Progress In Electromagnetics Research Letters, Vol. 117, 97-101, 2024 PIER Letters

(Received 8 December 2023, Accepted 31 January 2024, Scheduled 13 February 2024)

Varactor Loaded Phase Shifter with Frequency-Adaptive Control Circuit

Waleed Alomar, Abdullah Alburadi*, Meshaal Alyahya, and Hussein Shaman

King Abdulaziz City for Science and Technology
Next-Gen Connectivity & Wireless Sensors Institute Riyadh, Kingdom of Saudi Arabia

ABSTRACT: This paper introduces a novel RF phase shifter design that operates at constant phase shift over operation frequency range. The proposed phase shifter utilizes the conventional reflective-type phase shifter which is inherently frequency-dependent. The introduced reflective-type phase shifter design is integrated with an adaptive control circuit that varies the required DC voltage as a function of the frequency. Thus, the phase shift will be relatively constant throughout the frequency of operation compared to the conventional frequency-dependent reflective-type phase shifter. The phase shifter is designed to operate at 90° and is shown to maintain that phase shift with around 15° compared to the conventional design where the phase shift varies by more than 60° at the same bandwidth. The proposed design, including the adaptive controlled circuit, is fabricated, and the measured data agree with simulations.

1. INTRODUCTION

Phase shifters are very important microwave devices, which have several radio frequency (RF) and microwave applications [1]. Their various applications extend from electronic beam-forming in phased array antennas [2, 3] to measurement systems and modulators [4]. Phase shifters are also critical components in 5G and next-generation [5]. Furthermore, the ability to control the phase of the phase shifter will further showcase its critical role in microwave and millimeter-wave circuits and systems. Variable phase shifters are applicable by controlling the voltage, which can be realized with varactor diodes that have voltage-dependent capacitance with reverse biased. However, narrow bandwidth is a limitation for this type of phase shifter. One of the figures of merit to measure the performance of a phase shifter is to evaluate its bandwidth, insertion loss, accuracy, resolution, total phase variance, and return loss. Most importantly, the bandwidth of the phase shifter might limit the instantaneous bandwidth of the systems (e.g., phase array radars).

Analog phase shifters change the phase of an electromagnetic (EM) signal continuously in relation with an input control signal. Most likely, the signal will be a voltage control signal controlling the analog phase shifter. This can be achieved through the utilization of electrical lines with variable length (i.e., controlled by varactor diodes which operate in a reverse-biased mode). They provide a junction capacitance in relation with control voltage signal which will then affect the phase shift level [1].

Different RF techniques and structures have been utilized to design phase shifters with stable bandwidth and also achieve variable or constant phase shifting. Substrate-integrated waveguide technique to implement phase shifters has some advantages such as low transmission and radiation losses [6–8]. In [6], a new design approach to implement phase shifters is introduced using substrate-integrated waveguide. The phase shift is controlled using metal posts of various lengths, and then they are inserted at selected locations in the substrate-integrated waveguide. Additionally, in [7], substrate-integrated phase shifter design is introduced with an improved broadband performance. Air strip rows are introduced to increase the bandwidth. However, the introduced substrate integrated waveguide phase shifters do not offer an adaptive control circuit that can be applied to large number of phase shifters.

A differential phase shifter consists of four ports that are usually connected to two main transmission lines which are the main and reference one [9]. The desired phase shift is represented as the difference between the phases of the two transmission lines (i.e., main and reference). Various designs were reported with improved bandwidth [10–13]. In [10], pattern ground plane was utilized to introduce a new design of Schffman phase shifter. A slot under the coupled line was used with an additional rectangular conductor to decrease the odd-mode impedance. Alternatively, the phase shifter can be designed using double microstrip-slot with planar ±90° phase shifters [11]. Furthermore, a broad band double microstrip phase shifter design was introduced [12]. In that introduced design, phase shifting was developed using a microstrip-slot transition, and the design showcased a good amplitude and phase shift performance. However, in these types of phase shifters, the transmission phase is frequency-dependent though the differential phase is constant, which might not be desirable in some applications.

Additionally, phase shifters can be realized using circuits that generate a negative group delay (NGD) [14, 15]. However, phase shifters designed using NGD require RF active elements to compensate the associated loss, unlike those proposed in this design that have low power consumption.

* Corresponding author: Abdullah Alburadi (aalburadi@kacst.gov.sa).

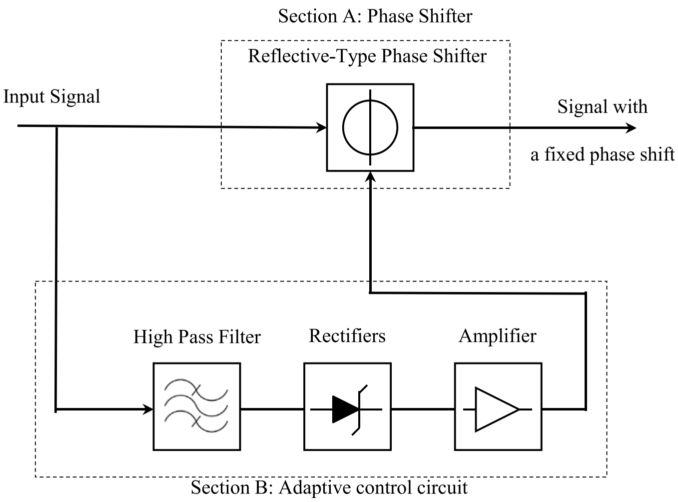

FIGURE 1. A block diagram detailed the design of the proposed phase shifter.

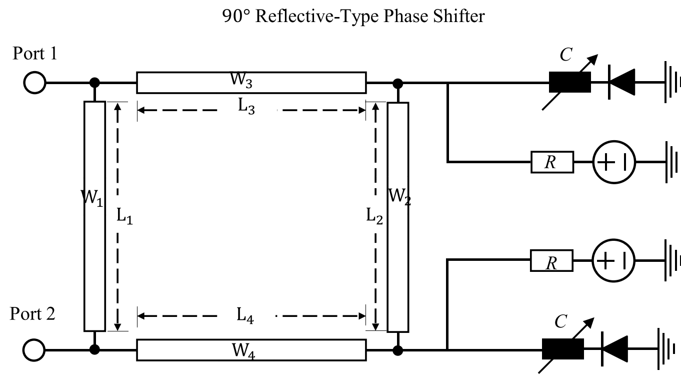

FIGURE 2. A block diagram detailed the design of the conventional phase shifter.

In this paper, a novel adaptive control design is integrated with the conventional design of RF phase shifters to overcome the limitation of frequency dependence. The proposed adaptive control circuit relies on a single active component (i.e., Op-Amp); therefore, the derived DC voltage can support a large number of reflective-type phase shifters. In Section 2, the fundamental mechanism of the proposed technique is discussed along with the analysis of each main section. First, the theory of the conventional reflective-type phase shifter is discussed. Then, the principle behind the adaptive controlled circuit is analyzed. In Section 3, the fabricated prototype is illustrated, showing good agreement with simulated results. The last part of the paper mainly summarizes the proposed concept/design with final concluding remarks.

2. DESIGN

2.1. System Level Design

The proposed design consists of two main sections which are the main phase shifter and control circuit as illustrated in Fig. 1. The phase shifter section utilizes the conventional quadrature phase shifter equipped with varactor diodes for controlling the phase shift across the frequency of operation. On the other hand, the adaptive control section acts as frequency dependent DC bias for the varactor diodes providing them with required voltage to maintain a fixed phase shift.

2.2. Quadrature Phase Shifter - Hybrid

The quadrature phase shifter is a loaded-line phase shifter that is referred to as reflective phase shifter. This is mainly a quadrature coupler which splits the input signal into two signals that 90° out of phase. Fig. 2 shows a conventional design of such a quadrature phase shifter. These signals are reflected from a pair loads and combined in phase at the phase shifter output, as long as the loads are identical in reflection coefficient (both magnitude and phase). One advantage of reflective phase shifter is the ability to achieve any desired phase shift by changing the load reactance. By adding varactor diode to the circuit as a load, the phase shift can be controlled electrically by biasing the voltage since the varactor capacitance changes with the applied voltage.

Using the conventional design in Fig. 2, a 90° phase shift can be obtained as depicted in Fig. 3 which is given by the solid line. One major drawback of this conventional design is the dependence of the phase shift on the frequency. This limits the frequency of the operation of the conventional phase shifter. The dashed red line in Fig. 3 illustrates the performance of the phase shifter given that a variable dc biased is applied at each frequency to maintain the required electrical length and thus maintain the constant phase of 90°.

2.3. Adaptive Control Circuit

To maintain a constant phase shift at the output as the frequency changes, a feedback DC voltage must be applied to the varactors to change their capacitance. The relation between the frequency and the required DC voltage can be estimated as a linear function of the form:

$$V_{\mathrm{DC}}(f) = A \times f + B \tag{1}$$

where f is the frequency of operation; A and B, are constant tuning variables.

A linear frequency to voltage translation can be achieved using a high-pass filter, where the filter cutoff frequency is higher than the upper limit of the phase shifter bandwidth (1.1 GHz in the proposed design). Since a linear filter response is required across a wide band, there is no need to choose higher order filters because of their sharp nonlinear response. In fact, a single inductor combined with the input impedance of the rectifier stage can be used to achieve such a response. Therefore, the value of the inductor is chosen to be 44 nH which enables the DC voltage response of the rectifier circuit to meet the desired one for maintaining a constant phase shift.

In the design of the half wave rectifier, it might be necessary to tune the electrical length of the transmission line (i.e., between the filter and rectifier) to ensure that it does not impact

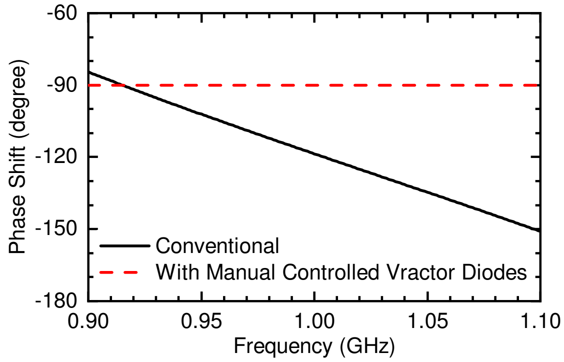

FIGURE 3. Response of conventional phase shifter of Fig. 2 and ideal phase shifter response.

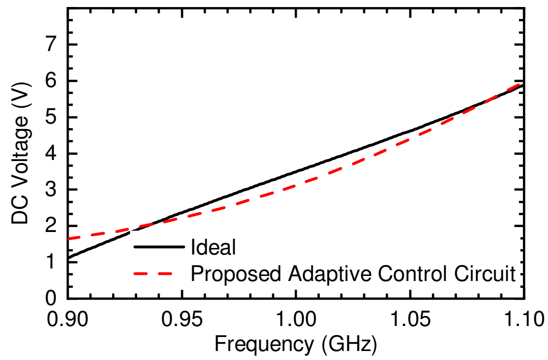

FIGURE 4. An ideal $V_{\mathrm{DC}}(f)$ response of (1) and the obtained one by using the proposed adaptive control circuit.

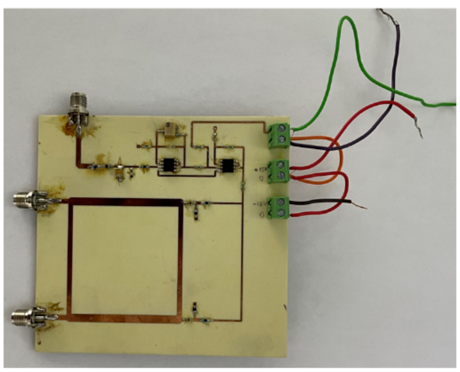

FIGURE 5. Fabricated prototype design.

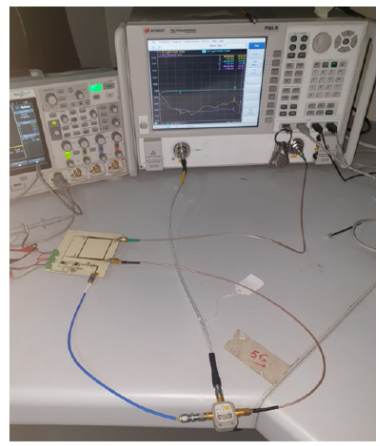

FIGURE 6. Prototype design measurement setup.

the overall control circuit response that is given by (1). It is also important for the RC network to have a time constant that is faster than any changes in the input signal frequency. In the case of frequency swept signal for example, the time constant must be much less than the sweep time.

At this stage, the frequency to DC voltage translation is completed; however, the slope and DC offset need to be adjusted. Thus, two op-amp circuits were used in this design to adjust the slope and DC offset. The first one is the conventional inverting amplifier circuit, while the second one is a summer op-amp circuit. A 150 kΩ variable resistor and an independent DC source are used to fine tune the response experimentally. After the op-amp stage, the output DC voltage is applied as a DC bias to the varactors to achieve the adaptive phase control. The achieved response of the designed control circuit is illustrated in Fig. 4 along with the ideal one.

3. INTEGRATION AND MEASUREMENT OF THE PROPOSED DESIGN

The aforementioned sections were integrated as one device to perform a constant phase shift over the frequency of operation. The phase shifter was designed initially to perform -90 (degrees) constant phase shift in (900–1100 MHz) band.

The phase shifter was then printed on a Roger RO4003C dielectric substrate with a thickness of 813 µm, dialectic constant of $\varepsilon_r = 3.55$, and loss tangent of $\tan\delta = 0.0021$ at 10 GHz backed by a ground plane. The fabricated prototype design and measurement setup are illustrated in Fig. 5 and Fig. 6. The final design values are given in Table 1.

The circuit was measured using Keysight PNA-X Vector Network Analyzer. Ideally, a small portion of the RF signal is taken to the control circuit through directional coupler, but due to the limited lab resources, a 3 dB power splitter followed by 10 dB attenuator to protect the main signal path. To overcome the limited isolation of the power splitter, the calibration is done at the phase shifter SMA port as illustrated in Fig. 7. This configuration allows for precise measurements of the complex S_{11} and S_{21} and ensures that reflections from control circuit are accounted for. This also mimics the practical use of the proposed phase shifter, where a fraction of the RF signal is coupled to the control circuit through a highly isolated directional couplers and when only one control circuit is used for an array of phase shifters.

Measurement and simulation results are shown in Fig. 8 along with phase shift response of the conventional design. The measured data are in a good agreement with the simulation results where the phase shift of the proposed design fluctuates by $\pm 6^\circ$ across the band of interest. Compared to the conventional phase shifter where the phase varies by 60 degrees, this design shows an improvement of 10 folds. Fig. 9 shows $|S_{11}|$

Design Parameter	Value (mm)
$L_1 = L_2$	40.00
$W_1 = W_2$	1.75
$L_3 = L_4$	41.00
$W_3 = W_4$	3.00

TABLE 1. Final design values.

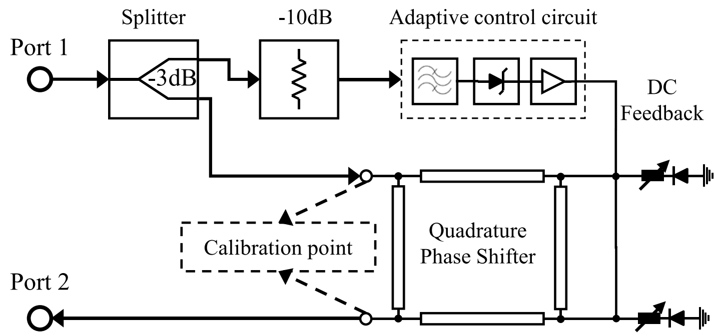

FIGURE 7. An illustration of the measurement setup that is shown in Fig. 5.

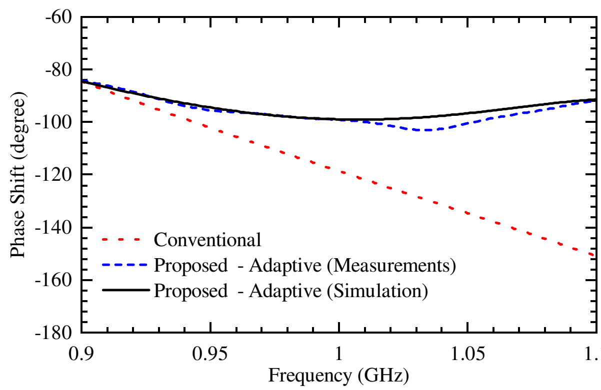

FIGURE 8. Phase shift response of of the proposed desing (measured and simulation data).

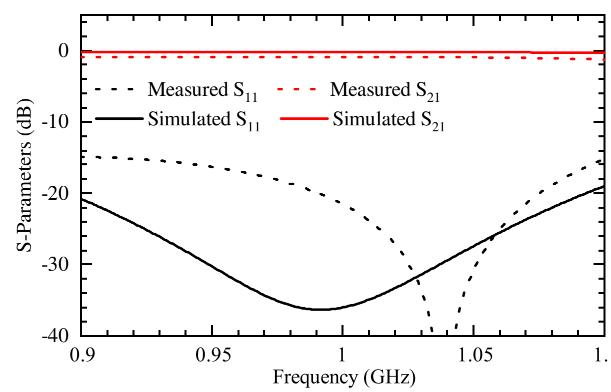

FIGURE 9. Simulation and measurement data of $|S_{11}|$ and $|S_{21}|$ for the proposed system.

and $|S_{21}|$ where a good agreement between the simulated and measured results is observed; however, there is a small difference between expected and measured S_{11} which is due to fabrication. The experimental results showcased the importance of the adaptive control circuit's presence to automate the voltage control and maintain a constant phase shift.

4. CONCLUSION

This paper introduces a new RF phase shifter design that operates at fixed phase shift over operation frequency. The designed phase shifter utilizes the conventional reflective-type phase shifter along with a novel adaptive control circuit that varies the required DC voltage as a function of the frequency. Thus, the phase shift will be maintained throughout the frequency of operation compared to the frequency-dependent conventional reflective-type phase shifter. The phase shifter has a phase difference (error) of $\pm 6^\circ$ over the bandwidth of operation compared to a conventional quadratic hybrid phase shifter where the phase varies by more than 60 degrees at the same bandwidth. The proposed design has illustrated the critical role of the adaptive control circuit in maintaining a constant phase shift.

ACKNOWLEDGEMENT

The authors would like to thank King Abdulaziz City for Science and Technology (KACST) for their continuous support.

REFERENCES

[1] Pozar, D. M., *Microwave Engineering*, 4th ed., John Wiley & Sons, 2012.

[2] Sazegar, M., Y. Zheng, H. Maune, C. Damm, X. Zhou, J. Binder, and R. Jakoby, "Low-cost phased-array antenna using compact tunable phase shifters based on ferroelectric ceramics," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 59, No. 5, 1265–1273, May 2011.

[3] Lin, C.-S., S.-F. Chang, C.-C. Chang, and Y.-H. Shu, "Design of a reflection-type phase shifter with wide relative phase shift and constant insertion loss," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 55, No. 9, 1862–1868, Sep. 2007.

[4] Chan, E. H. W., W. Zhang, and R. A. Minasian, "Photonic RF phase shifter based on optical carrier and RF modulation sidebands amplitude and phase control," *Journal of Lightwave Technology*, Vol. 30, No. 23, 3672–3678, Dec. 2012.

[5] Shehata, R. E. A., M. Hindy, H. Elmekati, and A. M. F. Elboushi, "Design of a beam-steering metamaterial inspired LPDA array for 5G applications," *Progress In Electromagnetics Research M*, Vol. 117, 151–161, 2023.

[6] Sellal, K., L. Talbi, T. A. Denidni, and J. Lebel, "Design and implementation of a substrate integrated waveguide phase shifter," *IET Microwaves, Antennas & Propagation*, Vol. 2, No. 2, 194–199, 2008.

[7] Peng, H., X. Xia, S. O. Tatu, and T. Yang, "An improved broadband SIW phase shifter with embedded air strips," *Progress In Electromagnetics Research C*, Vol. 67, 185–192, 2016.

[8] Liu, Q., Y. Liu, Y. Wu, J.-Y. Shen, S. Li, C. Yu, and M. Su, "A substrate integrated waveguide to substrate integrated coaxial line transition," *Progress In Electromagnetics Research C*,

Vol. 36, 249–259, 2013.

[9] Schiffman, B. M., "A new class of broad-band microwave 90-degree phase shifters," *IRE Transactions on Microwave Theory and Techniques*, Vol. 6, No. 2, 232–237, 1958.

[10] Guo, Y.-X., Z.-Y. Zhang, and L. C. Ong, "Improved wide-band Schiffman phase shifter," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 54, No. 3, 1196–1200, Mar. 2006.

[11] Wang, Y., M. E. Bialkowski, and A. M. Abbosh, "Double microstrip-slot transitions for broadband ±90° microstrip phase shifters," *IEEE Microwave and Wireless Components Letters*, Vol. 22, No. 2, 58–60, 2012.

[12] Yeung, S. H., Z. Mei, T. K. Sarkar, and M. Salazar-Palma, "Design and testing of a single-layer microstrip ultrawideband 90° differential phase shifter," *IEEE Microwave and Wireless Components Letters*, Vol. 23, No. 3, 122–124, 2013.

[13] Wang, J.-X., L. Yang, Y. Liu, Y. Wang, and S.-X. Gong, "Design of a wideband differential phase shifter with the application of genetic algorithm," *Progress In Electromagnetics Research Letters*, Vol. 48, 45–49, 2014.

[14] Ravelo, B., M. L. Roy, and A. Pérennec, "Application of negative group delay active circuits to the design of broadband and constant phase shifters," *Microwave and Optical Technology Letters*, Vol. 50, No. 12, 3078–3080, 2008.

[15] Keser, S. and M. Mojahedi, "Broadband negative group delay microstrip phase shifter design," in *2009 IEEE Antennas and Propagation Society International Symposium*, 1–4, North Charleston, SC, USA, 2009.