New Ultra-Wideband Phase Shifter Design with Performance Improvement Using a Tapered Line Transmission Line for a Butler Matrix UWB Application

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Abstract **─** A novel design of a compact Ultra-Wideband (UWB) phase shifter with a new stub shape is presented in this paper. The proposed structure is formed using three layers of conductors interleaved with layers of substrates between each of the conductor's layers. This multilayer technique was proposed to realize a design that is small in size, and a 23 mm × 50 mm compact phase shifter design was accomplished. In addition, the implementation of tapered transmission line techniques improved phase shifter performance, when compared with the conventional design without tapered transmission lines. A parametric study on the tapering of the transmission lines is presented and discussed. The measurement results of the phase shifter satisfactorily agreed with the simulation results. The phase shifters measured results demonstrated ± 5° phase deviation over the UWB frequency range. Moreover, the proposed phase shifter stubs successfully achieved 30% size reduction in comparison with the other available UWB phase shifter.

Index Terms **─** Compact size, multilayer technology, phase shifter, tapered line, ultra-wideband.

I. INTRODUCTION

In past decades, a variety of phase shifter designs have been reported. A phase shifter is one of the microwave devices that have been widely used in microwave applications, such as a Butler Matrices [1-2], a phased array antenna [3-4] and phase modulators. Since the Federal Communication Commission (FCC) approved the commercial implementation of UWB in 2002, rapid growth of UWB devices has been explored and also the phase shifter.

One way to obtain a phase shifter with broadband performance is by employing coupled transmission lines in the design. Early in 1958, B. M. Schiffman proposed a phase shifter that consisted of two transmission lines, with one of the transmission lines as a reference line and the other as a folded edge-coupled section [5]. By selecting the proper degree of coupling and the length of both lines, a very broad bandwidth phase difference between them can be achieved.

However, Schiffman's phase shifter was based on strip-line structures, where odd and even-modes have equal phase velocities along the coupled line when they propagate. When the circuit was employed in the form of microstrip lines, unequal odd and even-mode velocities occurred. This in turn produced poor phase shifter performance [6].

To date, few UWB phase shifter designs have been reported [7-10]. The phase shifter reported in [7] is one of the phase shifters that operated in the UWB frequency range. The phase shifter provided good performance for the UWB application but there was a trade off in size. In [8], the phase shifter is designed with two stubs, short circuited and open circuited at both ends of the microstrip lines. These combinations of short and open-circuited stubs at both ends offer an approximately constant phase difference between output ports. The value of the phase difference is determined by the characteristic impedance of both stubs with respect to the

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reference line. The drawback of the reported design is that the short circuit is in the form of the conducting pin, which is connected to the end of one of the stubs to the ground across the substrate. The corresponding technique will lead to a problem if it has to be realized in a durable or hard substrate.

Therefore in [9], the authors attempted to overcome the aforementioned problem in [8] by replacing the shorting pin with slots to the ground plane. The introduced slots improved the amplitude and the phase characteristic of the phase shifter. Moreover, the phase shifter reported in [9] had a better return loss within the UWB range when compared to [8]. However, these three types of phase shifters are in planar configurations. Thus, there is a need for a multilayer phase shifter, as the multilayer technology is one way to reduce device size and eliminate the crossover needs in the Butler Matrix design. The phase shifter reported in [10] described a phase shifter implementation in multilayer technology.

In this paper, a novel design of a UWB phase shifter is presented. While a variety of phase shifter designs have been reported, the proposed design is built upon the reported design in [10], which has tapered transmission lines and different stub shapes. Because of certain drawbacks associated with the design in [10], such as poor performance in terms of return loss, the proposed work aims to report a phase shifter with UWB performances. In order to meet these goals, slots at the stubs and a tapering transmission line from the input port to the stubs were introduced [10]. Hence, return loss improvement was achieved along with the added advantage of miniaturized stub dimensions. Moreover, additional bandwidth enhancement was obtained by tapering the transmission line [11] and the single slot on the patch led to good impedance matching [12]. The proposed phase shifter stubs exhibit a 30% smaller area size than the other available UWB phase shifters. Thus, this design has important features with regard to developing future phase shifter-based microwave devices, such as a UWB Butler Matrix beam forming network. The parametric analysis of the transmission lines will be discussed to observe the effect of the tapered line on the performance of the phase shifter.

II. DESIGN APPROACH

The design specifications of the proposed phase shifter are shown in Figs. 1 (a) and 1 (b). The device is formed using a microstrip line with multilayer technology.

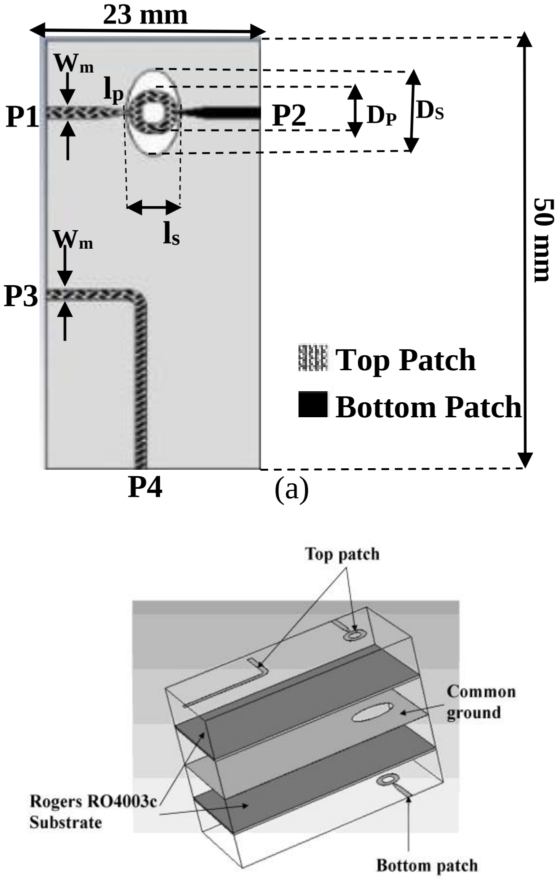
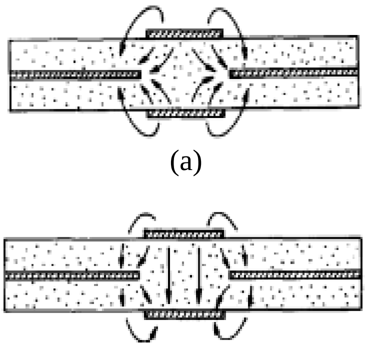


Fig. 1. Design specification of the proposed phase shifter: (a) one-dimensional and (b) three-dimensional.

Multilayer technology was chosen because it provides broad coupling over a very wide band, as there is a slot on the common ground plane that is located in the middle layer. Furthermore, this technology allows smaller device sizes. Four ports are available for the proposed phase shifter: Port 1 (P1), Port 3 (P3) and Port 4 (P4) are located in the top layer, while Port 2 (P2) is located in the bottom layer. The broadside coupling between both P1 and P2 is located in the top and bottom layers. The device is designed on Rogers RO4003C with a thickness of 0.508 mm. The dielectric constant of the material is 3.38.

The phase shifter design is based on even and odd-mode analysis. Figures 2 (a) and 2 (b) illustrate the schematic electric field for the even and odd-modes, respectively. For even-mode excitation, various wave propagation modes will be produced. The magnetic conductor replaces the ground slot and due to the force of the perfect magnetic conductor, the electric field is pushed to the edges of the ground slot, as illustrated in Fig. 2 (a). On the other hand, as illustrated in Fig. 2 (b), for the odd-mode excitation analysis, the ground slot is replaced by a perfect electric conductor. The upper part of the coupler was turned into a microstrip line with a characteristic impedance of Z_{0o}. The electric field in this excitation is concentrated in the parallel-plate region that is formed by the patch and the ground plane.


(a)

(b)

Fig. 2. The electric field of: (a) even-mode analysis and (b) odd-mode analysis [13].

The following steps were taken in order to establish the new proposed phase shifter. From [10], the coupling was chosen to be 0.73, the insertion loss was less than 0.5 dB and the return loss was better than 10 dB for the 45° phase shifter.

The values of the even and odd-mode characteristic impedances are denoted by Z_{0e} and Z_{0o}, respectively. The corresponding parameter can be obtained with the predetermined value of the coupling (0.73) using the following equations [14]:

$$Z_{0e} = Z_0 \sqrt{\frac{\left(1+10^{-\frac{C}{20}}\right)}{\left(1-10^{-\frac{C}{20}}\right)}}, \qquad (1)$$

$$Z_{0o} = Z_0 \sqrt{\frac{\left(1-10^{-\frac{C}{20}}\right)}{\left(1+10^{-\frac{C}{20}}\right)}}, \qquad (2)$$

where C is the coupling factor, which is equal to 3 dB and the value of the characteristic impedance Z_0 is 50 Ω. Hence, the value of Z_{0e} and Z_{0o} are found to be 126.6 Ω and 19.8 Ω, respectively. Then, the coupled region needs to be calculated using (3) and (4) [14]:

$$Z_{0e} = \frac{60\pi}{\sqrt{\varepsilon_r}} \frac{K(k_1)}{K'(k_1)}, \qquad (3)$$

$$Z_{0o} = \frac{60\pi}{\sqrt{\varepsilon_r}} \frac{K(k_2)}{K'(k_2)}, \qquad (4)$$

where ε_r is the dielectric constant of Rogers R4003C, which is equal to 3.38, $K(k)$ = first kind elliptical integral and $K'(k) = K\left(\sqrt{1-k^2}\right)$. The parameters for k_1 and k_2 are determined using equations (5) and (6). These equations are used to find the dimension of the stubs, D_p and the slot D_s:

$$k_1 = \sqrt{\frac{sinh^2\left(\frac{\pi D_S}{16h}\right)}{sinh^2\left(\frac{\pi D_S}{16h}\right) + cosh^2\left(\frac{\pi D_p}{16h}\right)}}, \qquad (5)$$

$$k_2 = \tanh\left(\frac{\pi D_p}{16h}\right), \qquad (6)$$

where D_s is the diameter of the elliptical for the slot, D_p is the diameter of the elliptical-slot for the microstrip patch and h is the thickness of the substrate.

The length of the phase shifter's stubs and slot, l must be attained. The value of l is chosen to be equivalent to a quarter of the effective wavelength at the centre frequency $\frac{\lambda_e}{4}$. Next, the design procedure is to obtain the width of the transmission and reference line w_m. This can be achieved using equation (7) [14]:

$$\frac{w_m}{h} = \begin{cases} \dfrac{8e^A}{e^{2A}-2}, \\ \dfrac{2}{\pi}\left[B - 1 - \mathrm{D} + \dfrac{\varepsilon_r - 1}{2\varepsilon_r}(E)\right], \end{cases} \qquad (7)$$

where

$$D = \ln(B-1),$$

$$E = D + 0.39 - \frac{0.61}{\varepsilon_r},$$

$$A = \frac{Z_0}{60}\sqrt{\frac{\varepsilon_r+1}{2}} + \frac{\varepsilon_r - 1}{\varepsilon_r + 1}\left(0.23 + \frac{0.11}{\varepsilon_r}\right),$$

and

$$B = \frac{377\pi}{2Z_{0o}\sqrt{\varepsilon_r}}.$$

Using equations (5) to (7), the calculated dimensions of the phase shifter are as follows: w_m=1.18 mm, D_s=7.5 mm, D_p=4.9 mm and l_p=l_s=7.2 mm. Then, the transmission line is tapered with an angle θ of 15^0. Subsequently, the slotted structure at the stubs is optimized to determine the dimension that gives the best performance. All the simulations for this design were carried out using the CST Microwave Studio software. Table 1 shows the computed and optimized dimension values. As seen in Table 1, the dimension of the stub's area in the designed phase shifter is 30% smaller than the phase shifter proposed in [10].

Table 1: Computed and optimized values of the design parameters

Parameter Value (mm)	D_s	D_p	l_p	l_s
Calculated	7.5	4.9	7.2	7.2
Optimized	10.0	5.0	5.0	5.7

III. ANALYSIS OF THE PERFORMANCE OF THE TAPERED LINE DESIGN

Three simulations were carried out to study the effect of the tapered transmission line on the performance of the phase shifter, including the return loss (S11), insertion loss (S21) and the phase difference between S21 and the reference line. Figures 3 (a) and 3 (b) show the phase shifter designs with and without the tapered transmission line, respectively.

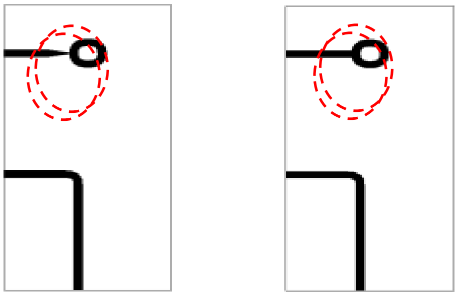
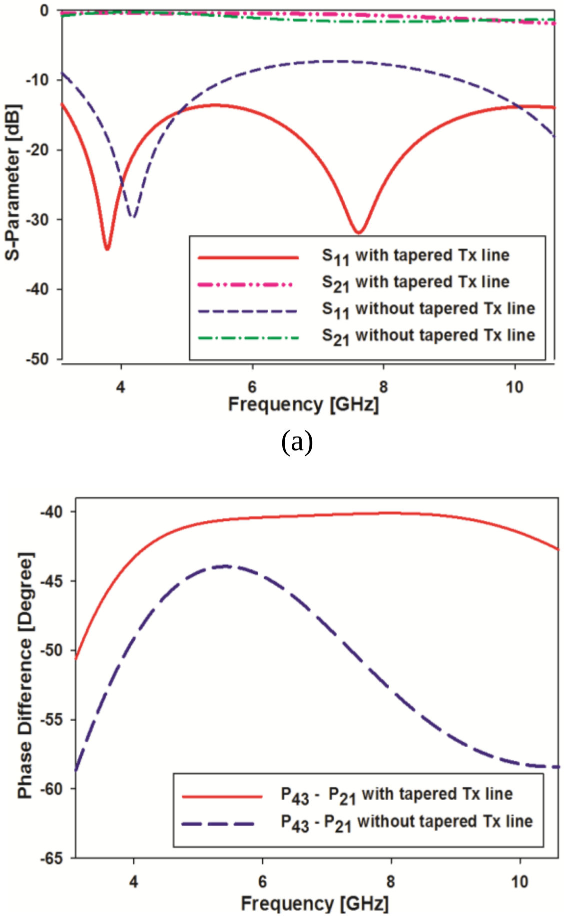

(a) (b)

Fig. 3. Designed phase shifter: (a) with the proposed tapered transmission line and (b) without the tapered transmission line.

Figures 4 (a) and 4 (b) show the differences in the scattering parameter and the phase performances of the designed phase shifter, respectively. Based on both figures, a significant difference is observed between the phase shifters. In Fig. 4 (a), the simulation results for the scattering parameters of both phase shifter designs show that the return loss is better than 13.1 dB and the insertion loss is better than 1.9 dB for the phase shifter with the tapered transmission line. For the phase shifter without the tapered transmission line, the return loss tended to be only better than 7.3 dB and the insertion loss was better than 1.7 dB. In Fig. 4 (b), the phase difference between S21 and the reference line S43, is 45° ± 5° for the simulation of the phase shifter with the tapered transmission line; whereas, for the simulation of the phase shifter without the tapered transmission line, the phase difference is 45° ± 15°over the band.

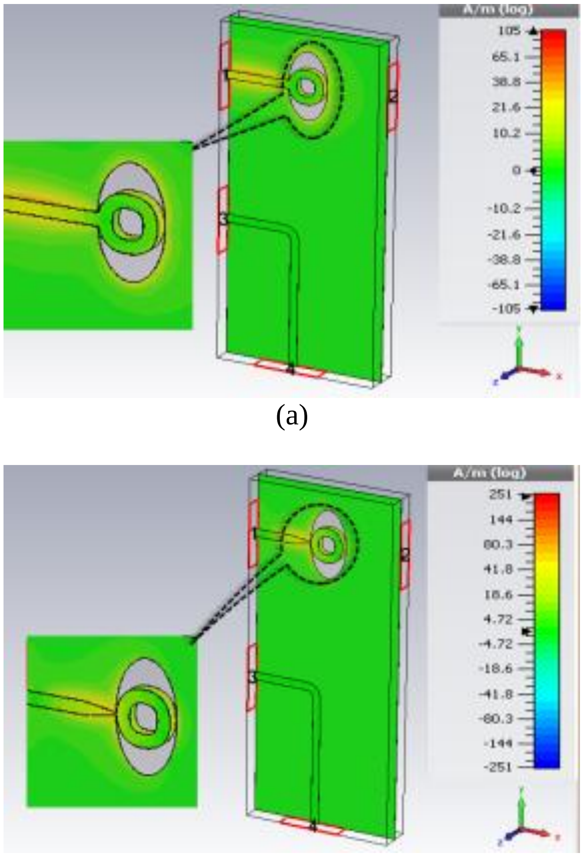
From the analysis, it is observed that the proposed phase shifter with the tapered transmission line provides better performance than the one without the tapered transmission line. Figures 5 (a) and 5 (b) show the current distribution for the phase shifter designs with and without a tapered transmission line, respectively; which can explain the manner of the analysis mentioned in Fig. 4.



(a)
(b)

Fig. 4. Comparison between the phase shifter designs with and without a tapered transmission line for: (a) the scattering parameter and (b) the phase difference of the fabricated phase shifter.

The current distribution shown in Fig. 5 (a) is gathered around the transmission line that has been tapered. Moreover, the current distribution seen in Fig. 5 (b) is partially flowing at the input port, but when it approaches the stubs, the current distribution reduces. This situation in Fig. 5 (b) shows that the signal from the input port does not go completely toward the stubs, as the signal is partially lost as it travels to the stub. This situation led to the poor simulation results for the phase shifter without the tapered transmission line shown in Fig. 4. Therefore, with the tapered transmission lines, the performance of the phase shifter can be improved by maintaining other parameters value.



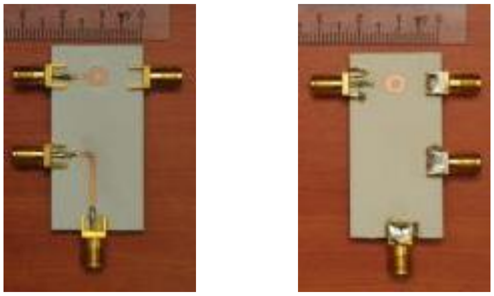
(a)

(b)

Fig. 5. Current distribution of the phase shifter design: (a) with the tapered transmission line and (b) without the tapered transmission line.

IV. RESULTS AND DICUSSION

In order to verify the performance of the proposed phase shifter design, a prototype was fabricated. Figures 6 (a) and 6 (b) show the front and the back of the fabricated phase shifter, respectively. The prototype phase shifter was then measured using a Vector Network Analyzer (VNA).



(a) (b)

Fig. 6. The fabricated phase shifter: (a) front view and (b) back view.

The comparisons of the simulation and measurement results for the return loss, insertion loss and the phase difference of the phase shifter are shown in Figs. 7 and 8, respectively. Based on the results shown, there is satisfactory agreement between the simulation and measurement results.

For the simulation results, based on Fig. 7, the return loss is better than 13.1 dB and the insertion loss is better than 1.9 dB; whereas, for the measurement results, the return loss and the insertion loss were better than 10.2 dB and 3.5 dB, respectively. In Fig. 8, the phase difference between S21 and the reference line S43, is 45° ± 5° for the simulation; whereas, for the measurement results, the phase difference is 45° ± 6° over the UWB band.

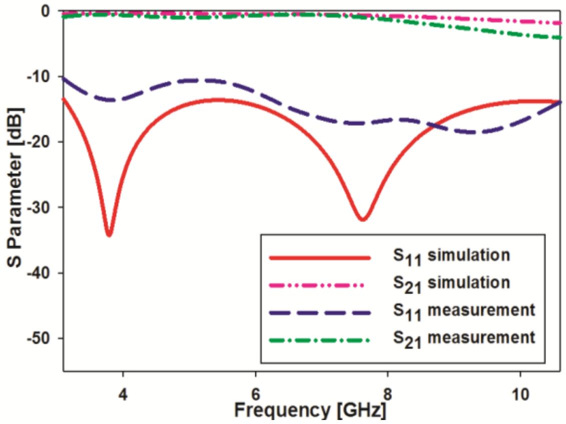


Fig. 7. Comparison between the simulation and measurement results for the scattering parameter of the fabricated phase shifter.

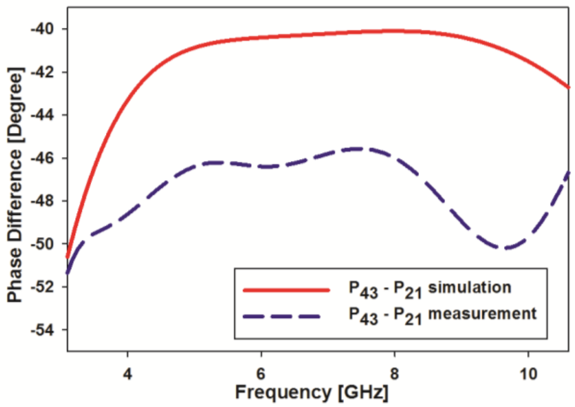


Fig. 8. Comparison between simulation and measurement results for the phase difference of the fabricated phase shifter.

From both figures, it can be observed that there are slight dissimilarities between the simulation and measurement results. Several reasons have been identified with regard to why the fabricated phase shifter did not perform exactly as the simulation results. A recent literature review shows that an air gap problem has a large impact on the performance of multilayer technology devices [15]. Since the fabrication process was done manually, using non-conductive glue to hold both substrates, an air gap might have occurred during the fabrication process. In order to overcome this problem, highly accurate machines should be used in the fabrication process. Moreover, additional insertion loss dissimilarities between the simulation and measurement results are due to the SMA connectors that were included in the measurements but not in the simulations [10].

V. CONCLUSION

A novel design of a phase shifter with a new stub shape and dimensions of 23 mm × 50 mm has been presented. The proposed design was accomplished using multilayer technology and the structure was formed using three layers of conductors interleaved with a layer of substrate between each of the conductor layers. This multilayer technique was proposed to realize a design that was small in size. The implementation of tapered transmission lines improved the performance of the phase shifter when compared to a phase shifter without the tapered transmission lines. A parametric study showed that the tapered transmission line improved the performance of the coupler. Moreover, the measurement results for the coupler satisfactorily agreed with the simulation results. The proposed design can be used in ultra-wideband applications, since the phase deviation is only ± 5° over the UWB frequency range.

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