

# A WIDEBAND 360° ANALOG PHASE SHIFTER DESIGN

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## ABSTRACT

This paper proposes a reflection-type wideband 360° analogue phase shifter. The phase shifter employs a branch-line coupler circuit to achieve a wideband operation and a varactor-diode circuit to achieve a wide phase-shift range. Analytical formulas are derived to optimize the parameters in the coupler circuit for wideband operation and reduced attenuation ripple, and in the varactor circuit to minimize the frequency dependency of the output phase. Simulation results using the Advanced Design Systems (ADS 2005A) show that the design has a wide bandwidth, wide phase shift range, and low attenuation ripple, and is highly linear across the operation bandwidth.

**Index Terms** — Branch-line coupler, Wideband phase shifter, Reflection type, Varactors

## I. INTRODUCTION

Analogue phase shifters are widely used in communication systems, radar systems and microwave automatic control systems. Very often, simplicity is a major requirement in these applications. Phase shifters can be made by loaded transmission line techniques which require many diodes and several wavelengths of transmission lines to achieve a 360° phase shifting [1]. Reflection-type phase shifters can however be made smaller but close to the ideal performance by connecting varactor diodes at the ports of a coupler or circulator [1]. In the design of a reflection-type phase shifter, the following requirements should be considered: 1) the phase-shifting range, 2) the attenuation ripple, 3) the wide-bandwidth requirement, and 4) the linearity of phase shifting versus the controlled voltage [1-2]. Several methods have been designed to satisfy these requirements [1, 3]; however, none of them can achieve all four requirements in a single circuit. In [2], a varactor diode with series inductance was used to obtain a phase-shifting range of less than 180 degree, so a multi-stage phase shifter was needed to produce a 360° phase shift. The authors in [3] described a 360° -phase shifter only at a given centre frequency. A wideband-phase shifter was studied in [4]. It however only provided a phase-shifting range of less than 180° .

In this paper, we propose a new design for a wideband analogue phase shifter which can provide a phase-shifting

range of 360° . It is a reflection-type phase shifter, consisting of a 3-dB hybrid coupler and a varactor-diode circuit to achieve a wideband operation as well as a wide phase-shifting range. The characteristics of the phase shifter is determined and so optimized by adjusting the widths and lengths of the transmission lines on the substrate. In the following sections, we first describe the wideband 3-dB coupler design in section II. The analytical formulas for using varactors to achieve a 360° phase shift in the phase shifter are derived in section III. The performances of the phase shifter using the computer aided tool ADS 2005A are presented in section IV. Conclusions are given in section V.

## II. THE WIDEBAND COUPLER DESIGN

In the reflection-type phase shifter, a 3-dB coupler is usually used to split the input signal into two signals which are combined to produce the output signal. Figure 1 (a) shows a conventional 3-dB hybrid coupler, also called the branch-line coupler, which is a four-port device. The input signal in port #1 is equally divided into two signals in ports #2 and #3, with a 90° phase difference. This structure can easily be implemented by using micro-strips, but it suffers from the drawback of being narrow-band. Methods have been studied to modify the conventional coupler structure to become a wide-band coupler [5-7], e.g., adding open stubs at the symmetry-planes of the coupler, splitting a low-impedance line into two paralleled high-impedance lines, and connecting an open stub at the branching junctions [5]. Although these methods can avoid low-impedance lines, they result in reduction of the coupler bandwidth [5].

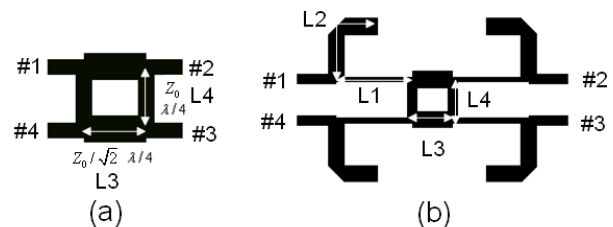


Figure 1 (a) Conventional Coupler.

(b) Wideband Coupler.

Putting a matched network, i.e., a series transmission line and a parallel open stub, in the junction of the coupler can improve the bandwidth of a branch-line coupler [5-6]. A

wideband coupler using this method is shown in Fig. 1(b) where a wideband matching network ( $L_1$  and  $L_2$ ) is placed between input port #1 and the branch junction. From the transmission line theory, the electrical parameters of a transmission line are determined by its width and length for a given substrate board. The performance of the wideband coupler in Fig. 1(b) is therefore determined and so can be optimized by varying the widths and lengths of stubs  $L_1$ ,  $L_2$ ,  $L_3$  and  $L_4$ .

In [5-6], the authors presented some complex analyses to determine the parameters of these lines. Our approach here is to minimize an error function in the operating frequency band, hence to increase the operating bandwidth.

An ideal 3-dB hybrid coupler has its S-parameters  $S_{21}$  and  $S_{31}$  equal in amplitude and phase difference of 90 degree. With these criterions, we can define an error function for the coupler as:

$$F = \int_{f_{lower}}^{f_{upper}} [ |A_{S_{21}}(f) - A_{S_{31}}(f)|^2 + ( |P_{S_{21}}(f) - P_{S_{31}}(f)| - 90 )^2 + |A_{S_{21}}^2(f) - 0.5|^2 + |A_{S_{31}}^2(f) - 0.5|^2 ] df \quad (1)$$

where  $A_{S_{21}}(f)$  and  $A_{S_{31}}(f)$  are the amplitudes of  $S_{21}$  and  $S_{31}$  respectively,  $P_{S_{21}}(f)$  and  $P_{S_{31}}(f)$  are the phases of  $S_{21}$  and  $S_{31}$  respectively,  $f_{lower}$  is the lowest operating frequency, and  $f_{upper}$  is the highest operating frequency. For an ideal 3-dB hybrid coupler, the error function  $F$  in (1) should be zero, i.e.,  $F = 0$ .

It is difficult to have an analytical solution for (1), thus we propose to use numerical evaluation. Here we denote  $f_i$  as a frequency in the range from  $f_{lower}$  to  $f_{upper}$  and modify the error function to:

$$F' = \sum_{f_i} |A_{S_{21}}(f_i) - A_{S_{31}}(f_i)|^2 + \sum_{f_i} ( |P_{S_{21}}(f_i) - P_{S_{31}}(f_i)| - 90 )^2 + \sum_{f_i} |A_{S_{21}}^2(f_i) - 0.5|^2 + \sum_{f_i} |A_{S_{31}}^2(f_i) - 0.5|^2 \quad (2)$$

which can be evaluated numerically. The width and length of the lines leading to the minimum of the error function  $F'$  can then be obtained.

### III. THE WIDEBAND PHASE SHIFTER DESIGN

The layout of our proposed phase shifter is shown in Fig. 2. It consists of a wideband coupler and a reflection function unit. The input signal in port #1 is equally divided by the coupler into two signals which are directed to two balanced branches, #2 and #3, with  $90^\circ$  phase difference. By terminating the balanced branches #2 and #3 each with two

identical varactor diodes, the signals are reflected with the same phase [8]. The reflected signals from the balanced branches #2 and #3 are recombined in phase in the coupler to produce the output signal from port #4. While in the input port #1, the reflected signals are  $180^\circ$  out of phase and so cancelled off with each other [8]. When the reverse-bias voltage applied to the varactor diodes changes, their capacitances and so their impedances change. This in turn changes the amplitude and phase shift of the reflected signals. In our study, we attempt to design a phase shifter with  $360^\circ$  shifting range and the operation bandwidth of 600MHz at the center frequency of 6.6GHz.

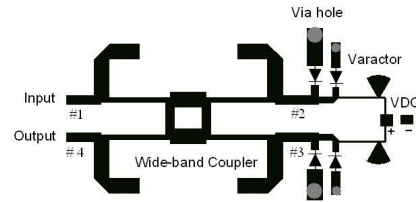


Figure 2 Layout of proposed phase shifter.

Studies have shown that connecting two series-tuned varactor diodes in parallel can achieve a larger phase-shifting range and smaller attenuation ripple than those using a single varactor diode [1, 3, 9]. The author in [3] presented a circuit using a series resonance of a diode with inductive effect at lower bias and another series resonance of a diode with inductive effect at higher bias. The two resonant units ( $X_d$  and  $X_s$ ) are connected together via a quarter-wave transformer as shown in Fig. 3(a). This phase-shifter has a  $360^\circ$  phase shift, but the phase shift varies with frequency [3]. In our design, we propose to use a series transmission line at each of the resonant units as shown in Fig. 3(b) to minimize the frequency dependency of the phase shifter.

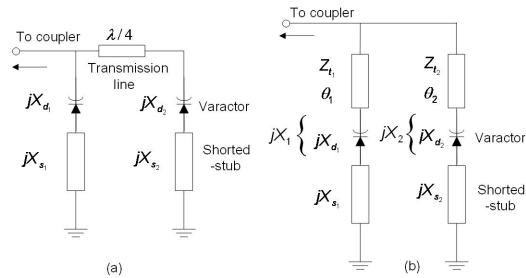


Figure 3 (a) Phase shifter using  $\lambda/4$  transmission line. (b) Wideband phase shifter.

From the transmission line theory, the impedances of the two branches in Fig. 3(b) can be obtained as:

$$X_1 = Z_{t_1} \frac{(X_{d_1} + X_{s_1}) + Z_{t_1} \tan \theta_1}{Z_{t_1} - (X_{d_1} + X_{s_1}) \tan \theta_1} \quad (3)$$

$$X_2 = Z_{i_2} \frac{(X_{d_2} + X_{s_2}) + Z_{i_2} \tan \theta_2}{Z_{i_2} - (X_{d_2} + X_{s_2}) \tan \theta_2} \quad (4)$$

where  $Z_{i_1}$  and  $Z_{i_2}$  are the characteristic impedances of the series transmission lines,  $\theta_1$  and  $\theta_2$  are their electrical lengths,  $X_{d_1}$  and  $X_{d_2}$  are the impedances of the varactor diodes, and  $X_{s_1}$  and  $X_{s_2}$  are the impedances of the shorted-stubs.

The input impedance to the coupler is:

$$X = \frac{X_1 X_2}{X_1 + X_2} \quad (5)$$

The reflection coefficient is:

$$\Gamma = \frac{jX - Z_0}{jX + Z_0} = \frac{j\bar{X} - 1}{j\bar{X} + 1} = |\Gamma| e^{j\Phi}; \bar{X} = \frac{X}{Z_0} \quad (6)$$

where  $Z_0$  is the characteristic impedance of the input and output arms of the coupler. So,

$$\Phi = \pi - 2 \tan^{-1}(\bar{X}) \quad (7)$$

From (7), it can be seen that, for  $360^\circ$  phase shifting, the variable  $X$  needs to be varied from negative infinity to positive infinity. This could be approximately implemented by tuning one series transmission line to resonant at the minimum reverse bias and the other series transmission line to resonant at the maximum reverse bias.

To minimize the dependence of the phase shift on frequency, we consider

$$\frac{\partial \Phi}{\partial f} = -\frac{1}{1 + (\bar{X})^2} \frac{\partial \bar{X}}{\partial f} = -\frac{1}{1 + (\bar{X})^2} \frac{X_2^2 \frac{\partial X_1}{\partial f} + X_1^2 \frac{\partial X_2}{\partial f}}{(X_1 + X_2)^2 Z_0} \quad (8)$$

where

$$\begin{aligned} \frac{\partial X_i}{\partial f} = & -\frac{Z_{i_1} (X_{d_i} + X_{s_i}) + Z_{i_1}^2 \tan \theta_{i_1}}{(Z_{i_1} - (X_{d_i} + X_{s_i}) \tan \theta_{i_1})^2} \left[ \frac{\partial Z_{i_1}}{\partial f} - \frac{\partial (X_{d_i} + X_{s_i})}{\partial f} \tan \theta_{i_1} \right. \\ & \left. + \frac{\partial \theta_{i_1}}{\partial f} \right] + \frac{\partial Z_{i_1} (X_{d_i} + X_{s_i}) + 2Z_{i_1} \tan \theta_{i_1}}{Z_{i_1} - (X_{d_i} + X_{s_i}) \tan \theta_{i_1}} \frac{\partial \theta_{i_1}}{\partial f}; \quad i = 1, 2 \end{aligned} \quad (9)$$

If the value of (8) is zero within the operating frequency band, the phase shifting will be independent of frequency. We therefore define an phase deviation function as:

$$F = \sum_{f_i} \left| \frac{\partial \Phi}{\partial f} \right|^2 \quad (10)$$

where  $f_i$  is a frequency in the operating frequency band. The design process is thus to search for the transmission lines' characteristic impedances  $Z_{i_1}$  and  $Z_{i_2}$  and line lengths  $\theta_1$  and  $\theta_2$  that give a minimum value of  $F$  in (10).

## IV. RESULTS OF CIRCUIT PERFORMANCES

### 4.1 Performance of the wideband coupler

The computer aided design tool, ADS 2005A, has been used to minimize the error function in (2), i.e. maximize the coupler bandwidth. In the optimizing process, the initial line characteristic impedances of  $L_1$  and  $L_2$  were both set to  $50 \Omega$ , and their lengths were set to  $\lambda/2$  at the center frequency. The lengths  $\lambda/2$  were selected to make the matching network  $L_1$  and  $L_2$  wideband [7]. The characteristic impedances of  $L_3$  and  $L_4$  were set to  $35.4 \Omega$  and  $50 \Omega$  respectively, same as those used in the conventional coupler, and the electric lengths were both set to  $\lambda/4$  at the centre frequency. In practice, the range of the characteristic impedance of these lines is limited by the usable impedance for the substrates in the frequency band, which is a function of the substrate thickness.

Figure 4 shows the performance of the wideband coupler by optimizing the widths and lengths of the transmission lines ( $L_1, L_2, L_3$  and  $L_4$ ) using ADS 2005A. Although the phase shifter is designed to operate at 6.3GHz-6.9GHz, we can see that the coupler can achieve a much wider bandwidth. Within the frequency band of 5.6GHz-7.6GHz, the wideband coupler has less than 0.3 dB unbalance of  $S_{21}$  and  $S_{31}$ , while the phase difference of the two ports #2 and #3 are within  $89.2^\circ$  and  $90.5^\circ$ . For a conventional coupler operating at the same bandwidth, Fig. 5 shows that there is a more than 4dB unbalance of  $S_{21}$  and  $S_{31}$  and that the phase difference ranges from  $76^\circ$  to  $90^\circ$ .

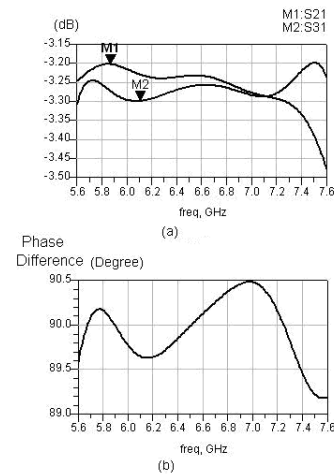


Figure 4 Performance of wideband coupler. (a) Amplitudes of coupling coefficients  $S_{21}$  and  $S_{31}$ . (b) Phase difference between port #2 and port #3

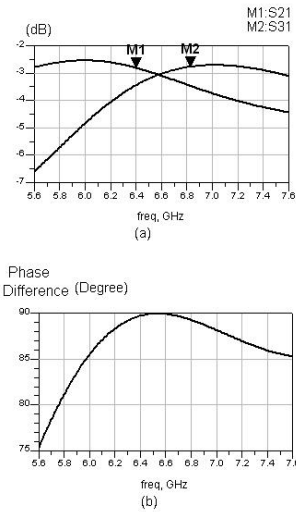


Figure 5 Performance of convention coupler. (a) Amplitudes of coupling coefficients  $S_{21}$  and  $S_{31}$ . (b) Phase difference between port #2 and port #3.

#### 4.2 Performance of the Phase shifter

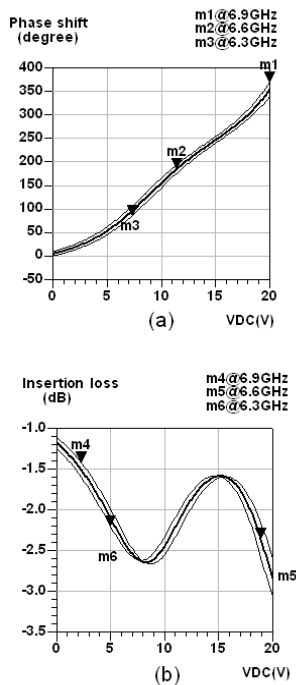


Figure 6 (a) Phase shifting at different frequencies. (b) Insertion loss of the phase shifter.

Figure 6 shows the simulation results using ADS2005A for the phase shifting and insertion loss of the proposed phase shifter at different frequencies. It can be seen that when the reverse biased voltage of the varactor diodes varies from 0 to 20V, the phase shift changes from  $0^\circ$  to

$360^\circ$ . The phase errors between the edge frequencies of 6.3 GHz and 6.9 GHz and the centre frequency of 6.6 GHz are within  $8^\circ$ . The ripples of the insertion loss across the frequency band are less than 2dB. The results in [3] also could achieve a  $360^\circ$  phase shift and 1.4dB insertion loss ripple, it was only for the frequency of 10GHz. However, our proposed design has a wide bandwidth performance.

#### V. CONCLUSIONS

A wideband  $360^\circ$  phase shifter has been proposed. The phase shifter consists of a wide-band coupler circuit and a varactor diodes circuit. The bandwidth and phase shifting range are determined by the widths and lengths of the transmission lines of the circuits. The formulas for optimizing the performance, in terms of maximizing the bandwidth and minimizing the ripple across frequency band, have been derived and studied. Simulation results have shown that the proposed phase-shifter can achieve a phase shift range of  $360^\circ$  from 6.3GHz to 6.9GHz with an insertion loss of less than 2dB. At the band edges of 6.3GHz and 6.9GHz, the phase derivations are less than  $8^\circ$ .

#### REFERENCES

- [1] R. V. Garver, "360° Varactor Linear Phase Modulator", *IEEE Transactions on Microwave Theory and Techniques*, Vol. MTT-17, NO.3, Mar 1969, pp.137-146.
- [2] S. K. Koul and B. Bhat, *Microwave and Millimeter Wave Phase Shifters*, Vol.2, Norwood: Artech House, 1991.
- [3] T. W. Yoo, J. H. Song and M.S. Park, "360° Reflection-type Analogue Phase Shifter Implemented with A Single 90° Branch-Line Coupler", *Electronic Letters*, Vol.33, No.3, Jan 1997, pp. 224-226.
- [4] B. Ulriksson, "Continuous Varactor-Diode Phase Shifter with Optimum Frequency Response", *IEEE Transactions on Microwave Theory and Techniques*, Vol. MTT-27, July 1979, pp. 650-654.
- [5] M. Muraguchi, T. Yukitake and Y. Naito, "Optimum Design of 3-dB Branch-line Couplers Using Micro-strip lines", *IEEE Transactions on Microwave Theory and Technique*, Vol. MTT-31, No.8, Aug 1983, pp. 674-678.
- [6] G. P. Riblet, "A Directional Coupler with Very Flat Coupling", *IEEE transactions on Microwave Theory and Techniques*, Vol. MTT-26, No.2, Feb 1978, pp. 70-74.
- [7] B. Mayer and R. Knochel, "Brach-line-couplers with improved Design Flexibility and Broad Bandwidth", *IEEE MTT-S Digest*, 1990, pp. 391-394.
- [8] Skyworks, Application Note: A Varactor Controlled Phase Shifter for PCS Base Station Applications, Available at: <http://www.skyworksinc.com>
- [9] Y. H. Liew, J. Joe and M. S. Leong, "A Novel 360° Analog Phase Shifter with Linear Voltage Phase Relationship", *Microwave Conference Asia Pacific*, Vol.1, Nov, 1999, pp. 17-20.