A Novel Type Phase Shifter Using Rat Race Hybrid

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Abstract—In this paper, we proposed a novel type phase shifter using rat-race hybrid with one additional quarter-wavelength transmission line for phase compensation and two varactors as phase controlling elements. The circuit has been simulated by IE3D and fabricated on FR-4 substrate. The simulated and measured results are in good agreement with in the frequency of interest.

1. INTRODUCTION

Phase shifters are widely used in phase array radar systems [1, 2] for radiation beam steering on searching and tracking, and modern wireless communication system’s base station antennas for adjusting the radiation coverage to improve the service quality. Phase shifter circuit can be simply made by different transmission lines and switches. In 1965, J. F. White used high power PIN diodes and transmission lines created L/S bands phase shifter circuit [3]. Cheah, Y. C., Paoloni, F. J. proposed a variable attenuators and phase shifters also using PIN diodes in 1984 [4]. Neidert, R. E., Krowne, C. M. in 1985 proposed a voltage-controlled phase shifter [5]. Lian, C., Rosenau, S. A., Zhang, W. K., Chang, C. C., Domier, C. W. and Luhmann, N. C. used lumped element in phase shifter design in 2000 [6].

The deployment of Radio Frequency Identification (RFID) is increasingly popular in many fields, ranging from access control, livestock management to logistics, and the available frequency band are 125 kHz, 13.56 MHz, 869 MHz, 902–928 MHz, 2.45 GHz, and 5.8 GHz. As the antenna is an integral part of whole RFID system design, the antenna is crucial to the overall system performance.

The proposed phase shift circuit is shown Fig. 1, port 3 is input, port 2 is output, and port 4 is shunted to ground through a capacitor, port 1 is also shunted to ground through a quarter-wave transmission line and a capacitor with the same value as that at port 4. The circuit forming a phase shift structure in which the phase will change with the capacitor values. The proposed structure has been simulated by using the software, IE3D, to have a comparison on phase shift between the simulation and measurement results.

![Figure 1: Schematic diagram of the proposed phase shift circuit.](image-url)
as depicted in Figs. 2 (a) and (b) respectively, where \( \theta_1, \theta_2 \) and \( \theta_3 \) denote the electrical lengths, \( Z_1 \) and \( Z_2 \) are the characteristic impedances. The upper half circuit, cascaded by two transmission line sections and lump circuit, can be expressed in matrix form of Eq. (1), and the lower half circuit is in Eq. (2), where \( Z_C \) is the impedance of capacitor and \( Z_{in} \) is the input impedance of the transmission line, \( Z_3 \) and \( \theta_3 \) connected with shunted capacitor \( C \).

\[
\begin{bmatrix}
\cos \theta_1 & j Z_o \sin \theta_1 \\
\frac{1}{Z_o} \sin \theta_1 & \cos \theta_1
\end{bmatrix}
\begin{bmatrix}
1 & 0 \\
\frac{1}{Z_c} & 1
\end{bmatrix}
\begin{bmatrix}
\cos \theta_2 & j Z_o \sin \theta_2 \\
\frac{1}{Z_o} \sin \theta_2 & \cos \theta_2
\end{bmatrix}
\]
\begin{align}
(1)
\end{align}

\[
\begin{bmatrix}
\cos \theta_1 & j Z_o \sin \theta_1 \\
\frac{1}{Z_o} \sin \theta_1 & \cos \theta_1
\end{bmatrix}
\begin{bmatrix}
1 & 0 \\
\frac{1}{Z_{in}} & 1
\end{bmatrix}
\begin{bmatrix}
\cos \theta_1 & j Z_o \sin \theta_1 \\
\frac{1}{Z_o} \sin \theta_1 & \cos \theta_1
\end{bmatrix}
\]
\begin{align}
(2)
\end{align}

\[
Z_c = \frac{1}{j \omega C}
\]
\begin{align}
(3)
\end{align}

\[
Z_{in} = Z_{TL} \cdot \frac{Z_c + j \cdot Z_{TL} \cdot \tan \theta_3}{Z_{TL} + j \cdot Z_c \cdot \tan \theta_3}
\]
\begin{align}
(4)
\end{align}

The total transmission matrix, \( ABCD \) matrix, shown in Eq. (1) has the elements \( A_1, B_1, C_1 \) and \( D_1 \), shown in Eqs. (5)–(8) respectively, and vise versus Eq. (2) is expressed in Eqs. (9)–(12).

\[
A_1 = \cos \theta_2 \left( \cos \theta_1 + \frac{j Z_o \sin \theta_1}{Z_c} \right) - \sin \theta_1 \cdot \sin \theta_2)
\]
\begin{align}
(5)
\end{align}

\[
B_1 = j Z_o \sin \theta_2 \left( \cos \theta_1 + \frac{j Z_o \sin \theta_1}{Z_c} \right) + j Z_o \sin \theta_1 \cos \theta
\]
\begin{align}
(6)
\end{align}

\[
C_1 = \cos \theta_2 \left( \frac{j \sin \theta_1}{Z_o} + \frac{\cos \theta_1}{Z_c} \right) + j \cos \theta_1 \sin \theta_2
\]
\begin{align}
(7)
\end{align}

\[
D_1 = j Z_o \sin \theta_2 \left( \frac{j \sin \theta_1}{Z_o} + \frac{\cos \theta_1}{Z_c} \right) + \cos \theta_1 \cdot \cos \theta_2)
\]
\begin{align}
(8)
\end{align}

\[
A_2 = -\sin^2 \theta_1 + \cos \theta_1 \left[ \cos \theta_1 + \frac{j Z_o \sin \theta_1 (Z_{TL} + \frac{\tan \theta_3}{Z_c})}{Z_{TL} (Z_c + j Z_{TL} \tan \theta_3)} \right]
\]
\begin{align}
(9)
\end{align}

\[
B_2 = j Z_o \cos \theta_1 \sin \theta_1 + j Z_o \sin \theta_1 \left[ \cos \theta_1 + \frac{j Z_o \sin \theta_1 (Z_{TL} + \frac{\tan \theta_3}{Z_c})}{Z_{TL} (Z_c + j Z_{TL} \tan \theta_3)} \right]
\]
\begin{align}
(10)
\end{align}

\[
C_2 = \frac{j \cos \theta_1 \sin \theta_1}{Z_o} + \cos \theta_1 \left[ \frac{j \sin \theta_1}{Z_o} + \frac{\cos \theta_1 (Z_{TL} + \frac{\tan \theta_3}{Z_c})}{Z_{TL} (Z_c + j Z_{TL} \tan \theta_3)} \right]
\]
\begin{align}
(11)
\end{align}
\[ D_2 = \cos^2 \theta_1 + jZ_o \sin \theta_1 \left[ \frac{j \sin \theta_1}{Z_o} + \frac{\cos \theta_1(Z_{TL} + \frac{\tan \theta_1}{w(\omega)})}{Z_{TL}(Z_c + jZ_{TL} \tan \theta_3)} \right] \]  

(12)

The whole circuits \( ABCD \) matrix with elements \( A, B, C \) and \( D \) are in Eqs. (13)–(16) respectively. The matrix can then transfers into scattering parameters as Eqs. (17) and (18). The phase of \( S_{21} \) has the expression of Eq. (19). Where Eq. (19) \( a \) and \( jb \) denote the real part and image part of \( S_{21} \) parameters respectively.

\[ A = \frac{A_1B_2 + A_2B_1}{B_1 + B_2} \]  

(13)

\[ B = \frac{B_1B_2}{B_1 + B_2} \]  

(14)

\[ C = \frac{(A_2 - A_1)(D_1 - D_2) + (B_1 + B_2)(C_1 + C_2)}{B_1 + B_2} \]  

(15)

\[ D = \frac{D_1B_2 + B_1D_2}{B_1 + B_2} \]  

(16)

\[ S_{11} = \frac{A + \frac{B}{Z_o} - C \times Z_o - D}{A + \frac{B}{Z_o} + C \times Z_o + D} \]  

(17)

\[ S_{21} = \frac{2}{A + \frac{B}{Z_o} + C \times Z_o + D} \]  

(18)

\[ \angle S_{21} = \tan^{-1} \frac{jb}{a} \]  

(19)

When \( Z_1 = Z_2 = Z_3 = 70.7 \Omega, \theta_1 = 90^\circ, \theta_2 = 270^\circ, \theta_3 = 90^\circ \) are carried in the Eqs. (18) and (19) with center frequency 925 MHz and capacitance 2.81 pF, we can get \( S_{21} = -0.1259 - j0.9359 \) with phase \(-97.65^\circ\); and the \( S_{21} = -0.7728 - j0.6009 \) with phase \(-142.13^\circ\) while center frequency is 2.45 GHz and capacitance 2.81 pF. By knowing the scattering parameter \( S_{21} \) at the center frequency, we can determine phase changing at different capacitance values.

3. CIRCUIT DESIGN

A phase shift circuit was implemented based on the derived equations and simulated by using EM simulation tool, IE3D. FR-4 substrate was used, with thickness 1.6 mm and dielectric constant 4.3. The two varactors (\( D_1 \) and \( D_2 \)) model no. SMV1234, SKYWORK, are applied on the two circuits of center frequency 925 MHz and 2.45 GHz with a range from 1.32 pF to 9.63 pF. The characteristic impedances of input and output port are both 50 Ohm.

The layout of the circuit is shown in Fig. 3(a). The lengths of \( L_1, L_2, W_1 \) and \( W_2 \) can be calculated by Line Gauge of IE3D are 46.02, 4.5, 47.55, 1.64, 3.1 and 0.41 mm respectively, at 925 MHz. This physical circuit is shown in Fig. 3(b) with 95.32 mm \( \times \) 52.12 mm. The frequency response of both simulation and measurement results is shown in Fig. 3(c), where the dash line denotes the simulation results by IE3D, solid line is measured results when the varactors biased at 4V. The corresponding phase of \( S_{21} \) is shown in Fig. 3(d). It has a good agreement of frequency response between measurement and simulation at 925 MHz.
The Figs. 4(a)–4(d) demonstrate the simulated and measured results of another phase shifter circuit designed at 2.45 GHz, where the circuit dimension are 38.02 mm × 23.13 mm, \( L_1: 17.37 \text{ mm} \), \( L_2: 4.52 \text{ mm} \) and \( L_3: 17.95 \text{ mm} \), \( W_1: 1.64 \text{ mm} \), \( W_2: 3.1 \text{ mm} \) and \( W_3: 0.41 \text{ mm} \).

The relationship between phase changing and the bias voltage of varactors are shown in Fig. 5(a) and Fig. 5(b) at 925 MHz and 2.45 GHz respectively. The varactors bias voltage from 0 V–5 V at 925 MHz and 0 V–7 V at 2.45 GHz has a good linearity result shown in Fig. 5(a) and Fig. 5(b).
4. CONCLUSIONS

In this paper, we proposed a novel type phase shifter using rat-race hybrid with one additional quarter-wavelength transmission line for phase compensation and two varactors as phase controlling elements. The equivalent circuit of this phase shifting structure was obtained by calculating the $ABCD$ matrices. The phase will be changed by the different capacitor values or different bias voltages applying to varactors. The circuit has been simulated by IE3D and fabricated in FR-4 substrate. The simulated and measured results are in a good agreement with in the frequency of interest.

REFERENCES