Wideband Phased Array System at K-Band for Satellite Down-link Applications

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***Abstract*—This paper presents a wideband electronically steerable circularly polarized receive phased array antenna system at K-band (17.7 GHz to 20.2 GHz) for satellite downlink applications. A scalable 64-element antenna array module in a multi-layered PCB is designed using a dual-polarized proximity-fed square-ring patch radiator with stacked circular-ring patch as the antenna element. For circular polarization (CP) radiation, the two feeds are excited orthogonally in 90° out of phase with each other. To enhance CP performance, each 2 × 2 antenna subarray is excited in a sequentially rotated manner with one Rx beamforming core chip. The 64-element array module with aperture size of 60mm × 60mm demonstrates a measured 12.5° half-power beam width (HPBW), around 22 dBic antenna gain and less than 2.5 dB axial ratio (AR) across the frequency band. The beam can be steered to ±60° in all planes without grating lobes. Furthermore, to demonstrate the scalability, a 256-element phased array is prototyped and measured.**

***Index Terms*—antenna, circularly polarized, phased array, beamforming, K-band, wideband antenna, satellite downlink.**

I. Introduction

In recent years, there has been an ever-increasing demand on high-speed and large-capacity wireless communication so that the communication frequency expends to much higher frequency spectrum. Millimeter-wave (mmWave) phased array technology at the K/Ka-bands is playing the key role in next generation wireless communication, up-/down-link satellite systems, and connectivity systems. A beam steering/beamforming antenna system is the key element for mmWave satellite systems. To ensure highly reliable satellite communication at the mmWave, the phased array antenna system must be circularly polarized (CP) and high gain with narrow beam [1].

Various phased array antennas [2-6] at the K-band have been developed for satellite and radar applications in the literature. In [2], A 16×16 phased array antenna using dielectric filling waveguide antenna element was developed at the K-band (19.6GHz–21.4GHz). A K/Ka dual-band dual CP coplanar phased array antenna with high isolation was presented in [3]. The K/Ka-band arrays are both composed of 8×4 elements and arranged with separated radiating apertures in a coplanar support. The array antenna is able to scan the CP beams to ±40° with axial ratio (AR) less than 3 dB. In [4], a K/Ka-band phased-array antenna was reported for vehicular applications, where the receiving antenna array is configured by 32 dipoles backed with metallic reflector. With inter-element distance of $0.531\lambda_0$ at frequency of 20.2 GHz, the phased-array antenna can achieve beam scanning of ±60° with gain loss of 4.5 dB. A simple truncated corner stacked patch antenna with probe feed was used in [6] to design the circularly polarized phased array antenna in three different array lattices at K-band.

II. Antenna Element Configuration and Design

Fig. 1 shows the proposed dual-feed stacked antenna element structure (cross-sectional view and 3D top view) at K-band for wideband applications. Dual feed antenna element is used to generate two modes (vertical and horizontal) for circularly polarized phased array design. Multilayered PCBs are used to design the antenna element for low cost. Dual feedlines are designed on the RO4003 substrate with thickness of 0.406 mm. A stacked circular-ring slotted patch is printed on the RO4003 substrate with thickness of 0.813 mm and a square-ring slotted patch radiator is printed on the RO4450F substrate with thickness of 0.305 mm. Antenna ground plane area is $0.5\lambda_o \times 0.5\lambda_o$ at 20 GHz.

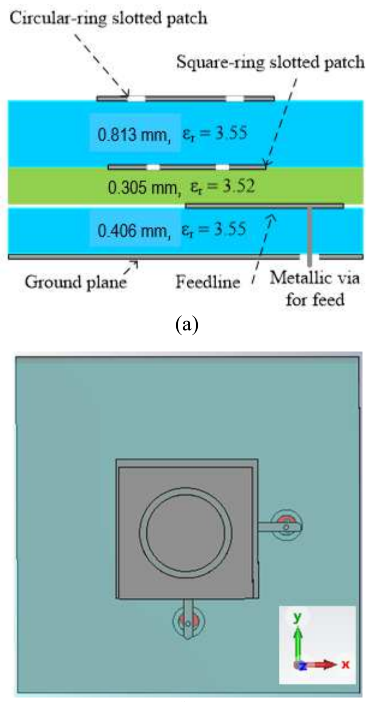


Fig. 1. Antenna element configuration: (a) cross-sectional view and (b) 3D top view.

Fig. 2 shows the simulated results of the antenna element reflection coefficient (impedance bandwidth) and mutual coupling. The antenna can operate within a broad bandwidth of 3.6 GHz (17.4- 21.0 GHz (for $|S_{11}| < -10$ dB). The mutual coupling between the two feeding ports, $|S_{21}|$, is lower than -19dB across the bandwidth. The two ports feature identical impedance characteristics as the antenna element has systematical structure. The circularly polarized performance of the antenna element can be characterized based on axial ratio (AR) and gain parameters by combined vertical and horizontal modes with 90° phase shift as shown in Fig. 3. The realized gain is greater than 5.0 dBic and the axial ratio is less than 2dB across the desired bandwidth. Figs. 4(a)-4(c) illustrated 3D radiation patterns of the antenna element, respectively, at 17.7 GHz, 19.0 GHz, and 20.2 GHz. The 3dB gain beamwidth is more than 90° as shown in Fig. 5(a) and the 3dB AR beamwidth is more than 180° across the bandwidth as shown in Fig. 5(b).

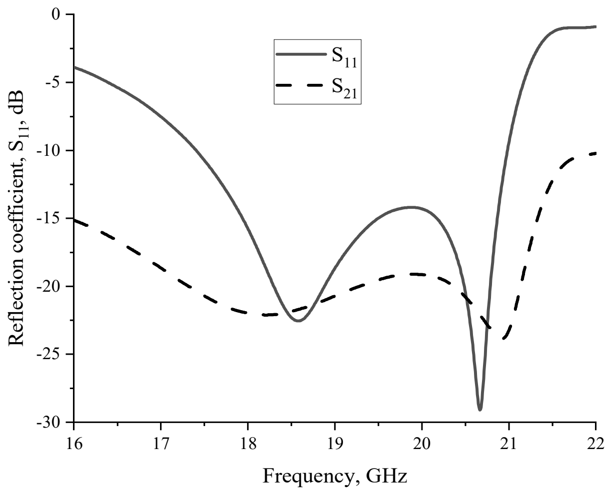


Fig. 2. Simulated reflection coefficent and mutual coupling.

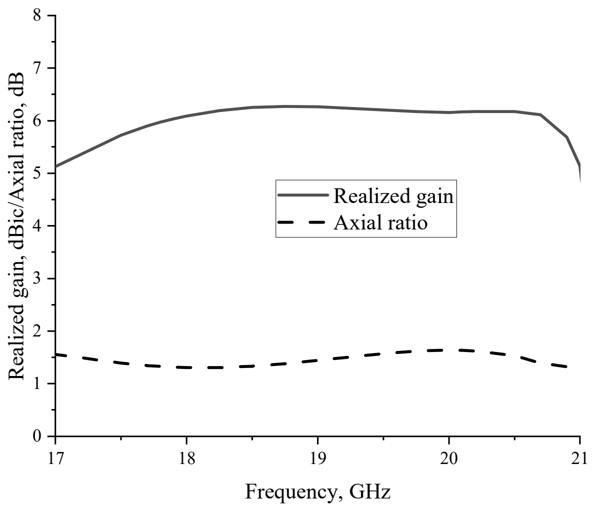


Fig. 3. Realzed gain and axial ratio simulated at boresight of the antenna element.

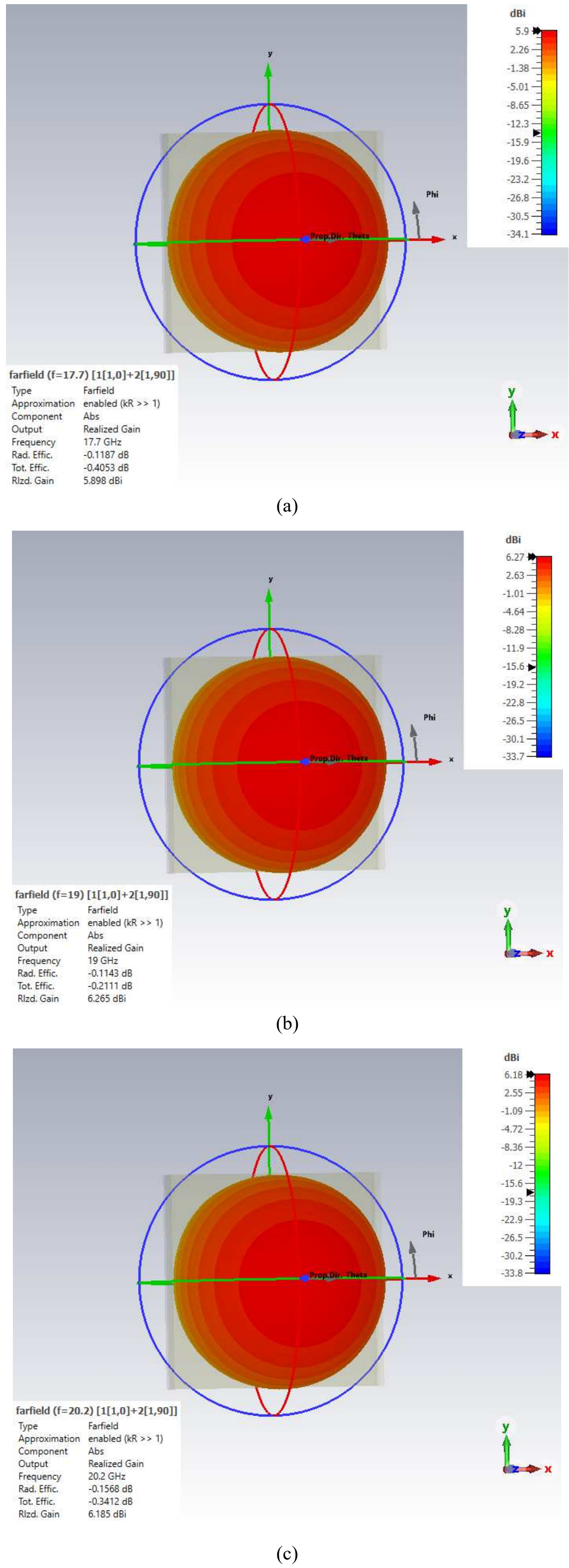
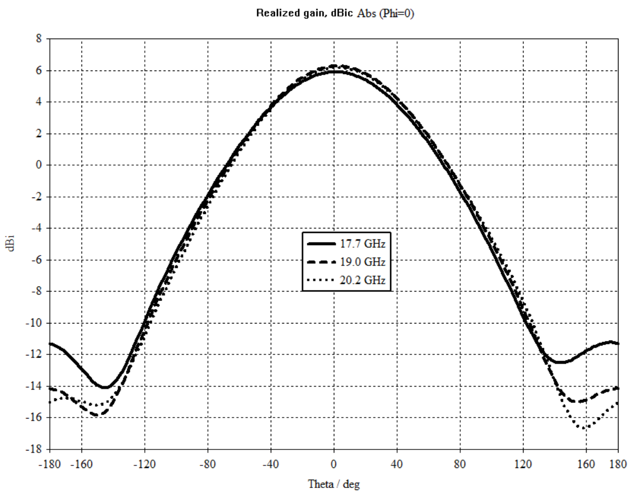
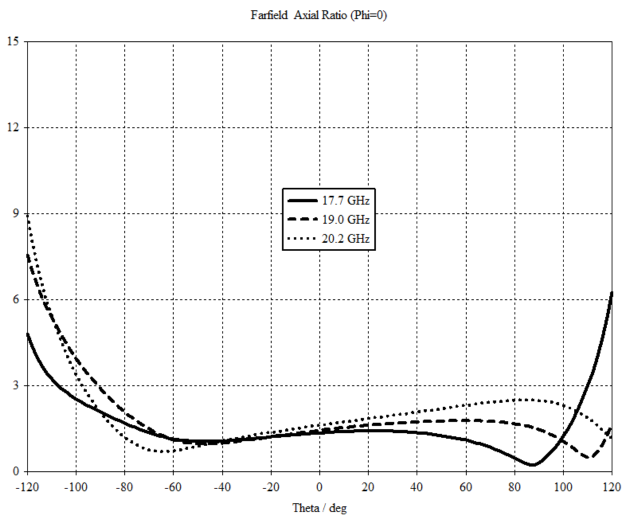


Fig. 4. Simulated 3D radiation patterns of the antenna element; (a) 17.7 GHz, (b) 19.0 GHz, and (c) 20.2 GHz.



(a)



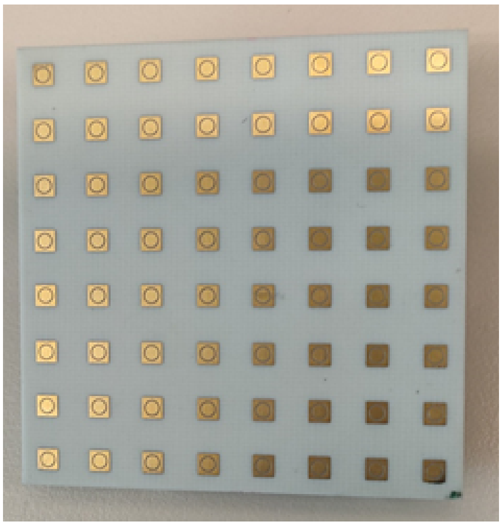
(b)

Fig. 5. Simulated gain and AR beamwidth of the antenna element at 17.7 GHz, 19.0 GHz, and 20.2 GHz.

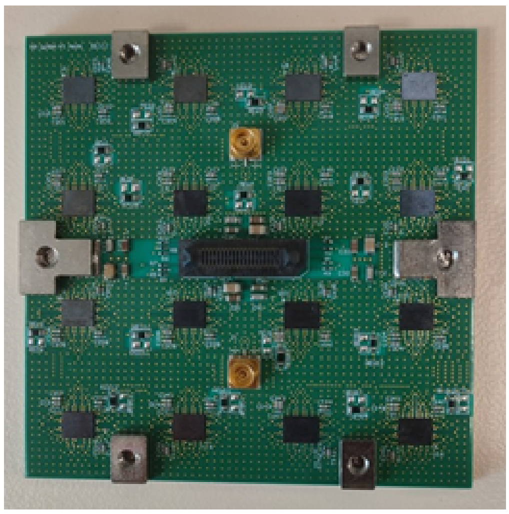
III. MODULAR 64-ELEMENT PHASHED ARRAY

The 64-element K-band receive (Rx) phased array module is designed in a scalable modular structure based on RF beamforming architecture and laid on a single PCB. As discussed in section II on antenna element design, Rogers 4003C core substrate and 4450F prepeg were used for the PCB stackup. One array module consists of 8×8 dual-feed antenna elements excited by 16 RF beamforming core chips. It also integrates on-board stripline RF beamforming network and array calibration network, which combines all the signals collected by the 64 calibration probes placed at the corners of patch antennas. Fig. 6 shows a photograph of the 64-element Rx phased array module, where the top side (Fig. 6a) is with antenna elements and the bottom side (Fig. 6b) is with Rx beamforming core chips. The array aperture measures 60mm×60mm wherein the antenna elements are arranged in square lattice with element spacing of 7.5-mm ($0.5\lambda_o$ at 20 GHz).

The silicon quad core Rx beamforming chip enables individual gain/phase control for eight RF channels and supports four dual polarization (DP) radiating elements with full polarization flexibility (linear, right-hand CP, left-hand CP). Four DP antennas supported by one Rx beamforming chip forms the 2×2 quad unit cell of the phased array, as illustrated in Fig. 7. Furthermore, the 2×2 sub-array are excited in a sequentially rotated manner to increase the 3dB AR bandwidth. The received K-band RF signals from the 16 beamforming core chips are fed through coaxial transitions to the beamforming network based on a four-stage stripline Wilkinson power combiner, which is embedded inside the PCB board. Two SMPM connectors provide interfaces to the RF beamforming network and the calibration network. A 40-pins edge type high-speed connector at the board center is used to route DC power and SPI digital lines to the beamforming chips to control phase and attenuation setting for beam steering and amplitude tapering.



(a)



(b)

Fig. 6. Photograph of the 64-element K-band Rx phased array module: (a) top side with antenna elements and (b) bottom side with beamforming core chips.

The 64-element K-band Rx phased array module was measured in a full anechoic chamber. Fig. 8 plots the measured far field radiation pattern at 19 GHz. The 64-element array features sub-1 degree beam scanning resolution and less than 2 dB scan loss with scanning angle of ±45°, while keeping all side lobe levels of below -11 dB. Fig. 9 plots the measured AR versus beam scanning angles. AR is less than 2.5 dB over beam scanning angle of ±45°, which indicates good circularly polarized performance of the phased array. The half-power beam width and boresight gain of the 64-element phased array antenna (after de-embedding chip gain) are around 12.5° and 22 dBic over the frequency band, respectively.

The modular design has a great advantage of built-in scalability. It gives the flexibility to scale up the antenna array size by simply adding more modules. Thus system G/T can be easily increased to meet the application specific link budget requirements. Fig. 10 shows the integration of a 256-element phased array using four 64-element array modules. In the same way, a 1024-element phased array can be easily constructed using sixteen 64-element antenna array modules. Fig. 11 demonstrates the sub-1° beam scanning resolution by plotting the measured radiation patterns of the 256-element array at 19 GHz with scanning angle of ±5° and 1° scanning step. The beam can be scanned to ±60° without grating lobes, as shown by the normalized radiation pattern plotted in Fig. 12. While scanning loss increases to around 5 dB, side lobe levels are still below -10 dB.

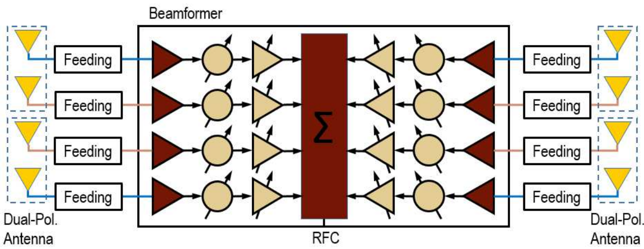


Fig. 7. Block diagram of the RF beamforming 2 × 2 DP antenna sub-array with eight-channel Rx BF chip.

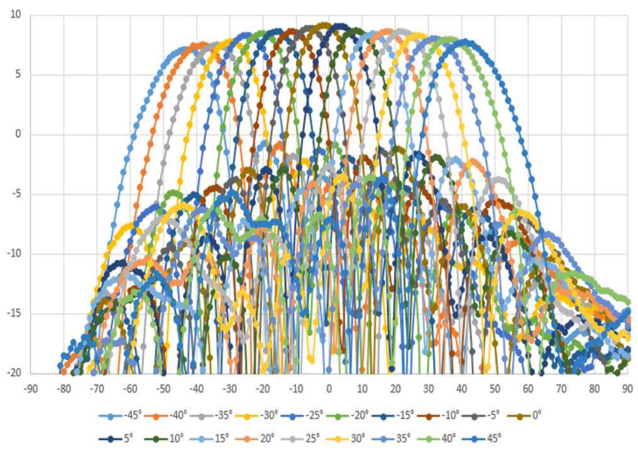


Fig. 8. Measured far field beam patterns of the 64-element phased array module at 19 GHz.

Fig. 9. Measured axial ratio of the 64-element antenna array at 19 GHz.

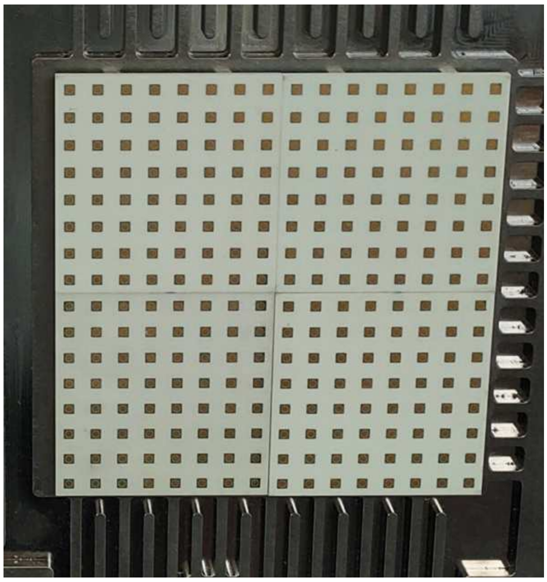


Fig. 10. Modular integration of 256-element phased array using four 64-element array modules.

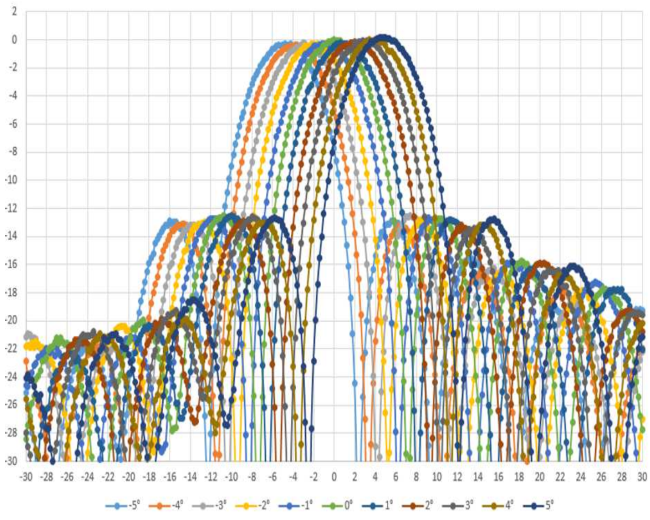


Fig. 11. Measured radiation patterns of the 256-element phased array with scanning angles of ±5° and 1° scanning step.

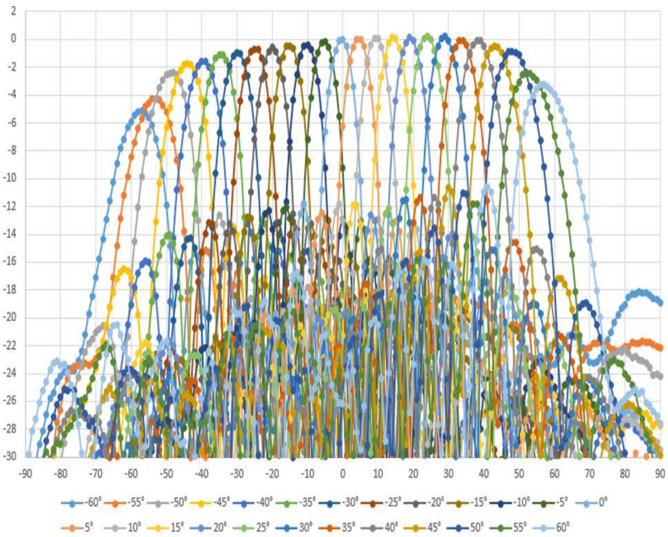


Fig. 12. Measured radiation patterns of the 256-element phased array with scanning angles of ±60° and 5° scanning step.

IV. Conclusion

A highly integrated modular electronically steerable circularly polarized 64-element receive phased array module at K-band (17.7 GHz to 20.2 GHz) has been developed for satellite downlink applications. Measurement results have validated the design with 3-dB beamwidth of 12.5°, antenna gain of around 22 dBic, and axial ratio (AR) less than 2.5 dB across the frequency band. The phased array is able to scan to ±60° in all planes without grating lobes, with sub-1° beam scanning resolution. Furthermore, the modular design make it easy to scale the antenna array to a larger aperture upon system requirements as it is demonstrated by a 256-element phased array prototype formed using four 64-element array modules.

Acknowledgment

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References

[1] S. Mener, R. Gillard, and L. Roy, "A dual-band dual-circular polarization antenna for Ka-band satellite communications," *IEEE Antennas and Wireless Propagation Letters*, vol. 16, pp. 274 – 277, May 2016.

[2] H.W. Wang, H.J. Sun and G.D. Han, "An active receiving phased array for Satellite Communication in K-band," *IEEE International Conference on Computational Electromagnetics* (ICCEM), pp. 1-4, 2016.

[3] N.F. Liu, Y.J. Cheng and Y.F. Wu, "K/Ka dual-band dual-circular-polarized coplanar phased array antenna with high isolation for satellite communication," *International Conference on Microwave and Millimeter Wave Technology* (ICMMT), pp. 1-3, 2020.

[4] Z. Golubicic´, S. Dragas, and Z. Cvetkovic, "A K- and Ka-band vehicular phased-array antenna", *Microwave Journal*, vol. 47, pp. 58-74, 2004.

[5] N. Ghaffarian, et al., "Characterization and calibration challenges of an K-band large-scale active phased-array antenna with a modular architecture," *Proceedings of the 50th European Microwave Conference*, Utrecht, The Netherlands, pp. 1039-1042, 2021.

[6] Y. Yorozu, M. Hirano, K. Oka, and Y. Tagawa, "Performance Comparison of K-Band Sequentially Rotated Wideband Circularly Polarized Phased Arrays using Different Array Lattices," *IEEE 19th International Symposium on Antenna Technology and Applied Electromagnetics* (ANTEM), 2021.