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Article

A Compact W-Band Reflection-Type Phase Shifter with Extremely Low Insertion Loss Variation Using 0.13 µm CMOS Technology

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Abstract: This paper presents a reflection-type phase shifter (RTPS) at W-band in a 0.13 µm complementary metal oxide semiconductor (CMOS) process. The RTPS is composed of a 90° hybrid coupler and two identical reflection loads. Lumped-distributed element transmission line is introduced in the 90° hybrid coupler to reduce the chip size. Series inductor-capacitor (LC) resonators are used as the reflective loads and parallel inductors are deployed to reduce insertion loss variation. By cascading two-stage RTPS, 90° phase shifting range and 10.5 dB insertion loss with 1 dB variations from 80 GHz to 90 GHz are achieved. An impressive 0.1 dB variation is obtained at 86 GHz.

Keywords: W-band; reflection-type phase shifter; insertion loss variation; series LC resonators; lumped and distributed elements; CMOS technology

1. Introduction

Phase shifters (PS) play an extremely important role in phased array systems [1,2]. Among the available options, reflection-type phase shifter (RTPS), adapting the passive loads, suffers from small phase shift, poor linearity and inconvenience of digital controlling; however, there are a lot of advantages, such as continuous phase shifting, compact circuit structure, bidirectional phase shifting, and zero direct current (DC) power consumption [3–8]. Although a variable-gain amplifier (VGA) can be used to compensate the amplitude distortion within the phased array system, it would cause a lot of complexity to the control mechanism and the system performance would be more reliable on the PS and VGA [3], especially at higher frequencies such as the W-band. Several designs of real-time power system simulator (RTPSs) with regard to insertion loss variation at 2 GHz on printed circuit board (PCB) [4], 2.45 GHz [5] and 24 GHz [3] in the complementary metal oxide semiconductor (CMOS) process are reported. Some publications have also demonstrated RTPSs operating at higher frequency bands, e.g., V-band [6,7] and W-band [8], but none of them consider the insertion loss variation.

The authors present an RTPS design with compact size, zero DC power consumption and low insertion loss variation in this paper. A schematic diagram is presented in Figure 1 of the proposed RTPS, which includes a 90° hybrid coupler with two identical reflection loads. The phase shifting range is determined by the phase angle of the reflection coefficient. The lumped-element transmission line is introduced in the 90° hybrid coupler to reduce the size. The tunable reflective loads are realized through series LC resonators; in this way, the insertion loss variation is significantly reduced.

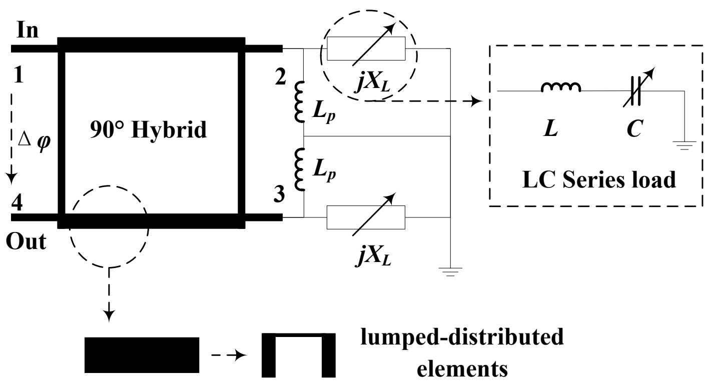

Figure 1. Schematic of the proposed reflection-type phase shifter (RTPS).

2. Design Concept

The branch line coupler is popular as a hybrid in microwave circuit design, especially in planar circuitry; however, it requires a large chip area. The loaded line is an alternative solution to reduce the size of transmission-line based circuits such as branch-line and ring hybrids [7,9].

In this paper, lumped-distributed elements are added into the wider branch lines of the hybrid coupler to decrease the length [9], as shown in Figure 1, where the solid symbol line is the simulated result of the lumped-distributed elements loaded 90° hybrid, while the hollow symbol line is the conventional 90° hybrid. The narrow branch lines are designed as rat-race lines to reduce the length. The passive components are finally simulated and optimized using the full-wave simulator (HFSS) with the considerations of the design rules of the 0.13 μm CMOS process. In this way, the chip size is effectively reduced without decreasing the performance of the hybrid, as can be seen from the comparison between the simulated S parameters of the hybrid coupler with lumped-distributed elements loaded and the conventional hybrids, as presented in Figure 2.

Figure 1 also depicts the schematic diagram of the implemented series LC resonator load, consisting of a MOSFET varactor with an inductor (in the dashed box) in series. The maximal relative phase shifting range $\Delta\varphi_{max}$ is given as:

$$\Delta\varphi_{max} = 2 \cdot \tan^{-1}(2 \cdot \Delta X_L / Z_0) \quad (1)$$

and is determined by the load reactance variation range ΔX_L [4].

In order to decrease the insertion loss variation, a parallel inductor L_p is added at each load. The resistant R_p in [4] is not presented in this work, since the parasitic resistance of the finite-Q inductor will play the same role. As a result, the parasitic effect caused by the physical structure of the resistant can be removed.

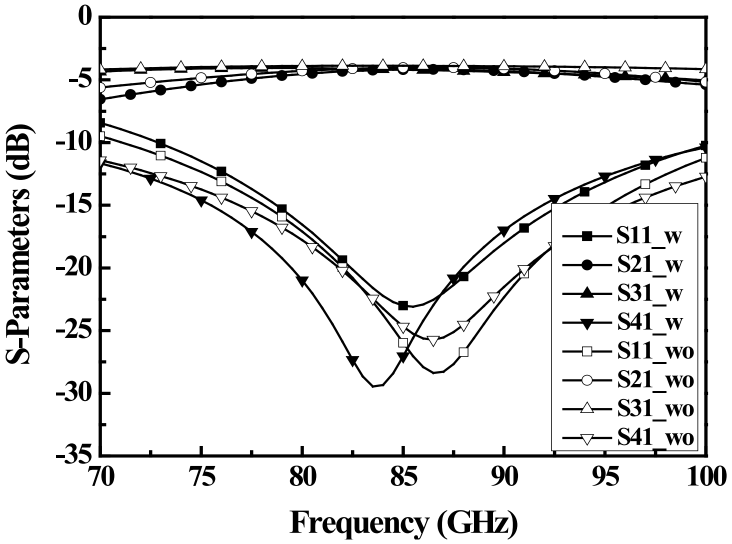

Figure 2. Simulated results of the lumped-distributed elements loaded 90° hybrid compared with the conventional 90° hybrid.

3. Measurement

Figure 3 shows the micrograph of the proposed RTPS with series LC resonator loads and lumped-distributed elements, where the chip size is 0.51 mm^2 including the testing pads. The RTPS performance was measured through on-wafer testing.

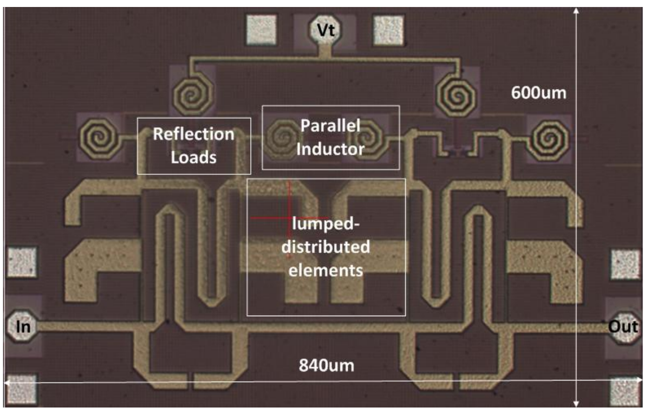

Figure 3. Micrograph of the proposed RTPS.

Figure 4 depicts the measured phase shifting range from 80 to 90 GHz with the control voltage changing from 0 V to 2.0 V. The phase tuning range is greater than 90° in the whole band. The return losses are more than 15 dB and the insertion loss variation is less than 1 dB from 80 to 90 GHz giving a

10 GHz bandwidth. At 86 GHz, the insertion loss variation is even less than 0.1 dB. The insertion loss is 10.5 dB on average, which is shown in Figure 5. Note that the testing pads are not de-embedded from the measurements.

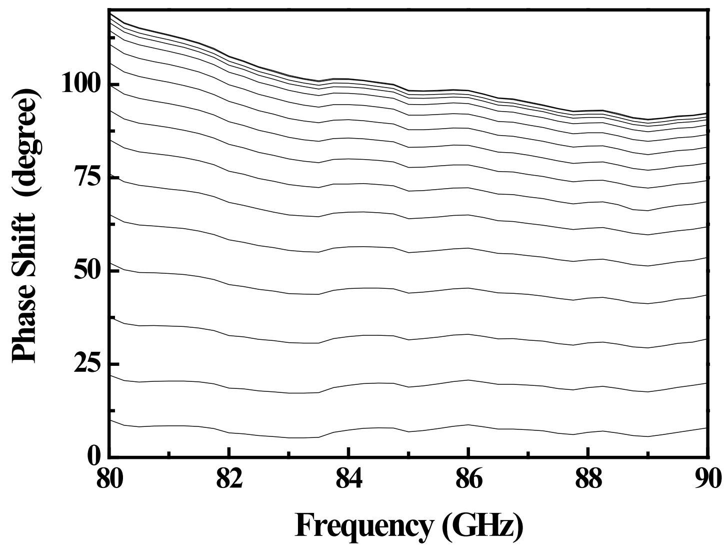

Figure 4. Measured phase shift of the proposed RTPS

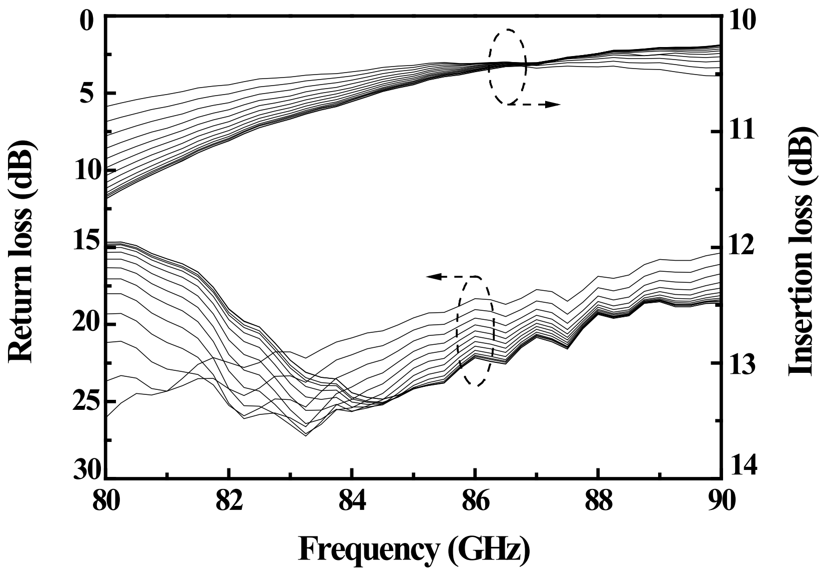

Figure 5. Measured return loss and insertion loss of the proposed RTPS.

Table 1 shows the measured results comparisons of this proposed PS with other reported RTPSs using silicon-based technology [3,6–8]. By using 0.18 μm CMOS technology, the RTPS circuits in [3,6] operate at 24 GHz and 60 GHz, respectively, while the RTPS circuits in this paper is working at 80–90 GHz with a comparable insertion loss to those designs at lower frequencies. The authors of [8] reported a RTPS design using 0.12 μm SiGe BiCMOS technology at the same frequency band as our work; however, the phase shifting range and insertion loss variation are 65° and ±3.5 dB, while ours are 101° and ±0.05 dB, respectively. Finally, the PS in this work consumes zero DC power, which has a great potential in low-power consumption applications.

Table 1. Comparisons between the measured results of the proposed Phase shifters (PS) monolithic microwave integrated circuit (MMIC) with other reported RTPSs using silicon-based technology.

Reference	Technology	Frequency (GHz)	Phase Shift	Insertion Loss Variation	Chip Area (mm²)
[3]	0.18 µm CMOS	24	360°	10.1–12.5 dB (±1.2 dB, ±10.6%)	0.33
[6]	0.18 µm CMOS	60	270°	9.8–14.8 dB (±2.5 dB, ±20.3%)	0.18
[7]	0.13 µm CMOS	60	100°	5.1–7.8 dB (±1.35 dB, ±20.9%)	0.2
[8]	0.12 µm BiCMOS	94	65°	7–14 dB (±3.5 dB, ±33%)	0.21
		80	119°	10.5–11.5 dB (±0.5 dB, ±4.5%)	
This work	0.13 µm CMOS	86	101°	10.4–10.5 dB (±0.05 dB, ±0.5%)	0.51
		90	92°	10.25–10.75 (±0.25 dB, 2.4%)	

4. Conclusions

This paper presents a W-band RTPS using a 0.13 µm CMOS technology. The phase tuning range is greater than 90° in the frequency range of 80–90 GHz, with the insertion loss variations below ±0.5, ±0.1, and ±0.25 dB at 80, 86 and 90 GHz, respectively. To the best of the authors' knowledge, the proposed phase shifter has the lowest insertion loss variation of all reported RTPSs.

Author Contributions

All authors contributed equally to this work.

Conflicts of Interest

The authors declare no conflict of interest.

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