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Reflective-Type Phase Shifter Design with a Patch Antenna for a 250 GHz On-Chip Beamforming System

Kyoungmin Lee[1], Yunkyeong Koh and Moonil Kim[a]
School of Electrical Engineering, Korea University
E-mail : [1]leemin7@korea.ac.kr

Abstract **- This paper introduces a reflective-type phase shifter (RTPS) and a defected ground patch antenna design for configuring a 4-bit 250 GHz on-chip beamforming system using a SiGe HBT device. The patch antenna is designed to operate at 250 GHz, with a defected ground structure implemented to address the issue of narrow bandwidth. Four ground slots, each sized 50 x 121 μm^2, are fabricated, and measurement results show that the patch antenna operates within the 240-257 GHz band. The RTPS is designed using a 90° hybrid coupler and variable loads using varactors. The 90° hybrid coupler is made compact by overlapping two adjacent 50-Ω quarter-wavelength lines and forming a slot on the ground plane. The varactor is based on a diode-connected SiGe HBT device, and its size is selected as the largest available 7.2 mm in length to maximize the capacitance variation with the bias input. Two RTPS unit cells are connected in series to achieve a 360° phase shift, and the measurement results demonstrate a 4-bit phase shift.**

Keywords **— Terahertz beam-forming system, reflective-type phase shifter, defected ground patch, beam-steering simulation, SiGe HBT process**

I. INTRODUCTION

High-frequency bands, such as the millimeter-wave and terahertz bands, are gaining attention due to their wide bandwidth and ability to enable high-speed transceiver systems [1]. Additionally, as high-sensitivity and high-resolution imaging systems, which originally developed for radio astronomy, are now being applied to fields such as medical imaging, security, safety, and biological spectroscopy [2], interest in achieving fast scanning performance through beam steering is increasing. However, in these high-frequency bands, challenges such as free-space path loss, high atmospheric absorption, and low device output arise. A method proposed to solve these problems is antenna phased array. A beamforming array system can enhance antenna gain and effective isotropic radiated power, thereby mitigating the high channel loss typically encountered in the terahertz band [3].

The essential components of beamforming systems are the antenna and the phase shifter circuit. Typically, an off-chip antenna is used in array systems because the antenna array structure requires a larger area than individual circuit elements, making it difficult to integrate the array within a chip. However, in the terahertz band, using an off-chip antenna poses challenges due to high parasitic reactance and significant transmission losses in interconnections such as wire bonding [4]. For this reason, designing an antenna array within an on-chip environment becomes essential in the sub-millimeter wave band. Nevertheless, on-chip antennas have the disadvantage of narrow bandwidth, primarily due to the limited thickness of the chip. Therefore, research on methods to increase the operating bandwidth of on-chip antennas is necessary without increasing area.

Two conditions must be met for designing the phase shifter in an H-band on-chip beam-steering system. The first condition is that 360° phase control should be possible, and the second condition is that circuit area, DC power consumption, and DC bias network complexity should be minimal considering the limited integrated chip area.

In this paper, the RTPS and a defected ground patch antenna design for a 250 GHz on-chip beamforming system is proposed and the performance is validated through measurements. The antenna structure, designed using a defected ground, and its performance are discussed in Section II. The analysis and performance of the phase shifter design are presented in Sections III and IV, respectively. Finally, in Section V, an 8-element 250 GHz beam-forming array system implementation consisting of the designed phase shifter circuit and antenna is explained. The impact of circuit and antenna performance on beam-steering operation is also analyzed using the High Frequency Structure Simulator (HFSS).

II. DEFECTED GROUND PATCH ANTENNA DESIGN

The use of an on-chip antenna is essential at high frequencies, such as the H-band. However, commonly used patch antenna faces challenge in achieving stable performance due to its very narrow bandwidth in an integrated chip environment. If sufficient bandwidth is not secured, a mismatch between the operating frequencies of the antenna and the phase shifter may occur, which can degrade the performance of the beamforming system. To address this issue, substrate-direction radiating structures are also being studied, but when using a silicon substrate, the high loss can significantly reduce radiation efficiency. Therefore, it is not a suitable method in the SiGe IC environment.

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[a] Corresponding author; mkim@korea.ac.kr

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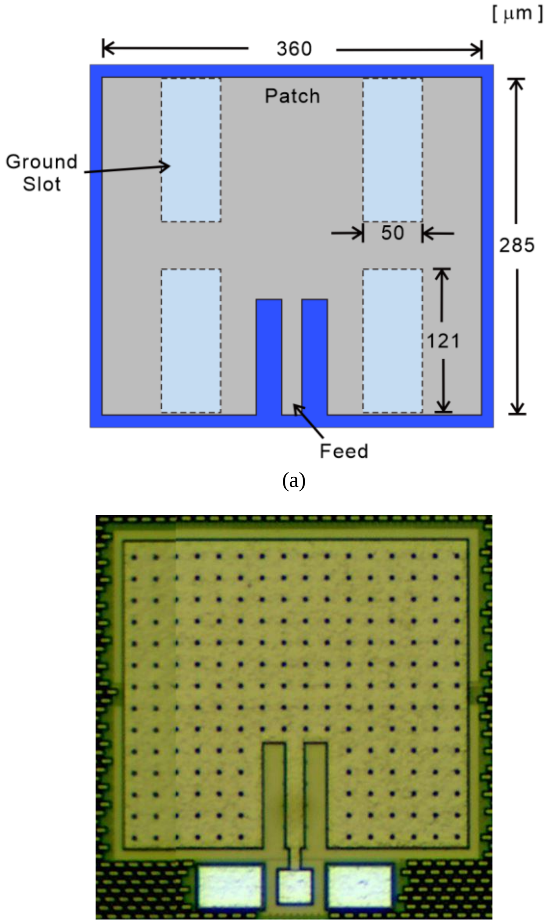
The patch antenna is easy to integrate with the circuit, but the shallow height of the SiO_2 layer, used in the on-chip circuit design, causes a high Q factor, which limits the operating bandwidth. Some studies have explored the use of parasitic structures to increase bandwidth [5], but this approach gives low area efficiency for use in on-chip array systems. To increase bandwidth, the depth between the patch and the ground metal needs to be expanded. However, in the IHP SiGe process, the thickness of the SiO_2 layer is fixed at less than 10 µm. To solve both the area and bandwidth problem, a defected ground technique, which involves adding slot patterns to the ground plane, is being researched [6].

In this study, a patch antenna is designed using the Top Metal 2 (TM2) layer, positioned at the top of the SiO_2 layer, to form the patch with a height of 9.23 µm. The design includes slots on the ground surface to increase the electrical length between the patch and the ground. As the electrical length increases, the Q factor decreases, resulting in an increased bandwidth. HFSS simulations confirm that this design doubles the 5-dB bandwidth compared to a simple patch design. This effect also increases the electrical height between the patch and the ground plane, which also increases radiation efficiency. As shown in Fig. 1(a), a 360 x 285 µm² patch antenna, operating at the 250 GHz band, is designed with four slots, each measuring 50 x 121 µm², placed on the ground. The simulation results show that the maximum directivity is calculated to be around 4.79 dB.



(a)

(b)

Fig. 1. (a) Layouts and (b) photograph of the defected-ground patch.

The designed antenna is fabricated, as shown in Fig. 1(b), and measured using a Vector Network Analyzer (VNA). The mismatch results of simulation and measurement are shown in Fig. 2. From the antenna phase measurements, it is confirmed that resonance occurs in the 240-257 GHz band, with an estimated center frequency of 248.5 GHz. The measurement results also show higher loss in the high-frequency band compared to the simulation. While the bandwidth is improved by using the defected ground structure, the high material loss of the silicon substrate affects the antenna performance due to the ground slots.

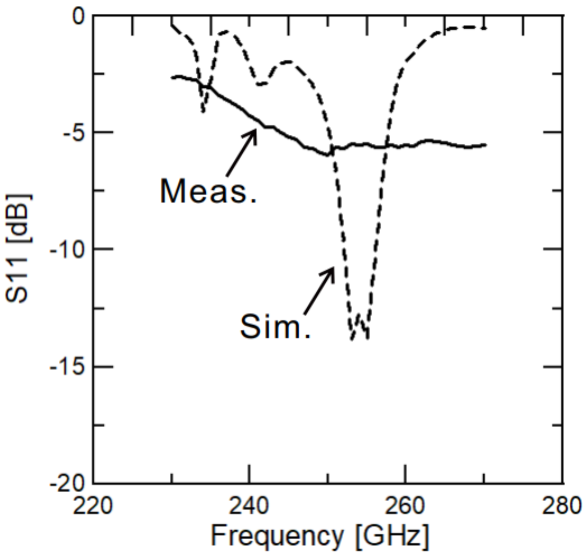
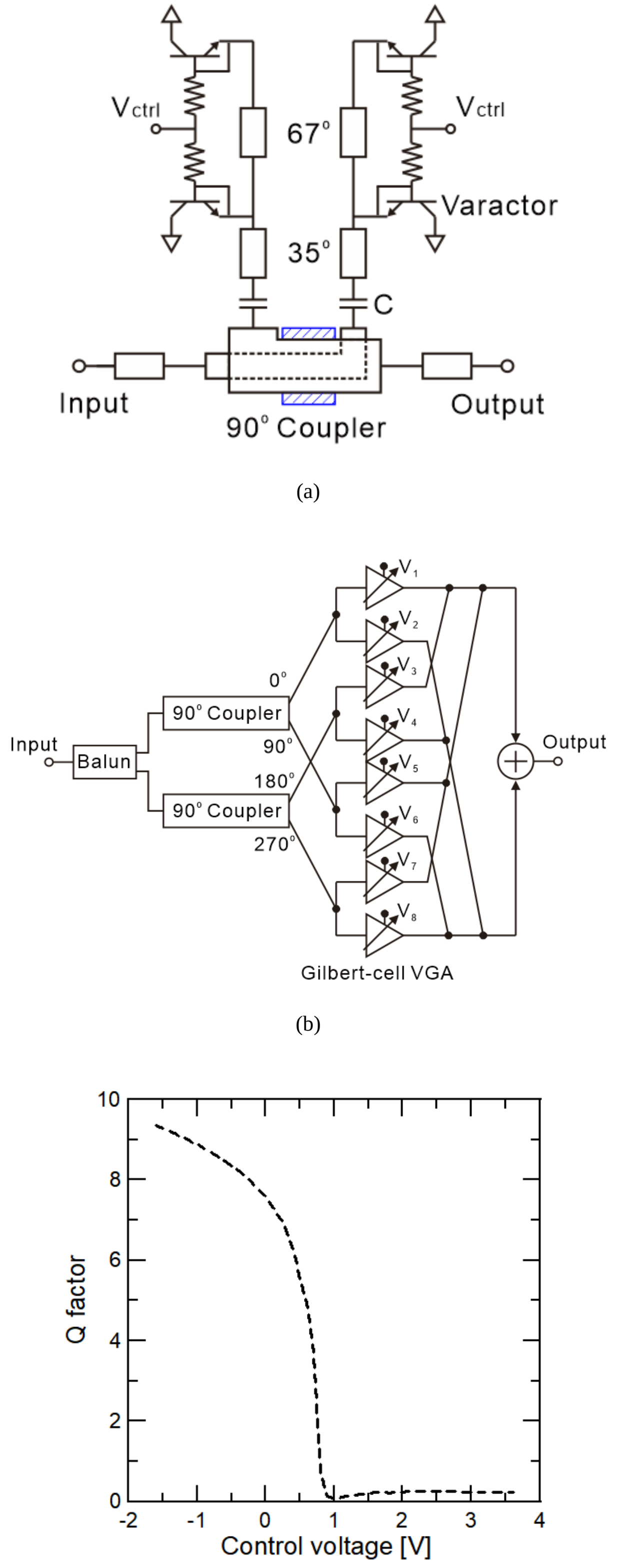


Fig. 2. Measured and simulated antenna impedance of the patch.

III. REFLECTIVE-TYPE PHASE SHIFTER DESIGN

The phase shifter topology used in the beamforming array is a RTPS, as shown in Fig. 3(a). The RTPS structure includes a 90° hybrid coupler with a variable reflective load connected to two ports of the coupler. As the capacitance value of the load changes, the phase shift degree varies, and the phase-shifted signal is reflected to the output port. Since the RTPS topology consists solely of a 90° coupler and some loads, it occupies a very compact area and minimizes the complexity of the DC bias network [7]. The 90° hybrid coupler is designed by overlapping 90-degree 50 Ω lines of Top Metal 1 (TM1) and TM2 at different height positions, with a slot on the ground used for coupling. Advanced Design System (ADS) momentum simulation results confirm that S_{21} and S_{31} are -3 dB and -3.6 dB at 250 GHz, respectively, with a phase of 86.5 degrees, which is close to 90 degrees.

A typical phase shifter that has been widely designed in the past is a vector-sum circuit using Gilbert-cell as shown in Fig. 3(b) [8]. This type of phase shifter is complex and requires a large area due to the various circuit components, as shown in Fig. 3(b). The principle of operation is depicted in the block diagram of Fig. 3(b). After the input signal is distributed by a balun, it is further divided using a 90° hybrid coupler, resulting in in-phase and quadrature-phase signals.



(a)

(b)

(c)

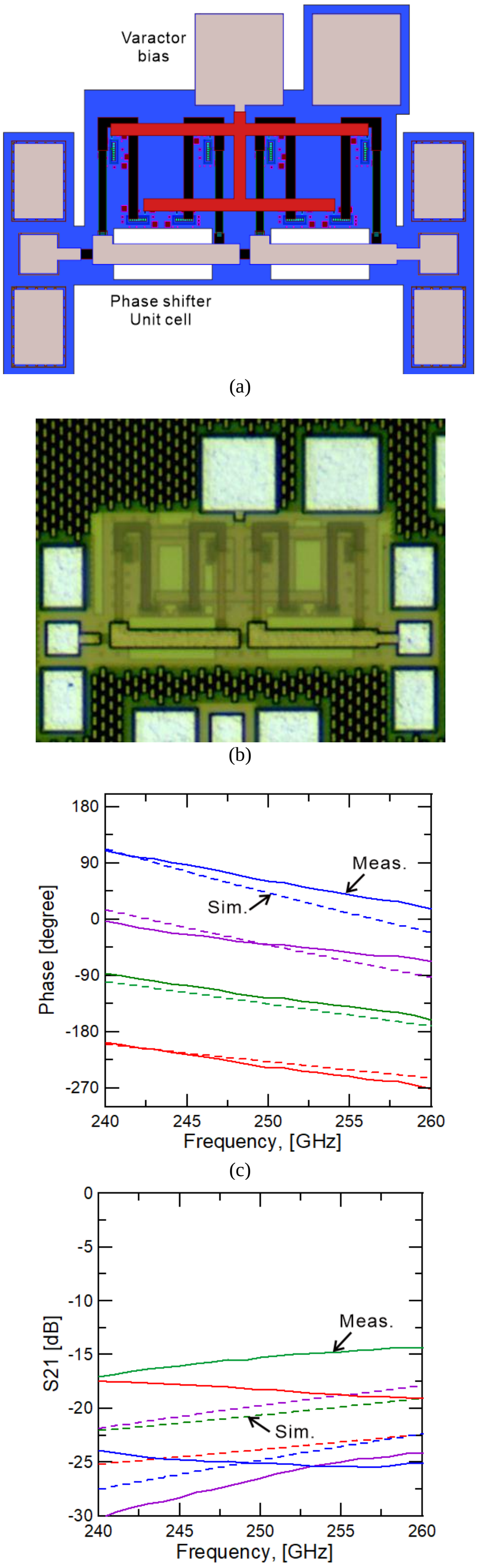
Fig. 3. (a) Schematic of fabricated RTPS unit cell, (b) block diagram of typical vector-sum phase shifter using Gilbert-cell VGAs and (c) Q-factor of diode-connected varactor.

These signals are then input to the Gilbert cell, which functions as a variable gain amplifier (VGA), and the phase is shifted according to the VGA output with control bias.

This type of phase shifter is inherently challenging to design compactly, as a Gilbert-cell amplifier occupies a large area, and the design also requires a balun and two 90° hybrid couplers. Additionally, the bias network becomes inevitably complicated because all VGAs need to be individually adjusted. As a result, there is a limitation to designing a compact phased array within an IC with restricted area. In contrast, the RTPS is advantageous in terms of area efficiency since it only requires a variable load. The load utilizes a SiGe HBT configured as a diode-connected varactor, which has a significantly smaller size compared to the amplifier structure. The value of the capacitance tuning range (Cmax/Cmin) of the diode-connected varactor device used in phase shifter circuit is about 33. It is calculated with ADS. The Q-factor calculation result is also as shown in Fig. 3(c). The phase shifter is designed using two varactors with calculated characteristics. When the two varactors are placed at 67-degree line intervals, the largest phase tuning range is obtained.

A typical diode-connected device uses a method of connecting the base and collector. However, when the base and emitter are connected, a wider range of phase shifts is possible according to the change in bias voltage in this SiGe device process. This result is verified through ADS simulation. Therefore, the diode-connected method in the circuit shown in Fig. 3(a) is used. In general, in the high frequency band, there is interconnect parasitic capacitance in addition to the capacitance that changes due to the bias voltage. The value of this parasitic capacitance can be estimated through the varactor measurement. However, as a result of the phase shifter measurement, it is confirmed that the simulation and measurement results are similar in terms of phase change. From this result, it is confirmed that the most affected capacitance in the operation frequency is the junction capacitance changed by the bias voltage, and the parasitic capacitance is not significant.

The varactor is a 900 nm x 8-finger device, which is the largest available device in this SiGe HBT process. This device is used to maximize the change in the capacitance value. However, simulation results from ADS indicate that achieving continuous phase changes is difficult due to insufficient capacitance variation from a single varactor. To enhance performance, two 7.2 µm varactor devices are employed in each reflective load to increase the range of phase delay changes. Since only 180 degrees of change is possible even if the load is adjusted, two RTPS unit cells are connected in series for use in the beamforming system, allowing for a phase difference close to 360 degrees.



(a)

(b)

(c)

(d)

Fig. 4. (a) Layout and (b) photograph of the RTPS. (c) Differential phase and (d) insertion losses of the RTPS.

IV. PHASE SHIFTER MEASUREMENT

The layout of the designed RTPS circuit is shown in Fig. 4(a). To simplify the DC bias network of the beamforming system, the entire RTPS circuit is designed to be controlled with a single bias. The two-unit cells from Fig. 3(a) are connected to form the structure depicted in Fig. 4(a). The fabricated circuit, shown in Fig. 4(b), is measured using a VNA.

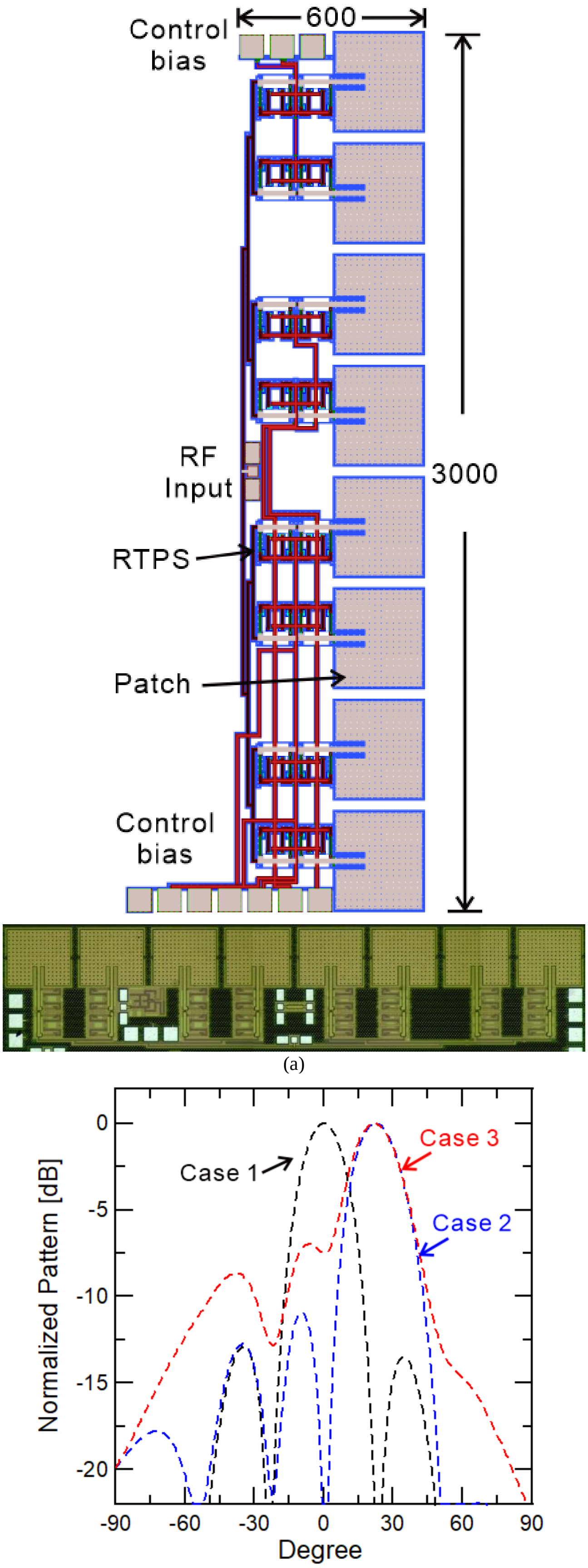
As shown in Fig. 4(c), the phase measurement results demonstrate a 4-bit phase configuration at 250 GHz, with phase shifts of 0°, 102°, 187°, and 298°. At 260 GHz, the phase shifts are 0°, 84.4°, 177°, and 287°, showing a phase difference close to the expected 4-bit configuration, consistent with the simulation results. The phase shifter operates across a bandwidth of 20 GHz, within the 240-260 GHz range. However, as the frequency increases, the phase change decreases, making sufficient control more difficult.

The insertion loss of the RTPS is shown in Fig. 4(d), with losses exceeding -15 dB and non-uniform magnitude. The discrepancy of magnitude between the measurement and simulation results is likely due to differences in parasitic components and loss characteristics between the device modeling and the actual performance of the varactor used. Additionally, the loss variation in coupler is estimated to result from higher-than-expected loss due to the silicon substrate.

V. BEAMFORMING ARRAY DESIGN

Using the designed antenna and RTPS, an 8-element beamforming array system is fabricated, as shown in Fig. 5(a). The distance between the antennas is 0.3 λ, which is narrower than the commonly used 0.5 λ due to the limit of the chip area. While this may increase the side lobe level, it still allows for beamforming performance testing. Each of the eight RTPS units is controlled by a single bias respectively, allowing the phase of each phase shifter to be adjusted according to the bias control. The RF input is delivered through an RF probe, and the output of each RTPS is connected to each antenna, where the final output signal is radiated by the patch antenna.

The beam-steering performance can be confirmed, as shown in Fig. 5(b), based on simulation results that take into account the RTPS output amplitude and phase. Fig. 5(b) shows the radiation pattern results simulated with the beamforming array. Case 1 is the result of in-phase input to eight antennas, and case 2 and 3 show results with phase sets of (0,0, 90, 90, 180, 180, 270, 270) is input in order. Case 2 assumes equal magnitudes for all antennas, while Case 3 uses a 10 dB power difference to reflect the actual RTPS performance. In Case 3, the side lobe level increases compared to Case 2, but the beam-steering performance of the main beam remains achievable. We plan to verify the beam-steering performance through future measurements.



(a)

(b)

Fig. 5. (a) Layout and photograph of 250 GHz beam-forming system and (b) simulated beam-steering pattern result with different input.

VI. CONCLUSION

The element circuit design for the 250 GHz beamforming system and the beamforming array are fabricated using a SiGe HBT device. While the designed defected ground patch antenna exhibited higher-than-expected material loss due to the silicon substrate, measurements confirmed that it could radiate within the operating range of the RTPS. The RTPS output amplitude is low and non-uniform, with significant loss, but it successfully achieved 4-bit phase shifts in the 240-260 GHz band. The beamforming system is constructed by integrating these two individual circuits into an 8-element array, and its performance is validated through HFSS simulation. Although simulation shows the side lobe levels increase due to amplitude differences, beam-steering is still achievable with up to a 10 dB amplitude variation. The next step is to verify the system's performance through pattern measurements of the fabricated SiGe IC.

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Kyoungmin Lee received the B.S. degree in electrical engineering from Korea University, Seoul, South Korea, in 2015, where he is currently working toward the Ph.D. degree. His research topics include development of antenna and passive microwave sensor system for millimeter wave band. His current research is design detector and antenna based on InP DHBT in terahertz region and package integrated circuits in waveguide and lens antenna.

Yunkyeong Koh is currently an undergraduate student in electrical engineering at Korea University. Her research interests are design and measurements of terahertz integrated circuits that include power amplifiers and oscillators.

Moonil Kim is a currently professor in Electrical Engineering, Korea University. His current research interests include development of both passive and active circuit components required in construction of terahertz communication and imaging systems.