IEEE Access
Multidisciplinary ⁝ Rapid Review ⁝ Open Access Journal

Received May 15, 2020, accepted June 14, 2020, date of publication June 25, 2020, date of current version July 7, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.3004867

End-Fire Vivaldi Antenna Array With Wide Fan-Beam for 5G Mobile Handsets

WON-WOO LEE[1], **IN-JUNE HWANG**[2], **AND BEAKCHEOL JANG**[3], **(Member, IEEE)**
[1]ICT Convergence Research Division, Korea Expressway Corporation Research Institute, Hwaseong 18489, South Korea
[2]Group for Electromagnetic Wave Metrology, Korea Research Institute of Standards and Science, Daejeon 34141, South Korea
[3]Department of Computer Science, Sangmyung University, Seoul 13557, South Korea

Corresponding author: Beakcheol Jang (bjang@smu.ac.kr)

ABSTRACT In this paper, we present a portable end-fire antenna array design for the fifth-generation (5G) mobile handsets that exploits a Vivaldi antenna and shows a wide fan-beam on the elevation plane. We make the proposed antenna array more efficient by printing on a 10-layer printed circuit board (PCB) lamination in a vertical direction of the ground plane edge. Using the proposed Vivaldi antenna array design, the radiation characteristics of 4 × 1 linear arrays are fabricated. To validate the feasibility, we perform simulations and experiments. Simulation results show that the total efficiencies of the antenna array are higher than about 8.16 – 9.46 dBi for the scanning range between 0° to 60°. Measurement results display that the antenna has S11 reply less than −10 dB in the frequency area of 27.5 to 28.5 GHz and wide beamwidth (130.8° in elevation plan, 21.35° in azimuth plan). There is a high accord between the calculated and measured results and we consider that the results in this study can be well achieved by designers who design the wide beamwidth high-speed antennas of 5G mobile terminals.

INDEX TERMS Wide fan-beam, end-fire antenna array, mmWave, 5G.

I. INTRODUCTION

5G cellular systems should use high-frequency spectrums to support wide bandwidth and high data rates [1]–[5]. Millimeter-wave (mmWave) spectrum from 30 to 300 GHz is recognized as the key solution that supports multi-gigabit per second (Gbps) Communication speed over wireless links and solves the data explosion of 5G system. Experts have been exploring the prospect of the 28, 38, and 73 GHz mmWave frequency bands of 5G communication. MmWave has the characteristics of stronger directivity and higher path loss than conventional cellular frequency waves (below 6 GHz), so it is very challenging to apply mmWave to cellular mobile communications. Recent study activities have allowed reinterpretation of mmWave as a practicable candidate for mobile communications [6]. 5 G is one of the most prominent technologies that utilize the high data rate attained via broad-spectrum bandwidths of the additional spectrum [7].

The far-field radiation direction of an antenna is categorized into the broadside radiation and the end-fire radiation. Because the broadside radiation deteriorates by various obstructive factors such as the hand effect [8], both the broadside radiation and the end-fire radiation are required to widen the radiation coverage of mobile terminals.

The mmWave antenna with many modules for different functions, such as display, data communications, and cameras, should be tightly configured within the narrow PCB space within the mobile unit. Therefore, the minimization of the antenna dimension including via-based antipodal antenna using a multi-layer PCB structure [9].

The lesser antennas can be used on the top or bottom portion of the mobile handset PCB to shape phased array antennas with end-fire radiation pattern [10]–[12]. Reference [10] presents a novel antenna design at 28 GHz to actualize vertical and horizontal polarizations using ultra-thin PCB substrates. This paper aims to enhance the mmWave transmission and reception efficiency by handling severe losses due to polarization mismatch. However many vias are required to produce this antenna, and the performance of via is irregular in mass production.

Reference [11] is based on the wideband printed antenna of dipole type and modified to be matched for mmWave band applications. A phased array that contains eight-antenna elements is designed for high gain performance. However, the space between antennas is too large (7.5mm) to apply it to the small space of mobile phones.

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

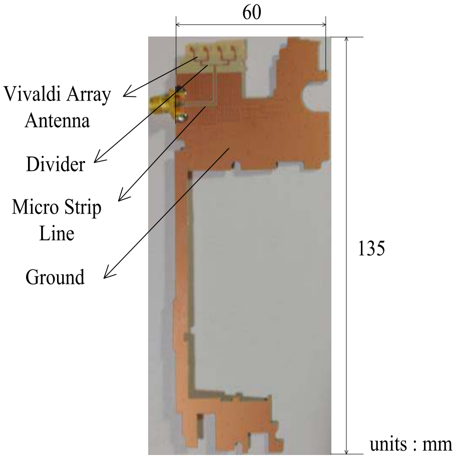


FIGURE 1. Photography of fabricated array antenna system.

Reference [12] demonstrates a new and 28 GHz beam scanning quasi-Yagi array method of very thin 32-element with a well-optimized single element, which has performance that is broad bandwidth of 12.8% (3.6 GHz) and sufficient radiation pattern appropriate for future 5G mobile handset. However, the number of antenna elements is too many.

References [13], [14] show a high-efficiency microstrip-fed Yagi-Uda antenna for millimeter-wave applications. However, the frequency bandwidth is narrow (3-4GHz) and antenna size is large (12.1-24.6mm).

References [15], [17] discusses the research with realizing largescale antenna arrays at mmWave frequency bands for future 5G cellular devices. But this studies had drawbacks in realization of the real device form factors due to the large size(length and width) and difficult manufacturing structure.

In this paper, we present an array antenna design with a wide beamwidth for 5G mobile handset using Vivaldi antennas [18]. Vivaldi antennas are inherently resistant to circuit manufacturing tolerances because they have broadband characteristics and easy impedance matching characteristics. Therefore, in the manufacturing process, the implementation is not more complicated than the dipole antenna or Yagi antenna. That is, the Vivaldi antenna is very useful for the tolerance of RF performance for mass production such as a smartphone. Through simulation and measurement results, the proposed antenna is determined to be applicable for 5G mobile terminals. We perform simulations using computer simulation technology (CST) (Microwave Studio 2016) [19]. The simulation results show that this antipodal Vivaldi antenna satisfies common requirements for 5G mobile handset applications.

II. ANTENNA STRUCTURE

Fig. 1 shows the fabricated antenna array on a form factor accurate PCB of which outline shape is exactly the same as one of a commercial smartphone in the market. The dimensions of the PCB are 60 × 135 × 0.79 mm^3. ISOLA, IS300MD substrate with permittivity of 3.1 is used. The Isola substrate is often used in the printed circuit board for mmWave application because of its low loss performance at very high-frequency bands. PCB represents 60 μm substrate thickness and 20 μm copper thickness with a tangent loss of 0.003 [20].

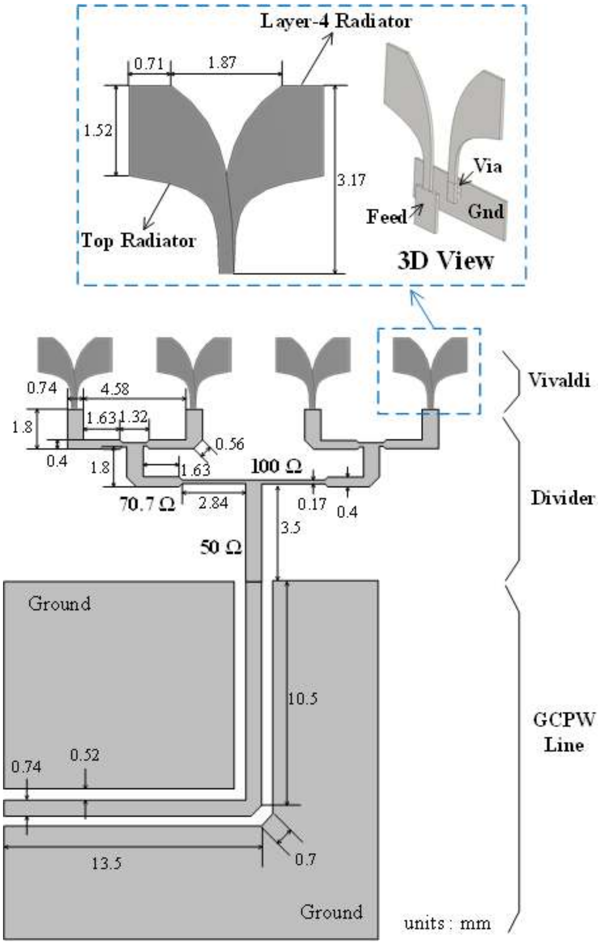


FIGURE 2. Structure of the proposed antenna and divider of integrated feeding network.

Fig. 2 shows the unit element of the Vivaldi antenna and 4 × 1 array antennas. The antenna array is generally composed of 2^N antenna elements. This is because 2^N-way is advantageous structure for designing a power divider that minimizes losses and makes impedance matching easy. When constructing an array antenna, the spacing between the antennas is usually half wavelength, and the half wavelength in the 28 GHz band is approximately 5 mm. Unlike a base station, the mobile handset has a small form factor, so the size of the antenna array that can be inserted is limited. Considering this background, the number of elements in the antenna array that can be inserted into the mobile terminal is realistically 2, 4, and 8.

The size of the array is determined based on the size of the unit Vivaldi is 3.29 × 3.17 mm^2 and a feeding network. The configuration of the studied Vivaldi antenna is comprised of two tapered arms that lie on the opposite side of the substrate as shown in the top side of Fig. 2.

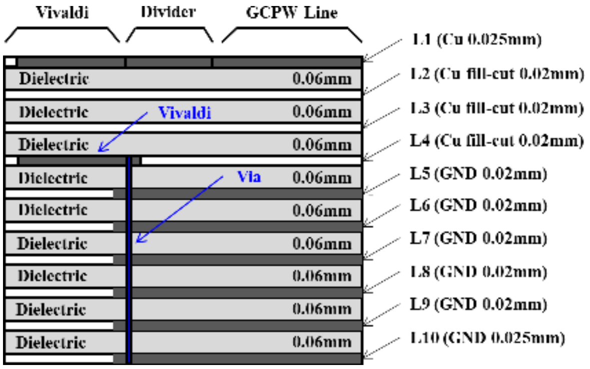


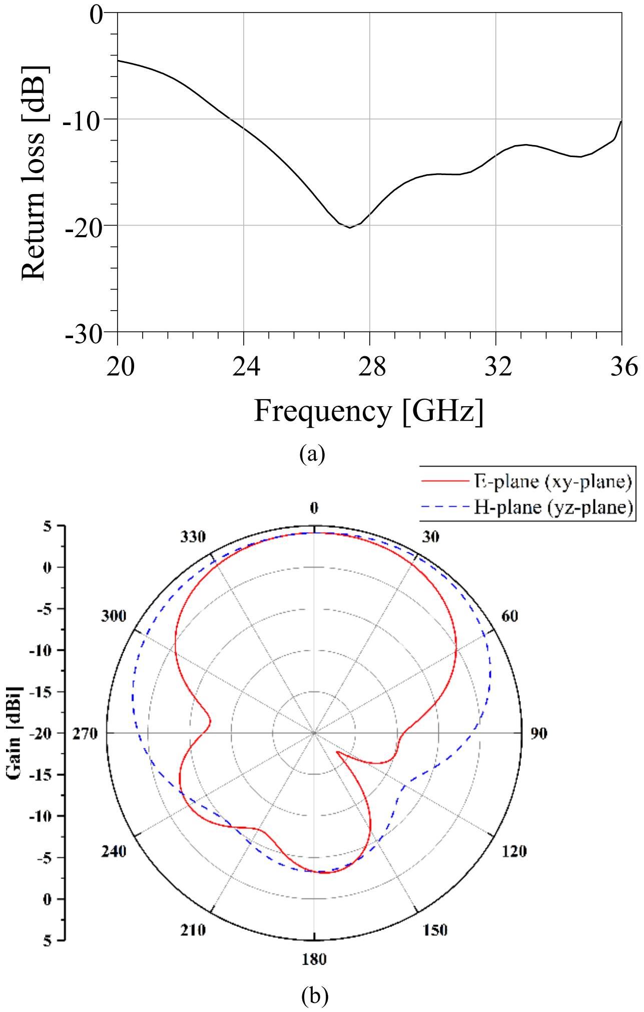
FIGURE 3. Structure of the proposed antenna for cross-sectional view of the proposed antenna array.

The feed network is implemented by choosing a symmetric three stage T-junction power divider as shown in Fig. 2. The input signal is spread between 4 linear antenna subarrays by using a power divider network of two-stage T-junction, each subarray covers 4 parallel Vivaldi with tapering width. The communal feed is designed in a method that it supplements signals which are of equal magnitude and phase to each antenna to generate a radiation pattern. The input impedance of the antenna is designed to 50 Ω and, since the power distribution is done in parallel, the transmission line characteristic impedance is 100 ohm. A quarter-wavelength impedance changer with 70.7 Ω impedance is used to change back to 50 Ω [21].

If an antenna array is added to an actual mobile device, it will be used in combination with a beamforming IC. In the case of such an active type array, reflected waves generated due to mismatch in an active device including an amplifier located on a path may be coupled to other antennas or devices and have a great influence. However, in the passive type array, which is the implemented case of this paper, the isolation performance is not very important because there is no significant difference in performance between the T-junction power divider and the Wilkinson power divider which emphasize isolation performance. In addition, Most beamforming ICs have 4 channels, so the array configuration using 4 antennas is the most realistic. Therefore, the passive type array presented in this paper is an example for analyzing and verifying performance when constructing an array with the proposed antenna.

The lamination of PCB can be split into the Vivaldi, the divider, the antenna layer and the stripling layer as depicted in Fig. 3. The Vivaldi antenna is comprised of an antenna and shorting bias that is constructed using the standard stacked-via technology. Also, the combined physical size of the antenna and shorting vias are improved to be nearly 1/4 of guided wavelength to generate resonance and impedance matching at 28 GHz.

Regarding future needs for RFIC integration, 10 layers of dielectric substrates are utilized as a next step. The maximum heights of the substratum are 300 μm, as three layers are filled. The antenna structure consists of just two metal plates.



(a)

(b)

FIGURE 4. Simulated characteristics for the proposed single vivaldi antenna, (a) return loss, (b) 2D radiation pattern.

III. SIMULATION

Fig. 4 illustrates the simulation return loss and 3D radiation patterns of the single antenna at 28 GHz. Return loss, S11(dB), the frequency bandwidth is high, and it also realized a well-matched impedance, as shown in Fig. 4. As illustrated, the antenna has more than 8 GHz bandwidth.

The simulated 2D radiation patterns show a good end-fire radiation activity in the middle of the functional band, with adequate gain levels.

The 4-element 4×1 mm-wave phased array antenna design is simulated to confirm beam-angle scanning property and its performance at end-fire beamforming is shown in Fig. 5. The end-fire beam forming demonstrates 9.46 dBi peak realized array gain for 0° and 8.16 dBi peak gain 60°. The simulated antennas have a performance of wide beam angle range attribute with the same performances for (+/−) angles which can be effective to cover the wanted beam angle range of 5G communications.

Fig. 6 shows the simulation return loss for Fig. 2 (a). As can be seen from Fig. 6, S11 is −28 dB at the frequency of

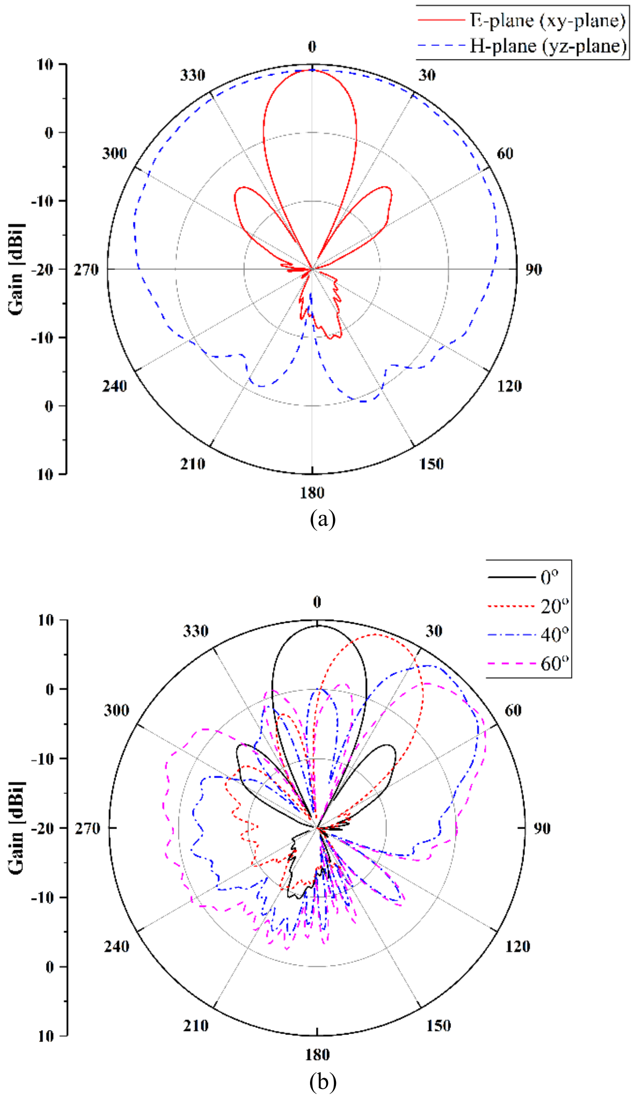


FIGURE 5. Simulated radiation pattern of the array antennas at different scanning angles, (a) 2D radiation pattern (0°), (b) 2D radiation pattern (0°, 20°, 40°, 60°).

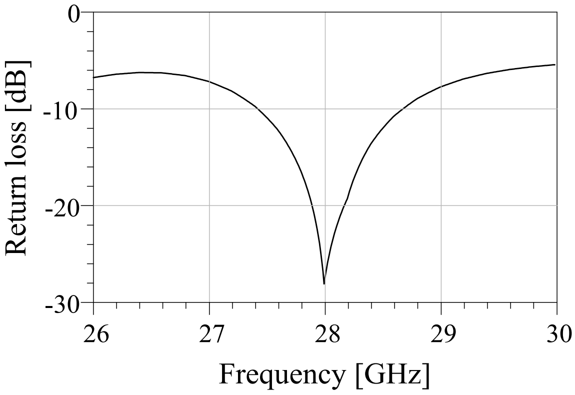


FIGURE 6. The simulated reflection coefficient of proposed an array antennas.

28 GHz. And it is better than −10 dB in the frequency range between 27.4 and 28.7 GHz.

Fig. 7 (a) explain the simulated 3D radiation patterns of the antenna array with power divider at 28 GHz. The simulation results have displayed a gain of 8.34 dBi, sidelobe level less than −8.1 dB, and a 3 dB beam-width of 165° in the elevation plane and 25° in the azimuth plane. The pattern's direction of main lobe is not tilted off broadside by 0°. Fig. 7 (b) express the 2-D polar radiation pattern in the elevation plane and the azimuth plane.

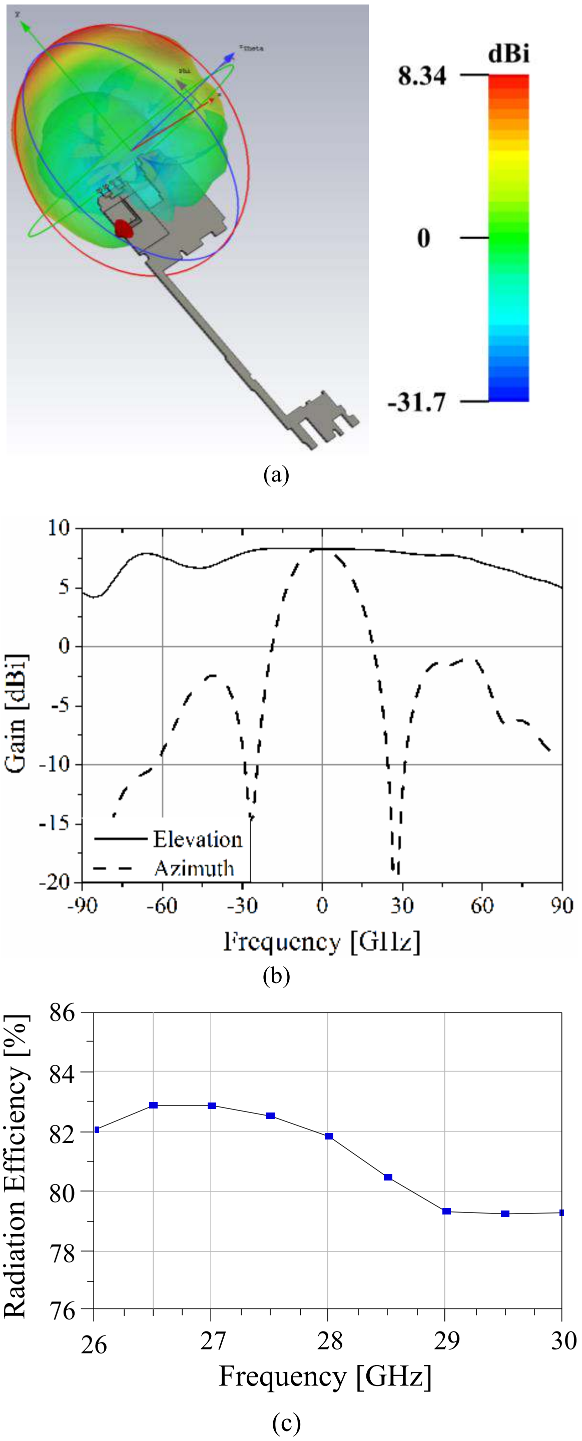


FIGURE 7. Simulated radiation pattern of an antenna array, (a) 3D far field radiation, (b) 2-D the polar graph, (c) Simulated radiation efficiency of the fabricated array.

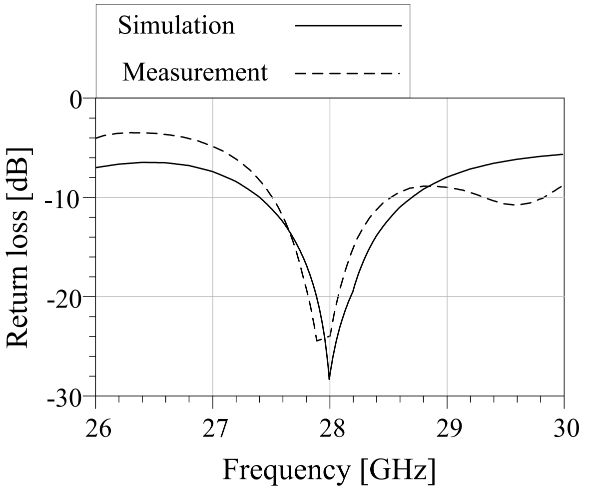


FIGURE 8. Measured return loss characteristics for the proposed antenna.

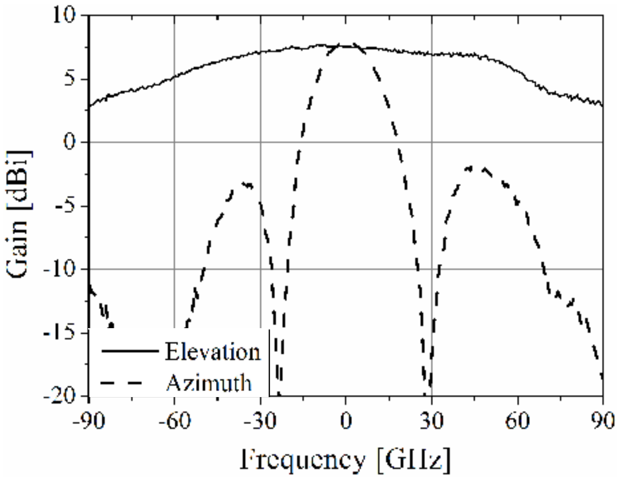


FIGURE 9. Measured radiation pattern for the proposed antenna.

The simulated radiation efficiency of the fabricated array is as shown in Fig. 7 (c) below. The simulated radiation efficiency of the array is higher than 79.2 % within the range of 26-30 GHz. It shows an average radiation efficiency of about 80% in the 28 GHz band, showing that the antenna structure radiates efficiently in the band.

IV. ANTENNA PERFORMANCE

Fig. 8 shows the simulated and measured result for reflection coefficients (|S11|) of the array excited at ports. The measurement result shows that the antenna array with its feeding network provides efficient performance with $|S11| < -10$dB across an impedance bandwidth of 27.5 to 28.5 GHz.

Fig. 9 shows the measured elevation plane and azimuth plane at 28GHz. It is experiential that the antenna array displays a well-matched wide beamwidth in elevation plane. The measured result for peak gain at 28GHz is 8.01dBi and a 3 dB beamwidth of 130.8° in the elevation plane and 21.3° in the azimuth plane, and it is smaller than the simulation results, i.e.8.3dBi, which caused by the the non-uniform of the substrate for the manufacturing processes or the extra loss of the attachments of the antenna. The measured radiation patterns show a good agreement with the simulated results.

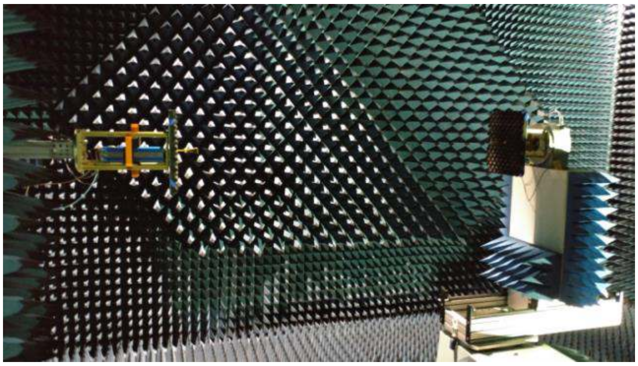


FIGURE 10. mmWave antenna measurement system.

The antenna array is fed through the end-launch type SMA connector and the microstrip line in Fig. 1(a), and the feed signal is distributed to each antenna through a 4-way T-junction power divider.

About the measurement experiment environment, the return losses of single antenna and array antenna were measured by using Agilent E8364B vector network analyzer capable of operation over the range of 10 MHz to 50 GHz. Antenna radiation patterns were measured in an anechoic chamber as shown in Fig. 10 at the Electromagnetic Wave Technology Institute, Seoul, South Korea. The size of the anechoic chamber is 6 ×9 × 4.8 m^3, and its measurement frequency range is from 2.0 GHz to 110 GHz covering the mmWave bands. The measurement system consists of ORBIT/FR [22] equipment. Through radiation pattern measurement, data such as beam peak gain, main beam direction, beamwidth, sidelobes, null, and polarization can be obtained.

V. CONCLUSION

In this paper, we present a linear array Vivaldi antenna with conformal for 5G mobile handsets. The proposed antenna performs a good wide beam width in elevation plane with a measured gain of 8.01dB at 28GHz. It occupies the only corner of the circuit board; therefore, it is more space-effective than the existing mmWave linear array antenna systems.

Simulation and experiment results show well that our proposed array-antenna has good performance for directivity, radiation, and total efficiency properties at wanted scanning angles and supports the wanted beam coverage of the 5G communications.

REFERENCES

[1] T. S. Rappaport, S. Sun, R. Mayzus, H. Zhao, Y. Azar, K. Wang, G. N. Wong, J. K. Schulz, M. Samimi, and F. Gutierrez, "Millimeter wave mobile communications for 5G cellular: It will work!" *IEEE Access*, vol. 1, pp. 335–349, 2013.

[2] S. Rajagopal, S. Abu-Surra, Z. Pi, and F. Khan, "Antenna array design for multi-gbps mmWave mobile broadband communication," in *Proc. IEEE Global Telecommun. Conf. (GLOBECOM)*, Dec. 2011, pp. 1–6.

[3] N. Ojaroudiparchin, M. Shen, and G. F. Pedersen, "Investigation on the performance of low-profile insensitive antenna with improved radiation characteristics for the future 5G applications," *Microw. Opt. Technol. Lett.*, vol. 58, no. 9, pp. 2148–2151, 2016.

[4] S. Rangan, T. S. Rappaport, and E. Erkip, "Millimeter-wave cellular wireless networks: Potentials and challenges," *Proc. IEEE*, vol. 102, no. 3, pp. 366–385, Mar. 2014.

[5] H. Kim, B.-S. Park, S.-S. Song, T.-S. Moon, S.-H. Kim, J.-M. Kim, J.-Y. Chang, and Y.-C. Ho, "A 28-GHz CMOS direct conversion transceiver with packaged 2×4 antenna array for 5G cellular system," *IEEE J. Solid-State Circuits*, vol. 53, no. 5, pp. 1245–1259, May 2018.

[6] J. Lee, Y. Song, E. Choi, and J. Park, "mmWave cellular mobile communication for Giga Korea 5G project," in *Proc. 21st Asia–Pacific Conf. Commun. (APCC)*, Oct. 2015, pp. 179–183.

[7] GSM Association. (Dec. 2014). *Understanding 5G: Perspectives on future technological advancements in Mobile*. White Paper, Accessed: Jun. 2015. [Online]. Available: https://gsmaintelligence.com/research/?file=141208-5g.pdf

[8] Z. Ying, K. Zhao, T. Bolin, J. Helander, D. Sjoberg, S. He, A. Scannavini, L. J. Foged, and G. Nicolas, "Study of phased array in UE for 5G mm wave communication system with consideration of user body effect," in *Proc. 10th Eur. Conf. Antennas Propag. (EuCAP)*, Apr. 2016, pp. 1–2.

[9] I.-J. Hwang, B. Ahn, S.-C. Chae, J.-W. Yu, and W.-W. Lee, "Quasi-yagi antenna array with modified folded dipole driver for mmWave 5G cellular devices," *IEEE Antennas Wireless Propag. Lett.*, vol. 18, no. 5, pp. 971–975, May 2019.

[10] W. Hong, S. T. Ko, Y. Lee, and K. H. Baek, "Compact 28 GHz antenna array with full polarization flexibility under yaw, pitch, roll motions," in *Proc. EuCAP*, Apr. 2015, pp. 1–3.

[11] Y. W. H. W. G. Yang, "Design of dipole beam-steering antenna array for 5G handset applications," in *Proc. Prog. Electromagn. Res. Symp. (PIERS)*, Aug. 2016, pp. 2450–2453.

[12] H. Xia, J. Lei, L. Meng, and G. Yang, "Design and analysis of a compact reconfigurable phased antenna array with 3D coverage for 5G applications in portable devices," in *Proc. Prog. Electromagn. Res. Symp. (PIERS)*, Aug. 2016, pp. 2459–2463.

[13] R. A. Alhalabi and G. M. Rebeiz, "High-gain yagi-uda antennas for millimeter-wave switched-beam systems," *IEEE Trans. Antennas Propag.*, vol. 57, no. 11, pp. 3672–3676, Nov. 2009.

[14] R. A. Alhalabi and G. M. Rebeiz, "Differentially-fed millimeter-wave yagi-uda antennas with folded dipole feed," *IEEE Trans. Antennas Propag.*, vol. 58, no. 3, pp. 966–969, Mar. 2010.

[15] W. Hong, S.-T. Ko, Y. Lee, and K.-H. Baek, "Multi-polarized antenna array configuration for mmWave 5G mobile terminals," in *Proc. Int. Workshop Antenna Technol. (iWAT)*, Mar. 2015, pp. 60–61.

[16] N. Ojaroudiparchin, M. Shen, and G. F. Pedersen, "A 28 GHz FR-4 compatible phased array antenna for 5G mobile phone applications," in *Proc. Int. Symp. Antennas Propag. (ISAP)*, Nov. 2015.

[17] J. Bang and J. Choi, "A SAR reduced mm-wave beam-steerable array antenna with dual-mode operation for fully metal-covered 5G cellular handsets," *IEEE Antennas Wireless Propag. Lett.*, vol. 17, no. 6, pp. 1118–1122, Jun. 2018.

[18] P. J. Gibson, "The vivaldi aerial," in *Proc. 9th Eur. Microw. Conf.*, Sep. 1979, pp. 101–105.

[19] *Computer Simulation Technology (CST) Microwave Studio Suite 2016*. [Online]. Available: http://www.cst.com

[20] [Online]. Available: http://www.isola-group.com/

[21] C. A. Balanis, *Antenna Theory Analysis and Design*. New York, NY, USA: Wiley, 2005.

[22] [Online]. Available: http://www.orbitfr.com/

WON-WOO LEE received the B.S. degree in electronics and physics from Kwangwoon University, South Korea, in 2000, the M.S. degree in microwave engineering from Kwangwoon University, in 2002, and the Ph.D. degree in electrical and computer engineering from Hanyang University. He is currently with the ICT Convergence Research Division, Korea Expressway Corporation Research Institute. His research interests include the area of design and analysis of LTE systems, 5G millimeter-wave systems, and antenna and microwave circuit design.

IN-JUNE HWANG received the B.S. degree in electrical and electronic engineering from Yonsei University, Seoul, South Korea, in 2013, and the M.S. and Ph.D. degrees in electrical engineering from the Korea Advanced Institute of Science and Technology (KAIST), Daejeon, South Korea, in 2015 and 2019, respectively. Since 2019, he has been a Senior Research Scientist with the Division of Physical Metrology, Group for Electromagnetic Wave Metrology, Korea Research Institute of Standards and Science (KRISS), Daejeon. His current research interests include electromagnetic field strength, antenna measurement standards, millimeter-wave antennas, phased array antenna systems, energy harvesting, and RF wireless power transfer.

BEAKCHEOL JANG (Member, IEEE) received the B.S. degree from Yonsei University, in 2001, the M.S. degree from the Korea Advanced Institute of Science and Technology, in 2002, and the Ph.D. degree from North Carolina State University, in 2009, all in computer science. He is currently an Assistant Professor with the Department of Computer Science, Sangmyung University. His primary research interests include wireless networking, big data, the Internet of Things, and artificial intelligence. He is a member of the ACM.

• • •