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Single-Ended Oscillation-Based Test Technique for Passive RF Phase Shifters

Johannes J. P. Venter, Tinus Stander

Abstract— Phased array systems have become paramount to the development of next generation wireless communication networks, with errors on phase shifters contributing to beam pointing error. Oscillation-based built-in self-testing (OBIST) of phase shifters may improve on this accuracy. We propose a single-ended oscillation-based test technique for passive RF phase shifters. The method uses a negative resistance oscillator topology, where the phase shifter is used to capacitively load the active negative resistance circuit resulting in a dependency between relative phase shift and output oscillation frequency. Simulation results indicate an average sensitivity of 0.14 MHz/° of phase shift around a nominal 617 MHz output oscillation when testing an X-band reflection-type phase shifter, while the addition of OBT circuitry increases the phase shifter's mid-band insertion loss by 0.93 dB.

Keywords— Phase shifters, oscillation-based test, built-in self-test, phased arrays.

I. INTRODUCTION

Phased array systems have become an integral part of next generation communication systems, due to the flexibility of dynamic beam steering to optimize data speeds and minimize interference [1]. In analog or hybrid beamforming [2], phase shifters are required to effect beam steering. Phase shifters have imperfect phase tuning performance, resulting in an error in beam pointing angle [3]; a reduction in relative phase shift error would, therefore, aid the improvement of overall system performance [3], [4]. It has been proposed that oscillation-based test (OBT) methods for phase shifters can be utilized to improve phased array system performance [3], [5], as a calibrated RF source is not required to generate an input test vector.

OBT techniques have been applied to various RF circuits such as analogue-to-digital converters, active and passive filters, low-noise amplifiers, as well as mm-wave phase shifters [5], [6], [7]. The technique in [5] transforms the phase shifter, or device under test (DUT), into an oscillator using a cross-coupled oscillator topology. This method uses quarter wavelength transmission lines to isolate the OBT circuitry from the phase shifter, requiring no series switches. While this is advantageous, given the loss and variability of the required switches, the isolation circuitry would be too large to implement on-chip for lower frequencies.

In [6], embedded passive RF transmission lines and filters are tested using a single-ended OBT method by loading an existing RF oscillator with the DUT and monitoring the variation in oscillation frequency. In this work, we extend on this approach to present a single-ended OBT technique with which discrete passive RF phase shifters can be tested, which paves the way for oscillation-based built-in self-test (OBIST) implementations of phased array front-ends. Using a single-ended measurement technique minimizes the number of switches in the signal path, resulting in reduced losses incurred due to the OBT circuitry.

II. PROPOSED APPROACH

Fig. 1 shows the canonical form of a negative resistance RF oscillator circuit [6]. For oscillation to occur the following condition needs to be satisfied [6]:

$$Z_{IN}(\omega) + Z_L(\omega) = 0, \quad (1)$$

where $Z_{IN}(\omega) = R_{IN} + jX_{IN}$ is the complex input impedance of the negative resistance device and $Z_L(\omega)$ is the load (resonator) impedance.

For negative resistance oscillators using negative conductance circuits, a commonly used rule-of-thumb states that [8]

$$R_L = \frac{-R_{IN}}{3}, \quad (2)$$

where R_L and R_{IN} are the real parts of the small-signal load resistance and negative resistance, respectively. With the condition in (2) being met, the main determinant of the oscillation frequency is where the load and negative conductance circuit reactance values cancel out [8]:

$$X_L = -X_{IN}. \quad (3)$$

Assuming that the real part of the load impedance (R_L) remains constant across frequency, it can be shown that when X_{IN} is varied the condition in (3) will be satisfied at a different frequency point. This creates a dependency between the X_{IN} value of the negative resistance and the oscillation frequency of the resulting oscillator. Given this, it is possible to create a

frequency controllable oscillator, when the reactance part of the negative resistance circuit is made tunable, as shown in Fig. 2. This concept may be applied to OBT of passive RF phase shifters.

Fig. 1. Canonical RF circuit for negative resistance oscillator

Fig. 2. Conceptual representation of proposed OBT method

A common passive phase shifter topology is a reflective-type phase shifter (RTPS). The RTPS consists of a 3-dB hybrid coupler and reflective loads placed at the through- and coupled-ports [5], [9]. A block diagram of an RTPS is shown in Fig. 3, where Γ_L represents the reflective loads.

A RTPS at frequencies outside the passband of the hybrid coupler may be modelled, approximately, as a series RLC circuit, as illustrated in Fig. 4. The equivalent capacitance of the circuit (C_{eq}) varies as the RTPS relative phase shift is varied by changing the biasing of the tuning varactors; the values for L_{eq} and R_{eq} remain relatively constant. When considering the phase shifter outside the passband, the value of input impedance would be extremely large replicating an open circuit. This enables the RTPS to be used as capacitive loading, below the resonance of the equivalent RLC circuit, in the active negative conductance circuitry. Thus, variance in C_{eq} (Fig. 4) results in a change in X_{RTPS} (Fig. 2) which changes the frequency point at which the condition in (3) is satisfied. This creates a dependence between the oscillation frequency of the resultant OBT circuit and the relative phase shift of the RTPS. Such an OBT circuit (conceptually represented in Fig. 2) may be used to test and calibrate RTPS relative phase shift.

Fig. 3. Architecture diagram of RTPS

Fig. 4. RLC equivalent circuit of RTPS

III. IMPLEMENTATION

A commonly used negative conductance circuit using one transistor and two positive feedback capacitors is shown in Fig. 5 [8]. For a negative conductance circuits, the best load (resonator) topology to use is a series topology [7] also shown in Fig. 5.

The DUT (phase shifter under test) is incorporated into the active negative resistance circuitry prior to designing the RF oscillator. The oscillation frequency range of the RF oscillator should be chosen in such a way that maximum variation in reactance is achieved across the RTPS phase shift range.

The design methodology employed in [9] was used to implement the RTPS, as this architecture is simple and achieves wideband operation which is of particular importance in practical phased array systems. A detailed circuit diagram of the reflective loads used in the RTPS, along with the modelling of the varactor parasitics, are shown in Fig. 6.

The transistor used in the negative conductance circuit is the Infineon BFP740F NPN RF heterojunction bipolar transistor (HBT), and for the single pole double throw (SPDT) switch at the output of the RTPS a MACOM MASW-002103-1363 PIN diode switch is used due to its low insertion loss at X-band. The varactors used for the RTPS design are the same varactors (MACOM MA46580) used in [9], with a total capacitance ranging from 0.13 pF to 2.2 pF, which has a parasitic series inductance of $L_S = 0.27$ nH, a series resistance of $R_S = 2.2$ Ω, and a parallel capacitance of $C_P = 0.108$ pF. Table I summarizes the biasing conditions and component values of the OBT circuit.

TABLE I
SUMMARY OF OBT CIRCUIT PARAMETERS

Parameter	Value
V_C	3 V
V_B	1 V
I_E	3.3 mA
L_L	13.0 nH
C_L	15.8 pF
R_L	10.4 Ω
C_1	12.8 pF
C_2	13.5 pF
R_{OSC}	50 Ω

The oscillation output node is across the collector resistance (indicated by V_{mon} in Fig. 5) of the negative conductance circuit. This node is well isolated from the rest of the circuitry, resulting in negligible change in oscillation frequency for various port impedance values. This facilitates easy access to the OBT circuit output to measure the oscillation frequency. It is also important to note that the impedance seen at the input of the RTPS has a negligible effect on the performance of the OBT circuit. This is because the oscillation frequency of the OBT circuit is in the stopband of the hybrid coupler used in the

RTPS, with C_{eq} forming an effective high impedance between the test circuitry and the input of the phase shifter.

Fig. 7 conceptually illustrates how the proposed OBT method may be used, in an OBIST system, to calibrate and test RF phase shifters. The phase shifter is switched from normal operation in the RF front-end chain into OBT mode using the SPDT switch. In OBT mode there is a signal processing block that monitors, down-converts, and digitizes the RF oscillation frequency. Thereafter, there is a control block that processes the digital data and computes the changes that need to be made in the control signals of the RF phase shifter to optimize receiver performance.

Fig. 5. Schematic of proposed OBT circuit, with circuit in OBT mode

Fig. 6. Schematic of RTPS reflective loads (Γ_L in Fig. 5)

Fig. 7. High level representation of phase shifter OBIST concept in RF receiver chain

IV. SIMULATION RESULTS

All simulations were conducted in Keysight ADS 2018 using the harmonic balance solver for the OBT circuit and the linear circuit solver for the determination of the S-parameter results. Simulations used ideal transmission line components, with transistor, SPDT switch, and varactor models included, as supplied by the respective manufacturers.

The OBT oscillation frequency f_0 and the RTPS relative phase shift for various varactor bias voltages is shown in Fig. 8. The RTPS exhibits 373° phase shift range at 10 GHz and 52 MHz variation in f_0 , resulting in an average sensitivity of $0.14 \text{ MHz}/^\circ$. This is, however, only the average value over the full tuning range, as the OBT circuit is clearly much more sensitive to change in RTPS relative phase shift values below 150° , with minimal change in oscillation frequency for larger relative phase shifts. This is a drawback of the current solution and would require further investigation to increase the sensitivity for larger relative phase shifts. Fig. 9 shows the oscillation output magnitude varies from -0.77 dBm to -2.7 dBm .

The average and worst-case S-parameter results of the RTPS, with and without the OBT circuitry, is shown in Fig. 10. The transmission response (S_{21}) shape remains similar with the addition of 0.93 dB insertion loss, at 10 GHz , for the RTPS with OBT due to the added series losses of the SPDT switch placed at the output of the RTPS. There is minimal additional return loss at the lower end of the RTPS passband, however, the return loss increases for the upper passband frequencies. Minor reduction (880 MHz) in the -10 dB input match passband is observed.

Fig. 8. OBT f_0 and RTPS relative phase shift for various varactor bias voltages

Fig. 9. Oscillation magnitude for various varactor bias voltages

Fig. 10. Comparison of average RTPS S-parameter performance over tuning capacitance range with and without OBT circuitry (Worst case responses indicated in dashed line)

V. CONCLUSION

We have presented a single-ended oscillation-based test technique for the characterization of passive RF phase shifters. The OBT technique consists of a negative resistance oscillator topology, where the active negative resistance is loaded with the phase shifter under test. This configuration results in a variation of the reactance of the active negative resistance for various phase shifter phase states, which changes the oscillation frequency of the OBT circuit. The method makes use of a single port, which reduces the degradation in phase shifter performance when the OBT circuitry is added.

A proof-of-concept design is presented in simulation carried out using a RTPS phase shifter. It was observed that the circuit exhibits an average sensitivity of 0.14 MHz/° to relative phase shift over a relative phase shift range of 373°. There is marginal degradation in the phase shifter S-parameter performance (0.9 dB additional insertion loss and 880 MHz reduction in -10 dB input match bandwidth) due to the OBT circuitry.

Future work will include improving sensitivity for large relative phase shift states, prototyping and characterizing the detectability of phase shift error under stress, as well as implementing differential power detection of f_0 as demonstrated in [10], [11], [12].

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