Investigations on An X-Band Experimental 64 Element Active Phased Array

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Abstract:

This paper presents design and development of an active phased array in X-Band with 64 elements. The array has been designed and evaluated successfully meeting with the design specifications. The present paper discusses the various design aspects of the array along with the pattern measurement aspects. An array calibration method has been proposed to achieve very low sidelobe levels (<-40dB) for a large size active array. The measured results of the antenna array and its various components are also listed. This X-Band active array has been realized for the first time in India. This work has been carried with an impetus towards X-Band active phased array radars development within the country.

Key Words: active phased array, active element pattern, transmit/receive module, noise Figure..

I. INTRODUCTION

State of the art airborne radars use electronically scanning active aperture arrays with a wide scanning volume over a wide operational bandwidth. The advantages of active phased arrays are innumerable**[1,2,3]**. In Active Electronically Scanned Arrays(AESAs), the multiplicity of elements allows precise control of beam patterns. The main advantages of wide bandwidth active phased array antennas are the beam agility, increased Electronic Counter Counter Measure(ECCM) performance, high availability and the Low Probability of Intercept(LOI) features**[4,9]**. The frequency agility feature as an ECCM measure for the active array heavily depends on the bandwidth of the array, which in turn mainly depends on the array element. The bandwidth requirements of phased arrays increases because of new applications demanding wider operating bandwidths. Wide bandwidth phased arrays have many applications, where multifunctional systems being one of the most popular uses. Another important factor in the design is the scan sector, for which the antenna element beamwidth becomes a significant parameter. The wide angle scan is possible only with a wide beamwidth antenna element.

The design of such a high performance, cost effective Active Aperture Array within the weight, size and volume constraints is very critical right from choosing the array grid architecture, radiating element structures and array feed networks. These types of radars require transmit/receive modules (TRM) to be integrated with each of the antenna element in the active phased array for electronic scanning capabilities and high EIRP to achieve longer radar ranges. This paper presents detailed design and development of the array and also measured results to validate the studies carried out.

II. ARRAY ARCHITECTURE AND DESIGN

The 64(16 x4) antenna elements are arranged in four numbers of vertical sticks called planks with 16 elements each. The elements are arranged in a triangular grid fashion (which uses 13% less elements compared to rectangular grid) with spacing suitable to cater for a scan volume of +/- 60° in Azimuth and +/-50° in Elevation at the highest frequency of operation (f_h). The Required radar coverage Diagram is given in Figure.1(a). In the Diagram, the inner ellipse shows the actual coverage area. The outer rectangular area coverage is also possible with slight degradation in the antenna gain performance. The triangular arrangement, required coverage and the schematic of antenna array have been shown in **Figure. 1.**

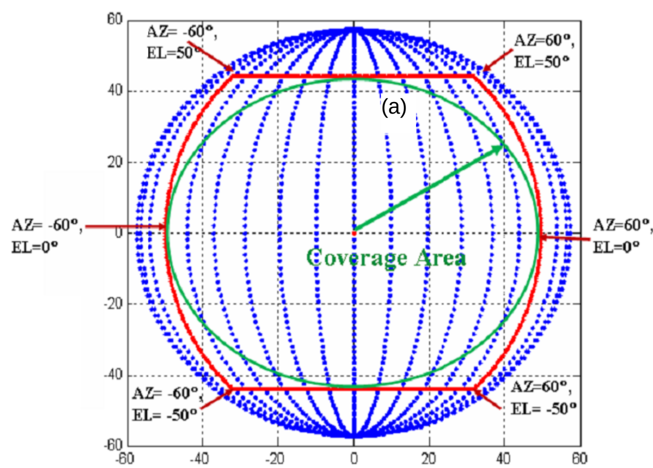
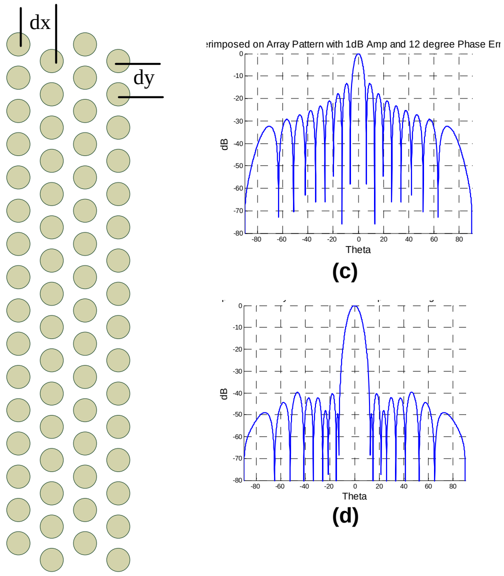


Figure.1 64 Element array -(a) Required Coverage Diagram



(b)

Figure. 1: 64 Element array **(b)** Element arrangement **(c)**Transmit Radiation Pattern **(d)**Receive Radiation Pattern

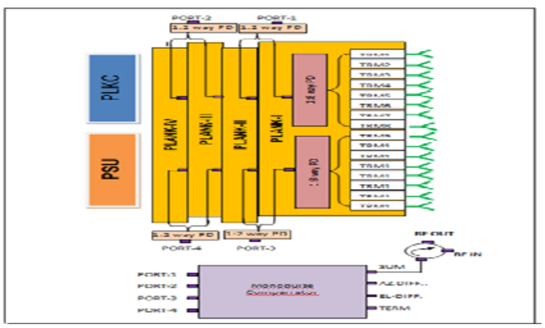


Figure. 1(e) Schematic of 64 element antenna array

Parameter	9-10GHz
Frequency range	21dB±0.5dB in TX
Gain	20dB±0.5dB in RX
Beam Width	7.5°±0.5°(El),26.5°±2°(Az) RX
	5.5°±0.5°(El),24.5°±2°(Az) TX
Sidelobe level	26dB±2dB(El) ,13dB±2dB(AZ) in RX
	13dB±2dB(El&AZ) in TX

Table 1. Designed Specifications of Array

The antenna array consists of 4 planks each with 16 antenna elements integrated with 16 Transmit/Receive Modules and associated RF feed network, power supply, Digital Controllers and cooling network. The array has been conFigure.d to generate monopulse output in Azimuth and Elevation axis. The specifications of the array is given in **Table 1**.

1 ANTENNA ELEMENT

The choice of antenna element is very critical in designing active arrays particularly for airborne applications. The first step in the design of any active phased array is to investigate the array architecture and configuration. The array grid with suitable interelement spacing is required for the scan performance. The antenna element should be designed in such a way so as to fit into the array grid. In the present array the system requirements are met by using a very close interelement spacing(dx ~0.5λ and dy~ 0.5λ), which places an upper limit on the size of the elements. Acceptable performance is determined by meeting radiation pattern, gain, impedance and polarization requirements over the bandwidth as well as scan range. To achieve large scan angles in all planes(AZ=±60°, EL=±50°), broad beamwidths are required in both the E and H planes. A narrow beamwidth element reduces the maximum scan angle achieved by an array due to loss of gain at large scan angles. The bandwidth (impedance as well as pattern) of the element must be large enough to meet the array requirements.

In the present case, A printed dipole has been used as the antenna element**[5,6]**. The dipole element has been designed for a wide bandwidth(11% in X-Band) and wide beamwidth of the order of 120 deg. in Azimuth and 100 deg. in Elevation.

2 ANTENNA ELEMENT PERFORMANCE IN THE ARRAY ENVIRONMENT.

The effect of mutual coupling on array performance can be studied in terms of embedded element or active element pattern. To study these effects, a 16 x 4 element array has been fabricated and tested the performance of the antenna element in the array environment and the results are shown in Figure. 2. The single element pattern in the array environment will provide the phased array antenna gain at the position of the scanned beam as a function of scan angle.

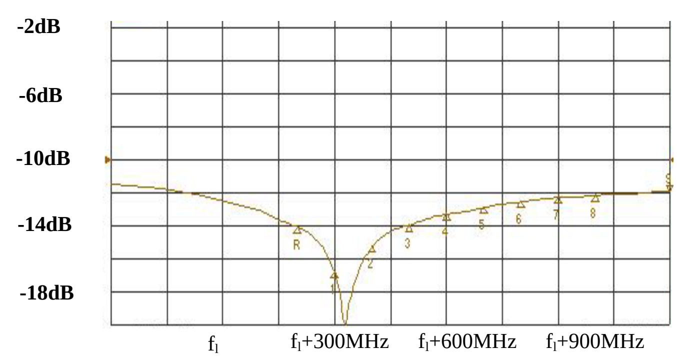


Figure. 2: (a) Return Loss of antenna element

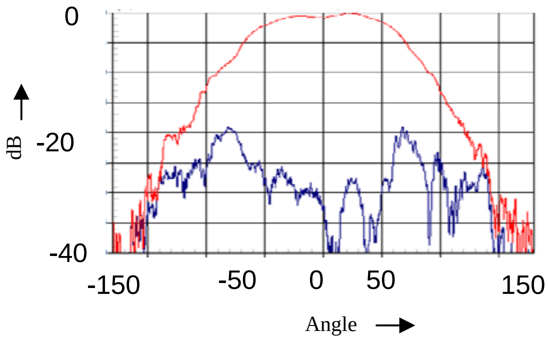


Figure. 2: (b) Radiation Pattern of Antenna Element(EL)

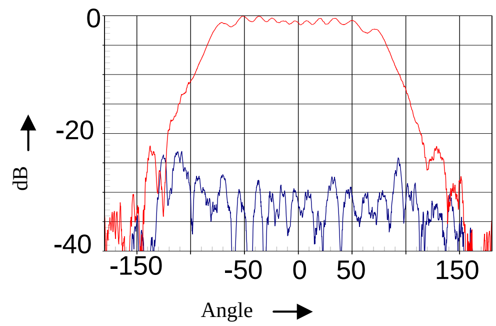


Figure. 2: (c) Radiation Pattern of Antenna Element(Az)

Figure. 2: (d) Antenna Elements arranged in (16 x4) array

3 TRANSMIT/RECEIVE MODULE(TRM)

The T/R Modules(TRMs) are the key elements in active phased arrays**[7,8,11,12**]. The cost and performance of the active array critically depend on the availability of compact, light weight, low consumption and high reliability T/R modules. The major functions of the T/R module include the generation of transmit power, low noise amplification of the received signals from the respective radiating element, required phase shift in the transmit and receive mode for beam steering and variable gain setting for aperture weighting through attenuators and proper interface to the array beam steering controller as well as array beam former and radiating element. The schematic diagram of the T/R module used in the active phased array described in this paper is shown in **Figure. 3(a)**. The realised module is shown in **Figure.3(b)& 3(c)**. Here, the transmit chain of the T/R Module consists of Solid state power amplifiers to boost the signal from the Array RF manifold and pass it on to the antenna. The output can be a few watts to several 100 watts depends on the application requirement. The receive chain consists of a Limiter followed by a Low Noise Amplifier(LNA).

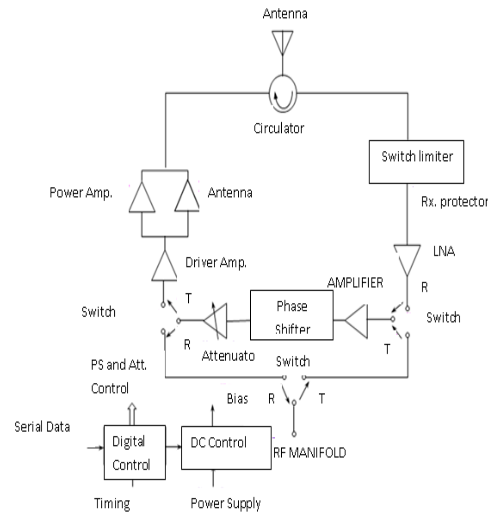


Figure. 3(a): Schematic of Transmit/Receive Module

An innovative architecture has been conceived for the Transmit/Receive Module (TRM) in X-Band in order to minimize coupling effects between adjacent TRM paths when used in active phased arrays. In this design, a monopack housing has been chosen and hence the size of TRM is very much constrained and challenge lies in identification of suitable components which can be housed in a single enclosure. The digital attenuator and phase shifter are placed in the common path of transmit and receive module. The RF chain of the TRM is made out of a 3 chip configuration which consists of MMIC(Microwave Monolithic Integrated Circuit) based core chip, Power Amplifier and LNA. the core chip contains the phase shifter and attenuator and also the buffer amplifiers. A temperature monitoring system also has been built into the module for monitoring the online temperature of the module. A T/R Module controller(TRMC) based on FPGAs housed inside the T/R Module**[12]**. The key functionality of a TRMC is to latch the phase and attenuation values to phase shifter and attenuator in the common leg of the RF chain in a synchronized way, so that beam can be shaped and steered in the space for both transmit and receive modes[8]. Besides, it should monitor the health status of the module in terms of temperature, power and DC supply check.

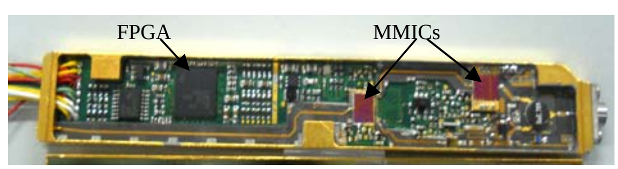


Figure. 3 (b) Photograph of Transmit/Receive Module(exploded view).

Figure. 3 (c) Photograph of Transmit/Receive Module(top view).

The T/R Module(TRM) has been housed in its own package (monopack TRMs) in order to minimize coupling effects between adjacent TRM paths when used in active phased arrays. The TRM consists of MMIC based Transmit//Receive chains with a core-chip consists of phase shifter, and attenuator placed in the common leg of the T/R Module. The Architecture of the TRM has been selected to fit within a size of 100mm x 14mm x 4.5mm with a weight of 20gm. The TRMC is able to transmit/receive serial data with speed around 20Mbps in full duplex mode. For ensuring good signal integrity, the TRMC has LVDS lines for sending and receiving data and command respectively. The TRMC monitor the temperature of power amplifier in the RF chain continuously and send the values serially to the other controller up the hierarchy on a query basis. The TRM digital controller has to switch the attenuation and phase values for both transmit and receive modes, meeting the required timing specifications.

III. ANTENNA ARRAY REALIZATION

The 64 element antenna array with all the associated electronics and cooling arrangement has been realised and is shown in **Figure. 4**.

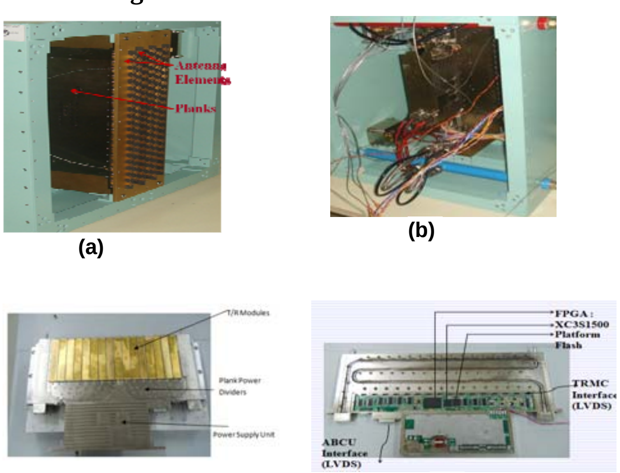


Figure. 4: 64 element array (a) Front View (b) Rear view

(c): Top view of Plank (d): Rear view of Plank

Figure. 4(a) shows the antenna front view with antenna elements and **Figure. 4(b)** shows the rear side of the array. The arrangemnet of T/Rmodules in the plank is shown in **Figure. 4(c)** and the cooling arrangement is shown at the back side of plank in Figure.4(d).

The array has been assembled and tested for its health status. During the health checking all the Planks, TRMs has been addressed and checked for its proper functionality through a Graphical User Interface designed for checking the array. After verifying the health of each unit the array has been declared functionally good and ready for the radiation pattern measurement.

IV. ANTENNA ARRAY TESTING

In order to maintain the antenna performance under all specified conditions appropriate built-in tests and calibration means have to be incorporated in the Active Antenna Array Unit(AAAU). The TRMs have been subjected to gain/phase measurements over the frequency band in transmit as well as in receive configuration. The modules have also been tested over the temperature of -40°C to +55°C. The 1 dB compression point of the different modules are also investigated. Each of these results are shown in the following sections.

1: TRM gain/phase Curves

In order to maintain good performance the attenuator should maintain a constant phase over the attenuation states(2^n, where n is number of attenuator bits) and the phase shifter should maintain a constant attenuation over the entire phase states(2^n, n is the number of phase shifter bits) over the frequency bandwidth of operation. Practically there will be some error in the attenuation and phase values which can be set by the phase shifter and attenuator. These errors have to be corrected in active arrays by suitable methods in order to obtain optimum array performance. There employs a digital control circuitry to activate/deactivate the phase shifter and attenuator bits depends on the sidelobe level and scan requirements. The realised TRMs have been tested for its phase and attenuation behaviours over the phase shifter and attenuator states using a suitable Automatic Test Equipment(ATE). A typical test result of a TRM is shown in **Figure. 5(a)**.

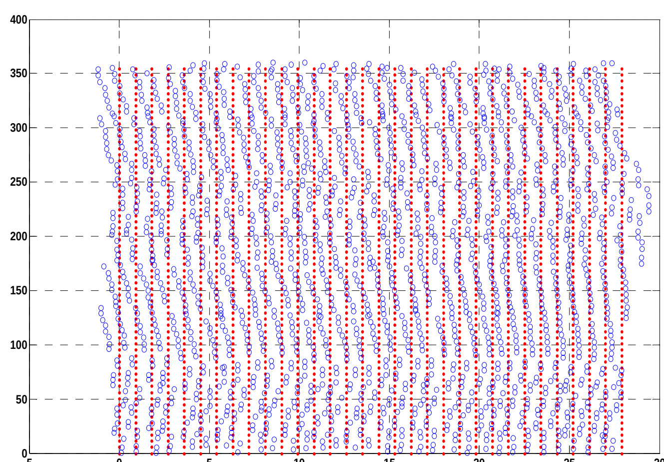


Figure. 5(a). Typical measured TRM states(circles) and Ideal TRM states(dots)

Figure. 5(b) shows the measured and optimized phase errors for each of the phase shifter states. A suitable Algorithm can be used to achieve the nearest states and the TRM states can be mapped into a TRMP-MAP. A Nearest State Algorithm(NSA) has been proposed to use here and the theoretical studies are presented. **Figure.5(c)** shows the measured and optimized attenuation errors for each of the attenuator states. These errors can be corrected by suitable algorithms and the results shows an rms phase error of ~1.8° and an rms attenuation error of 0.28dB which are very promising values to be used with active phased arrays to achieve good antenna array performance.

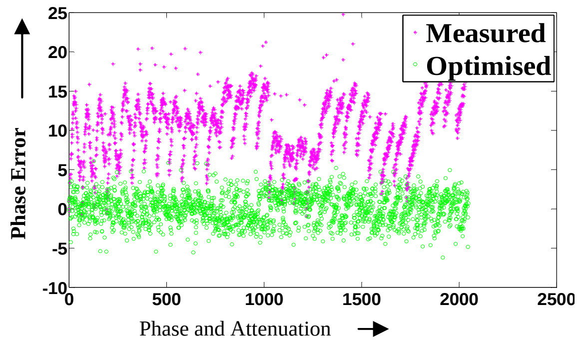


Figure.5(b) Measured and optimised Phase errors

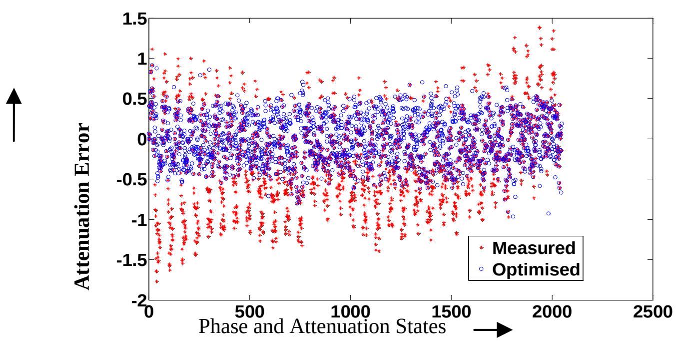


Figure.5(c) Measured and Optimised Attenuation errors

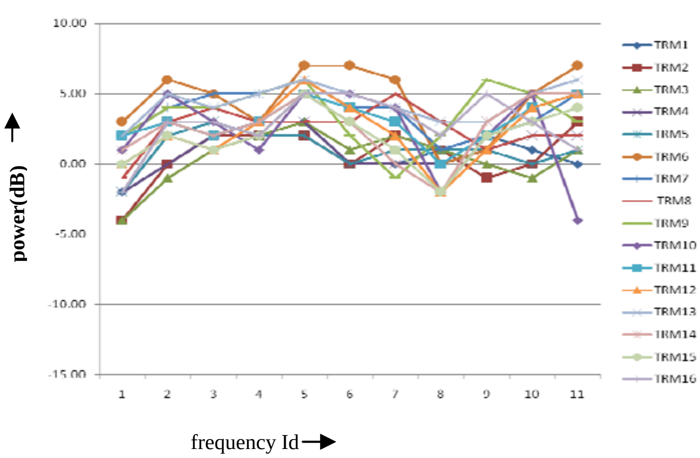


Figure.6. Differences in P1-dB compression point of TRMs in Plank-1

2. P1 DB COMPRESSION POINT OF TRMS

The P1dB Compression point of TRMs have measured for all the 64 Modules in different planks. A Typical measured results is shown in **Figure.6** for plank1. This shows that different modules are reaching the P1 dB compression point at different input power levels. It shows that typically the variation is from -4dBm to +6dBm. This indicates the importance of transmit calibration of the active array in order to maintain a uniform radiation pattern.

3: TRM TEMPERATURE

The present Active Array Antenna Unit(AAAU) is based on temperature compensation of the TRMs. The influence of temperature affects the transmission/reception data of the TRMs. Typical variations over Rx and Tx gain is presented.. **Figure. 7(a) and Figure. 7(b)** have shown the gain variations for a typical transmit and receive module over the lowest(f_l), center(f_c) and highest(f_h) frequencies.

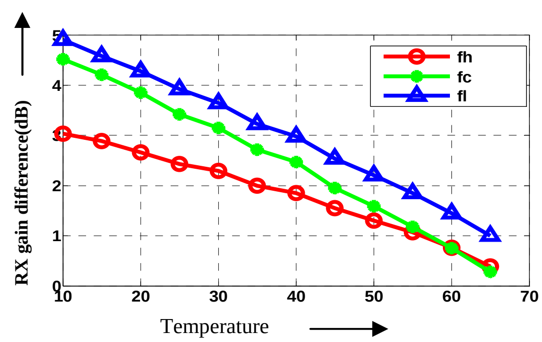


Figure..7(a): variation of Rx gain over temperature and frequency.

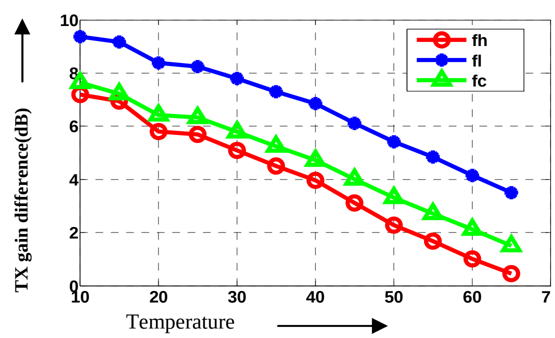


Figure.7(b) variation of Tx gain over temperature and frequency.

4. RADIATION PATTERN MEASUREMENT.

The antenna array testing has been carried out in near field antenna test range. This has been accomplished using Single element adjustment method**[10]**. In this method only one TRM is switched on, all others are off. The RF-Probe of the Near-Field Scanner is moved in front of the switched on radiating Element(RE), close to the RE. The TRM is set to one defined control state set and the insertion amplitude and phase (S21 or S12) are measured over the frequency band(f_1GHz to f_2GHz) using a narrow frequency grid of 100MHz. The same phase and attenuation values will be used within this frequency step. This frequency sweep has been repeated for further TRM Control State settings. Afterwards, the probe is moved to the next RE and the above described procedure is repeated for the same Control State Settings. All RF-Paths are measured in this way.

In an offline evaluation process[10], these Single Element Adjustment(SEA) frequency sweeps are compared among each other and are normalized to an average amplitude and phase called the 'Error Value'(EV). Each of these frequency spots will have a separate amplitude/phase data set. After the normalization, the error values have been used for corrections added to the desired aperture excitations for each antenna element or RF path. This method is independent of the Scan Angle, because only one Radiating Element is switched on while doing the measurement. The correction data can therefore be used as a basic adjustment data set for all scan angles. After the Adjustment, all Radiating Elements are switched on and the Near-Field Measurements performed for different scan angles.

In the process of SEA , the systematical TRM deviations will be calibrated out together with the systematical deviations caused by the tolerances of the RF distribution network. The measured deviations of each individual RF path of the assembled array (including all the systematical RF deviations of the complete antenna) will be registered and normalised by comparison with a suitable reference element. Typical Radiation patterns of the array as a result of the SEA have been shown in **Figure. 8**. The Boresight transmit pattern and receive patterns of the array have been shown in **Figure.8(a)** and **Figure.8(b)**. The transmit pattern scanned to 50 deg. is shown in **Figure. 8(c)**. Receive pattern scanned to 30 deg. is shown in **Figure.8(d)** along with the monopulse pattern. The Receive mode radiation pattern gives a Sidelobe level of -29dB for a taylor 30dB distribution with a beamwidth of 7.5 deg. meeting with the design specifications. The measured values of the 64 element array has been shown in **Table 2**.

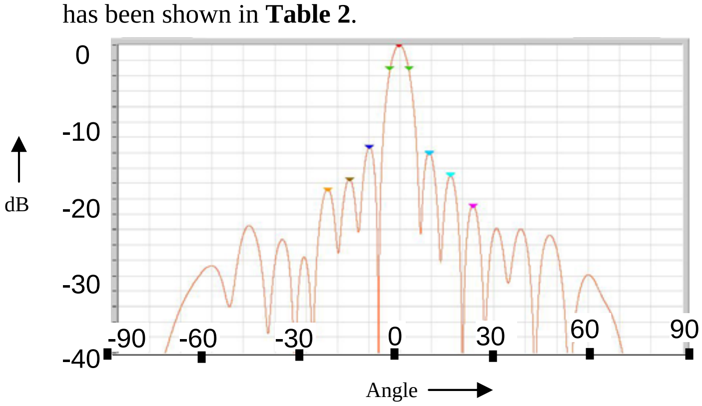


Figure. 8(a): Transmit Radiation pattern@@θ=0°

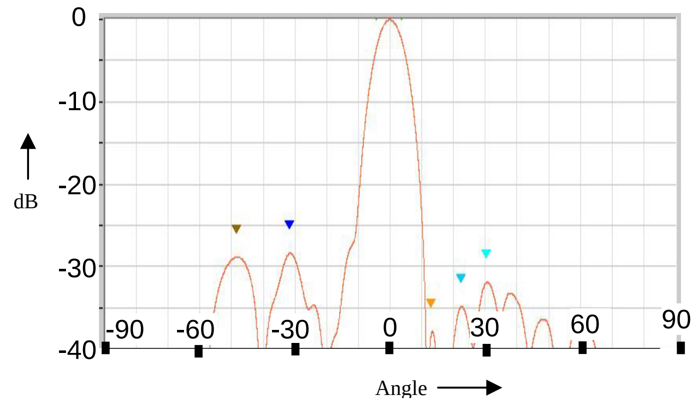


Figure. 8(b): Receive Radiation pattern @θ=0°

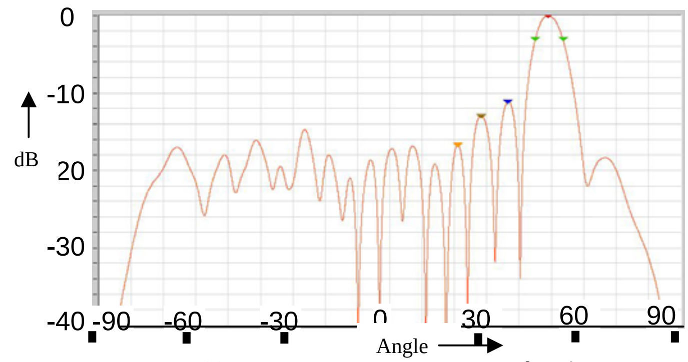


Figure. 8(c): Transmit Radiation pattern @ θ=50°

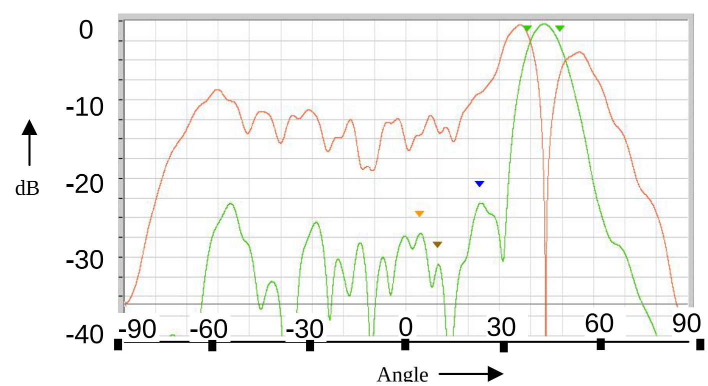


Figure. 8(d): Receive Monopulse Radiation pattern @θ=30°

Parameter	9-10GHz
Frequency range	21.5dB in TX
Gain	20.4dB in RX
Beam Width	8.07°[EL],27.14°[AZ]in RX
	5.82° [EL],25.94°[AZ]in TX
Side lobe level	26dB(EL),13.5dB(AZ)in RX
	13.2dB (EL&AZ) in TX

Table 2 Achieved Results of Array

All the results are according to the design specifications except the proper sidelobe formation with specified nulls as per the theory. This is because of the inherent amplitude and phase errors of the TRMs.These Errors will be nullified once we apply the NSA and P1 dB correction and temperature correction to the TRMs. Figure. 9 shows the computed 3D plot of a large size array(~1000 elements) after applying these corrections where the beam is scanned to 60 deg. in azimuth and 50 deg.in Elevation. Here the average Sidelobe level is ~44dB which is a desirable value for airborne applications..

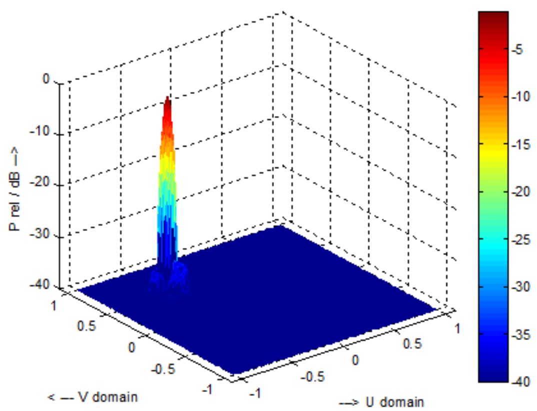


Figure. 9: Radiation pattern of large size array after applying NSA and temperature compensation.

Once the array has been calibrated there should not be any change of the RF hardware. In case of replacement of a T/R Module on a Plank the required TRM-MAP data will be updated in the corresponding controller. The SEA as well as temperature compensation will remain the same[10].

V. CONCLUSION

In the present work, an experimental 64 element active phased array in X-band has been designed, developed and tested successfully meeting the specifications as required. The realized array segment can be used as a building block for developing large size active phased arrays. The array offers a wide impedance bandwidth of 11% in X-band with wide scan angle performance of ±60° degrees in the azimuth and ±50° in elevation plane. The basic array configuration and its calibration aspects have been presented.

Measured results for typical TRMs over temperature and the radiation patterns after SEA have been presented. A method to achieve very low sidelobe levels (<-40dB) for large sized array (~1000 elements) are also presented. The measured results of the 64 Element array met design specifications. This work is expected to be useful in development of X-band Active Electronically Steered Radars for airborne applications.

ACKNOWLEDGMENT

Authors would like to express their gratitude to the Director, LRDE, for his support, encouragement and permission to publish this paper. The authors are also thankful to Shri. Chaitanya(Ex.Sc-B, LRDE) and M/s. AMPL Ltd, Hyderabad for their contribution in realising and testing the array.

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Dr. K. S. Beenamole received her Ph.D in Electronics from Osmania University in 2009, M.Tech in Electronics in 1996, from Cochin University of Science and Technology and B.Tech from Mahatma Gandhi University in 1992. Presently she is working as a Scientist in LRDE. Her interests include antenna array synthesis/analysis and development of active antenna array units for Active Phased Array Radars. She is responsible for the cutting edge Technology Development of 'Monopack Transmit*I* Receive *(*T/R) Module' for X-BAND Active Phased Arrays with Industry collaboration. This technology development program on the X-Band have proven the concept and established the first level Technology Base for X-band Active Array development in the country. She is a recipient of the National Research & Development Cooperation (NRDC), India Award 2005, IETE-Smt Ranjana Pal Memorial Award-2012 and IETE CDIL Award-2014. She has received DRDO Technology Group Award in 2001 &2010 and Outstanding Team Work Award in 2003. She is a recipient of National Science Day Silicone Medal and Commendation Certificate in 2009. She has received one Patent for her innovative design of Printed Microstrip Patch Antenna Array for Battlefield Surveillance Radar(BFSR-SR) and has applied for two Patents. She has one Copyright. She has published more than 50 research papers in the National/International Journals and Conferences. She is a member of Society of EMC Engineers and Fellow of ATMS and IETE.

Hemprasad Ghanta is working as a Scientist in Electronics and Radar Development establishment. He has completed his M-Tech, RF Design & Technology in 2011. He is involved in the design and development of IFF Dipole arrays, Active Aperture Arrays and different optimization techniques like GA, PSO, etc for antenna optimization. His area of interest are fractal antennas, antenna arrays and antenna pattern synthesis. He has published seven Technical paper in various journals/proceedings. He has applied for a patent on antenna to waveguide adapter.

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