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A Wideband Monofilar Helical Reflectarray Antenna With Large-Angle Beam-Scanning Performance

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ABSTRACT A circularly polarized wideband reflectarray is presented using a monofilar single-turn helical antenna as reflecting element. An 11 × 11 elements reflectarray is designed, simulated and measured in X-band which demonstrates a wide bandwidth and large-angle beam-scanning performance. Phase range of 360° is obtained by rotating off-centred reflecting elements. Full wave simulations show that 1-dB bandwidth of 29.1% is achieved at the center frequency of 10 GHz with a maximum gain of 23.9 dB at normal angle of incidence ($\boldsymbol{\phi} = 0°$, $\boldsymbol{\theta} = 0°$) where the measured gain for the focused beam is 23.6 dB with an aperture efficiency of 51.7%. Simulated and tested axial ratio is less than 3 dB from 8.9 GHz to 10.7 GHz. Moreover, large-angle beam scanning performance is verified by changing the angle of incidence from +30° to −30° in both orthogonal planes and maximum gain loss is tested to be less than 1.3 dB at all scanned angles. Feasibility of design is demonstrated by the measured radiation performance and the results are in good agreement with the simulations.

INDEX TERMS Beam scanning, helical antenna, large-angle, monofilar, reflectarray.

I. INTRODUCTION

High gain antenna is a crucial requirement in case of long distance communication. Unlike parabolic reflectors and array antennas traditionally used for high gain applications [1], reflectarray, transmitarray and resonant cavity antenna have emerged as very attractive choice in recent times for satellite applications and wireless communication [2]–[4]. These antennas with planar structures have advantages like simplicity of design, low cost of manufacture and higher efficiency.

The conceptual design of Reflectarray antennas dates back to 1963, however, there has been rapid advancement in this type of antennas in last few decades due to advent of low-profile printed antennas [5]. "ReflectArray" antenna derives its origin from parabolic reflector and conventional array antenna. It exploits benefits of reflector antenna and phased array antenna including high gain, low losses, low cross polarization and mechanism of electronically controlling the beam scan angle and shape. Reflectarray is made up of an array of radiating elements which provide appropriate phase shift to impinging wave so that reflected beam is formed in desired directions. On the flip side, reflectarray antenna suffers from limitations of narrow bandwidth due to the inherent low bandwidth patch element used as unit cell and phase error introduced at off-centre frequency. Since phase is compensated at each element for particular wavelength only, major drift from center frequency results into high loss as well as phase error [6]. Furthermore, performance of reflectarray deteriorates at oblique angles of incidence. Various approaches have been used to enhance the bandwidth of the microstrip reflectarray antenna by using aperture-coupled elements [7], single-layered multi-resonant radiating elements [8] and unit element of various shapes [9]–[11]. Moreover, features of dynamic control of the phase have been introduced electronically by using p-i-n diode switches [12], varactor diodes [13] and Microlectromechanical system (MEMS) RF switches [14], in other implementations mechanical actuation has been used to change

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TABLE 1. Dimensions of the reflecting element.

Parameters	r_1	r_2	h_1	d
Value in mm	1 mm	5 mm	4 mm	1 mm

physical orientation of reflecting elements by using motors in [15]. In addition to implementation of beam scanning methodologies through element phase control, feed tuning techniques have also been presented using dual reflectarray antenna [16], [17] and electromagnetic metasurfaces for horn antenna [18].

Circularly polarized reflectarray has been studied extensively for satellite communications due to certain benefits like mitigation of polarization mismatching, insensitivity to "Faraday rotation" and reduction of multipath fading [19]. Microstrip patches have been mostly used to design reflectarray for circular polarization [20], [21]. Helical antenna is known to be one of the best antennas for radiating circularly polarized waves and it has a broad bandwidth performance, high gain and good axial ratio as well [22]. Till date, to the best knowledge of the authors, a single design has been proposed in X-band using the helical antenna as reflecting element [23], where a dual-branch Helical antenna is used as reflecting element to design a reflectarray which demonstrates a wideband and good beam scanning performance. However, dual-branch helical element with shaft, which is otherwise suitable for high power handling requirements, adds to complexity and mass of the reflectarray. A close to planar structure needs to be designed which is simpler in configuration and has a wider bandwidth and a larger beam scanning.

In this article, a monofilar single-turn helical element has been used for the first time to design a simple and efficient reflectarray antenna. It has been demonstrated that the proposed design has better performance in terms of bandwidth and wide angle beam handling capability improving therefore the state of the art. Moreover, being monofilar and single turn, the proposed antenna is a good competitor for use in the satellite applications where stowed volume is required to be minimized. Mutual coupling between the elements has been mitigated effectively at oblique angle of incidence, hence introducing flexibility in design for beam scanning within the range of 60° in both orthogonal planes. This article is organized as follows: In Section II, the basic helical reflecting element is discussed along with its phase range, design and optimization. A detailed account of 11 × 11 elements circularly polarized helical reflectarray is presented in Section III. Simulated and measured results of the proposed reflectarray are presented and discussed in Section IV validating the broad bandwidth and beam-scanning performance. Conclusions are drawn in Section V.

II. HELICAL ELEMENT DESIGN

Helical element is selected with diameter of a 10 mm so that circumference is equal to the wavelength at the

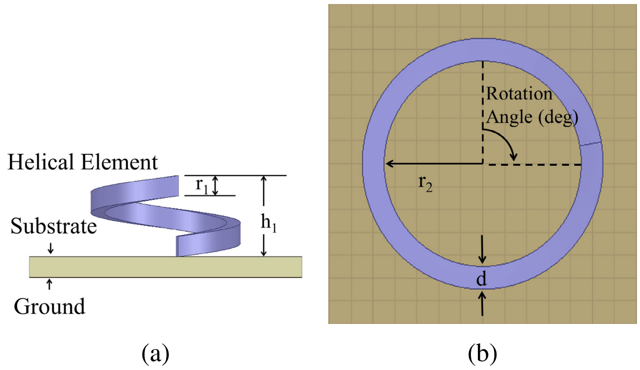


FIGURE 1. Configuration of helical element design (a) Side-view and (b) Top-view.

design frequency of 10 GHz to achieve a perfect axial mode radiation [24]. ANSYS High Frequency Structure Simulator (HFSS) is used to design and simulate the entire design. Floquet port excitation and master-slave boundaries are used to impinge a right-handed circularly polarized plane wave on the reflecting element in an infinite periodic array environment. An extensive parametric analysis of the helical element is carried out by varying pitch and number of turns. Based on the results of the parametric analysis, a single turn helical element is proposed and designed, as shown in Fig. 1(a) and (b). Table 1 shows the optimized dimensions of the helical element. Fig. 2(a) shows simulated reflection coefficient of helical element plotted against frequency from 8 GHz to 12 GHz. The amplitude of reflection coefficient is expected to be close to 0 dB because dielectric and conduction losses are small in amplitude and there are no grating lobes due to ground plane [5]. Phase range of the helical element is obtained at the center frequency of 10 GHz by the rotation of the reflecting element. The angle of reflected beam varies by twice the angle of rotation of the helical element which is in agreement with theory [25]. The phase range obtained by rotation of the helical element from 0° to 180° under normal angle of incidence at 10 GHz is shown in Fig. 2(b). Results of co-polar and cross-polar phase amplitudes are shown in Fig. 2(c). Helical element has cross polar (left-handed circularly polarized wave) amplitude of −23 dB and −17 dB at two spot frequencies; 9 GHz and 11.5 GHz respectively which shows the wideband behaviour of the reflecting element, whereas minimum difference between co-polar and cross-polar amplitude is observed at 10.5 GHz. A high gain and wideband performance is expected from the optimized helical reflecting element due to accurate circumference matching with wavelength and dual resonance observed at two frequency spots, as shown in Fig. 2(c).

III. REFLECTARRAY DESIGN

Keeping the size of the helical reflectarray similar to [23], a reflectarray of 11 × 11 elements was designed. As the radius of unit cell has been selected as 5 mm as compared to unit cell radius of 6.5 mm in [23], an additional row of

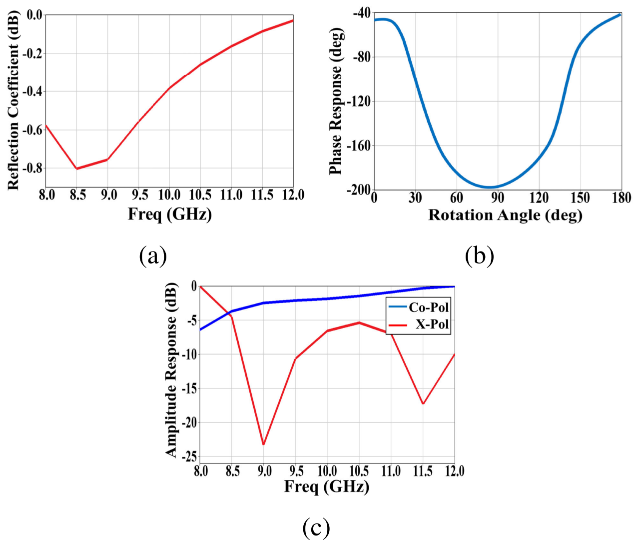


FIGURE 2. Simulated (a) Reflection coefficient versus frequency (b) Phase response versus rotation angle and (c) Amplitude response versus frequency of proposed helical element.

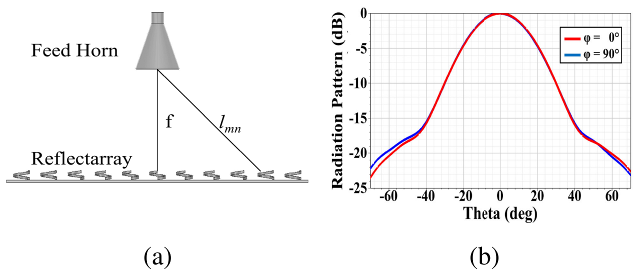


FIGURE 3. (a) Reflectarray proposed design, and (b) Radiation pattern of feed horn in two principal planes at 10 GHz.

elements was adjusted on either sides of the proposed array while keeping the physical aperture size of the antenna similar to the design in [23]. The proposed design of reflectarray is shown in Fig. 3(a). The equation used to rotate the off-center elements for compensation of the phase delay is

$$\phi_{m,n} \text{ in degrees} = k[l_{m,n} - f] - \text{integer multiple of } 360^\circ \quad (1)$$

where $\phi_{m,n}$ is the phase required at each element, k is the wavenumber in free space, $l_{m,n}$ is path length of individual element from the feed horn and f is feed horn distance from center element. After calculations of phase required at individual element, each element is manually rotated at an angle which is half in value to the phase calculated using (1) where the normal angle of incidence is assumed for all elements in an array. However, as reflecting element off-center distance increases, an error in the phase calculation is introduced which has adverse effects on the gain of reflectarray. This error is of the order of 25° at an angle of incidence of 40° as compared to normal incidence response, whereas this calculation error increases to 50° when the feed horn is inclined at an angle of 60° [5].

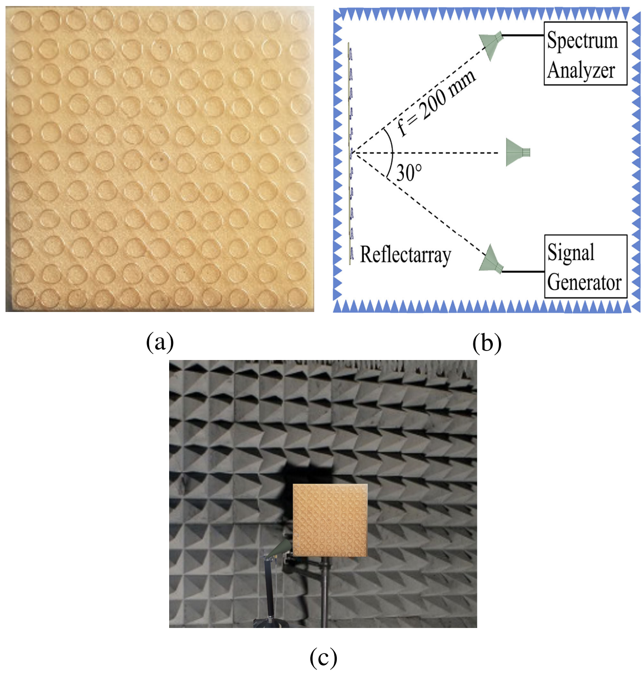


FIGURE 4. (a) Fabricated reflectarray on foam backed by substrate and ground, (b) Schematics of measurement setup, and (c) Measurement setup.

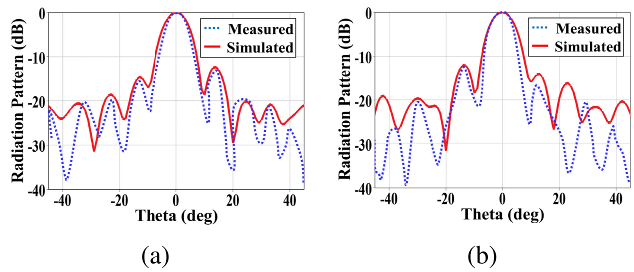


FIGURE 5. Measured and simulated radiation patterns of reflectarray at 10 GHz, normalized to the measured gain of 23.6 dB and simulated gain of 23.9 dB, respectively, in (a) XZ plane, and (b) YZ plane.

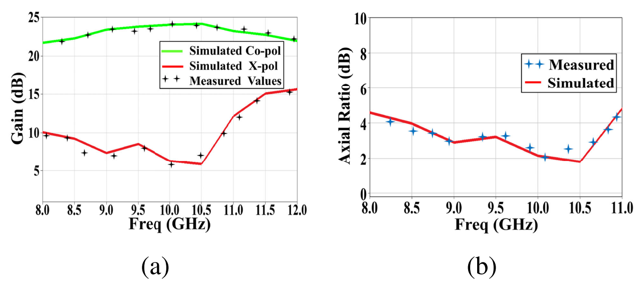
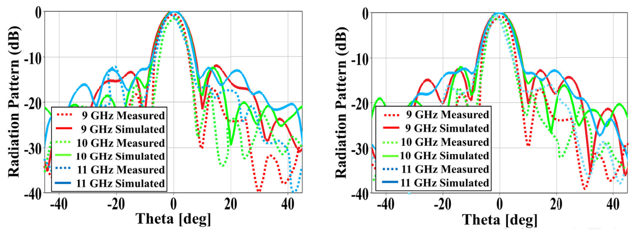


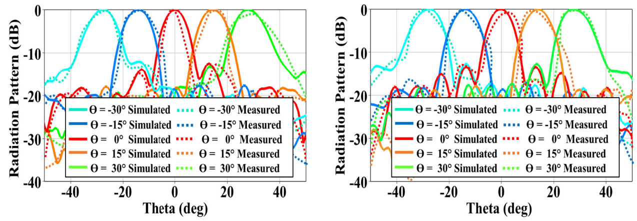
FIGURE 6. (a) Measured and simulated gain versus frequency, and (b) Measured and simulated axial ratio versus frequency under normal angle of incidence.

Two measures have been introduced in the design to increase the oblique angle beam handling capability of the reflectarray antenna. It was found in [26] that by decreasing the inter-element spacing, the gain bandwidth performance



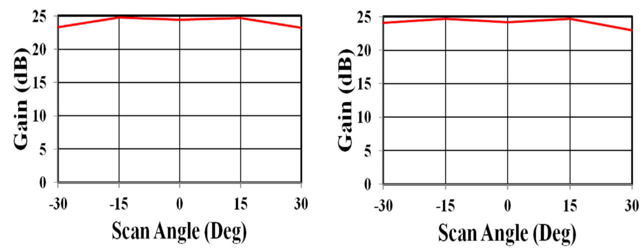
(a) (b)

FIGURE 7. Normalized radiation patterns in (a) XZ plane and (b) orthogonal plane at 9 GHz, 10 GHz and 11 GHz.



(a) (b)

FIGURE 8. Measured and simulated normalized radiation pattern of beams from $\theta = -30°$ to 30° in (a) XZ plane and (b) YZ plane at 10 GHz.



(a) (b)

FIGURE 9. Gain versus scan angle of beams from $\theta = -30°$ to 30° in (a) XZ plane and (b) YZ plane at 10 GHz.

of the reflectarray at the oblique angle of incidences can be improved. This is due to the reduction of the inter-element spacing, beamwidth narrowing and beam shape deformation is comparatively less pronounced at an oblique angle of incidence. Keeping this factor in focus, inter-element spacing has been kept as 0.6λ while designing reflectarray instead of 0.65λ which was selected by authors in [23]. In this way, a design with optimized inter-element spacing has been used to avoid grating lobes and mutual coupling effects as well as to handle waves impinging at an oblique angle. Secondly, it is known that elements which are in the central area of the reflectarray aperture, scatter back re-radiated and reflected component in the desired direction. The elements close to the edge re-radiate the wave in the desired direction however the reflected components travel to undesired directions due to the larger angles of incidence and consequently cause side lobes [5]. In order to mitigate this effect of the reflected components of the edge elements, larger values of f/D ratio are suitable (f is focal length and D is array diameter). Hence, f/D ratio of 1 has been selected for the proposed reflectarray. Normalized radiation pattern of feed horn in two orthogonal planes is shown in Fig. 3(b).

The fabricated reflectarray is shown in Fig. 4(a), schematics of measurement setup are shown in Fig. 4(b) and actual measurement setup is shown in Fig. 4(c). A reflectarray prototype of 11×11 helical elements has been fabricated. A total of 121 helical elements have been placed on substrate using RF transparent foam. Rogers RT/duroid 5880 (tm) is used as dielectric substrate with $\varepsilon_r = 2.5$, $\tan\delta = 0.0005$, thickness = 1 mm. The inter-element spacing is 18 mm so that the size of the reflectarray is 200×200 mm^2. A feed horn is placed at a distance of 200 mm (f/D = 1) from reflectarray aperture which impinges a right-handed circularly polarized beam on the reflectarray under the normal angle of incidence. The feed horn has a gain of a 15.1 dB at 10 GHz with −3 dB beamwidth of 34° and reflection coefficient of −25 dB. Beam scanning capability of proposed antenna is measured by moving feed horn from normal angle of incidence to 30° and −30° with the hop of ±15° keeping f = 200 mm from center of antenna aperture.

IV. RESULTS

Full wave simulations are carried out using ANSYS HFSS from 8 GHz to 12 GHz at a center frequency of 10 GHz with 500 MHz step. The proposed model is simulated first with a normal angle of incidence and a right-handed circularly polarized beam is radiated in broadside direction. The simulated gain is 23.9 dB in both orthogonal planes and measured gain is 23.6 dB. The normalized radiation patterns under normal angle of incidence in two principal planes are plotted in Fig. 5(a) and (b) along with measured results. Aperture efficiency is 51.7% and a symmetrical beam is formed in both orthogonal planes. The 1-dB gain bandwidth of 29.1% is obtained from 8.6 GHz to 11.5 GHz with simulated gain of 23.9 dB and measured gain of 23.6 dB at 10 GHz. Simulated and measured results are shown in Fig. 6(a). Amplitude of cross-polar (left-handed circularly polarized wave) remains less than 10 dB from 8 GHz to 10.8 GHz (70% of entire band) and is 17.8 dB less than co-polar (right-handed circularly polarized wave) at 10 GHz. Excellent wideband performance of proposed design is attributed to the selection of the reflecting element with broadband performance based on an extensive parametric analysis, as already shown in Fig. 2(c). Axial ratio of design is less than 3 dB from 8.9 GHZ to 10.7 GHz and shown in Fig. 6(b). Normalized radiation patterns at 9 GHz, 10 GHz and 11 GHz in orthogonal planes are shown in Fig. 7(a) and (b). Beam is symmetrical and the sidelobe level is less than −10 dB at three frequencies in both principal planes.

Beam scanning feature is simulated by changing angle of incident beam from $\boldsymbol{\theta} = -30°$ to 30° in both XZ and YZ plane. Movement of feed horn in an angular curve is simulated at −30°, −15°, 0°, 15° and 30°. Simulated and measured normalized radiation patterns for angle of incidence

TABLE 2. Comparison table.

Reference	Element shape	Frequency (GHz)	1-dB Bandwidth (%)	Beam Scanning Feature (in degree)
[11]	Phoenix	10 GHz	29	No
[10]	Cross loop	30 GHz	25.16	15°
[27]	Meander	10 GHz	26	No
[28]	Metal only Slot-Type Element	12.5 GHz	8.3	No
[29]	Metal only Phoenix Element	12.5 GHz	12.8	No
This work	Helical element	10 GHz	29.1	-30° to 30°

TABLE 3. Comparison table.

PARAMETERS	[23]	THIS WORK
Center Frequency	9.3 GHz	10 GHz
Reflecting Element	Dual-branch Helical antenna	Monofilar single-turn Helical antenna
Unit cell radius, height	10 mm, 10 mm	5 mm, 5 mm
Array elements	9 x 9	11 x 11
Antenna aperture (L x W)	200 mm x 200 mm	200 mm x 200 mm
f/D ratio	0.85	1
Inter-element spacing	0.65λ	0.6λ
1-dB gain bandwidth	24.2%	29.1%
Measured gain at center frequency	23.4 dB	23.6 dB
Maximum gain at scan angle	23.7 dB at $\boldsymbol{\theta}$ = 20°	24.8 dB at $\boldsymbol{\theta}$ = 15°
Scanning angle in XZ plane	-10° to 30°	-30° to 30°
Scanning angle in YZ plane	-30° to 30°	-30° to 30°
Maximum gain loss at oblique angle	less than 1.5 dB	less than 1.3 dB

from $-30°$ to $30°$ in both planes are shown together in Fig. 8(a) and (b). Due to the appropriate adjustment of inter-element spacing and f/D ratio, the proposed design demonstrates a very good beam handling capability at oblique angles. Maximum gain loss in nine beam scan cases is simulated and tested to be less than 1.3 dB from normal to the most oblique angles. The measured gain is plotted against the scanned angles in XZ and orthogonal YZ plane in Fig. 9(a) and (b). A maximum gain of 24.8 dB is obtained at $\pm 15°$ due to the reduced shadowing effect at the offset feed position. The measured results are in good agreement with simulated results. The difference between the simulated and the measured results is attributed to a manual rotation of each helical element which resulted into slightly inaccurate phase calculation of the reflected wave. Moreover errors in the fabrication and measurement setup also led to certain degree of imprecision. However the overall results are within acceptable limits. A comparison of bandwidth and beam scanning feature between reflectarrays using other shapes of unit cell and this work has been presented in Table 2. Moreover, a detailed comparison of the design configuration proposed in this paper and the results from reference [23] are presented in Table 3.

V. CONCLUSION

A wideband circularly polarized helical reflectarray with a large-angle beam scanning capability has been designed, manufactured and measured. Taking [23] as a reference, the proposed design has exhibited superior performance in terms of 1-dB gain bandwidth and beam scanning angle range with simpler configuration and low mass even if the manufacturing imprecision is relatively large. The simulated 1-dB gain bandwidth is 29.1% and beam scanning angle is demonstrated in $\pm 30°$ in both XZ and YZ planes with gain loss less than 1.3 dB. Measured axial ratio is less than 3 dB from 8.9 GHz to 10.7 GHz and from $-30°$ to $30°$ in both XZ and YZ plane. Helical reflectarray proposed is low cost and easy to manufacture due to simplicity of the design as compared to the dual-branch helical element with shaft as proposed in [23]. Moreover, being close to a planar design, the proposed reflectarray has improved the state of the art for circularly polarized antenna arrays for satellite applications.

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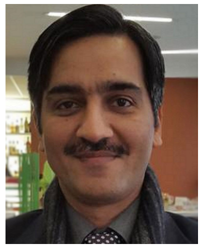

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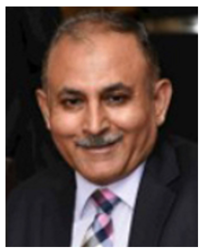

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