

26 GHz phase shifters for multi-beam nolen matrix towards fifth generation (5G) technology

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ABSTRACT

This paper presents the designs of phase shifters for multi-beam Nolen matrix towards the fifth generation (5G) technology at 26 GHz. The low-cost, lightweight and compact size 0° and 45° loaded stubs and chamfered 90°, 135° and 180° Schiffman phase shifters are proposed at 26 GHz. An edge at a corner of the 50 Ω microstrip line Schiffman phase shifter is chamfered to reduce the excess capacitance and unwanted reflection. However, the Schiffman phase shifter topology is not relevant to be applied for the phase shifter less than 45° as it needs very small arc bending at 26 GHz. The stubs are loaded to the phase shifter in order to obtain electrical lengths, which are less than 45°. The proposed phase shifters provide return loss better than 10 dB, insertion loss of -0.97 dB and phase difference imbalance of ± 4.04° between 25.75 GHz and 26.25 GHz. The Rogers RT/duroid 5880 substrate with dielectric constant of 2.2 and substrate thickness of 0.254 mm is implemented in the designs.

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1. INTRODUCTION

Phase shifter is used extensively nowadays as a passive component, which able to provide a specific phase difference between two output ports of main line and reference line that specifically plays a vital role in beamforming network such as Nolen [1-5], Blass [6-10] and Butler matrices [11-15]. Thus to enhance the capability in phase shifting, myriad types of phase shifters have been studied and proposed by researchers. One of the designs, as reported in [16], utilized mounting tunable components, which are varactor diodes. The adjustable phase differences between -157° and 193° at 1.5 GHz are achieved by varying bias voltages of the varactor diodes. This design has the simulated and measured return loss and insertion loss, which are better than 10 dB and 2.6 dB for distinct phase differences between 1 GHz and 2 GHz, respectively. The high insertion loss especially is mainly caused by the diodes' parasitic capacitances. In addition, the presence of the varactor diodes increases the complexity of the circuit configuration.

In order to design a simpler configuration of the phase shifter without any active component, a square-shaped phase shifter using multi-layer technology is proposed in [17]. The performance degradation of the return loss, insertion loss and phase difference at less than 5.1 GHz have occurred might be due to the issues of misalignment and presence of air gap between the substrate layers. In order to circumvent this issue, a single layer phase shifter consisting a T-shaped open stub loaded transmission line (main line) at the center of the half wavelength transmission line and a reference line using Schiffman uniform line topology in [18]

has been designed. The performance degradation of the proposed phase shifter at less than 2.5 GHz and beyond 5.5 GHz is occurred due to the junction discontinuities of the loaded T-shaped open stub.

Another simpler configuration of the phase shifter using single layer technique based on a short-circuited stub as well as a weak-coupled line is proposed in [19]. The reference line is bent due to a long electrical length. The simulated and measured return loss and insertion loss responses of the proposed phase shifter are better than 10 dB and less than 0.5 dB between 0.66 GHz and 2.56 GHz, respectively. The fabrication limitation for the minimum 0.1 mm realizable gap between the edge-coupled lines contributes discrepancies in the return loss and insertion loss responses at less than 0.66 GHz and beyond 2.56 GHz. Meanwhile, another single layer phase shifter design with a fixed 45° Schiffman meander line topology is proposed at 35 GHz in [20] by using the same bending technique as reported previously in [19]. The configuration design is very simple and easy to fabricate. The simulated return loss and insertion loss show better than 10 dB and approaching 0 dB at 35 GHz. The simulated phase difference characteristic is 45° at 35 GHz.

In this paper, the designs of 0° (reference line), 45°, 90°, 135° and 180° (main line) phase shifters specifically for multi-beam Nolen matrix are presented using single layer technique at 26 GHz utilizing Rogers RT/duroid 5880 substrate with dielectric constant of 2.2 and substrate thickness of 0.254 mm. The elliptical stub and chamfered rectangular stub are introduced for 0° and 45° phase shifters, whereas Schiffman phase shifter using arc bending approach is used for the remaining 90°, 135°, and 180° phase shifters.

2. PHASE SHIFTER DESIGN

Two loaded stubs and six Schiffman phase shifters are designed at 26 GHz as depicted in Figure 1, which then can be integrated with couplers in developing the proposed Nolen matrix. The Schiffman phase shifter topology is not applicable to be applied for the phase shifters less than 45° as it needs very small arc bending at a super high frequency, which difficult to be fabricated due to the fabrication limitation of the minimum 0.1 mm for the microstrip width. Hence, the design approach using stub loaded is introduced for 0° (reference line) and 45° phase shifters of the switched-beam Nolen matrix. The stubs are loaded to the 50 Ω transmission line in order to obtain electrical lengths, which are less than 45°. Dimensions of x-radii (r_x and r_{x2}) and y-radii (r_y and r_{y2}) of the elliptical stubs as depicted in Figure 1 (a) and Figure 1 (b) are optimized to enhance flatness of the phase characteristic for the 0° (reference line) and 45° phase shifters, respectively. The length and width of the chamfered rectangular stubs for the 45° phase shifters are optimized to improve the impedance matching of the Nolen matrix.

Nevertheless, the stubs loaded approach is not suitable to be applied for the remaining phase shifters with electrical lengths greater than 45° as it needs large space for extending the radius of elliptical stubs, r_{x2} . Hence, the Schiffman phase shifter using arc bending approach is proposed for the remaining phase shifters (90°, 135° and 180°). The widths of the Schiffman phase shifters, W_1 remain same as the widths of feeding transmission lines but the lengths of the Schiffman phase shifters, L_{sx} are changing relative to the required phase values. These corresponding extended lengths of Schiffman phase shifters are bent into arcs. The phase difference of the phase shifters that due to the different length between main and reference transmission line that can be determined by using (1) [20-21]:

$$\text{Phase difference, } \Delta\Phi = \frac{2\pi(L_m - L_r)}{\lambda_g} \quad (1)$$

where L_m , L_r and λ_g are the main length, reference length, and guide wavelength, accordingly. The main length, L_m and reference length, L_r are optimized to obtain the desired phase difference between the main line and the reference line.

As seen in Figure 1 (c), the edge at a corner of the 50 Ω microstrip line Schiffman phase shifter is chamfered with detailed illustration as shown in Figure 2 for the purpose of achieving the best performance result and less power loss of the device. The chamfering edge also known as mitred bend technique is employed in the design of Schiffman phase shifter. A mismatch loss will occur as the right-angled bend of the conventional microstrip line increases a small amount of capacitance. Usually, the transmission line is bent at 45° in order to reduce the associated mismatch [22]. In addition, the chamfering edge at the corner of the microstrip line reduces the excess capacitance and unwanted reflection as well as readjust the microstrip line back to the 50 Ω. This chamfering edge will provide good compensation for the super high frequency. Referring to Figure 2, the chamfering edge at each corner of the 50 Ω microstrip line Schiffman phase shifter can be deployed with optimum values of chamfering dimensions when the condition of $0.5 \leq W/h \leq 2.75$ and $\epsilon_r < 25$ is selected as given by (2) to (5) [23-24]:

$$D=W_t \sqrt{2} \tag{2}$$

$$x=W_t \sqrt{2} (0.52 + 0.65 e^{-1.35 \frac{W_t}{h}}) \tag{3}$$

$$A=\sqrt{2} (x - \frac{D}{2}) \tag{4}$$

$$M=(52 + 65 e^{-1.35 \frac{W_t}{h}}) \times 100\% \tag{5}$$

where D , W_t , x , h , A and M are the diagonal length for the outer corner of the unchamfered bend, the width of the 50 Ω transmission line, diagonal length for the inner corner of the unchamfered bend, substrate thickness, compensated length for optimal bend and optimum miter percentage, respectively.

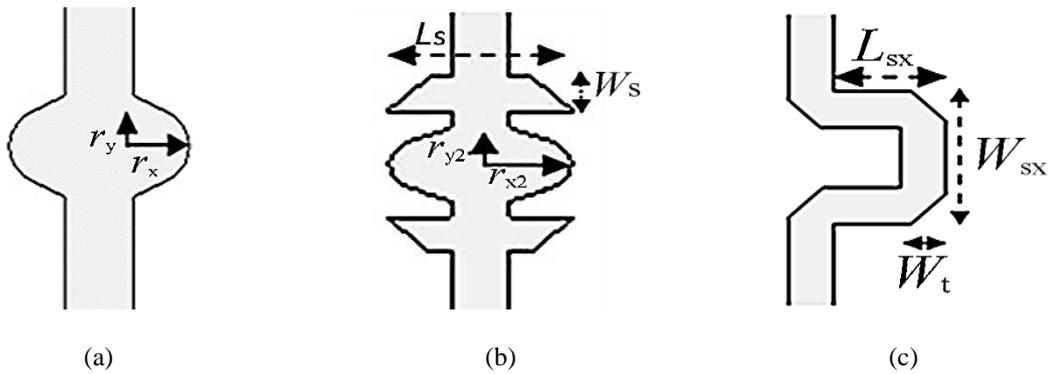


Figure 1. Layout of the phase shifters, (a) 0° stub loaded phase shifter (reference line), (b) 45° stub loaded phase shifter (main line), (c) Schiffman phase shifter (main line)

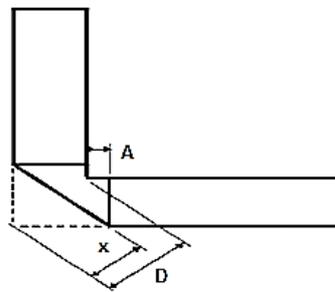


Figure 2. Dimension for a chamfering edge at a corner of 50 Ω microstrip line [23]

However, the optimum values of the chamfering dimension can be acceptable if the optimum miter percentage, M is approximately 50% when the condition of $W_t/h \geq 2.75$ and $\epsilon_r \leq 25$. The optimum miter percentage, M can be calculated using (5) [25]. The optimized dimensions of the proposed phase shifters are listed in Table 1. The performance of the designed phase shifters will be discussed in the next section.

Table 1. Optimized dimensions of the proposed phase shifters

Phase Shifters	Dimension (mm)							
	r_x	r_y	r_{x2}	r_{y2}	L_s	W_s	L_{sx}	W_{sx}
Stub loaded 0° phase shifter (reference line)	0.85	0.56						
Stub loaded 45° phase shifter			1.23	0.56	3.20	0.50		
Schiffman 90° phase shifter							1.75	2.79
Schiffman 135° phase shifter							2.25	2.79
Schiffman 180° phase shifter (Left)							3.04	2.79
Schiffman 180° phase shifter (Right)							0.97	2.79
Schiffman 0° phase shifter (reference line)	0.85	0.56						
Additional Schiffman 0° phase delay			1.23	0.56	3.20	0.50		

3. RESULTS AND ANALYSIS

The performance of the proposed 45° , 90° , 135° , and 180° phase shifters are assessed across the designated frequency interval between 25.75 GHz and 26.25 GHz and plotted in Figure 3 to Figure 6, respectively. The phase differences of the phase shifters ranging from 45° to 180° are compared to reference lines of 0° . As seen in Figure 3, reflection coefficients, S_{ii} ($i=1, 2, 3, 4$) of the proposed 45° stub loaded phase shifter are lower than -10 dB across the operated frequency interval between 25.75 GHz and 26.25 GHz, which indicate almost 90 % input power is delivered to the antenna and reflected power is less than 10 %. Meanwhile, the transmission coefficients, S_{21} and S_{43} are approximately -0.48 dB between 25.75 GHz and 26.25 GHz. The phase difference between the main line and the reference line is $45^\circ \pm 1.63^\circ$ between 25.75 GHz and 26.25 GHz. At the center frequency of 26 GHz, both reflection coefficients, S_{11} and S_{22} of the proposed 45° stub loaded phase shifter are -10.37 dB, whereas both reflection coefficients, S_{33} and S_{44} are -36.73 dB. The transmission coefficients, S_{21} and S_{43} are -0.47 dB and -0.07 dB at 26 GHz, respectively. Whilst, the phase difference between the main line and the reference line is $44.49^\circ \pm 1.63^\circ$ at 26 GHz. Therefore, the simulation results of the proposed 45° stub loaded phase shifter show well performance at the designated frequency of 26 GHz in comparison to the specifications as summarized in Table 2.

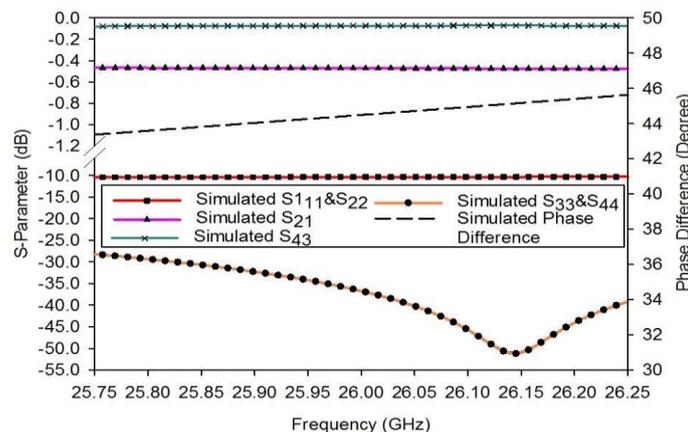


Figure 3. Results of S-parameters and phase difference for 45° stub loaded phase shifter

Referring to Figure 4, across the designated frequency range between 25.75 GHz and 26.25 GHz, the reflection coefficients, S_{11} , S_{22} , S_{33} and S_{44} of the proposed 90° Schiffman phase shifter in Figure 2 (c) are less than -10 dB. Meanwhile, the transmission coefficients, S_{21} and S_{43} are approximately -0.47 dB between 25.75 GHz and 26.25 GHz. The phase difference between the main line and the reference line is $90^\circ \pm 1.05^\circ$ across 25.75 GHz to 26.25 GHz. As seen at 26 GHz, both reflection coefficients, S_{11} and S_{22} of the 90° Schiffman phase shifter are -10.45 dB, whereas the reflection coefficients, S_{33} and S_{44} , -21.17 dB. The transmission coefficients, S_{21} and S_{43} are -0.46 and -0.36 dB at 26 GHz, respectively. Whilst, the phase difference performance between the main line and the reference line is 90° at 26 GHz. Regarding the obtained results, the proposed 90° Schiffman phase shifter satisfies good agreement at 26 GHz.

The S-parameter and phase difference performances of the proposed 135° Schiffman phase shifter are plotted in Figure 5. The excellent results of reflection coefficients at each port, which are S_{11} , S_{22} , S_{33} and S_{44} for the proposed 135° Schiffman phase shifter can be observed in Figure 5 to be lower than -10 dB between 25.75 GHz and 26.25 GHz. Whilst, the transmission coefficients, S_{21} and S_{43} are roughly -0.53 dB across the designated frequency range. The phase difference between the main line and the reference line is $135^\circ \pm 1.59^\circ$ between 25.75 GHz and 26.25 GHz. As seen at 26 GHz, the respective reflection coefficients, S_{11} , S_{22} , S_{33} and S_{44} of the 135° Schiffman phase shifter are -10.45 dB, -10.45 dB, -26.03 dB and -26.05 dB. The simulated S_{21} is -0.46 dB, whereas the simulated S_{43} is -0.51 dB at 26 GHz. Whilst, the phase difference performance between the main line and the reference line is 135° at 26 GHz. Therefore, the results of the proposed 135° Schiffman phase shifter indicate well phase shifting, transmission and return loss performance as required at 26 GHz.

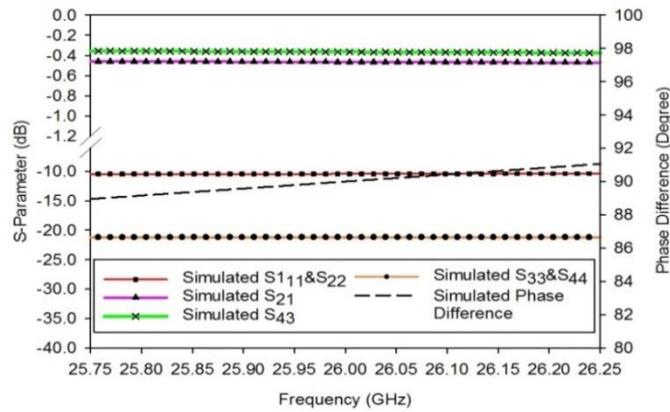


Figure 4. Results of S-parameters and phase difference for 90° Schiffman phase shifter

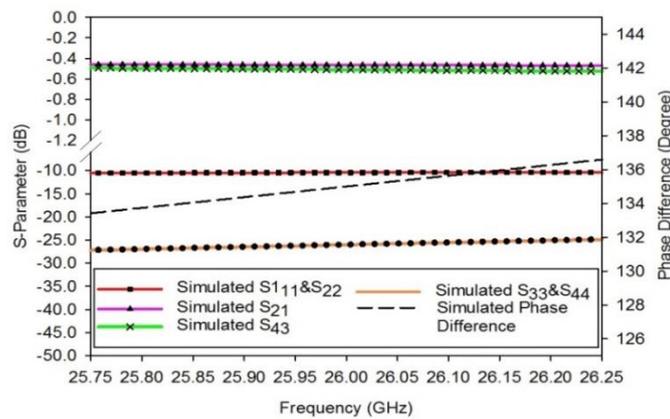


Figure 5. Results of S-Parameters and phase difference for 135° Schiffman phase shifter

Meanwhile, as observed in Figure 6, the reflection coefficients, S11, S22, S33 and S44 at the respective ports of the proposed 180° Schiffman phase shifter are lower than -10 dB. Whilst, the transmission coefficients, S21 and S43 are almost -0.97 dB between 25.75 GHz and 26.25 GHz. The phase difference between the main line and the reference line is $180^\circ \pm 4.04^\circ$ between 25.75 GHz and 26.25 GHz. At the center frequency of 26 GHz, both reflection coefficients, S11 and S22 of the 180° Schiffman phase shifter are -10.45 dB, whereas both reflection coefficients, S33 and S44 are -21.18 dB. The transmission coefficients, S21 and S43 are -0.13 dB and -0.97 dB at 26 GHz, respectively. Whilst, the phase difference between the main line and the reference line is 180.22° at 26 GHz. As seen, the proposed 180° Schiffman phase shifter offers a good performance at 26 GHz as specified.

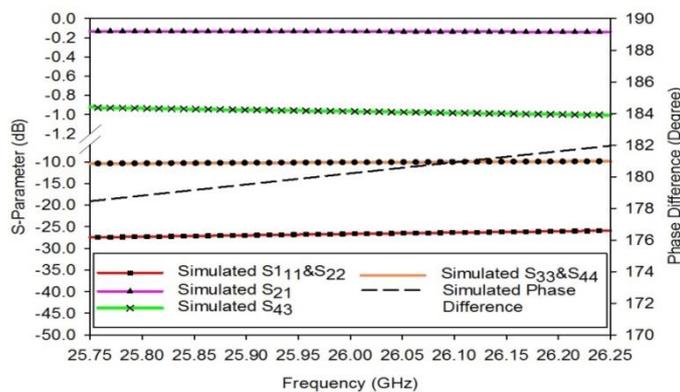


Figure 6. Results of S-parameters and phase difference for 180° Schiffman phase shifter

The performance results of the phase shifters are summarized in Table 2. As seen, the reflection coefficients, S_{ii} ($i=1, 2, 3, 4$) of each phase shifter is less than -10 dB. Whilst, the amplitude imbalances of the S_{21} and S_{43} are less than -0.97 dB. The phase imbalances for the phase differences with respect to the reference lines of the phase shifters are less than 4.04° . Conclusively, all assessed results of the proposed phase shifters are satisfactorily met the design requirements.

Table 2. Summary of the proposed phase shifters' performances between across 25.75 GHz to 26.25 GHz

Component	Parameter	Specification	Performance
45° phase shifter	S_{ii} ($i=1, 2, 3, 4$)	≤ -10 dB	≤ -10 dB
	S_{21} and S_{43}	0 dB ~ -1 dB	≈ -0.48 dB
	Phase difference with respect to reference line	$45^\circ \pm 5^\circ$	$45^\circ \pm 1.63^\circ$
90° phase shifter	S_{ii} ($i=1, 2, 3, 4$)	≤ -10 dB	≤ -10 dB
	S_{21} and S_{43}	0 dB ~ -1 dB	≈ -0.47 dB
	Phase difference with respect to reference line	$90^\circ \pm 5^\circ$	$90^\circ \pm 1.05^\circ$
135° phase shifter	S_{ii} ($i=1, 2, 3, 4$)	≤ -10 dB	≤ -10 dB
	S_{21}	0 dB ~ -1 dB	≈ -0.53 dB
	Phase difference with respect to reference line	$135^\circ \pm 5^\circ$	$135^\circ \pm 1.59^\circ$
180° phase shifter	S_{ii} ($i=1, 2, 3, 4$)	≤ -10 dB	≤ -10 dB
	S_{21} and S_{43}	0 dB ~ -1 dB	≈ -0.97 dB
	Phase difference with respect to reference line	$180^\circ \pm 5^\circ$	$180^\circ \pm 4.04^\circ$

4. CONCLUSION

The 0° , 45° , 90° , 135° and 180° phase shifters that capable to operate between 25.75 GHz and 26.25 GHz for Nolen matrix application have been presented. The employment of single layer technique eases the fabrication process at the super high operating frequency. All results of the proposed phase shifters are satisfactorily met the design requirements, wherein the input return loss and insertion loss for each phase shifters are better than 10 dB, as well as less than -0.97 dB, respectively and the phase deviation for the proposed phase shifters is $\pm 4.04^\circ$ across the designated frequency range between 25.75 GHz and 26.25 GHz. Therefore, the proposed two loaded stubs and three Schiffman phase shifters are suitable to be integrated with couplers in forming the Nolen matrix at 26 GHz and. In addition, they can be good candidates to be applied to other millimetre wave 5G band beamforming applications due to their simple design configuration, lightweight, low insertion loss, and low phase error.

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