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COMPACT ULTRA-WIDEBAND PHASE SHIFTER

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Abstract—Design of a compact planar phase shifter is described that possesses ultra-wideband (UWB) performance. The proposed device is composed of $50\,\Omega$ input/output microstrip-lines which are connected to a low-impedance rectangular microstrip patch, and located at close proximity to each other. The common ground-plane incorporates a

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slot-line terminated with two rectangular slots, which are located under the rectangular patches in order to provide effective electromagnetic coupling between the microstrip-line and slot-line. Thus a phase shifter is realized with ultra-wideband characteristics on a single substrate. The length of the slot-line and width of patch determines the desired phase shift required between the input and output ports. It is demonstrated that the design can provide phase shift anywhere between 4°–27° across the entire UWB frequency band from 3.1 to 10.6 GHz. The simulated results show fixed phase shift $5.625° \pm 0.865°$, $11.25° \pm 1.93°$ and $22.5° \pm 2.5°$ with insertion-loss less than 0.5 dB and return-loss better than 12 dB across the ultra-wideband frequency span. The phase shifter is relatively compact in size with a dimension of $15 \times 25\,\text{mm}^2$. The phase shifter was fabricated and its performance measured to validate the simulation results.

1. INTRODUCTION

Phase shifters are fundamental components in numerous microwave circuits and subsystems, which are widely used in electronic beam-scanning phased arrays and radars. In recent years, UWB phase shifters have been widely studied for next generation systems. A typical phase shifter includes a coupled transmission-line device for broadband performance and is commonly referred to as the Schiffman differential phase shifter [1]. It consists of two transmission-lines that mainly exploit the phase difference between the reference guide and the specific degree of the phase shift at a given port. Schiffman's study was based on stripline transmission-lines, where phase velocities are equal in both the odd and even modes. However, when the Schiffman phase shifter is realized using microstrip technology, because of the unequal odd and even mode velocities, poor performance is achieved [2]. Much effort has been put to improve the performance of the Schiffman phase shifter by, for example, using of a cascade pairs of coupled transmission-lines connected together [3] and multiple parallel-coupled quarter-wave sections [4]. By modifying the ground-plane underneath the coupled lines, wideband Schiffman phase shifter is achieved from 1.0 to 3.5 GHz with $\pm 5°$ phase imbalance [5]. Also in an effort to improve the performance of the edge-coupled phase shifters, Taylor and Prigel [6], used a wiggling technique to design a broadband phase shifter. This approached used the wiggled edged coupled microstrip lines as a means of slowing the odd-mode microwave-energy propagation velocity to equal the even-mode propagation velocity and achieve broadband operation. The results indicate narrowband performance and suggest fabrication difficulties due to the very narrow space required between the coupled lines to accomplish a good performance. Other techniques employed to build planar phase shifters include Ahn and Wolff [7] who introduced several asymmetric Ring-hybrid phase shifters, which consists of a ring hybrid and reflecting terminations. The measured and simulated results in [7] indicate that the proposed design does not have the broadband characteristics of the edge-coupled structures. More recently Abbosh [8] proposed a method to realize a phase shifter that exploits broadside coupling between top and bottom elliptical microstrip patches via an elliptical slot located in the mid layer, which forms the ground-plane. The design method has been used to design 30° and 45° phase shifters on a multilayer substrate. The dimension of these phase shifters is $25 \times 20\,\text{mm}^2$.

In this paper, we propose an ultra-wideband phase shifter implemented on a single substrate with the use of the microstrip to slot-line transition technique. This configuration consists of two microstrip-lines with rectangular patches terminating their ends etched on top of the substrate and a slot-line with rectangular ends etched on the ground-plane. The slot-line is orthogonally oriented with respect to the input/output microstrip-lines. This configuration is demonstrated to provide phase shifts anywhere within the range 4°–27° over an ultra-wideband frequency span. The proposed method is used to demonstrate designs providing phase shifts of 5.6°, 11.25° and 22.5°. The simulated and measured results show that the phase shifter design achieves phase stability better than ±2.5°, insertion-loss less than 0.5 dB, and return-loss better than 10 dB across 3.1–10.6 GHz. In addition, the proposed phase shifter is of a simple construction and compact design that lends itself to low cost fabrication.

2. UWB PHASE SHIFTER DESIGN

It is well known that the phase shift can be realized by changing either the phase constant of the propagating signal or the physical length over which the signal traverses between input and output ports. It means than at a given operating frequency f, that:

$$\varphi(f) = \beta(f)\, l \tag{1}$$

where $\beta(f)$ are the phase constant of the microstrip transmission line. $\beta(f)$ can be derived using formulas given as in [9], i.e., $\beta(f)$ can be simplified to

$$\beta(f) = \sqrt{\left(\frac{\pi\sqrt{\varepsilon_r}f}{150}\right)^2 - \left(\frac{\pi}{w}\right)^2} \tag{2}$$

where f in GHz, and w is in millimetres.

This expression indicates phase constant of a signal can be changed by altering its width between two lines (for example if we consider two lines with different widths w_1, w_2) also by changing its physical length. The phase shift across a physical length Δl can be calculated using (1). The first order derivative of $\varphi(f)$ is [9]

$$\frac{d\varphi\left(f\right)}{df} = \frac{\pi\varepsilon_r\Delta l}{150^2} \times \frac{f}{\sqrt{\left(\frac{\sqrt{\varepsilon_r}f}{150}\right)^2 - \left(\frac{1}{w_d}\right)^2}} > 0 \qquad (3)$$

This implies that if we alter physical length, then $\varphi(f)$ changes linearly with increasing frequency. Also, if we have unequal-width, $\varphi(f)$ decreases versus increasing frequency according to below formula

$$\frac{d\varphi\left(f\right)}{df} = \frac{\pi\varepsilon_r\Delta l f}{150^2\sqrt{\left(\frac{\sqrt{\varepsilon_r}f}{150}\right)^2 - w_1^{-2}}} - \frac{f}{\sqrt{\left(\frac{\sqrt{\varepsilon_r}f}{150}\right)^2 - w_2^{-2}}} < 0 \qquad (4)$$

Based on this principle the configuration of the proposed phase shifter is shown in Fig. 1. As shown the phase shifter comprises of two microstrip-lines connected to rectangular microstrip patches on the top layer of the substrate and a slot-line connecting two rectangular slots in the ground-plane. The slot-line is orthogonal with respect to the microstrip-line. The input signal fed into one microstrip-line propagates along the line and is electromagnetically coupled to the slot-line at the interface between the capacitive rectangular patch and the rectangular ground-plane slot. The slot-line guides the wave to the adjoining rectangular slot and couples the energy to the output microstrip-line via the second rectangular patch. The length of the microstrip-line and the slot-line are about one quarter guide-wavelength. The width of the rectangular slot was calculated according to [10].

According to (3) and (4), the physical length and unequal-width limits the operational bandwidth of the phase shifter. This phenomenon was verified by simulation. In the first phase shifter design the physical length was changed ($c - a = 1$ mm) while the width was fixed. As shown in Fig. 2, the phase shift varies linearly with frequency. In the second design, the length was fixed and the patch width ($W_3 - W_1 = 1.5$ mm) was changed. This resulted in the phase shift to decrease with frequency. Hence, this performance is used to realize a wideband phase shifter.

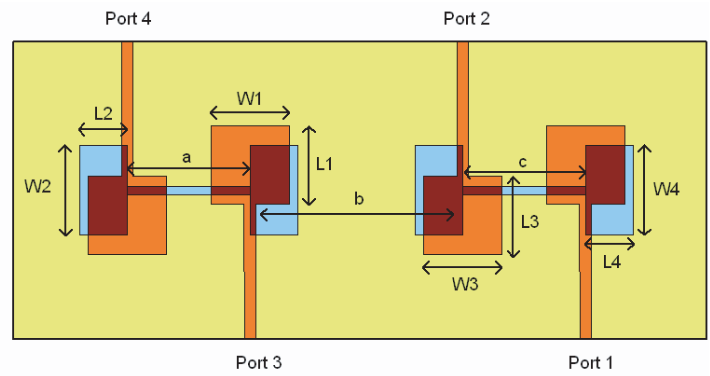


Figure 1. Configuration of the proposed wideband phase shifter.

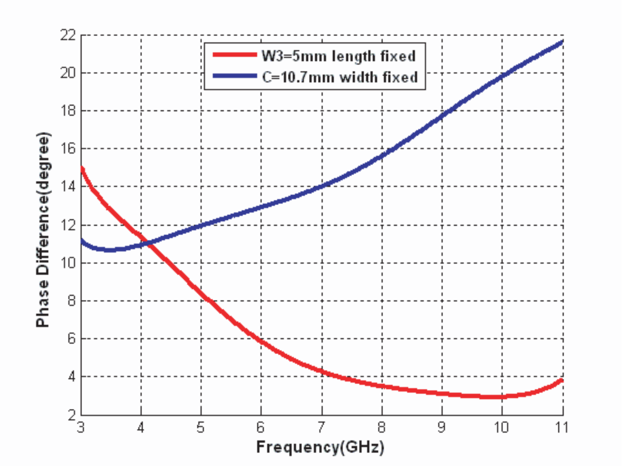


Figure 2. Phase shift property due to physical length change and unequal-width change.

3. PARAMETRIC STUDY

The proposed wideband phase shifter, in Fig. 1, has four parameters that dictate its phase shift property performance. These parameters are W_3, L_3, c and L_4, respectively. Fig. 2 shows how the width of patch W_3 affects the phase, while all other parameters were kept fixed. This graph shows the phase can be controlled by marginally changing W_3, and the phase shift decreases with frequency from 3 to 8 GHz, thereafter becoming constant accept for a width of 6 mm where the phase begins to rise. The affect of slot width L_4 is shown in Fig. 3. In this case, the phase decreases with frequency from 3 to 7.5 GHz after which it rises. The patch length L_3 affected the phase shift in an identical fashion to Fig. 4.

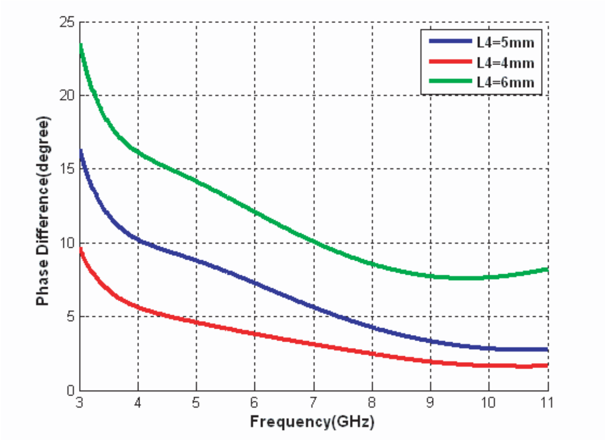


Figure 3. Phase shifts generated by different widths for fixed length.

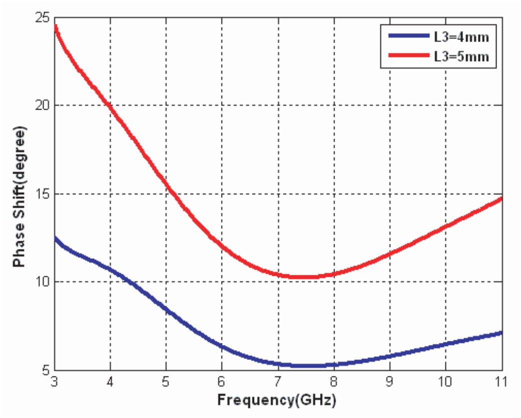
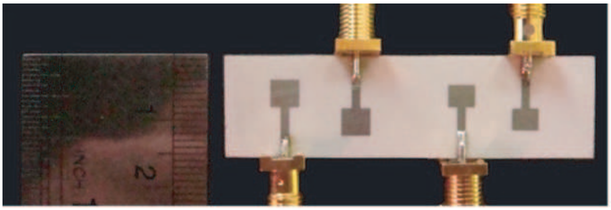


Figure 4. Phase shifts generated by different patch lengths for fixed width.

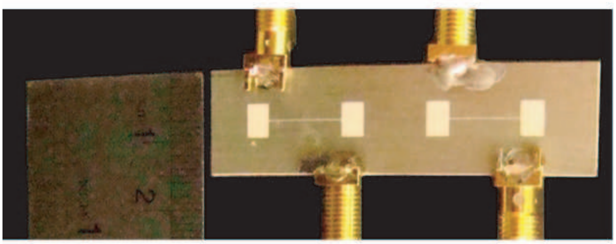
4. SIMULATED AND MEASURED RESULTS

The validity of the proposed phase shifter was tested by fabricating it and measuring its performance over the ultra-wideband frequency range 3.1–10.6 GHz. The substrate used to construct the device was Rogers R04003C ($\varepsilon_r = 3.38$, $h = 0.508$ mm, loss-tangent = 0.0027). The length of the 50 Ω microstrip feed-lines and the length of slot-line on the ground-plane are approximately one quarter guide-wavelength. The device in Fig. 1 is shown to provide phase shifts of 5.625°, 11.25°, 22.5° degrees between ports 1 and 2, while ports 3 and 4 were used as a reference guide. A photograph of manufactured 22.5° phase shifter is shown in Fig. 5. The dimension of this phase shifter is $25 \times 15\,\text{mm}^2$.

The software HFSSv10 was used to analyze the affect of the phase shifters parameters, as defined in Fig. 1, on its performance. This analyzes enables the phase shifters performance to be optimized by adjusting the length and widths of the rectangular microstrip patches, rectangular slots and their positions relative to each other. The dimensions of the input and output transmission-lines, i.e., W_1, L_1, W_2 and L_2, were kept constant in the simulation analysis. The simulated and measured result in Fig. 6 shows that the phase shifter provides a return-loss better than 10 dB and insertion-loss less than 0.5 dB across 3 to 11 GHz.



(a)



(b)

Figure 5. Photograph of the phase shifter. (a) Top layer. (b) Bottom layer.

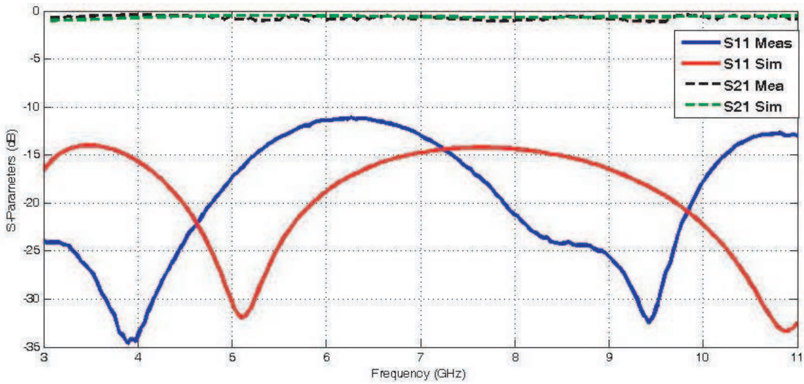


Figure 6. Simulated and measured performance of the proposed phase shifter.

Table 1. Values of design parameters (unit in millimeters).

phase	W_1	W_2	W_3	W_4	L_1	L_2	L_3	L_4	a	b	c
22.5	3.9	4.8	4.2	4.8	3.2	3.2	4	3.2	8.3	14.3	9.25
11.25	3.9	4.8	4.5	4.8	3.2	3.2	3.29	3.2	8.3	14.3	8.75
5.625	3.9	4.8	4.4	4.8	3.2	3.2	3.1	3.2	8.3	14.3	8.51

The study undertaken indicates that a wideband phase shift can be achieved by changing the distance of slot-line c between the input and output ports, and by varying the patch width W_3. It was found that to reduce the phase error the parameters L_3 and W_3 need to be optimized. The parameters to realize phase difference of 5.625°, 11.25°, 22.5°, are given in the Table 1.

The simulated and measured phase shift ($\Delta\Phi$) for the 22.5° phase shifter is shown in Fig. 7. The correlation is good between 3 and 5 GHz, and between 8 and 9 GHz. The measured phase shift is 22.5° ± 2.5° between 3 and 11 GHz. As indicated in the introduction we are comparing our proposed structure with a phase shifter by Abbosh's in reference [8]. In fact Abbosh proposes a structure that generates a phase shift of 30 and 40 degree with broadside coupling technique. He didn't study the phase difference for low phase degrees, so we proposed a structure that covers this deficiency. However, we recognise that certain application will require higher phase shifts, like 45°, 90°, and 180°. In addition, this study doesn't include housing as it demonstrates the principle of the innovation. The housing will improve the performance when designed properly by minimising radiation loss.

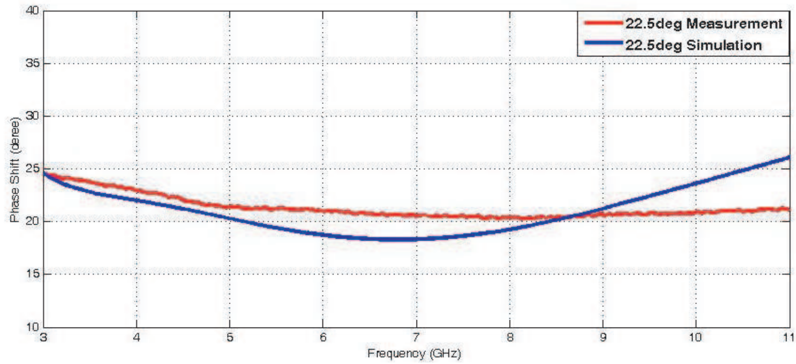


Figure 7. Measured performance of the proposed phase shifter.

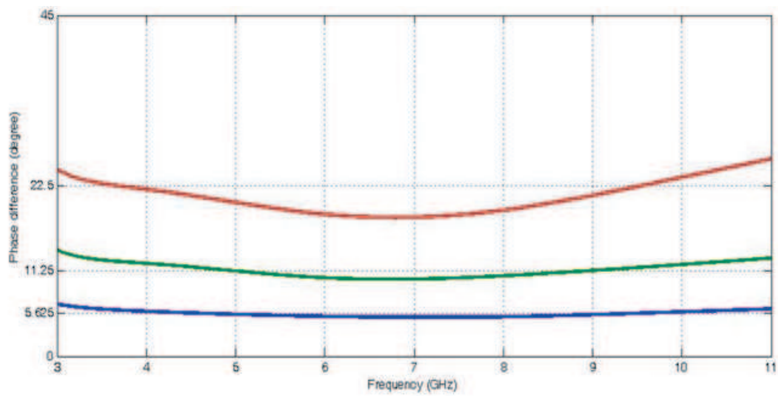


Figure 8. Simulation results of the proposed phase shifter.

Figure 8 shows the simulated performance of the three phase shifters using the proposed technique. The dimensions of the other two phase shifters are given in Table 1. The phase tolerance of the two phase shifters are $5.625° \pm 0.865°$ and $11.25° \pm 1.93°$ over 3 to 11 GHz.

5. CONCLUSION

A technique is described to design a phase shifter for UWB application. In the proposed phase shifter the signal propagates between the input and output ports via microstrip-line, ground-plane slot-line, and microstrip-line. Coupling is enhanced via capacitive rectangular microstrip patches connected at the end of the feed-lines, and by using rectangular slots at either ends of the slot-line in the ground-plane. This configuration also enhances the device's operational bandwidth. The phase shifter is relatively compact size in size ($15 \times 25\,\mathrm{mm}^2$) and is suitable for providing phase shifts in the range 4°–27°. To validate our work we have fabricated phase shifter for 22.5°. The phase shifter provides very good insertion-loss and return-loss characteristics across the UWB frequency range.

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