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Reflectarray with logarithmic spiral lattice of elementary antennas on its aperture

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A B S T R A C T

A reflectarray with logarithmic spiral lattice of elementary antennas on its aperture is presented. In a logarithmic spiral lattice, elementary antennas are arranged in a grid of an outwardly spiral so as to have no translational periodicity. Infinite array approach has been used to determine reflection phase curve since in the aperiodic logarithmic spiral lattice, the effective unit cell area remains the same. Based on this lattice, a prime focus fed reflectarray centered at 16 GHz has been designed and developed. The measured gain is 30.5 dBi and side lobe levels are −29 dB and −22 dB in E- and H-plane respectively. Aperture efficiency of the proposed reflectarray is 37% and its 1-dB gain bandwidth is 4.1%. Good agreement between measured and simulated results reinforces the validity of the design process. A comprehensive investigation of reflectarrays' performance with different lattices is conducted which shows lower side lobe levels for reflectarray with logarithmic spiral lattice.

1. Introduction

A flat or conformal reflecting surface made up of suitably designed elementary antennas placed in a particular lattice, illuminated by a feed antenna, constitutes a reflectarray. Electromagnetic performances of the elementary antennas have to be suitably designed in order to obtain the required performance of the whole reflectarray system. Reflectarray is superior over a reflector in terms of low-profile, light-weight, facile fabrication, easy installation and compatibility with active devices [1]. Also reflectarray can be conformal to the mounting surface and require low space where reflectors occupy a large space for its installation. Moreover, reflectarray antennas offer the possibility of beam steering, like conventional phased arrays, but eliminate the complexity and losses of the feeding network, hence exhibiting higher efficiency [1]. Thus, reflectarrays have several attractive applications including earth stations, onboard antennas in satellite communication systems, microspacecraft missions and antennas for radar, to name just a few [2].

A desired radiation pattern for a reflectarray can be achieved by exploiting various parameters of the reflectarray. These parameters include element shape, element spacing and location on the reflectarray aperture, number of elements and aperture shape of the reflectarray. The effect of element shape [3,4], element spacing [5] and aperture shape of the reflectarray [6,7] has been discussed in literature for quite some time. Although substantial progress has been achieved in the design of reflectarray with periodic configurations of elementary antennas on its aperture but the impact of aperiodic configurations has not been studied much. Only recently aperiodic array configurations have been studied [8] and some attempts have been made to achieve optimized element locations for aperiodic configurations on reflectarray aperture [9,10]. Impact of aperiodic configuration of elementary antennas, in the form of logarithmic spiral lattice, on reflectarray aperture for fixed beam applications is the focus of this paper.

Conventionally, grid patterns of elementary antennas on reflectarray aperture are in the form of periodic rectangular or circular lattice. Although logarithmic or golden spiral lattice has been reported in the literature for conventional microstrip arrays [11] but it has never been reported in the context of reflectarray. In this paper, a reflectarray with logarithmic spiral lattice of microstrip patches of varying length has been designed, simulated and fabricated; where measured results are in good agreement with the simulated patterns. This type of lattice is used because it guarantees a really good radial and azimuth spreading in the element positions [12]. It also allows the reduction of side lobe level without resorting to an amplitude tapering [11]. Moreover, no grating lobes appear in a logarithmic spiral lattice especially when the array is electronically scanned [12]. In addition, the logarithmic

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spiral lattice has almost equal unit cell size per radiating element thus unit cell characterization can be done using infinite array approach as in conventional rectangular lattice [18].

In the last section of the paper, a performance comparison of the reflectarray with logarithmic spiral lattice has been carried out with reflectarrays having conventional rectangular and circular lattices. Reflectarray with logarithmic spiral lattice shows significant improvements in side lobe levels as compared to reflectarrays with conventional lattices.

2. Design of aperiodic reflectarray using logarithmic spiral lattice

Basic geometry of an aperiodic microstrip reflectarray is shown in Fig. 1. The reflecting surface is illuminated by a primary feed located at $z = z_o$. The reflecting surface is made up of N patches with (x_n, y_n) the coordinates of the nth element. R_i is the distance from the feed phase center to the nth element.

Complete design of a microstrip reflectarray using variable-sized patches basically consists of six steps and is described here in accordance with a prime focus fed reflectarray having logarithmic spiral lattice operating at 16 GHz. Focal length of the designed reflectarray is 192 mm and diameter is 350 mm, thus giving an f/D ratio of 0.55.

2.1. Selection of feed antenna

In order to properly illuminate all the elements of the reflectarray, a feed antenna should be designed so that it gives superior taper and spillover efficiencies. Furthermore, aperture size of the feed antenna should be small so that it could not degrade the radiation pattern of the reflectarray. Thus, any of the horn antenna [13], slotted waveguide antenna [14], helix antenna [15] or microstrip patch array [16,17] can be used to feed the reflectarray. However, horn antenna is mostly used as feed for reflectarray due to its high gain, lower aperture size and controlled taper efficiency. In this paper, a linearly polarized pyramidal horn with aperture size of 24 mm × 27 mm has been used as feed antenna. Gain of the feed horn is 13 dBi and half power beamwidths are 37° and 42° in E- and H-plane respectively.

2.2. Selection of reflectarray substrate

A low-loss dielectric with a low value of relative permittivity should be chosen as a substrate for reflectarray [16]. In selecting a substrate for designing a reflectarray with patches of variable size, two issues must be considered i.e., attainable phase range should be greater than or equal to 360° and phase curve should have a lower slope in order to counter fabrication errors. Both of these factors depend on the thickness of the substrate [1]. As the thickness of the substrate is increased, the slope of phase curve is decreased but at the same time attainable phase range becomes smaller than full 360° range. Thus a suitable thickness of substrate has to be chosen that gives a compromise between slope of phase curve and attainable phase range. Availability and cost of the substrate are also considered in the selection of reflectarray substrate. Here, a 0.635 mm thick Rogers RT5880 substrate with a relative permittivity of 2.2 and a dielectric loss tangent of 0.001 with 1 oz electrodeposited copper on both sides has been used as reflectarray substrate. Full 360° phase range has not been achieved with this substrate using patches of variable sizes, but due to availability of the substrate, few degrees in the phase range have been compromised.

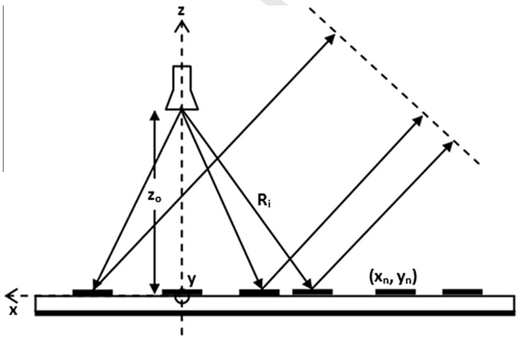

Fig. 1. Geometry of microstrip aperiodic reflectarray.

2.3. Grid spacing determination

One of the constraints in the design of reflectarray is to avoid overlapping as well as too large spacing between elementary antennas on reflectarray aperture. This design constraint is automatically satisfied in logarithmic spiral lattice where elements are neither overlapping nor too far from each other as long as size of the reflectarray is small. In this lattice, elementary antennas are arranged according to the following polar equations [12].

$$r = \frac{s}{\sqrt{\pi}}\sqrt{m} \tag{1}$$

$$\theta = 2\pi m\tau \tag{2}$$

here m is the number of the elementary antenna on reflectarray aperture ($m = 1,2,3\ldots$), s is the one-dimensional linear spacing between one elementary antenna to another, which is 0.6 λ_o in this case, and τ is the golden ratio given by

$$\tau = \frac{1+\sqrt{5}}{2} \approx 1.618 \tag{3}$$

Eqs. (1)–(3) are employed to determine the positions of elementary antennas on reflectarray aperture. This results in logarithmic spiral lattice as shown in Fig. 2.

2.4. Determination of required phase delay at each unit cell

Unit cells of the reflectarray are placed at the grid points shown in Fig. 2. Each unit cell must have an appropriate reflection phase that will transform the incident spherical wave into a reflected plane wave. Required phase at each unit cell of the reflectarray has been determined by drawing a comparison between the configurations of a parabolic reflector and a flat microstrip reflectarray [6]. Overall required phase pattern on reflectarray aperture is shown in Fig. 3 for designed reflectarray.

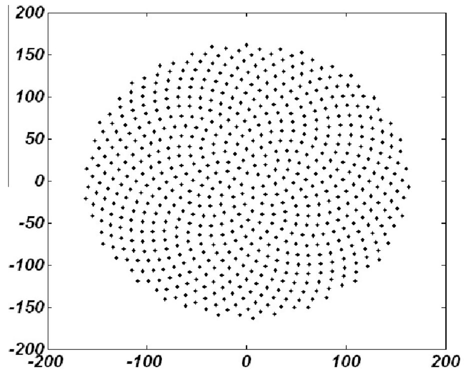

Fig. 2. Positions of elementary antennas on reflectarray aperture with center of reflectarray at (0,0).

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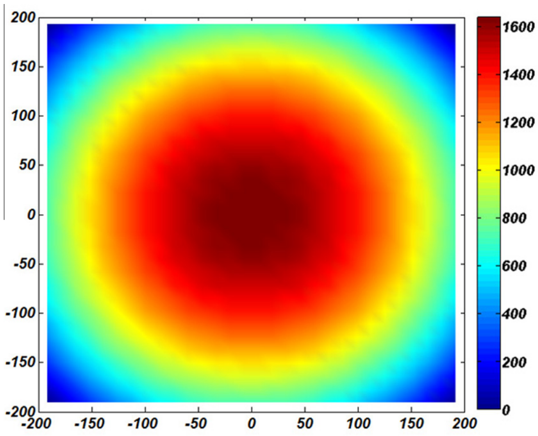

Fig. 3. Required phase pattern on reflectarray aperture with center of reflectarray at (0,0).

2.5. Determination of required dimensions for elementary antennas

An elementary antenna having particular dimensions, corresponding to required phase of the unit cell, is placed at the center of each unit cell. In the reflectarray design, described in this paper, microstrip patches of variable size have been used as elementary antennas for reflectarray aperture. Required length for these microstrip patches have been determined using reflection phase curve obtained from infinite array approach [16]. Infinite array approach which employs local periodicity can be used to characterize unit cell as long as the equivalent unit cell area remains the same for all the elements [18].

In logarithmic spiral lattice, equivalent area of the unit cell is almost the same as long as the size of the reflectarray is kept small. Thus, infinite array approach has been used here to calculate the reflected field from each elementary antenna of the reflectarray. Reflection phase curve of the elementary antenna for reflectarray is shown in Fig. 4.

One dimension of the microstrip patch is obtained from this curve while other dimension is fixed at 5.7 mm which is the resonant length of the patch for the designed reflectarray. Varying length of the patch is placed in the direction of E-field of the feed horn while fixed length is placed in the direction of H-field of the feed horn. It can be seen from Fig. 4 that maximum attainable reflection phase range is 338° instead of full 360°. 26 out of 665 unit cells in designed reflectarray lie in this unattainable range of 339° to 360°. Lengths of patches in these unit cells have been fixed at 3 mm, which is the length of the patch corresponding to highest attainable reflection phase. Various parameters of the designed reflectarray are given in Table 1.

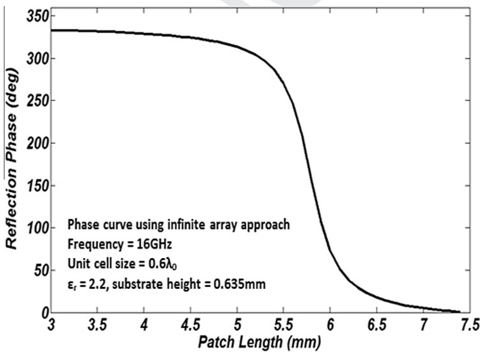

Fig. 4. Phase curve versus patch length.

Table 1
Different parameters of the reflectarray.

Design frequency	16 GHz
Number of elements	665
Reflectarray diameter	350 mm
Focal length	192 mm
Substrate thickness	0.635 mm
Relative permittivity	2.2
Loss tangent	0.001
Unit cell size	$0.6\lambda_0$

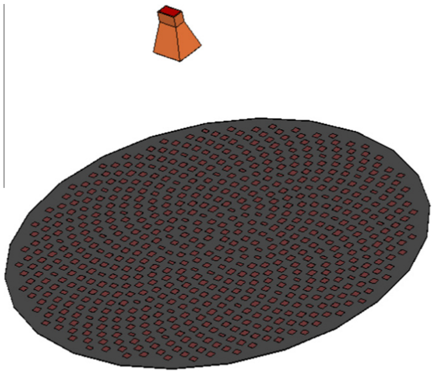

Fig. 5. Simulation model of reflectarray along with feed horn.

2.6. Simulation of the reflectarray

Designed reflectarray has been simulated in order to validate the design process and various parameters involved in the design. Simulation setup of the reflectarray with feed horn is shown in Fig. 5.

For accurate simulation of the antenna, a large number of mesh cells (almost 400 million) has been used to represent the antenna problem. This large problem has been simulated on cluster computing facility consisting of 4 computers with hex-core processor and 48 GB RAM on each node. Simulated radiation patterns of the designed reflectarray along with measured results have been given in the following section.

3. Results and discussion

Fabricated reflectarray along with measurement setup is shown in Fig. 6. Measured and simulated radiation patterns of the reflectarray are shown in Fig. 7.

Measured gain of the proposed reflectarray is 30.5 dBi resulting in an aperture efficiency of 37%. Measured radiation patterns show

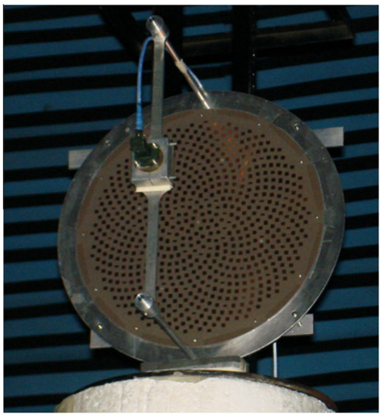

Fig. 6. Fabricated reflectarray along with feed horn.

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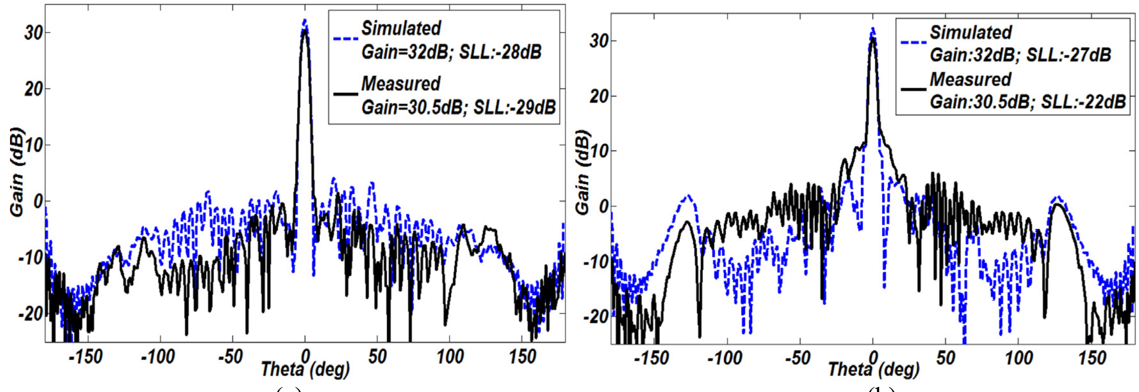
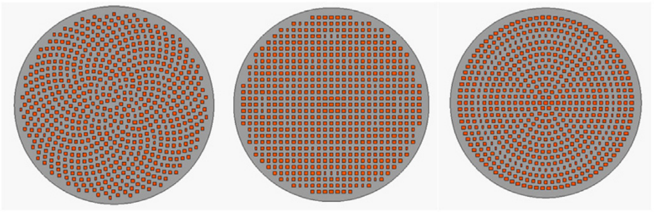


(a) (b)

Fig. 7. Radiation patterns of the reflectarray with logarithmic spiral lattice in (a) E-plane and (b) H-plane.

side lobe levels (SLL) of −29 dB in E-plane and −22 dB in H-plane. Beamwidth of the reflectarray is 4.2° in E-plane and 3.8° in H-plane. Measured gain is slightly less than simulated gain of 32 dBi which can be attributed to the errors in the exact placement of the phase center of the feed antenna at the focal point of the reflectarray or fabrication errors of the elementary antennas on reflectarray substrate. In simulation setup of the reflectarray, stand of the horn has not been included and substrate has been considered lossless in order to simplify the simulation problem. These simplifications can also contribute to the differences in gain of measured and simulated radiation patterns. In E-plane radiation pattern, measured SLL are better than simulated SLL but in H-plane radiation pattern, measured SLL are slightly inferior to simulated one. It can be attributed to the residual phase errors of the elementary antennas and the aluminum stand holding the feed horn. Also in H-plane radiation pattern, vestigial lobes or shoulders has been seen which is indicative of the phase errors in the aperture illumination [19].

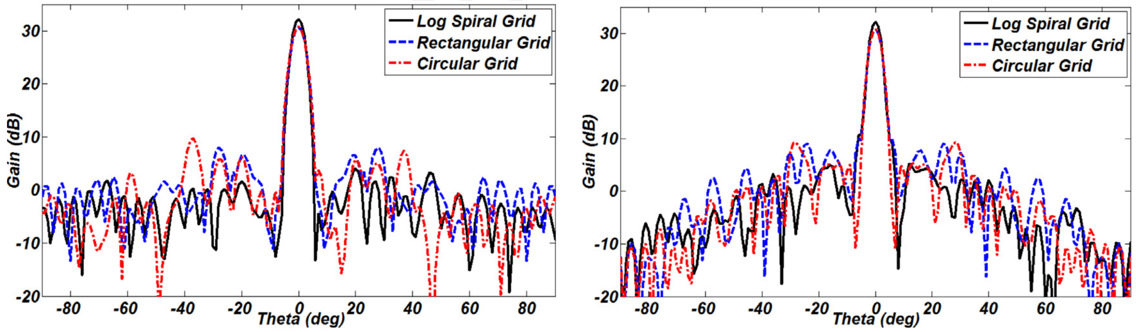


(a) (b) (c)

Fig. 8. Reflectarray aperture with (a) log spiral lattice (b) rectangular lattice and (c) circular lattice.

4. Comparison of reflectarray with different lattices

In this section, a performance comparison of the reflectarray with logarithmic spiral lattice and conventional rectangular and circular lattices has been carried out. Reflectarray apertures with



(a) (b)

Fig. 9. Radiation patterns for reflectarray with different grid lattices in (a) E-plane and (b) H-plane.

Table 2
Performance of reflectarrays simulated with different grid lattices.

		Reflectarray with logarithmic spiral grid	Reflectarray with rectangular grid	Reflectarray with circular grid
Total number of elements		665	665	665
Total gain		32.2 dBi	30.7 dBi	30.8 dBi
Side lobe level	E-plane	−28.2 dB	−22 dB	−21 dB
	H-plane	−27 dB	−20.7 dB	−21.4 dB
Half-power beamwidth	E-plane	4°	4.4°	4.5°
	H-plane	3.6°	4°	4.1°

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these three lattices are depicted in Fig. 8 while simulated radiation patterns for these reflectarrays are shown in Fig. 9.

Significant improvements in side lobe levels of both E- and H-planes has been observed for reflectarray with logarithmic spiral lattice as compared to reflectarray with conventional lattices while aperture size of the reflectarray and number of elementary antennas on its aperture remains the same. Some improvement in gain of the reflectarray with logarithmic spiral lattice has also been observed. Improvements in the performance of the reflectarray having logarithmic spiral lattice is due to the fact that this lattice yields an optimized radial and azimuthal spreading of elementary antennas on the reflectarray aperture [11]. A quantitative performance comparison of these reflectarrays has been given in Table 2.

5. Conclusion

The design and analysis of reflectarray with logarithmic spiral lattice of elementary antennas on its aperture has been presented. Design equations of logarithmic spiral have been used to obtain grid points of elementary antennas on reflectarray aperture. Designed reflectarray is fabricated and measured for radiation patterns. Overall gain of the reflectarray has been measured to be 30.5 dBi with SLL of −29 dB in E-plane and −22 dB in H-plane. A performance comparison of this reflectarray has been carried out with reflectarrays having conventional (rectangular and circular) lattices. An improvement in gain of about 1.5 dBi and improvements in SLL of 6.2 dB in E-plane and 6.3 dB in H-plane have been achieved for proposed reflectarray as compared to reflectarray with conventional rectangular lattice.

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