

High Power Linearized RF Phase Shifter Using Anti-Series Diodes

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Abstract—We present the design and development of a new reflection-type phase shifter (RTPS) that uses anti-series diodes to achieve high linear output power. Using this topology, the PS provides a continuous phase shift of 180° at 1.88 GHz. The measured 1-dB compressed RF output power ($P_{1\text{ dB}}$) available from the PS is greater than 28 dBm over the entire phase-control range.

Index Terms—Anti-series, diode, distortion, high linearity, high power, reflection-type phase shifter (RTPS), varactor.

I. INTRODUCTION

RADIO frequency (RF) phase shifters (PSs) are extensively used in wireless communication systems such as phased array antenna systems, power amplifier (PA) phase-controlled compensation circuits, and adaptive PA matching networks. These PSs require continuous phase-control with low transmission loss, high linearity, and capability of handling high power over the entire phase-control range.

Analog phase shifting can be realized using loaded transmission-line, reflection-type (RT), and vector modulator based PSs [1]. Varactor diodes are the primary tuning elements in all the continuous PSs. Distortion in variable capacitance diodes affects the linearity of analog PSs and limits the maximum linear RF output power from a PS. Loaded transmission-line phase shifters (LTPS) are basically time delay elements having low loss, and are attractive for multiband implementation [2], [3]. However, multiple distributed sections are required to achieve the desired phase range. As the number of varactor diodes used is twice the number of sections, distortion in these PSs increases and results in lower $P_{1\text{ dB}}$ levels. Vector modulated phase shifters (VMPS) use amplitude as well as phase adaptations to obtain a phase shift of 360° [4], [5]. Although, these modulators do not require high capacitance range varactors, they are complex circuits containing low pass/high pass sections, VGAs, and combiners. Reflection-type phase shifters (RTPSs) are most popular for continuous phase tuning and have been implemented in GaAs and Si based technologies [6]–[9]. A conventional RTPS uses a 90° hybrid coupler and reflective terminations for phase tuning. Larger phase range can

TABLE I
PERFORMANCE OF ANALOG PSS

Work	Phase Shift	Min Input $P_{1\text{ dB}}$ (dBm)	Max S_{21} (dB)	Freq. Band (GHz)
LTPS [2]	360°	12	-4	5-6
VMPS [5]	360°	16.5	-9	4.7-5.6
RTPS [6]	360°	2	-9	5.15-5.7
RTPS [9]	138°	20	-1.8	16-18

be achieved using series resonated or parallel resonated loads [6]. RTPS uses only a pair of diodes and is the best topology for high linearity phase tuning applications. However, even a single varactor diode in each load path restricts the linearity of the PS as the power level is increased. Table I summarizes the performance of all the three types of analog PSs reported in literature. As seen from Table I, although a phase shift of 360° can be achieved, the maximum linear RF power available at the output of these PSs is not more than 18 dBm.

In this letter, we present the design and development of a novel RTPS that uses anti-series diode configuration to obtain low distortion. The hybrid coupler based PS has a continuous phase change of 180° at a frequency of 1.88 GHz as the control voltage is varied from 0 to 8.5 V. Measured insertion loss of the PS is less than 3.5 dB, while the measured 1-dB compressed RF output power is greater than 28 dBm throughout the phase-control range. To the best of our knowledge, this is the only RTPS which can handle a linear RF output power of 28 dBm over the whole phase tuning range of 180° .

II. PHASE SHIFTER DESIGN

A. Varactor-Diode Configuration

The capacitance of a diode is expressed as [10]

$$C(V) = \frac{K}{(\phi + V)^n} \quad (1)$$

where V is the applied reverse bias voltage, ϕ is the built-in potential of the diode, K is a constant, and n is the power law exponent. $n \approx 0.5$ for uniformly doped diodes and $n > 0.5$ for hyperabrupt junction diodes. Hyperabrupt junction diodes have a nonlinear doping profile which facilitates a larger capacitance change as the reverse bias voltage is increased and a larger tuning ratio occurs. Hence, these diodes have better capacitance-voltage (CV) linearity and tunability. However, the maximum linear power from a single diode is limited due to the second and third order distortion products.

Manuscript received October 24, 2005; revised January 3, 2006. This work was supported in part by the National Science Foundation ECS-0401375 and the University of California, Davis. The review of this letter was arranged by Associate Editor F. Ellinger.

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Digital Object Identifier 10.1109/LMWC.2006.872121

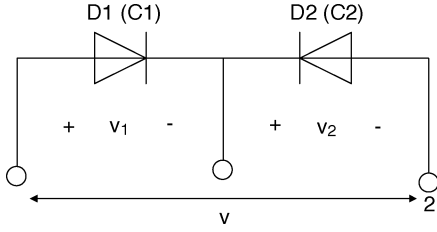


Fig. 1. Anti-series diode configuration.

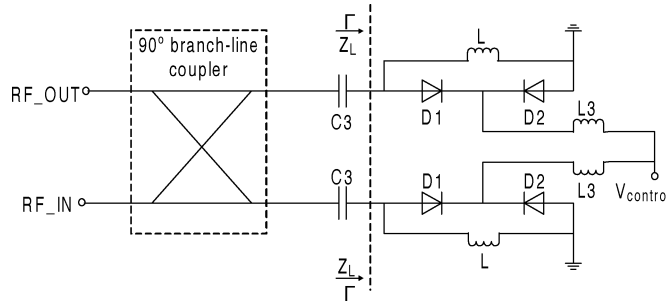


Fig. 2. Schematic of hybrid coupler based RTPS.

Consider that two diodes are connected in an anti-series configuration as shown in Fig. 1. The voltage dependent capacitance across the two diodes is

$$C_1(v_1) = K_0 + K_1 v_1 + K_2 v_1^2 + \dots \quad (2)$$

$$C_2(v_2) = L_0 - L_1 v_2 - L_2 v_2^2 + \dots \quad (3)$$

where v_1 and v_2 is the RF voltage across the diode. K_1 , L_1 are the second order distortion terms and K_2 , L_2 are third order distortion terms. If the two diodes are matched ($C_1 = C_2$; $K_1 = L_1$ and so on), then the total capacitance between nodes 1 and 2 is

$$C = \frac{K_0}{2} + \frac{K_2}{8} \left[1 - \frac{1.5K_1^2}{K_0K_2} \right] v^2 + \dots \quad (4)$$

It is seen from (4) that the second order distortion term is ideally zero, while the third order distortion term reduces significantly. References [10] and [11] show that for $n \approx 0.5$, the third order distortion term vanishes ideally. Thus, anti-series diode configuration produces very low distortion levels.

B. RTPS

The schematic diagram of a novel RTPS consisting of a 90° hybrid coupler and a pair of reflective loads with anti-series diodes is shown in Fig. 2. A branch-line type hybrid coupler has twice the peak power handling capability as compared to the circulator based coupler and hence branch-line coupler is used in this work. Each reflective termination is a parallel resonant circuit comprised of diodes D1–D2 connected in anti-series for low distortion capacitive tuning, and inductors L . This configuration enhances the available linear RF power at the output of the PS. The coupler can be implemented using microstrip transmission

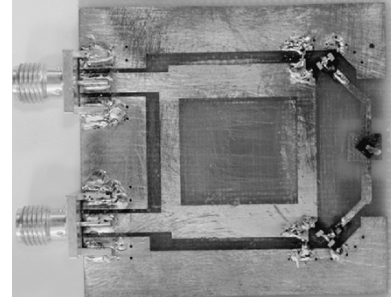


Fig. 3. Picture of RTPS at 1.88 GHz.

lines [1] or lumped elements [12]. The dc blocking capacitors C3 and RF chokes L3 are used for dc insertion.

The reflective coefficient Γ due to the resonant load is given as

$$\Gamma = \Gamma e^{j\varphi} = \frac{Z_L - Z_o}{Z_L + Z_o} \quad (5)$$

Z_L , the impedance of the reflective load is

$$Z_L = \frac{j\omega L}{1 - 2\omega^2 LC} \quad (6)$$

where C is the capacitance across each diode. As the reverse bias voltage applied to the diodes is increased, capacitance C varies from C_{\max} to C_{\min} and the phase φ of the reflection coefficient alters. The phase shift through the network is given by

$$\Delta\varphi = 2 \left| \arctan \left(\frac{Z_{L\max}}{Z_o} \right) - \arctan \left(\frac{Z_{L\min}}{Z_o} \right) \right| \quad (7)$$

The larger, the capacitance tuning ratio $C_T = C_{\max}/C_{\min}$, the greater is the phase shift achieved from the network.

III. MEASUREMENT RESULTS

Fig. 3 shows the implementation of the novel RTPS at 1.88 GHz. Hybrid coupler is built using microstrip transmission lines on a standard 62-mil-thick FR4 board having a dielectric constant of 4.5. The hyperabrupt silicon varactor diodes from Infineon have a high capacitance ratio, a peak reverse breakdown voltage of 35 V, and a low series resistance of 1.8Ω at 1 V. Effective Q of each diode, including the packaged parasitics, alters with the tuning voltage and is as high as 10 at 1.88 GHz. ADS simulations of each load termination consisting of anti-series diodes and inductance $L = 10$ nH, shows that phase of the reflection coefficient varies from $\varphi = 130^\circ$ to $\varphi = -50^\circ$ at 1.88 GHz as control voltage changes from 0 to 8.5 V.

S -parameter measurements are performed on the PS using Agilent E8364B Performance Network Analyzer. The measured transmission phase through the RTPS in the 1.88-GHz band is shown in Fig. 4. A continuous phase shift of 180° is achieved from the PS as the control voltage is varied from 0 to 8.5 V. Input and output return loss is less than -8.5 dB as seen in Fig. 5, whereas the insertion loss has a minimum value of -1.64 dB and

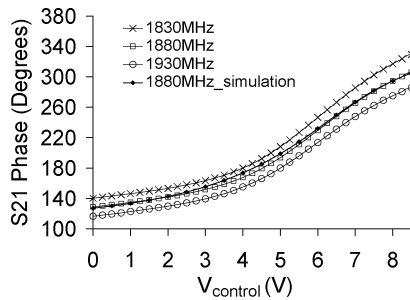


Fig. 4. Measured and simulated transmission phase of RTPS over control voltage.

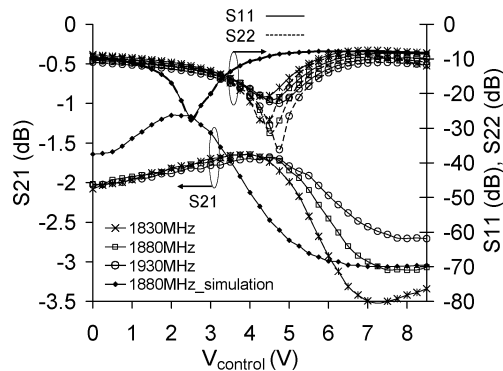


Fig. 5. Measured and simulated S -parameters of RTPS over control voltage.

reaches a maximum value of -3.5 dB as the phase is changed over the control range within the 100-MHz bandwidth. As visualized from the plots, the measured transmission phase and S -parameters, at 1.88 GHz closely match with the ADS simulations.

Linearity of the PS is analyzed by measuring the available RF output power. As seen from Fig. 6, the measured 1-dB compressed RF output power ($P_{1\text{ dB}}$) is greater than 28 dBm over the entire 180° phase-control range. Simulations predicated the output $P_{1\text{ dB}}$ to be greater than 30 dBm, all through the control voltage change of 8.5 V at 1.88 GHz. Bandwidth of the PS can be increased beyond 100 MHz by reducing the phase tuning range. Further, a RTPS with each reflective termination having a single reverse-biased varactor diode and inductance L3 for parallel resonance is realized for the purpose of comparison. The single diode-RTPS has a worst case measured output $P_{1\text{ dB}}$ of 21 dBm (Fig. 6), over a phase shift range of 180° as the control voltage is altered from 0 to 14 V. This demonstrates that the anti-series diodes linearize the PS, improve the maximum available linear RF power and reduces the tuning voltage range. Implementation of this PS is relatively simple and can be easily integrated into a wireless system module.

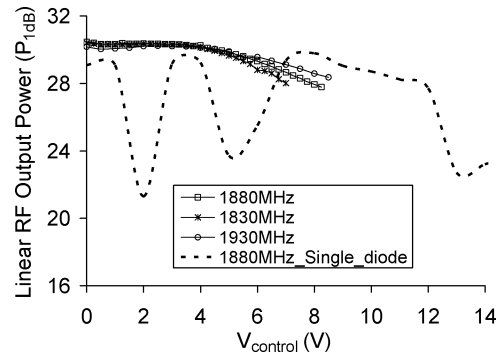


Fig. 6. Measured output $P_{1\text{ dB}}$, of the novel RTPS at 1.83 GHz, 1.88 GHz, and 1.93 GHz, and single diode-RTPS at 1.88 GHz, over control voltage.

IV. CONCLUSION

The design and development of a novel RTPS capable of handling high linear RF output power is presented in this letter. Anti-series diode reflective terminations empower the PS to maintain an output $P_{1\text{ dB}}$ of greater than 28 dBm over a phase tuning range of 180° . This work facilitates the use of RF PSs in high power adaptive tuning applications.

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