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Design And Development Of Dual Band Electronic Scanning Array For Duplex Wireless Applications With High Gain Elliptically Polarized And Beam Scanning Capability With Butler Matrix Multiple Beamforming.

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ABSTRACT

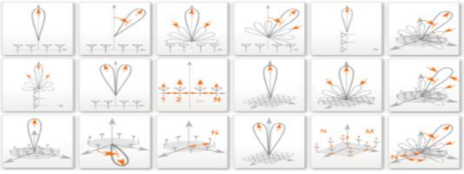
An antenna Array is subjected to the same measurable parameters as any antenna but these parameters change as the array is scanned. In other words, we can say that the array characteristics become a response to the periodic environment and the resulting array parameters have to be determined as a function of scan. As far as the individual isolated elements in the array are concerned, they behave very differently when embedded in an array, still the elements determine the array polarization, fundamental bandwidth and gross features of the array radiation pattern and the inter-element mutual-coupling within the array lattice. The only condition imposed by the array is that the spacing between the elements need to be small enough to avoid the grating lobes or “blindness”. In this paper we propose a circularly polarized scanning beam array which has dual band notching characteristics in the 2.4 GHz and 5.8 GHz range. This array is able to scan the whole 0-360° of angular space providing enormous spacio-temporal angular diversity and has a high gain of over 15dBi. The axial ratio has been plotted as a function of frequency in the X-band (8-12 GHz) and it has been found that the array provides an axis ratio of 1:2(minor: major =1:2) i.e. Perfect polarization ellipse at 5.8 GHz. Also, the array is able to notch two different frequencies for “WLAN” as well as “UHF RFID Reader” application in the 2.4 and 5.8 GHZ band. At the end of the paper a Butler Matrix formulation of a Multi-Beam Beam Former Array is carried out and simulated using HDL and FPGA Board in Simulink. –link 2020a. Simulation Results substantiate with experimental and theoretical outcomes.

KEYWORDS: Scanning beam, Beam former, UHF, RFI notch, Butler Matrix, axial ratio.

I. INTRODUCTION

I.[a]. Electronic Scanning vs Mechanical Scanning.

Mechanical Scanning of “**Track While Scan”** radars can often be proved to be limited when we talk about target handling capacity. As quoted in previous literature studies [2], slow scanning methods and large power concern cannot sometimes cope up when targets are moving at a high speed. Directing and steering the beams optimally with mechanical systems cannot respond instantaneously and at times can increase target capacity. The non-linearities caused in mechanical scanning can be offset by ESA steering since optimum positioning of radar beams can completely eliminate these non-linearities. Thus, an ESA can offset this advantage. The underlying principles behind Beam steering theory is derived from principles of EM Radiation employing Interference theories.



Methods of Beam Steering:

Previously the literature discusses about the theory required to compute the relative phase shift between adjacent radiating elements in order to direct the beam of an array-type antenna to a specific direction to increase the directivity. In practice there are three methods of accomplishing this phase difference.

Time Delay Scanning

First method discusses about adjusting the relative time delay between the elements for achieving desired phase relationships, can increase the utility at times however, can prove to be impractical due to cost concern, complex design and bulkiness.

Frequency Scanning

Frequency scanning is again another simpler method of Phased array radar implementation and is also relatively inexpensive. The serpentine wavelength can be chosen such that an integral number of wavelengths fit into the predefined length at a particular resonant frequency f_0.

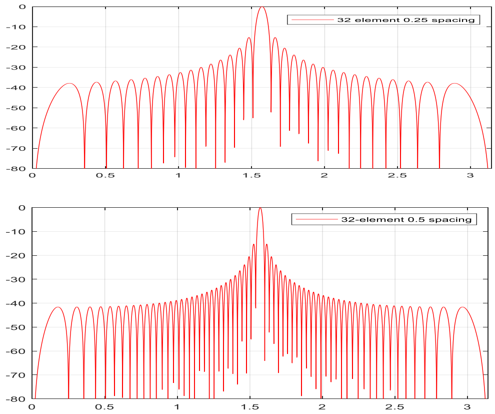
= *n* (*n* = any integer greater than zero)

Where λ0 = serpentine line wavelength at frequency *f0*.

Phase Scanning

In a phase-scanned radar system, phase shifter networks are employed to shift the appropriate "phases" of elements. The aim remains the same as the previous one but this time the phase difference between elements is achieved by translating the incoming energy of the phase elements adjustable between 0 to + 2*Pi radians. To offset the desired beam at a target, position the phase shifts are tuned and each element phases are adjusted to appropriate value.

Fig.1. Electronically Scanned Arrays.



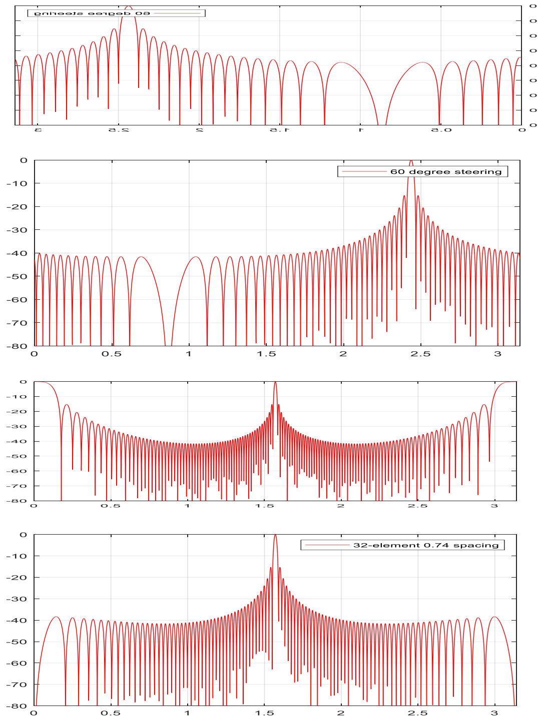


Fig.2. (a) Array factors for 32-element array. (a) 0.25λ spacing. (b) 0.50λ spacing. (c) 0.25λ spacing steered to 60-degree. (d) 0.5λ spacing steered to 60-degree. (e)and(f)0.75λand λ-spacing shows the presence of grating lobes.

II. Mathematical Formulation:

II.[a]. Complex Array Gain pattern:

For Amplitude only/Phase only synthesis the complex Gain of the array can be formulated as:

$$G_{array}(\theta, \Phi) = G(\theta, \Phi)$$
$$\sum_{n=1}^{N} An\ exp(jK0\ n\ a\ \sin\theta\ \cos\Phi) / \sqrt{\sum_{n=1}^{N} |\, An|^2} \quad \text{(i)}$$

Normalized Gain:

$$\iint_0^{2\Pi} |G(\theta,\Phi)|^2 \sin\theta\, d\theta\, d\Phi = 4\Pi(1-L) \quad \text{(ii)}$$

Where L=antenna loss factor.

$$B_n = A_n/\exp(j\psi_n) \quad \psi_n = -K_0\,(n-1)\,a \sin\theta_0.\text{(iii)}$$

I. Circularly Polarized Phased Scanning Arrays.

As opposed to Reflector Antennas Phase scanning arrays are capable of providing high gain, agility and commendable gain patterns as compared to reflector antennas which require mechanical movements to steer the array. In contrast ESA steering is capable of electronically scanning as opposed to mechanical movements. This enables low delay of around µsec. for scanning as opposed to msec. for reflector antennas used for

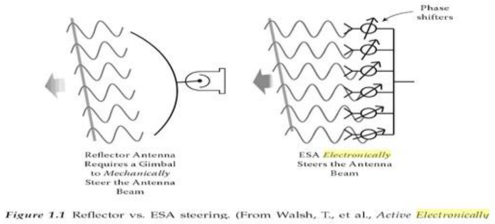


Fig.3. Reflector Vs ESA steering

III.[a]. **General 1-D Formulation:**

III.[a1]. No-Scanning:

General 1-D array formulation consists of M-elements with uniform spacing d. The overall length of the array, L, is equal to Md. The elements are centred at x=0 and the element positions can be determined by:

$$x_m = (m-0.5(M+1))\ d, \text{ where } m=1,2\ldots\ldots M. \qquad \text{(iv)}$$

the elements have complex co-efficients a_m and performs a delay and sum operation to produce the composite signal adding coherently. Summing up the voltages coherently can lead to the AF expression as:

$$AF= \sum_{m=1}^{M} Am\ exp(\frac{j2\pi}{\lambda xm} sin(\theta)) \qquad \text{(v)}$$

AF is the array factor and it is the spacial distribution of Array elements

The complete description of the special distribution is described by the Element factor as against the Array factor which is not a complete description of this Spacial response. A reasonable expression to the Spatial response can be the raised Cosine Element Factor (EF). The expression for the element pattern EP can then be described as.

$$EP= \cos\frac{EF}{2}\ \theta \qquad \text{(iv).}$$

In real applications, the Element Patten behaves differently. An ESA, in its measurement range, is subjected to non-uniformities at the edges which will modify the element pattern.

$$F(\theta) = \cos\frac{EF}{2}\ \theta\ .\sum_{m=1}^{M} Am\ exp(\frac{j2\pi}{\lambda xm} sin(\theta)) \qquad \text{(vii)}$$

III.[b]. **With Scanning:**

With Scanning, the idea becomes totally inevitable. Scanning requires adjusting the time delay and Phase of each element and after rewriting the equation in eq. (iv) above and expanding the complex voltage at each element the resulting eq. becomes

$$AF = a_m\, e^{j\theta m}\ exp(\frac{j2\pi}{\lambda xm} sin(\theta)) \qquad \text{(viii)} \qquad \text{(v)}$$

$$F(\theta) = \cos\frac{EF}{2}\ \theta\ .\sum_{m=1}^{M} am\ exp(\frac{j2\pi}{\lambda xm} sin(\theta) - \frac{j2\pi}{\lambda xm} sin(\theta 0)) \qquad \text{(ix)}$$

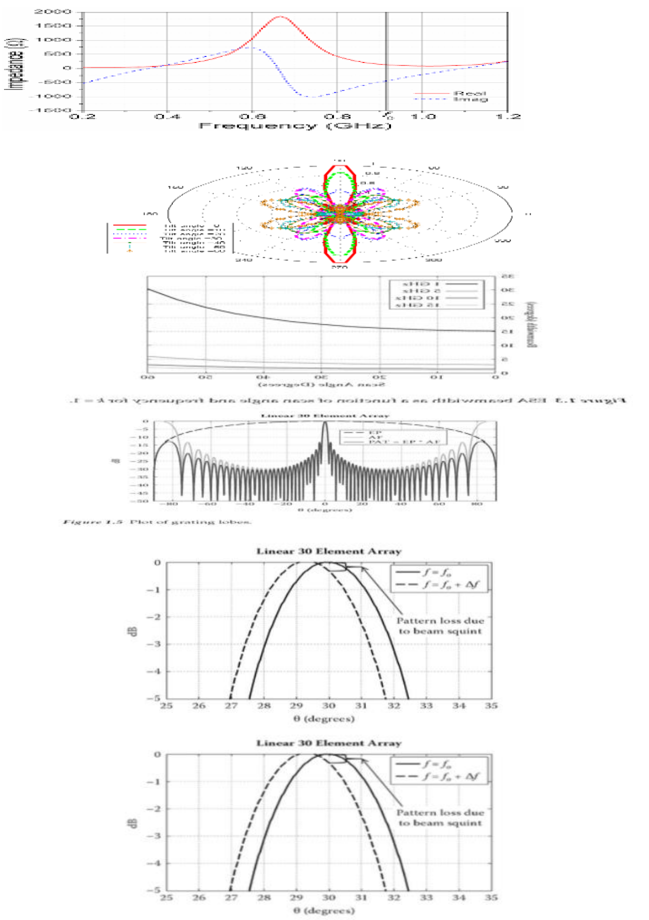


Fig.4. (a) plot of scan vs tilt angle. (b) Frequency vs. impedance of scanning array. (c) Beam width vs scan angle and frequency at k=1. (d) Plot of grating lobes. (e) and (f) Array pattern squint.

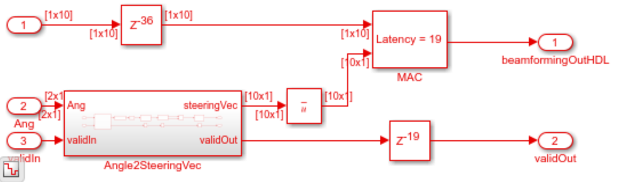
IV. Beam former configurations using FPGA, DSP, etc.

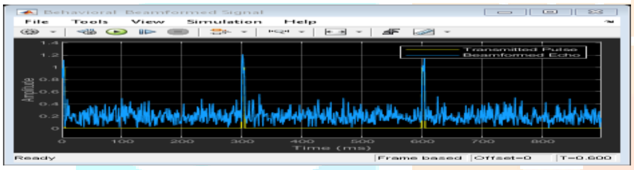
The FPGA popularity is growing day by day for its growing DSP applications. Here we have tried to implement a Scanning Radar antenna array using FPGA.The Implementation was done on HDL test bench using Co-simulation model with the target specifications **Xilinx Vivado synthesis tool; Virtex7 family; Device xc7vx485t; package ffg1761, speed -1; and target frequency of 300 MHz**.The Implementation was carried out on MATLAB Phased Array Simulink using FPGA board with a 10- element ULA with half –wavelength spacing between elements with a thermal noise at each antenna element of -3dBW and an operating frequency of 100MHz.

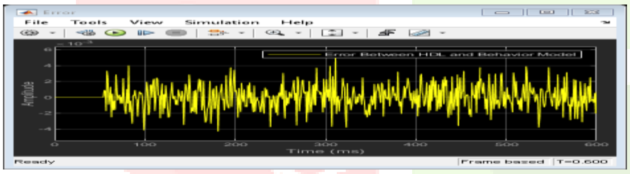
IV.[a]. The Digital Beam former

The signals from various elements of Digital Phased Array antenna elements add constructively or destructively forming the main beam that can be made to point in a specific direction and at the same time reduce the side lobes. This is a weighted approximation of different signals at different antenna elements which are both complex numbers and are then added to form the beam with the beamformer configuration capable of changing the direction of the main beam to the desired angle. The computation involved in the beamformer is a weighted sum and is given by:

$$Y= \sum_{i=1}^{n} wi.xi \qquad (x)$$







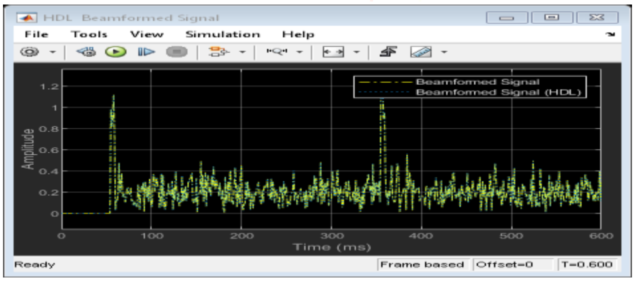


Fig.5a) Behavioural Beamformed Signal). Error signal). HDL Beamformed signal Digital Beamforming using HDL.

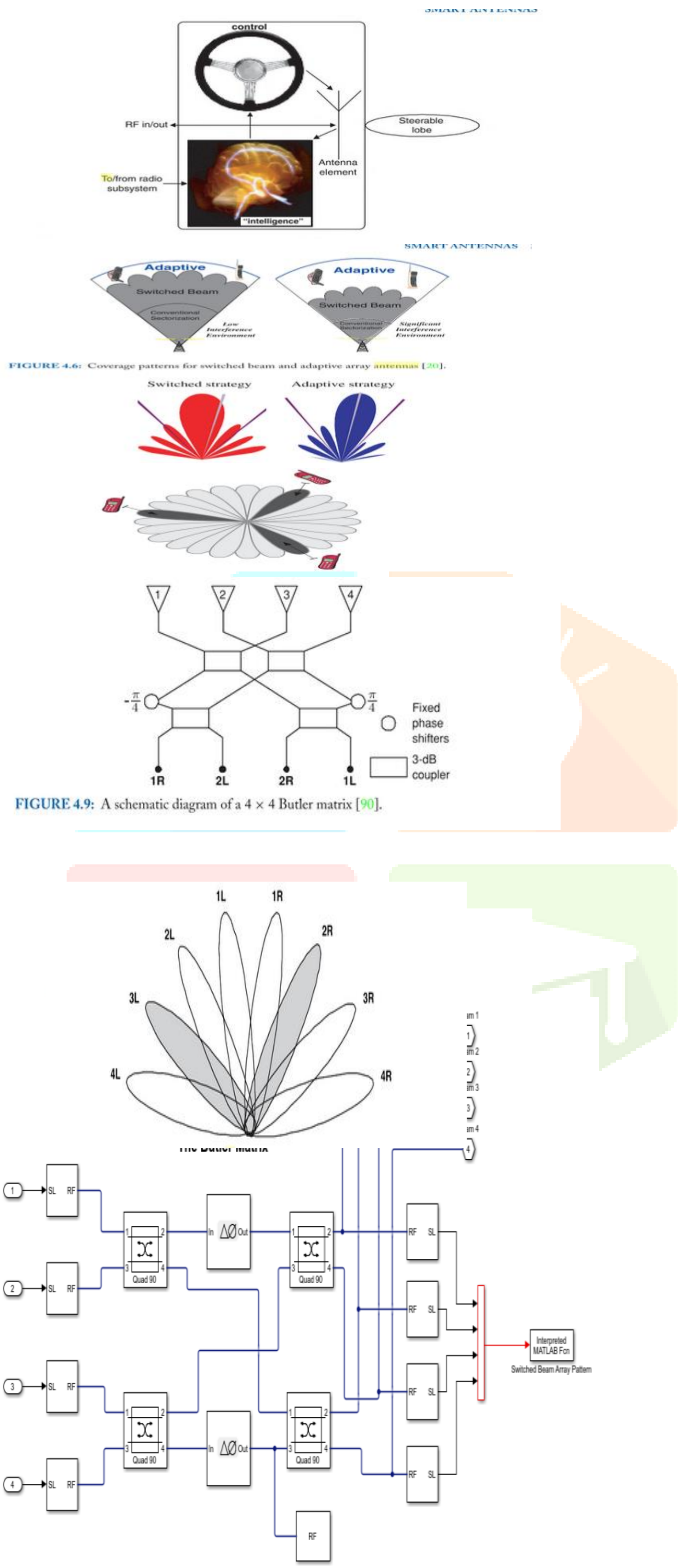
V. Buttler Matrix Formulation of Multiple Beam Phased Scanning Arrays.

The scanning beam based on basic switching selects the scan with the strongest received signal using phase adjustment between the elements resulting in a directed main beam throughout the angular space with a 360-degree coverage. Instead of shaping the directional antenna patterns, the switched beam system combines the outputs of multiple antennas to form narrow sectored (directional beams) with more special selectivity as opposed to conventional single element approaches. Other sources in literature defines this as Phased Array which forms multiple beams with one beam switched towards the desired user or a single beam formed by (phase adjustment only), that is steered towards the desired signal. A more generalization to the switched lobe concept is the Dynamic Phased Array (DPA). In this approach a DOA algorithm is embedded inside the system. The DOA is first estimated and then the parameters are adjusted according to the steering direction. This maximizes the received power but has a trade-off between Power and Design complexity.

The elements used in these arrays must be connected to the sources and/or feed network. Butler Matrix is a widely known multiple beamforming network. It is a linear, passive feeding N*N, N can be as many (here 4*4) network with beam steering capability of Phased arrays with N outputs and N inputs or “Beam Ports”. The Butler Matrix forms a special FFT operation providing N orthogonal beams when N is a power of 2. A Butler Matrix feed array can scan the entire 360° angular space and an RF switch enables the selection of the appropriate beam. A Butler Matrix also has the capability of beam steering by exciting the beam ports with amplitude and Phase weights followed by a variable uniform phase taper. A total of $N/2*\log_2 N$ hybrids and $N/2 * \log_2(N-1)$ fixed phase shifters are used to form the network. The hybrids can be either 90° or 180° 3-dB hybrids, depending upon the symmetrical distance of the beams towards the broadside or whether one of the beams is to be in the broadside boresight direction.

A Butler-Matrix serves two functions:

(a) Distribution of RF signal to radiating antenna elements.
(b) Orthogonal beamforming and beam steering.



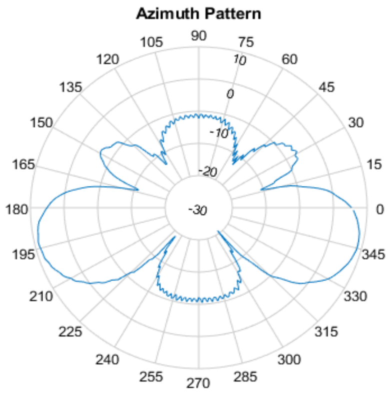


Fig.7. (a) Smart antenna. (b) Coverage pattern for switched beam and adaptive array. (c) Multiple-beamforming. (d) A 4*4 Butler Matrix. (e) Orthogonal beams of an 8*8 Butler Matrix's) Simulink set up for Butler Matrix's) Beamforming.

VI. RADIO FREQUENCY IDENTIFICATION(RFID)

Radio-frequency identification (RFID) technology enables remote and automated gathering of data and transferring this information from RFID tags to the Readers wirelessly. Using RFID, the exchange of data between tags and readers is rapid, automatic and both Los and NLOS wireless propagation can be achieved. When a Card (tag) is brought in proximity to the RFID reader, it communicates with the tag, the reader receives the data and follows one of the encoding steps. The data is sent over TX line and then the UART module in MCU receives the data and thus further processes it. RFID is much more secured than any other entry systems and its cost is also too low due to which it has widespread popularity in supply chain management.

	LF	HF	UHF	Active
Frequency	125 – 134.2 KHz	13.56 MHz	850 – 960 MHz	100 KHz – 2.45GHz
Range	0.2 – 2m	Up to 1m	Up to 3m	Up to 100m
Cost	Typ. 3 GBP	(Typ. 0.50 GBP)	(Typ. 0.30 GBP)	(Typ. 20 GBP)
Memory	Typ. 64 bits	Typ. 2048 bits	Typ. 96 bits	Typ. 32 bits
Penetration of Materials	V. Good	Good	Poor	V. Good
Data Rate	Slow	Fast	Fast	Fast
Reader Cost	50 – 500 GBP	50 – 3000 GBP	1000- 3000 GBP	200-600 GBP
Read Multiple Tags	Poor	Good	Very Good	Good
Applications	Animal Tags, Vehicle Immobilisers, Industrial Applications	Item Tracking, Access Control, Smart Labels	Box and Pallet tracking Some Item Tracking	Industrial Applications, Asset Tagging Location Systems

Fig. 8(a) RFID module. (b) Frequency range of RFID. (c) Working principle of RFID. (d) Active and Passive RFID tags. (e) Types of RFID tags.

VII. Results:

In the initial part of the paper a 100-element antenna array gain was synthesized using Genetic Algorithm. The optimized gain obtained after applying Meta-Heuristics to the problem Space was obtained to be -19.17dBi. It took about 15 minutes to complete the simulation over a 1-GHz Quad-Core Pentium processor with RAM expanded to 8GB.The algorithmic parameters are:

Posize=300
Mutrate=0.10
No. of bits=10
No. of generations=1000

The designed array antenna was applied at the load side of an X-band (8-12 GHz) microwave test bench and the antenna gain were estimated. It was observed that the optimization results substantiate with the experimental outcome. Also, the return loss at the measured VSWR of 1.5 was calculated. A typical return loss value of an ESA is -13dB and experimentally it was found out to be -13.97dB which is far excellent.

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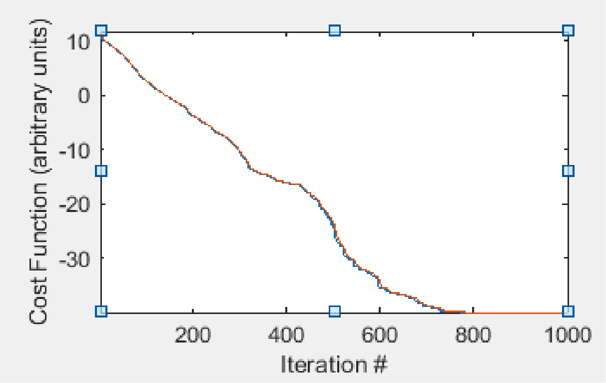
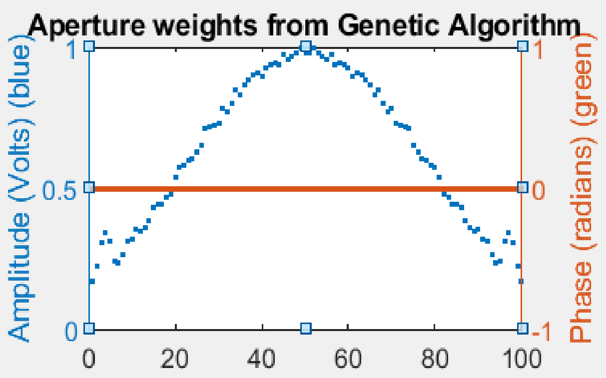
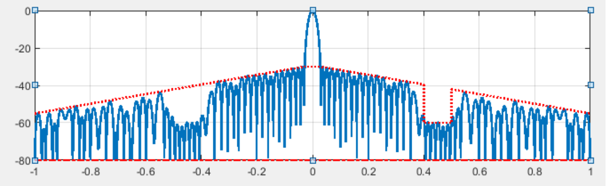
optimized function is test function
pop size = 300 mutate = 0.10 # par = 100
#generations=1000 best cost= 0.11
binary genetic algorithm
each parameter represented by 10 bits

Calculated Gain=-20*log (best cost) =-19.17dBi.
best solution or array co-efficient (Amplitude only):







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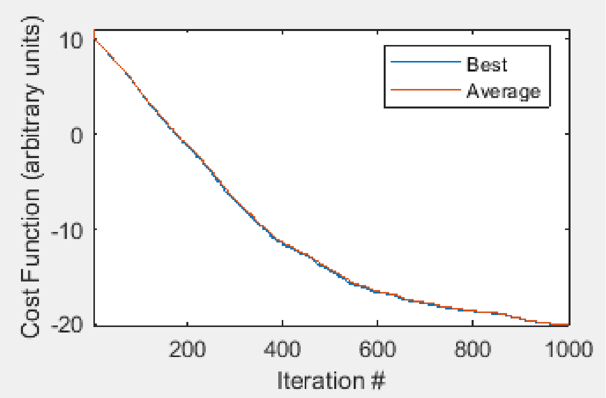
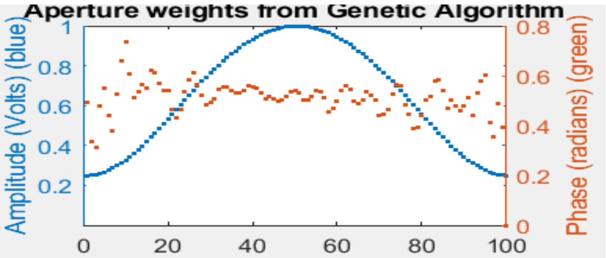
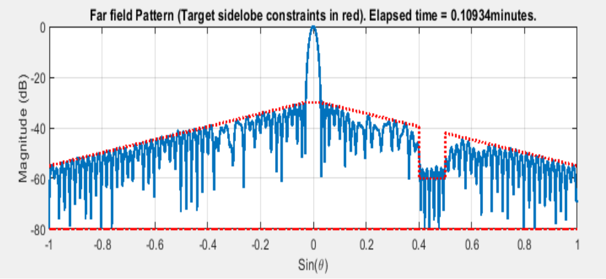






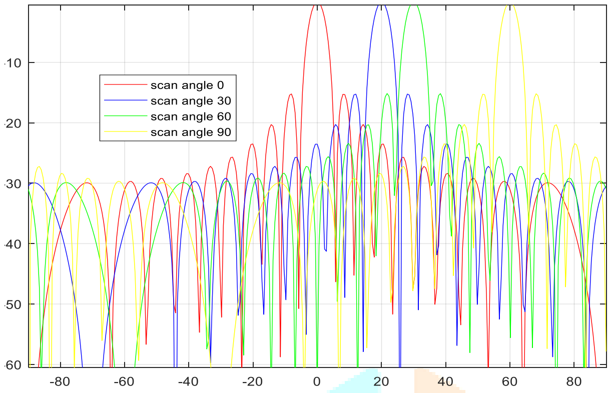


Fig.9. Normalized Gain vs Phase of Scanning Beam Array.

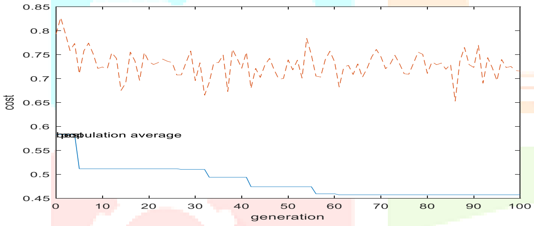
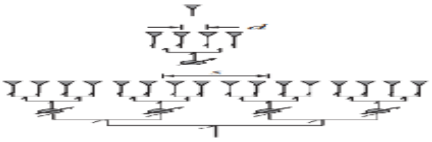
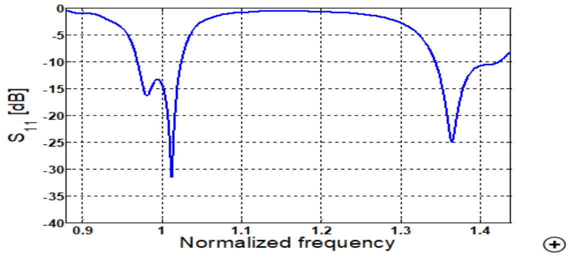


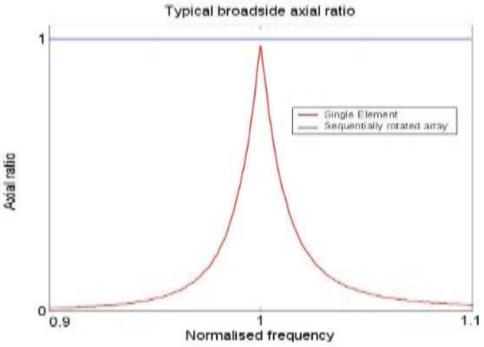
Fig.10.Global Best Fitness values. (Convergence).

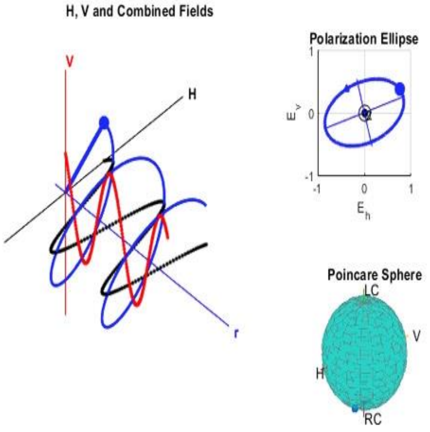


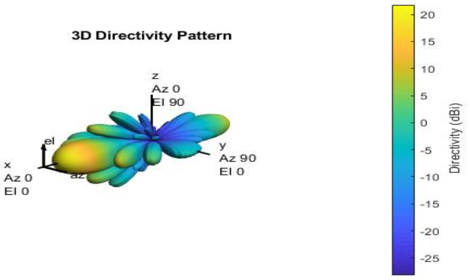
Design of the Sequentially rotated 2-by-2 circular patch array with stubs in Antenna Magus Software.

The axial ratio has been plotted as a function of frequency for 8-12GHz X-band microwave and has been plotted using Antenna Magus software. The axis ratio at 5.8 GHz was found to be 1:2 means a perfect Polarization ellipsoid. Simulated results calculate the axis ratio as Major:0.8 and Minor=0.4, ie. major/minor Ratio is 1:2.









The first fig. below shows the plot of axial ratio vs Normalized frequency for a scanning array. The second figure shows the Polarization ellipse and the third fig. shows the scanning beam beamforming simulation for Butler-Matrix formulation of Electronically steered Arrays. Both second and third figures are plotted using MATLAB 2019a Phased Array Antenna System toolbox.

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