IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 7 September 2022, accepted 27 September 2022, date of publication 3 October 2022, date of current version 10 October 2022.
Digital Object Identifier 10.1109/ACCESS.2022.3211303

RESEARCH ARTICLE

A Simultaneous Beam Steering and Polarization Converting S-Band Transmitarray Antenna

MYEONGHA HWANG[1], **GYOUNGDEUK KIM**[1], **JONGYEONG KIM**[2], **AND SANGKIL KIM**[1], **(Senior Member, IEEE)**
[1]Department of Electronics Engineering, Pusan National University, Busan 46241, Republic of Korea
[2]Hanwha Systems, Yongin 17121, Republic of Korea

Corresponding author: Sangkil Kim (ksangkil3@pusan.ac.kr)

This work was supported by the Challenging Future Defense Technology Research and Development Program of Agency for Defense Development in 2019 under Grant 9127786.

ABSTRACT In this paper, a multi-functional transmitarray antenna consisting of miniaturized unit cells for S-band radar applications is proposed. The unit cell size is $0.4\lambda_0 \times 0.4\lambda_0$, and it is composed of a receiving (Rx) antenna, a miniaturized inductively-loaded reflection-type phase shifter, a PIN diode switch for polarization conversion, and a dual-polarization transmitting (Tx) antenna. The types of Rx and Tx antennas are coupled-fed stacked patch antennas. The designed reflection-type analog phase shifter has a 36 % smaller area than the conventional reflection-type hybrid coupler-based phase shifter. It has a 3-bit phase-shifting capability realized with a $0 \sim 330°$ analog phase shifting. The designed SPDT PIN diode switch can select the polarization of the transmitted wave and accept a high input RF power of 23 dBm. The proposed 8×8 transmitarray antenna with F/D of 0.33, made from its unit cell, has a gain of about 7.9 dBi and performs 90° 2D beam steering for vertical-to-horizontal and vertical-to-vertical polarization conversions at the center frequency.

INDEX TERMS Transmitarray antenna, miniaturized phase shifter, reflection-type phase shifter, beam steering, polarization conversion.

I. INTRODUCTION

There has been a growing interest in remote electromagnetic (EM) wave detection for vehicle radar or next-generation satellite communications in recent years. Numerous research papers on array antennas capable of multi-functional beam scanning have been reported because of their various applications [1], [2], [3], [4], [5], [6], [7]. The widely used beam scanning antennas for remote sensing are mechanically rotating dish reflectors, active phased arrays, and transmitarray or reflectarray antennas. The conventional active phased array antennas are most widely used for beam steering but require complex feeding networks, high power, high-cost transceiver module, etc. Therefore, transmitarray and reflectarray antennas have attracted huge attention as alternatives to active phased array antennas, especially in the military and satellite communication industries that use extremely high or limited power. Since transmitarray and reflectarray antennas are very similar in structure and are classified according to the direction of the feeding antenna and the radiation direction from the array antenna, an appropriate array antenna among these two types is usually selected according to the design environment.

There are three main approaches to unit cell design of a transmitarray [4]: (a) multi-layer frequency selective surface (M-FSS) [8], [9], [10], (b) metamaterial/transformation [11], [12], [13], and (c) receiver-transmitter design [14], [15], [16] approaches. Since the multi-layer FSS structure is separated by either an air gap or a thick substrate, the M-FSS approach is difficult in transmitarrays with a low profile. On the other hand, the configuration having metamaterial characteristics is designed to vary the effective permittivity (ε_{eff}) and permeability (μ_{eff}) of the substrate or a specific material in the metamaterial/ transformation approach. Since this approach uses a simple metal pattern on a substrate or uses a specific material, it has a complexity issue in implementing a 2-bit

The associate editor coordinating the review of this manuscript and approving it for publication was Luyu Zhao.

or more phase shifting performance. This research uses the receiver-transmitter design approach because of the required unit cell's ease of fabrication (compatible with multi-layer PCB and SMT processes), low profile property, and broad phase-shifting range (2-bit or more).

Generally, it is necessary to phase control each unit cell for beam steering. In addition, each unit cell has a phase shifter using a PIN diode or a varactor. The PIN diode-based phase shifting controls the current flow using two or more PIN diodes to achieve discrete (or digital) phase shifting of 1 or 2-bit states. However, the PIN diode-based phase shifting has limited beam steering because of rough phase compensation. Hence, a reflection-type phase shifter having a hybrid coupler is widely used for continuous analog phase shifting in a wide range due to its simple and practical structure. However, the typical reflection-type phase shifter requires a large space due to its hybrid coupler's quarter-wavelength ($\lambda_g/4$) transmission line structure. Therefore, it is critical to realize a miniaturized unit cell by reducing the size of its reflection-type phase shifter to avoid a larger transmitarray.

Many reported reconfigurable transmitarray designs have focused only on beamforming or polarization conversion. In addition, polarization conversion in most studies was restricted to converting a linearly polarized (LP) wave into a circularly polarized (CP) wave using the element rotation technique [16], [17], [18]. Only a few reported research papers presented LP-to-LP conversion and beam steering capability using a transmitarray structure. Likewise, the proposed transmitarray antenna of this research multi-functionally performs beam steering and linear polarization conversion (vertical-to-vertical or vertical-to-horizontal). In particular, linear polarization conversion is achieved by integrating a dual-polarized Tx square patch antenna and a single pole double throw (SPDT) PIN diode switch. The phase shift function is implemented using a miniaturized broad range reflection-type phase shifter. Notably, a 3-bit phase shifting is implemented using an analog phase shifter in this research to take advantage of both digital and analog phase shifting methods. This 3-bit phase shifter is capable of fine phase tuning at each state.

The organization of this paper is as follows. The structure and measurement of receiving (Rx) and transmitting (Tx) antennas, the miniaturized reflection-type phase shifter, and the SPDT PIN diode switch in a unit cell are studied briefly in Section II. This section also discusses the unit cell's performance using a 1 × 2 transmitarray antenna. Subsequently, Section III experimentally studies the beam steering and polarization conversion of the proposed 8 × 8 transmitarray antenna. Finally, Section IV concludes the research.

II. DESIGN AND VERIFICATION OF A MINIATURIZED UNIT CELL

A. ANTENNA AND RF CIRCUIT DESIGN OF UNIT CELL

Fig. 1 (a) and (b) show the block diagram and structure of the proposed transmitarray's miniaturized unit cell. A vertically polarized feeding horn antenna radiates EM wave, and

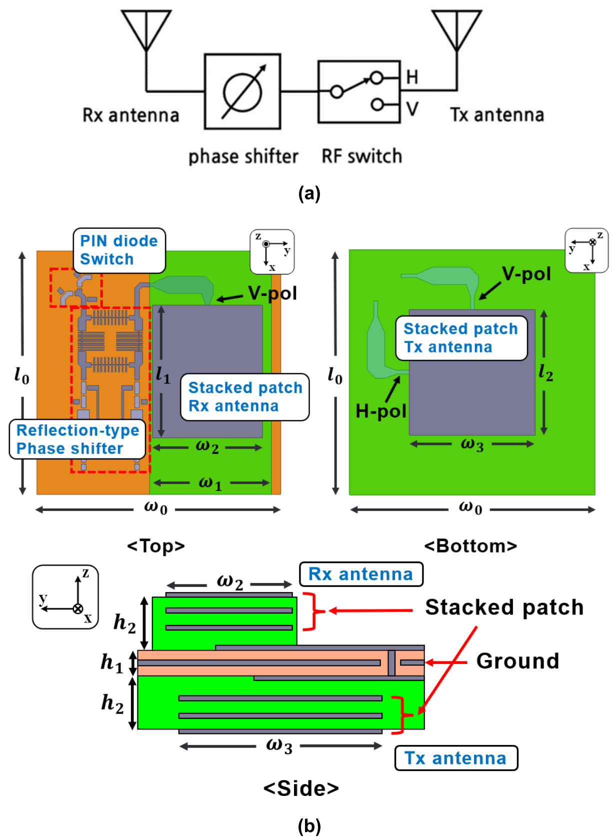
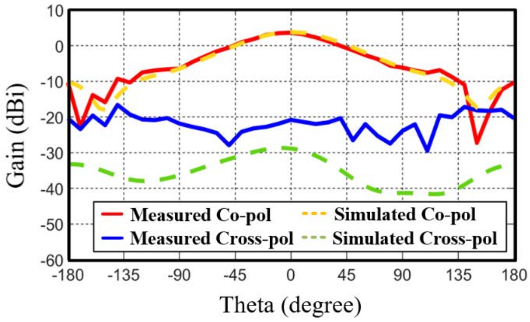


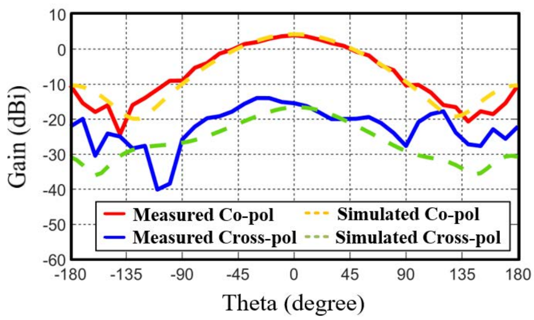
FIGURE 1. Proposed miniaturized transmitarray unit cell: (a) block diagram and (b) structure; ω_0 = 40 mm, ω_1 = 20 mm, ω_2 = 18 mm, ω_3 = 20.5 mm, l_0 = 40 mm, l_1 = 21.5 mm, l_2 = 20.5 mm, h_1 = 0.8 mm, and h_2 = 3 mm.

it is received by a vertically polarized (V-pol) Rx antenna. The phase of the Rx signal is adjusted to the desired phase value by a reflection-type phase shifter using a miniaturized hybrid coupler. The polarization of the transmission wave to be transmitted through a dual-polarized transmitter (Tx) patch antenna is converted to horizontal (called a V-to-H-pol conversion) or maintained (called a V-to-V-pol conversion) by the SPDT PIN diode switch. The proposed unit cell was fabricated on an FR4 ($\varepsilon_r = 4.4$ and tan $\delta = 0.023$) substrate and designed in a miniaturized size ($0.4\lambda_0 \times 0.4\lambda_0$) to avoid grating lobe and scanning blinds. The unit cell of the proposed transmitarray is designed to cover a 3.3 % fractional frequency bandwidth (BW = 100 MHz) in S-band. ANSYS HFSS 2021 R1, a full-wave FEM (Finite Element Method) EM simulation tool, and Keysight ADS 2021 were used to evaluate this design.

The Rx and the Tx antennas operating in the S-band are designed in this research as coupled-fed stacked patch antennas because of their high gain and low-profile properties, as shown in Fig. 1(b). Fig. 2 shows the measured radiation patterns of Rx and Tx antennas. The Rx antenna has the measured 3.8 dBi peak gain and 80° beamwidth and the Tx antenna has the measured 4.2 dBi peak gain and 80° beamwidth, respectively. The respective measured

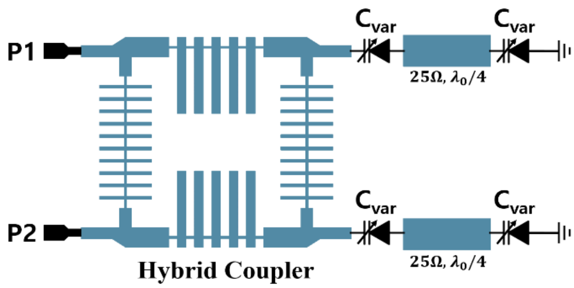


(a)

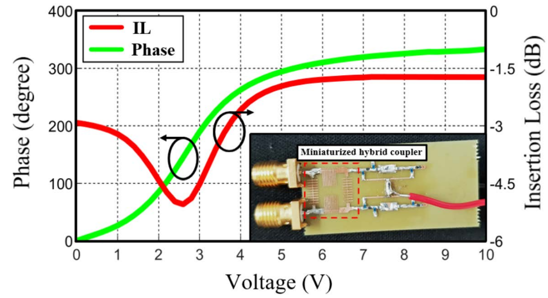


(b)

FIGURE 2. Measured antenna radiation patterns: (a) Rx and (b) Tx antennas.



(a)

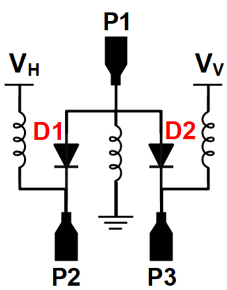


(b)

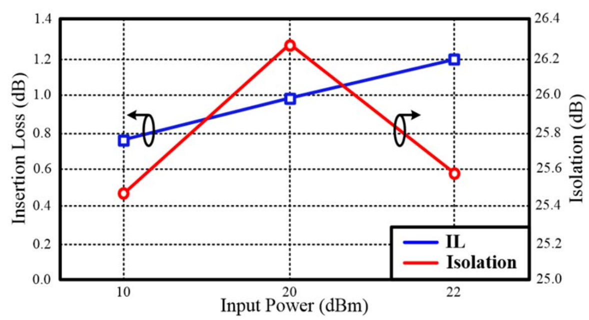
FIGURE 3. Miniaturized reflection-type phase shifter: (a) circuit diagram and (b) relative phase shift and IL according to a DC bias voltage.

fractional bandwidth of Rx and Tx antennas was 3.3 % at the operating frequency. Fig. 3 shows the circuit diagram of the proposed reflection-type phase shifter, relative phase shift, and insertion loss (IL) according to a DC bias voltage. The reflection-type phase shifter has a 36 % smaller area ($0.08\lambda_0 \times 0.09\lambda_0$) than conventional hybrid couplers ($0.14\lambda_0 \times 0.14\lambda_0$) by replacing a quarter-wavelength ($\lambda_g/4$) branch line of the conventional coupler with a transmission line having slow-wave characteristics [19]. The reactive loads consisting of two varactors and a $\lambda_g/4$ transmission line are connected in series to widen the phase shift range. The fabricated phase shifter has a continuous (analog) phase shifting range of $0 \sim 330$ degrees. It corresponds to a 3-bit digital phase shifting range (45 degrees phase quantization). The measured IL was $1.8 \sim 5.5$ dB depending on the DC voltage. This IL variation is due to the resonance of varactors and the loaded $\lambda_g/4$ transmission line.

Fig. 4 shows the circuit diagram of the proposed SPDT PIN diode switch, IL (S_{21}) and isolation (S_{32}) between two output ports according to the input power when D1 is in the ON state and D2 is in the OFF state. The proposed SPDT PIN diode switch is arranged as follows. Unlike the conventional SPDT diode switch where the anode of one diode and the cathode of the other diode are connected, the anodes of both diodes are connected in common. Both PIN diodes share a common DC ground terminal at the anode, and the bias of each diode is controlled by two DC bias lines at the cathode. For instance, the proposed SPDT PIN diode switch is able to handle 23 dBm of RF power (from P1 to P2) when



(a)



(b)

FIGURE 4. Proposed SPDT PIN diode switch: (a) circuit diagram and (b) IL (S_{21}) and isolation (S_{32}) according to the input power.

$V_H = +1.4$ V & $V_V = -5.0$ V because the peak voltage swing of 23 dBm on 50 Ω transmission line is about 4.5 V which is lower than the reverse bias of 5.0 V. The measured return losses (RL) of the PIN diode switch are more than

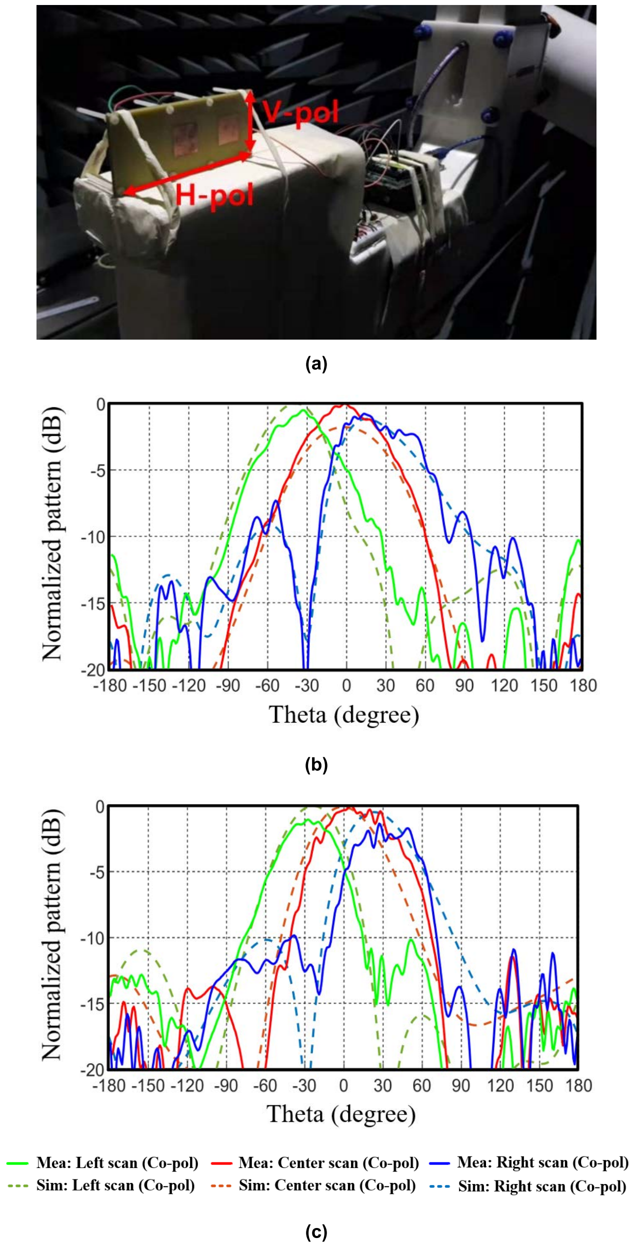


FIGURE 5. 1 × 2 array antenna measurement: (a) the measurement setup, normalized radiation patterns for (b) V-to-V-pol and (c) V-to-H-pol conversions.

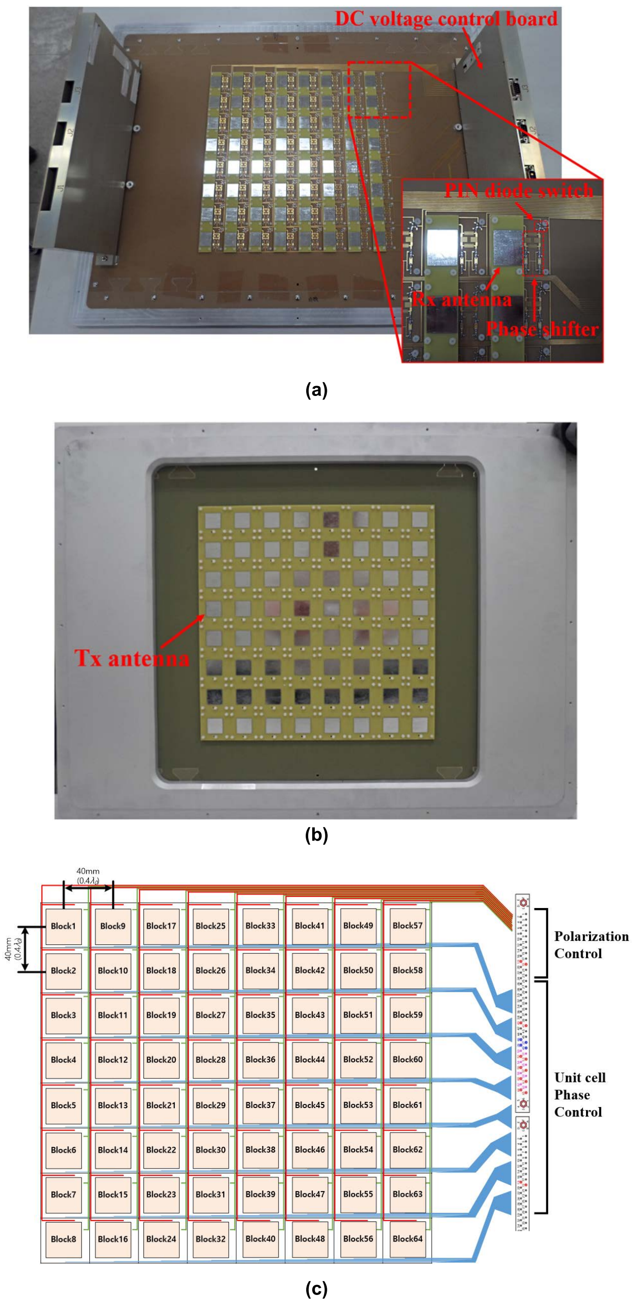
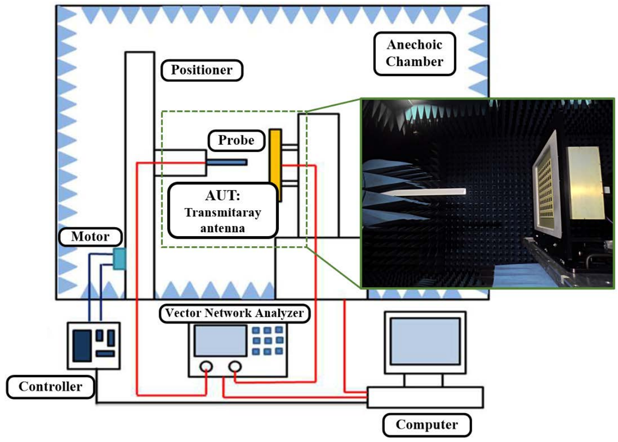


FIGURE 6. 8 × 8 transmitarray prototype: (a) Rx side, (b) Tx side, and (c) DC voltage control line diagram.

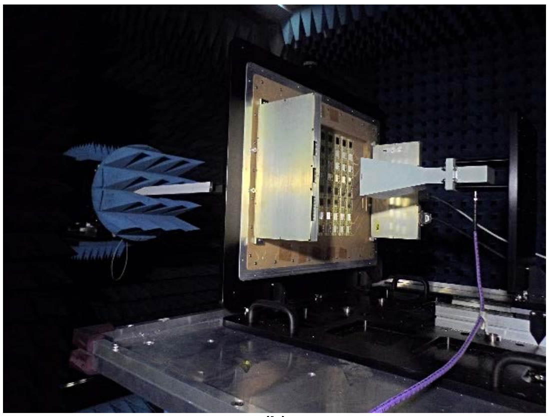
15 dB, and the IL increased as the input power increased and was found to be 1.2dB at 22dBm input power.

B. UNIT CELL VERIFICATION

A 1 × 2 array antenna was designed and fabricated based on the proposed unit cell structure to verify its polarization conversion and beam steering capability. As shown in Fig. 5(a), the radiation patterns of the 1 × 2 array antenna were measured in an anechoic chamber. The applied phased difference between antenna elements were −90 (green lines), 0 (red lines), +90 (blue lines) degrees, and their measured normalized radiation patterns were shown in Fig. 5(b) and (c). The measured gain at 0° phase difference was −0.33 dBi for maintaining the wave polarization (V-to-V-pol conversion) and −0.9 dBi for polarization conversion (V-to-H-pol conversion). The measured beam steering angle range was −27° to 27° for V-to-V-pol and −33° to 13° for V-to-H-pol conversions. This asymmetrical beam steering angle of 1 × 2 array antenna was caused by a rectangular ground plane which has an asymmetrical ground plane for the V-to-H conversion mode. It should be noted that the polarization conversion and phase shifting capability of the proposed unit cell structure are clearly observed. It also shows a good agreement between

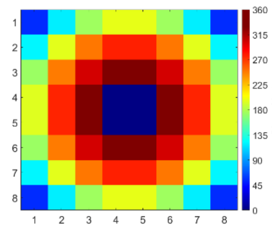


(a)

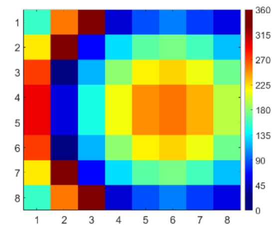


(b)

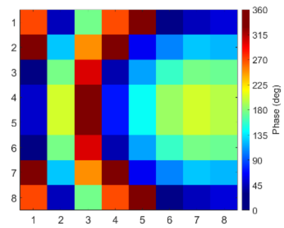
FIGURE 7. Near-field measurement on the 8 × 8 transmitarray antenna: (a) the measurement setup and (b) this antenna mounted in the measurement setup.



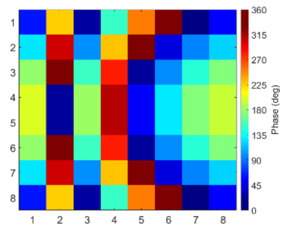
(a)



(b)



(c)



(d)

FIGURE 8. Each 8 × 8 transmitarray antenna unit cell's required phase compensation for a (Az, El) of (a) (0, 0), (b) (15, 0), (c) (30, 0), and (d) (45, 0).

TABLE 1. 8 × 8 transmitarray antenna's losses.

Spillover loss (dB)	0.23
Tx antenna loss (dB)	3.27
Rx antenna loss (dB)	3.28
Phase shifter average loss (dB)	3.5
PIN diode switch loss (dB)	0.7
Total loss (dB)	10.75

the simulated and measured performances of the designed 1 × 2 array antenna.

III. THE 8 × 8 TRANSMITARRAY ANTENNA

A. THE 8 × 8 TRANSMITARRAY ANTENNA FABRICATION AND NEAR-FIELD MEASUREMENT

Fig. 6 shows an 8 × 8 transmitarray antenna prototype fabricated from the designed unit cell. The 8 × 8 array size was chosen based on the spillover loss and F/D length. This transmitarray antenna incorporated with the DC voltage control board measures 660 mm × 490 mm (width × length), and its size without the DC voltage control board incorporated in it is 320 mm × 320 mm. The 16 vertical DC bias lines for the polarization control are printed for V and H-pol controls (8-bias-line each). Since the phase control line adjusts each unit cell's phase, 64 phase control lines are connected one-on-one to the unit cells horizontally. The Tx/Rx antenna and the PCB, including phase shifters, SPDT switches, and bias lines, were tightly assembled by nylon bolts and nuts. This 8 × 8 transmitarray antenna was fabricated on an FR4 substrate instead of a low-loss substrate because this research aims to present the proof-of- concept of a beam steering and polarization reconfigurable transmitarray using an analog phase shifter and a PIN diode switch of miniaturized unit cell at S-band for radar applications. Fig. 7 shows the near-field measurement on the fabricated 8 × 8 transmitarray antenna in an anechoic chamber. The far-field measurement is widely used to test the antenna performance, but it is challenging to build an anechoic chamber for a large antenna array system due to its huge far-field range. On the other hand, the near-field measurement is an efficient way to measure the performance of a large array structure because of its compact measurement setup [20]. In particular, it can also measure the performance of each unit cell because of the small size of the probe. 2D plane Near-field pattern is measured by a rectangular waveguide probe and is transformed into far-field radiation pattern. Moreover, the phase of each array element was calculated by back-projection, projecting the measured near-field electromagnetic wave energy onto the antenna aperture surface [21], [22]. This research used a 10 dBi horn antenna (LB-284-10-C-NF, A-info [23]) as a feeding source horn antenna. The distance between the horn and 8 × 8 transmitarray antennas was set to 150 mm, resulting in a focal length ratio (F/D ratio) of 0.33. The DC voltage control board applies a +1.4 V forward bias to the activated polarization control line and a −5 V reverse bias to

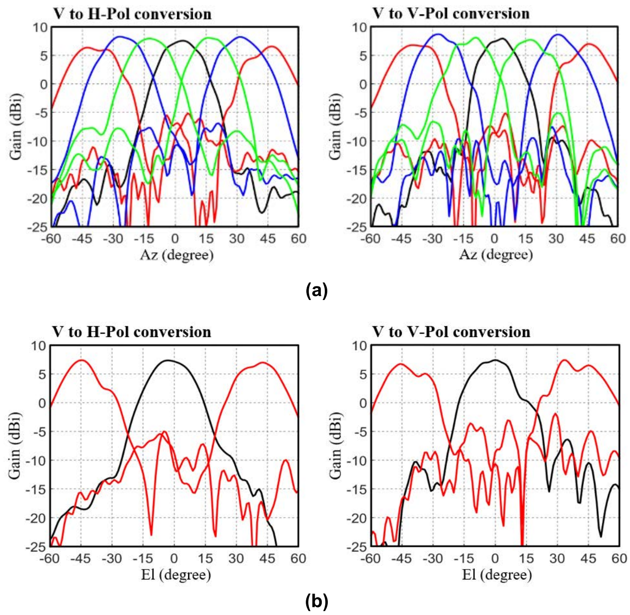


FIGURE 9. Beam steering of the 8 × 8 transmitarray antenna in terms of radiation patterns at the center frequency: (a) Az and (b) El angles.

another deactivated polarization control line for polarization conversion. It also applies a voltage of 0 to 10 V to obtain the required phase compensation of each unit cell for beam steering at a specific angle. Fig. 8 shows the required phase compensation of each unit cell for (0, 0), (15, 0), (30, 0), and (45, 0) beam steering angles expressed in the azimuth-over-elevation, (Az, El), coordinate system. In addition, each negative azimuth or elevation beam steering angles can be obtained by the flipped phase compensation of Fig. 8 because the 8 × 8 transmitarray is symmetric.

B. EXPERIMENTAL RESULTS

The radiation patterns in the V-to-H-pol and V-to-V-pol conversions were measured with the required phase compensation of the unit cell mentioned above. Fig. 9 shows the beam steering of the 8 × 8 transmitarray antenna in terms of radiation patterns at the center frequency for different azimuth (*Az*) and elevation (*El*) angles. The measured gain at the azimuth angle was 7.9 dBi and 7.4 dBi for V-to-V-pol and V-to-H-pol conversions, respectively, at the center frequency. Likewise, the measured gain at elevation angle was 7.3 dBi for V-to-V-pol and V-to-H pol conversions, respectively, at the center frequency. The beamwidths and the steerable beam angles at both azimuth and elevation angles were 19° and +/- 45°, respectively. The 8 × 8 transmitarray antenna's 2D radiation patterns for V-to-V-pol and V-to-H-pol conversions under different (*Az*, *El*) angles are shown in Fig. 10. In particular, the 8 × 8 transmitarray antenna's measured efficiency was 8.1 %, which was in good agreement with its 8.4 % theoretical efficiency. Table 1 shows the loss analysis results of the 8 × 8 transmitarray antenna, including coupling loss (spillover loss) between the horn and transmitarray antennas. Notably, most of the 8 × 8 transmitarray antenna's losses are attributable to the substrate (FR4 board). These losses can be reduced significantly using a low-loss substrate, such as a Teflon-based one.

This study on the 8 × 8 transmitarray antenna shows that this antenna has been successfully designed for multi-function performance, such as simultaneous polarization conversion and beam steering. A performance comparison between the measured performances of the proposed 8 × 8 transmitarray antenna and the literature-reported ones is summarized in Table 2. It shows that the proposed 8 × 8 transmitarray antenna has high phase resolution performance compared to other literature-reported transmitarray antennas. In addition, this antenna realizes beam steering and polarization conversion with the smallest unit cell size reported so far in the literature. The miniaturization techniques presented in this paper is scalable to other applications that sidelobes need to be suppressed or space is limited, such as small satellite communication for next-generation communications. The beam steering angle of this antenna is much larger than +/−45°, but the measurement setup has limited it. Theoretically, the proposed 8 × 8 transmitarray

TABLE 2. Performance comparison between the proposed 8 × 8 and literature-reported transmitarray antennas.

Ref.	Freq. Band	Unit Cell Size	Phase Shifting Method	Beam Steering Angle	Pol. Conv.	Array Size
[24]	C	$0.39\lambda_0 \times 0.39\lambda_0$	1-bit (Digital)	+/-15°	No	10 × 10
[25]	Ku	$0.49\lambda_0 \times 0.49\lambda_0$	1-bit (Digital)	+/-50°	No	10 × 10
[26]	Ku	$0.33\lambda_0 \times 0.33\lambda_0$	1-bit (Digital)	+/-50°	No	16 × 16
[14]	X	$0.47\lambda_0 \times 0.47\lambda_0$	1-bit (Digital)	+/-15°	Yes (LP→LP)	4 × 4
[27]	Ka	$0.5\lambda_0 \times 0.5\lambda_0$	2-bit (Digital)	+/-60°	No	14 × 14
[16]	C	$0.48\lambda_0 \times 0.48\lambda_0$	0 ~ 360° (Analog)	+/-60°	Yes (LP→LP/CP)	8 × 8
[28]	C	$0.49\lambda_0 \times 0.49\lambda_0$	1-bit + 0 ~ 180° (Hybrid)	+/-60°	No	16 × 16
This research	**S**	**$0.4\lambda_0 \times 0.4\lambda_0$**	**0 ~ 330°** (Analog)	**+/-45°**	Yes (LP→LP)	**8 × 8**

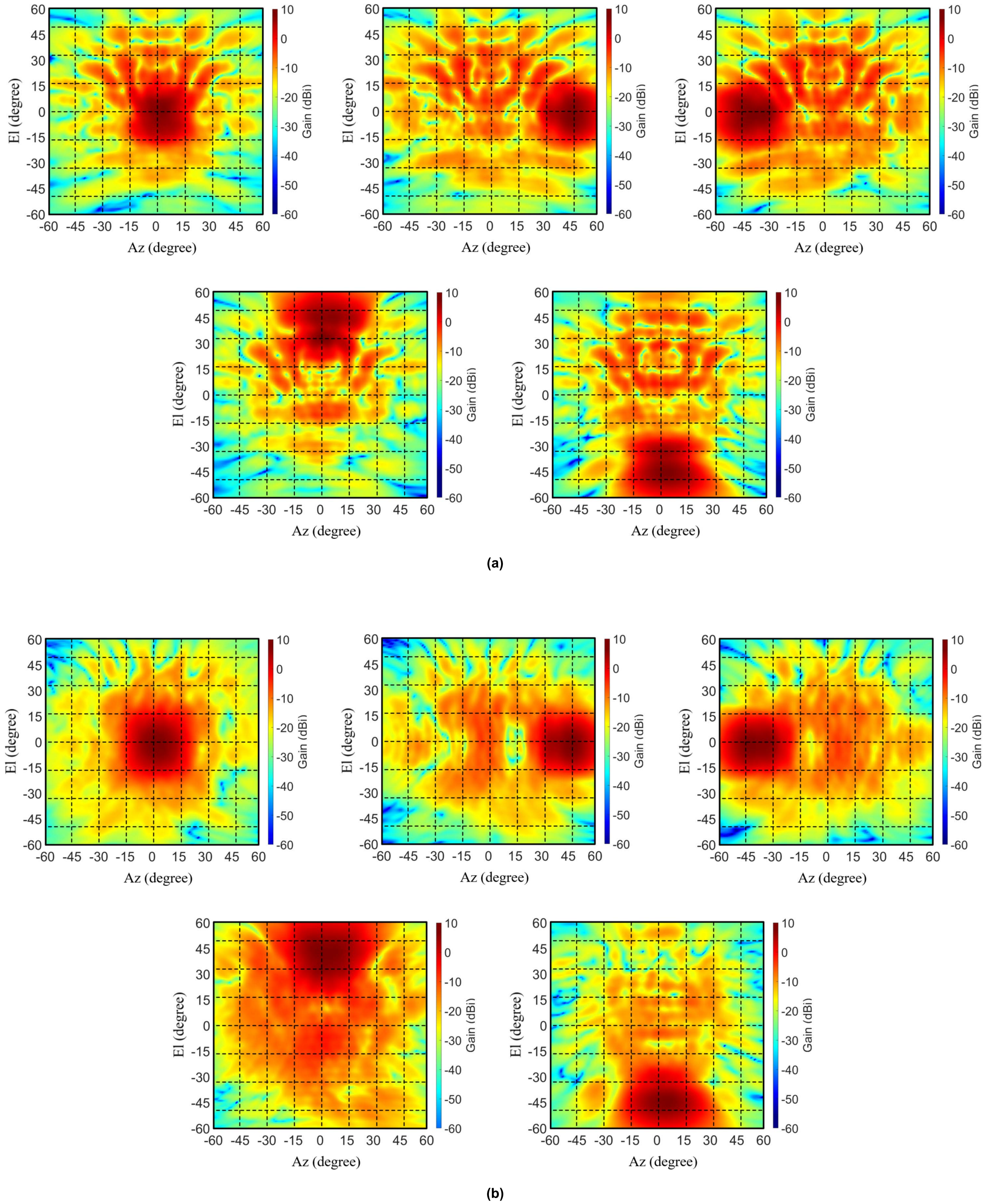


FIGURE 10. 8 × 8 transmitarray antenna's 2D radiation patterns for (a) V-to-V-pol and (b) V-to-H-pol conversions under (*Az*, *El*) = (0, 0), (+/−45, 0), (0, +/−45) angles.

antenna performs a +/−60° beam steering in a 2D (*Az*, *El*) plane.

IV. CONCLUSION

This research proposed a multi-functional transmitarray antenna using a miniaturized unit cell for S-band radar applications. The miniaturized unit cell consists of an Rx antenna, an inductively-loaded miniaturized reflection-type phase shifter, an SPDT PIN diode switch for polarization conversion, and a dual-polarization Tx antenna on its $0.4\lambda_0 \times 0.4\lambda_0$ structure. The Rx/Tx antennas are coupled-fed stacked patch antennas. The reflection-type phase shifter has a 36 % smaller area than conventional hybrid couplers, and it also has a 3-bit phase-shifting capability realized with a 0 ∼ 330° analog phase shifting. This unit cell's SPDT PIN diode switch uses +1.4 V forward and −5 V reverse bias voltages to handle a high input RF power of 23 dBm. Finally, an 8 × 8 transmitarray antenna with F/D of 0.33 made from the proposed unit cell has a gain value of 7.9 dBi and more than a 90° 2D beam steering capability for V-to-H-pol and V-to-V-pol conversions. Notably, its measured efficiency of 8.1 % is due to the high loss of the FR4 substrate, and this loss can be reduced using a low-loss substrate, such as a Teflon-based one. The proposed transmitarray is scalable design that has broad application range, such as radar, satellite, and next generation communications.

REFERENCES

[1] S. V. Hum and J. Perruisseau-Carrier, "Reconfigurable reflectarrays and array lenses for dynamic antenna beam control: A review," *IEEE Trans. Antennas Propag.*, vol. 62, no. 1, pp. 183–198, Jan. 2014.

[2] J. R. Reis, M. Vala, and R. F. S. Caldeirinha, "Review paper on transmitarray antennas," *IEEE Access*, vol. 7, pp. 94171–94188, 2019.

[3] P. Nayeri, F. Yang, and A. Z. Elsherbeni, "Beam-scanning reflectarray antennas: A technical overview and state of the art," *IEEE Antennas Propag. Mag.*, vol. 57, no. 4, pp. 32–47, Aug. 2015.

[4] A. H. Abdelrahman, F. Yang, A. Z. Elsherbeni, P. Nayeri, and C. A. Balanis, *Analysis and Design of Transmitarray Antennas*. San Rafael, CA, USA: Morgan & Claypool, 2017.

[5] J. Wang, V. Manohar, and Y. Rahmat-Samii, "Enabling the Internet of Things with CubeSats: A review of representative beamsteerable antenna concepts," *IEEE Antennas Propag. Mag.*, vol. 63, no. 6, pp. 14–28, Dec. 2021.

[6] Z. Xiao, L. Zhu, Y. Liu, P. Yi, R. Zhang, X.-G. Xia, and R. Schober, "A survey on millimeter-wave beamforming enabled UAV communications and networking," *IEEE Commun. Surveys Tuts.*, vol. 24, no. 1, pp. 557–610, 1st Quart., 2022.

[7] M. Jian, G. C. Alexandropoulos, E. Basar, C. Huang, R. Liu, Y. Liu, and C. Yuen, "Reconfigurable intelligent surfaces for wireless communications: Overview of hardware designs, channel models, and estimation techniques," *Intell. Converged Netw.*, vol. 3, no. 1, pp. 1–32, Mar. 2022.

[8] W. Pan, C. Huang, P. Chen, M. Pu, X. Ma, and X. Luo, "A beam steering horn antenna using active frequency selective surface," *IEEE Trans. Antennas Propag.*, vol. 61, no. 12, pp. 6218–6223, Dec. 2013.

[9] J. R. Reis, R. F. S. Caldeirinha, A. Hammoudeh, and N. Copner, "Electronically reconfigurable FSS-inspired transmitarray for 2-D beamsteering," *IEEE Trans. Antennas Propag.*, vol. 65, no. 9, pp. 4880–4885, Sep. 2017.

[10] A. A. Omar, H. Huang, and Z. Shen, "Absorptive frequency-selective reflection/transmission structures: A review and future perspectives," *IEEE Antennas Propag. Mag.*, vol. 62, no. 4, pp. 62–74, Aug. 2020.

[11] H. Li, C. Ma, F. Shen, K. Xu, D. Ye, J. Huangfu, C. Li, L. Ran, and T. A. Denidni, "Wide-angle beam steering based on an active conformal metasurface lens," *IEEE Access*, vol. 7, pp. 185264–185272, 2019.

[12] S. E. Hosseininejad, K. Rouhi, M. Neshat, A. Cabellos-Aparicio, S. Abadal, and E. Alarcon, "Digital metasurface based on graphene: An application to beam steering in terahertz plasmonic antennas," *IEEE Trans. Nanotechnol.*, vol. 18, pp. 734–746, 2019.

[13] A. H. Naqvi and S. Lim, "A beam-steering antenna with a fluidically programmable metasurface," *IEEE Trans. Antennas Propag.*, vol. 67, no. 6, pp. 3704–3711, Jun. 2019.

[14] B. Rana, I.-G. Lee, and I.-P. Hong, "Digitally reconfigurable transmitarray with beam-steering and polarization switching capabilities," *IEEE Access*, vol. 9, pp. 144140–144148, 2021.

[15] J. Y. Lau and S. V. Hum, "Reconfigurable transmitarray design approaches for beamforming applications," *IEEE Trans. Antennas Propag.*, vol. 60, no. 12, pp. 5679–5689, Dec. 2012.

[16] C. Huang, W. Pan, X. Ma, B. Zhao, J. Cui, and X. Luo, "Using reconfigurable transmitarray to achieve beam-steering and polarization manipulation applications," *IEEE Trans. Antennas Propag.*, vol. 63, no. 11, pp. 4801–4810, Nov. 2015.

[17] L. Di Palma, A. Clemente, L. Dussopt, R. Sauleau, P. Potier, and P. Pouliguen, "Circularly polarized transmitarray with sequential rotation in Ka-band," *IEEE Trans. Antennas Propag.*, vol. 63, no. 11, pp. 5118–5124, Nov. 2015.

[18] P. Naseri, S. A. Matos, J. R. Costa, and C. A. Fernandes, "Phase-delay versus phase-rotation cells for circular polarization transmit arrays—Application to satellite Ka-band beam steering," *IEEE Trans. Antennas Propag.*, vol. 66, no. 3, pp. 1236–1247, Mar. 2018.

[19] K.-O. Sun, S.-J. Ho, C.-C. Yen, and D. van der Weide, "A compact branch-line coupler using discontinuous microstrip lines," *IEEE Microw. Wireless Compon. Lett.*, vol. 15, no. 8, pp. 519–520, Aug. 2005.

[20] C. Balanis, *Antenna Theory, Analysis, and Design*, 4th ed. New York, NY, USA: Wiley, 2016.

[21] D. Paris, W. Leach, and E. B. Joy, "Basic theory of probe-compensated near-field measurements," *IEEE Trans. Antennas Propag.*, vol. AP-26, no. 3, pp. 373–379, May 1978.

[22] A. C. Newell, R. D. Ward, and E. J. McFarlane, "Gain and power parameter measurements using planar near-field techniques," *IEEE Trans. Antennas Propag.*, vol. AP-36, no. 6, pp. 792–803, Jun. 1988.

[23] *2.60–3.95 GHz Standard Gain Horn Antenna*, Standard LB-284-10, A-INFO. Accessed: Sep. 15, 2021. [Online]. Available: http://www.ainfoinc.com.cn/en/pro_pdf/new_products/antenna/Standard%20Gain%20Horn%20Antenna/tr_LB-284-10.pdf

[24] I. Munina, P. Turalchuk, A. Verevkin, V. Kirillov, D. Zelenchuk, and A. Shitvov, "A study of C-band 1-bit reconfigurable dual-polarized transmitarray," in *Proc. 13th Eur. Conf. Antennas Propag. (EuCAP)*, Mar. 2019, pp. 1–5.

[25] Y. Wang, S. Xu, F. Yang, and D. H. Werner, "1 bit dual-linear polarized reconfigurable transmitarray antenna using asymmetric dipole elements with parasitic bypass dipoles," *IEEE Trans. Antennas Propag.*, vol. 69, no. 2, pp. 1188–1192, Feb. 2021.

[26] M. Wang, S. Xu, F. Yang, and M. Li, "Design and measurement of a 1-bit reconfigurable transmitarray with subwavelength H-shaped coupling slot elements," *IEEE Trans. Antennas Propag.*, vol. 67, no. 5, pp. 3500–3504, May 2019.

[27] F. Diaby, A. Clemente, R. Sauleau, K. T. Pham, and L. Dussopt, "2 bit reconfigurable unit-cell and electronically steerable transmitarray at Ka-band," *IEEE Trans. Antennas Propag.*, vol. 68, no. 6, pp. 5003–5008, Jun. 2020.

[28] J. Tang, S. Xu, F. Yang, and M. Li, "Design and measurement of a reconfigurable transmitarray antenna with compact varactor-based phase shifters," *IEEE Antennas Wireless Propag. Lett.*, vol. 20, no. 10, pp. 1998–2002, Oct. 2021.

MYEONGHA HWANG received the B.S. degree from the Department of Electronics Engineering, Pusan National University, Busan, Republic of Korea, in 2020. He is currently working on a machine learning assisted RF system for wireless monitoring applications with Pusan National University.

GYOUNGDEUK KIM received the B.S. degree in electronics engineering from Pusan National University, South Korea, in 2020, where he is currently pursuing the M.S. and Ph.D. degrees. His current research interests include antenna design and RF systems.

JONGYEONG KIM received the B.S. and M.S. degrees in electrical and electronics engineering from Chung-Ang University, South Korea, in 2018 and 2020, respectively.

Since 2021, he has been a Research Engineer with Hanwha Systems, South Korea. His current research interests include metasurface antenna and phased array antenna, RF systems, and RADAR systems.

SANGKIL KIM (Senior Member, IEEE) received the B.S. degree *(magna cum laude)* from the School of Electrical and Electronics Engineering, Yonsei University, Seoul, Republic of Korea, in 2010, and the M.S. and Ph.D. degrees from the School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA, USA, in 2012 and 2014, respectively. From 2015 to 2018, he worked with Qualcomm, Inc., San Diego, CA, USA, as a Senior Engineer. He joined as a faculty with the Department of Electronics Engineering, Pusan National University, Busan, Republic of Korea, in 2018. He has published 43 articles in peer reviewed journals and five book chapters. His main research interests include mmWave phased antenna array, machine learning assisted backscattering communication, RF biosensors, energy harvesting, and printed RF electronics. He is a member of the IEEE MTT-26 RFID, Wireless Sensors, and the IoT Committee. He received the IET Premium Award *Microwave, Antennas and Propagation*, in 2015, and the KIEES Young Researcher Award, in 2019.