



Alexandria University
Alexandria Engineering Journal

www.elsevier.com/locate/aej
www.sciencedirect.com



ORIGINAL ARTICLE

mmWave self-beam-tilting antenna array with low complexity and wide coverage



Ye-Bon Kim, Junhyuk Cho, Han Lim Lee *

School of Electrical and Electronics Engineering, Chung-Ang University, Seoul 06974, South Korea

Received 7 February 2023; revised 4 May 2023; accepted 5 June 2023

KEYWORDS

Antenna array;
 Beamforming antenna;
 Compact antenna;
 High gain antenna;
 mmWave antenna;
 Switched antenna array

Abstract This paper proposes an effective planar mmWave switched beamforming antenna array with low complexity and wide beam coverage. The proposed structure is configured using multiple linearly polarized self-beam-tilting-antenna (SBTA) elements, eliminating the requirement of a phase-adjustable block for beamforming. Each SBTA element can generate different main beam directions by itself without using complicated feed networks. Moreover, unlike typical Butler matrix-based beamforming arrays, the proposed SBTA array does not require passive hybrid couplers to adjust the phases for beamforming operations. Accordingly, the proposed feed network-less antenna avoids circuit complexity, feed network insertion losses, or increases in size and fabrication costs, rendering it suitable for mmWave compact antenna applications. To verify the proposed concept and beamforming performance, a 1×4 SBTA array was fabricated at 28 GHz using a conventional printed circuit board (PCB) process. The size of the fabricated antenna (excluding test connectors) was $1.12 \lambda_0 \times 1.68 \lambda_0 \times 0.08 \lambda_0$ (λ_0 for free-space wavelength), and the measured 10-dB impedance bandwidth was approximately 5.9 %. Furthermore, the measured main beam switching directions were found at -34° , -52° , $+51^\circ$, and $+38^\circ$ with measured gains of 6.7, 6.1, 5.9, and 6.6 dBi, respectively, at 28 GHz.

© 2023 THE AUTHORS. Published by Elsevier BV on behalf of Faculty of Engineering, Alexandria University. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

1. Introduction

The integration of an antenna (or antenna array) within a package is considered an important issue due to the requirement of a converged design for both the IC and antenna as a single module. As displayed in Fig. 1 (a), typical antenna structures for mmWave handset applications are mainly based

on microstrip patch or quasi-Yagi types due to their merits of easy fabrication, light weight, low-profile, and planar structures [1–6]. To support beamforming operation, beamforming ICs (BFICs) are required to drive relative phase and amplitude balance between each antenna element in an array. Typical beamforming architectures can be configured using either phased or switched arrays, as depicted in Fig. 1 (b) and 1 (c), respectively. The typical Butler-Matrix-based beamforming antenna configuration is displayed in Fig. 1(c). When comparing both architectures, the phased array with BFICs can produce more flexible beam steering performance compared to the switched beamforming antenna (SBA), which is usually configured using a passive Butler-Matrix as a feed network [7–

* Corresponding author.

E-mail addresses: equality@cau.ac.kr (Y.-B. Kim), ny845@cau.ac.kr (J. Cho), hanlimlee@cau.ac.kr (H.L. Lee).

Peer review under responsibility of Faculty of Engineering, Alexandria University.

<https://doi.org/10.1016/j.aej.2023.06.006>

1110-0168 © 2023 THE AUTHORS. Published by Elsevier BV on behalf of Faculty of Engineering, Alexandria University. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

18]. Moreover, the losses in the SBA due to the passive feed network are very large within the mmWave range, resulting in fabrication and packaging difficulties. Furthermore, the design of the feed network to control phase and amplitude balance for switched beamforming is another challenge in mmWave applications. Although several reconfigurable feed networks with PIN diodes [19-22] or switched impedance matching circuits [23-26] have been reported, these approaches require additional circuit complexity, area occupation, or power consumption. Since power consumption is a primary concern in mobile applications, the SBA can be advantageous if base stations or cellular relays can provide strong communication channels. Therefore, a new architecture for an efficient mmWave SBA module that eliminates the requirement of an

array feed network is proposed in this article. The proposed architecture is based on a self-beam-tilting antenna (SBTA) array, where a selected antenna element can generate a tilted beam in a specific direction. The proposed SBTA array can provide switched beamforming operation with an RF switch only, resulting in a reduction of insertion losses, circuit complexity, and area occupation by the conventional feed network. Thus, the proposed SBTA can provide an optimal solution for low-cost mmWave antenna applications.

2. Design and analysis of the proposed antenna array

Fig. 2 displays the proposed SBTA architecture with two exemplary 1×4 configurations. The proposed 1×4 SBTA

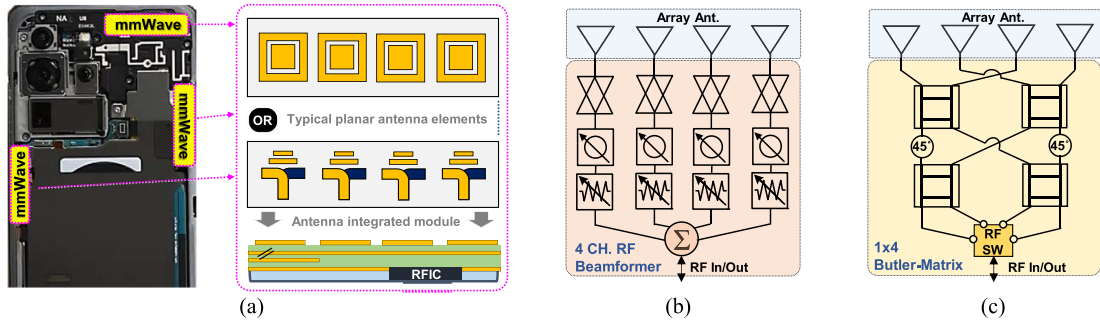


Fig. 1 Typical (a) antenna elements and beamforming configurations for (b) phase array and (c) switched array with Butler-Matrix.

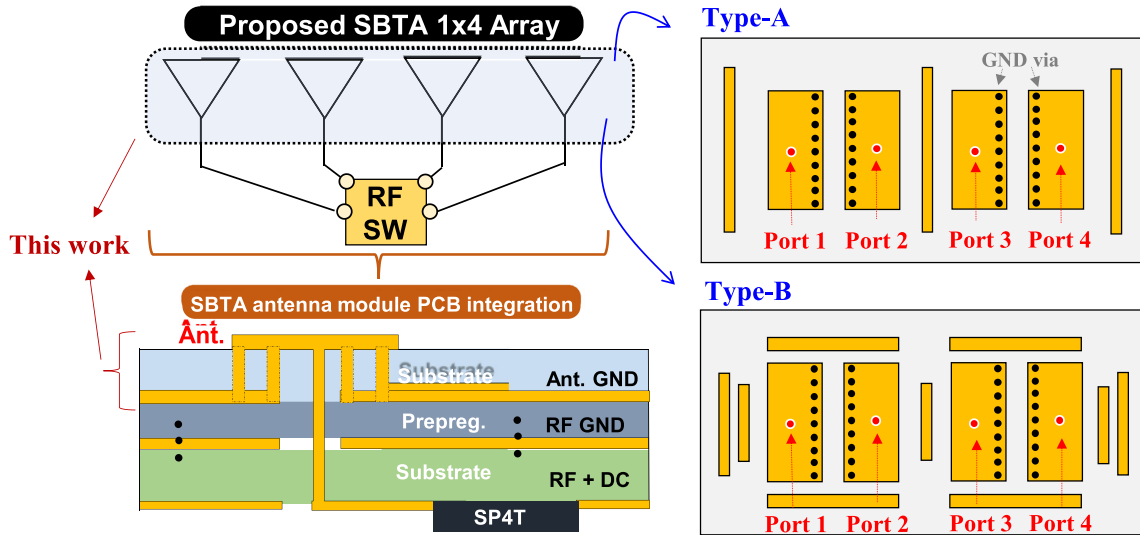


Fig. 2 Proposed mmWave SBTA array architecture with exemplary configurations (type-A and type-B).

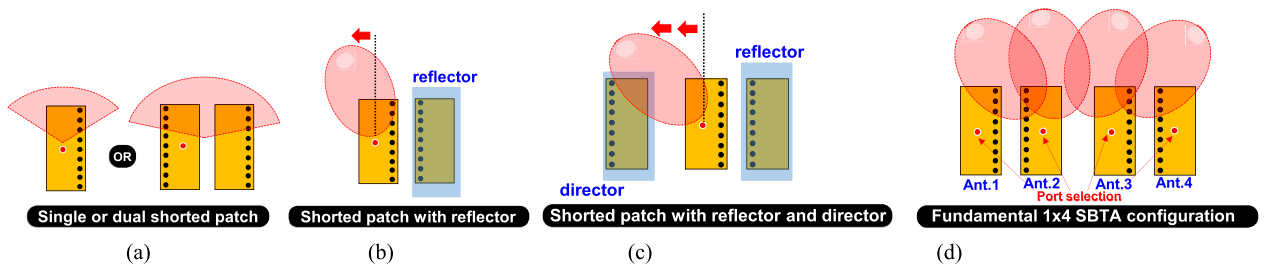


Fig. 3 Shorted patch antenna with (a) single or dual configuration, (b) another shorted patch as a reflector, (c) multiple shorted patches as a reflector and a director, and (d) fundamental SBTA configuration.

array was configured using four planar antenna elements and would be easily integrated with a single-pole-four-throw (SP4T) RF switch. The fundamental structure was fabricated on a double-sided printed circuit board (PCB) consisting of an antenna layer and a ground layer. To verify the SBTA concept and performance, two exemplary SBTA array structures (denoted as type-A and type-B) are suggested and analyzed in this article.

To understand the operating principles of the SBTA antenna, the evolution steps of shorted patch or planar magnetic dipole antenna are first presented, as displayed in Fig. 3 (a). The shorted patch is generally used to reduce the size of conventional patch antennas. Moreover, a pair of shorted patches with single port excitation has been reported for antennas with a wide beamwidth [7,27-30]. Furthermore, the dual shorted patch antenna with a back-to-back configuration can be used, as displayed in Fig. 3 (b). The shorted patch next to the antenna with an excitation port operates as a reflector, resulting in the main beam direction being tilted. To further shift the main lobe location, an additional shorted patch can be placed next to the main antenna with an excitation port, as depicted in Fig. 3 (c). The added patch operates as a director while the other patch still works as a reflector, increasing the tilted beam angle. Based on the placement of multiple shorted-patch antennas, the fundamental 1×4 configuration displayed in Fig. 3 (d) can be implemented. Here, each antenna has an excitation port and only one main radiator can be selected at a time. Then, when one antenna becomes excited, the nearby shorted patches operate either as reflectors or directors. Thus, depending on the antenna selection, four different main beam directions can potentially be generated without the help of phase shifters or Butler-Matrix-based feed networks.

To design effective tilted beam radiators, a pair of shorted patches, four-short patches, and four-short patches with additional parasitic conductors were analyzed using 3-D electromagnetic (EM) simulations. The pair of shorted patches with two excitation ports was designed at 28 GHz, as displayed in Fig. 4 (a). When the Antenna 1 is excited, the magnetic current M_2 becomes the main source of the field spreading widely in the xz -plane due to the relatively smaller field contributions of M_1 and M_2 . At the same time, since the extra magnetic wall is seen by the shorted side of Antenna 2, the boresight of the radiation field gets tilted toward the Antenna 1. Similarly, the same operation principle can be applied to the Antenna 2 due to the symmetry. Fig. 4 (b) shows that the reflection coefficients for the two adjacent shorted patches were revealed to be identical. Furthermore, to view the field distribution according to the selected antennas, surface currents were simulated, as displayed in Fig. 4 (c). When Antenna 1 was selected with port 1 excitation, Antenna 2 acted as the reflector and provided a magnetic wall. Thus, the surface current could be concentrated toward the selected antenna alone. Similarly, when Antenna 2 was selected, the radiation occurred symmetrically with a tilted beam in the opposite direction. The shifted main beam locations can be observed from the radiation patterns at 28 GHz displayed in Fig. 4 (d). The simulated main beams with linear polarization were found at -18° and $+18^\circ$ with an identical peak gain of 7.62 dBi. Referring to Fig. 4 (d), since the cross-polarization level was too low compared to the co-polarization, the simulated cross-polarization patterns are omitted.

Next, another shorted patch working as a director was added to further tilt the beam from Antenna 2 with the reflector, as depicted in Fig. 5 (a). According to variations of the

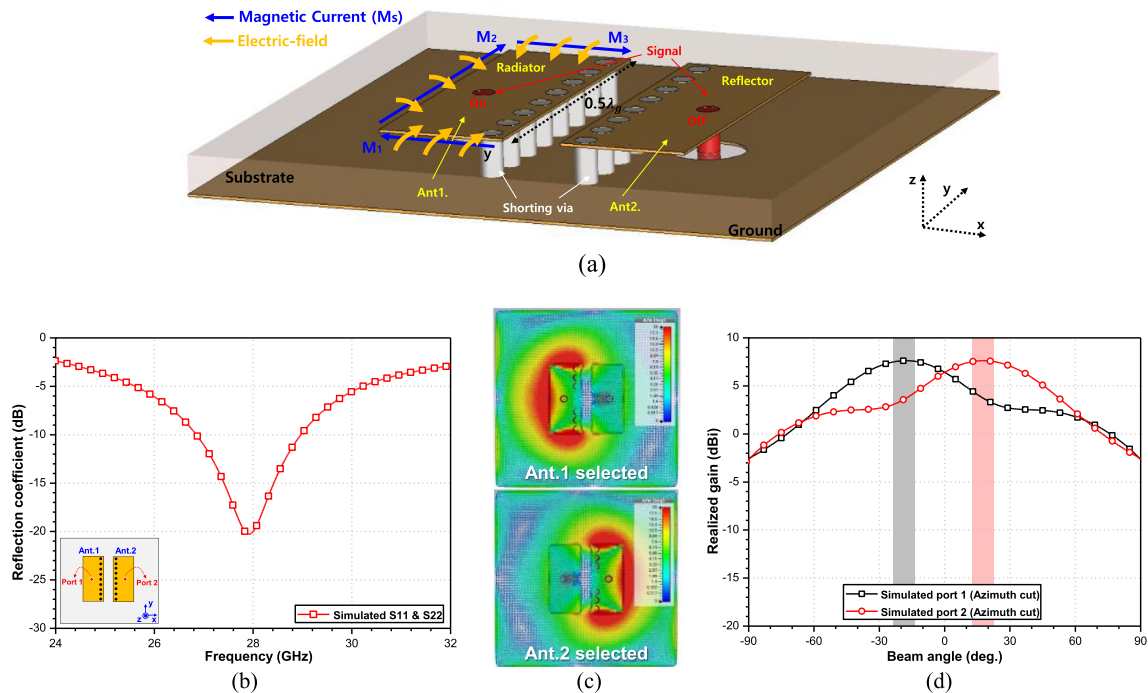


Fig. 4 Dual-short patch with (a) operation model and simulated (b) reflection coefficient, (c) surface current distribution and (d) radiation patterns at 28 GHz in xz -plane.

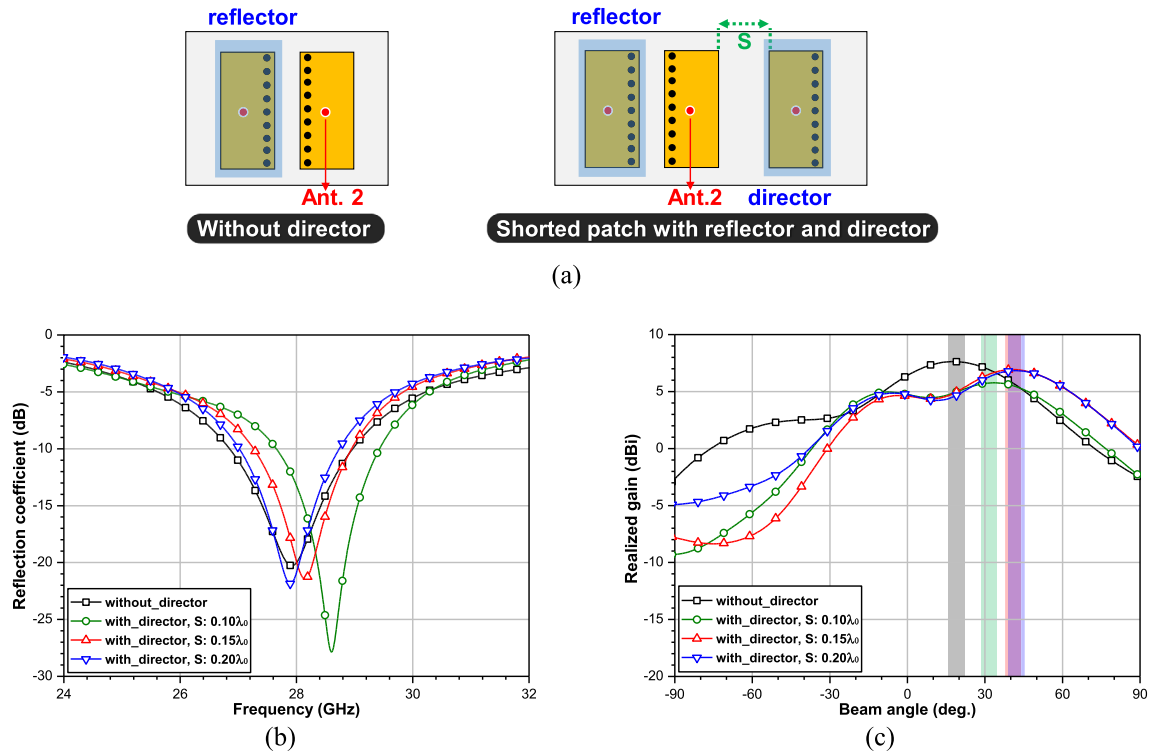


Fig. 5 Pair of shorted patches with (a) additional shorted patch as the director, and the simulated (b) reflection coefficients and (c) radiation patterns at 28 GHz according to variations in S .

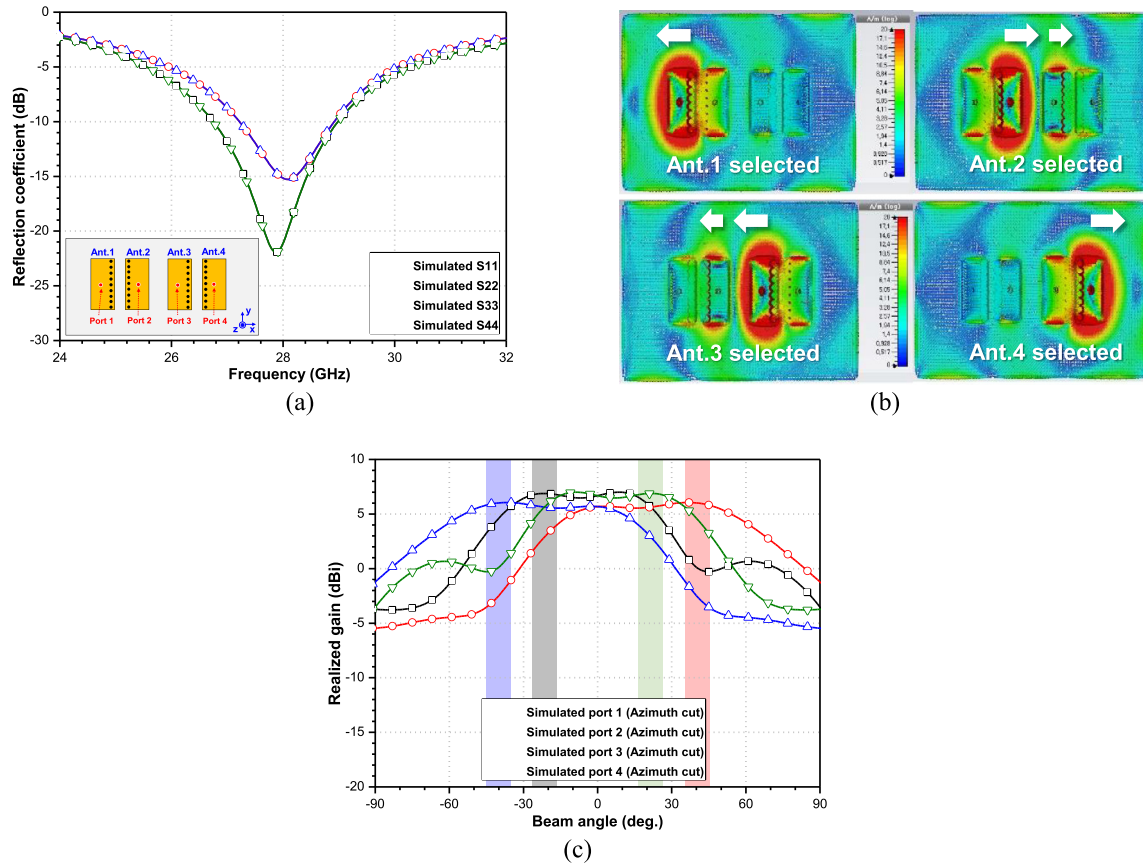


Fig. 6 Four-short patch configuration with simulated (a) reflection coefficient, (b) surface current distribution, and (c) radiation patterns at 28 GHz in xz -plane.

spacing (S) between Antenna 2 and the director, the center frequency of Antenna 2 could be shifted, as presented in Fig. 5 (b). Furthermore, the main lobe angle of Antenna 2 could be increased from 18° without the director to more than 40° with a director spacing of $0.15 \lambda_0$, as displayed in Fig. 5 (c).

To reveal the complete effects of the additional shorted patches, four-short patch antennas were designed at 28 GHz with simulated reflection coefficients, as displayed in Fig. 6 (a). Fig. 6 (b) presents the simulated surface current distribution for each antenna selection. When Antenna 1 was excited, Antenna 2 provided a magnetic wall and acted as the reflector, generating the tilted main beam. When Antenna 2 was excited, Antenna 1 behaved as the reflector, whereas Antenna 3 became the director for Antenna 2 to further concentrate the beam in a shifted boresight. Since Antennas 3 and 4 were symmetric with Antennas 1 and 2, the same oper-

ation tendency could be observed. The simulated radiation patterns for each antenna at 28 GHz are displayed in Fig. 6 (c). The peak gains for Antennas 1, 2, 3, and 4 were 7.01, 6.06, 6.06, and 7.01 dBi, respectively, while the main beam directions were located at -21° , $+37^\circ$, -37° , and $+21^\circ$, respectively. It should be noted that all the shorted patches were linearly polarized, and the cross-polarization patterns were omitted again because the cross-polarization levels were very low to warrant plotting in Fig. 6 (c).

Given the fundamental operation tendency of the multiple shorted patch configuration, two modified types of SBTAs are proposed in this article, as displayed in Fig. 7 (a). The type-A and type-B structures in 1×4 array configurations had identical total volumes (including the ground plane) of $1.12 \lambda_0 \times 1.68 \lambda_0 \times 0.08 \lambda_0$ at 28 GHz. The design parameters are summarized in Fig. 7 (a), while Fig. 7 (b) and

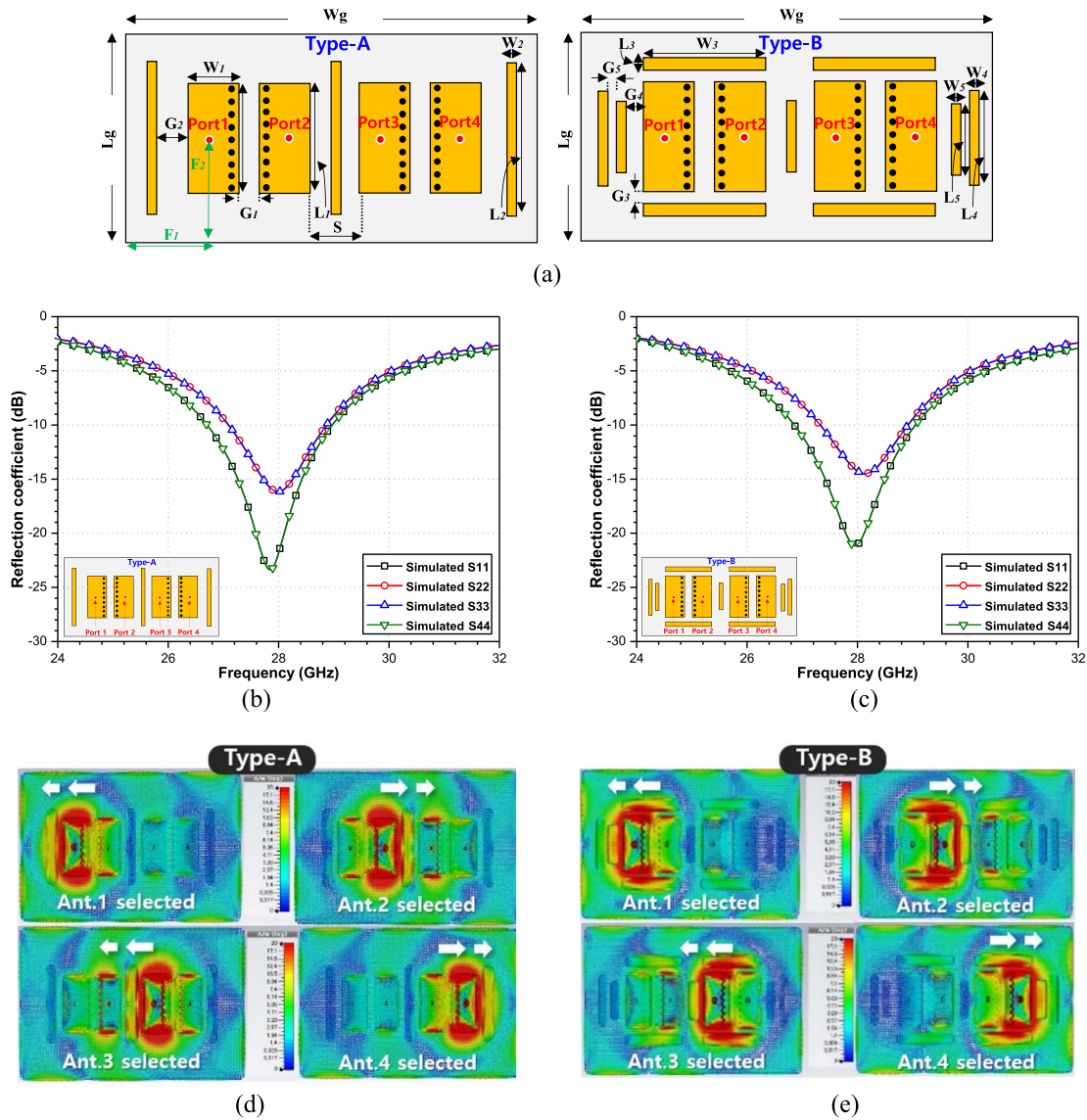


Fig. 7 Proposed type-A and type-B structures with (a) top-views and design parameters ($W_g = 18 \text{ mm}$, $L_g = 12 \text{ mm}$, $F_1 = 4.15 \text{ mm}$, $F_2 = 6 \text{ mm}$, $G_1 = 0.7 \text{ mm}$, $G_2 = 0.45 \text{ mm}$, $G_3 = 0.8 \text{ mm}$, $G_4 = 1 \text{ mm}$, $G_5 = 4.4 \text{ mm}$, $S = 1.7 \text{ mm}$, $L_1 = 4.4 \text{ mm}$, $L_2 = 6 \text{ mm}$, $L_3 = 0.6 \text{ mm}$, $L_4 = 4 \text{ mm}$, $L_5 = 3 \text{ mm}$, $W_1 = 1.8 \text{ mm}$, $W_2 = 0.4 \text{ mm}$, $W_3 = 4.6 \text{ mm}$, $W_4 = 0.4 \text{ mm}$, $W_5 = 0.4 \text{ mm}$), (b)–(c) simulated reflection coefficients, and (d)–(e) 3-D simulated surface current distributions.

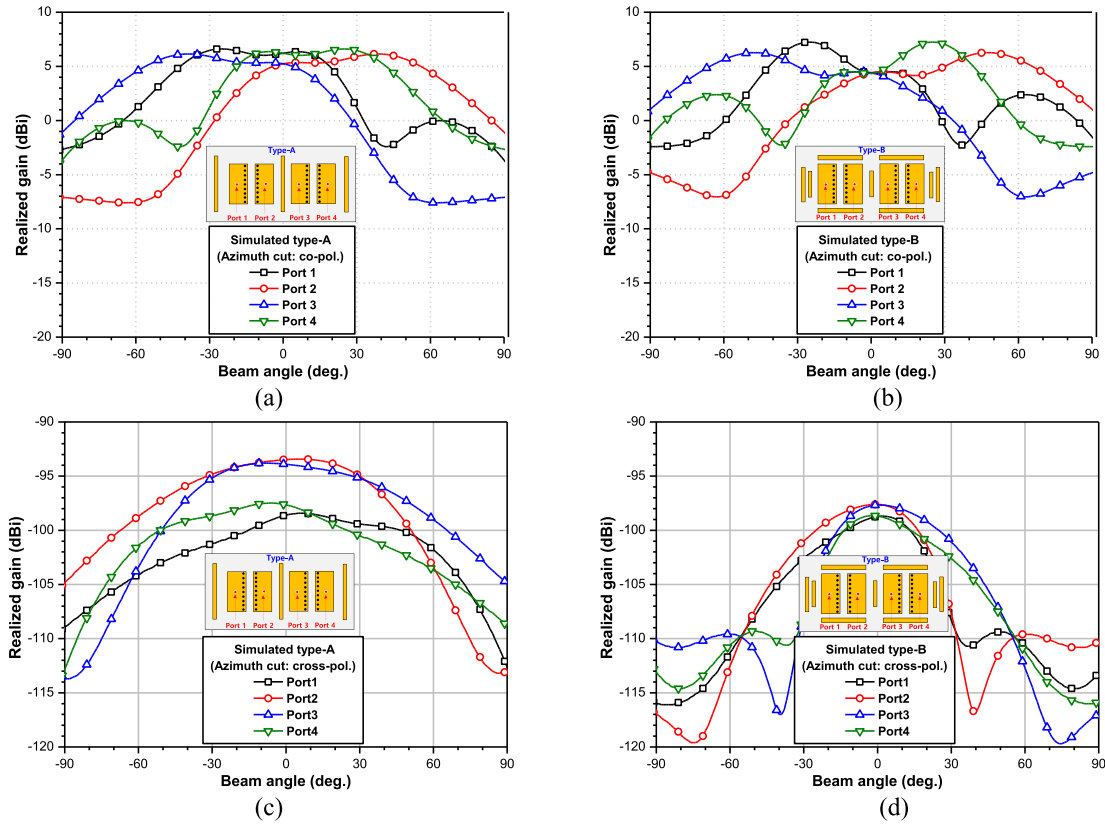


Fig. 8 Simulated radiation patterns of the proposed type-A and type-B antennas with (a)-(b) co-polarizations and (c)-(d) cross-polarizations at 28 GHz.

(c) present the simulated reflection coefficients of the type-A and type-B structures, respectively. To further shift the boresight angle of the antennas for the type-A configuration, a director was placed between the antenna elements. Then, to determine the effect of the additional director, 3-D EM simulations for the surface current distribution were conducted, as presented in Fig. 7 (d). Comparing the simulated surface current distribution for the type-A structure with a simple four-shorted patch configuration, more current was focused toward the shifted directions for all four antennas. Furthermore, the type-B configuration adopted more parasitic conductors acting as directors to guide the magnetic field strongly toward the shifted boresight. Fig. 7 (e) displays the simulated surface current distribution for the proposed type-B antenna. At a center frequency of 28 GHz, the surface current was more focused in a shifted direction.

Simulations of the radiation patterns of the type-A and type-B structures at 28 GHz are displayed in Fig. 8. The simulated peak gains for type-A Antennas 1, 2, 3, and 4 were 6.61, 6.14, 6.14, and 6.61 dBi, respectively, and the main lobes were located at -25° , $+39^\circ$, -39° and $+25^\circ$, respectively. The simulated total 3-dB beam coverage with respect to the maximum gain was approximately $\pm 68^\circ$. Furthermore, the simulated peak gains for type-B Antennas 1, 2, 3, and 4 were 7.24, 6.26, 6.26, and 7.24 dBi, respectively, with the main lobes located at -25° , $+48^\circ$, -48° and $+25^\circ$, respectively. The sim-

ulated total 3-dB beam coverage with respect to the maximum gain was approximately $\pm 78^\circ$.

The overall performances of the simulated type A and type B SBTA arrays are summarized in Table 1.

3. Fabrication and measurement

Since the type-B structure exhibited slightly better performance in terms of realized gain and beam coverage, only the proposed type-B SBTA array was verified with measurements. Fig. 9 (a) displays the fabricated SBTA array with a Taconic TLY-5 substrate having a dielectric constant of 2.2 and a thickness of 0.508 mm. The total dimensions of the fabricated antenna (including the ground plane) were $1.12 \lambda_0 \times 1.68 \lambda_0 \times 0.08 \lambda_0$ at 28 GHz. In this study, the SP4T RF switch was not integrated together to first verify the pure SBTA performances only. Thus, each antenna under test (AUT) was selected by connecting it directly with an RF cable, while the other antenna elements were terminated with 50Ω loads, as displayed in Fig. 9 (a). Fig. 9 (b) and 9 (c) display the simulated and measured reflection coefficients of each antenna element, where the measured minimum 10-dB impedance bandwidth of the pure SBTA was approximately 5.9 %. Furthermore, the radiation patterns of the proposed SBTA array were tested in a mmWave anechoic chamber, as depicted in Fig. 9 (a), and the measured results are presented in Fig. 10.

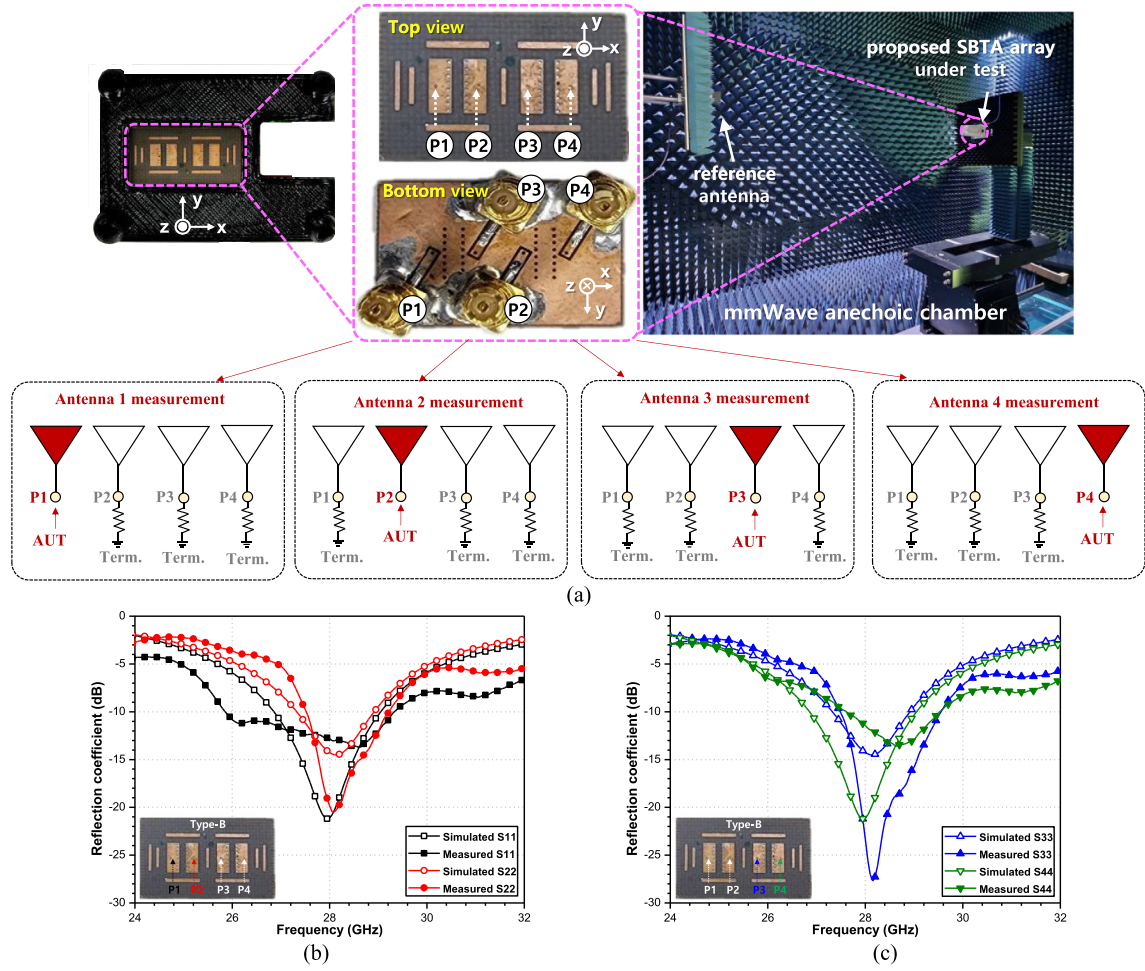


Fig. 9 Proposed SBTA array with (a) fabrication and test environment, and (b)-(c) simulated and measured reflection coefficients.

Table 1 Summary of Proposed 1×4 SBTA Arrays at 28 GHz.

Array Type	Total volume with ground plane (λ_0^3)	Radiation efficiency (%)	Total efficiency (%)	Center Freq. (GHz)	10-dB impedance bandwidth (GHz)	Main beam steering angle ($^\circ$)	Peak gain (dBi)
Type-A	$1.12 \times 1.68 \times 0.08$	97	80	28	26.8 – 29.0	–39 to + 39	6.61
Type-B	$1.12 \times 1.68 \times 0.08$	97	76	28	26.9 – 29.1	–48 to + 48	7.24

Fig. 10 displays the simulated and measured radiation patterns of the type-B SBTA array over a range of frequencies. The measured main beam locations of Antennas 1, 2, 3, and 4 at 27 GHz were -38° , $+51^\circ$, -52° , and $+32^\circ$, respectively, as depicted in Fig. 10 (a), with measured peak gains of 6.0, 5.6, 5.7, and 6.1 dBi, respectively. Furthermore, the measured half-power beamwidths (HPBW) of Antennas 1, 2, 3, and 4 were approximately -34° , $+52^\circ$, -51° and $+38^\circ$, respectively. The measured main beam locations of Antennas 1, 2, 3, and 4 at 28 GHz were -34° , $+52^\circ$, -51° , and $+38^\circ$, respectively, with measured peak gains of 6.7, 6.1, 5.9, and 6.6 dBi, respectively. Furthermore, the measured HPBW of Antennas 1, 2, 3, and 4

were approximately 29° , 42° , 53° , and 29° , respectively, while the measured main beam locations at 29 GHz were -29° , $+53^\circ$, -52° , and $+28^\circ$, respectively. The measured peak gains of Antennas 1, 2, 3, and 4 were approximately 5.9, 5.3, 5.2, and 6 dBi, respectively, while the measured HPBW were approximately 42° , 52° , 49° , and 37° , respectively.

Finally, the overall performance of the proposed type-B SBTA array was compared with other mmWave passive switched beamforming antennas, as summarized in Table 2. Unlike the previously reported antennas, the proposed SBTA array exhibited wide beam coverage without the help of a passive feed network while occupying the smallest array area.

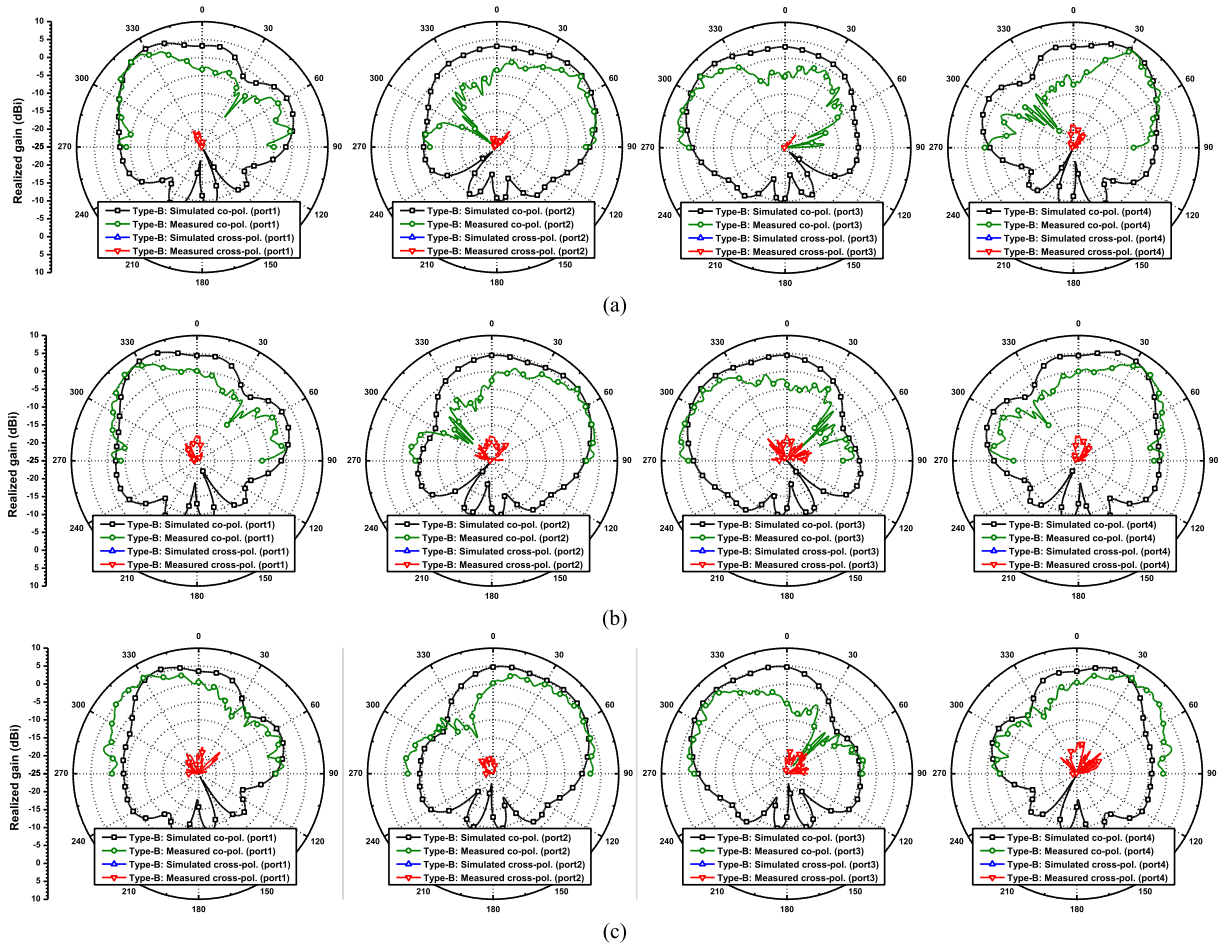


Fig. 10 Measured radiation patterns of the proposed type-B SBTA array at (a) 27 GHz, (b) 28 GHz, and (c) 29 GHz.

Table 2 Summary of The Proposed 1×4 SBTA Array Performance Comparison With State-of-the-Art mmWave Planar Passive Arrays.

Ref	Array Size	Passive beamforming feed network	Array area including ground plane (λ_0^2)	Center Freq. (GHz)	10-dB impedance bandwidth (GHz)	Main beam steering angle ($^\circ$)	Peak gain (dBi)
[13]	1×4	yes	—	35	33.2 – 37.1	–45 to + 44	12
[14]	1×4	yes	1.7×2.1	28	24.2 – 25.0	–39 to + 39	9.9
[15]	1×4	yes	5.2×5.0	30	28.3 – 33.0	–42 to + 42	11.7
[16]	1×4	yes	3.36×4.48	28	25.4 – 27.6	–43 to + 34	6.7
[17]	1×4	yes	—	28	27.0 – 28.3	–45 to + 45	4.5
[18]	1×4	yes	—	26	24.0 – 28.0	–40 to + 40	9.4
This work (type-B)	1×4	no	1.12×1.68	28	27.6 – 29.5	–52 to + 51	6.7

4. Conclusion

In this paper, a new compact SBTA structure that could produce multiple tilted beams by using only antenna elements with an RF switch was proposed. Each antenna element was termed SBTA and the 1×4 SBTA array was fabricated and verified in the 28 GHz operation band. Unlike conventional Butler-Matrix SBAs, the proposed antenna array did not require

any passive couplers or complicated feed networks for beam-forming operations. Since the feed network losses could be eliminated, the realized gain per radiator could be increased in the mmWave band. The proposed 1×4 SBTA array exhibited high gain and multiple main beam directions based on SBTA selections at 28 GHz. The measured main beams of the proposed SBTA at 28 GHz were -34° , $+52^\circ$, -51° , and $+38^\circ$ with measured peak gains of 6.7, 6.1, 5.9, and 6.6 dBi,

respectively. Furthermore, the measured HPBW's were approximately 29°, 42°, 53°, and 29°, respectively. Compared to the previously reported passive switched beamforming antennas, the proposed SBTA was very compact with wide beam coverage, while also eliminating the use of passive feed networks. Although integrating the SBTA with an RF switch will be addressed in future work, the proposed SBTA array represents an efficient candidate for various mmWave applications requiring low complexity, losses, profile, and power consumption.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

This research was supported in part by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (NRF- 2021R1A4A2001316), and in part by the Development of Civil Military Technology Project from the Institute of Civil Military Technology Cooperation (ICMTC) under Grant 21-CM-RA-02, and in part by the Institute for Information & communications Technology Planning & Evaluation (IITP) grant funded by the Korea government (MSIT) (No.2019-0-00138, Development of Intelligent Radar Platform Technology for Smart Environments).

References

- [1] M. Stanley, Y. Huang, H. Wang, H. Zhou, A. Alieldin, S. Joseph, A capacitive Coupled Patch Antenna Array With High Gain and Wide Coverage for 5G Smartphone Applications, *IEEE Access* 6 (2018) 41942–41954.
- [2] I.-J. Hwang, B. Ahn, S.-C. Chae, J.-W. Yu, W.-W. Lee, Quasi-Yagi Antenna Array With Modified Folded Dipole Driver for mmWave 5G Cellular Devices, *IEEE Antennas Wireless Propag. Lett.* 18 (5) (2019) 971–975.
- [3] C. Di Paola, S. Zhang, K. Zhao, Z. Ying, T. Bolin, G.F. Pedersen, Wideband Beam-Switchable 28 GHz Quasi-Yagi Array for Mobile Devices, *IEEE Transact. Antennas Propag.* 67 (11) (2019) 6870–6882.
- [4] Y. Luo et al, A Zero-Mode Induced mmWave Patch Antenna With Low-Profile, Wide-Bandwidth and Large-Angle Scanning for 5G Mobile Terminals, *IEEE Access* 7 (2019) 177607–177615.
- [5] M.I. Magray, S.-W. Su, J.-H. Tarng, Differential-Fed, Dual-Aperture Based, Quasi-End-Fire 5G mmWave Antenna-in-Package Design, *IEEE Access* 10 (2022) 89091–89100.
- [6] X. Xia et al, Millimeter-Wave $\pm 45^\circ$ Dual Linearly Polarized End-Fire Phased Array Antenna for 5G/B5G Mobile Terminals, *IEEE Transact. on Antennas and Propag.* 70 (11) (2022) 10391–10404.
- [7] Y.-B. Kim, S. Lim, H.L. Lee, Electrically Conformal Antenna Array With Planar Multipole Structure for 2-D Wide Angle Beam Steering, *IEEE Access* 8 (2020) 157261–157269.
- [8] J. Kim, H.L. Lee, High Gain Planar Segmented Antenna for mmWave Phased Array Applications, *IEEE Transact. Antennas Propag.* 70 (7) (2022) 5918–5922.
- [9] M. Ansari, H. Zhu, N. Shariati, Y.J. Guo, Compact Planar Beamforming Array With Endfire Radiating Elements for 5G Applications, *IEEE Transact. Antennas Propag.* 67 (11) (2019) 6859–6869.
- [10] Y.-J. Kim, Y.-B. Kim, H.-J. Dong, Y.S. Cho, H.L. Lee, Compact Switched-Beam Array Antenna with a Butler Matrix and a Folded Ground Structure, *Electronics* 9 (1) (2019) 2.
- [11] Y. Cao, K.-S. Chin, W. Che, W. Yang, E.S. Li, A Compact 38 GHz Multibeam Antenna Array With Multifolded Butler Matrix for 5G Applications, *IEEE Antennas Wireless Propag. Lett.* 16 (2017) 2996–2999.
- [12] H.-J. Dong, Y.-B. Kim, H.L. Lee, Reconfigurable Quad-Polarization Switched Beamforming Antenna With Crossed Inverted-V Array and Dual-Butler Matrix, *IEEE Transact. Antennas Propag.* 70 (4) (2022) 2708–2716.
- [13] Z. Mousavi, P. Rezaei, Millimetre-wave beam-steering array antenna by emphasizing on improvement of Butler matrix features, *IET Microw. Antennas Propag.* 13 (9) (2019) 1287–1292.
- [14] S. Kim, S. Yoon, Y. Lee, H. Shin, A Miniaturized butler matrix based switched beamforming antenna system in a two-layer hybrid stackup substrate for 5G applications, *Electronics* 8 (11) (2019) 1232.
- [15] A. Ashraf, A.-R. Sebak, A.A. Kishk, PMC Packaged Single-Substrate 4×4 Butler Matrix and Double-Ridge Gap Waveguide Horn Antenna Array for Multibeam Applications, *IEEE Transact. Microw. Theory Techniques* 69 (1) (Jan. 2021) 248–261.
- [16] S. Lee, Y. Lee, H. Shin, A 28-GHz Switched-Beam Antenna with Integrated Butler Matrix and Switch for 5G Applications, *Sensors* 21 (15) (2021) 5128.
- [17] X. Li et al, Leaky-Wave Antenna Array With Bilateral Beamforming Radiation Pattern and Capability of Flexible Beam Switching, *IEEE Transact. Antennas Propag.* 70 (2) (2022) 1535–1540.
- [18] W. Kong, Y. Hu, J. Li, L. Zhang, W. Hong, 2-D Orthogonal Multibeam Antenna Arrays for 5G Millimeter-Wave Applications, *IEEE Transact. Microwave Theory Techniques* 70 (5) (2022) 2815–2824.
- [19] Y.-Y. Lin, C.-L. Liao, T.-H. Hsieh, W.-J. Liao, A Novel Beam-Switching Array Antenna Using Series-Fed Slots With PIN Diodes, *IEEE Antennas Wireless Propag. Lett.* 16 (2017) 1393–1396.
- [20] G. Jin, M. Li, D. Liu, G. Zeng, A Simple Planar Pattern-Reconfigurable Antenna Based on Arc Dipoles, *IEEE Antennas Wireless Propag. Lett.* 17 (9) (2018) 1664–1668.
- [21] Y. Yashchyshyn et al, 28 GHz Switched-Beam Antenna Based on S-PIN Diodes for 5G Mobile Communications, *IEEE Antennas Wireless Propag. Lett.* 17 (2) (2018) 225–228.
- [22] Z. Wang, S. Liu, Y. Dong, A Compact, Broadband, Monopole-Like Endfire Antenna With Reconfigurable Patterns for 5G Applications, *IEEE Transact. Antennas Propag.* 70 (8) (2022) 7199–7204.
- [23] H.-S. Tae, K.-S. Oh, H.-L. Lee, W.-I. Son, J.-W. Yu, Reconfigurable 1×4 Power Divider With Switched Impedance Matching Circuits, *IEEE Microw. Wireless Compon. Lett.* 22 (2) (2012) 64–66.
- [24] H.L. Lee, D.-H. Park, M.-Q. Lee, J.-W. Yu, Reconfigurable 2×2 Multi-Port Amplifier Using Switching Mode Hybrid Matrices, *IEEE Microw. Wireless Compon. Lett.* 24 (2) (2014) 129–131.
- [25] Han Lim Lee, Moon-Que Lee, Jong-Won Yu, Reconfigurable 4×4 multi-port amplifier with switchable input and output matrices, *IET Microw. Antennas Propag.* 10 (12) (2016) 1312–1321.
- [26] K.-S. Kim, J.-S. Yoo, J.-W. Kim, S. Kim, J.-W. Yu, H.L. Lee, All-Around Beam Switched Antenna With Dual Polarization for Drone Communications, *IEEE Transact. Antennas Propag.* 68 (6) (2020) 4930–4934.
- [27] C.-M. Liu, S.-Q. Xiao, H.-L. Tu, Z. Ding, Wide-Angle Scanning Low Profile Phased Array Antenna Based on a Novel Magnetic Dipole, *IEEE Transact. Antennas Propag.* 65 (3) (2017) 1151–1162.

- [28] C.-M. Liu, S. Xiao, X.-L. Zhang, A. Compact, Low-Profile Wire Antenna Applied to Wide-Angle Scanning Phased Array, *IEEE Antennas Wireless Propag. Lett.* 17 (3) (2018) 389–392.
- [29] J.-S. Yoo, S.-T. Khang, T.-D. Yeo, J.-W. Yu, Compact Meander Magnetic Dipole Antenna for Wide-Angle Scanning, 2018 IEEE Int. Symp. on Antennas and Propag. & USNC/URSI Nat. Radio Science Meeting, Boston, MA, USA, (2018), 1611–1612.
- [30] Y.-B. Kim, H.-J. Dong, K.-S. Kim, H.L. Lee, Compact Planar Multipole Antenna for Scalable Wide Beamwidth and Bandwidth Characteristics, *IEEE Transact. on Antennas and Propag.*, 68,5 (2020) 3433–3442.