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Broadband planar 90 degrees loaded-stub phase shifter

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ABSTRACT

The differential phase shifter is an interesting four-port passive microwave network composed of two separate lines, the main line and the reference line, and providing stable phase difference between the two output signals over the specified bandwidth of interest. The most common differential phase shifter is the coupled-line Schiffman phase shifter. In this paper, a novel 90 degrees differential microstrip phase shifter configuration employing a half wavelength transmission line loaded with three open stubs is presented, the proposed design could achieve excellent performance with low phase variation over a wide bandwidth compared to the standard Schiffman phase shifter. The simulated results accomplished with the use of CST Microwave Studio and advanced design system (ADS), were found to be in good agreement and have shown that the proposed loaded-stub phase shifter achieved less than 1.1 dB insertion loss, greater than 13 dB return loss and constant 90±5 degrees phase shift over an 89 percent bandwidth

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1. INTRODUCTION

Broadband phase shifters are common useful passive microwave devices, which are widely and extremely demanded in modern wireless communication systems, such as antenna feeding networks, beamforming, and electronic beam-scanning of phased arrays [1-11]. As solutions to design planar phase shifters with broadband characteristics, several kinds of structures have been proposed, such as Schiffman phase shifters, broadside coupling structures, and loaded transmission line configurations. In the well-known Schiffman differential phase shifter, a coupled section and a reference transmission line are used to achieve a 90° phase shift with a phase ripple of 10° in 80% bandwidth [12]. In order to attaint broad bandwidth with small phase deviation, other configurations based on the original Schiffman structure were proposed, employing cascaded coupled sections, double coupled sections, parallel and double parallel coupled sections [13]. However, in order to achieve a larger bandwidth, these designs require the use of narrow microstrip lines and extremely tight coupling in the coupled sections, which is not always easy to implement. To overcome this problem, some improved Schiffman phase shifters have been reported. By modifying the ground plane underneath the coupled lines, the bandwidth was improved to 70% with a phase error of 5 degrees [14], and by using dentate microstrip and patterned ground plane, the bandwidth was increased to 80% with a phase deviation of 5 degrees [15]. However, these designs are so intricate and still require a narrow gap between the coupled lines, especially at the ultra-wideband frequencies.

Besides Schiffman configurations, broadside coupled structures is another way to realize broadband phase shifters. In [16], Abbosh proposed a novel ultra-wideband phase shifter configuration exploiting broadside coupling between top and bottom elliptical microstrip patches via an elliptical slot located in the middle ground layer. Although the proposed design had a compact size and an achieved bandwidth of 109% with a phase ripple of ±3°, it could only give a phase shift range from 25° to 48°. In [17], Sorn succeeded in developing Abbosh phase shifter to 90° phase shift by terminating two output ports of the coupled section with a reactive load. The developed circuit provided a 90° differential phase shift with a deviation of less than ±4° over an 80% bandwidth. However, as a three-layer structure, it suffers from complexity, high-cost fabrication, and moreover, it may cause compatibility issues during circuit integration. To overcome these challenges, Abbosh introduced a two-layer coupling structure employing broadside-coupled microstrip-coplanar waveguide (CPW) [18]. Although the reported design allows achieving a 90°±3° phase shift over 114% bandwidth, it makes the installation more complicated because of the employed ground plane, the same as in [14] and [15].

Another main type of phase shifter with a simple design and wideband characteristics is the loaded-stub phase shifter. It has attracted increasing attention lately, and thus several papers with different design methods were published. In [19], a configuration composed of a fixed $\lambda/2$ main line and $\lambda/8$ parallel open and short stubs was employed to develop a 90° phase shifter but with low bandwidth of 67% referring to a phase deviation of ±2°. In [20], a combination of open-circuit and short-circuit multi-section stubs was proposed to design a compact 45° phase shifter with 100% bandwidth for a maximum phase error of ±3.2°. However, for 90° phase shifter, it had been found that the bandwidth decreases to 50%, referring to a phase variation of 5°. In [21], a structure comprising a transmission line loaded with two shorted $\lambda/4$ stubs was proposed to realize a phase shift range from 20° to 70° over a large bandwidth, resulting in 109% bandwidth for a 45° phase shifter. However, in order to obtain excellent performance, high impedance stubs are required. Besides, the phase deviation is getting quite larger when the desired phase shift is more than 60°. Although the phase shifters [19-21] feature compact size and easy fabrication, they have limited achievable phase shift range and low bandwidth.

Aiming for a higher overall performance and wide phase shift range, an efficient designing procedure employing a half wavelength transmission line loaded with open stub was shown in [22], which achieved a phase shift range from 60° to 120° and bandwidth of around 82% was obtained for 90°±6.4° phase shift using T-shaped open stub. Based on the same method and in an attempt to improve the circuit area and performance, a compact broadband 90° phase shifter with M-shaped open stub-loaded transmission line was presented in [23]. As the occupied area of the proposed M-shaped stub was reduced to 70% of the T-shaped stub, the aimed goal in terms of miniaturization was successfully attained, but at the cost of decreasing the bandwidth to 75%, defined by 6.2° phase variation. Two stub-loaded structure was studied as well [24], and it was shown to give phase shift up to 135 degrees, and an achieved bandwidth of 85% with phase error below ±4 was attained for 90° phase shifter loaded with two arrow-shaped stubs. In this letter, a novel design of broadband phase shifters exploiting three open stub-loaded transmission line is investigated, detailed theoretical analysis, and design equations are given. Moreover, one broadband 90° phase shifter highly suitable for applications in L and S bands is designed employing a combination of 0.5λ transmission line with three T-shaped stepped-impedance open stubs

2. THEORETICAL ANALYSIS

The configuration layout of the proposed loaded-stub phase shifter is presented in Figure 1. It consists of two different circuits, a half-wavelength long transmission line loaded with three open stubs and one uniform transmission line, which are labeled as the main line and the reference line, respectively. The differential phase shift for this type of circuit is obtained by calculating the phase difference between the signals at their output ports. Characteristic impedances of the main line and reference line are set as Z_m and Z_0, respectively. Characteristic admittance of the open circuit stub is jY_s. Electrical lengths of the main line and reference line at frequency f are defined by:

$$\theta_m = \theta_{m0}\frac{f}{f_0}\,,\ \theta_r = \theta_{r0}\frac{f}{f_0} \tag{1}$$

where θ_{m0} and θ_{r0} are the electrical lengths of the main line and reference line at the center frequency f_0, respectively.

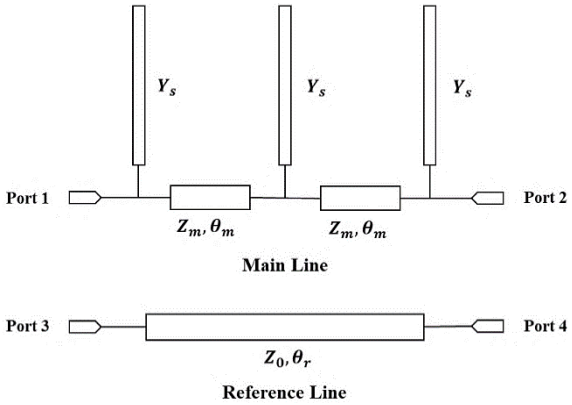


Figure 1. Configuration layout of the proposed phase shifter

By considering the main line as a cascade connection of five two-port networks, the resulting transmission (ABCD) matrix can be easily defined by multiplying the ABCD matrices of the five individual two-ports [25]:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ jY_s & 1 \end{bmatrix} \begin{bmatrix} \cos\theta_m & jZ_m \sin\theta_m \\ j\frac{1}{Z_m}\sin\theta_m & \cos\theta_m \end{bmatrix} \begin{bmatrix} 1 & 0 \\ jY_s & 1 \end{bmatrix} \begin{bmatrix} \cos\theta_m & jZ_m \sin\theta_m \\ j\frac{1}{Z_m}\sin\theta_m & \cos\theta_m \end{bmatrix} \begin{bmatrix} 1 & 0 \\ jY_s & 1 \end{bmatrix}$$

thus

$$\begin{aligned} A = D &= \cos(2\theta_m) - \frac{3}{2} Z_m Y_s \sin(2\theta_m) + Z_m^2 Y_s^2 \sin^2(\theta_m) \\ B &= jZ_m \sin(2\theta_m) - jZ_m^2 Y_s \sin^2(\theta_m) \\ C &= (\cos\theta_m - Z_m Y_s \sin\theta_m)\left(j3Y_s \cos\theta_m + j\frac{2}{Z_m}\sin\theta_m - jZ_m Y_s^2 \sin\theta_m\right) \end{aligned} \quad (2)$$

According to the conversions between two-port network parameters given in [25], the scattering parameters of the main line can be expressed in terms of ABCD parameters as follows:

$$S_{11} = S_{22} = \frac{\frac{B}{Z_m} - CZ_m}{2A + \frac{B}{Z_m} + CZ_m} \quad (3)$$

$$S_{12} = S_{21} = \frac{2}{2A + \frac{B}{Z_m} + CZ_m} \quad (4)$$

So, the phase difference of the proposed configuration can be calculated as follows:

$$\Delta\phi = phase\ (S_{43}) - phase\ (S_{21}) = \theta_r - \tan^{-1}\left[\frac{\frac{B}{Z_m} + CZ_m}{2A}\right] \quad (5)$$

In order to achieve the optimal performance of this phase shifter at the center frequency f_0, which corresponds to $S_{11} = 0$ and $S_{21} = 1$, then $\theta_{m0} = \pi/2$ can be obtained from (2), (3) and (4), and thus the electrical length of the reference line θ_{r0} can be easily determined by the desired phase shift :

$$\theta_{r0} = \Delta\phi + 2\theta_{m0} = \Delta\phi + \pi \quad (6)$$

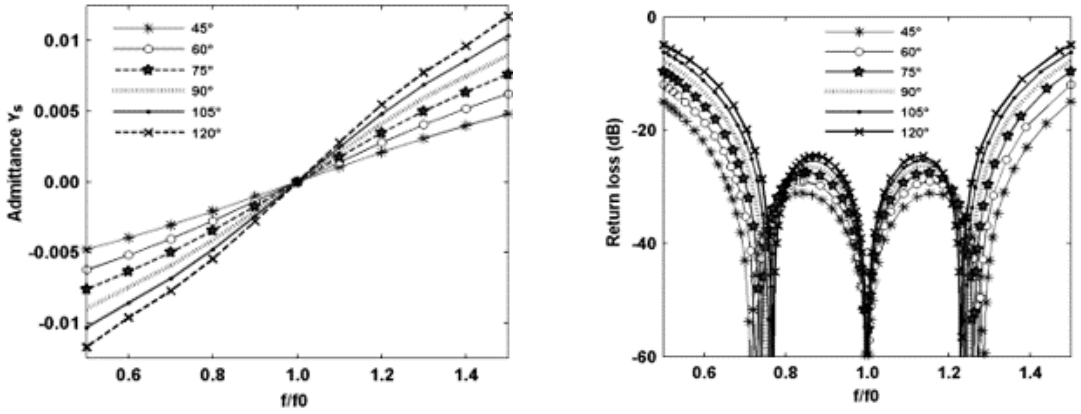
For $Z_m = 50\ \Omega$, the phase shift $\Delta\phi$ can be expressed in terms of the unknown admittance Y_s as follows:

$$\Delta\phi = \theta_r - \tan^{-1}\left[\frac{2\sin(2\theta_m)+3Z_mY_s\cos(2\theta_m)}{2\cos(2\theta_m)-3Z_mY_s\sin(2\theta_m)+2Z_m^2Y_s^2\sin^2(\theta_m)}\right] \quad (7)$$

The optimal admittance Y_s to obtain flat differential phase response within the frequency band ranging from $0.5\ f_0$ to $1.5\ f_0$, can be calculated using (7), Figure 2 (a) shows the calculated admittance for differential phase shifts of 45°, 60°, 75°, 90°, 105°, and 120°. Since the admittance Y_s is obtained from (7) as shown in Figure 2 (a), then the return loss of the main line expressed in (3) can be simplified to:

$$S_{11} = \frac{jZ_mY_s[1+2\cos(2\theta_m)+2Z_mY_s\sin(2\theta_m)-Z_m^2Y_s^2\sin^2(\theta_m)]}{2\cos(2\theta_m)-3Z_mY_s\sin(2\theta_m)+2Z_m^2Y_s^2\sin^2(\theta_m) \\ +j[2\sin(2\theta_m)+3Z_mY_s\cos(2\theta_m)-2Z_m^2Y_s^2\sin(2\theta_m)+Z_m^3Y_s^3\sin^2(\theta_m)]} \quad (8)$$

The calculated return loss using the above (8) is shown in Figure 2 (b). The plotted results show wide bandwidth characteristics, especially for small phase shift values. The investigated three stub loaded structure also shows uninterrupted and better return loss over more than 60% bandwidth when the differential phase shift is greater than 120 degrees. According to the analysis mentioned above, the design process is both clear and concise. The proposed configuration is highly practical for the implementation of a broadband phase shifter with low cost, easy manufacturing, and good return loss performance.



(a) (b)

Figure 2. Three stub calculated results; (a) optimal admittance, (b) Return loss determined with optimal admittance

3. DESIGN AND SIMULATION RESULTS

To validate the proposed design method, a broadband 90° phase shifter loaded with three open stubs is designed and simulated. The design operating frequency is chosen at 2.5 GHz, and the selected microstrip technology is a low-cost FR 4 epoxy substrate with a relative dielectric constant of 4.4, a loss tangent of 0.025 and a thickness of 1.6 mm. In order to approach the calculated ideal admittance of the half wavelength open stub, a T-shaped step-impedance open stub is proposed to realize compact occupied area along with broader bandwidth. The schematic layout of the proposed 90° phase shifter circuit with defined dimension parameters is shown in Figure 3 (a), and methods to control the admittance value of the adopted open stub are shown in Figures 3 (b-e). Note that all the port impedances are set to 50 Ω.

The design and optimization are performed using CST Microwave Studio. The circuit parameters of the width (W_1, W_2, W_3, W_4 and W_5) and length (L_a, L_b and L_c) are set for proper input impedance matching and minimum phase variance within the target bandwidth. After several series of optimization, the optimum performance of the proposed phase shifter is achieved, and the final dimensions are as follows: $W_0 = 3.05$ mm, $W_1 = 0.75$ mm, $W_2 = 0.45$ mm, $W_3 = 0.835$ mm, $W_4 = 5.0$ mm, $W_5 = 4.4$ mm, $L_0 = 11.0$ mm, $L_1 = 4.0$ mm, $L_2 = 2.0$ mm, $L_a = 18.0$ mm, $L_3 = 0.5$ mm, $L_4 = 2.5$ mm, $L_b = 3.0$ mm, $L_c = 13.0$ mm, $L_5 = 32.55$ mm, $L_6 = 40.0$ mm, $L_7 = 8.39$ mm.

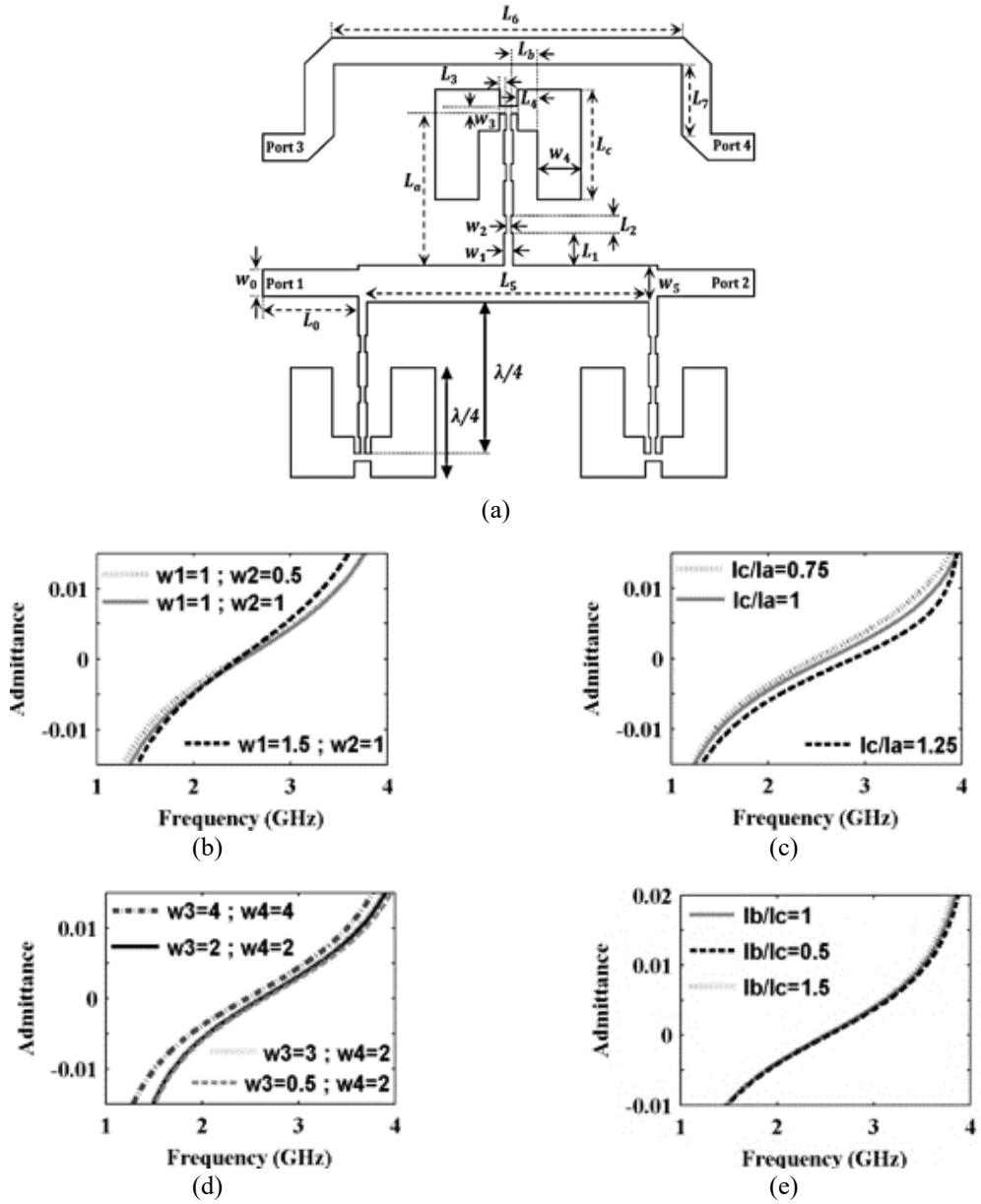
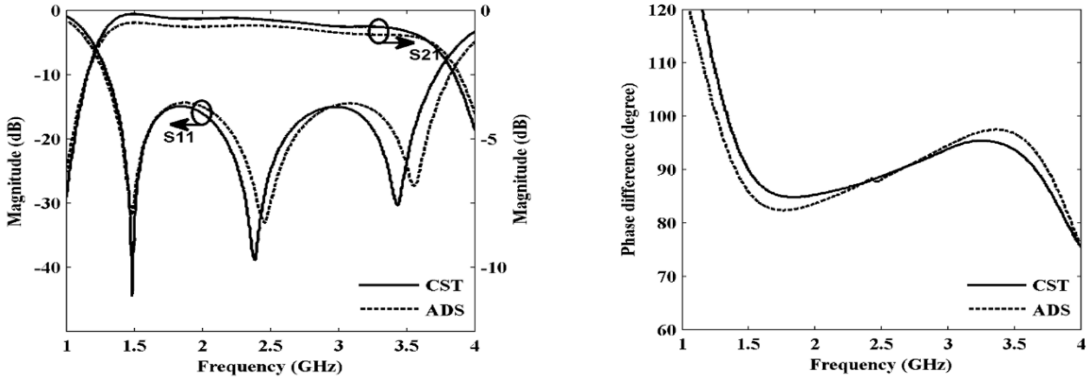


Figure 3. Configuration of the proposed phase shifter using three T-shaped stepped-impedance open stubs and means to control their admittance value; (a) Schematic layout, (b), (c), (d) and (e) means to control the admittance of the T-shaped stepped-impedance open stubs

To discuss and evaluate the performance of the proposed configuration, the previously designed phase shifter is simulated by using two electromagnetic simulators, the 3D planar EM solver CST Microwave Studio (CST MWS) and momentum the 2.5D EM simulator integrated into advanced design system (ADS) software. Comparison between the simulated S-parameters amplitude and phase difference response between output ports of the proposed 90° loaded-stub phase shifter (phase (S_{43}) – phase (S_{21})), are displayed in Figures 4 (a-b), respectively.

As can be seen, the simulated results using ADS and CST MWS are in good agreement and thereby validate the presented new phase shifter design which is shown to exhibit, referring to the simulated results in Figures 4 (a) and 4 (b), better than 13 dB return loss and less than 1.1 dB insertion loss along with a differential phase shift of 90°±5° from 1.4 to 3.65 GHz covering around 89% relative bandwidth, which indicates a broadband characteristic. Besides the good achieved performances, the proposed phase shifter is relatively compact size with overall dimensions of 56×52 mm, including the reference line. A comparison between the proposed phase shifter circuit and other published loaded-stub phase shifters is presented in Table 1. As can be seen, the introduced phase shifter features good properties in terms of circuit area, phase deviation, and achieved bandwidth in comparison to its operating frequencies.



(a) (b)

Figure 4. Comparison of CST and ADS simulated results of the designed 90º loaded-stub phase shifter; (a) amplitude response, (b) phase shift response

Table 1. Comparison of the designed phase shifter to other configurations

Configuration /Ref	Phase differential	Design Freq. (GHz)	Frequency Band (GHz)	FBW	The effective area (mm^2)
[22]	90° ± 6.4°	4	[2.3 – 5.5]	82%	(22<) × 16.4 (excluding reference line)
[23]	90° ± 6.2°	4	[2.7 – 6]	75%	23 × 19.3 (excluding reference line)
[24]	90° ± 4°	4	[2.5 – 6]	85%	56 × 30 (excluding reference line)
This work	90° ± 5°	2.5	[1.4 – 3.65]	89%	56 × 52 (including reference line)

4. CONCLUSION

A new differential phase shifter structure, capable of providing a constant phase difference of up to 120 degrees with broadband characteristics, has been presented in this paper. The proposed single layer circuit employs a three open stub-loaded transmission line, which enables an easy design and fabrication. Theoretical analysis and design equations were given, and thus the design process to achieve a full variety of differential phase output was simplified. Based on design equations, a 90° phase shifter with three open T-shaped step-impedance stubs has been conceived and simulated. Based on the obtained results, the designed phase shifter has a simple design, compact size, and wide bandwidth. Considering these excellent performances along with the wide operating frequency band ranging from 1.4 to 3.65 GHz, the proposed 90° phase shifter is highly recommended for applications in advanced wireless communication systems, such as in circular polarized antenna feeder networks, beam-forming, and beam-scanning of phased array systems.

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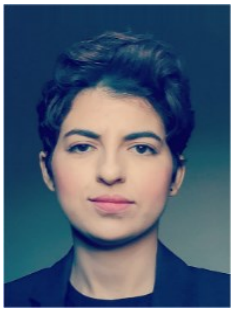

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