90° and 180° Phase Shifter Using an Arbitrary Phase-Difference Coupled-line Structure

Yezi Dong¹, Luhong Mao¹a), Qiwei Song², Sheng Xie¹

¹School of Electrical and Information Engineering, Tianjin University, Tianjin 300072, China
²Institute of Automation, Chinese Academy of Sciences, Beijing, 100190, China

a) lhmao@tju.edu.cn

Abstract: In this paper, an arbitrary phase-difference structure using short-circuit stubs and coupled-line with weak coupling is presented. Compared with conventional coupled-line phase shifters, the proposed coupled-line configuration covers a wide phase range over a broad band. The simulation exhibits a phase range from 15° to 180°. To verified the configuration, 90° and 180° phase shifters are fabricated and measured. According to the measurement results, both 90° and 180° phase shifters achieve bandwidths over 60% with in-band performance of return loss greater than 10 dB, insertion loss less than 1 dB, and phase deviation less than ±5°.

Keywords: Arbitrary phase-difference, coupled-line, phase shifter
Classification: Microwave and millimeter wave devices, circuits, and systems

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1 Introduction

Phase shifter is widely used in modern microwave systems. It is a critical component in beamforming applications, such as phase-array antenna systems and intelligent antenna systems. Moreover, phase shifter can connect with power divider to work as a three-port hybrid with specific phase difference in microwave applications [1].

Several kinds of structures have been proposed to achieve broadband phase shifters with different degrees. The conventional Schiffman phase shifter [2] and some modified configurations [3-5] can achieve a nearly constant phase shift over a wide band, but it is difficult to obtain a phase shift more than 90° due to the requirement of extremely tight coupling which results in unrealizable narrow coupling gaps. A modified configuration based on Schiffman phase shifter with parallel open and short λ/8 stubs was presented in [6] which is suitable for large phase shifts such as 90° and 180°. Transmission line loaded with short-circuit stubs can realize a phase shift range from 20° to 70° over a large bandwidth [7]. Meanwhile, transmission line loaded with open-circuit stub can achieve a phase shift range from 60° to 120°, and a bandwidth of 82% is obtained for 90° phase shifter using T shape open stub [8]. Broadside coupling structures can achieve a phase range from 25° to 48° with one section [9] or from 30° to 90° with two sections [10] across the ultra-wideband (UWB). However, this structure requires three layers of printed circuit board (PCB) which may cause incompatibility with other components during circuit integration. Aiming at wideband wide phase shift range design, a structure using parallel coupled lines and L-shaped networks was presented in [11], which achieved a phase shift range from 45° to 180° across 100% fractional bandwidth.

In this paper, a broadband arbitrary phase-difference structure using short-circuit stubs and coupled-line with weak coupling is presented. In Section II, the proposed structure is analyzed by using even- and odd-mode analysis. The simulations exhibit that the proposed coupled-line configuration can achieve a
wide phase shift range from 15° to 180° over a bandwidth greater than 60%. For verification, 90° and 180° phase shifter are fabricated and measured in Section III.

2 Circuit Design and Analysis

The topology of proposed arbitrary phase shifter is shown in Fig. 1(a). The phase shift path (Path 1) consists of a coupled-line and three parallel short-circuit stubs. One of the short-circuit stub with characteristic impedances \( Z_1 \) and electrical length \( \theta_1 \) is connected to the middle of coupled-line with even- and odd-mode characteristic impedances \( Z_e \) and \( Z_o \). The other two stubs with characteristic impedance \( Z_2 \) and electrical length \( \theta_2 \) are connected to the ends of coupled-line. The reference path (Path 2) uses two short-circuit stubs loaded onto a transmission line instead of a simple reference line. This topology provides additional degrees of freedom for design to realize different phase shift.

Fig. 1 The proposed arbitrary phase shifters (a) topology, (b) even- and odd-mode equivalent circuit.

The S-parameters of both phase shift path and reference path can be found with the even- and odd-mode analysis technique. The equivalent even- and odd-mode sub-circuit of the designed phase shifter is shown in Fig. 1(b). The reflection coefficients \( \Gamma \) and S-parameters of both paths can be expressed as

\[
\Gamma_{ei} = \frac{Z_{ei} - Z_0}{Z_{ei} + Z_0}, \quad \Gamma_{ol} = \frac{Z_{ol} - Z_0}{Z_{ol} + Z_0}, \quad \text{for } i = 1 \text{ or } 3 \tag{1}
\]

\[
\begin{bmatrix}
S_{ij}
\end{bmatrix} = \begin{bmatrix}
\Gamma_{ei} + \Gamma_{ol} & \frac{\Gamma_{ei} - \Gamma_{ol}}{2} \\
\frac{\Gamma_{ei} + \Gamma_{ol}}{2} & \Gamma_{ei} - \Gamma_{ol}
\end{bmatrix}, \quad \text{for } i = 1, j = 2 \quad \text{or } i = 3, j = 4 \tag{2}
\]

where \( Z_{ei} \) and \( Z_{ol} \) (\( i = 1 \text{ or } 3 \)) are the even- and odd-mode input impedance of port 1 and 3, and \( Z_0 \) is the port impedance which is equal to 50 Ω. According to Fig. 1(b), the even- and odd-mode input impedance of each path can be calculated as

\[
Z_{ei} = \frac{j(2Z_eZ_1Z_2 \tan \theta_1 \tan \theta_2 + Z_e^2Z_2 \tan \theta \tan \theta_2)}{Z_e^2 \tan \theta + 2Z_eZ_1 \tan \theta_1 + Z_eZ_2 \tan \theta_2 - 2Z_1 \tan \theta \tan \theta_1 \tan \theta_2} \tag{3}
\]
where $\Delta \Phi$ is the proposed phase difference of two path.

By introducing short-circuit stubs $Z_2$ and $Z_3$, extra variables are added to the equations of even- and odd-mode impedance of each path. A phase shift more than 90° can be achieved with weak coupling. A simulation example of phase differences varied from 15° to 180° with a step size of 15° is shown in Fig. 2. In this example, the parameters of coupled-line are set as constant where $Z_e = 60 \, \Omega$, $Z_o = 30 \, \Omega$, and $\theta = 90°$ at center frequency $f_0$. The range of characteristic impedances of the rest of microstrip lines is between 30 and 100 Ω where the width of microstrip line is realizable on PCB. The electrical lengths $\theta_1$, $\theta_2$, and $\theta_5$ are varied from 60° to 100°. The length difference between $\theta_3 + 2\theta_4$ and $2\theta$ approaches to $\Delta \Phi$. As a constraint condition, the in-band insertion loss is lower than 0.5 dB and return loss is greater than 12 dB for each paths. The simulated result shows that the proposed configuration can achieve about 70% bandwidth for phase deviation of ±5° in a wide phase shift range. The proposed coupled-line structure shows good potential to realize broadband arbitrary phase shifter with weak coupling.
Besides the large phase shift range, the introducing of short-circuit stubs also provide a band-pass feature to both phase shift path and reference path. The phase shifter can achieve the desired phase difference and offer a function of bandpass filter at the same time. A simulation example of a 90° bandpass phase shifter is demonstrated in Fig. 3. In this simulation example, the phase shifter achieves a 60% bandwidth for phase deviation less than ±5° and return loss greater than 12 dB. At the same time, the phase shift path (S21) and reference path (S43) have similar transmission characteristics. Both paths demonstrate bandpass feature and the passband of each path is almost the same. However, the bandwidth will decrease, if the similar bandpass feature is targeted in design. The phase shifter
with a bandpass feature is useful in the front end of receiver. It can connect with a low-pass power divider to constitute a three-port hybrid with arbitrary phase shift and bandpass function.

3 Implement and Experiment Results

For experimental verification, the 90° and 180° phase shifters were prototyped. The designed microstrip circuits were built on a Rogers 4003C with a dielectric constant of 3.38 and a thickness of 1.524 mm. The spacing gap in coupled-line of each design is 0.2 mm. The photographs of the implemented 90° and 180° phase shifters are shown in Fig. 4. The board size of 90° phase shifter is 71×51 mm², and the board size of 180° phase shifter is 80×51 mm². Because a thick PCB is used, wide microstrip line is required. Additional short lines are needed to connect the coupled-line and short-circuit stubs and keep a distance between parallel lines. This results in a slightly difference between the realizations and topology. In the realization of 180° phase shifter, stepped impedance short-circuit stub is employed to compose stub $Z_2$ in phase shift path.

![Photograph of designed phase shifters](image)

**Fig. 4** The photograph of the designed phase shifters: (a) 90°, (b) 180°.

The fabricated phase shifters are measured by Keysight E5071C network analyzer. The phase shift path (Path 1) and reference path (Path 2) of phase shifters was tested separately to obtain the two-port S-parameter of each path. When one path is tested, both ports of the other path are connected to a 50 Ω load. Fig. 5 and Fig. 6 demonstrate the measured results of 90° and 180° phase shifter. In these figures, S21 refers the phase shift path, and S43 refers the reference path.

Due to the nonideal I/O connecters and the effect of extra connecting lines, the bandwidth of fabricated phase shifters is a bit worse than simulations of theoretical topology. But the measured results showed that both 90° and 180° broadband phase shifters can be realized using coupled-line with week coupling which is in good agreement with simulations.
In the measurement of 90° phase shifter, the insertion loss of phase shift path is less than 1 dB in the range of 1.7-3.5 GHz, and the minimum insertion loss of each path within this frequency range is about 0.2 dB. The phase deviation of 90° phase shifter is less than ±5° in the range of 1.75-3.45 GHz. Within this frequency range, the return losses of both paths are better than 10 dB. The measured bandwidth of the proposed structure is defined by the return loss better than 10 dB, insertion loss less than 1 dB, and phase deviation less than ±5°, therefore, the fabricated 90° phase shifter achieved 65% bandwidth from 1.75 to 3.45 GHz, and the in-band insertion loss difference between two paths is less than 0.3 dB.

Fig. 5 The measured S-parameters and phase difference of 90° phase shifter.

Fig. 6 The measured S-parameters and phase difference of 180° phase shifter.
In the measurement of 180° phase shifter, the phase deviation is less than ±5° in the range of 1.55-2.95 GHz. Within this frequency range, both paths can achieve a return loss better than 10 dB. The insertion loss of phase shift path is less than 1 dB in the range of 1.52-2.94 GHz, and the minimum insertion loss of each path within this frequency range is about 0.3 dB. Using the same bandwidth definition, the fabricated 180° phase shifter achieved 62% bandwidth from 1.55 to 2.95 GHz, and the in-band insertion loss difference between two paths is less than 0.5 dB. The measured results verified that the proposed phase shifter structure using short-circuit stubs and coupled-line with weak coupling can achieve wide phase shift range with over 60% bandwidth.

4 Conclusion
A broadband arbitrary phase-difference structure using short-circuit stubs and coupled-line with weak coupling was presented in this paper. The even- and odd-mode analysis was made for the proposed topology. To verified the wide phase shift range of the proposed coupled-line structure with weak coupling, the simulation of different degrees from 15° to 180° was given in the case that feasible microstrip line is used. In further discussion, the bandpass features of both paths is shown with a simulation example which obtained similar pass band in two paths. For experimental verification, 90° and 180° phase shifter were fabricated and measured. As the proposed structure can provide arbitrary phase shift in broadband, it may be used for any phase bit in beamforming applications or connect with a power divider to constitute a broadband three-port arbitrary phase-difference hybrid.

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