ISSN: 2278 – 909X
International Journal of Advanced Research in Electronics and Communication Engineering (IJARECE)
Volume 5, Issue 11, November 2016

Rotman Lens Fed Linear Phased Array Antenna: A Comprehensive Review

Ch Viswanadham[1]
[1]PhD Student, ECE, Andhra University,
Visakhapatnam, Andhra Pradesh, India – 530 003
Phone # +919441184448

Prof. P Mallikarjuna Rao[2]
[2]Professor, Department of ECE, Andhra University,
Visakhapatnam, Andhra Pradesh, India – 530 003
Phone # +91891 – 2531488

ABSTRACT *– Various modern radar, radiometers, electronic warfare and communication systems move towards the implementation of highly directive and active space filtering radio frequency (RF) front ends. Networks with the capability to form multiple radiation beams within short span of time are therefore becoming essential. Addressing the different space sectors at the same time leads to a higher system capacity by re-using the time, code and frequency. Over the years two passive beamforming networks prevailed: the Rotman lens and the Butler matrix. Rotman lens is usually preferred over the Butler matrix. Rotman type lens is useful tool for multiple beam forming, because of its frequency independent characteristics. They are the true time delay (TTD) devices. The outputs of the lens generate different phased signals and fed to linear horn arrays to form the highly directive beams in space. Thus Rotman lens fed linear phased array antennas are popular in aerospace and defense sectors. This paper reviews the concepts of Rotman lens and linear phased arrays and the work carried out so far, their capabilities and the current & future trends in the communication field*

Key words; Radio Frequency, True Time Delay, Beam Forming Network

I INTRODUCTION

Rotman Lens fed phased array antennas are most popular compact and wideband antenna with a typical architecture, and hence, it is necessary to provide a review of the concept of the development of these elements. The concept of these complicated and complex lenses can be understood, if the basic concepts of the beam-forming networks are understood thoroughly. Rotman lenses are attractive candidates for use in beam forming networks (BFNs). The lens is used in the radar surveillance systems to detect the targets in multiple directions due to its multi-beam capability without physically moving the antenna system. This lens is now integrated into many radars and Electronic Warfare systems around the world. This kind of lenses share commonalities with the dielectric lenses and the reflector antennas. The various development procedures and techniques for effective design of the Rotman lens antenna are brought in the current paper. This paper mainly serves as a review of the concepts and ideas for the design of the modern Ultra Wideband (UWB) Antenna with Band Width Ratio (BWR) of more than 3. The details of these antennas are provided in the subsequent paragraphs in the current paper. The last section deals with the current trends and the scope for improvements in the design and development of Rotman lens fed Linear Phased Array Antenna for various applications including EW.

II BEAMFORMING NETWORKS

A typical beam former network is as shown in the Figure - 1. It usually consists of M number of input ports and N number of output ports where N is the number of array elements to be fed. Beamformers produce the required amplitude and phase distributions over the array elements in order to direct the beam into the desired direction. Depending on the requirements on the array aperture, beamformer can be formed as planar (2-D) or three dimensional (3-D). The 2-D beamformers produce steerable fan beams while 3-D beamformers produce steerable pencil beams.

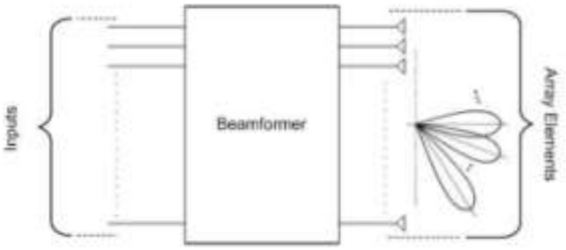


Figure - 1: Typical Beam-forming Network

Beam-forming networks may be classified in many different ways but in this paper, the classification proposed by Hansen [1] is presented.

1. *Network Beam-formers*

The network beam forming networks are the earliest of the three types. Buttler matrix is a simple example of this type of network BFNs. This type of network uses alternate rows of hybrid junctions and fixed phase shifters. There are also other types of matrices such as Blass and Nolen matrices.

1.1 Advantages

This type of networks may be easily constructed using the strip or microstrip configurations. The beam cross over levels remains unchanged.

1.2 Disadvantages

The beam widths and beam angles change with frequency. So it is disadvantageous when applications require constant beam widths.

2 *Digital Beam-formers*

Digital BFNs use a computer or chip processor to control electronic components in order to produce exact amplitude and phase distributions for the array elements. Preamplifiers (LNAs), Analog-to-Digital (A/D) and Digital-to-Analog (D/A) converters are used in the digital beam former topology

2.1 Advantages

This type of BFNs can produce any number of multiple beams with zero phase error, infinite scanning steps and flexible amplitude tapering.

2.2 Disadvantages

Digital BFNs are limited to low microwave frequencies due to the limited bit-bandwidth product of the current A/D converter technologies. Very fast processors are also required to handle the digitized RF data. This limits the processing speed.

3 *Microwave Lens Beam-formers*

Microwave lens beamformers use path length mechanism to introduce desired phase distributions on the array elements. As a microwave lens BFN, constrained lenses are used where the rays are guided by metal plates. Input ports are connected to the beam ports that radiate a signal within the lens cavity and then the receiving ports receive the signal and transmit it to the antenna array. Positions of the beam and receiving ports and transmission line lengths are arranged so that the desired phase and amplitude distributions are obtained across the array aperture.

3.1 Advantages

These BFNs are especially used in wideband applications since the path-length design used in their design is independent of frequency. High power or low profile beamformers can be acquired according to the requirements since they can be implemented using waveguides, micro strip and strip line technologies.

3.2 Disadvantages

Finite insertion losses and inherent losses occur due to the hybrid couplers, fixed phase shifters, and transmission lines that make up the matrix.

III SURVEY ON MICROWAVE LENSES

Microwave lens is a structure capable of focusing the electromagnetic energy into a point. The microwave region defines the region with the electromagnetic spectrum with wavelength between 1mm and 300 mm. During its development in 1950s, metallic plate and constrained line techniques were originally adopted in designing the Ruze Lens [2] and the R-2R microwave lens [3-5]. The array shape was designed to be circular with confined dimensions in the R-2R lens, which has ultimately limited its usefulness in practice. In 1957, a general theory of improved constrained lens was invented by Gent [6], and it was named bootlace lens because of its general structure shown in Fig-2. According to [7] and [8], the Gent lens was adopted to design the precision aircraft landing system in Australia and the United States in 1970s. At the mean time, group of researchers in MIT funded by the Army Research Lab (ARL) carried research on the improvement of microwave lens design too. In 1960, Rotman and Tuner applied Gent general lens design schemes in their early warning radar systems [9]; in 1962 they reported a 3 perfect focal point microwave lens, which has greatly improved the phase error and design freedoms of the original Ruze Lens [10]. After this, systems based on the Rotman lens design was applied in Raytheon in 1967 [11] and further tested in the leading-edge of an F-4 aircraft in 1972 [9]. After Archer [12, 13] and recent researchers proposed idea of designing printed Rotman Lens, more and more applications based on the microstrip and stripline designs are booming up [14-18]. Although the microwave lenses are dominated by the Rotman lens designs (RLD) since then, with the insight visions of model’s fundamental limits, researchers have developed and modified 3 focal lenses [19-22], methods of designing the 4 focal [23] and non-focal lens [24].

IV GENERAL DESIGN PROCEDURES

In general, the design of microwave lenses involves the following five steps

- Microwave lens specifications
- Geometry optical (GO) lens parameters
- Port, transmission line implementation
- Performance estimation of complete lens
- Fabrication and measurement

Research is being carried out in every step of this procedure.

V DESIGN APPROACHES

1. *The conventional approach of Rotman*

In the conventional design of Rotman lens, the generalized equations obtained by Gent [25] for lenses of arbitrary shape are used [26]. The lens parameters are defined as shown in Figure - 2. The focal arc locates the feeding elements and it is also called as the beam contour. Besides, the inner lens contour locates the receiving elements where the outer lens contour locates the radiating array elements. In the inner lens contour design three focal points are used: two symmetrical off-axis focal points (F1 & F2) and one on-axis focal point (G). The shape of the focal arc is chosen as a circle containing the three focal points. Unlike the other types of lenses, including the Ruze [27] model for which the parameters Y (the y-coordinate of an arbitrary point on the inner lens contour) and N (the coordinate of a radiating array element connected to the receiving element locating at P(X, Y)) equal to each other; Rotman lens allows Y and N to be different. So, this provides more degrees of freedom in the design. In order to derive design equations for the lens contour, optical path-length equality and the lens geometry are used.

2. *The symmetrical lens approach of Shelton*

Shelton [28] developed a symmetrical lens configuration as a modification to the Rotman lens. The beam and the inner lens contours are identical and symmetrical with respect to a symmetry plane as seen in Figure - 3. This design is useful for comparable number of input and output ports. The design equations of this type of lens are more complicated than that of proposed by Rotman.

3. *Katagi's Approach*

Katagi [28] suggested an improved design method of Rotman lens in which a new design variable is introduced and the phase error on the aperture is minimized. As it can be seen in Figure - 4, Katagi defined a subtended angle (α) corresponding to one of the off-axis focal points as it is defined in Rotman's model. However, the scan angle (β) corresponding to the excitation from F1 is assumed to be different from the subtended angle (α) though scan angles were assumed to be equal to the corresponding subtended angles in Rotman's design model. Hence, Katagi [28] introduced a new design variable consisting of the ratio of the scan angle and the subtended angle corresponding to one of the off-axis focal points. Therefore, this variable provides a new degree of freedom compared to the conventional design. Katagi [28] also suggested that the shape of the beam contour is not necessarily a circular arc.

4. Refocusing approach of Gagnon

Gagnon [29] introduced refocusing procedure for dielectric-filled Rotman lens according to Snell's law. Therefore, applying Snell's law yields a ratio of $\sqrt{\varepsilon_r}$ between the sine's of the scan angle and the subtended angle of the beam contour. This approach provides beam and array port positions which give improved coupling to the outermost beam ports, especially for printed lenses used with small arrays.

5. Design Trades of Hansen

Hansen [30] used six basic design parameters: focal angle, focal ratio, beam angle to ray angle ratio, maximum beam angle, focal length and array element spacing. A seventh parameter, ellipticity, allows the beam contour to be elliptical instead of circular. The parameters beam angle (subtended angle) to ray angle (scan angle) ratio and ellipticity are additions to the parameters of the conventional design. Hansen explained the effects of the seven design parameters on the shape, and on the geometric phase and amplitude errors of a Rotman lens in detail [30].

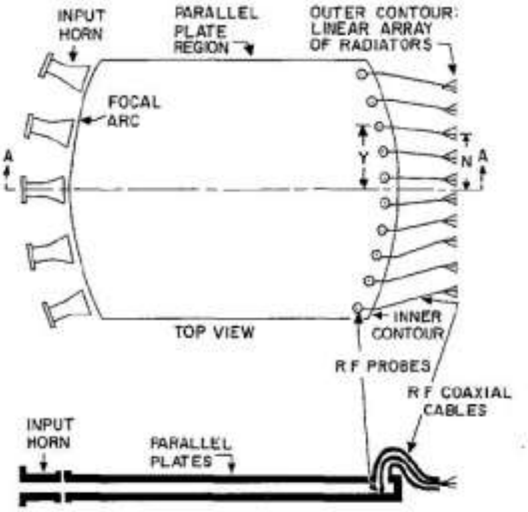


Figure - 2: Rotman lens Configuration

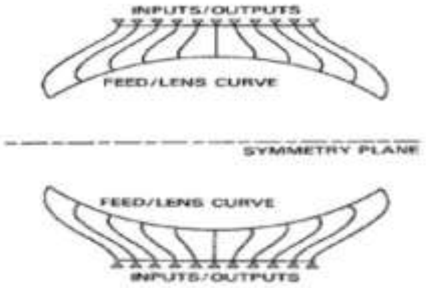


Figure - 3: Symmetrical Lens Model

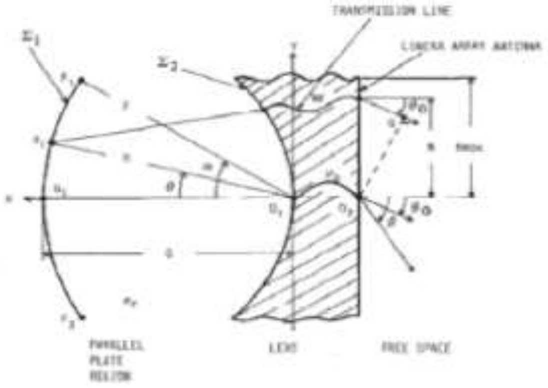


Figure - 4: Katagi's model

VI DESIGN PARAMETERS & THEIR EFFECTS

A Rotman lens is built using microstrip techniques, feeding a patch antenna array. It satisfies the qualities required in an antenna as it provides high gain, large scan angles, conformal geometry and low cost. There is a lot of scope in optimizing various parameters which are useful in designing Rotman lens antenna. The antenna is capable of producing multiple beams which can be optimized to steer without changing the antenna orientation. It consists of a set of input and output ports arranged along an arc. The lens structure between both sets of ports functions as an ideal transmission line between the individual input and output ports. The signal applied to the input port is picked up by the output port. The different electrical lengths between a specific input and all output ports, generates a linear progressive phase shifts across the output ports of the lens. Dummy ports are also an integral part of the Rotman lens and serve as an absorber for the spillover of the lens and thus it reduces multiple reflections and standing waves which deteriorate the lens performance. The design of the lens is governed by the Rotman-Turner design equations [10] that are based on the geometry of the lens. Input ports lie on the beam contour and the output ports lie on the array contour. There are three focal points namely F_1, F_2 and G_0. G_0 is located on the central axis while $F_1$and F_2 are symmetrically located on the array contour at an angle of +α and – α respectively. It is quite clear that the co-ordinates of two off-axis focal points F_1, F_2 and one on axis focal point G_0 are (-Fcosα, Fsinα), (-Fcosα, -Fsinα) and (-G, 0) respectively. The equations generate the positions of the antenna ports based on three perfect focal points (G1, F1, and F2). The defining parameters of the Rotman lens are the on axis and off axis focal lengths G_0, F_1 and F_2, internal scan angle α, focal ratio the number of beam and antenna ports and the external scan angle. When a feed is placed at a non focal point, then the corresponding wave front will have a phase error, but for wide angle scanning capabilities it is necessary to place the feed at non focal points. The design parameters for the lens with different substrates in the cavity, transmission line and the inner receiving contour are given below [31] and description of the design parameters are placed at Table-1.The limiting factors in the design of Rotman lens are (a) Reflections from side walls (b) Grating lobes (c) Array factor and (d) Phase error.

$$y = \eta(1 - w)$$

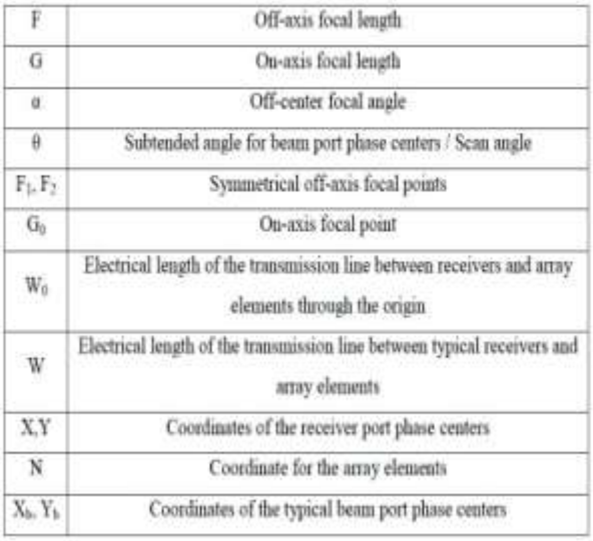
$$x = -\frac{(g-1)}{(g-a_0)}w - \frac{(b_0^{\,2}\eta^2)}{2(g-a_0)}$$

$$a = \left[1 - \eta^2 - \left({(g-1)}/{(g-a_0)}\right)^2\right]$$

$$b = \left[2g\left({(g-1)}/{(g-a_0)}\right) - \left({(g-1)}/{(g-a_0)^2}\right)b_0^{\,2}\eta^2 + 2\eta^2\right] - 2g$$

$$c = \left[\left({(gb_0^{\,2}\eta^2)}/{(g-a_0)}\right) - \left({(b_0^{\,4}\eta^4)}/{4(g-a_0)^2}\right) - \eta^2\right]$$

$$w = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$



F	Off-axis focal length
G	On-axis focal length
α	Off-center focal angle
θ	Subtended angle for beam port phase centers / Scan angle
F_1, F_2	Symmetrical off-axis focal points
G_0	On-axis focal point
W_0	Electrical length of the transmission line between receivers and array elements through the origin
W	Electrical length of the transmission line between typical receivers and array elements
X,Y	Coordinates of the receiver port phase centers
N	Coordinate for the array elements
X_b, Y_b	Coordinates of the typical beam port phase centers

Table-1: Description of Design Parameters

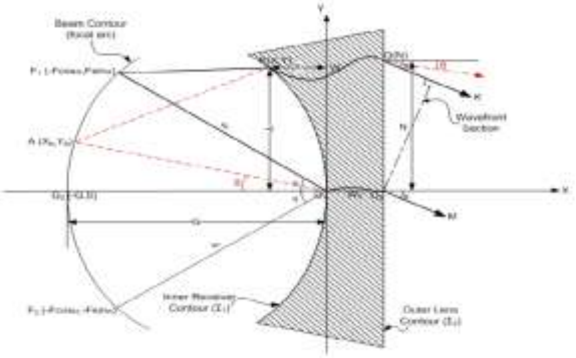


Figure - 5: Design Parameters of Rotman Lens

All of the design parameters affect the phase error performance of the lens. However the parameters g, e, n_{max} and α affect the lens coordinates directly. The parameter ε_r affects the lens size by scaling the coordinates. Since the focal length F is the normalization factor, overall geometrical size of the lens depends on F. Also, the choice of the focal length, F together with the parameter n_{max} specifies the distance between the antenna elements and this distance affects the operating frequency bandwidth of the lens. To analysis this variation “Damla Duygu Tekbas” of “Middle East Technical University” has designed a matlab program. The various results are as follows:

1. *Effect of g:*
    - With decreasing g, beam contour flattens
    - With increasing g, lens contour flattens
2. *Effect of* n_{max}*:*
    - Optimum g value decreases with increasing n_{max}
    - Maximum normalized path-length error increases with increasing $\mathbf{n_{max}}$
3. *Effect of e:*
    - Optimum e value increases with increasing n_{max}
4. *Effect of* ε_r*:*
    - With increasing ε_r the lens contour shrinks
    - larger dielectric constants are more advantageous than smaller dielectric constants since the phase-error is reduced

5. *Effect of α:*

- It can be observed that the maximum path-length error increases with increasing α. Therefore, for large angles, the conventional design approach [10] should be modified in order to improve the phase-error characteristics in wide-angle applications
- Beam contour becomes extremely large for large angles compared to the inner receiver contour and the lens structure becomes infeasible to manufacture. This problem can be solved by choosing the scan angle different from the subtended angle of the beam contour and hence the beam contour can be reduced to more feasible sizes even for large angles.

6. *Effect of F:*

- There is no lower bound for F and larger F means larger lens and larger lens will cause more insertion loss. Besides, since F is the normalization factor, path-length errors will also increase for larger F. Thus, it is reasonable to choose the off-axis focal length as small as possible. However, since the antenna connectors require a certain distance between them in order to make measurements possible, F cannot be chosen very small. The distance between the array elements is 0.1F due to the parameter definition in Rotman lens design procedure.

VII LINEAR PHASED ARRAY ANTENNAS

1 Linear Arrays

An array of identical elements all of identical magnitude and each with progressive phase are referred to as uniform array. The array factor can be obtained by considering the elements to be point sources. If the actual elements are not isotropic, the total field can be formed by multiplying the array factor of the isotropic sources by the field of single elements. The Array factor (AF) of N element uniform array is given by

$$AF = \sum_{n=1}^{N} e^{j(n-1)(kdCos\theta+\beta)}$$

Where d is the spacing between the elements in the array.

The directivity of N element broad side array for large array lengths is given by

$$D = 2N\left(\frac{d}{\lambda}\right)$$

and the directivity of N element end fire array of large array length is given by [107]

$$D = 4N\left(\frac{d}{\lambda}\right)$$

The gain of the antenna array is given by [104]

$$G_{ARRAY} = G_{ELE} + 10LOG(N)$$

Where '*N*' is the number of elements, G_{ELE} is the gain of array element and G_{ARRAY} is the gain of the overall array.

2 Phased Arrays

A phased array antenna is composed of lots of radiating elements each with a phase shifter. Beams are formed by shifting the phase of the signal emitted from each radiating element, to provide constructive/destructive interference so as to steer the beams in the desired direction.

3 Element pattern

The polar radiation pattern of a single element is referred as "element pattern". It is possible for the array to be built recursively; for example the element may itself be an array, as would be the case if we had an array of Yagi-Uda antennas. A Yagi-Uda antenna may be thought of as an array of dipoles with different amplitudes and phases of the dipole currents.

4 Array pattern

The array pattern is the polar radiation pattern which would result if the elements were replaced by isotropic radiators, having the same amplitude and phase of excitation as the actual elements, and spaced at points on a grid corresponding to the far field phase centers of the elements. The resultant pattern of an array is achieved by multiplying the array pattern with the element pattern (Pattern multiplication).

The arrangements of linear array are shown at Figure-6 & 7 respectively.

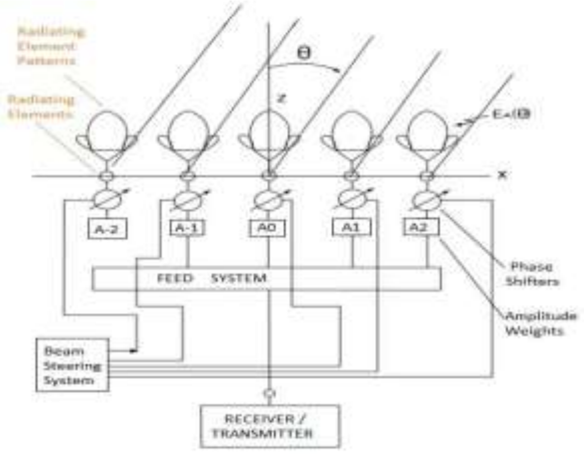


Figure - 6: Arrangement of linear array

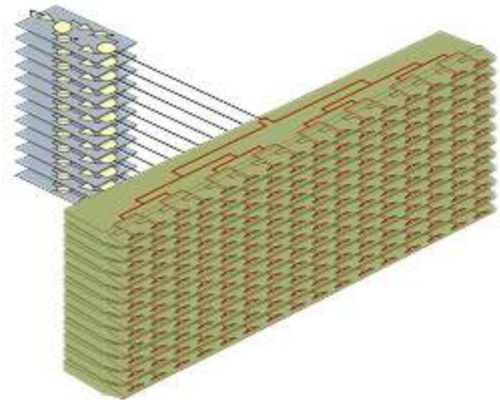


Figure - 7: Linear array of phased array antenna

5 Advantages:

- High gain width los side lobes
- Ability to permit the beam to jump from one target to the next in a few microseconds
- Ability to provide an agile beam under computer control
- Arbitrarily modes of surveillance and tracking
- Free eligible Dwell Time
- Multifunction operation by emitting several beams simultaneously
- Fault of single components reduces the capability and beam sharpness, but the system remains operational

6 Disadvantages:

- Coverage is limited to a 120 degree sector in azimuth and elevation
- Deformation of the beam while the deflection
- Low frequency agility
- Very complex structure (processor, phase shifters)
- Still high costs

VIII ROTMAN LENS FED PHASED HORN ARRAY ANTENNA

Rotman lens fed phased horn array antenna provides simultaneous high gain multiple beams with each beam possessing full gain of array aperture. The phasing network is modeled using Rotman lens. The lens offers the possibility of variable refractive index which provides many degrees of freedom to design lenses with multiple foci as compared to optical lenses which are made of dielectric with fixed refractive index and hence single on axis focal point.

The Rotman lens consists of TEM mode parallel plate transmission region with input and output ports called beam and array ports, respectively. Coaxial transmission lines of unequal lengths connect the array ports to the radiating elements of the array. These variable length transmission lines which constitute a transmission delay provide variable refractive index to achieve the path length compensation. The length of these transmission lines and array port positions are designed to provide perfect focusing along the input circular arc. The focusing is a consequence of providing equal electrical path length from a given focal point out to the corresponding radiated wave front to each element of the array. These lens-fed array systems provide optimum utilization of system resources in time, space and frequency. Rotman lens fed array system is cost-effective with inertia-less scanning capability and finds extensive application in: (i) ECM against simultaneous multiple threats, (ii) surveillance, (iii) point to multi-point communication, (iv) remotely piloted vehicle system for multiple drone control and broad-band data retrieval links, (v) integrated multipurpose system accomplishing the functions of radar, ECM, surveillance and communication, (vi) satellite communication with spot beam coverage capability, and (vii) low side lobe pattern generation. The antenna is capable of BWR >2 with 15 simultaneous beams.

Figure - 8: Rotman lens fed Linear array of phased array antenna (Courtesy: Internet)

Many researchers are working to improve the performance of Rotman lens fed horn array to achieve optimum performance over the wide frequency coverage at high power levels. The critical parameters to be improved are active VSWR, array gain, mutual coupling between elements and power handling capability, which makes the antenna array more suitable for effective jamming of radars.

IX ADVANCEMENTS IN THE FIELD

Elliptical Refocusing of Rotman type lens has been proposed by P. K. Singhal [32]. Phase error has been calculated and it has been compared with the error obtained with the Rotman Lens which was analyzed using the contour integral technique and is found that the lens obtained with elliptical focal arc was more compact.

A Rotman Lens design using a graded dielectric substrate was proposed by Lora Schulwitz [33], which alleviates the problems associated with the coherent spill-over loss of the conventional Rotman Lens. In this design, a gradient of dielectric permittivities is introduced within the lens. This allows for the bending of the rays within the lens, thus better focusing the energy between the beam and array ports, with minimal power terminated in the side ports of the lens.

A wide banded planar multi-input/output port Rotman lens for phase array antennas was proposed by Wan Chen [34]. This design consists of lens and delay lines. A useful segmented design of the delay line is applied to improve the transmission efficiency. A principle of dummy port is used to improve the output characteristics.

In 2015, Min Yu [35] has proposed a localized angle-time spread function (ATSF)-based filtering method to reduce out-of-focus blurs. For imaging purposes, a Rotman Lens intrinsically requires that the scattered waves arriving at the array be plane waves. However, this requirement cannot be met in near-field imaging applications, as the scattered waves from targets in the near field defocus at the beam ports of the lens because of the nonplane wave scattering. As a result, out of focus blur appears in the near-field images, thus leading to degradation of the picture quality. With the proposed method, the deblurring process becomes simple for Rotman Lens.

In 2003 Singhal et al. proposed the fact that the height of the array and feed contours must be the same for maximum power transfer and better lens performance [36]. Effect on shape of beam and array contour by variation in scanning angle, focal ratio, and element spacing were prime issues of his work.

Zongxin [37] developed a compact printable Multi beam antenna array. The antenna system was composed of a printed Rotman lens and an antipodal dual elliptically tapered slot antenna array; both of the two components were studied, respectively, at first, and then integrated on a single printed circuit board to make up the integrated unit of the multi beam antenna array.

Ardavan Rahimian[38] has presented a novel design of steerable microwave beamforming networks employing a 4x4 Rotman Lens for operation at 3.15 GHz, an 8x8 Rotman lens for operation at 6.3 GHz and a cascaded 4x4 buttler matrices for operation at 3.15 GHz. This design is suitable for use in inter-vehicle and roadside-to-vehicle automotive communications electronically steered arrays.

Simon [39] has presented a tool that combines the planar circuit analysis with a full-wave, moment method (MoM) analysis of the individual tapered feed ports. This tool uses the polynomial representation of the stripline geometry potential Green’s functions. The results have also been compared with NARL (Numerical Analysis of Rotman Lens) to verify the tool.

Tae-Young Kim, Young-Min Yoon, Gun-Su Kim, and Boo-Gyoun Kim, [40] has provided detailed analysis of loading 7 element patch array antenna with inductive load to achieve better performance on mutual coupling between the array element. The author has presented that the inductive loading has improved VSWR, mutual coupling and side lobe levels.

Chao-Hsing Hsu, [41] proposed a local two way convergent algorithm to improve the traditional genetic algorithm by adding the nulls in the interference path to improve the SIR ration of the array. The algorithm has converged after 386 iterations and provided better SIR.

A. Helaly, A. Sebak and L. Shafai [43], presented a method for optimizing the phase center of linear array due to imperfections in array geometry. He has considered a 20 element array with 0.5λ at 5 GHz and demonstrated the shift in phase center due to imperfections in the geometry of the array

M. S. R. Bashri, Tughrul Arslan and Wei Zhou [45], has simulated dual frequency four element linear phased array and demonstrated theoretical results for extending the band width of the linera array. He has simulated rectangular patch cut on ground plane and extended the band width by few MHz.

Yong-Jun Lee, Jong-Woo Seo, Jae-Kwon Ha and Dong-Chul Park [46], have presented null steering technique to reject the interference in Genetic Algorithm and analyzed null depth and accuracy and cost function is proposed.

Bidirectional phase center motion (BPCM) was proposed by Shiwen Yang [49] and designed L band patch array which has exhibited -35 dB side lobe levels. The authors have proposed c-scheme and D-scheme BPCMs. C-scheme BPCM has exhibited very low side lobe levels in the order of -29dB. The D scheme BPCM has exhibited a synthesis of very side lobe levels with Doppler shift.

S. E. Valavan, D. Tran, A. G. Yarovoy and A. G. Roederer [53], have presented a compact linear array with patch antennas have been simulated and experimental results were presented. Wide angle scanning was experimented and results have shown that low mutual coupling has been exhibited in X- band.

Xin Shi, Shaohui Quan and Guoyu He [54], have improved the Genetic algorithm (GA) with fitness function and demonstrated low side lobe levels at different distances in 8 element array. Detailed mathematical analysis has been presented for synthesis of side lobes.

R S. Tahim, J. Foshee, and K. Chang [55], have developed TR module based phase array antenna at 20 GHz with beam steering of ±20 degrees with insertion loss of 1 dB and steering over 0 to 360 degrees. Taper Slot Array antenna with high gain TR module with dual frequencies was demonstrated by the authors.

In 1960, Wilhelm H. Von Aulockt [57], has brought many important properties of phase array antennas like steering bema width and control beam angles. The change in phase delay between the elements effectively controls the beam position. The simulated and measured results of 1-D and 2-D were presented in the paper.

In 2004, W. Aertsl and G. A. E. Vandenbosch [60], have demonstrated the optimum inter element spacing is inverse of the period in the u = Cos Ө domain causing the first grating lobe lie just behind the edge of the visible interval. The author highlighted as the number of elements are infinite the beam width is zero.

A. S. Daryoush and B. Choe [61], have explained the feasibility of the reconfiguration of antenna elements of the phased arrays for suitable applications and explained about the effect of the centre elements in the beam formation of the phased arrays. The control of frequency, inter element spacing and individual radiation patterns plays major role in the reconfiguration of the array.

Authors, SeyedKasra Garakoui, Eric A.M. Klumperink, Bram Nauta, and Frank E. van Vliet [62], have explained about the delay circuits in the phased array system leads to beam squint and control methods will help to reduce the ebam squint to the maximum extent possible. The author has presented beam squint formula as a function of difference in frequency (difference in time delay) and is given by equation $\Delta\theta = -\frac{\tan\theta_0}{f_0}\Delta f$, which is very useful formula for estimating the beam squint of the phased array.
Rajeev Jyoti, Soumyabrata Chakrabarty, Sanjeev Kulshrestha and V. K. Singh, [63] have presented in IMaRC-2014, a multilayer configuration of phased array antenna for Satellite and imaging radars and the array antenna is configured with tiles which are excited with suitable feed network. The band width of the phased array was improved to 4% with active array technology from 1% with fixed beam antenna technology. The authors have also proposed holographic technique for obtaining excitation coefficients on the aperture when radiation pattern is known and observed that no degradation in the electrical performance of the array.

Monica Obermier, ARFL and Edward J. Powers [68], have explained the effect of inter modulation products of high power amplifiers TWTA, SSPA on the main and side lobes of the phased array antenna and proposed to use equal array factor for all angles which will yield an IM factor of unit at all angles.

Takana Kaho, Tadao Nakagawa, and Katsuhiko Araki [70], have proposed C/IM technique in 6 element array for improving the intermediation products in active phased array antennas.

In [71], the authors, John P. Gianvittorio and Yahya Rahmat-Samii, have brought out regarding the tight packing of fractal linear array antennas for PS wireless communications. The elements are proposed with fractals which reduces the size of the element while there is no change in the inter element spacing of the elements, thus reducing the mutual coupling between the elements and 15 dB improvement was observed in this array.

According to ZhengyuPeng, Tiancun Hu, Wangzhao Cui, Jiangtao Huangfu and Changzhi Li [73], particle swam optimization and genetic algorithms are converged after more than 20 iterations and provide narrow beam width patterns, which are incompetent for providing wider angular beam coverage. The authors have proposed modified power inversion algorithm, in which the beam width is controlled by Gaussian noise and flatness the nulls to get effective wider beam width. The authors demonstrated this unconventional method to increase the beam width of the array.

M. Ali Soliman, W. Swelam, Ali Gomaa and T. E. Taha [74], designed a steerable patch array antenna with very low side lobes and coupling between elements, by directing the energy in to main lobes of the array in dual frequencies and the resultant reflection coefficient is better than -15 dB in the dual band of interest

The authors Kuan Min Lee, Allen T.S. Wang, and Ruey Shi Chu E [75], proposed interleaved design approach to obtain dual band and dual polarized phased array antenna for ship, submarine and airborne systems.

Sean Z. Bu and Afshin S. Daryoush [76], proposed biquadratic programming method to reconfigure the arrays during the failure of some of the array elements, by varying the phase of the remaining active elements. The author has presented numerical results of 13 elemnt linear array and compared the results of Eigen value and cophasal methods.

R. N. Simons, G. E. Ponchak, R. Q. Lee and N. S. Fernandez, have proposed a four element co-planar waveguide phase array antenna in Ku Band and proved that the radiation patterns are excellent in the band of interest.

The optical linear phased array designed for a wide angle scanning is presented by ZeevIluzl and Amir Boag [79]. To facilitate a wide-scanning capability while avoiding grating lobes, the inter-element spacing smaller than one wavelength is selected. A patch antenna radiating element coupled to a Silicon dielectric waveguide is designed. The simulation results for the single antenna and a linear array are presented in the paper.

In 2011, EhsanTavakoli, Mahmoud Tabandeh and Sara Kaffash, have proposed an optimum radiation pattern achieved by a phased array (PA) antenna for wireless Network-on-Chip applications and compared with their PA characteristics to basic linear dipole antenna [80]. Using CST Microwave Studio for simulation, a high transmission gain of -37.4 dB at 20 GHz is achieved from the pair of PA antennas at a separation of 6.25 mm on a high resistive silicon substrate which is at least 20 dB better than the dipole pair.

In 2001, S. Chen. C. du Toit. K. Hersey, et al [83] have proposed an antenna which uses vertical linear polarization and scans from -45° to +45° in the azimuth plane and has a fixed cosecant squared beam in the elevation plane. The authors presented the performance and measurement results for a 1-D scanning phased array antenna with a 16x16 element configuration. Gain is measured to be 22.5 dBi at 0° scan. The measured radiation patterns, gains and active return loss for scans from 45° to +45° in 5° steps demonstrate consistent patterns with no grating lobes and blindness. This performance is attributed to minimum mutual coupling effects of this microstrip patch array.

Harold R. had presented a regular polygon configuration of flat antenna panels to de-spin the beam of a spinning spacecraft [85]. An individual panel having an 8 element linear array of square dual probe-fed patches and a micro strip line feed network were modeled with Ansoft Ensemble and analyzed using MOM to predict beam patterns and other critical parameters. With eight panels on sides of a regular hexagon, each panel is displaced from its nearest neighbor by 45°. The beams radiated by square micro strip patches on adjacent panels overlap in azimuth at their half-power points, since @, = 45°. An 8 element linear array of square microstrip patches on each panel provides >13 dBi gain with margin for steering (up to ϴ = 25°). With the micro strip line feed network coupled to an eight element array, Ensemble predicts a VSWR ≤1.5 over 150 MHz at the input port around an operating frequency of 8.45 GHz.

J. G. van Hezewijk [89], has explained the element excitation method for determination of excitation of antenna elements in an active phased array as a function of the amplitude and phase setting, which is used for aligning the amplitude and phase seetings of the antenna elements of an active phased array for a desired radiation pattern.

In [90], the authors, Jiang Wei Yang Qihe and Guo Yanchnng, presented the appropriate range technique for improving the performance of the phased array in many applications.

A.S. Daryoush and M. Ghanevati [92] have concluded that true time delay of elements provides the radiation beam without squint.

S. Ebadi, K. Forouraghi , S. A. Sattarzadeh [94], have presented about the Low side lobe levels in the far-field pattern of an array antenna are usually synthesized using an amplitude taper. A low side lobe can also be gained using a phase taper across the array. Phase tapering has a simple feed network compared to amplitude tapering. In this approach, instead of amplitude-weighting the signal applied to each element through a complex feed network, the phases are weighted and the resulted signal is applied to each element via the beam steering phase shifters. The array design in this case reduces to determination of the phase at each antenna element. The authors have applied Pattem Search Algorithm to the problem of a low side lobe level phased array antenna design. The resulted side lobe level for a uniform array with 60 equispaced elements is -17.87dB which can be satisfying for a phase only array antenna. The resulted phases have also a unique interesting distribution due to the algorithm properties.

J. Roger, C. Aubry, D Renaud, F Devambez [97], had presented a simple and efficient method allowing the adaptation of electronically steerable antennas using quantized phase shifters. Adaptation aims to maximize the desired signal to external noise ratio. The process which does not involve the knowledge of the directions of external noise sources uses only the quantized phase shifters for adaptation. The performance of this process has been estimated by calculations using a simplified model, by simulation and by experimentation on a sixty element array. The results demonstrate the method efficiency. The author has presented some results obtained with a linear array with a Gaussian noise source

- increase of desired signal to external noise ratio > 30 dB everywhere out of the main beam
- gain loss in pointing direction (0.2 dB)
- Axis deviation ≤0.02 degree

The author also presented the results of simulation with five simultaneous noise sources

- increase of desired signal to external noise ratio > 20 dB.

A. S. E. Valavan, et al, in [98], investigated the impact of truncation on linear arrays with dual-band patch radiators. With the aid of full-wave simulations, it is demonstrated that maintaining array lengths of at least 8λ and 6λ (defined at the lowest operational frequency) for linear arrays oriented along the E-plane and H-plane respectively, would help in mimicking large (infinite) arrays and thereby adequately capture the edge element behavior at both operational frequencies. For the lowest operational band these results agree with results available in literature for single band patch antenna arrays. However, in order to achieve similar convergence at the highest operational frequency, array lengths of at least 11λ and 7λ (defined at the high frequency of operation) are required for the E-plane and H-plane arrays respectively to mimic an infinite array. This seems to be a property specific to the dual-band array.

B. Tomasic and A. Hessel, demonstrated the amplitude is constant up to the end fire gating lobe angle which is at 42° off broadside for dx=0.6X and at 25° for dx=0.7X in [99]. Since the phase is referenced to the excited element, indicates that in this region the "phase center" coincides with the element location.

Balanis [102], derived expressions for array factor and radiation patterns for 1D & 2D linear phased arrays and explained about the applications of linear phased arrays in DOA measurements of EW receivers.

In [103], S. Bassam and J. Rashed-Mohassel, simulated and constructed an exponential TEM horn antenna with Chebyshev impedance taper. The results show, better matching at the feed point and over wide range of frequencies. In this design, impedance changes smoothly from the feed line to the antenna aperture. The author has demonstrated, in comparison with exponential impedance taper, Chebyshev impedance taper has wider frequency band with improved VSWR less than 2.

Mike Stasiowski of Cobham Defense Electronic Systems has designed and manufactured two different broadband phased array antennas [104]. The 3:1 array was characterized as both individual radiating elements as well as patterns using fixed power divider assemblies. The 9:1 array CAD design was straightforward and based on the successful measurement to prediction correlation of the 3:1 array provides confidence the measurement of the larger antenna would also be successful. A number of challenges were identified and overcome in the design, layout, material selection and fabrication of the antenna array.

A Rogers, simulated 96 element X-band phased array fed with a 12 way squint less wideband waveguide E-plane divider based on feed proposed by Rogers [105].

In 2014, Harshpreet Singh Bakshi, Amit Gupta, Sonali Dutta, and A Prabhakar, described the applications of Rotman lens fed linear horn array and indicated that Raytheon is developing such antenna for EW applications [106].

X CONCLUSION

Rotman Lens is a device that uses the free space wavelength of a signal injected into a geometrically configured waveguide to passively shift the phase of inputs into a linear antenna array in order to scan a beam in any desired direction. Hence, the shape and length transmission lines are to be appropriately chosen. This leads to difficulties in the design of the lens because of the cost of the lens itself and also the price of the photo etching. Linear phased array antenna along with Rotman lens was manufactured by many companies to obtain high gain in the required direction for radar and satellite applications. The beam is steered over azimuth and elevation direction based on the phases changes among the array elements. Rotman lens fed linear array was in use for direction finding in EW field, however, advancements indicated that further the linear antennas could be good candidate for jamming the radar signals with very high power. The E field sectorial horn as an array element in the linear phased array provides high gain and fast switching the beams in the desired direction. The requirements of high power, low VSWR over wide operating frequency ranges poses challenging tasks to researchers. Though the array antenna is in use for ECM, limited functionality is achieved. Many scientists are working to improve the performance of Rotman lens fed horn array to achieve optimum performance over the wide frequency coverage at high power levels. The critical parameters to be improved are active VSWR [104], array gain, mutual coupling between elements and power handling capability, which makes the antenna array more suitable for effective jamming of radars. The paper mainly was dealt with the different development processes of the Rotman Lens and linear arrays, which are more relevant to the modern defense requirements to safeguard the nation.

XI REFERENCES

[1] R.C. Hansen, “*Phased Array Antennas*”, New York: John Wiley and Sons, 1998.

[2] J.Ruze, "*Wide-angle metal-plate optics*," Proc. IRE, vol. 38, p. 6, January 1950.

[3] J. Brown, “*Microwave Lens: Methuen”*, 1953.

[4] J. Brown, *"Lens Antennas"* in Antenna Theory. Vol. Part 2: McGraw-Hill, 1969

[5] J. Brown, Jones, S.S., "*Microwave Lenses*," Electronic Engineering, vol. 22, p. 6, Apr-Oct 1950.

[6] H. Gent, "*The bootlace aerial*," Royal Radar Establishment J., p. 11, Oct. 1957.

[7] J. Shelton, "*Focusing characteristics of symmetrically configured bootlace lenses*," Antennas and Propagation, IEEE Transactions on [legacy, pre - 1988], vol. 26, pp. 513-518, 1978.

[8] R. M. Cox and J. R. Sebring, "*MLS-A practical application of microwave technology*," IEEE Transactions on Microwave Theory and Techniques, vol. MTT-24, p. 8, Dec. 1976.

[9] G. J. Monser, "*Advances in Lens-Fed Multibeam Technology*," NTIS, p. 22, Feb 1992.

[10] W. Rotman and R. Turner, "*Wide-angle Microwave Lens for Line Source Applications*," IEEE Transactions on Antennas and Propagation, vol. 11, pp. 623-632, 1963.

[11] D. H. Archer and M. J. Maybell, "*Rotman lens development history at Raytheon Electronic Warfare Systems 1967-1995*," 2005, pp. 31-34 vol. 2B.

[12] D. H. Archer, "*Lens-Fed Multiple-Beam Arrays*" Microwave J., vol. 18, p. 6, Oct 1975.

[13] D. H. Archer, "*Lens-Fed Multiple Beams Arrays*" Microwave J., vol. 27, p. 6, 1984.

[14] A. Al-Zayed, L. Schulwitz, and A. Mortazawi, "*A dual polarized millimeter-wave Multibeam phased array*" 2004, pp. 87-90 Vol.1.

[15] L. T. Hall, D. Abbott, and H. J. Hansen, "*Design and simulation of a high efficiency Rotman lens for MM-wave sensing applications*" 2000, pp. 1419-1422.

[16] J. Herd and D. Pozar, "*Design of a microstrip antenna array fed by a Rotman lens*," 1984, pp. 729-732.

[17] C. Metz, J. Grubert, J. Heyen, A. F. Jacob, S. Janot, E. Lissel, G. Oberschmidt, and L. C. Stange, "*Fully*

integrated automotive radar sensor with versatile resolution" Microwave Theory and Techniques, IEEE Transactions on, vol. 49, pp. 2560-2566, 2001.

[18] Y. M. Tao and G. Y. Delisle, "*Lens-fed multiple beam array for millimeter wave indoor communications*", 1997, pp. 2206-2209 vol.4.

[19] T. Katagi, S. Mano, and S. Sato, "*An Improved Design Method of Rotman Lens Antennas,*" IEEE Transactions on Antennas and Propagation, vol. 32, pp. 524-527, 1984.

[20] T. Katagi, S. Mano, S. Sato, S. Tahara, and E. Tomimatsu, "*An Improved Design Method of Rotman Lens Antennas,*" IEEE Transactions on Antennas and Propagation, vol. 20, pp. 136-139, 1982.

[21] M. S. Smith, "*Design Considerations for Ruze and Rotman Lens,*" The Radio and Electronic Engineer, vol. 52, pp. 181-187, 1982.

[22] R. C. Hansen, "*Design Trades for Rotman lenses,*" IEEE Transactions on Antennas and Propagation, vol. 39, pp. 464-472, 1991.

[23] C. Rappaport and A. Zaghloul, "*Optimized Three-dimensional Lenses for Wideangle Scanning,*" IEEE Transactions on Antennas and Propagation, vol. 33, pp.1227-1236, 1985.

[24] J. Dong, A. I. Zaghloul, and R. Rotman, "*Non-Focal Minimum-Phase-Error Planar Rotman Lens,*" in URSI National Radio Science Meeting Colorado, 2008.

[25] S.S.D. Jones, H. Gent and A.A.L. Browne, "*Improvements in or Relating to Electromagnetic-Wave Lens and Mirror Systems"*, British Provisional Patent Specification No. 25926/56, August 1956.

[26] W. Rotman and R.F. Turner, "*Wide-Angle Microwave Lens for Line Source Applications*", IEEE Transactions on Antennas and Propagation, vol. 11, pp. 623-632, Nov. 1963.

[27] J. Ruze, "*Wide-Angle Metal-Plate Optics*", Proc. IRE, vol. 38, p. 6, January 1950.

[28] T. Katagi, S. Mano and S.I. Sato, "*An Improved Design Method of Rotman Lens Antennas"*, IEEE Transactions on Antennas and Propagation, 1984, vol. ap-32,no. 5, pp. 524-527.

[29] D.R. Gagnon, "*Procedure for Correct Refocusing of the Rotman Lens According to Snell's Law*", IEEE Transactions on Antennas and Propagation, 1989,vol. 37, no. 3, pp. 390-392.

[30] R.C. Hansen, "*Design Trades for Rotman Lenses*", IEEE Transactions on Antennas and Propagation, 1991, vol. 39, no. 4, pp. 464-472.

[31] Shruti Vashist, M.K.Soni and P.K. Singhal, "*Review on the development of Rotman Lens Antenna*", Hindawi Publishing Corporation, Chinese Journal of Engineering, Volume 2014, 9 pages.

[32] P.K. Singhal, R.D.Gupta and P.C.Sharma, "*Theoretical Investigations of Elliptical Refocusing of Rotman type Lens for Multiple Beamforming"*, Journal of Microwaves and Optoelectronics, Vol. 3, N.o.4, April 2004.

[33] Lora Schulwitz and Amir Mortazawi, "*A new low loss Rotman lens design using a graded dielectric substrate*", IEEE Transactions on microwave theory and techniques, VOl.56, No. 12. December 2008

[34] Wan Chen, Jiahui Fu, Qun Wu and Jun Hua, "*A Design of Rotman Lens for Phase Antenna Array*"

[35] Min Yu, Deshuang Zhao, Yuanwei Jin and Bing-Zhong Wang, "*Near-Field Image Restoration for Rotman Lens by Localised Angle-Time Spread Function-Based Filtering Method"*, IEEE Transactions on Antennas And Propagation, Vol.63, No.5, May 2015.

[36] P.K.Singhal, P.C.Sharma, and R.D.Gupta, "*Rotman lens with equal heights of array and beam contours*" IEEE Transactions on Antennas and Propagation, Vol.51, no.8, 2048-2056, 2003.

[37] Wang Zongxin, Xiang Bo, and Yang Fei, "*A Multibeam antenna array based on printed Rotman Lens*", International journal of Antennas and Propagation, Vol. 2013, 6 pages, 2013.

[38] Ardavan Rahimian, "*Microwave Beamforming Networks Employing Rotman Lenses and Cascaded Butler Matrices for Automotive Communications Beam Scanning Electronically Steered Arrays"*, Microwaves, Radar and Remote Sensing Symposium, August 25-27, 2011, Kiev, Ukraine.

[39] Peter S.Simon, "*Analysis and Synthesis of Rotman Lenses*", Proceedings of the 22nd AIAA International Communications Satellite Systems Conference and Exhibit Monterey, Calif, USA, May 2004.

[40] Tae-Young Kim, Young-Min Yoon, Gun-Su Kim, and Boo-Gyoun Kim, "*A Linear Phased Array Antenna Composed of Inductive Loaded Patch Antennas*", IEEE Antennas and Wireless Propagation Letters (Volume: 10), 2011.

[41] Chao-Hsing Hsu, **"***Optimizing beam pattern of adaptive linear phase array antenna using local genetic algorithm***"**, Antennas and Propagation Society International Symposium, 2005 IEEE (Volume: 1B), 2005

[42] Hiroyuki Arai, Chomora Mikeka, **"***Phase Control in Small Linear Antenna Arrays Based on LNA's Parasitic Phase Shifts*, Antenna Technology: Small Antennas and Novel Metamaterials**"**, Mar 2008

[43] A. Helaly; A. Sebak; L. Shafai, "*Phase centre movement in linear phased array antennas*", Antennas and Propagation Society International Symposium, May 1990

[44] Y.C. Guo, M.S. Smith, "*Phase weighting for linear antenna arrays*", Electronic Letters, Feb 1981

[45] M. S. R. Bashri, Tughrul Arslan, Wei Zhou, "*A dual-band linear phased array antenna for WiFi and LTE mobile applications*", Antennas & Propagation Conference (LAPC), 2015 Loughborough, Nov 2015

[46] Yong-Jun Lee, Jong-Woo Seo, Jae-Kwon Ha, Dong-Chul Park, "*Null steering of linear phased array antenna using genetic algorithm*", Microwave Conference, 2009. APMC 2009. Asia Pacific, Dec 2009

[47] Jian Zhang, Xue-Song Yang, Jia-Lin Li, Bing-Zhong Wang, "*A linear phased array with reconfigurable dynamic Yagi-Uda patch antenna elements*", Microwave and Millimeter Wave Circuits and System Technology (MMWCST), 2012 , Apr 2012

[48] V.N. Bakhvalov, V.A. Burmasov, Yu.V. Klonova, "*Linear phased antenna array with low level of side radiation*", Antenna Theory and Techniques, 2003. 4th International Conference on (Volume: 1), 9-12 Sept. 2003

[49] Shiwen Yang, "*Linear antenna arrays with bidirectional phase center motion*", IEEE Transactions on Antennas and Propagation (Volume: 53, Issue: 5), May 2005

[50] Levente Dudas, Peter Kovacs, Rudolf Seller, "*Smart antenna - phase controlled linear antenna array*", Applied Electromagnetics and Communications, 2007. ICECom 2007. 19th International Conference, 24-26 Sept. 2007

[51] F.R. Castella, J.R. Kuttler, "*Optimized array antenna nulling with phase-only control*", IEE Proceedings F - Radar and Signal Processing, Jun-91

[52] Liang Wen, Tao Zeng, Xiao Liang Li, "*Error analysis in phased array antenna pattern simulation*", Computer Engineering and Technology (ICCET), 2010 , 16-18 April 2010

[53] S. E. Valavan, D. Tran, A. G. Yarovoy and A. G. Roederer,, "*Linear dual-band phased arrays with wide-angle scanning capability*", Radar Conference (EuRAD), 2015 European, 9-11 Sept. 2015

[54] Xin Shi, Shaohui Quan, Guoyu He, "*Design and optimization of liner phased array antennas with different distance based on genetic algorithm*", Antennas, Propagation and EM Theory, 2008. ISAPE 2008. 8th International Symposium, 2-5 Nov. 2008

[55] R S. Tahim, J. Foshee, and K. Chang, "*Integrated multi frequency phased array antenna*", Antennas and Propagation Society International Symposium, 2001. IEEE, 8-13 July 2001

[56] Chung-Yong Chan, Multi objective, "*Design of Linear Antenna Arrays Using Bayesian Inference Framework*", IEEE Transactions on Antennas and Propagation (Volume: 62, Issue: 11), 20-Aug-14

[57] WILHELM H. VON AULOCKt, "*Properties of Phased Arrays*", Proceedings of the IRE (Volume: 48, Issue: 10), Oct. 1960

[58] Ashok A. k Agarwal, E.L Williamson, J.G Ferrante, "*Design criteria for wideband active phased array antennas*", Antennas and Propagation Society International Symposium, 1997. IEEE, 1997 Digest (Volume: 2), 13-18 July 1997

[59] Liang Yu, Junmin Liu, Chunjuan Bo, "*Analyze and simulation of linear antenna array fed with composite right/left-handed transmission line*", Communication Technology (ICCT), 2011 IEEE 13th International Conference, 25-28 Sept. 2011

[60] W. Aertsl, G. A. E. Vandenbosch, "*Optimal inter-element spacing in linear array antennas and its application in satellite communications*", Microwave Conference, 2004. 34th European (Volume: 3), 12-14 Oct. 2004

[61] A. S. Daryoush, B. Choe, "*Optically reconfigured active phased array antennas*", Antennas and Propagation Society International Symposium, 1988. AP-S, Digest, 6-10 June 1988

[62] Seyed Kasra Garakoui, Eric A.M. Klumperink, Bram Nauta, Frank E. van Vliet, "*Phased-array antenna beam squinting related to frequency dependency of delay circuits*", Radar Conference (EuRAD), 2011 European, 12-14 Oct. 2011

[63] D.T.K. Tong, M.C. Wu, "*Multi wavelength optically controlled phased-array antennas*", IEEE Transactions on Microwave Theory and Techniques (Volume: 46, Issue: 1), Jan-98

[64] M.S. Smith, "*Phased array fundamentals, Phased Array Radar*, IEE Tutorial Meeting, 18-Sep-89

[65] Rajeev Jyoti, Soumyabrata Chakrabarty, Sanjeev Kulshrestha & V. K. Singh, "*Multilayer printed active phased array antenna for radar imaging satellite*", Microwave and RF Conference (IMaRC), 2014 IEEE International, 15-17 Dec. 2014

[66] Randy L. Haupt, "*Timed and Phased Array Antennas*", Wiley-IEEE Press, 2015

[67] H. Zmuda, E.N. Toughlian, "*Broadband nulling for conformal phased array antennas using photonic processing*", Microwave Photonics, 2000. MWP 2000. International Topical Meeting, 2000

[68] Monica Obermier, ARFL, Edward J. Powers, "*The effects of nonlinear high power amplifiers on space based phased array antenna patterns*", Phased Array Systems and Technology, 2000. Proceedings. 2000 IEEE International Conference, 2000

[69] R.S. Chu, A. Wang, K.M. Lee, "*Surface Systems, Analysis of wideband tapered element phased array antennas*", Antennas and Propagation Society International Symposium, 1994. AP-S. Digest (Volume: 1), 20-24 June 1994

[70] Takana Kaho, Tadao Nakagawa, and Katsuhiko Araki, "*Reduction of intermediation distortion in active phased array antenna systems using a distortion controller*", Microwave Symposium Digest, 2002 IEEE MTT-S International (Volume: 2), 2-7 June 2002

[71] John P. Gianvittorio and Yahya Rahmat-Samii, "*Fractal loop elements in phased array antennas: reduced mutual coupling and tighter packing*", Phased Array Systems and Technology, 2000. Proceedings. 2000 IEEE International Conference, 2000

[72] S. C. Liu, "*A fault correction technique for phased array antennas*", Antennas and Propagation Society International Symposium, 1992. AP-S. , 18-25 June 1992

[73] Zhengyu Peng, Tiancun Hu, Wangzhao Cui, Jiangtao Huangfu, Changzhi Li, "*Unconventional Beam forming for Quasi-Hemispheric Coverage of a Phased Array Antenna*", IEEE Antennas and Wireless Propagation Letters (Volume:12), 11-Dec-13

[74] M. Ali Soliman , W. Swelam, Ali Gomaa, T. E. Taha, "*Steerable dual-band planar micro strip phased array antenna for 3G and 4G wireless communication systems*" IEEE Antennas and Wireless Propagation Letters, 12-16 Sept. 2011

[75] Kuan Min Lee, Allen T.S. Wang, and Ruey Shi Chu E, "*Dual-band, dual-polarization, interleaved cross-dipole and cavity-backed disc elements phased array antenna*", Antennas and Propagation Society International Symposium, 1997. IEEE, 1997 Digest (Volume: 2), 13-18 July 1997

[76] Sean Z. Bu and Afshin S. Daryoush, "*Comparison of reconfigurable methods of active phased array antenna*", Antennas and Propagation Society International Symposium, 1993. AP-S. Digest, June 28 1993-July 2 1993

[77] Liang Li, Shu Zhang, Xinying Diao, "*Compensation method for the beam pointing accuracy of phased array antenna in condition of phase quantification*", Electrical and Control Engineering (ICECE), 2011 International Conference, 6-18 Sept. 2011

[78] R. N. Simons, G. E. Ponchak, R. Q. Lee, N. S. Fernandez, "*Coplanar waveguide fed phased array antenna*", Antennas and Propagation Society International Symposium, 1990. AP-S, Merging Technologies for the 90's. Digest, 7-11 May 1990

[79] Zeev Iluzl , Amir Boag, "*Wide-angle scanning optical linear phased array*", Microwaves, Communications, Antennas and Electronic Systems (COMCAS), 2015 IEEE International Conference , 2-4 Nov. 2015

[80] Ehsan Tavakoli, Mahmoud Tabandeh, Sara Kaffash, "*An optimized phased-array antenna for intra-chip communications*", Antennas and Propagation Conference (LAPC), 2011 Loughborough, 14-15 Nov. 2011

[81] B.E. Stuckman, J.C. Hill, "*Method of null steering in phased array antenna systems*", Electronics Letters (Volume: 26, Issue: 15), 19-Jul-90

[82] William G. Cowley, Harry E. Green, "*Phased-array antennas for inter-satellite links*", Communications Theory Workshop (AusCTW), 2010 Australian, 2-5 Feb. 2010

[83] S. Chen. C. du Toit. K. Hersey, D. Pao. V. Karasack. J. Patel, M. Ramesh, C. Sui and E. Ekelman, "*Azimuth scanning, Ka-band phased array antenna*", Antennas and Propagation Society International Symposium, 2001. IEEE (Volume: 3), 8-13 July 2001

[84] Yihong Chen, R.T. Chen, "*A fully packaged true time delay module for a K-band phased array antenna system demonstration*", IEEE Photonics Technology Letters (Volume: 14, Issue: 8), Aug. 2002

[85] HAROLD R., "*Electronically de-spun phased array antenna for spinning spacecraft*", Antennas and Propagation Society International Symposium, 2001. IEEE (Volume: 4), 8-13 July 2001

[86] F. Soltankarimi, J. Nourinia, C. Ghobadi, "*Side lobe level optimization in phased array antennas using genetic algorithm*", Spread Spectrum Techniques and Applications, 2004 IEEE Eighth International Symposium, 0 Aug.-2 Sept. 2004

[87] R.P. Hsia, W.-M. Zhang, C.W. Domier, N.C. Luhmann, **"***A hybrid nonlinear delay line-based broad-band phased antenna array system***"**, IEEE Microwave and Guided Wave Letters (Volume: 8, Issue: 5), May 1998

[88] H.M. Aumann, **"***Continuously adjustable phase center displacement in phased array antenna***"**, Antennas and Propagation Society International Symposium, 1992. , 18-25 June 1992

[89] J. G. van Hezewijk, **"***Fast determination of the element excitation of active phased array antennas***"**, Antennas and Propagation Society International Symposium, 1991. AP-S, Digest, 24-28 June 1991

[90] Jiang Wei Yang Qihe, Guo Yanchnng, **"***Appropriate change technique (ACT) for phased array antennas***"**, Antennas and Propagation Society International Symposium, 1997. IEEE, 1997 Digest (Volume: 2), 13-18 July 1997

[91] Susan P. Williams and Larry E. Corey Georgia, **"***Mechanisms that contribute to the far-field polarization properties of phased-array antennas***"**, Antennas and Propagation Society International Symposium, 1989. AP-S, Digest, 26-30 June 1989

[92] A.S. Daryoush and M. Ghanevati, **"***True time delay challenge in optically controlled phased array antennas***"**, Antennas and Propagation Society International Symposium, 1997. IEEE, 1997 Digest (Volume: 2), 13-18 July 1997

[93] E. DuFort, **"***High-resolution emitter direction finding using a phased array antenna***"**, IEEE Transactions on Acoustics, Speech, and Signal Processing (Volume: 31, Issue: 6), Dec-83

[94] S. Ebadi, K. Forouraghi , S. A. Sattarzadeh, **"***Optimum low side lobe level phased array antenna design using pattern search algorithms***"**, Antennas and Propagation Society International Symposium, 2005 IEEE (Volume:1B), 2005

[95] B. Wardrop, **"***Experimental linear phased array with partial adaptivity***"**, Communications, Radar and Signal Processing, IEE Proceedings F (Volume: 130, Issue: 1), Feb, 1983

[96] Yan-Qiu Zhao, **"***Three-dimensional phased array antenna analysis and simulation***"**, Microwave, Antenna, Propagation and EMC Technologies for Wireless Communications, 2009, 27-29 Oct. 2009

[97] J. ROGER, C. AUBRY, D RENAUD, F DEVAMBEZ, **"***An Adaptive Phased Array Antenna using Simple Algorithm***"**, Microwave Conference, 1977. 7th European, 5-8 Sept. 1977

[98] A. S. E. Valavan, M. Simeoni and A. G. Yarovoy MTS-R (IRCTR), **"***Impact of truncation on finite-sized dual-band linear phased arrays***"**, Radar Conference (EuRAD), 2012 9th European, Oct. 31 2012-Nov. 2 2012

[99] B. Tomasic, A. Hessel, **"***Linear phased array of coaxially-fed monopole elements in a parallel plate guide***"**, Antennas and Propagation Society International Symposium, 1982 (Volume: 2), May 1982

[100] F. F. Dubrovka, S.Y. Martynyuk, V.V. Marchenko, "*Ultra Wide Band Linear Horn Array*:, 5th international conference on Antenna Theory and Techniques, 24-27 May, 2005, Kyiv, Ukraine, pp. 283-286

[101] Tengfei Xia, Shiwen Yang, and Jiaqing You, "*A Broadband Linear Phased Array Bases on Mutual Coupling*", IEEE transaction, 2008, pp. 170-173

[102] Constantine A. Balanis, "*Antenna Theory – Analysis and Design with multimedia CD*", Wiley India edition, 3rd edition, 2012.

[103] S. Bassam and J. Rashed-Mohassel, *"A Chebyshev Tapered TEM Horn Antenna"*, PIERS ONLINE, VOL. 2, NO. 6, 2006

[104] Mike Stasiowski, "*Broadband array antenna*", Cobham Defense electronic systems, Nuard Division, MD 21215

[105] A Rogers, "*Wideband Squintless Linear Arrays*", The Marconi Review, Volume XXXV, Number 187, Fourth Quarter 1972, pp 221 – 243.

[106] Harshpreet Singh Bakshi, Amit Gupta, Sonali Dutta, and A Prabhakar , "*Microwave antennas in defence for electronic Warfare application"* Volume-2, Issue-3, Mar 2014.

[107] S. A. Schelkunoff, "A Mathematical Thoery of Linear Arrays," Bell System Technical Journal, Vol 22, pp. 80-107, 1943

XII BIO DATA OF AUTHOR (S)

Ch Viswanadham, born in Ampolu, a village in suburbs of Srikakulam, Andhra Pradesh, India joined Bharat Electronics Limited, a premier defense electronics industry in 1990 immediately after B Tech (ECE) from Nagarjuna University, Guntur, Andhra Pradesh. He worked in various Naval EW Systems from design to field trails. He has received internal R&D

award for developing light weight ESM system for Indian Naval Ships. He has been deputed to Israel, Spain & South Korea to participate in technical discussions on EW systems with international companies. He has completed Master's degree in Digital Systems from Osmania University, Hyderabad in 1997, while working at BEL. Presently he is working as Senior Deputy General Manager (D&E) and heading RF & MWP group. He has presented many technical papers in BEL-House journal, national & international journals and conferences. He is Fellow of IETE & IE (I), Life member of SEMCE (I) & CSI and MIEEE. He is pursuing PhD in Andhra University, Visakhapatnam. His areas of interest are antennas, radomes, RF & Microwave designs and wide band / narrow band receivers.

Prof. P Mallikarjuna Rao, has completed B.E. degree from Andhra University and worked as Assist Professor in SRKR College of Engineering and completed M E degree at Andhra University in control systems during his tenure as Associate/Assistant professor. He is very good academician with lot of enthusiasm in teaching and is having 27 years of teaching experience. Due to this, he has also completed PhD in ECE with specialization in antenna arrays and received best PhD award for the year 1999. Presently he is working as Professor and Chairman, Board of Studies in ECE of Andhra University. He has guided many B.E, ME and PhD students for their project works / research programs. He is author of many electronic and communication engineering text books for engineering students. He has published numerous papers in national and international seminars / conferences. His area of interests are EMI / EMC, Array Antennas, Broadband Antennas, Microwave Communications, Analog Communications, etc., He is Fellow of IETE, Life Member of SEMCE (I) and Life Member of ISTE.