Modular Ka-Band Transmit Phased Array Antenna for SATCOM Applications

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***Abstract* — An active electronically scanned dual circularly polarized wideband transmit phased array antenna at Ka-band (27.5 GHz to 31 GHz) is proposed for satellite communications. The transmit (Tx) phased array module is designed with 256 dual-polarized antenna elements fed by 64 eight-channel Tx beamforming core chips on a multi-layered PCB. The antenna element has a stacked square-ring slotted patch structure with two orthogonally positioned proximity-feed ports. The dual-feed can be excited orthogonally for circular polarization (CP) and offers the flexibility to reconfigure the CP radiation, either left-handed CP (LHCP) or right-handed CP (RHCP). Furthermore, each 2×2 antenna cell can be arranged using sequential rotation manner to enhance the CP performance. The 256-element transmit array has an aperture size of 80mm × 80mm and a measured effective isotropic radiated power (EIRP) of 58 dBm, 6.2° half-power beam width (HPBW), sub 1 dB axial ratio (AR), and ±60° scanning range free of grating lobes. Scalability of the modular design is validated by implementing a 1024-element Tx phased array antenna with four 256-element array modules.**

***Index Terms*— antenna, beamforming, circular polarization, phased array, transmit, Ka-band, satellite communication.**

I. Introduction

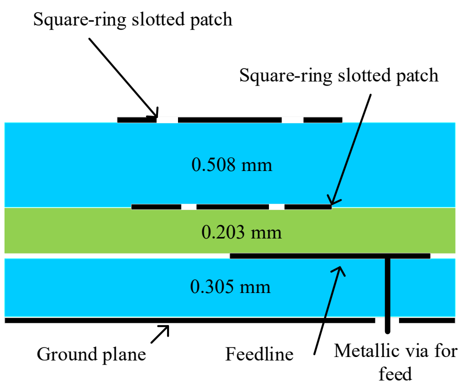
With the launch of many low earth orbit (LEO) and medium earth orbit (MEO) commercial satellite networks in recent years, satellite communication (SATCOM) has attracted widespread interest in providing global broadband connectivity due to its advantage of wide coverage without geographical restrictions. The convergence of terrestrial and satellite communications in future 5G and 6G systems promises to provide an unrivalled user experience through seamless wireless connectivity across the entire globe with unlimited, ultra-fast, and ubiquitous communications. Further, to meet the ever-increasing demand for large-capacity and high-speed data link wireless communication frequencies have expanded from the sub-GHz band to the millimeter wave (mmWave) spectrum.

Low-cost active electronically scanned arrays (AESAs) at mmWave especially the K/Ka-bands are a key component in high throughput SATCOM [1]. Compared to traditional mechanical scanning antennas, the AESAs provide fast electronic beamsteering between different satellites, which is critical for uninterrupted links. For a reliable mmWave SATCOM link, the AESAs must have CP radiation with high EIRP and a narrow beam [2]. Several Ka-band phased array antenna structures have been reported for satellite/radar applications [3-7].

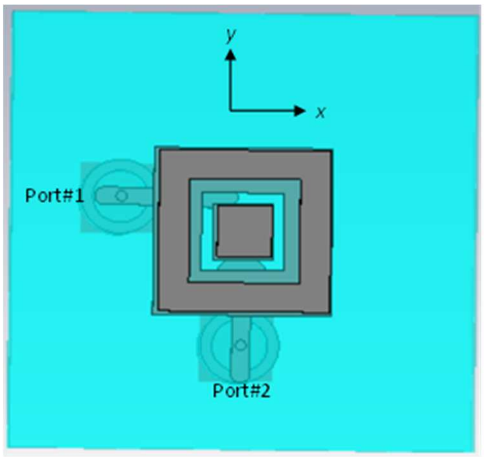
This paper presents a modular 256-element dual-CP transmit phased array antenna at Ka-band (27.5 GHz -31 GHz) for SATCOM applications. The highly integrated architecture design will facilitate low-cost implementation of SATCOM AESAs. With the modular design, a larger aperture phased array antenna with a higher gain and enhanced EIRP can be easily formed and this is validated by a 1024-element Tx array implemented using four 256-element array modules.

II. Ka-band Antenna Element Design

The antenna element is designed in low-cost multiple PCB layers. Fig. 1(a) and Fig. 1(b) show a cross-sectional view and a top view of the proposed Ka-band dual-feed stacked microstrip antenna structure, respectively. The ground plane size of the antenna element is $0.5\lambda_o \times 0.5\lambda_o$ (half-wavelength at 30 GHz). For dual-CP applications, the antenna element is designed with two orthogonally positioned feeds. A 0°/90° or 90°/0° excitation is applied to generate RHCP or LHCP radiation respectively. The proximity feed microstrip lines are designed on the RO4003C substrate (relative permittivity ε_r = 3.55, loss tangent tanδ = 0.0027) with a thickness of 0.305 mm. The lower radiator is a square-ring slotted patch printed on the 0.203-mm-thick RO4450F (ε_r = 3.52, tanδ = 0.004) substrate. Above it, a stacked square-ring slotted patch as the upper radiator is printed on the 0.508-mm-thick RO4003C substrate. To facilitate the board routing for installing the beamforming chips with a rectangular package and pin layout, one feeding port needs to be slightly offset from the patch center. Port #1 thus has 0.4 mm offset by orthogonal axis as shown in Fig 1(b).



(a)



(b)

Fig. 1. Structure of the Ka-band dual-feed stacked patch antenna element: (a) cross-sectional view, and (b) top view.

The antenna element's simulated results including port reflection coefficients (S_{11} and S_{22}) and mutual couplings between the two feeding ports (S_{21} and S_{12}) are plotted in Fig. 2. The antenna element has a broad impedance bandwidth of 4 GHz (27 GHz –31 GHz) for both $|S_{11}| < -10$ dB and $|S_{22}| < -10$ dB. Due to the offset feeding configuration, the mutual coupling is a bit strong with $|S_{21}|$ less than -12 dB over the band. The circularly polarized performance of the Ka-band antenna element is characterized by combining orthogonal (vertical and horizontal) polarized modes with a 90° phase shift. Fig. 3 shows the simulated gain and axial ratio (AR) of the CP antenna element at boresight. The realized gain is higher than 5.5 dBic and the AR is lower than 2.5dB across the desired band of 27.5 GHz – 31 GHz. The simulated 3D radiation patterns at 27.5 GHz, 29.0 GHz, and 31.0 GHz are shown in Figs. 4(a)-4(c) respectively. The simulated 3dB gain and AR beamwidth are larger than 90° and 180°, respectively.

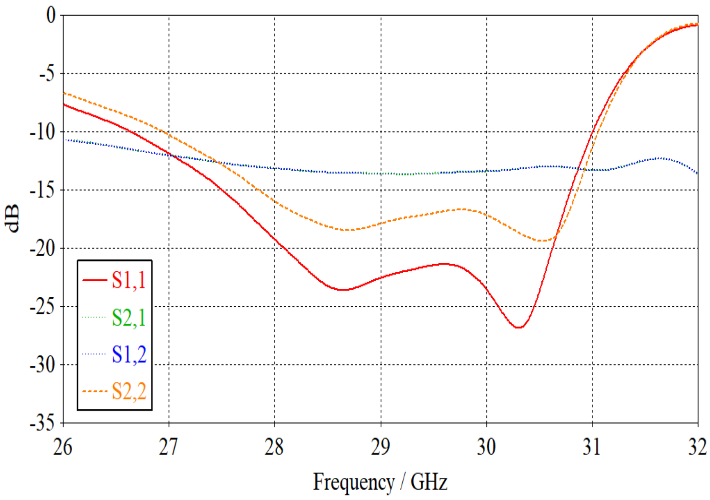


Fig. 2. S-parameters: Reflection coefficient and mutual coupling.

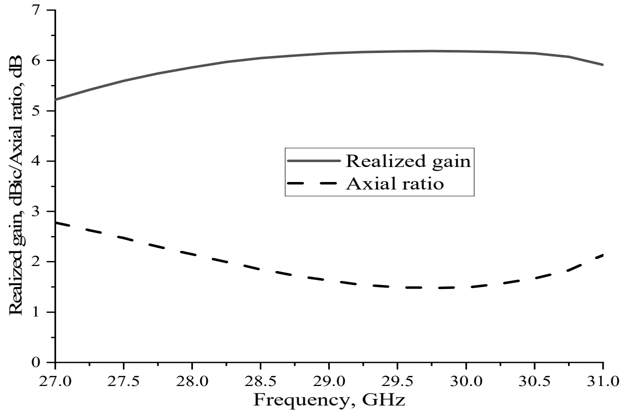


Fig. 3. Realized gain and axial ratio with frequency at boresight.

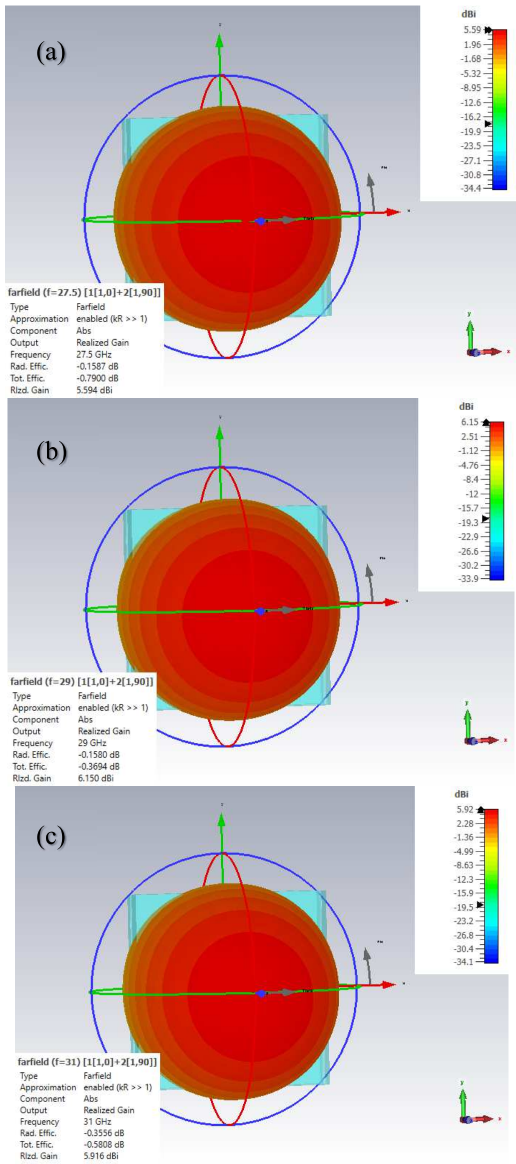


Fig. 4. 3D radiation patterns; (a) 27.5 GHz, (b) 29.0 GHz, and (c) 31.0 GHz.

III. KA-BAND MODULAR TRANSMIT PHASED ARRAY ANTENNA DESIGN

The Ka-band transmit phased array is designed based on a full RF beamforming architecture in a scalable modular structure with 256 dual-feed antenna elements fabricated on a multi-layered PCB. Fig. 5 illustrates the overall board architecture of the phased array antenna. The PCB stackup uses core substrate RO4003C and prepeg RO4450F, same as the designed Ka-band antenna element. The transmit array integrates 256 dual-feed antenna elements placed on a 16×16 square grid and 64 eight-channel silicon RF beamforming chips. The integrated stripline beamforming network (BFN), which is based on Wilkinson power dividers and implemented in a fully balanced H-topology, distributes the Ka-band signal with equal magnitude and phase delay from the array input to each beamformer. An on-board calibration network is also integrated, which collects and combines the signals coupled from the 256 calibration probes placed directly underneath the corner of each patch antenna. The built-in calibration design has the advantage that in-situ self-calibration can be performed on-demand or periodically without the need of external probes and additional peripheral hardware. The calibration technique uses multi-element measurement methods relying on orthogonal code modulation to simultaneously calibrate all the array elements.

The silicon quad core Tx beamforming chip has eight RF channels, each with independent 6-bit phase control and 5-bit gain control. Fig. 6 shows a block diagram of the beamformer supporting four dual polarization (DP) antenna elements. It has full polarization flexibility since the beamformer can independently control the feeding phase and amplitude on each antenna element to obtain linear polarization (vertical or horizontal), LHCP, or RHCP. The 256 antenna elements of the array module are arranged as sub-arrays of 2×2 unit cell consisting of four DP antennas fed by one Tx beamforming chip. Furthermore, sequentially rotated excitation can be applied to the 2×2 sub-array to increase the AR bandwidth, as illustrated in Fig. 7.

A photograph of the fabricated modular 256-element transmit phased array antenna is shown in Fig. 8. The antenna elements are printed on the top layer (Fig. 8a) while the Tx beamforming core chips and other SMT compatible components are soldered on the underside (Fig. 8b). Other layers were used for digital control, power, BFN, calibration, and the antenna ground. The array input to the beamforming network and the output from the calibration network are interfaced through two SMPM connectors respectively. Four 40-pins edge type connectors located at four quadrants center of the board are used to supply DC power to the beamformers and to set phase and gain for beam scanning and amplitude tapering, programmed via a serial peripheral interface. The array aperture measures 80 mm × 80 mm with the antenna elements placed on a square grid of 5-mm spacing (0.5λ_o at 30 GHz). The grid distance is chosen to ensure in the visible region no grating lobe appearing when scanning the beam.

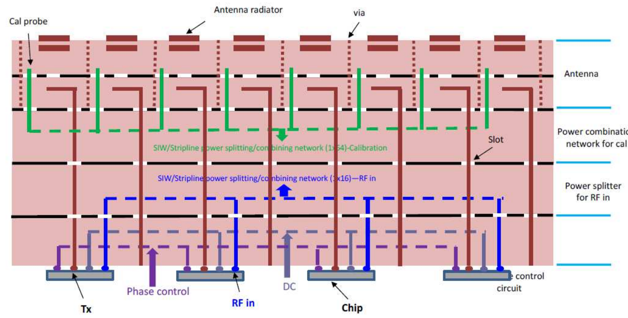


Fig. 5. Board architecture of the modular phased array antenna.

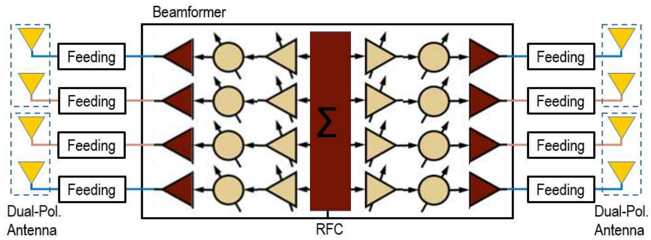


Fig. 6. Block diagram of the Tx BF chip suppoting four DP antennas.

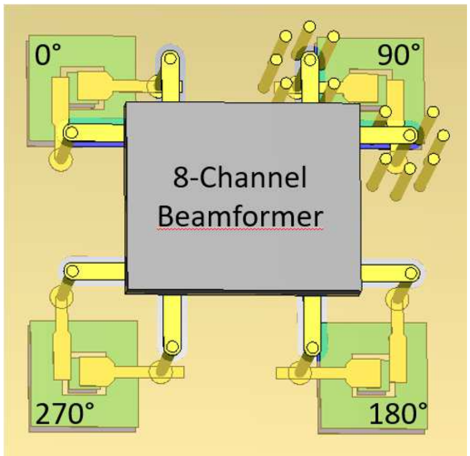
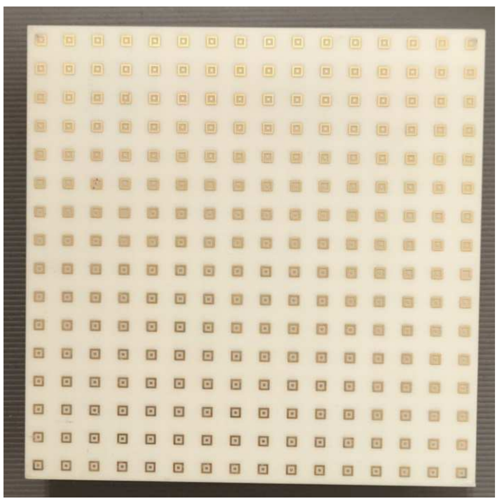
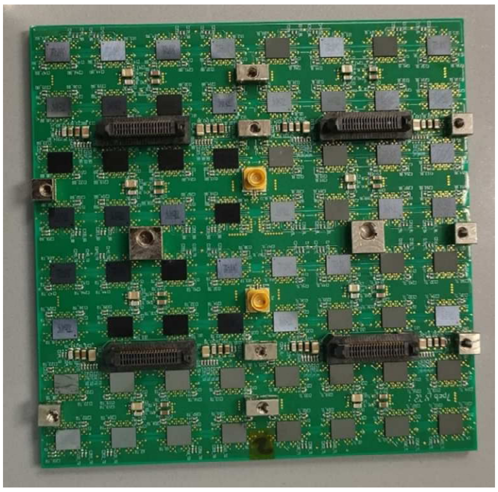


Fig. 7. Unit cell 3-D model of the 2×2 sub-array with four DP stacked-patch antennas fed by one Tx beamformer in a sequentially roated manner.



(a)



(b)

Fig. 8. Photograph of the fabricated 256-element Ka-band modular Tx phased array antenna: (a) antenna side, and (b) components side with 64 beamformer chips.

The 256-element transmit phased array antenna was measured in an anechoic chamber with a measurement range of 10 meter and MIDAS 7.0 fully-automated antenna measurement software. Fig. 9 plots the superimposed far field radiation patterns measured at 29 GHz as the antenna array scans from -60° to 60° with a step of 5°. The 256-element Tx array antenna features sub-1 degree beam scanning resolution and can scan to ±60° free of grating lobes. Levels of all side lobes are maintained lower than -11 dB for the phased array antenna under uniform amplitude excitations. The beam patterns exhibit less than 3 dB scan loss as the transmit array scans beam to ±45°. The scan loss is increased to about 5 dB when the beam scans to ±60°. It is expected that the beam scan loss can be reduced by improving the port isolation as the antenna feeding ports have relatively strong mutual coupling (see Fig. 2) due to the offset feeding configuration. The measured AR is plotted in Fig. 10 as the beam scans to ±60°. The transmit array achieves a good CP radiation as indicated by the sub-1 dB AR over the beam scanning angle of ±45°. The half-power beam width of the 256-element transmit phased array antenna is around 6.2° and the boresight antenna array gain is around 28 dBic after de-embedding the gain of the beamforming chip. The 256-element Tx phased array antenna achieves a measured EIRP of around 58 dBm per polarization, corresponding to 61-dBm EIRP for CP. Lower side lobe levels can be achieved by applying amplitude taper as shown in Fig. 11 where side lobe levels are reduced to below -20 dB with a Chebyshev taper.

The inherent scalability gives a great advantage to the modular phased array antenna design architecture. The 256-element module is scalable at all the four board sides and, when tilted together, has the flexibility to synthesize patterns and scale up array size without grating lobes to meet the system EIRP requirements. As an example to validate the scalability, Fig. 12 demonstrates a Ka-band 1024-element transmit phased array antenna integrated with four 256-element modules. By scaling up the aperture size, the EIRP is increased by 12 dB to reach 63 dBm (33 dBW) for CP radiation. The 1024-element Tx AESA antenna can scan the beam to ±60° free of grating lobes, as shown in Fig. 13 where the superimposed radiation patterns measured at 29 GHz are plotted. The beam patterns maintain lower than -12 dB side lobe levels while the 3-dB beamwidth is sharpened to around 3.3°. Fig. 14 plots the measured beam patterns as the 1024-element Tx AESA antenna scans to ±5° at 1° resolution.

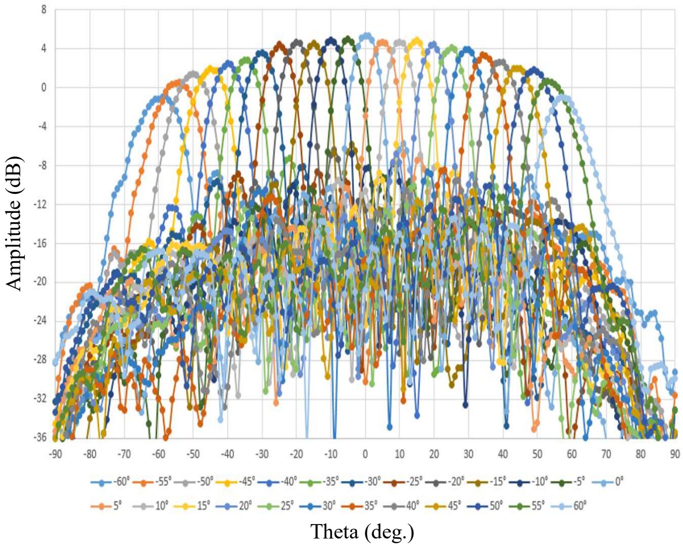


Fig. 9. Measured radiation patterns at 29 GHz as the 256-element Tx phased array antenna scans to ±60° with a step of 5°.

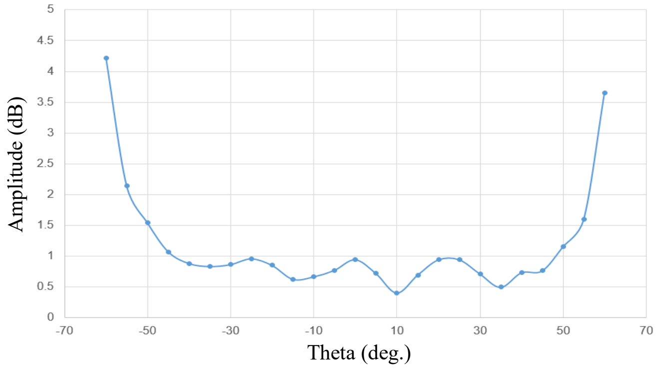


Fig. 10. Measured axial ratio at 29 GHz as the 256-element Tx phased array antenna scans to ±60° with a step of 5°.

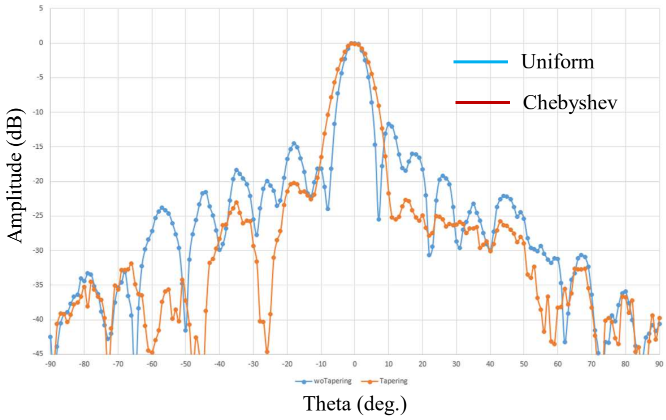


Fig. 11. Measured boresight beam patterns of the 256-element Ka-band Tx phased array under uniform excitation and a Chebyshev taper.

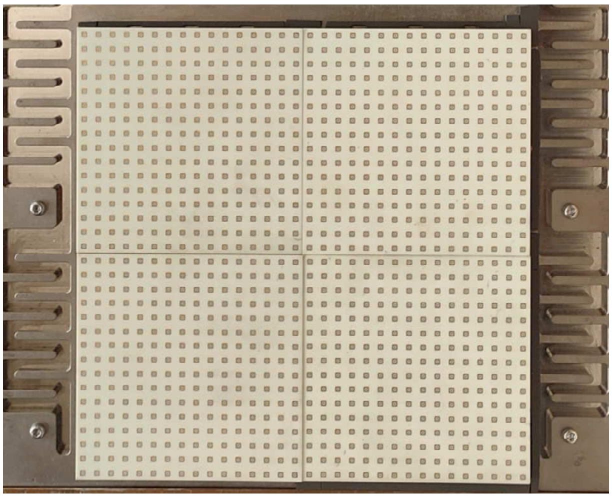


Fig. 12. 1024-element Tx phased array antenna integrated with four 256-element modules.

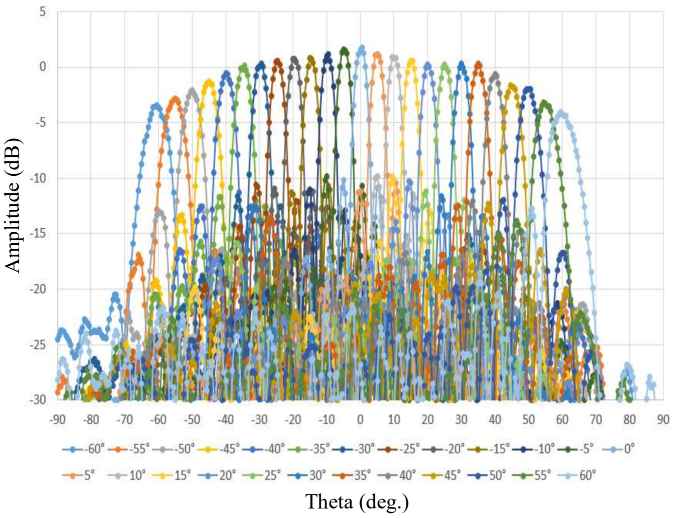


Fig. 13. Measured radiation patterns as the 1024-element Tx AESA antenna scans to ±60° at 5° scaning step.

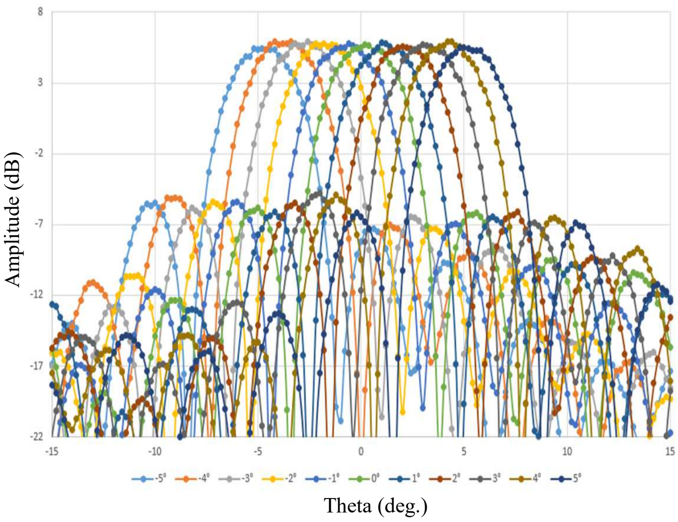


Fig. 14. Measured radiation patterns as the 1024-element Tx AESA antenna scans to ±5° at 1° scanning step.

IV. Conclusion

A 256-element Ka-band active electronically scanned dual circularly polarized wideband Tx phased array antenna has been developed for SATCOM applications. The design has a highly integrated modular architecture and can be easily scaled up to any larger aperture size. Measured results validates the design with 58 dBm EIRP, a 3-dB beamwidth of 6.2°, and less than 1 dB AR at 29 GHz. The beam can be scanned to ±60° with sub-1° resolution and free of grating lobes. To show scalability of the modular design for a higher EIRP, a Ka-band 1024-element Tx phased array antenna is implemented and measured with four 256-element array modules.

Acknowledgment

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References

[1] H. Al-Saedi, W. M. Abdel-Wahab, S. M. Raeis-Zadeh, E. Alian, et al., "Active phased-array antennas for Ka/K mobile satellite communications," *18th International Symposium on Antenna Technology and Applied Electromagnetics*, pp. 1-3, 2018.

[2] 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.

[3] T. Lambard, O. Lafond, M. Himdi, H. Jeuland, et al. "Ka-band phased array antenna for high-data-rate SATCOM," *IEEE Antennas and Wireless Propagation Letters*, Vol. 11, pp. 256-259, 2012.

[4] W.-H. Lim, S.-M. Moon, H. L. Lee, "Ka-band flat panel circularly polarized antenna array for LEO satellite communication systems," *Alexandria Engineering Journal*, vol. 78, pp. 584-591, 2023.

[5] W. M. Abdel-Wahab, H. Al-Saedi, M. Raeis-Zadeh , E. H. M. Alian, et al., "Affordable large scale active-phased array antenna for Ka-band mobile SATCOM applications", *13th European Conference on Antennas and Propagation*, 2019.

[6] H. Baghdadi, G. Royo, I. Bel, F. J. Cortés, et al., "Compact 2 × 2 circularly polarized aperture-coupled antenna array for Ka-band satcom-on-the-move applications," *Electronics*, 10, 1621, pp. 1-12, 2021.

[7] H. Al-Saedi, W. M. Abdel-Wahab, S. M. Raeis-Zadeh, et.al., "An integrated circularly polarized transmitter active phased-array antenna for emerging Ka-Band satellite mobile terminals," *IEEE Trans. Antennas Propag.*, vol.67, pp. 5344-5352, August 2019.