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| 13. SUPPLEMENTARY NOTES Final Report Attached | | | | | |
| 14. ABSTRACT CubeSats have evolved from an educational platform allowing universities to develop cost effective flight- ready spacecraft to standard platforms which allow for advanced technology demonstrations. Most CubeSats are used for earth science observation including optical, infrared, and microwave imaging for things such as atmospheric properties including clouds and precipitation, land topography and soil moisture, ocean surface salinity and temperature, snow and ice cover, and gravity and magnetic field monitoring. CubeSats occupy the low earth orbit (LEO) at 500 km above the earth, with the ceiling at 2180 km. All of these remote sensing applications generate large amounts of data, which require a SATCOM down | | | | | |
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Contract Number: N000141612166

Title: Development of W-Band Millimeter-Wave Links for Nanosat Applications

Major Goals:

CubeSats have evolved from an educational platform allowing universities to develop cost effective flight- ready spacecraft to standard platforms which allow for advanced technology demonstrations. Most CubeSats are used for earth science observation including optical, infrared, and microwave imaging for things such as atmospheric properties including clouds and precipitation, land topography and soil moisture, ocean surface salinity and temperature, snow and ice cover, and gravity and magnetic field monitoring. CubeSats occupy the low earth orbit (LEO) at 500 km above the earth, with the ceiling at 2180 km. All of these remote sensing applications generate large amounts of data, which require a SATCOM downlink with high data rates. We have proposed the development of a CubeSat beacon which will allow for high data rate downlinks for remote sensing applications, as well as the characterization of channel propagation in the W-Band.

The goal of the project is the development of W-band millimeter wave links for CubeSat applications. To accomplish the task we have proposed two solutions. First solution is the development of W-band feed horn with polarizer structure for an offset reflector antenna. The second solution is the development of the W-band circular polarized series fed single plane beam steering array antenna with 4-bit phase shifter for CubeSat applications.

Below is the summary of the proposed plan:

- Detailed link budget analysis between CubeSat and ground station.
- Development and test of a W-Band feed horn and reflector antenna for a CubeSat platform.
- Development and test of a commercial off the shelf W-Band transmitter for a CubeSat platform.
- Development of a 4-bit phase shifter to be integrated to the series array antenna aperture.
- Development of a phased array antenna and transmitter for a CubeSat platform.
- Demonstration of a terrestrial W-Band high data rate point to point link using developed transceiver and antenna showing at least 200 Mbps performance.

Based on the proposal milestones, dates for important activities or phases for the reporting period are identified with their actual completion dates or the percentage of completion.

1.1 Reflector Antenna Trade Study (SDSU) – Proposed timeframe (Jan 2016-Apr 2016); Completion date: March 2016.

1.2 Reflector Antenna Design (SDSU) – Proposed timeframe (May 2016-Oct 2016); Completion date: September 2016.

1.3 Circular Polarized Feed horn Design (SDSU) – Proposed timeframe (June 2016-Nov 2016); Completion date: January 2017.

1.4 Transmitter System In Package (SIP) Design (SSC-PAC) – Proposed timeframe (July 2016-Dec 2016); Completion date: November 2016

1.5 Phased Array Transmitter Design (SSC-PAC) – Proposed timeframe (May 2016-Nov 2016); Completion date: August 2018.

1.6 Series Fed Patch Antenna Array Design (SDSU) – Proposed timeframe (March 2016-August

2016); Completion date: March 2017.

1.7 Reflector Antenna Fabrication (SDSU) – Proposed timeframe (Jan 2017-Feb 2017); Completion date: May 2017.

1.8 Reflector Antenna Characterization (SDSU & SSC-PAC) – Proposed timeframe (March 2017-May 2017); Completion date: October 2017.

1.9 Integrated Series Fed Patch Antenna Fabrication and Characterization (SDSU & SSC-PAC) – Proposed timeframe (Jan 2017-June 2017); Completion date: In progress (The integrated board is fabricated and the population of the components is to be done. We fabricated the board and antenna however, fabricated structure has faults and is being refabricated now. Once it is ready, will be tested in the mmWave mini-compact range of Antenna and Microwave Lab.

Accomplishments Under Goals:

The list of accomplished task based on the goals listed in the objective section are as follows:

(i) Detailed link budget analysis between CubeSat and ground station.

Although the prospect of high data rates is attractive at the millimeter-wave frequencies, the reality is that at these frequencies the wavelength is much smaller, and the associated free space path loss and propagation loss is much higher. Therefore characterization of the propagating channel between 75 – 110 GHz is critical, and using a CubeSat to do this is ideal.

The link budget calculations for a LEO downlink using Ka-, Q-, and W-Bands are presented in Table I in the pdf attached. Calculations are for clear sky links, which do not include the effects of heavy clouds and rain. The TX antenna size was constrained to 1U diameter of 10 cm, however the size could be increased to take 3U in length. The propagation loss was calculated based on O₂ and H₂O absorption curves which are defined by ITU Rec 676-9. Propagation loss in the millimeter-wave regime is often said to be severe, this is true, albeit only for terrestrial radio links. We estimated the noise figure (NF) based on COTS low noise amplifiers (LNA). We also assumed several other loss factors including polarization loss, antenna beam mismatch loss, and implementation loss due to phase noise. Finally, we assumed an arbitrary digital waveform, 8- PSK and calculated the Eb/No based on a BER of 10⁻⁶. As can be seen, link margins from 4.92 to 10.92 dB can be attained for distances of 1000km and 500km respectively. In practice, a 10 dB link margin is probably realistic. From available literature, CubeSats typically occupy LEO usually in a circular orbit at an attitude of 500 km. As can be seen, a 200 Mbps link can be obtained in the W-Band at 86 GHz with a modest link margin of 10.92 dB at a distance of 500 km.

(ii) Development of a W-Band feed horn and reflector antenna for a CubeSat platform.

A novel compact W-band left-hand circular polarized (LHCP) cylindrical waveguide feed horn antenna is developed. The proposed antenna features an inbuilt polarizer structure and single side-fed linear polarized input to offer symmetric radiation pattern. The internal polarizer structure consists of 9 pairs of circular cavities to generate a circularly polarized (CP) wave, eliminating the need for an orthomode transducer or complex septum as shown in Fig. 1 of the pdf attachment. The side-fed horn reduces the overall length by eliminating rectangular to circular waveguide transition. The optimized horn antenna's electrical dimension is $7.2\lambda \times 3.9\lambda \times 1.4\lambda$ at 84 GHz. The antenna has wideband impedance matching (S11 below -15 dB) and axial ratio (below 1.2 dB) from 79.5 GHz to 88 GHz as seen in Fig. 2(a) and 2(b) in the attachment. The simulated total antenna efficiency and peak LHCP gain is shown in Fig. 3. Radiation pattern for the horn at 86 GHz is presented in Fig. 4. It has 12 dB half angle beamwidth of 62° and shows symmetric radiation pattern in both E and H plane. The peak LHCP gain is 10 dBic and co- and cross separation is better than 25 dB. The horn is

used as a feed source for an offset parabolic reflector of 10 cm diameter and small $f/D = 0.25$ which can fit inside a CubeSat as shown in Fig. 5. The current distribution is presented in Fig. 6. The reflector antenna provides simulated right-hand circular polarization (RHCP) directivity of 36.6 dBic at 86 GHz with spillover loss of 0.83 dB as presented in Fig. 7. The feed reflector assembly is also simulated with the complete aluminum CubeSat chassis to obtain effective RHCP gain of 35 dBic. Full wave analysis tool of Ansys HFSS along with PO/PTD solver in Tiera GRASP is used to simulate all the antenna designs. Important reflector simulation and measured results are shown from Figs. 10-15. The feed horn and reflector is fabricated using CNC machining at Custom Microwave Inc. and the fabricated design is presented in Fig. 9. The antenna characteristics were tested in a MVG spherical near field chamber whose measurement set up is shown in Fig. 13(a). The feed horn antenna was also characterized in the newly installed mini compact anechoic chamber at San Diego State University as shown in Fig. 13(b). The measurement of the prototyped feed horn and offset parabolic reflector antenna validates the analysis and simulation results.

(iii) Development of a W-Band 4 bit phase shifter and transmitter for a CubeSat platform.

In order to support a beam steering phased array, phase shifters are necessary. In the W-Band, commercial phase shifters are simply not available. As such, we designed and fabricated custom phase shifters for transmit application. Typical phase shifters that are reported in literature at these frequencies usually utilize a vector sum/modulator phase shifter. Although the vector sum phase shifter is compact, simple to implement, they suffer from low linearity and have low compression points. For our application, we decided to implement a 4-bit phase shifter utilizing switched delay line architecture. The switched delay line is simple to implement, has high linearity, but is typically larger in size. We designed 2 variations of the switched delay line phase shifter, one utilizing COTs SP4T flip-chip switches, and another fully integrated design on silicon germanium. The developed phase shifter is shown in Fig. 16. It utilizes 4 SP4T MMIC switches (TGS4306-FC), which are cascaded in series. The switch has a typical insertion loss of 3 dB per state, 20 dB of isolation, and 8 dB typical thru state return loss. Ground-signal-ground (GSG) probe pads are used to launch the millimeter-wave signal. Thin traces provide the SP4T with DC biasing. Since the module has 2 metal layers, bondwires are used as crossovers. This can be seen in Fig. 17. The total size of the phase shifter module is 10 mm x 7.5 mm.

An Anritsu ME7808A millimeter-wave vector network analyzer was used for s-parameter measurements. Fig. 18 shows our test setup. Fig 19 shows the measured insertion loss for all 16-states, and as can be seen from 83 – 84 GHz the maximum insertion loss is 22.41 dB and the minimum insertion loss is 14.7 dB. Fig. 20 shows the measured insertion phase across all 16-states. Since at E-Band the wavelength is small, physically routing the delay lines around the SP4T switch was challenging. In order to route the 45° , 67.5° , 180° , and 270° delay lines, an extra wavelength was added. This results in uneven phase slopes and limits the usable bandwidth of the switched delay line phase shifter and also negates true time delay capability. The SP4T switch is rated from 70 – 90 GHz, however the usable bandwidth of the phase shifter is from 82 – 84 GHz.

Fig.21 shows the measured return loss of all 16-states, and as can be seen the return loss is better than 6.91 dB in the usable bandwidth. A second phase shifter was designed utilizing a commercial foundry process. This phase shifter was designed on Global Foundries Silicon Germanium 9HP technology. The benefit of an integrated design is that the insertion loss is minimized, therefore minimizing the total DC dissipation required to make link. The chip is 2.35 x 1.3 mm and utilizes PIN diodes for the SP4T switch. Full EM simulation was done in Keysight Momentum. The fabricated chip is shown in Fig. 22.

(iv) Development of a W-band circular polarized series fed single plane beam steering array.

A new wide beamwidth circular polarized radiating element known as the Butterfly antenna is proposed for series fed phased array antenna applications. The unit Butterfly radiating element investigated at millimeter wave band (86 GHz) demonstrates superior performance with axial ratio (AR) beamwidth of 140° and symmetric pattern performance compared to a conventional Herringbone antenna element. Comparison of the proposed butterfly antenna element with the conventional herringbone antenna element array is presented in Table II. A series-fed 8×24 planar array has symmetric beam steering capability of $\pm 34^\circ$ along $\phi = 0^\circ$ plane of the array as shown in Fig. 23 and Fig. 24. The novel butterfly array is also compared with a conventional Herringbone array design and its beam scanning performances are presented from Fig 25. While a full phased array antenna with its beamforming network is being developed and fabricated, a passive fixed beam aperture prototype of size 32×24 is fabricated as shown in Fig. 26 and experimentally verified for high purity right-hand circular polarized (RHCP) radiation pattern in the broadside direction as presented in Fig. 27. The fabricated phased array board is shown in Fig. 28. The population of the component on the board is pending due to the back order of an RF component. The integrated array will be measured in the antenna mini compact chamber at San Diego state University as soon as the complete populated board is available.

(v) Additional design work partially supported by the project: Wide Scan Multi-Beam Antenna

The requirement of beam scanning at large angles results in severe degradation in antenna gain and pattern. Various techniques such as phased array, lens and multiple beam reflector antenna can be used. Amongst these the torus reflector antenna has the significant advantage in terms of providing wide beam scan in the azimuth plane with minimal change in antenna gain and pattern envelope. A wide scan (± 30 degree) torus reflector antenna study has been carried out. The antenna performance was analyzed using the GRASP software which is based on PO+PTD techniques.

The torus reflector was designed for two F/D ratio of 0.6 and 1.0 respectively (Figs.29 & 31). Each reflector is illuminated by 9 circular waveguide feed horns and the antenna generates nine beams within the ± 30 degree beam scan. The simulation results for the two F/D's are shown in Fig.30 & Fig.32. Based on the simulated performance we can conclude that the torus reflector unlike the parabolic reflector can generate closely spaced multiple beams with very less deterioration in gain and pattern for wide scan angles. As can be seen from the results the gain drop at the edge angles is about 0.5 dB compared to the center beam which is a significant improvement compared to other alternative techniques.

Training Opportunities:

Two joint doctoral Ph. D. students (Mr. Ghanshyam Mishra and Mr. Ila Agnihotri) from San Diego State University were trained in the development of antenna design and their challenges in the millimeter wave frequency. The PI (Prof. Sharma) and Co-PI (Dr. Chieh) were directly involved in the research. Training was imparted in the design of feed horn antennas, phased array antenna system and challenges involved in their implementation. Focus was also provided for features such as material selection, surface roughness of the conductor, characterizing the loss of the system at mmWave.

Opportunity is also provided to the graduate students to publish the work in peer reviewed publications. At SPAWAR, new hires also known as new professionals (NPs) take tours with various groups. Mr. Bjorn Grubelich was a NP that joined Code 55250 at SPAWAR and participated on this project. He was trained to use the mmWave network analyzer and also ran

simulations in Cadence to verify operation of the phase shifter chip. Mr. Anh-Vu Nguyen was also a NP that took a tour with Code 55250. Anh-Vu helped to design the first W-Band phase shifter using COTS SP4T switches.

Results Dissemination

- The work on W-band millimeter wave link for CubeSat applications was presented as a poster presentation during the student research symposium SRS on March 2-3, 2018 at San Diego State University. The Student Research Symposium is a two-day event recognizing the outstanding scholarly accomplishments of SDSU students. The SRS provides a public forum where SDSU students present their research, scholarship or creative activities.
- The results were also presented at poster and Blitz oral presentation during Computational Science Research center CSRC ACSESS event, San Diego on April 6, 2018. Through a partnership with academia, the Applied Computational Science and Engineering Student Support (ACSESS) program provides U.S. industry with a unique opportunity to help capture and sustain global economic leadership. ACSESS provides access to the next generation of engineers, scientists and researchers in order to help businesses directly address critical industrial problems. These areas include product engineering, safety engineering, and environmental engineering.
- On 05/25/17 a program manager from the National Reconnaissance Office, Roselyn Deleon visited SPAWAR. We briefed her on this project.
- On 07/01/16 the Silicon Germanium phase shifter was presented at the National Security Agency (NSA) Microelectronics Symposium.
- On 06/01/17 the Silicon Germanium phase shifter was presented at GOMACTECH 2017 in Miami Florida.

Below are the list of the papers and patents published/ submitted/ under preparation from this project.

Journals

1. G. Mishra, S. K. Sharma, J. Chieh “A Circular Polarized Feed Horn with Inbuilt Polarizer for an Offset Reflector Antenna at W-band for CubeSat Applications,” IEEE Transaction on Antennas and Prop., published in March 2019 issue.
2. J. C. S. Chieh, J. Rowland, and **S. K. Sharma**, “Four-bit W-band switched line phase shifter in 90 nm SiGe”, ***IET Electronics Letter***, [Volume 54, Issue 17](#), 23 August 2018, p. 1040 – 1041
3. G. Mishra, S. K. Sharma, J. Chieh “A wide beamwidth circular polarized radiating element based series fed phased array antenna with integrated analog beamforming network at 86 GHz”, IEEE Transaction on Antennas and Prop., [under preparation]. (to be submitted by September 2018: *waiting on back order RF component*).
4. Jia-Chi S. Chieh, J. Rowland, Anh-Vu Nguyen, S. K. Sharma, “E-Band 4-Bit Phase Shifter using SP4T Flip Chip Switches”, IMAPS - International Microelectronics Assembly and Packaging Society Magazine, May/June 2018.

Patents

1. S. K. Sharma, J.-C.S. Chieh, G. Mishra, and A. Castro, “Circular Polarized Waveguide Feedhorn with Internal Polarizer Structure,” [Patent Disclosure approved].

2. S. K. Sharma, J.-C.S. Chieh, G. Mishra, “Circular Polarized Butterfly Series Fed Patch Antenna Array with Reduced Cross-Polarization Levels,” [disclosure approved].

Conference papers

1. G. Mishra, **S. K. Sharma**, and J. C. S. Chieh, “Analysis and Design of a W-Band Circular Polarized Feed Horn with Inbuilt Polarizer for Low f/D Offset Reflector Antenna”, **URSI EM Theory Symposium, EMTS 2019, San Diego, CA, 27– 31 May 2019 (Young Scientist Award paper)**.
2. G. Mishra, **S. K. Sharma**, and Jia-Chi Chieh, “Finite Metal Wall Effects of W-Band Circular Polarized Horn Antenna with Inbuilt Polarizer”, 2019 IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting, July 2019.
3. I. Agnihotri, and S. K. Sharma, “Analysis and Design of Axial Corrugated Ka-band Feed Horn”, URSI EM Theory Symposium, EMTS 2019, San Diego, CA, 27– 31 May 2019
4. G. Mishra, S. K. Sharma, and J. C. S. Chieh “A New Butterfly Radiating Element for Circular Polarized Series Fed Phased Array with Wide Axial Ratio Beamwidth at Millimeter Wave Band,”; 2018 IEEE International Symposium on Antennas and Propagation & USNC/URSI National Radio Science Meeting, Boston, MA, USA, 2018
5. S. Chieh, J. Rowland, **S. K. Sharma**, “A 4-Bit W-Band Switched Line Phase Shifter in 90nm SiGe”, GOMACTech 2018, Miami, March 2018.
6. Jia-Chi Samuel Chieh, Anh-Vu Nguyen, Jason Rowland, **S. K. Sharma**, “E-Band 4-Bit Phase Shifter using SP4T Flip Chip Switches”, International Symposium on Microelectronics 2017, Raleigh, NC, October 10-12, 2017, pp. 595-598.
7. G. Mishra, A. T. Castro, S. K. Sharma and J. C. S. Chieh, “W-band feed horn with polarizer structure for an offset reflector antenna for cubesat applications,”; 2017 IEEE International Symposium on Antennas and Propagation; USNC/URSI National Radio Science Meeting, San Diego, CA, USA, 2017, pp. 557-558.
8. G. Mishra, S. K. Sharma, J. C. S. Chieh and J. Rowland, “W-band circular polarized series fed single plane beamsteering array antenna with 4-bit phase shifter for cubesat applications”; 2017 IEEE International Symposium on Antennas and Propagation; USNC/URSI National Radio Science Meeting, San Diego, CA, USA, 2017, pp. 2555-2556.

Honors and Awards

1. **Young Scientist Award (YSA)** to Ghanshyam Mishra on the co-authored paper of Electromagnetic Theory Symposium (EMTS) 2019
2. **Tioga Research award for outstanding poster and oral presentation** was awarded to the graduate student Ghanshyam Mishra for the poster entitled “A New Butterfly Radiating Element for Circular Polarized Series Fed Phased Array with Wide Axial Ratio Beamwidth at Millimeter Wave Band,” during the ACSESS event organized by Computational Science Research Center CSRC, San Diego on April 6, 2018.
3. **Director’s award for outstanding poster and oral presentation** was awarded to the graduate student Ghanshyam Mishra for the poster entitled “W-Band Feed Horn with Polarizer Structure for an Offset Reflector Antenna for CubeSat Applications” during the ACSESS event organized by Computational Science Research Center CSRC, San Diego on April 21, 2017.

Protocol Activity Status

Distribution Statement:

Approved for public release; distribution is unlimited.

Participants

First Name: Satish **Last Name:** Sharma

Project Role: PD/PI

First Name:

Jia-chi **Last Name:** Chieh

Project Role: Co PD/PI

First Name:

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Last Name:

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Project Role:

Graduate Student (research assistant)

National Academy Member:

N

Months Worked:

12

Countries of Collaboration

First Name:

Ila

Last Name:

Agnihotri

Project Role:

Graduate Student (research assistant)

National Academy Member:

N

Months Worked:

6

Countries of Collaboration

Table I. Downlink budget for Ka-, Q-, and W-Bands for various distances.

| | Ka-Band (35 GHz) | Q-band (55 GHz) | W-band (86 GHz) | Unit |
|---|-------------------------|------------------------|------------------------|-------------|
| Satellite Transmitter Power | 1.0 | 1.0 | 0.6 | W |
| Satellite Transmitter Power | 30 | 30 | 28 | dBm |
| TX losses | -3 | -3 | -3 | dB |
| Tx Implementation Loss (Phase Noise) | -2 | -2 | -2 | dB |
| TX Antenna Gain (10 cm dish) | 31 | 36 | 40 | dBi |
| TX EIRP | 56 | 61 | 63 | dBm |
| Path Loss (2180 km LEO) | -166 | -194 | -197 | dB |
| Polarization Loss | -0.5 | -0.5 | -0.5 | dB |
| Antenna Misalignment Loss | -1 | -1 | -1 | |
| Other Misc. Losses (Atmosphere ITU Rec 676-9) | -1 | -6 | -5 | dB |
| Isotropic Signal Level Ground Station | -112.5 | -140.5 | -140.5 | dBm |
| Rx Antenna Gain (2 m dish) | 60 | 61 | 65 | dBi |
| Rx Signal Level | -52.5 | -79.5 | -75.5 | dBm |
| Rx Noise Temperature | 170 | 438 | 627 | K |
| Rx Noise Figure (Hittite) | 2 | 4 | 5 | dB |
| Rx G/T | 38 | 35 | 37 | dB/K |
| Rx C/No | 46.8 | 15.7 | 15.1 | dBHz |
| Rx Eb/No | 43.80 | 12.69 | 12.12 | dB |
| Required Rx Eb/No (8PSK BER 10E-6) | 14 | 14 | 14 | dB |
| Channel Bandwidth | 50 | 50 | 100 | MHz |
| Data Rate | 100 | 100 | 200 | Mbps |
| Link Margin (2180km) | 29.80 | -1.31 | -1.88 | dB |
| Link Margin (1000km) | 36.60 | 5.49 | 4.92 | dB |
| Link Margin (500km) | 42.60 | 11.49 | 10.92 | dB |

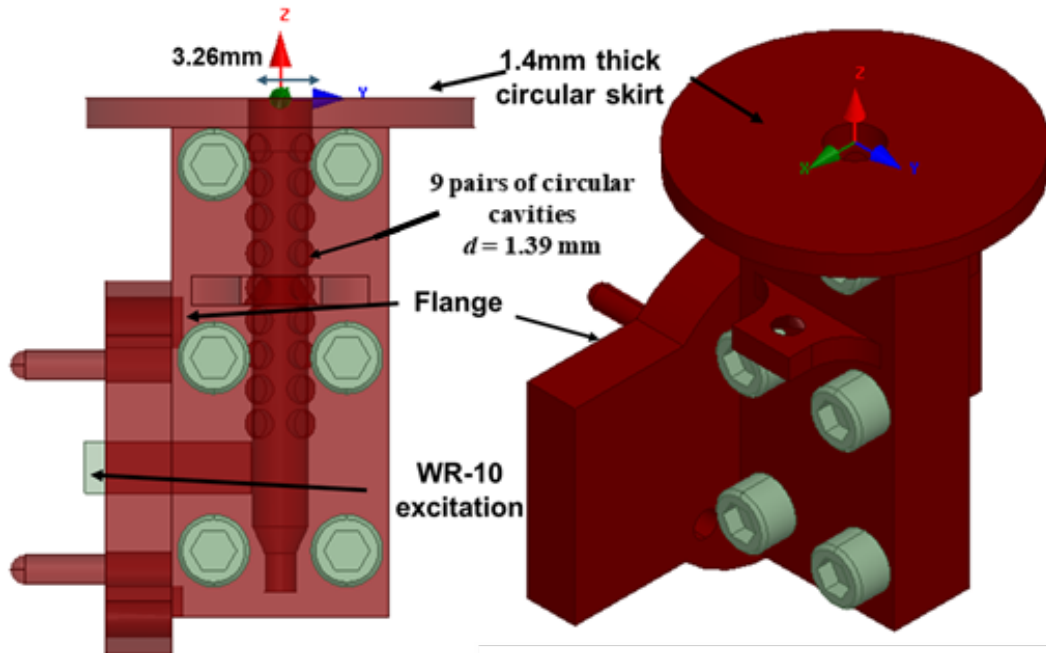


Fig. 1 Designed Geometry of a novel W-band feed horn polarizer.

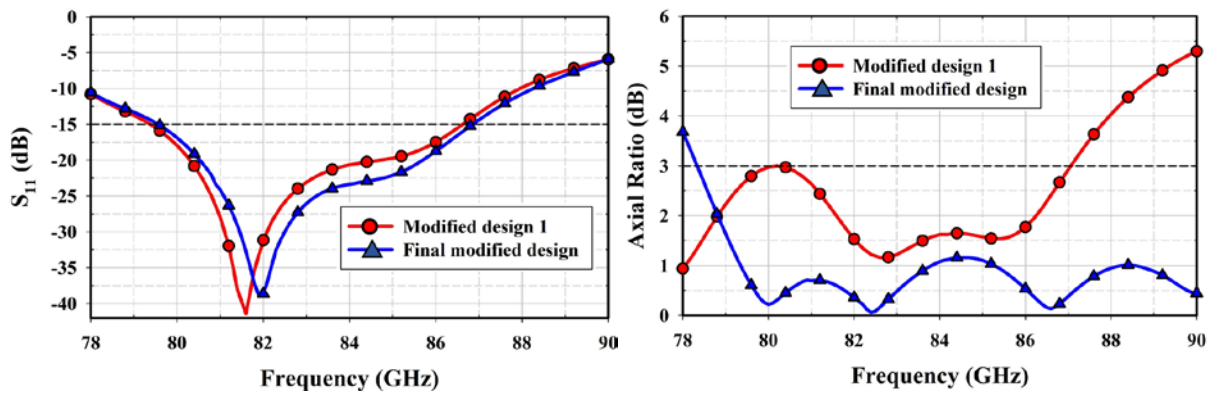


Fig. 2 Simulated reflection coefficient and axial ratio of the feed horn.

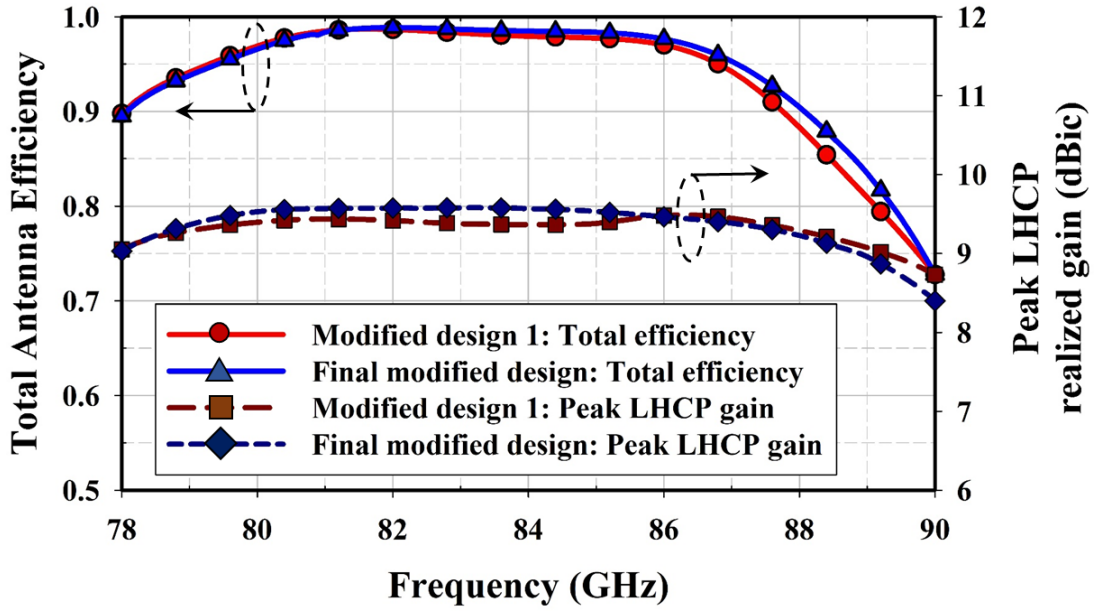


Fig. 3 Simulated total efficiency and peak LHCP gain of feed horn antenna.

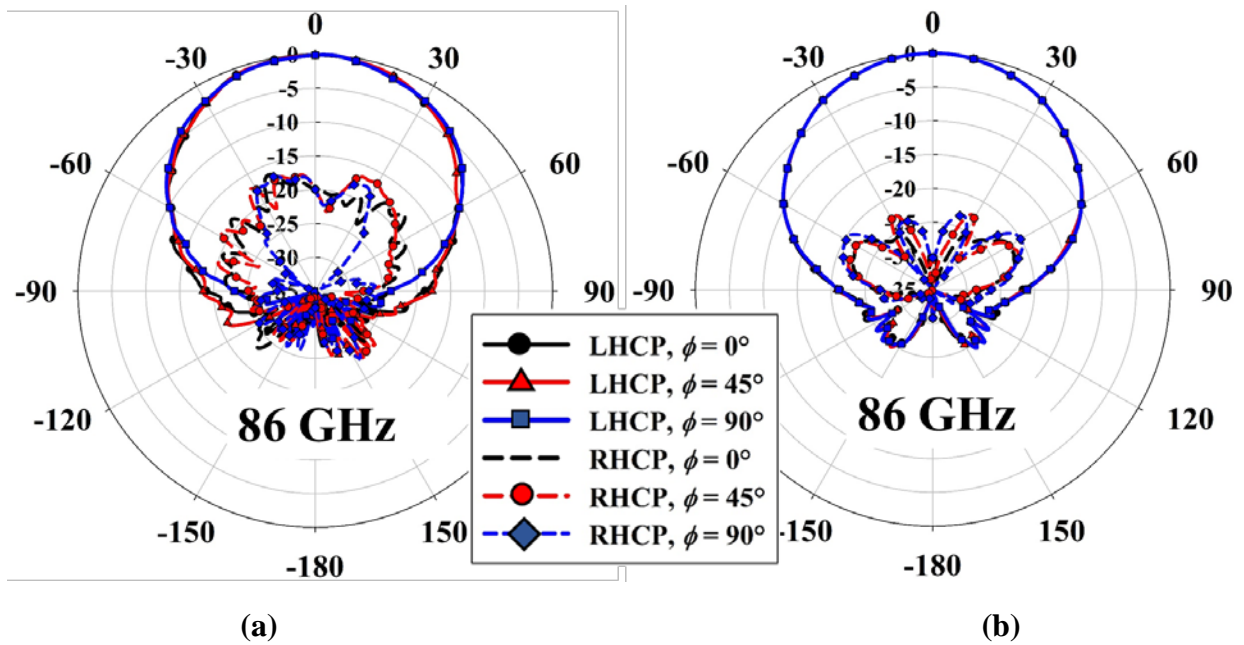


Fig. 4 Comparison of radiation pattern of feed polarizer (a) Initial design (b) Final optimized horn design at 86 GHz.

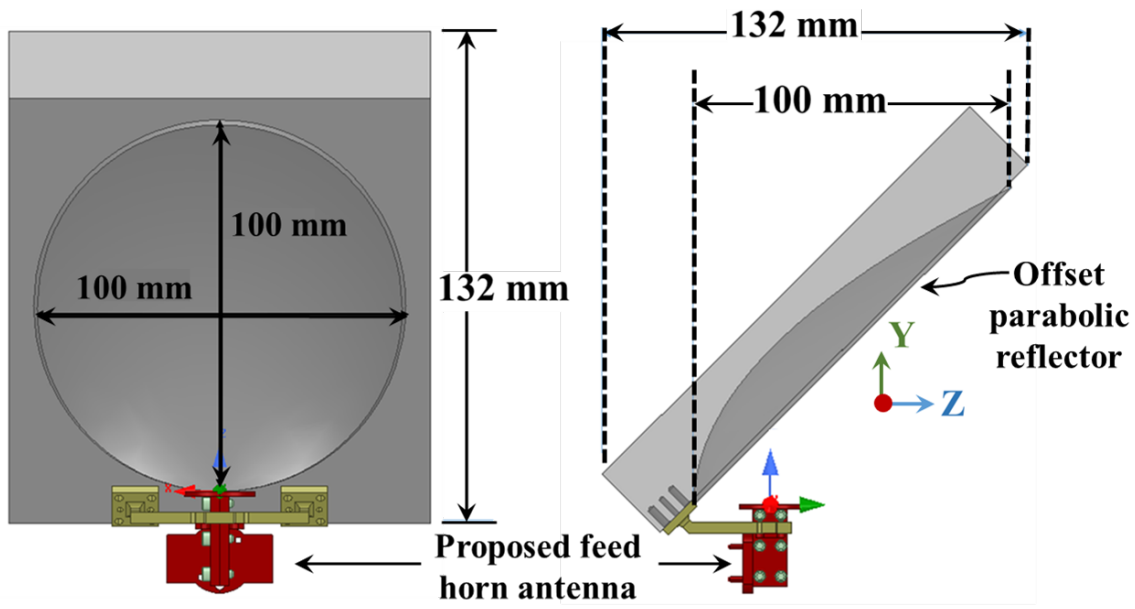


Fig. 5 Reflector and feed geometry integrated. Thick wall of reflector is for ease in fabrication.

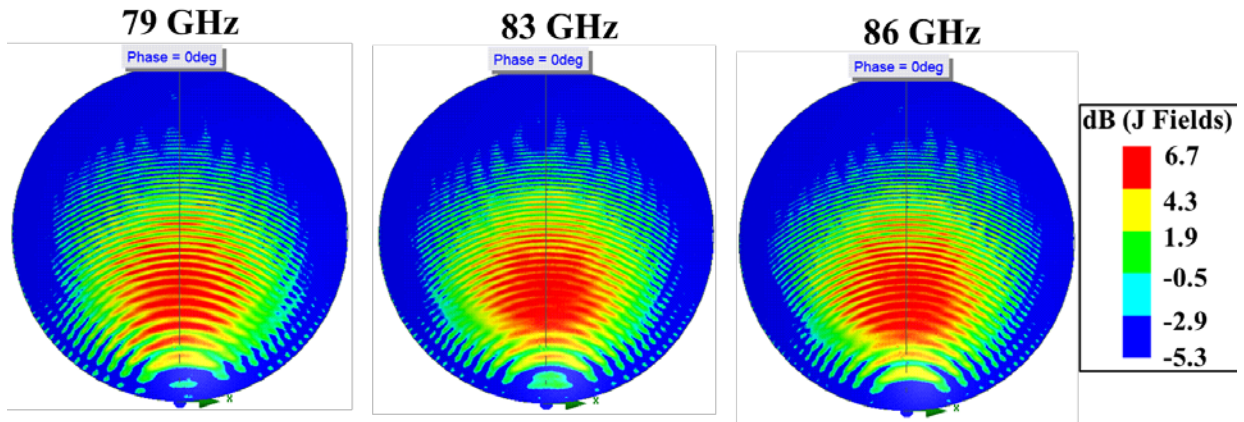


Fig. 6 Current distribution of the reflector at different frequency over the bandwidth.

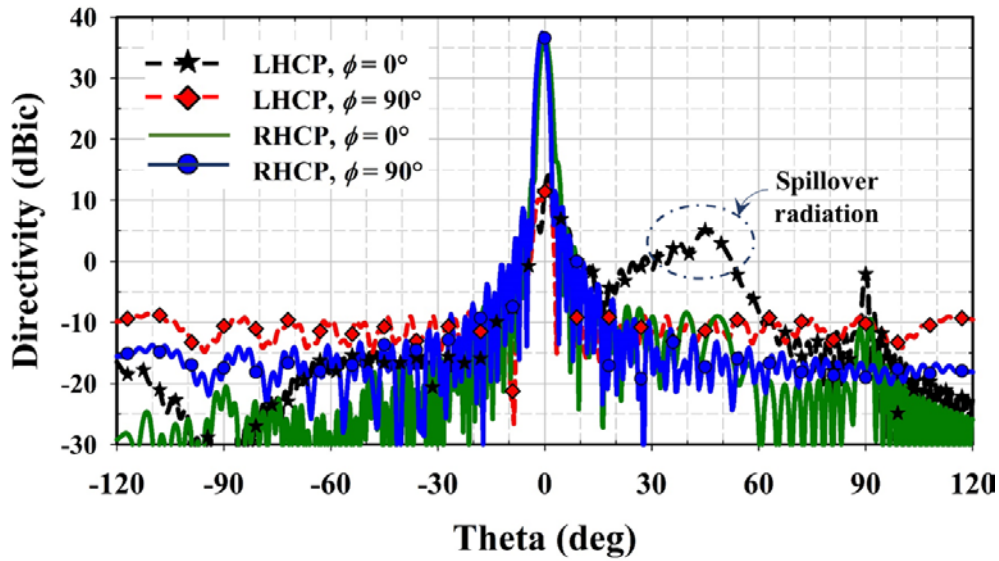


Fig. 7 Directivity pattern of the reflector at 86 GHz.

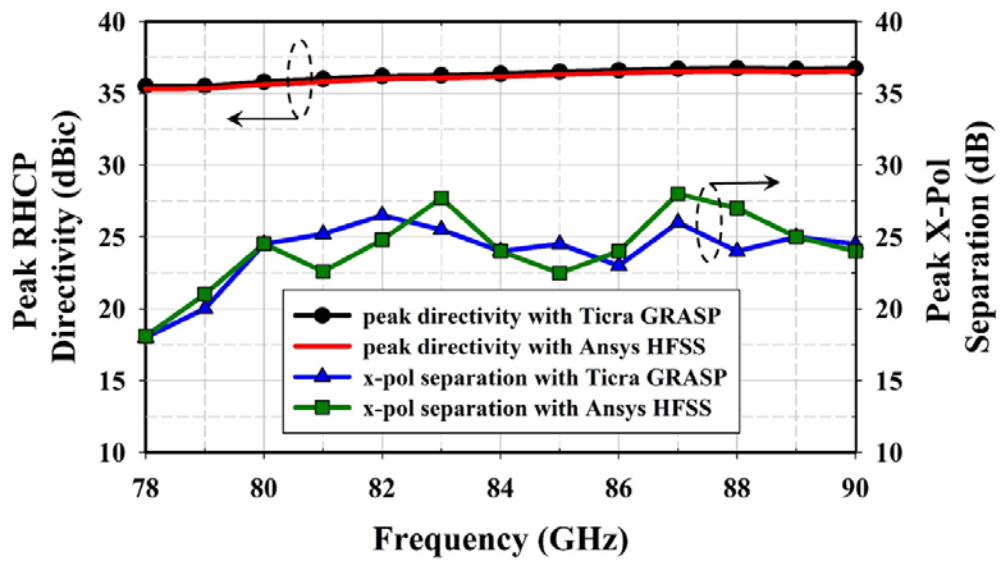
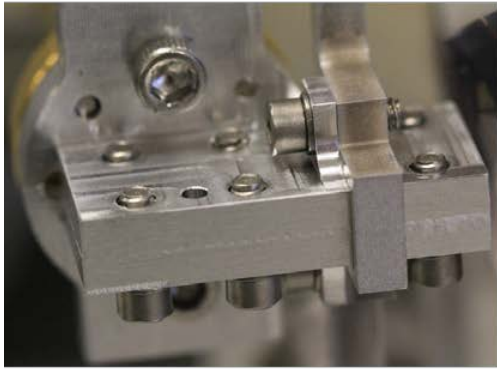
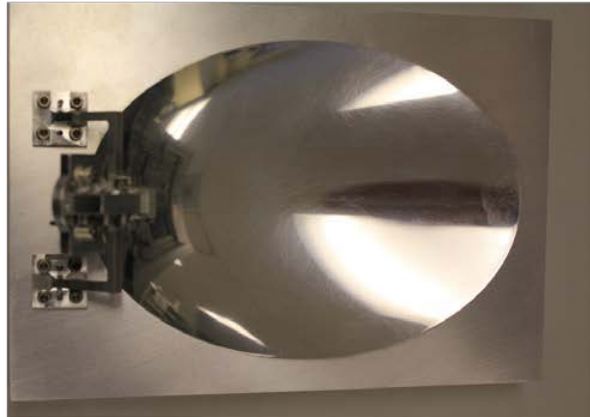


Fig. 8 Peak gain and cross-polarization separation of the reflector.



(a)



(b)

Fig. 9 Fabricated model (a) Feed horn antenna (b) Reflector and feed assembled.

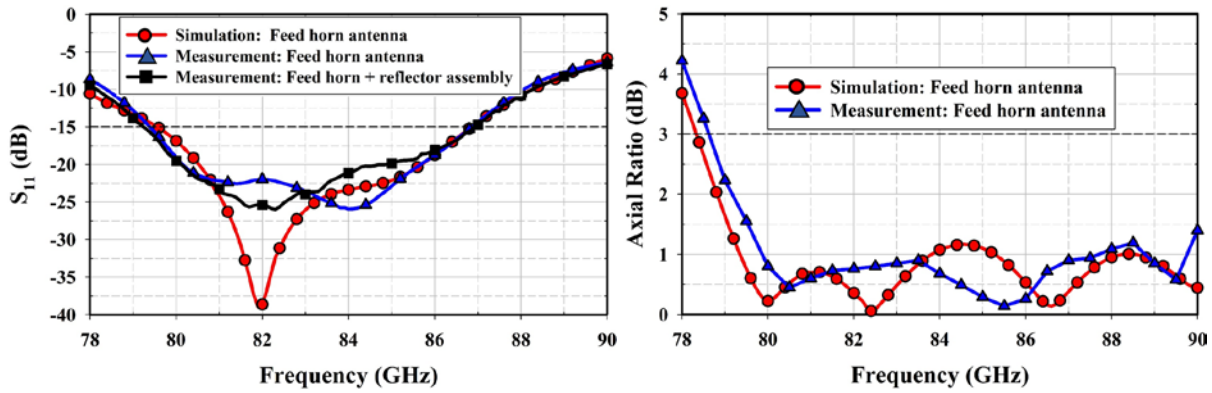


Fig. 10 Simulated and measured reflection coefficient and axial ratio of the feed horn antenna.

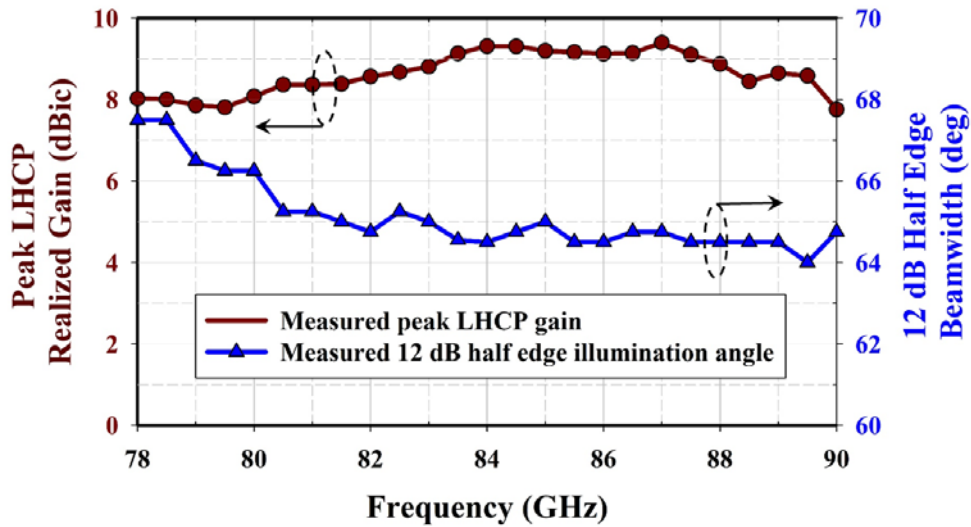


Fig. 11 Measured peak LHCP gain and 12 dB half edge illumination of the feed horn antenna.

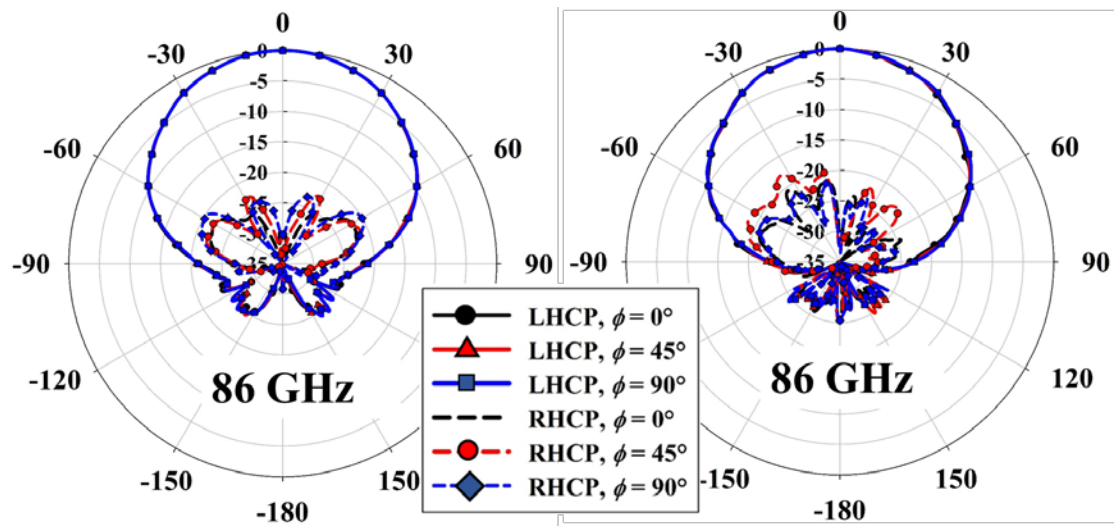
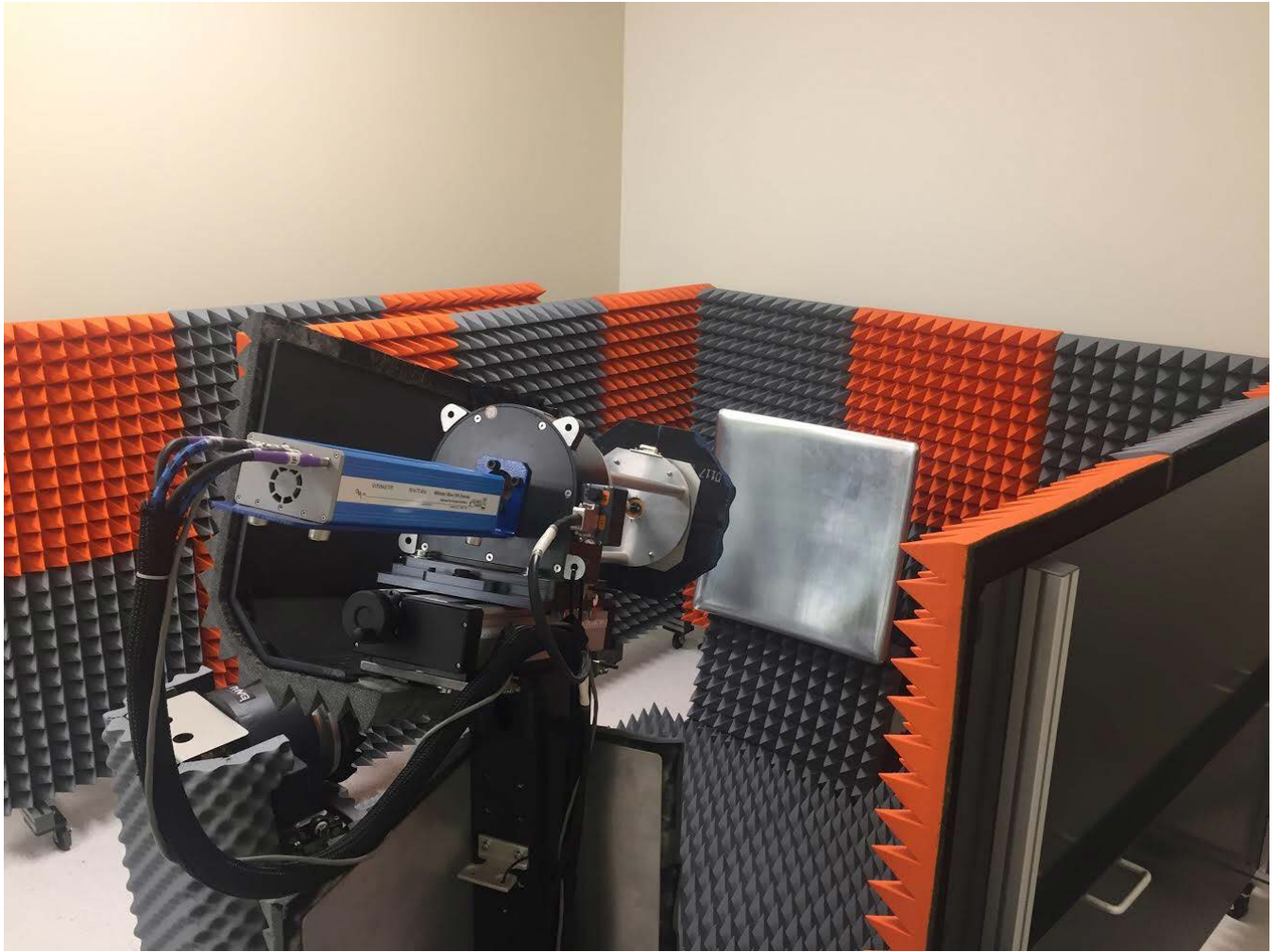


Fig. 12 Simulated and measured 2D radiation pattern of the feed horn antenna at 86 GHz.



(a)



(b)

Fig. 13. (a) MVG spherical near field experimental setup for measurement of integrated feed and reflector antenna (b) Mini-compact anechoic chamber at Antenna and Microwave Lab (AML Lab) at San Diego State University.

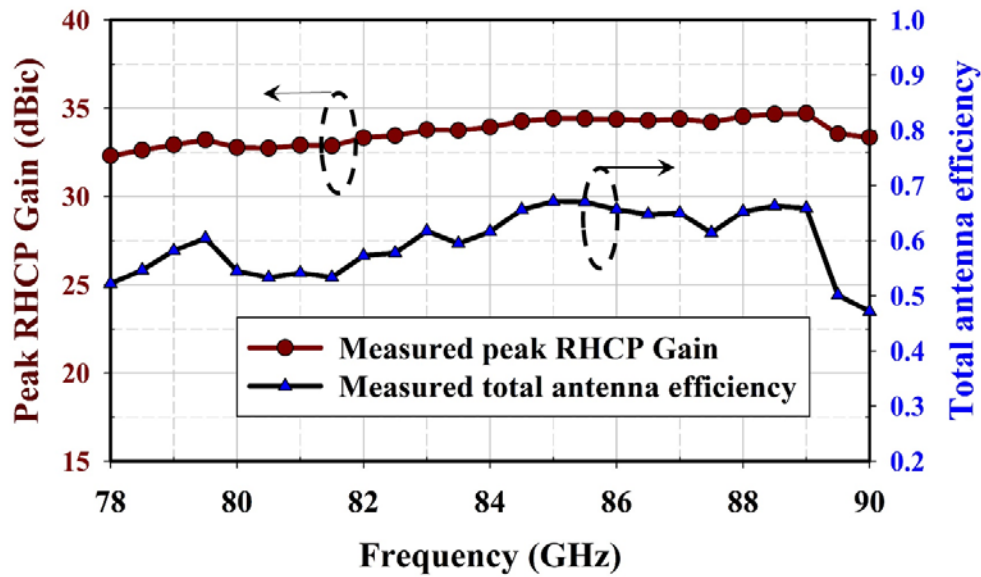


Fig. 14. Measured peak RHCP gain and total antenna efficiency of the integrated feed reflector antenna.

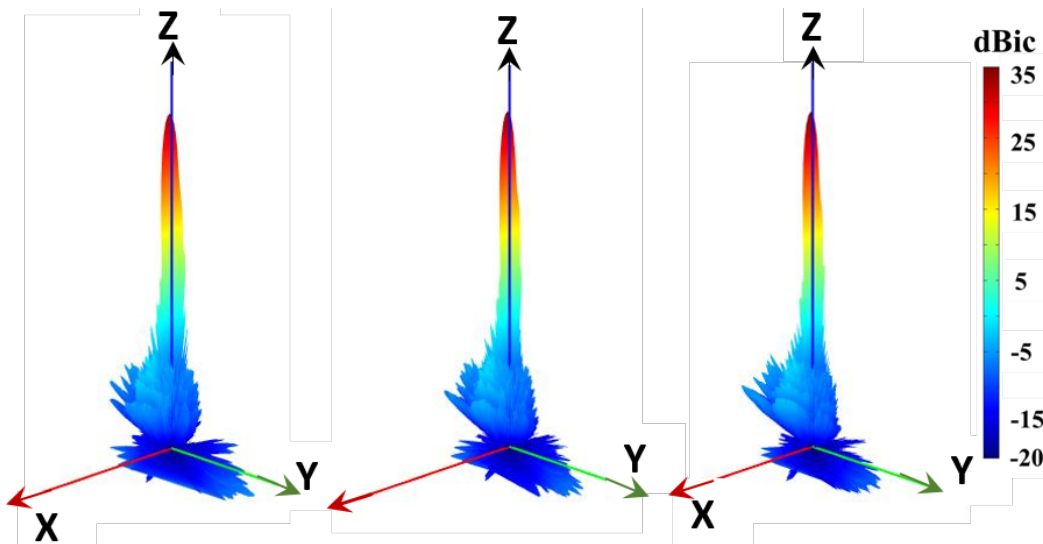


Fig. 15. Measured 3D RHCP gain of the integrated feed reflector antenna at 79 GHz, 83 GHz, and 86 GHz.

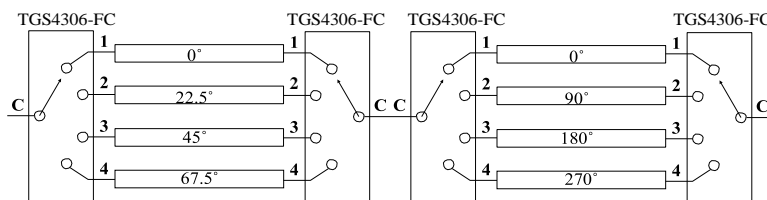


Fig. 16 Schematic of 4-bit phase shifter using SP4T switches.

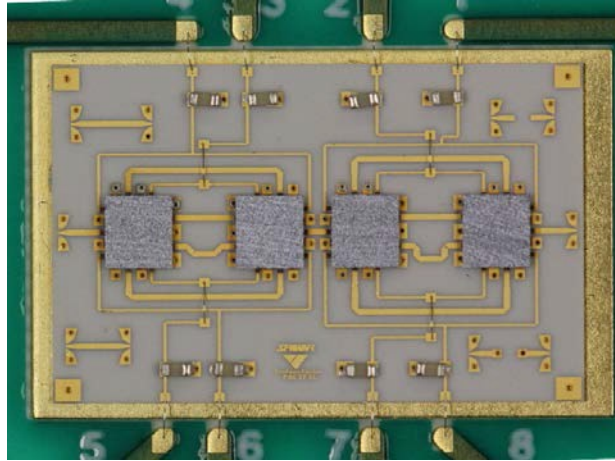


Fig. 17 4-Bit E-Band Phase shifter module with 4 flip-chip SP4T.

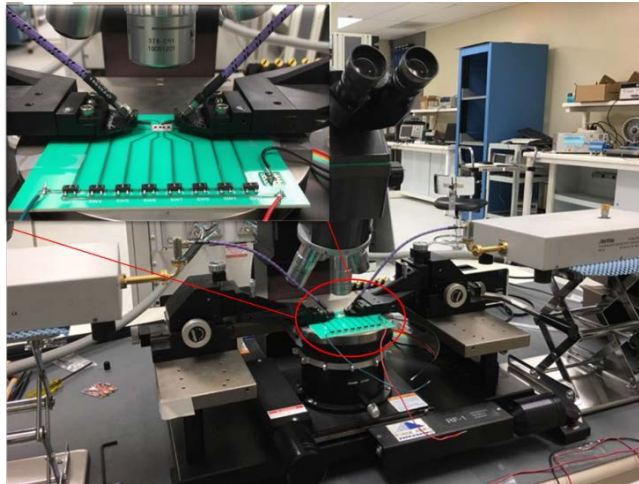


Fig. 18. Anritsu ME7808A millimeter-wave test setup.

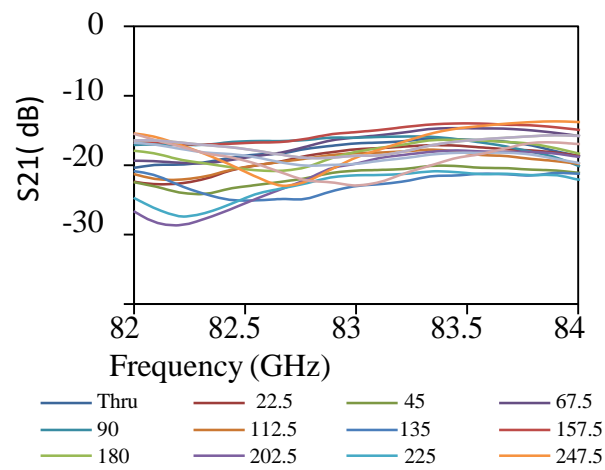


Fig. 19. Measured insertion loss of 16-states.

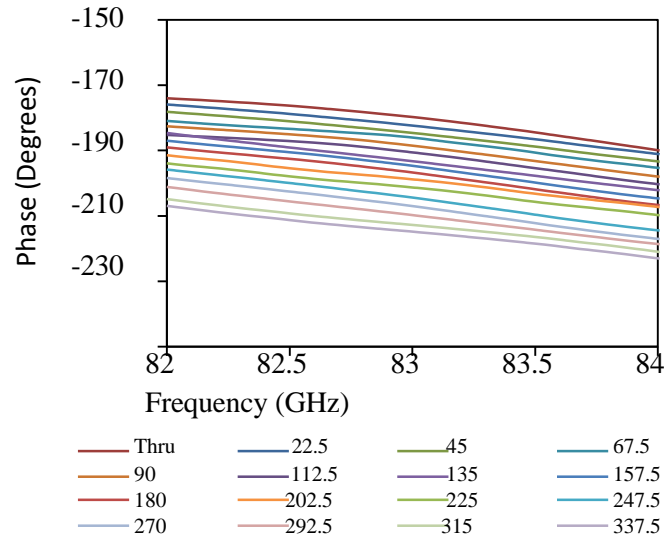


Fig. 20. Measured insertion phase of 16-states.

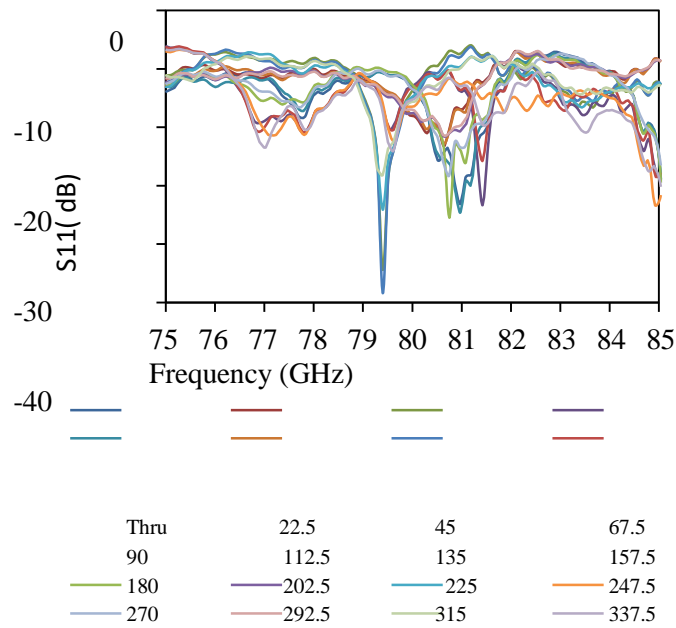


Fig. 21. Measured input return loss.

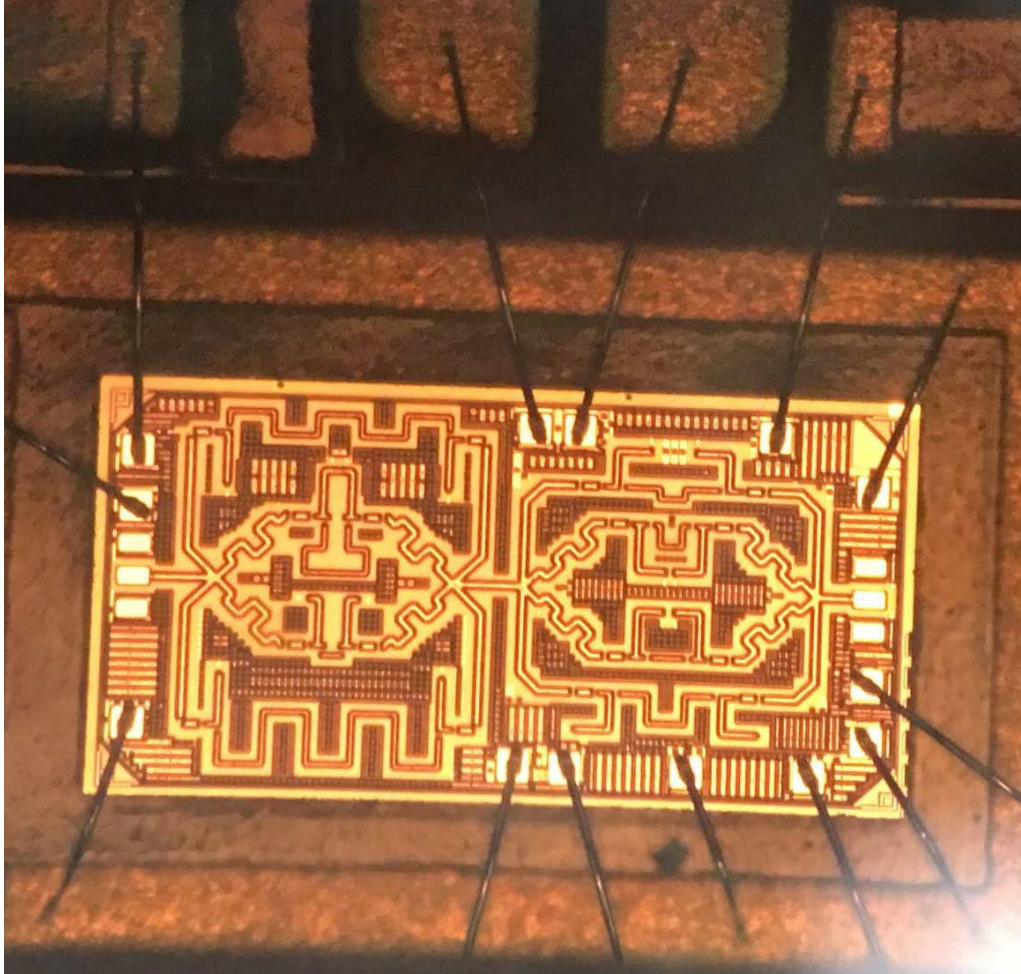


Fig. 22. Fabricated prototype of the 4-bit phase shifter on silicon germanium.

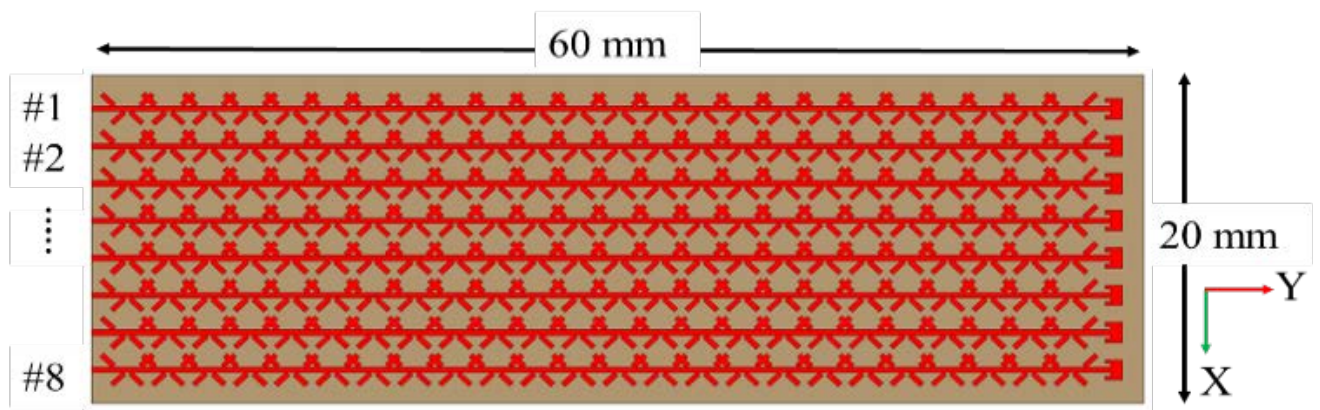
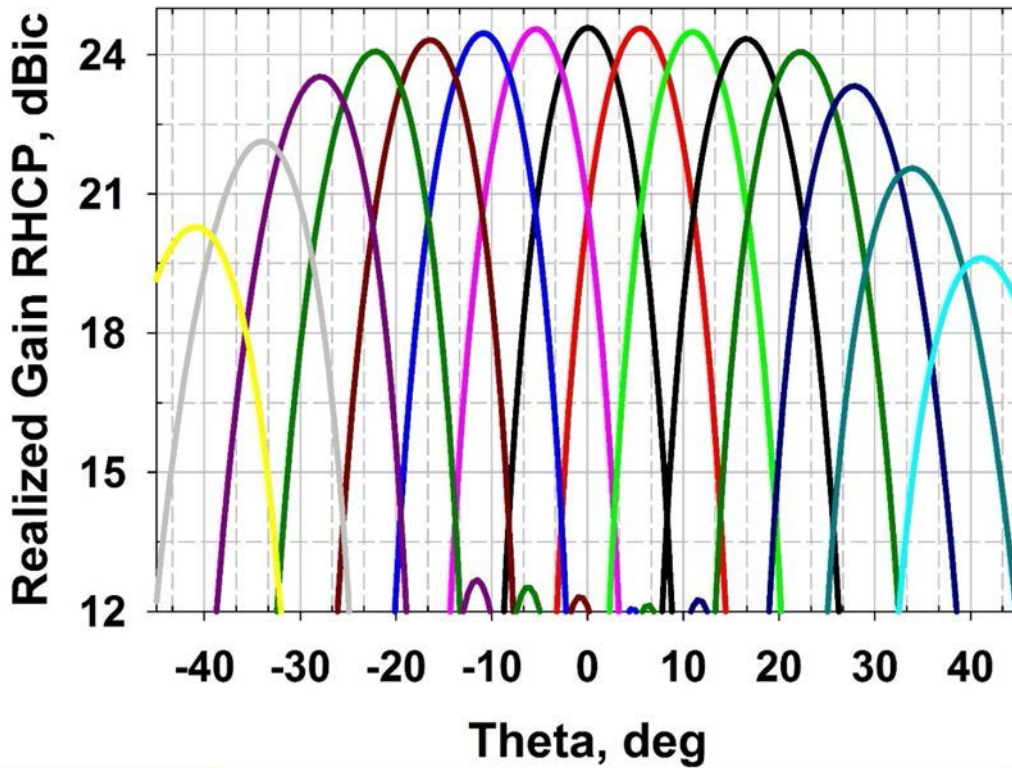


Fig. 23 Eight 1x24 linear arrays of novel butterfly shaped unit elements.

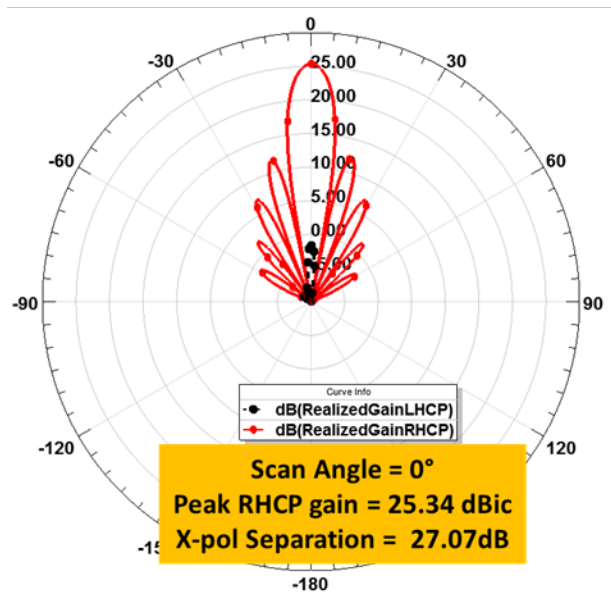
Table II. Comparison of the antenna parameters for the conventional Herringbone and proposed novel Butterfly shaped linear arrays.

| | 1 x 16 Linear array | | 1 x 24 Linear array | | 1 x 32 Linear array | |
|--|------------------------------------|------------------------------------|------------------------------------|------------------------------------|------------------------------------|----------------------------------|
| | Herringbone | Butterfly | Herringbone | Butterfly | Herringbone | Butterfly |
| Peak Realized Gain (dBic) | 15.29 dBic | 16.41 dBic | 15.94 dBic | 16.78 dBic | 15.7 dBic | 16.2 dBic |
| Acceptable Squint Bandwidth | 85.4 GHz - 86.8 GHz BW: 1.4 GHz | 84.4 GHz - 86.2 GHz BW: 1.8 GHz | 84.8 GHz - 86.2 GHz BW: 1.4 GHz | 85.2 GHz - 86.8 GHz BW: 1.6 GHz | 84.8 GHz - 86.2 GHz BW: 1.4 GHz | 84.2 GHz - 86 GHz BW: 1.8 GHz |
| Squint angle in the acceptable bandwidth | 1.5° / -1.0° | 1.6° / -1.8° | 1.2° / -1.1° | 1.6° / -1.4° | 1.2° / -1° | 1.6° / -2° |
| Total antenna efficiency | 67.50% | 69.97% | 68.09% | 70.50% | 67.80% | 67.07% |

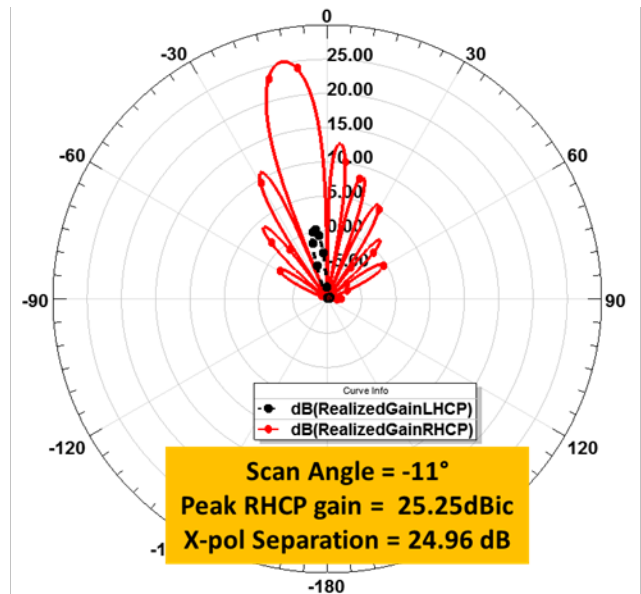


**Symmetric beam scanning of +/- 34°
for 3 dB reduction in gain**

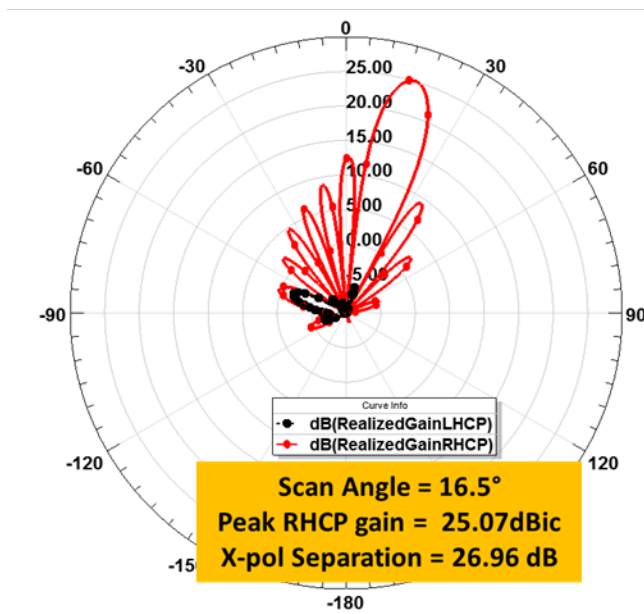
Fig. 24 Beam steering performance of the 8 x 24 aperture array using 4-bit phase shifter.



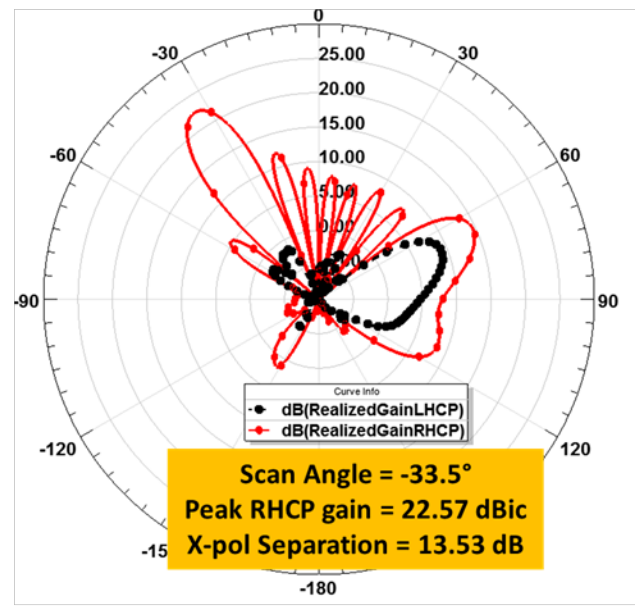
(a)



(b)



(c)



(d)

Fig. 25 Beam scanning radiation pattern with different progressive phase shift (a) 0° (b) 45° (c) -67.5° (d) 135° .

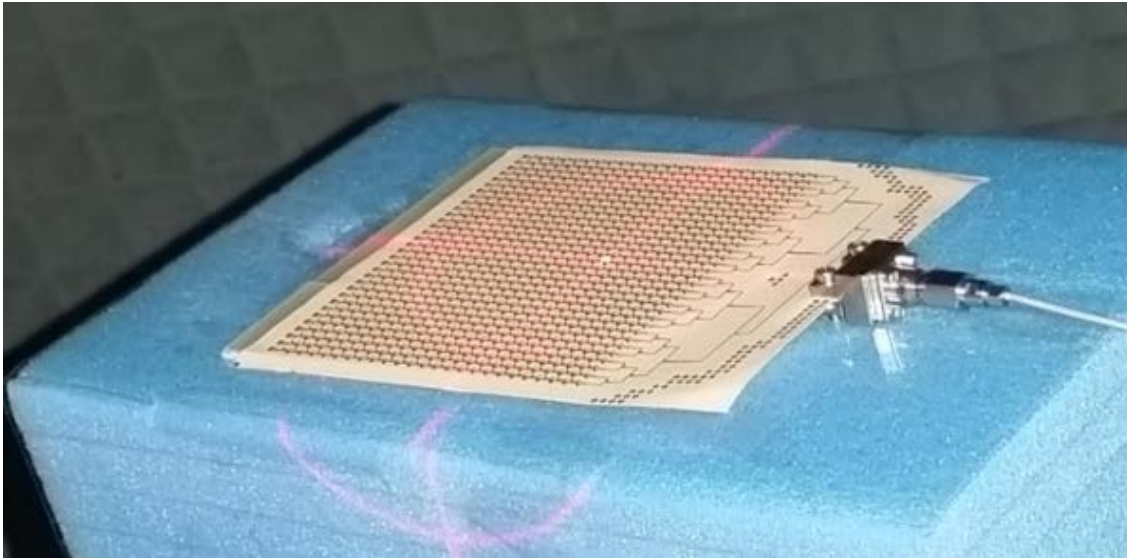


Fig. 26. MVG spherical near field experimental setup for measurement of 32×24 passive aperture array antenna.

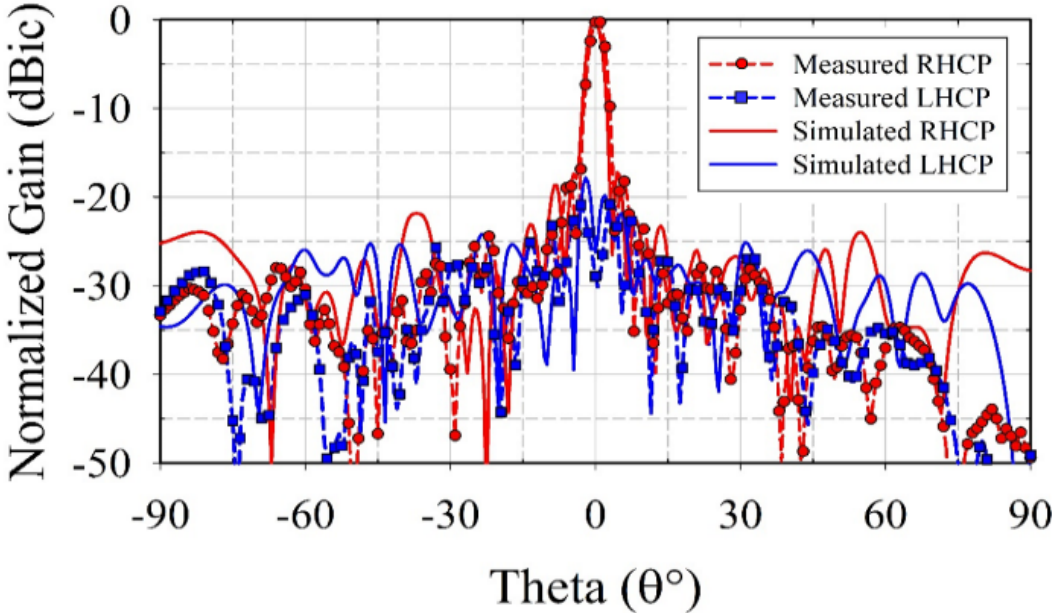


Fig. 27. Measured normalized gain of the 32×24 aperture array antenna.

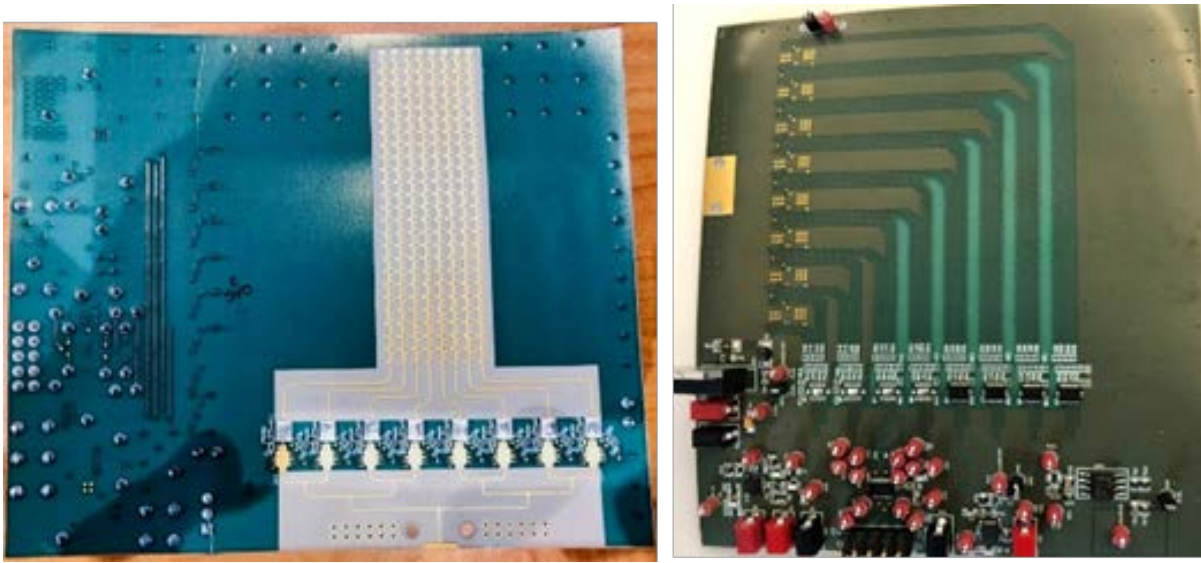


Fig. 28 Photograph of the fabricated phased array antenna with integrated beamforming board.

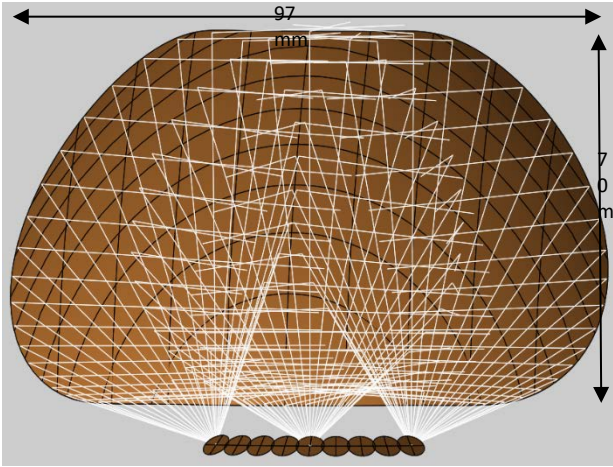


Fig.29: TICRA model of Torus Reflector with multiple feeds ($f/D = 0.6$)

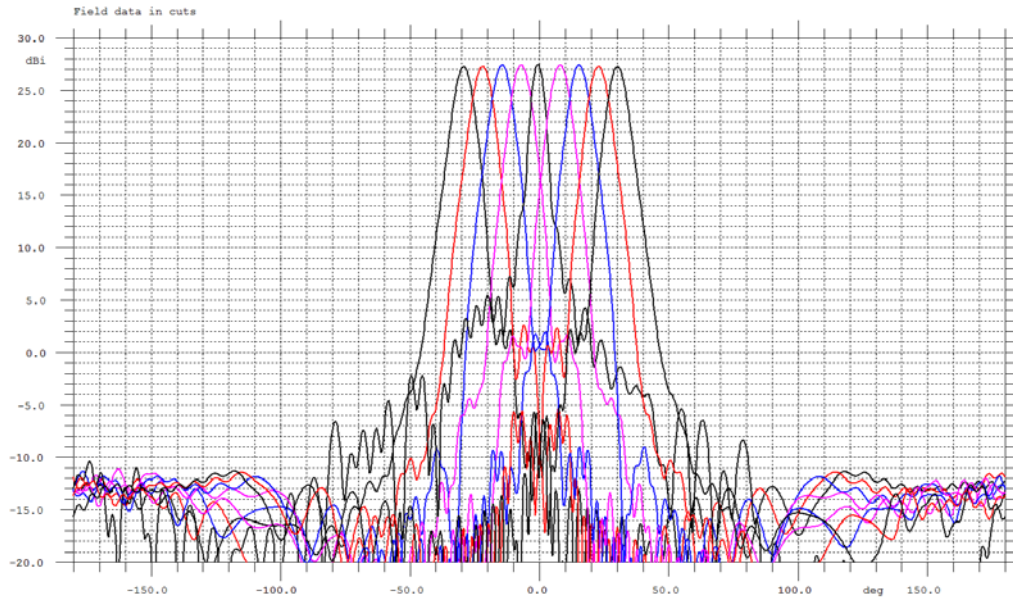


Fig.30 : Simulated secondary radiation pattern (Reflector F/D = 0.6)

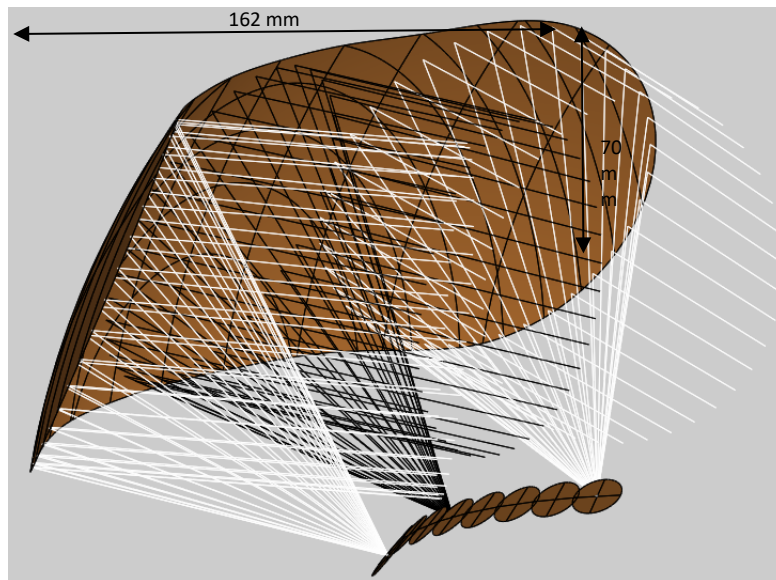


Fig.31: TICRA model of Torus Reflector with multiple feeds (f/D = 1.0)

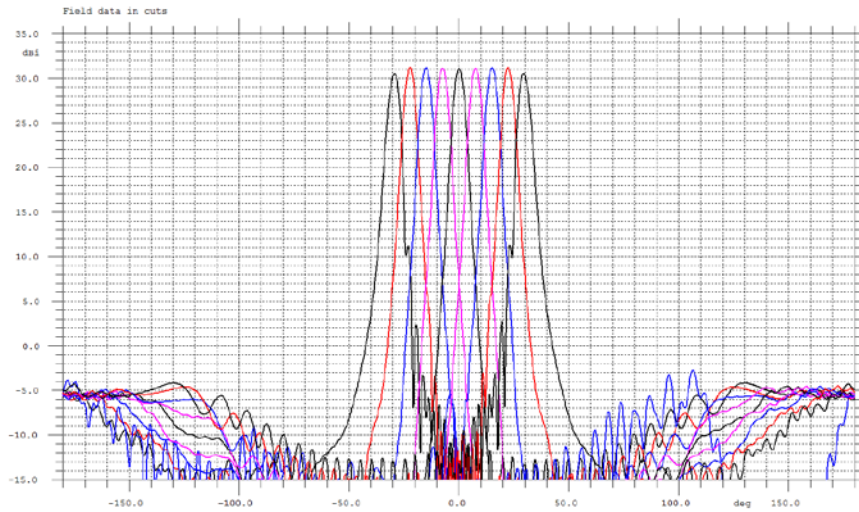


Fig.32: Simulated secondary radiation pattern (Reflector $F/D = 1.0$) showing multiple beams.

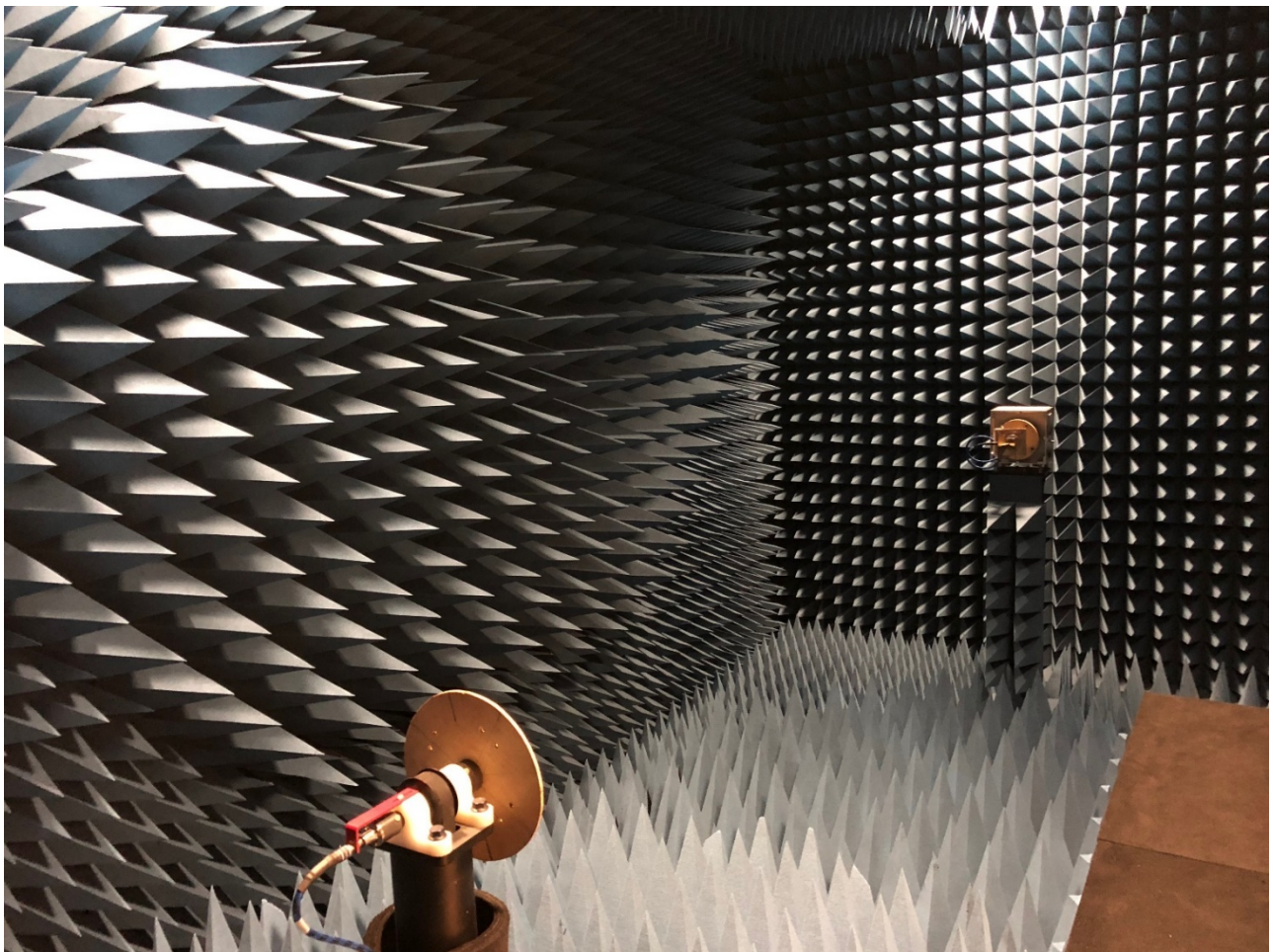


Fig. 33 Upgraded anechoic chamber at Antenna and Microwave Lab (AML Lab) at San Diego State University.

