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A 52–57 GHz 6-Bit Phase Shifter With Hybrid of Passive and Active Structures

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Abstract—It is very hard to realize a 6-bit resolution millimeter-wave phase shifter whether by passive structure or by active structure. A 52–57 GHz 6-bit phase shifter with hybrid of passive and active structures is proposed. The switched LC phase shifter is adopted for the passive structure because of its compact size, and the vector-sum phase shifter is chosen for the active structure in the 6-bit phase shifter. The proposed 6-bit phase shifter uses the passive structure to realize 5.625° and 11.25° phase shifts and uses the active structure to realize the $N \times 22.5^\circ$ phase shifts. Implemented in Taiwan Semiconductor Manufacturing Company 40-nm CMOS technology, the 6-bit phase shifter has a RMS error $<3.76^\circ$ and a RMS gain error <2.23 dB at 52–57 GHz. The proposed 6-bit millimeter-wave phase shifter achieves a high phase resolution with a compact size. The core die occupies an area of $500 \mu\text{m} \times 300 \mu\text{m}$ and consumes about 13 mA from a 1.1-V supply.

Index Terms—6-bit CMOS phase shifter, millimeter wave, monolithic microwave integrated circuit, phased array.

I. INTRODUCTION

WITH the development of wireless communication and integrated circuit technologies, millimeter-wave communication systems can achieve high data rate to meet the increasing demand for transporting large volumes of information. However, millimeter-wave experiences more attenuation and results in a decrease in SNR. The phased-array [1]–[5] technique is one of the most attractive methods to improve the SNR for the millimeter-wave communication systems.

Phase shifters are crucial components in the phased-array systems to control wave beam through changing the phase delay in every channel. Therefore, it is necessary for them to have high phase resolution. Phase shifters can be realized in passive forms [6]–[10], active

Fig. 1. Proposed 6-bit phase shifter.

forms [1]–[4], or other forms [11]. Passive structures usually need several cascaded stages to achieve a high phase resolution. However, different stages of the passive phase shifter have mutual effect on each other, and it is very hard to obtain 6-bit phase resolution. Although the passive phase shifter [8] achieves a 6-bit phase resolution, it occupies a large area which is an important factor in phased-array systems. As the phase shift is determined by the gains of I/Q paths in active phase shifters, the I/Q paths vary considerably for a small phase step with variation of parasitic capacitances. Such variation in parasitic capacitances leads to significant phase error at millimeter-wave frequencies. Thus, it is also very hard to obtain 6-bit phase resolution for the active structures.

In this letter, a 52–57 GHz 6-bit hybrid phase shifter that combines both passive and active structures is proposed, as shown in Fig. 1. The small phase steps are realized by the passive structure and the big phase steps are realized by the active structure. In this method, it simultaneously avoids the mutual effect of the cascaded stages in passive phase shifters and the significant variation of parasitic capacitances in active phase shifters. This letter is organized as follows. Section II presents the analysis and circuit design. Measurement results are shown in Section III and conclusion are drawn in Section IV.

II. DESIGN OF 6-BIT PHASE SHIFTER

A. Architecture

The proposed phase shifter consists of a passive structure, an active structure, and two transformer-type baluns, as shown in Fig. 1. An inductor is inserted at the input to improve the input matching. The width of all the metal traces used in the baluns is $5.4 \mu\text{m}$.

B. Passive Structure

The function of passive structure is to realize 5.625° and 11.25° phase shifts. The switched LC phase shifter is chosen for the passive structure, as shown in Fig. 2, because of

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Fig. 2. Passive structure of 6-bit phase shifter.

Fig. 3. Active structure of 6-bit phase shifter.

its small insertion loss and small area. However, the small phase shifts are very sensitive to parasitic parameters due to the small values of inductor and capacitance in switched LC phase shifter [10], and this effect is more serious at millimeter wave. Therefore, the electromagnetic (EM) simulation should be done very carefully to take the parasitic parameters into consideration especially for the 5.625° part. M_1, M_2, M_4, M_5 are connected to Metal 10, and the vias from Metal 1 to Metal 10 are modeled in high frequency structure simulator for EM simulation. The input impedance of the balun after the passive structure is optimized for a small change with different phase states to make sure the active structure has little effect on the small phase shifts.

C. Active Structure

The active structure consists of a quadrature all-pass filter (QAF) and an analog adder, as shown in Fig. 3. The QAF generates differential I/Q signals, and then the I/Q signals are synthesized for the desired phases by adding suitable I/Q amplitudes and polarities through an analog adder. The I/Q amplitudes are controlled by the voltage inputs VI and VQ, and the I/Q polarities are switched by digital inputs SI and SQ.

Fig. 4. Die photograph of the proposed 6-bit phase shifter.

Fig. 5. Measured results of 6-bit phase shifter. (a) Return loss. (b) $|S_{21}|$.

SQ. The active structure realizes the $N \times 22.5^\circ$ ($N = 1 - 15$) phase shifts by changing the ratio of Q-path's gain to I-path's gain and the two gains are controlled by VI and VQ. The current difference in I-path and Q-path is not significant for $N \times 22.5^\circ$ phase shifts. Therefore, there is a little difference of parasitic capacitances in I-path and Q-path, and the effect of the difference on the phase shifts is negligible.

III. MEASUREMENT RESULTS

The proposed 6-bit hybrid phase shifter is implemented in Taiwan Semiconductor Manufacturing Company (TSMC) 40-nm CMOS 7X1Z1U technology with 11 metal-layer back end. The die micrograph of the fabricated phase shifter is shown in Fig. 4. The die area including pads is $720 \mu m \times 460 \mu m$, where the core area is about $500 \mu m \times 300 \mu m$. The 6-bit phase shifter consumes about 13 mA from a 1.1-V supply. The measurement is done on-chip using Agilent N5247A VNA and Cascade Elite 300 probe station.

Figs. 5 and 6 illustrate the measured results of the proposed 6-bit phase shifter. Fig. 5(a) depicts the return loss of the 6-bit

TABLE I
COMPARISON WITH OTHER SIMILAR PHASE SHIFTERS

Ref	Structure	Freq. (GHz)	Resolution (bit)	RMS phase error (°)	RMS gain error (dB)	Pdc (mW)	$ S_{21} $ (dB)	Area (mm ²)	Input P _{1dB} (dBm)	Process
[1]	Active	52-64	5	<8	<1.2	25	2 *	NA	-17	0.13μm BiCMOS
[2]	Active	76-85	5	5.5-11	1.3-1.5	28	-16 ~ -4	NA	4	0.13μm BiCMOS
[6]	Passive	57-64	5	4.4-9.5	0.5-1.1	0	-16.4 ~ -12.2	0.09	9.5-12.5	65nm CMOS
[8]	Passive	57-64	6	1.9-2.3	NA	0	-23 ~ -17	0.54	NA	65nm CMOS
This work	Hybrid	52-57	6	2.8-3.76	2.07-2.23	14.3	-19 ~ -9	0.15	>10	40nm CMOS

* Simulated gain

Fig. 6. Measured results of 6-bit phase shifter. (a) Relative phase shifts. (b) RMS phase error and gain error.

phase shifter. The $|S_{11}|$ is better than -6 dB at 52–57 GHz, and the $|S_{11}|$ shows less variation than $|S_{22}|$. The average of the measured $|S_{21}|$ in Fig. 5(b) is very close to the simulated one.

The relative phase shifts for the 64 states covers 360° range, as shown in Fig. 6(a). The RMS phase error and gain error are shown in Fig. 6(b). The RMS phase error is less than 3.76° at 52–57 GHz ($<2.8^\circ$ at 52–55 GHz) and the RMS gain error is <2.23 dB at 52–57 GHz. The RMS gain error is larger than the active phase shifters because the intersection loss of passive structure varies with different phase states.

This work is compared with other similar phase shifters in Table I. A 6-bit phase shifter is realized in this letter and it

has a smaller size than passive phase shifters, which makes it suitable to use in phased-array systems with bulky channels.

IV. CONCLUSION

This letter proposed a 6-bit phase shifter with the hybrid of passive and active structures implemented in TSMC 40-nm CMOS technology. The proposed design is very compact and has small insertion loss. With the high-resolution phase shifters, the phased-array system can control the beam directions more accurately. Moreover, the compact size is promising in the miniaturized RF-shifting phased-array system.

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