Linearly and Circularly Polarized Reflectarray Antennas with 4-Arm Archimedean Spiral Lattice

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Abstract

In this paper, linearly and circularly polarized reflectarray antennas with 4-arm Archimedean spiral lattice (LP-RAASL and CP-RAASL) have been designed and simulated. A perforated unit-cell element for the reflectarray is developed to cover about 360^o phase variation range. The designed element has same phase response for vertical, horizontal and circular polarizations depending on the polarization of the incident wavefront. The 4-arm Archimedean spiral shape is used as a filled pattern for the positioning of the unit-cell elements of the reflectarray. The proposed reflectarray has a circular aperture with a radius of 370 mm, consisting of 400 unit-cell elements. The circular horn antenna is placed at 370 mm from the reflectarray surface. The analysis and design of the unit cell and the reflectarray antenna are carried out using the finite integration technique and the results are compared with that calculated using the finite element method for verification. The radiation characteristics of linearly-polarized reflectarray for focused beam at $\varphi=0^o$, and $\theta=0$, $\pm15^o$, $\pm 30^o$, $\pm45^o$, $\pm60^o$, and $\theta=\pm75^o$ have been investigated. The frequency bandwidth and the beamwidth of the reflectarray are increased by using modified LP-RAASL Two different methods for unit-cell element arrangements are considered. The 1-dB gain bandwidth is increased to 7.24 %. A circularly-polarized CP-RAASL for single beam and broad beam radiation characteristics have been introduced. The array produces CP in the axial direction and covers a range of 4.2 GHz.

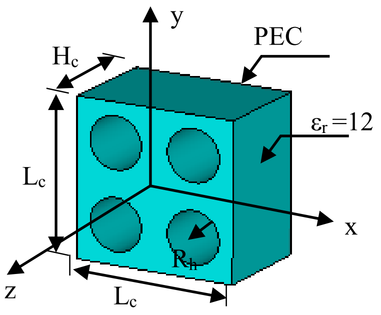
1. Introduction

The reflectarray concept was developed in the 1960s. Reflectarrays are low-cost, high gain antennas combining some of the best features of conventional parabolic reflectors and phased-arrays [1]. Combining the principles of phased arrays and geometrical optics, a reflectarray can produce predesigned radiation characteristics without requiring a complicated feeding network. Reflectarray collimates waves from a feeding antenna into a pencil beam by applying a phase correction to the scattered field at each element on the reflectarray aperture.. Several methods have been used as the phase shift mechanism such as, phase delay line, element rotation, and using the element with variable size [2]. Reflectarrays have been employed in various applications, such as satellite communications, and point-to-point communications due to their operational simplicity. Reflectarray antennas on cylindrical and spherical surfaces are demonstrated in [3]. Generally, grid patterns of the unit-cell elements on reflectarray aperture are in the form of periodic rectangular or circular lattice. Antenna arrays with logarithmic spiral lattice (sunflower) of microstrip patches of varying length have been investigated in [4]. Perforation of the dielectric substrate was used in reflectarray and transmitarray designs where a decrease in the overall weight was obtained.

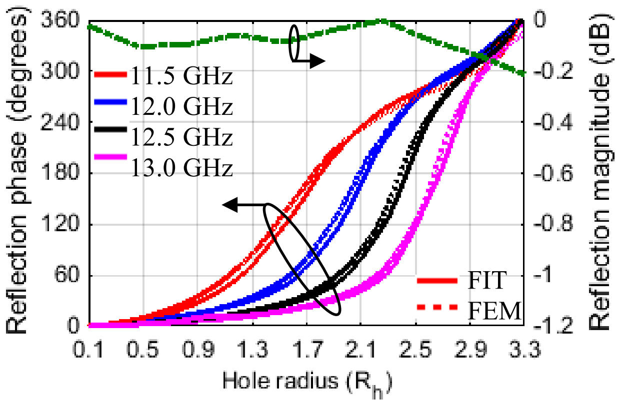
The objective of this paper is to investigate linearly-and circularly-polarized reflectarray antennas with 4-arm Archimedean spiral lattice. This type of lattice yields an optimized radial and azimuthal spreading of the unit-cell elements on the reflectarray aperture. It also allows the reduction of side lobe level without resorting to an amplitude tapering [5].The reflection characteristics of the social system are worked out with a full-wave computational technique that uses the finite integration technique (FIT) and the results are compared with that estimated with the finite element method. The report is formed as follows: Section III describes the aim of the unit-cell component. Section four offers the complete description of the design of the LP-RAASL. Section five presents the beam scanning operation in different directions. Section six introduces the radiation characteristics of CP-RAASL for single beam and broad beam radiation pattern. Finally, Section seven concludes the paper.

3. Design of unit-cell element.

The configuration of the proposed unit-cell is shown in Fig. 1a. The unit-cell dimensions are 15×15×10 mm^3 (L_c×L_c×H_c) using the HiK500F material with dielectric constant ε_r=12, and is placed above the perfect conductor ground plane. Each unit-cell element has four circular holes of equal radii, R_h. The required reflection phase is computed by considering an infinite periodic array model, where the mutual coupling between elements can be automatically taken into account. The separation distances between the holes and the number of holes are optimized to maximize the reflection of the structure at 12 GHz. The variations of the reflection coefficient, magnitude and phase, versus the hole radius are determined using the FIT technique and are illustrated at different frequencies in Fig. 1b. The results are compared with that calculated using FEM for validation. Good concordance between the two approaches is obtained. The unit-cell element introduces a reflection coefficient magnitude from 0 dB to -0.2 dB and 360^o phase variations for the hole radius, R_h, varied from 0.1 mm to 3.3 mm.. The unit-cell structure has same phase response for vertical, horizontal and circular polarizations due to the symmetry in its structure depending on the polarization of the incident wavefront.



a.



b.

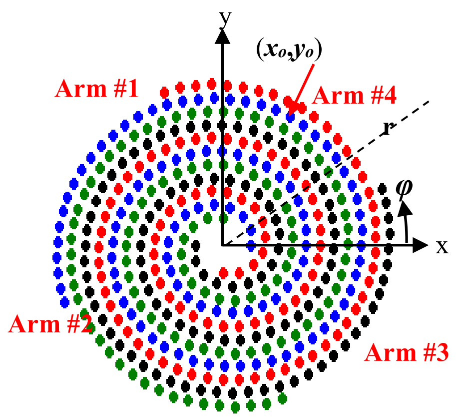
Figure 1 a. The 3-D structure of the unit-cell element. b. The variation of reflection coefficient phase and magnitude versus the hole radius of the perforated unit-cell at different frequencies.

4. Linearly-Polarized Reflectarray, LP-RAASL.

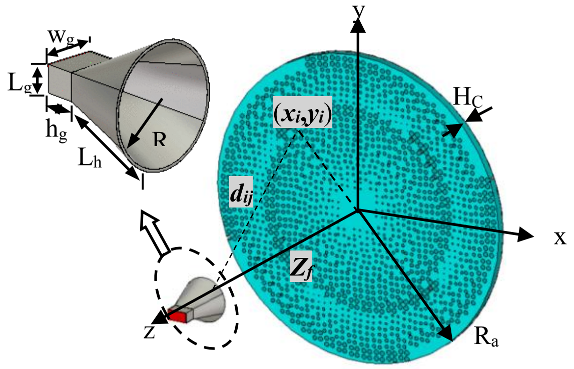
Figure 2a illustrates an LP-RAASL comprising 4-arm spirals. Each spiral is defined by the polar coordinate equation [1]:

$$r = a\varphi^N - \varphi' \quad for\ \varphi' = 0, \pi/2\ \ , \pi, 3\pi/2 \tag{1}$$

where r is the distance from the spiral center, φ is an angle measured from a baseline. φ' is the starting point for each spiral arm. The shape of the LP-RAASL is determined by the value of N, which determines the spiral increasing rate as φ is varied. The parameter "a" determines the distance between successive spiral loops at a given angle. In this paper, a=0.058, N=1, and φ is increased from π/4 to 6.13 π. A circular aperture with a maximum radius of 370 mm is completely filled with 100 unit-cell elements organized on a regular lattice in each arm as shown in Fig. 2a. Equation (1) is employed to determine the positions of the unit-cell elements on the reflectarray aperture. Figure 2b depicts the reflectarray layout under development, consisting of 400 unit-cell elements in x-y plane. The reflectarray is center-fed by linearly polarized circular horn antenna with dimensions L_g=11.9 mm, w_g=23.3 mm, h_g=15 mm, L_h=45 mm and R=26 mm located at 370 mm from the array aperture (F/D=1).



a. The unit-cell element arrangement for LP-RAASL



b. 3-D of LP-RAASL antenna structure

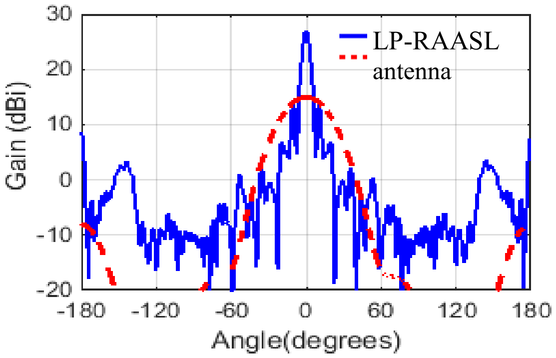
Figure 2. The detailed structure of perforated LP-RAASL antenna for reflected beam at (θ_o=φ_o=0°).

To focus the reflected waves into plane waves with designing deflection angles (θ_o, φ_o) and feed located at (x_f, y_f, z_f), the required reflected phase of the unit-cell, φ_{ij}, at the position (xi, y_{ij}) can be calculated by [6]:

$$\varphi_{ij}(x_{ij}, y_{ij}) = k_o(d_{ij} - \sin\theta_o(x_{ij}\cos\varphi_o + y_{ij}\sin\varphi_o)) \tag{2}$$

$$d_{ij} = \sqrt{(x_{ij} - x_f)^2 + (y_{ij} - y_f)^2 + (z_f)^2} \tag{3}$$

The computed radiation patterns of the LP-RAASL and horn antenna in E-plane and H-plane at f=11.6 GHz are shown in Fig. 3. The first side lobe levels (SLL) relative to the main lobe is 13.2 dB in the E-plane compared with 15.5 dBi for the H-plane. A maximum gain of 27 dBi with 3.9% (460 MHz) 1-dB gain bandwidth was achieved. The reflectarray has an inherent narrow bandwidth, because the phase of the reflection coefficient of each unit-cell element depends on the designed frequency. To increase the frequency bandwidth of the antenna, a modified LP-RAASL is used. The unit-cell elements in each spiral arm are designed at different frequencies (11.5 GHz, 12 GHz, 12.5 GHz, and 13 GHz) as shown in Fig. 4a. The 1-dB gain bandwidth is increased to 7.24 % (840 MHz) and the maximum gain is decreased to 23 dBi as appeared in Fig. 4b. The E-plane and H–plane patterns for the modified LP-RAASL at 11.6 GHz are shown in Fig. 6.



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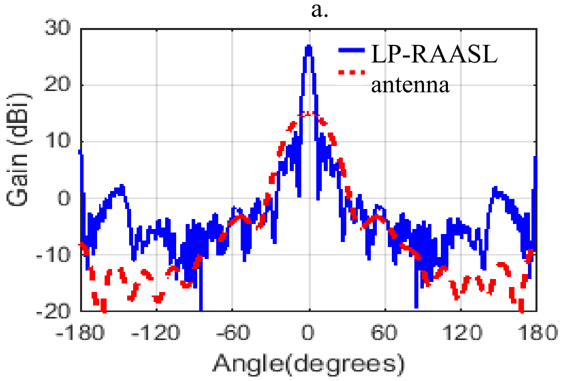
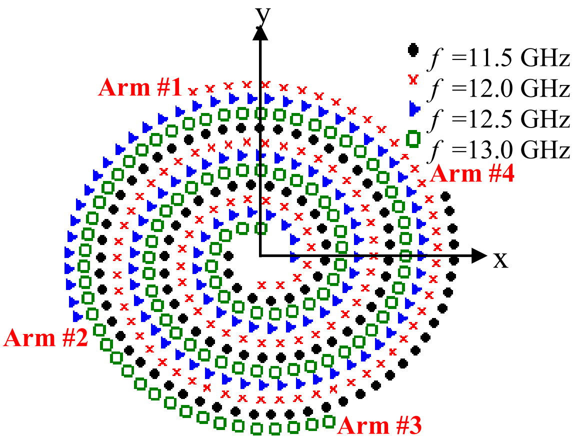
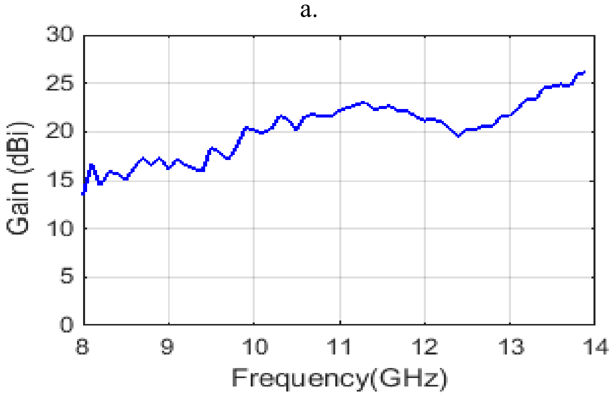


b.

Figure 3. The E- and H-plane radiation patterns versus elevation angle of LP-RAASL antenna and horn antenna at 11.6 GHz.



a.



b.

Figure 4. a. The unit-cell elements arrangement of modified LP-RAASL antenna. b. The peak gain versus frequency.

5- Beam Steering LP-RAASL

In this section, each LP-RAASL is a center-fed and designed to form a directive pencil beam in a particular direction, by the appropriate phasing of the radiating elements. The radiation patterns of the LP-RAASL configurations for eleven beams in different directions are illustrated in Fig. 5. The beams were designed to scan from -75º to +75º with 15º steps. In terms of beam pointing error, most beams are within the desired beam pointing direction. To increase the beamwidth of the main beam of the LP-RAASL two methods are used. In the first method, the 4-arm LP-RAASL elements are arranged independently to create four independent offset beams at $\theta_o = \pm 2^o$ and $\theta_o = \pm 4^o$ as represented in Fig. 6a. In the second method, chessboard arrangement for different four offset directions at the same frequency is used. The chessboard arrangement is constructed by rearranging the unit-cell elements of each spiral arm for the four arrays of the offset beams at $\theta_o = \pm 2^o$, and $\theta_o = \pm 4^o$ as shown in Fig. 6b. The radiation patterns in E- plane for both methods are shown in Fig. 7. The 3- dB beamwidth (HPBW) is 8 degrees for both methods, with a maximum gain of 22.3 dBi for method (1) and 21.3 dBi for method (2). SLL reduction for the case of chessboard arrangement is obtained.

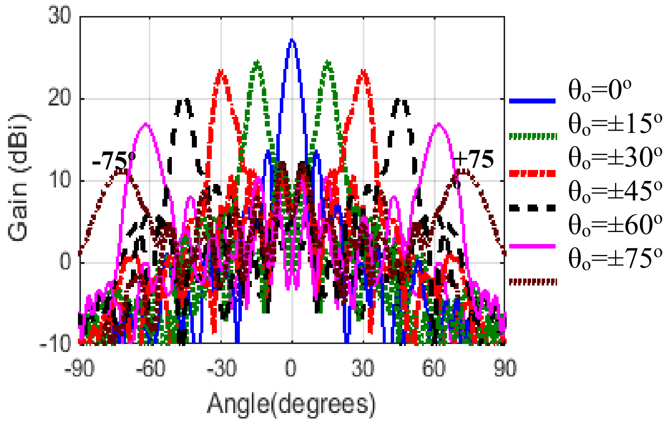
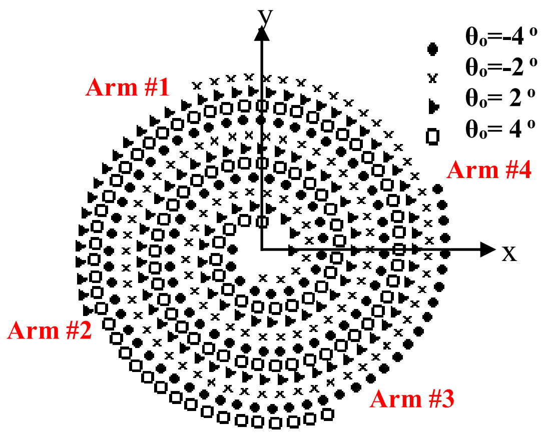
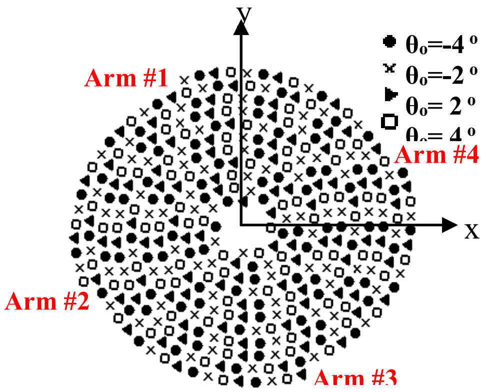


Figure 5. The gain versus elevation angle for LP- RAASL antenna at 11.6 GHz with offset beams at direction $\varphi=0^o$, and $\theta=\pm 15^o, \pm 30^o, \pm 45^o, \theta=\pm 60^o$. and $\theta=\pm 75^o$.



a. Method (1)



b. Method (2)

Figure 6. The unit-cells arrangement of the modified LP-RAASL antenna.

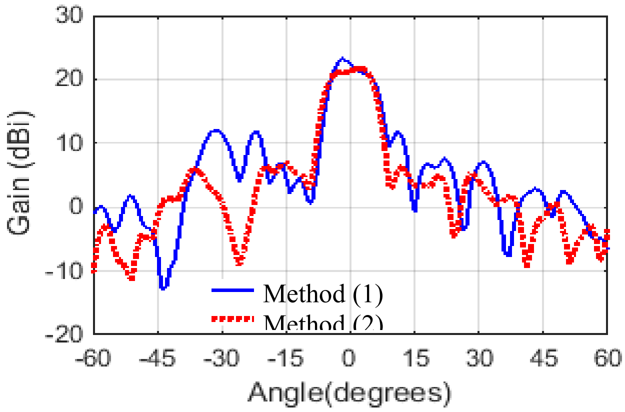


Figure 7. The gain patterns for LP-RAASL antenna at 11.6 GHz for Method (1) and Method (2) arrangement.

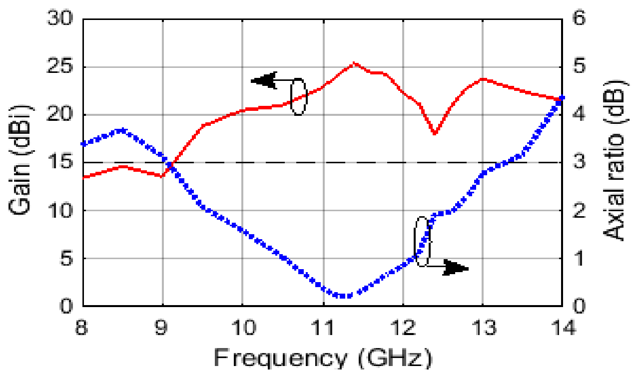


Figure 8. The gain and axial-ratio versus frequency for CP-RAASL at the boresight direction.

6. Circularly-Polarized Reflectarray, CP-RAASL

In this section, the circular horn is fed via two orthogonal coaxial probes with 90º phase shift to produce CP-field. The circular horn has HPBW is 4 degrees with cross-polar level lower than -27.8 dB in the bore-side direction. Gain of the feed horn is 13.2 dBi and HPBW is 40 degrees. The gain and axial ratio versus frequency are shown in Fig. 8. The peak gain is 25.3 dBi with 1-dB gain bandwidth of 0.4 GHz (3.4 %). The array produces CP in the axial direction with axial ratio, covers a range of 4.2 GHz. To increase the beam-width of the CP-RAASL, again the chessboard arrangement is used. A wide-beam is depicted with HPBW of 8 degrees and cross polarization level of 18.3 dB is depicted. The peak gain is 19.5 dBi with a frequency bandwidth of 0.4 GHz (3.4 %). The array produces CP covers almost the entire frequency band from 8 to 14 GHz.

7. Conclusions

Linearly-and circularly-polarized reflectarray antennas based on an Archimedean spiral lattice for satellite applications have been investigated. The reflectarray is composed of four arms Archimedean spiral and includes 400 unit-cell elements. It covers a circular aperture of radius 370 mm in x-y plane. The proposed unit-cell element consists of perforated dielectric sheet introduces 360º reflection phase variation. The array introduces a maximum gain of 27 dBi with SLL of 13.2 dB in the E-plane and 15.5 dBi in H-plane. 3.9% gain bandwidth is achieved. A modified LP-RAASL for bandwidth enhancement to about 7.24% is investigated by designing each spiral arm at different frequencies. Beam steering LP-RAASL configurations from -75º to +75º are designed and investigated. Two arrangements are used for designing a wide beamwidth LP-RAASL. The HPBW is increased to 8 degrees for both methods, with a maximum gain of 22.3 dBi for method (1) and 21.3 dBi for method (2). A circularly-polarized horn is used as a feeder for the CP-RAASL configurations. The peak gain is 25.3 dBi. The cross-polar level is lower than 31.8 dB. The array produces CP in the axial direction with axial ratio, covers a range of 4.2 GHz. The chessboard arrangement for the unit-cell elements is used of broad beam CP-RAASL of 8 degrees and cross polarization level of 18.3 dB is depicted.

7. References

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