaped UWB phase shifter is presented in Section II. In Section III, the design and results of the butterfly-shaped phase shifters are investigated and discussed. Finally, conclusions are given in Section IV.

II. TRAPEZOIDAL-SHAPED UWB PHASE SHIFTERS

A. Geometrical configuration

The configuration of the proposed trapezoidal shaped 45° microstrip phase shifter is shown in Fig. 1. It is simply consists of the designed trapezoidal shaped transition connected to port #1 and port #2. The reference transmission line is installed on the top layer between port #3 and port #4. By controlling the transition parameters (W_{p1}, W_{p2}, W_s, L_s) and the length of the reference transmission line l, the suitable phase shift can be achieved over the desired bandwidth. All proposed phase shifter designs are built using two RT Duroid 5880 substrates with thickness of 0.508 mm, relative permittivity of ε_r = 2.2 and loss tangent of $tan\delta$ = 0.0009. The overall dimensions of proposed phase shifters are 20 mm × 40 mm. The width of the microstrip feed line is set to be W_m = 1.3 mm for 50 Ω characteristic impedance.



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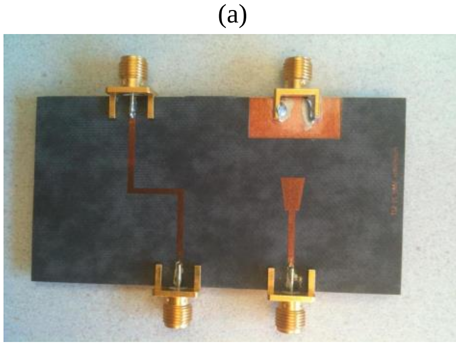


(b)

Fig. 1. Configuration of the proposed trapezoidal shaped UWB 45° phase shifter. (a) The whole structure and (b) photograph of fabricated phase shifter prototype.

B. Parametric study and design

Parametric studies have been carried out to address the effect of phase shifter physical parameters on the phase characteristics and the operational bandwidth but not shown here because of limited space.

C. Simulation and experimental results

Figure 2 shows the calculated phase shift $\angle S_{43} - \angle S_{21}$ for different phase shift values, i.e., 22.5°, 45° and 67.5° versus frequency.

It can be seen that the proposed phase shifters have good phase characteristic across the whole UWB frequency range. The achieved phases are 22.5°±5.5°, 45°±7° and 67.5°±6.5° through the desired UWB frequency band from 3.1 to 10.6 GHz. The optimized trapezoidal phase shifter parameters for different phase shift values of 22.5°, 45° and 67.5° are calculated numerically using simulations programs and tabulated in Table 1. The simulated and measured return and insertion losses for the 45° trapezoidal phase shifter are illustrated in Figs. 3 (a) & (b), respectively.

It can be seen that the simulated return and insertion losses are better than 10 dB and 1.2 dB in the 3.1-10.6 GHz band, respectively. There is a good agreement between both HFSS and CST simulation results. The measured return and insertion losses are good in the lower frequency band from 3.3 GHz to 9.6 GHz.

The phase difference ($\angle S_{43} - \angle S_{21}$) has been simulated and plotted in Fig. 4 (a). The simulated achieved phase difference is almost 45° with phase error of less than ±7° across the whole UWB frequency band. Also, the measured phases and phase difference between the ports (1, 2) and ports (3, 4) are shown in Fig. 4 (b). It can be noticed that phases are almost linear as a function of frequency and the measured phase difference achieved is varying around 45°, but it deteriorated at higher frequencies above 8.0 GHz.

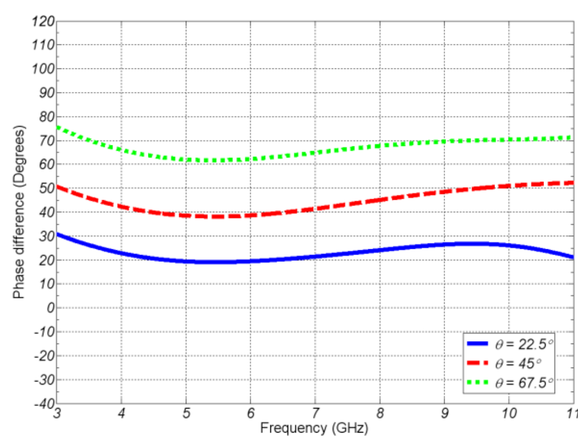
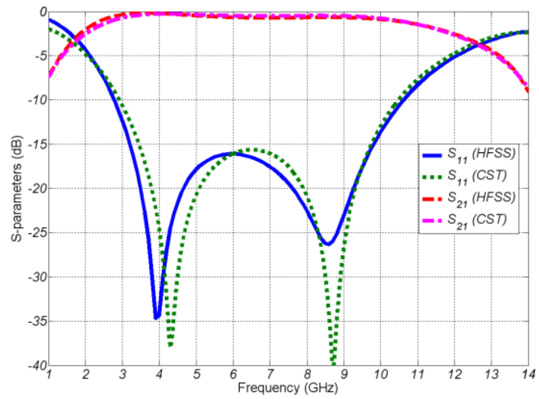


Fig. 2. Calculated phase shift $\angle S_{43} - \angle S_{21}$ of the trapezoidal phase shifter for different phase shift values, i.e., 22.5°, 45° and 67.5°.

Table 1: Parameters of the trapezoidal phase shifter for different phase shift values

Parameters (mm)	Phase Shift Values		
	22.5°	45°	67.5°
W_{p1}	5.2	3.7	2.0
W_{p2}	6.3	4.5	3.1
W_s	8.2	7.2	5.0
$L_s\ (= L_p)$	8.2	7.7	7.2
l	29.3	29.5	30.0



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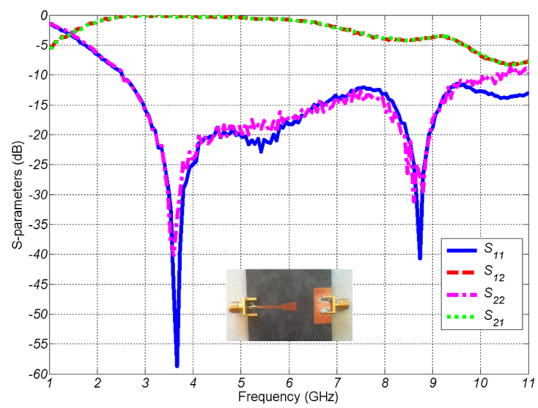

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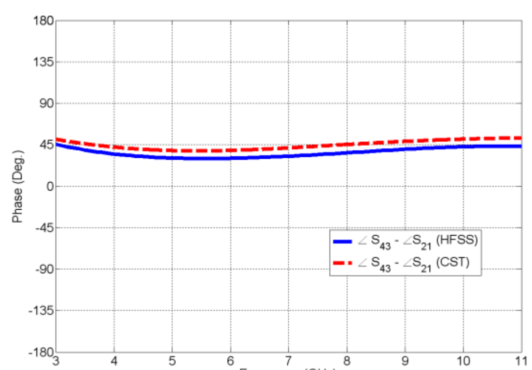
Fig. 3. (a) Simulated and (b) measured return and insertion losses of the proposed UWB 45° trapezoidal phase shifter.



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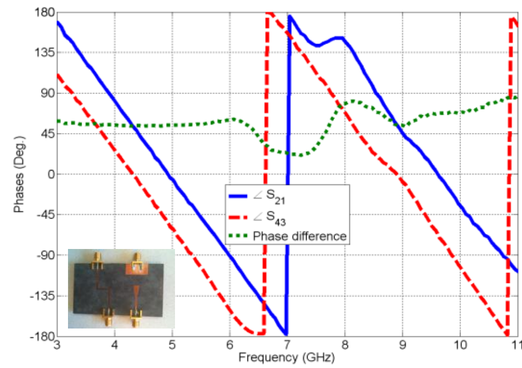


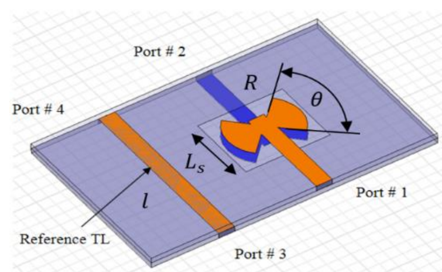
(b)

Fig. 4. (a) Simulated phase difference and (b) measured $\angle S_{21}$ & $\angle S_{43}$ phases and phase difference $(\angle S_{43} - \angle S_{21})$ of the proposed 45° trapezoidal phase shifter.

III. BUTTERFLY-SHAPED UWB PHASE SHIFTERS

A. Geometrical configuration

The configuration of the proposed butterfly shaped 45° microstrip phase shifter is shown in Fig. 5. It simply consists of the designed butterfly shaped transition connected to port #1 and port #2. The reference transmission line is installed on the top layer between port #3 and port #4. By controlling the transition parameters: radius R, angle θ, open-circuit stub length d, rectangular coupling slot width W_s, rectangular coupling slot length L_s and the length of the reference transmission line l, the suitable phase shift can be achieved over the desired bandwidth.



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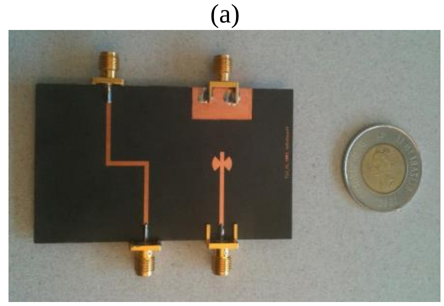


(b)

Fig. 5. Configuration of the proposed 45° phase shifter. (a) The whole structure and (b) photograph of fabricated phase shifter prototype.

B. Parametric study and design

Based on parametric studies, the optimized 45° butterfly phase shifter parameters are found to be: R = 2.2 mm, θ = 90°, d = 3.5 mm, W_s = 7.3 mm, L_s = 6.0 mm and l = 32 mm.

The calculated phase shift $\angle S_{43} - \angle S_{21}$ for different phase shift values, i.e., 22.5°, 45° and 67.5° versus frequency are shown in Fig. 6. It can be noticed that the proposed phase shifters have good phase characteristic across the whole UWB frequency range. The achieved phases are 22.5°±6°, 45°±9° and 67.5°±8.5° through the desired UWB frequency band from 3.1 to 10.6 GHz. The optimized parameters for the butterfly phase shifter for different phase values are calculated numerically using simulation programs and summarized in Table 2.

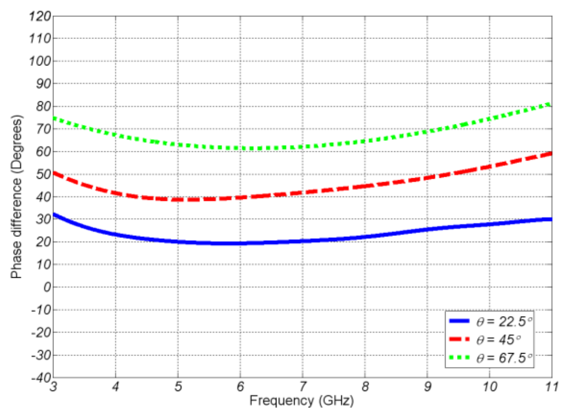


Fig. 6. The calculated phase shift $\angle S_{43} - \angle S_{21}$ of the butterfly phase shifter for different phase shift values, i.e., 22.5°, 45° and 67.5°.

Table 2: Parameters of the butterfly phase shifter for different phase shift values

Parameters	Phase Shift Values		
	22.5°	45°	67.5°
R (mm)	2.9	2.2	1.7
θ°	100°	90°	80°
d (mm)	3.7	3.5	3.0
W_s (mm)	8.5	7.3	5.3
L_s (mm)	6.2	6.0	5.0
l (mm)	33	32	31

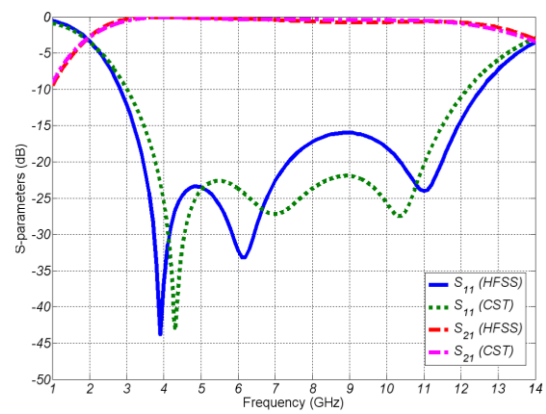
C. Simulation and experimental results

The simulated return and insertion losses for the 45° butterfly phase shifter are illustrated in Fig. 7 (a). Because of the symmetry of the butterfly transition, only return loss at port #1 is shown, i.e., $S_{11} = S_{22}$. It can be seen that the return loss (S_{11}) using both Ansoft HFSS and CST Microwave Studio is better than 13 dB across the whole UWB band. The simulated insertion loss between port #1 and port #2 (S_{21}) is better than 0.8 dB in the 3.1-10.6 GHz band. There is a good agreement between HFSS and CST results.

The measured S-parameters for the butterfly phase shifter are also shown in Fig. 7 (b). The measured results show good return losses and insertion losses, especially at low frequencies; i.e., below 7 GHz. The discrepancies in measured results may be due to the misalignment between the two layers and any other fabrication errors.

The phase difference between ports (1, 2) and ports (3, 4) has been calculated and plotted in Fig. 8 (a). It can be noticed that the phase is almost linear as a function of frequency.

The achieved phase difference ($\angle S_{43} - \angle S_{21}$) is almost 45° with phase error of less than ±7° across the 7.5 GHz UWB frequency bandwidth from 3.1 to 10.6 GHz. The measured phases and phase difference between the ports (1, 2) and ports (3, 4) are shown in Fig. 8 (b). It can be seen that the measured phase difference achieved is varying around 45° but it deteriorated at higher frequencies after 8 GHz.



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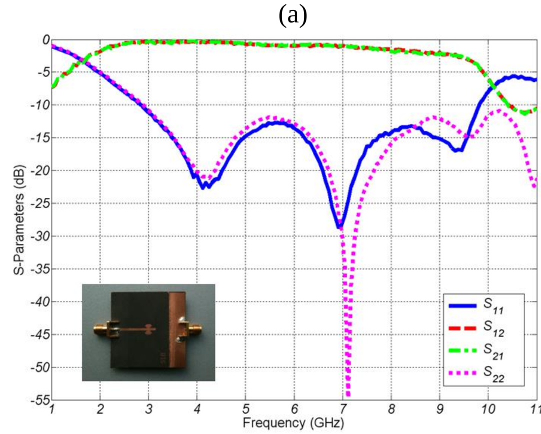

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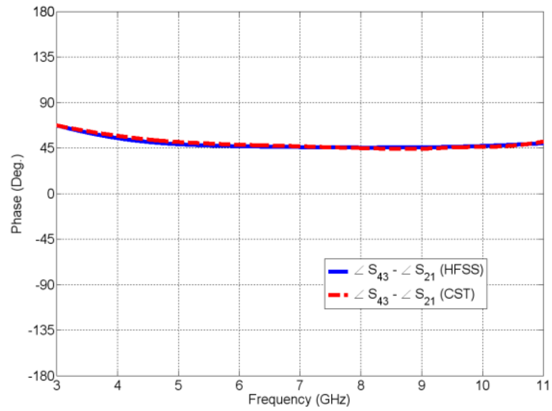
Fig. 7. (a) Simulated and (b) measured return and insertion losses of the proposed UWB 45° butterfly phase shifter.



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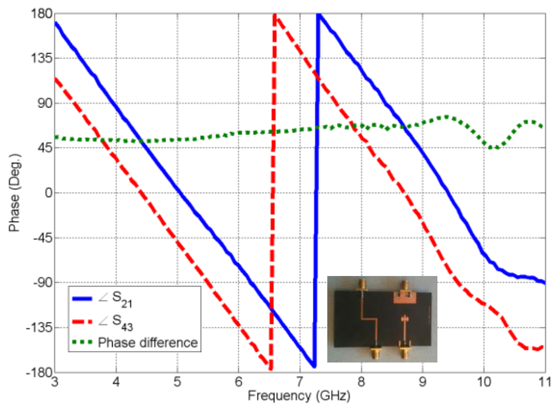

(b)

Fig. 8. (a) Simulated phase difference and (b) measured $\angle S_{21}$ & $\angle S_{43}$ phases and phase difference ($\angle S_{43} - \angle S_{21}$) of the proposed 45° butterfly phase shifter.

IV. CONCLUSION

The design of two different slot-coupled phase shifters for UWB applications has been presented. The proposed phase shifters utilize broadside coupling between trapezoidal and butterfly shaped microstrip patches at the top and bottom layers. Three different phase shift values for both phase shifter designs are proposed 22.5°, 45° and 67.5° to show the possibility to achieve wide range of phase shift values by proper adjusting their physical parameters. Two different 45° trapezoidal and butterfly prototypes have been fabricated and tested experimentally.

REFERENCES

[1] R. C. Hansen, *Chapter Ten—Multiple-Beam Antennas*, in Phased Array Antennas, ser. Wiley Series in Microwave and Optical Engineering, K. Chang, Ed., New York: Wiley, 1998.
[2] J. Butler and R. Lowe, "Beam-forming matrix simplifies design of electronically scanned antennas," *Electron. Design*, pp. 170-173, Apr. 1961.
[3] J. Blass, "Multidirectionnal antenna, a new approach to stacked beams," *IRE Int. Conf. Record*, vol. 8, pt. 1, pp. 48-50, 1960.
[4] J. Nolen, "Synthesis of multiple beam networks for arbitrary illuminations," *Ph.D. Dissertation*, Baltimore, MD, Radio Division, Bendix Corp, Apr. 1965.
[5] Y. T. Lo and S.W. Lee, *Antenna Handbook.* New York: Van Nostrand Reinhold, 1988.
[6] O. M Haraz and A. R. Sebak, "Two-layer butterfly-shaped microstrip 4×4 Butler matrix for ultra-wideband beam-forming applications," *Ultra-Wideband (ICUWB), 2013 IEEE International Conference on*, pp. 1,6, 15-18 Sept. 2013.

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