10 GHz CMOS hybrid reflective-type phase shifter with enhanced phase shifting range

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A new idea is presented to boost the phase shifting range of a reflective-type phase shifter (RTPS) by leveraging the parasitic capacitance; however, without any cost or design overhead. In contrast to the conventional RTPS, where the parasitic capacitance degrades the phase shifting range, a simple position interchange of electronic components leads to an enlarged tuning range. This mechanism is analysed thoroughly and validated by simulation and measurement results. Two RTPSs with different component positions are fabricated in a 65 nm CMOS technology. Grounding inductors leads to a more than 30° phase shifting range than the conventional ones without this arrangement. The S_{11} is measured at <−10 dB from 9 to 10.75 GHz and the S_{21} is −6 dB with <0.6 dB variations at 10.2 GHz. This technique also provides design insights for phase shifting and tuning range enhancement of general resonant networks.

Introduction: A variable phase shifter is a critical and widely used component in electronic systems, such as phased array radars [1], MIMO wireless communication etc. Phase shifting techniques include RC tuning, the transmission line, switch line, vector modulator etc. [2]. Among them, reflective-type phase shifters (RTPSs) have attracted much attention due to their wide bandwidth, isolated amplitude response and port matching from phase adjustment.

This Letter is also based on the RTPS structure with emphasis on enhancing the phase shifting range due to its importance. Ellinger [3] has provided a significant investigation into extending the phase tuning range. One technique is to use a series resonator formed by a varactor and an inductor as the reflective-type load to achieve a larger phase tuning range due to its higher-order feature [3, 4]. However, the large parasitic junction capacitance of varactors is always the key constraint, which greatly degrades the phase shifters tuning range.

In this Letter, a thorough theoretical investigation is conducted on the effects of the parasitic junction capacitance. On the basis of it, a new and effective method is proposed to leverage the parasitic capacitance to boost the phase shifting range by simply interchanging the location of the inductor and varactor of the reflective series resonant tank. To verify the technique's effects, two RTPSs with different LC component positions are designed and compared. Putting the inductor at the bottom increases the phase shifting range by more than 30°.

Principles of RTPS: The RTPS is based on a conventional 90° hybrid coupler, for which the direct and coupler ports are connected to the reflective-type loads and the other two ports are used as the input and output [3]. The output phase can be adjusted by tuning the reactive load impedance, which is normally realised by tuning varactors. To achieve a small form factor for on-chip integration, a CMOS RTPS is preferred to be built on lumped components. Different types of lumped component-based hybrid couplers can be adopted. In this Letter, the one with only two inductors is used because of its compactness as shown in the shaded region of Fig. 1, in which L_1, C_1, and C_2 form the 90° hybrid core. The reflective load, composed of varactor C_r and inductor L_r, tunes the phase by adjusting the bias voltage V_c on the varactor. Two factors, the minimum capacitance C_{min} and the tunable capacitance ratio r ($r = C_{max}/C_{min}$), determine the absolute phase tuning range $\Delta\varphi$ [3]

$$\Delta\varphi = 4\left|\arctan\left(\frac{1}{4\pi f_o C_{min} Z_o}\cdot\left(1-\frac{1}{r}\right)\right)\right| \qquad (1)$$

where f_o is the centre operating frequency and z_o is the port impedance. A smaller C_{min} leads to a larger phase tuning range. Generally, C_{min} decreases with varactor size. However, a smaller C_{min} requires a larger L_r, which then results in a higher insertion loss. Therefore, the choice of C_{min} should consider the design trade-offs between the tuning range and the insertion loss. The varactor is built with NMOS in an N-type well, which is negatively biased with the gate connected to ground and working in the depletion region to ensure its monotonicity. The capacitance ratio is about 5.

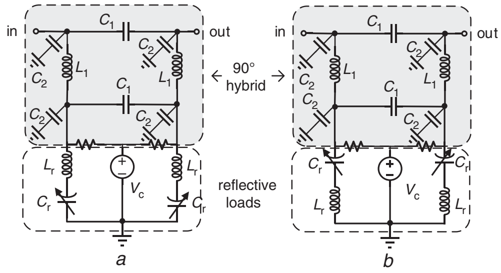

Fig. 1 *Conventional RTPS with varactor at bottom of resonant tank, and new RTPS with inductor at bottom*

a Conventional RTPS, varactor at bottom
b New RTPS, inductor at bottom

Phase shifting enhancement: Fig. 2*a* illustrates the cross-section of the negatively biased varactor. The parasitic junction capacitance C_p also affects the shifting phase. Although the varactor has a relatively large capacitance ratio, the parasitic junction capacitance ratio is smaller as it has a low Q due to the large parasitic substrate resistor R_p [5], which constrains the phase shifting range in the conventional configuration where the varactor is at the bottom as shown in Fig. 2*b*. To boost the phase shifting range, the LC position is interchanged by putting the inductor at the bottom as shown in Fig. 2*c*.

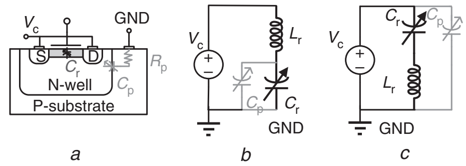

Fig. 2 *Cross-section of varactor, and resonator tank with varactor at bottom and with inductor at bottom*

a Cross-section of varactor
b Resonator tank, varactor at bottom
c Resonant tank inductor at bottom

The effect of C_p on the phase tuning range is illustrated in the Smith chart in Fig. 3. The fan $O\widehat{A}B$ represents the tuning range without C_p, where $\widehat{O'A} = \widehat{O'B}$ with the assumption that the middle capacitance value of the varactor is designed to resonate with L_r at the centre frequency f_o [3]. Therefore, the two sides $\widehat{O'A}$ and $\widehat{O'B}$ are symmetrical. Since the varactor is negatively biased, C_r decreases as V_c increases, making A move to B along the bold arc $\widehat{AB}$ as V_c increases. With the parasitic capacitance C_p, the moving curve against V_c becomes $O\widehat{A'}B'$, which shows the degradation of the phase shifting range as the effective capacitance ratio becomes smaller according to (1).

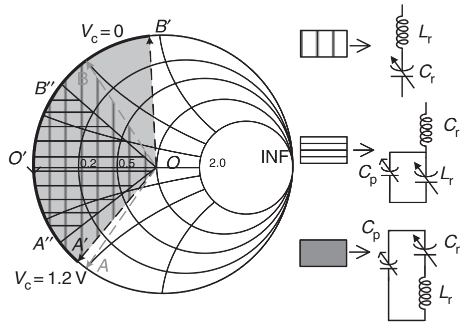

Fig. 3 *Use Smith chart to explain phase shifting range enhancement by putting inductor at bottom to leverage Cp effect*

When the positions of the inductor and varactor are interchanged, the parasitic capacitance C_p is parallel with the resonant tank. As widely known, adding the parallel capacitance makes the admittance on the Smith chart move clockwise along the constant conductance circle. That is, position B moves to B' and position A moves to A'. The parasitic junction capacitor C_p is also voltage dependent, and its capacitance increases as V_c increases. Therefore, $O\widehat{B}B'$ is larger than $O\widehat{A}A'$ because C_p is maximum when V_c is 0. As a result, the tuning range is enhanced.

The two phase shifters with different inductor positions have been designed for comparison, with the phase tuning range increased by more than 30° by putting the inductor at the bottom.

Measurement results: The two RTPSs with the varactor or inductor at the bottom were fabricated in a 65 nm technology and their photographs are shown in Fig. 4, with the chip area of 600 × 500 µm including PADs. The positions of the varactor are pointed out with Fig. 4*a* showing the varactor at the bottom and Fig. 4*b* showing the varactor in the middle. Fig. 5 shows the measurement setup by probe testing.

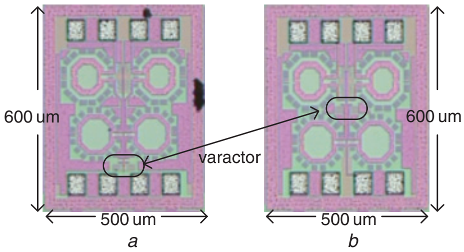

Fig. 4 *Chip photographs of two phase shifters with varactor at bottom and with inductor at bottom*

a Varactor at bottom
b Inductor at bottom

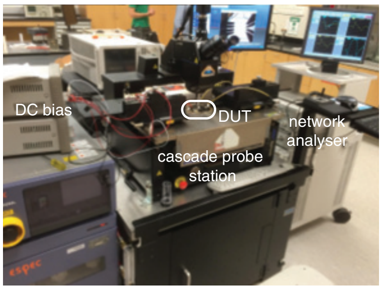

Fig. 5 *Measurement setup of phase shifter*

The phase shifter achieves an S_{11} below −10 dB from 9 to 10.75 GHz for all control voltages, shown in Fig. 6*a*, while minimum gain variations occurring at 10.2 GHz are below 0.6 dB, shown in Fig. 6*b*. The phase shifting ranges of the two different structures are shown in Fig. 7. Fig. 7*a* illustrates that the phase shift range for the conventional structure with the varactor at the bottom, shown in Fig. 1*a*, is 85° at 10.2 GHz with the control voltage changing from 0 to 1.2 V. Fig. 7*b* shows that the phase shifting range with the inductor at the bottom, shown in Fig. 1*b*, is 115°, which demonstrates more than 30° phase shifting range enhancement.

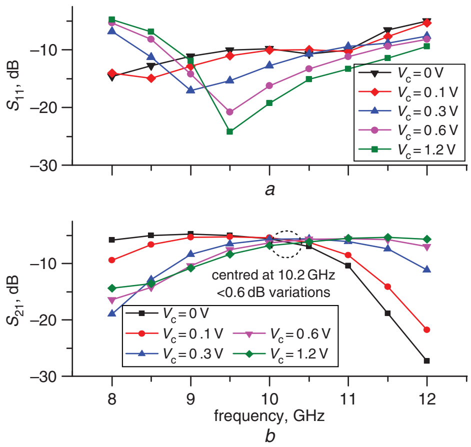

Fig. 6 *Measured S_{11} and S_{21} against frequency at different varactor control voltages*

a S_{11}
b S_{21}

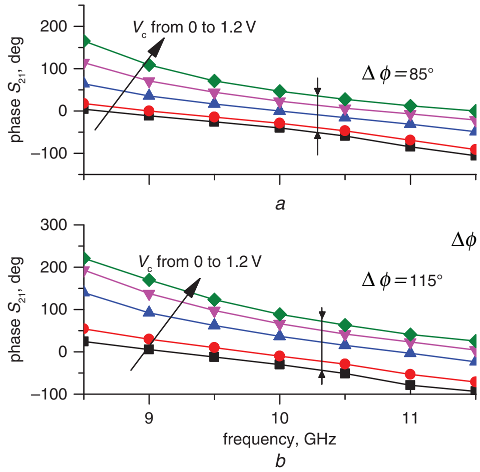

Fig. 7 *S_{21} phase of conventional configuration with varactor at bottom, and of new structure with inductor at bottom*

a Conventional configuration, varactor at bottom
b New structure, inductor at bottom

Conclusion: In this Letter, a new technique is presented to increase the phase shift range by leveraging the varactor parasitic capacitance. Without adding any complexity or design overhead, this technique is achieved by simply interchanging the LC position of the series resonant tank in the RTPS reflective load. The working mechanism of phase shifting enhancement is analysed theoretically and validated by measurement results with a more than 30° phase shifting range increase. This technique and its analytical results also provide design insights for general resonant networks to boost phase shifting and tuning ranges without any overhead.

Acknowledgments: The authors thank the ONR and S. Pappert and D. Van Vechten for funding support.

Submitted: *23 July 2015* E-first: *13 October 2015*
doi: 10.1049/el.2015.2515
One or more of the Figures in this Letter are available in colour online.

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