Electronically Tunable Reflection Type Phase Shifter Using PIN Diode As A Variable Resistor

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***Abstract*—This paper presents a new attempt to utilize the PIN diodes as variable resistors to realize a continuously tunable phase shifter. A diode is used in parallel to a capacitor. Thus, the diode resistance and hence the imaginary part of the impedance can be varied. The tuning range of a varactor capacitance is usually limited to 1:2. However, the resistance of a diode can vary from a few Ohms to a few kilo Ohm. Therefore, a much wider tuning range is possible. The next challenge is to reduce the power lost in the real part of the impedance. As an example, a reflection-type phase shifter (RTPS) is designed and implemented at 2.4 GHz.**

Keywords—Branch line coupler, reflection type phase shifter (RTPS), PIN Diode.

I. INTRODUCTION

Electronically tunable phase shifters are widely used in various RF circuits, the most important being the adaptive beamforming, beam steering, and null steering applications. Analog phase shifters are broadly divided into three categories. The loaded transmission line, the switched networks, and the reflection type [1]. A loaded transmission line uses some periodic loads in the form of active devices such as varactor diodes. Continuous electronic phase tuning is possible by changing the load impedance by bias voltages. However, it causes degradation in $|S_{11}|$. Further, the range of phase variation is usually less compared to the other two. Switched network type employs active devices like PIN diode or FET or MEMS as the switches. Then, different lengths of lines are switched back and forth to obtain different discrete time delays. Continuous tuning is not possible. Since the delay is being changed, the phase of $|S_{21}|$ always linearly increases with frequency. They usually suffer from high insertion loss because of the high ON resistance of the switches and long lengths of lines. The range of phase variation can be increased by using a reflection-type phase shifter (RTPS). RTPS uses a 3 dB 90° hybrid coupler. The variable loads are connected to the through and coupled ports of the coupler. The output is taken from the original isolation port of the coupler. The input signal is divided into two parts. The first part propagates through the arm connecting the input and output ports. The second part reflects back from the through and coupled ports. Two similar loads are connected to the through and coupled ports. The reflection of the signals is tuned by the loads. Finally, these two signals interfere at the output port. Continuous phase tuning is possible. With proper design parameters, the reflection of the signal from the load ends to the output port improves the $|S_{11}|$ and $|S_{21}|$.

In [1], an RTPS has been fabricated using varactor diodes. A varactor diode in reverse bias behaves as a variable capacitor. An RTPS using a single diode usually provides a small tuning range. Therefore, a common practice is to use multiple diodes in different series/shunt combinations to achieve a substantial amount of phase change [2]. This increases the cost and implementation area of the phase shifter. Also, the insertion loss becomes a function of the amount of phase shift. A full 360° RTPS using a single branch line coupler has been shown in [3]. It uses an identical load mentioned in [2] and analytically established a mathematical relationship in order to achieve 360° phase shift. In [4], a shunt resistor has been used to decrease insertion loss variation. The work in [5] examines the effect of shunt resistance.

PIN diodes show better performance at higher frequencies, especially at millimeter wave frequencies. They are most popular in switched line phased shifters [6]-[8]. The diode switches between low and high impedance states. In [6], an open stub along with PIN diodes are used to design a broadband phase shifter. In [7], [8], RTPS are also designed based on PIN diode-based loads. The PIN diode-based phase shifters actually change the time delay or the slope of the phase-frequency curve. Since they are used as switches, a continuous time or phase variation is not possible. Recently, a continuously tuneable dispersive delay line has been shown where the slope and the peak value of the delay have been controlled electronically by treating PIN diode as a variable resistor [9].

In all the above RTPS [6]-[8], PIN diodes are used as the switches. In this work, the PIN diodes are used as variable resistors to obtain continuous phase variation, for the first time to the best of the authors' knowledge. The resistance can be easily tuned by the dc bias current of the diode. Thus, continuous electronic tuning of the phase is possible. First, the design graphs are obtained using a lossless transmission line model. Finally, an RTPS is designed and implemented.

II. THEORY AND ANALYSIS

The impedance of a parallel combination of a resistor R and capacitor C is

$$Z_L = \frac{R}{1+(\omega RC)^2} - j\frac{1}{\omega C\left(1+1/(\omega RC)^2\right)}. \quad (1)$$

Therefore,

$$C_{eq} = C\left(1+\frac{1}{(\omega RC)^2}\right). \quad (2)$$

Thus, for a given C, the imaginary part can be easily tuned by the R of a PIN diode. Power lost in the diodes is small if the real part is either very small or very large. Next, the challenge is to obtain a wide tuning range by different combinations of the diodes and series/shunt stubs or SMD capacitors keeping power dissipation in the real part small. Here, in this first attempt, a combination of two diodes and two SMD capacitors are used as the load of the RTPS. The circuit is fabricated and experimentally validated.

Fig. 1 shows the configuration of the RTPS. It uses a traditional 3 dB branch-line hybrid coupler with $Z_1 = 35.35\ \Omega$, $Z_2 = 50\ \Omega$ and $\theta_1 = \theta_2 = 90^o$ at the design frequency f_0. The variable loads are connected to the through and coupled ports of the coupler. The simulated response of the coupler is shown in Fig. 2. The coupler shows at least 20 dB matching and isolation over 2.2-2.6 GHz. The phase imbalance is less than 0.4° over this frequency band. Agilent's ADS is used for all simulations. For a branch-line hybrid based RTPS, the phase variation angle (S_{21}) depends on the reflection coefficient Γ_L at the load port as

$$\angle S_{21} = -90^o + \angle\Gamma_L = -90^o + \tan^{-1}\left(\frac{2Z_0X_L}{R_L^2 - Z_0^2 + X_L^2}\right), \quad (2)$$

where $Z_L = R_L + jX_L$ is the load impedance and Z_0 is the port impedance.

Then, $$|S_{21}| = \left|\frac{R_L^2 + X_L^2 - Z_0^2 + j2Z_0X_L}{R_L^2 + X_L^2 + Z_0^2 + 2Z_0R_L}\right|. \quad (3)$$

Therefore, $\left(R_L^2 + X_L^2 - Z_0^2\right)$ should be minimized to decrease the insertion loss.

Fig. 3 shows the equivalent circuit of a PIN diode and the PCB layout of the load. Since the diode is used as a variable resistor, it is always in the forward bias condition. The capacitors are fixed SMD capacitors. In the simulations, actual spice models are used for the capacitors. For the example presented here, the circuit parameters are $C_1 = 10$ pF, $C_2 = 6.8$ pF, $C_3 = 1$ pF, $Z_4 = 50\ \Omega$, $\theta_4 = 5^o$, $Z_5 = 50\ \Omega$, $\theta_5 = 10^o$, $Z_3 = 20\ \Omega$, $\theta_3 = 90^o$, $Z_6 = 50\ \Omega$, $\theta_6 = 3^o$, $Z_7 = 50\ \Omega$, and $\theta_7 = 10^o$ at the design frequency of $f_0 = 2.4$ GHz. The low cost BAP64-02-115 PIN diodes are used in the design. The diode forward resistance R_D varies between 1 Ω to 700 Ω for a forward bias current of 100 mA to 1 mA, respectively. The maximum allowed current is 100 mA. It can be used till 6 GHz. The series inductance of the diode from the datasheet is 0.6 nH, and the shunt parasitic capacitance is 0.48 pF. Fig. 4 shows the impedance loci for Z_L for the above load parameters. The impedance varies between $8.69 + j21.38\ \Omega$ and $1.25 - j10.57\ \Omega$ at 2.4 GHz when the forward current varies over 1-100 mA. As shown in Fig. 5, the insertion loss of the RTPS $|S_{21}|$ remains within 3 dB for $1\ \Omega \le R_D \le 20\ \Omega$ and $175\ \Omega \le R_D \le 700\ \Omega$. Over the range, the corresponding phase angle(S_{21}) varies between -76.1^0 and -150^0. The $|S_{11}|$ is always below -20 dB.

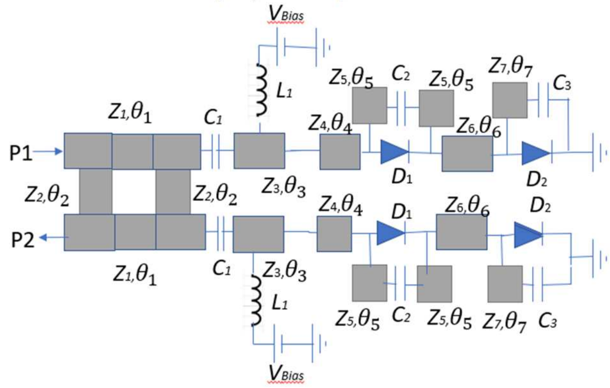


Fig. 1 Configuration of the RTPS and the loads.

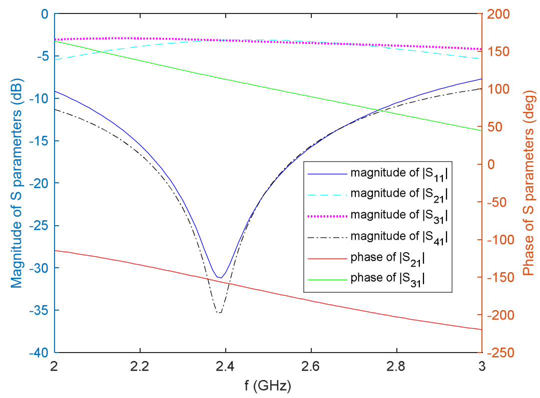


Fig. 2 Simulated response of the 3 dB hybrid coupler using the conventional port designation.

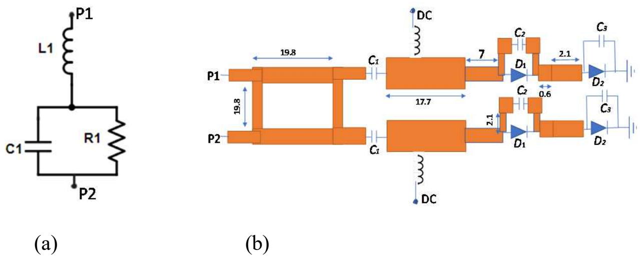


Fig. 3 (a) Equivalent circuit of a PIN diode in ON condition, and (b) the PCB layout of the load (unit: mm).

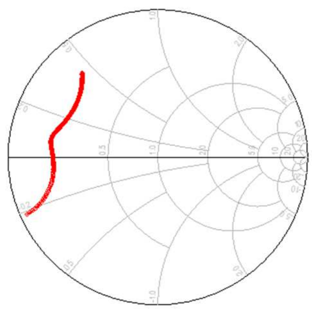
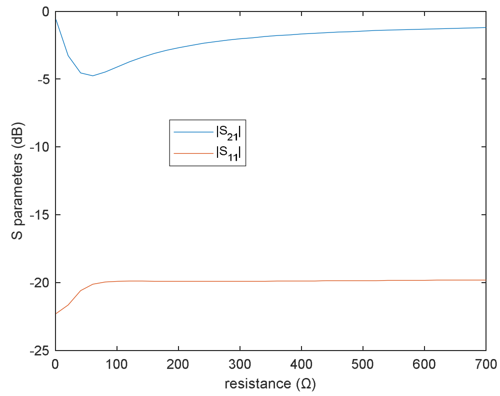


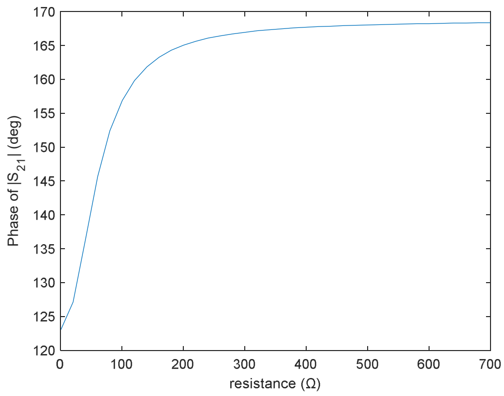
Fig. 4 Variation of load impedance Z_L for the forward current range of 1-100 mA at 2.4 GHz.

From the above studies, the following guidelines are presented based on observation.

- Diode parasitic play a significant role in the *S*-parameter. The parasitic resistance causes loss in the circuit. The insertion loss of the phase shifter is usually high for small forward resistance. Along with resistance, diode parasitic capacitance modulates the reactive part of the impedance. This causes a change in the phase of $|S_{21}|$ and tunning range.
- The SMD capacitors and inductors should have a self-resonant frequency less than the operating frequency.
- The capacitor C_1 is used as a dc blocking capacitor by which phase of $|S_{21}|$ is not affected. By increasing C_2, the phase can be increased but at the price of a higher loss. The magnitude of $|S_{21}|$ in the circuit can be improved by increasing C_3 in exchange for lower phase variation. So there always exists a trade-off between loss and phase variation in the circuit.
- The inductor L_1 is just used for biasing the PIN diodes.



(a)



(b)

Fig. 5 Variation of transmission line calculated (a) $|S_{11}|$, and $|S_{21}|$, and (b) phase of $|S_{21}|$ with the diode forward resistance R_D at 2.4 GHz

III. Fabrication And Measurement

The above RTPS is fabricated using a 0.813 mm thick RO4003C substrate with $\varepsilon_r = 3.55$, and loss tangent = 0.0027. A photograph of the fabricated prototype is shown in Fig. 6. Fig. 7 shows the measurement results for the RTPS. It is close to the predicted results from the co-simulation in ADS. Fig. 8 shows the linearity test of the fabricated circuit. The RTPS behaves as a linear device at least up to 23 dBm of input power. Because of unavailability of high-power source, it could not be measured above 23 dBm. The measured phase varies between 72° to 122° for a maximum allowed insertion loss of 3dB. The variation of $|S_{11}|$ and $|S_{21}|$ at f_0 are shown in Fig. 9. The insertion loss can be decreased by using a better quality PIN diode with small parasitic. The techniques described in [10] also can be tried.

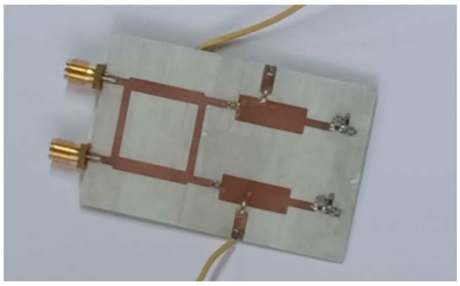
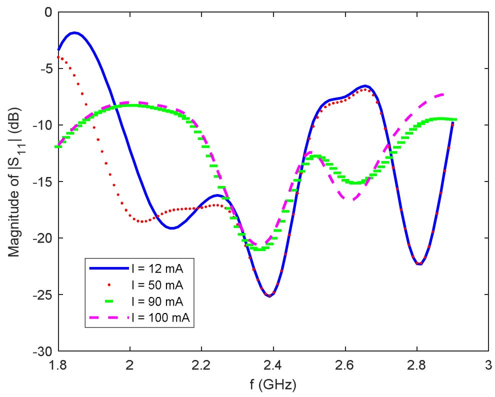
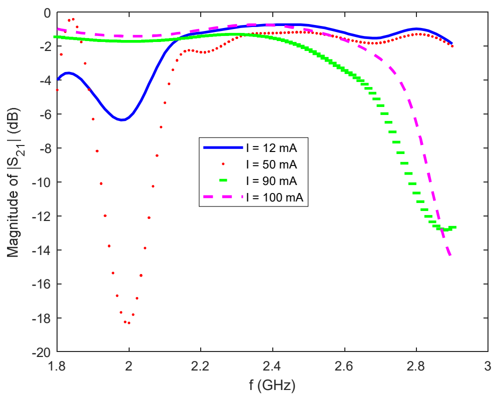


Fig. 6 A photograph of the fabricated prototype.



(a)



(b)

Fig. 7 Measured (a) $|S_{11}|$ (dB), and (b) $|S_{21}|$ (dB) of the RTPS.

IV. CONCLUSION

This work presents a new attempt to design an RTPS using PIN diode as variable resistors so that continuous phase tuning is possible. Since PIN diodes may operate at higher millimeter wave frequencies, thus the traditional problem of designing of an electronically tuneable phase shifter at millimeter wave frequencies may be solved. The basic condition to minimize the insertion loss for an RTPS is presented. Further research is being carried out to find a suitable series/shunt combination of the diodes and SMD capacitors to decrease the insertion loss further. For technology demonstration, a PIN diode based RTPS is fabricated and tested.

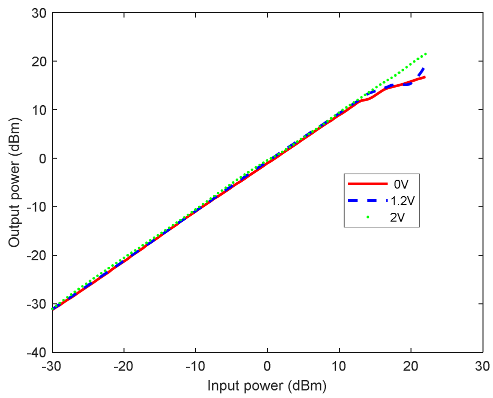
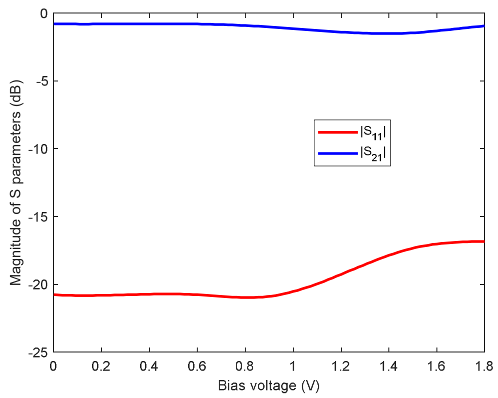
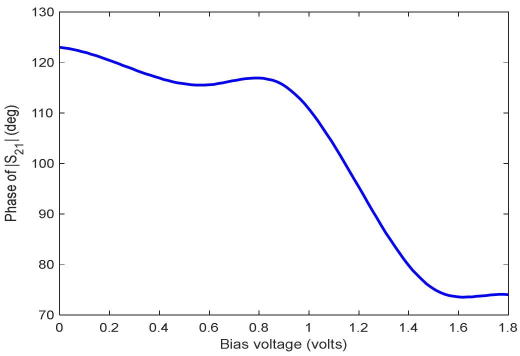


Fig. 8 Measured linearity test of the RTPS.



(a)



(b)

Fig. 9. Variation of measured (a) $|S_{11}|$ and $|S_{21}|$ (dB), and (b) phase of $|S_{21}|$ with bias voltage

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