An Ultra-Compact CMOS Variable Phase Shifter for 2.4-GHz ISM Applications

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***Abstract*—An ultra-compact monolithic microwave integrated circuit active variable phase shifter is proposed and implemented using CMOS technology. It is a reflective-type phase shifter consisting of a compact three-transistor active circulator and a second-order *LC* network. The use of an active inductor in the second-order *LC* network makes this phase shifter all active and ultra compact with a size of only 0.357 mm^2 including bonding pads. The phase shifter was designed and demonstrated at 2.4 GHz and has a linear and continuously tunable range of 120° across the 2.4-GHz industrial–scientific–medical band.**

***Index Terms*—Active circuits, circulators, CMOS, monolithic microwave integrated circuit (MMIC) phase shifters, multiple-input multiple-output (MIMO) systems.**

I. Introduction

CURRENTLY more and more multimedia services are integrated in portable devices, which increases the demand for high data rates in wireless communications. The limited RF bandwidth, however, presents a bottleneck for the data rates in such communication systems. Recently multiple-input multiple-output (MIMO) technology [1]–[3] has attracted much attention because it can offer significant increases in data rates without additional bandwidth. A wireless local area network (WLAN) standard (IEEE802.11n) is currently under development to engage the MIMO technology in 2.4-GHz industrial–scientific–medical (ISM) band applications for very high data rates [4], [5]. A key component in a MIMO system is a phased array in which several variable phase shifters adjust the phases of the multiple antennas in order to generate multiple beams for spatial multiplexing. Since MIMO systems usually have high circuit complexity, monolithic microwave integrated circuit (MMIC) implementations of the required phase shifters becomes beneficial and essential to such systems.

Previous techniques for MMIC variable phase shifters can be categorized into several types. The first technique is the distributed-type (DT) phase shifter, which uses transmission lines [6], [7] or metamaterial transmission lines [8] with distributed loads. By switching/tuning the distributed loads along the transmission lines, digital multiple-bit phase shifters can be realized. This technique requires transmission lines with lengths proportional to the signal wavelength, which would result in prohibitively large die sizes for applications in the 2.4-GHz ISM band. An alternative is to use cascaded *LC* lumped elements to emulate the transmission lines in order to reduce their sizes [9].

The second technique utilizes a vector sum of two or more RF signals with orthogonal phases. Some phase shifters using this technique are also known as vector-modulator phase shifters. Depending on their signal directions, this technique can be further divided into two sub-techniques, which are: 1) forward-type phase shifters (FTPSs) [10], [11] and 2) reflective-type phase shifters (RTPSs) [12]–[14]. Traditionally these two types depend on couplers to both split the input signal into multiple orthogonal-phase signals and combine these signals at the output. The variable phase shift is realized by tuning the amplitudes of the multiple orthogonal signals before their combination at the output. The reflective type is usually more compact since it uses the same coupler for signal splitting and combining (the split signals in the coupler are reflected by tunable elements at the second and third ports, and combined into the forth port), while the forward type has to depend on another coupler or combiner to combine its split signals. The use of wavelength-proportional passive couplers in this technique would also result in a large die size at 2.4 GHz and limits its applications in the 2.4-GHz ISM band. Similar to the first technique, these couplers can be replaced by lumped-element couplers implemented by *LC* networks to reduce the phase shifter's size [15]–[18]. Other non-traditional ways exist to implement these phase shifters without using couplers [19], [20].

Phase shifters that use an all-pass network (APN) fall into the third technique [21]–[23]. An ideal APN has 0-dB transmission for all frequencies (i.e., all-pass property), so it is inherently suited for a phase shifter. Its phase shift depends on the order of the *LC* network it uses. A second-order APN is the most commonly used [21]–[23], from which a compact phase shifter can be expected. Practical designs of these phase shifters usually include gain elements to compensate the loss due to their nonideal APN, such as a lossy *LC* inductor. Moreover, the nonideal APN also results in a gain ripple, which presents a finite bandwidth and could vary the insertion loss in the phase-shift tuning.

As mentioned in the above three techniques, lumped *LC* networks can replace the transmission lines and passive couplers to reduce the size of an integrated variable phase shifter. These networks, however, would require large-value inductors when they were designed at 2.4 GHz, which could still occupy a large die area. The large loss with these large-value inductors is the other problem when they are implemented using lossy silicon technology. Active inductors have been found useful to replace

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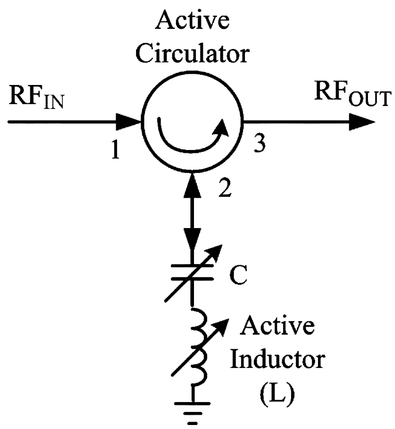

Fig. 1. Block diagram of the proposed variable phase shifter.

passive on-chip inductors in cases where power consumption considerations are not very stringent. The active inductors can provide high-Q inductance while keeping their sizes small compared to their passive counterparts, which make the designed phase shifters more compact. Previous phase shifters using active inductors can be found in [24] and [25].

In this paper, an ultra-compact reflective-type variable phase shifter using an active inductor and an active circulator is proposed and experimentally demonstrated. Whereas another active-circulator phase shifter was proposed in [26], only simulation results were given there without experimental verification. Here we use the active circulator to isolate the input and output signals, and a tunable second-order series *LC* network is then connected to the intermediate port of the circulator to reflect the RF signal, resulting in a variable phase shift range of 120° at 2.4 GHz. The use of a novel active inductor in the *LC* network makes the designed phase shifter all active and ultra compact with a die size of only 0.357 mm^2 including pads.

II. Proposed Variable Phase Shifter

Fig. 1 shows a block diagram of the proposed variable phase shifter. It is an RTPS based on an active circulator, but does not use the previously described vector-sum technique. The input RF signal is fed into Port 1 of the active circulator from the left and transmitted to Port 2. An active-inductor-based *LC* second-order network is placed at Port 2 to reflect the RF signal to Port 3 on the right for the output. The phase of the reflected RF signal can be varied by tuning the *LC* network, as explained below. To simplify the derivation, we assume that the active circulator and the *LC* network are both lossless. Furthermore, we neglect the fixed time delay and the effect of the finite isolation among the three ports of the circulator. Thus, the transmission from ports 1 to 3 of the circulator equals to the input reflection of the *LC* network, which is given by

$$S_{31} = \frac{Z_{LC} - Z_0}{Z_{LC} + Z_0} \tag{1}$$

where Z_{LC} and Z_0 refer to the *LC*-network impedance and the system impedance, respectively. Z_{LC} is given by

$$Z_{LC} = j(\omega L - 1/\omega C). \tag{2}$$

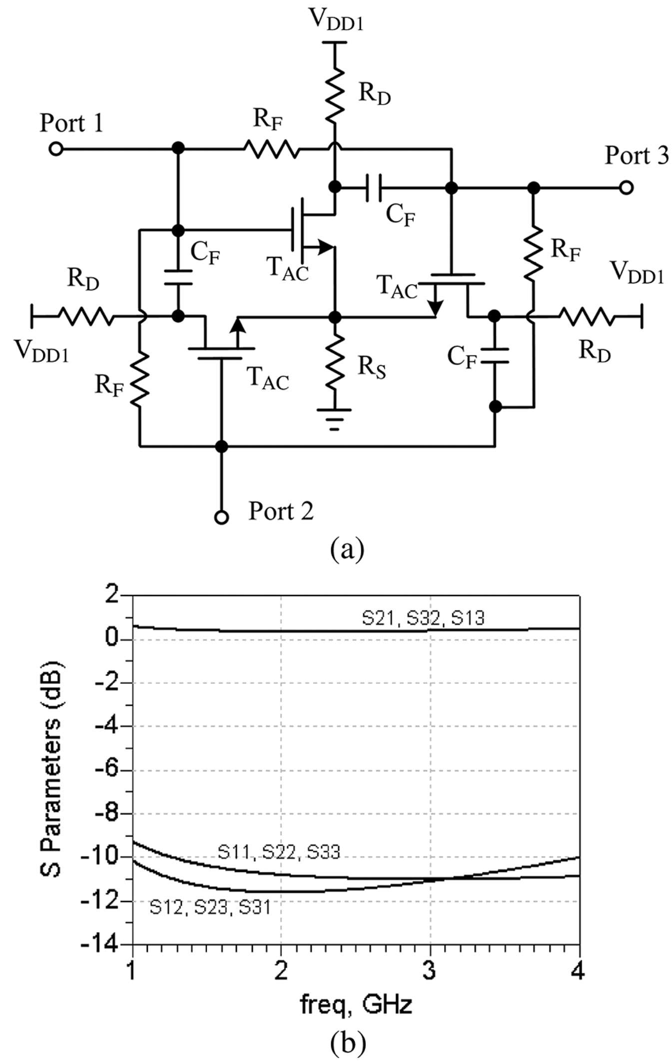

Fig. 2. (a) Compact three-transistor active circulator using CMOS technology. (b) Its simulated three-port S-parameters: transmissions ($S21, S32, S13$), isolations ($S12, S23, S31$), and reflections ($S11, S22, S33$).

Substituting (2) into (1) and simplifying leads to an expression for the phase shift of the transmission

$$\varphi = \angle S_{31} = \pm\pi - 2\tan^{-1}\left(\frac{\omega L - 1/\omega C}{Z_0}\right). \tag{3}$$

Equation (3) clarifies that tuning either L or C in the LC network can change the phase shift.

The active circulator used in this work is a full three-port circulator, as illustrated in Fig. 2(a). It consists of three nMOS transistors connected end to end in a ring using three capacitors C_F. Each transistor is equipped with a negative feedback using a resistor R_F and is source-coupled to the other two transistors through a shared source resistor R_S. The three transistors are biased using the same dc voltage from the ports. Compared to the other active circulators [27], [28], this three-transistor topology is the most compact. The circulator topology in Fig. 2(a) was initially proposed and demonstrated using bipolar transistors at a few megahertz [29], and was later implemented at microwave frequencies using GaAs field-effect transistors (FETs) with high voltage supplies over 10 V [30], [31]. We redesigned

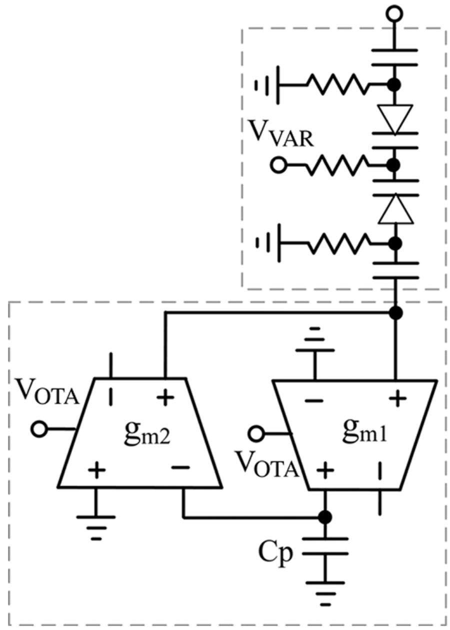

Fig. 3. *LC* network with an active inductor.

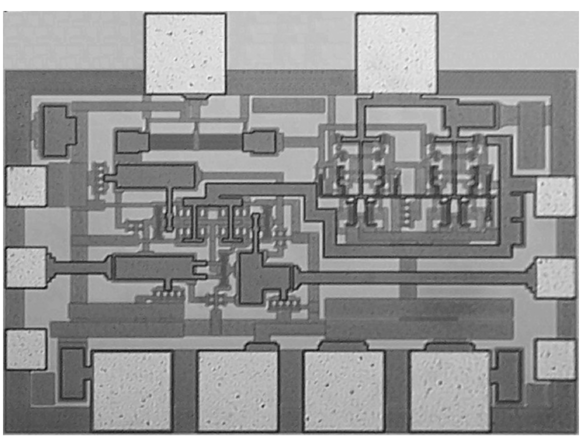

Fig. 4. Microphotograph of the fabricated variable phase shifter.

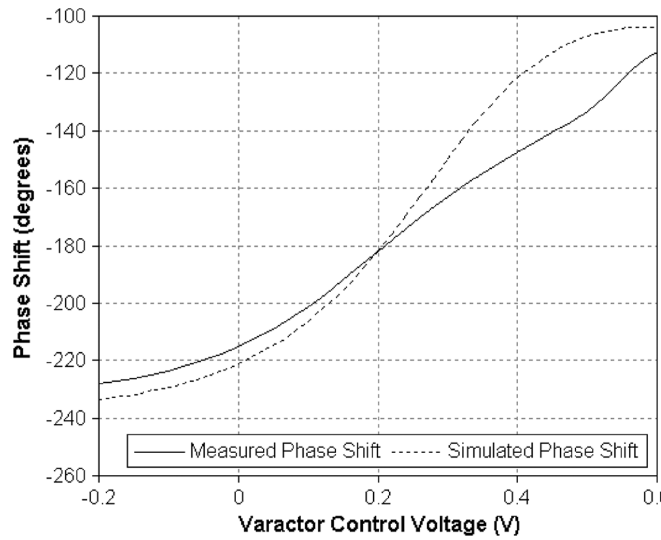

Fig. 5. Simulated and measured phase shift versus the varactor control voltage at 2.4 GHz.

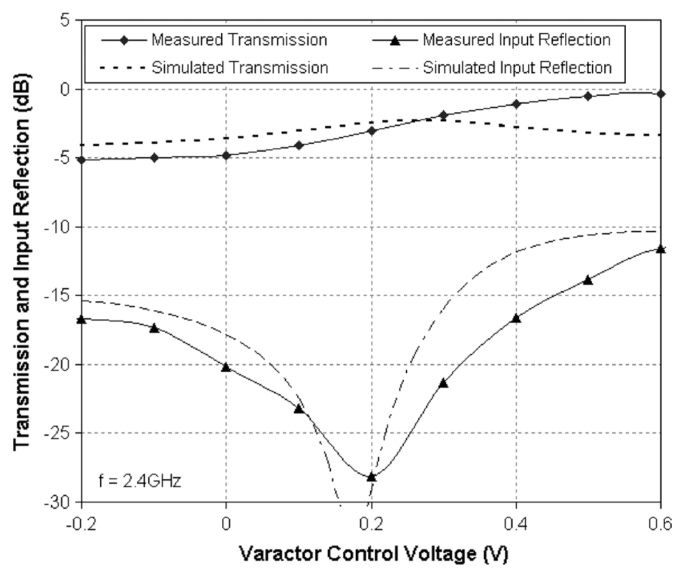

Fig. 6. Simulated and measured transmission and input reflection versus the varactor control voltage at 2.4 GHz.

this circulator using CMOS technology and minimized its voltage supply to $V_{DD1} = 3.5$ V. Fig. 2(b) shows the simulated S-parameters of the designed active circulator. The transmission coefficients between the three ports ($S21, S32, S13$) are flat across a wide band of approximately 3 GHz centered at 2.4 GHz. Within this band, the isolations ($S12, S23, S31$) and reflections ($S11, S22, S33$) of the three ports are all less than -10 dB, resulting in a wideband circulator.

The *LC* network is designed using a varactor network (C) and an active inductor (L), as illustrated in Fig. 3. The advantage of using the active inductor here is obvious in that it can make the phase shifter circuit all active and, thus, ultra compact. To realize this microwave active inductor, two CMOS high-speed differential operational transconductance amplifiers (OTAs) using a feedforward-regulated cascode topology are employed, which has been developed and demonstrated in our previous study [32]. The feedforward topology can remove the time delay with the OTA's voltage regulation and speed up its operation. As shown in Fig. 3, a common active-inductor topology [33] is adopted to implement the active inductor, where two OTAs are connected end-to-end to compose an impedance inverter. The active inductance is achieved by impedance inverting a capacitance C_P, which is formed by the OTA's input/output parasitic capacitance. The active inductance is given by

$$L = C_P/(g_{m1} \cdot g_{m2}) \tag{4}$$

where g_{m1} and g_{m2} are the transconductance of the two OTAs. Equation (4) suggests that the active inductance can be tuned by changing the two OTA's transconductance, which is done through the OTA's bias voltage V_{OTA} shown in Fig. 3. The varactor network in Fig. 3 comprises a pair of varactors in a series symmetric configuration. Their bias is completed through three high-value resistors and the bias voltage V_{VAR}. This bias voltage

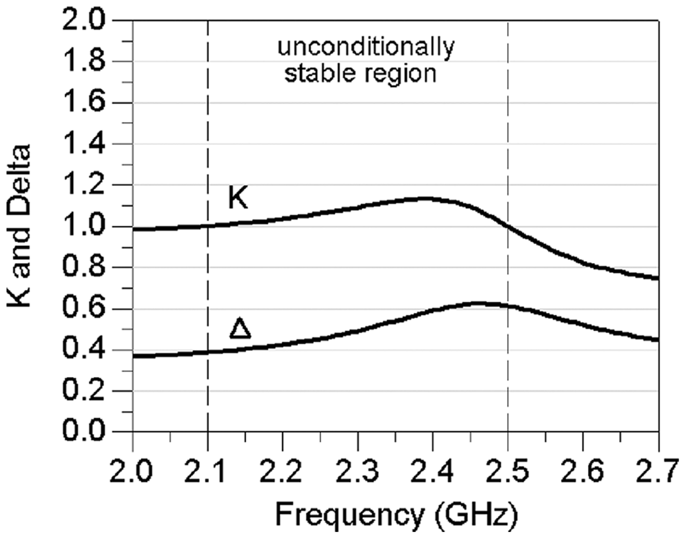

Fig. 7. Simulated stability factors K and Δ.

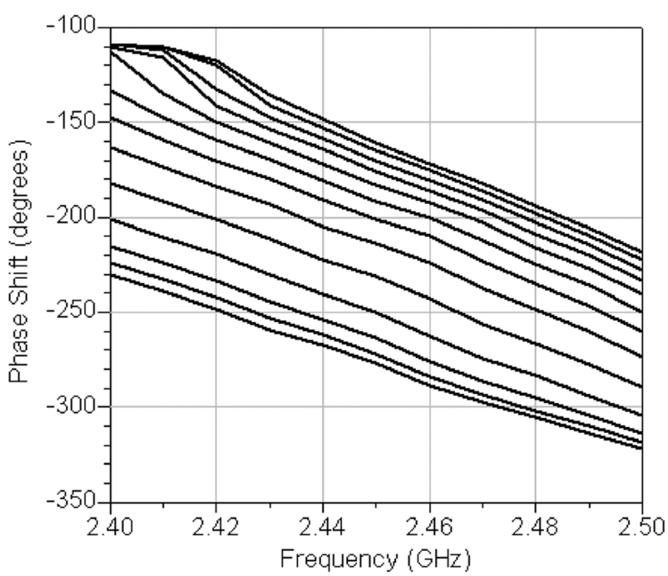

Fig. 8. Measured phase shift at different varactor control voltages (not in linear steps) across the 2.4-GHz ISM band.

V_{VAR} is used for the phase-shift tuning, i.e., the varactors in the *LC* network are selected to tune the phase shift.

III. Simulation and Experimental Results

A microphotograph of the fabricated variable phase shifter is presented in Fig. 4. It was fabricated using 0.18-μm CMOS technology with an ultra-compact core circuit size of 0.186 or 0.357 mm^2 including pads. The active inductor is designed to have an inductance of approximately $L = 8.5$ nH with a dc supply of ± 1.4 V, and the varactor network has a total capacitance of approximately $C = 0.5$ pF. This results in a resonant frequency in the 2.4-GHz ISM band for the designed *LC* network using the active inductor and the varactor network, as illustrated in Fig. 3. In the measurements, the active inductor and the active circulator were first biased to achieve a transmission close to 0 dB in the 2.4-GHz ISM band, and then the varactor network was used to tune the phase shift. The active inductor and

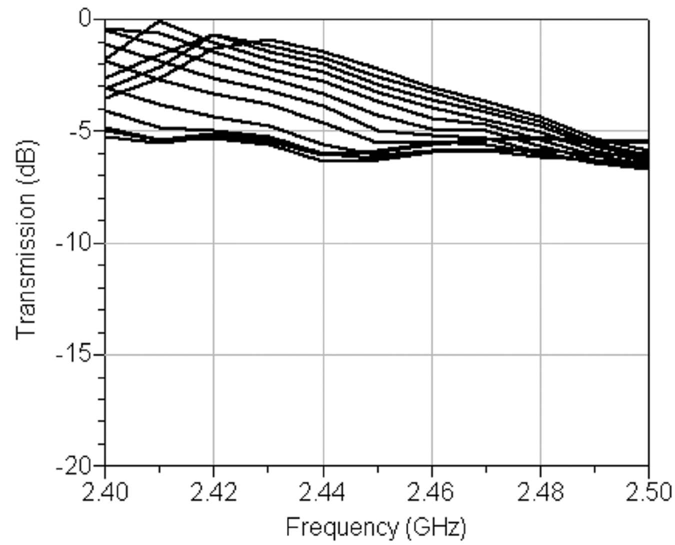

Fig. 9. Measured transmission with the phase-shift tuning.

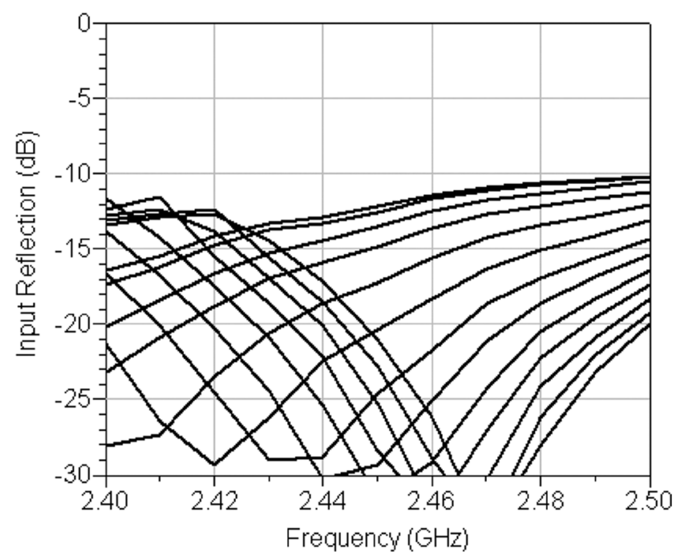

Fig. 10. Measured input reflection with the phase-shift tuning.

the active circulator consumed approximately 51 and 60 mW, respectively.

Fig. 5 presents both the simulated and measured phase shift versus its tuning voltage (the varactor control voltage) at 2.4 GHz. The measured curve shows that a smooth phase-shift tuning range of approximately 120° is achieved by changing the varactor control voltage. This result is reasonably predicted by the simulation for the most part. The simulated and measured transmission (insertion loss) and input reflection versus the tuning voltage are presented in Fig. 6, where both the measured curves are close to the simulated ones. The transmission varies from -5 to 0 dB from the measurement. The change of the transmission versus the varactor control voltage reflects the contribution of the varactor capacitance to the Q factor of the *LC* network, which depends on its inductor, capacitor, and parasitic resistance. This change can be reduced if a finer tuning of the OTA's control voltage V_{OTA} is combined. The input reflection during phase-shift tuning is lower than -10 dB, which

TABLE I
PERFORMANCE SUMMARY AND COMPARISON

Properties	This work	[9]	[16]	[17]	[21]
Technology	0.18μm CMOS	0.18μm CMOS	0.18μm CMOS	0.18μm CMOS	0.3μm GaAs
Technique	all-active RTPS	DT	FTPS	RTPS	APN
Die size (mm^2)	0.357	2.76	---	1.08	1.0
Frequency (GHz)	2.4	2.4/3.5/5.8	2.4/5.5	2.4	2.4
Phase shift range	120°	180°	360° (four cascades)	105°	100°
Max. Insertion loss (dB)	5	6.6	-4	4.6	5
Power consumption (mW)	111	45	28.8	---	152
Input P1dB (dBm)	6	---	---	10	---
NF (dB)	23.8	---	---	12	11.5

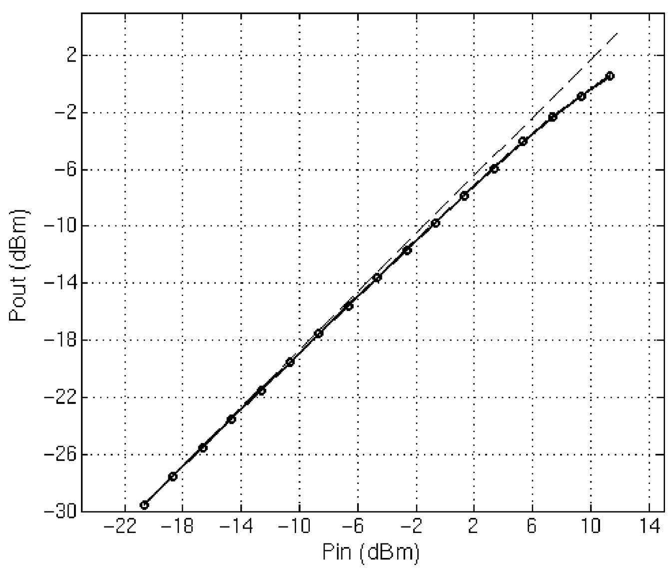

Fig. 11. Measured output power versus the input power.

is also predicted by its simulated curve. A stability study of the phase shifter shows an unconditionally stable region from 2.1 to 2.5 GHz in Fig. 7, which covers the 2.4-GHz ISM band.

To investigate the performance of the variable phase shifter over the 2.4-GHz ISM band, the phase shift versus frequency at different control voltages were measured and the results are displayed in Fig. 8. As illustrated, the phase-shift curve at each control voltage is nearly parallel to the others across the band with an average phase-shift tuning range of approximately 120°. Moreover, the linear phase shift versus frequency in each curve shown in Fig. 8 indicates a constant group delay or wideband property of the designed phase shifter in the 2.4-GHz ISM band. Figs. 9 and 10 present the measured transmission and input reflection coefficients versus frequency with the same control voltages. For all of these control voltages, the variation of the transmission coefficient is less than ± 2.5 dB and the input reflection coefficient is lower than -10 dB over the 2.4-GHz ISM band. The output reflection coefficient varies from -13 to -4 dB in the above tuning. A performance summary of this variable phase shifter and its comparison to other works in the same band is shown in Table I.

The output power versus the input power at 2.4 GHz was also measured and plotted in Fig. 11 to characterize the linearity of this phase shifter, which shows an input $P1$ dB of approximately 6 dBm. At the same frequency, a noise figure of 23.8 dB was measured for the phase shifter, which is close to its simulated noise figure, 22 dB. This is higher than that of those using passive networks/components, as seen in Table I. However, if this phase shifter is used in the output stages of a transmitter, then this noise figure is not very detrimental. Simulations were performed to further understand the sources of this noise figure. The source-coupled active circulator shows a noise figure of 11 dB (from its Port 1 to Port 3 with its Port 2 open). The noise analysis of this active circulator can be referred to [27]. This noise figure can be reduced if a passive circulator is used, but in that case, it would have to be off chip. The rest of the noise contribution is from the active inductor.

IV. CONCLUSION

In this paper, an MMIC reflective-type active variable phase shifter has been presented that is ultra compact due to its all-active implementation using CMOS technology. The variable phase shifter employs an active circulator and an active *LC* network, where the circulator is very compact, using only three transistors. A novel microwave OTA design is used to implement the active inductor used in this study, which makes the implemented phase shifter ultra compact. The phase shifter described here is suited for MIMO applications in the 2.4-GHz ISM band.

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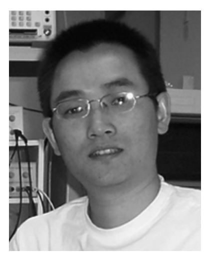

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