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A Narrow Beam, Beam Steerable and Low Side-Lobe Reflectarray Based on Macro Electro-Mechanical Technique

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Abstract—In this paper, an X-band, nonuniform and passive beam steering reflectarray antenna is presented. The beam steering is done with a small movement of a large element, i.e., the ground plane. The maximum $\pm 7.5°$ beam scanning from the antenna broadside is achieved by only $\pm 0.05\lambda$ ground tilting. In the proposed structure, the beam steering capability is provided by using passive elements that eliminate the need for active biased circuits. The linearity of beam scanning as a function of ground tilting is also investigated. Compared to the previous similar works, the antenna's half-power beamwidth and side lobe level are improved by about 9° and 20 dB, respectively. A primarily proposed reflectarray is fabricated to validate our claim.

1. INTRODUCTION

Since World War II, the need for beam steering antenna has been increased in radiating systems [1]. Two main procedures for beam steering are mechanical movement of feed or reflecting surface [2, 3] and the electrical steering of phased arrays [4]. There are some defects in both procedures which force us to tolerate among cost, speed, reliability, and other RF component issues [1]. The mechanical rotation has low cost, speed and precision. Active phased array antenna gives more agility and reliability. Instead, complexities and tight challenges are raised in the feed and bias of active elements. Moreover, to compensate significant losses, an amplifier is used increasing overall cost. The complexity of such structures restricts their application in sensitive military industries. Thus, new ideas have been proposed to implement affordable beam steering antennas. In this regard, reflectarray antenna has been introduced as a hopeful technique [5–7]. Also, their popularity increases because of their capability of implementation with new technologies [8, 9].

Reflectarrays use two common techniques to change the phase distribution: the feed tuning and aperture phase tuning. In the feed tuning technique, the phase distribution is created by displacement of feeds or switching between multi-feeds, which does not result in a continuous scanning. In the second category, the elements on a reflectarray aperture are equipped with a phase-tuning mechanism, essentially utilizing the mechanical nature of the antenna. In recent years, many methods have been applied to unit-cell designing able to vary phase such as varactor and PIN diodes [10, 11], micro-electro-mechanical switches (MEMS) [12], functional materials [13], and micro-motors [14, 15].

Varactor diodes and MEMS increase the scanning speed, but they have higher power consumption than other methods. These systems suffer from low power handling due to the nonlinearity of these electronically tuneable devices. On the other hand, a typical moderate-size reflectarray includes hundred to thousand diodes and switches together with their bias circuits, thereby increasing the complexity and cost of the design. In addition, Ohmic losses, due to bias lines and RF components, decrease the system efficiency. Functional materials such as liquid crystals [13], ferroelectric dielectrics [16], photonic controlled materials [17], and graphene [18, 19] are recently introduced for phase changing and beam

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rotating of reflectarrays. Although these technologies have shown interesting properties, they have not been studied as widely as other technologies, and almost all studies are done on a unit cell. Micro-motors are new miniaturized devices applied in beam-steerable reflectarray antennas. They can rotate elements or adjust their height. The application of the micro-rotators is limited to circularly polarized reflectarrays. Micro height adjustable motors are rarely studied for beam scanning. In addition, these devices are expensive and should be controlled element by element [14, 15].

In [20], an interesting phase-tuning mechanism is introduced for beam steering that could eliminate the aforementioned challenges. The researchers of [20] have proposed the idea of tilting the ground plane instead of applying phase shifter in each unit cell. Since the tilting of one macro-plate could be done with electromechanical actuators, this system has been nominated macro-electro-mechanical systems (MÆMS). This method does not require any solid-state phase shifter, varactor diodes, and any switches. It is really a considerable achievement because 2D beam steering occurs with a bit of the large element, ground, and movement. It has been shown that it is potentially implementable with fast electro-mechanical devices such as piezoelectrics [21]. Therefore, many complexities in previous schemes have been eliminated by separately controlling each unit cell [20].

Despite interesting achievements of [20], there are also some important challenges that should be addressed. First and foremost is widening beamwidth which makes it unpractical even in the broadside. High side lobe level is another defect which causes the presented antenna unable to provide the least of beam steering requirements. Through solving above mentioned challenges, we present a passive beam steering reflectarray antenna in this paper. By using nonuniform elements in the proposed reflectarray, the beamwidth and side lobe level are significantly improved. The elements are arranged by fitting the profile phase. This results in more beam rotating than identical element reflectarray. Therefore, we have introduced a practical narrow beam antenna with low complexity and high speed steering capability. In addition, the linearity of the beam scanning is investigated as a function of ground tilting.

2. DESIGN PROCEDURE

In this work, we aim to rotate the antenna radiation pattern by tilting the antenna ground. Thus, an air gap is placed between the ground and substrate to provide ground moving possibility. Assuming that all patches are identical, when the antenna ground tilts to one side, each of the elements spaces differently from the ground plane (Fig. 1). Consequently, the reflected phase of each row of the elements differs from another one. By controlling the reflected phase and making a progressive profile phase, we can rotate the antenna's main beam. In this manner, the reflectarray beam steering problem is simplified to a linear phase array problem. It is schematically shown in Fig. 1. However, the beam steering is implemented by this method, and nothing is done on beam form improvement up to now.

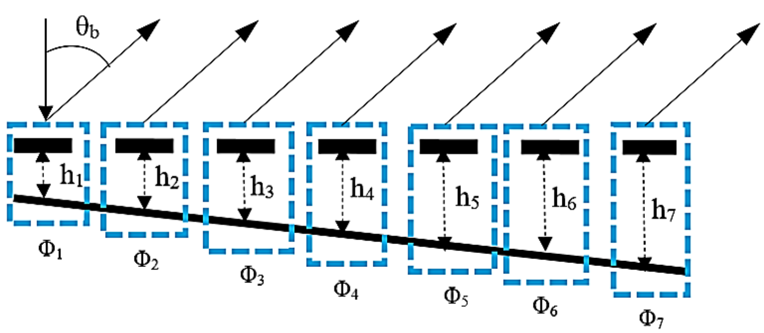


Figure 1. Schematic reflectarray and their element phase.

Since classic parabolic antennas are known for their high gain, low HPBW, and low SLL features, it is interesting to benefit from their features in flat microstrip antennas. The main idea behind a reflectarray is compensating the reflected wave phase of a flat surface to generate an in-phase wave the same as parabolic antenna front wave. It happens by adjusting the reflected phase of each element which varies with physical parameter of unit cell. Therefore, in order to design a practical reflectarray with narrow beamwidth, we should use nonuniform elements [22].

Non-similarity of elements in a nonuniform reflectarray causes that the reflected phase depends on both patch width (w) and gap height (h) parameters. This makes it possible that the relative profile phase of elements does not decrease progressively, in a general case. As a result, the antenna beam does not rotate appropriately. Thus, if we tend to design a beam steerable nonuniform antenna, two conditions should be fulfilled simultaneously: 1) the base element provides sufficient reflected phase range (profile phase). This is achievef by sweeping the element structural parameters [23]. 2) Elements with different structural parameters show linear phase variation behaviour versus gap height (h) and broad phase range. Therefore, the design procedure of the steerable nonuniform reflectarray can be summarized as shown in Fig. 2.

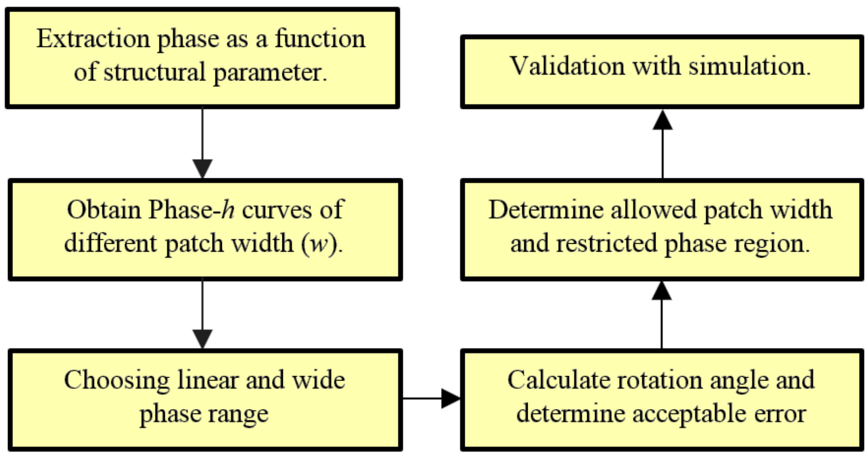


Figure 2. Design procedure of the steerable non-uniform reflectarray.

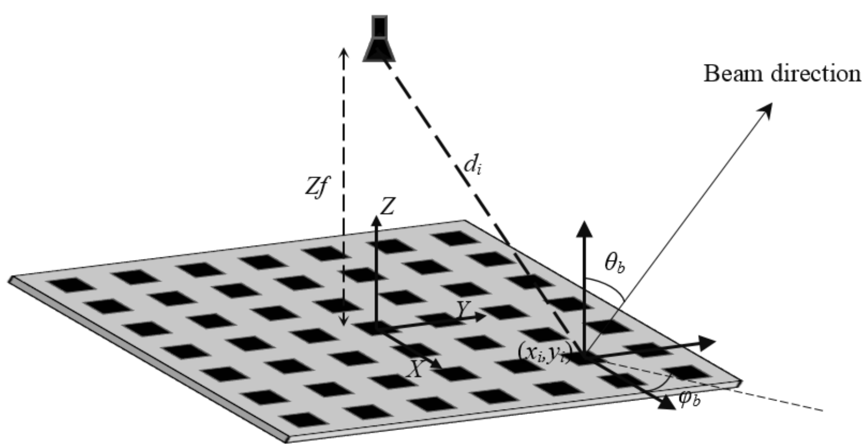


Figure 3. The reflectarray general view.

In the following, we present a steerable reflectarray using this procedure. Calculating the nonuniform reflectarray phase distribution is the primary step of reflectarray designing. According to local coordinates depicted in Fig. 3, the phase of each element is obtained from Equation (1).

$$\varphi_R(x_i, y_i) = k_0 \left(d_i - (x_i \cos\varphi_b + y_i \sin\varphi_b) \sin\theta_b\right) \tag{1}$$

where φ_R is the requirement phase factor of reflectarray surface, and (θ_b, φ_b) is the desired main beam angle coordinates. Also, (x_i, y_i), d_i, and k_0 are respectively the center of the ith element coordinates, the distance of feed phase center to the ith element center, and propagation constant in vacuum.

Equation (1) describes how phase requires each element in order to generate in-phase wave in the front of reflectarray. In the following we investigate the patch phase properties to implement the required phase of Equation (1).

a simple square patch is considered as a reflectarray element. A substrate with $\varepsilon_r = 3.4$ (Rogers RO4003) and 0.5 mm thickness is considered. The operation frequency is set to 9.5 GHz, and the size of unit cell is chosen to be 6.5 mm ($\approx 0.2\lambda$). After determining element geometry, we should check the phase range and implementation possibility from the element phase diagram [22]. Here we keep gap length (h) in a constant value, 0.75 mm, and investigate the element reflected phase as a function of patch width. As depicted in Fig. 4, the phase is calculated by full-wave simulation versus patch width.

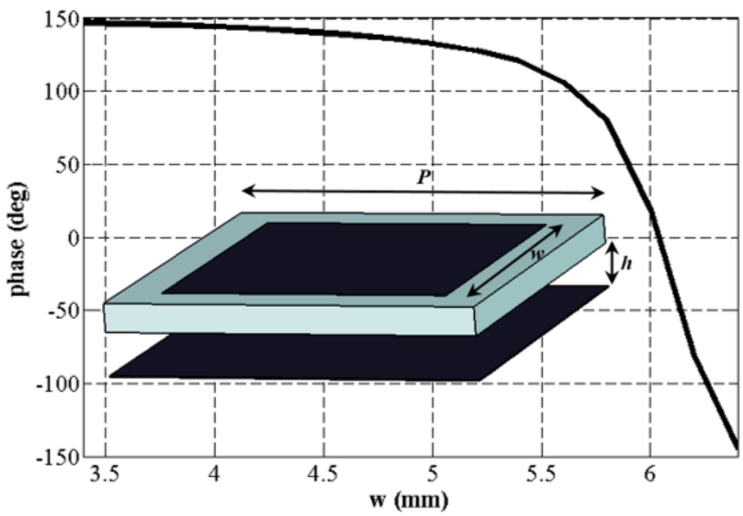


Figure 4. Unit cell and phase diagram as a function of patch width at 9.5 GHz.

It is observed in Fig. 4 that the phase range of selected element is about 300° (−150° to +150°). The phase range is 60° less than ideal, which restricts maximum gain of reflectarray. This issue can be resolved by choosing different geometries of based element [22].

By tilting the ground, different gap lengths (h) are allocated to the nonuniform elements. The reflected phase dependence on both patch width (w) and gap height (h) parameters cause that we cannot consider Fig. 4 phase — w diagram as a profile phase of the whole reflectarray. Therefore, as a solution, we should design a reflectarray such that most of its effective elements' sizes have nearly the same patch width. As a result, for a determined region of patch width we could consider one phase — h curve substitute of many of them.

To investigate the profile phase, we should obtain the reflected phase as a function of gap length (h). In Fig. 5, phase-h curves are shown for different patch sizes. When the ground tilts around its center, the gap length varies from 0 to 1.5 mm. Thus, from Fig. 5 we can determine the reflected phase of each element according to its patch width and the gap length created by ground tilting.

From Fig. 5, more slope of phase-h diagram translates to more rotation of radiation pattern according to phase array theory. We choose from Fig. 5 the most linear curve with an acceptable phase range. Broad phase range and more linearity lead to more beam rotation and lower side lobe level, respectively. It can be seen that the phase profile of $w = 6$ mm has both of these features. From phase array theory we can estimate the rotation of radiation pattern [20]:

$$\theta_b \approx \sin^{-1}\left(\frac{\lambda}{2\pi}\frac{\Delta\varphi}{D}\right) \tag{2}$$

where D is the whole length of reflectarray, and $\Delta\varphi$ is the phase range of related phase-h diagram (Fig. 5). The θ_b for $w = 6$ mm curve is calculated 7.2° when the phase range, reflectarray size, and operational frequency are considered 250°, 175 mm, and 9.5 GHz, respectively.

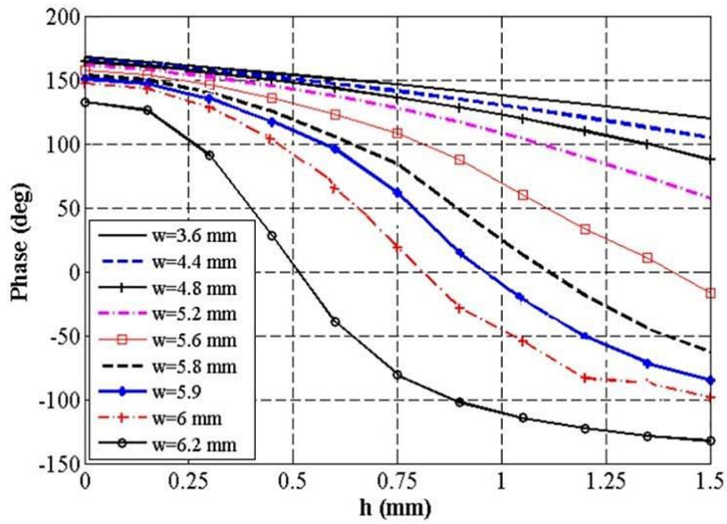
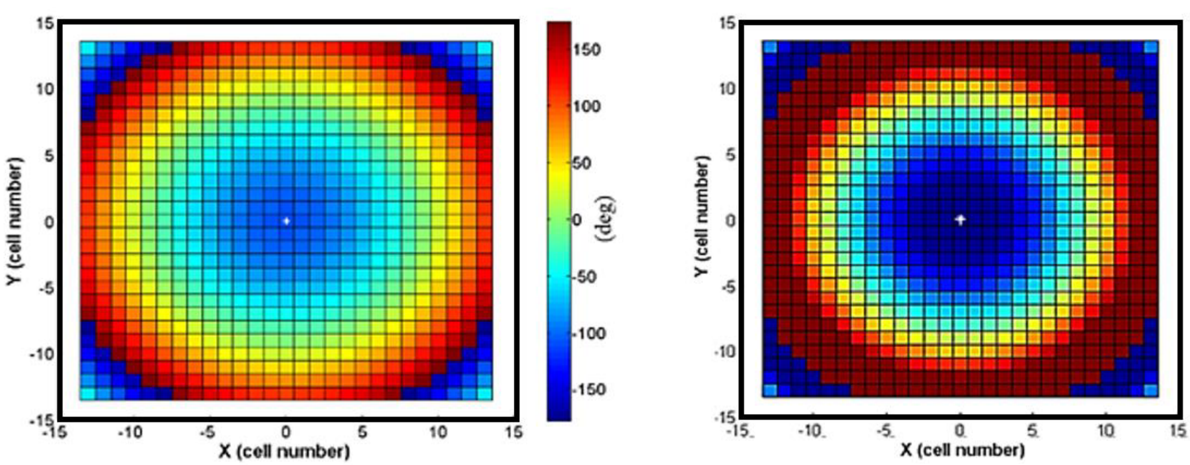


Figure 5. Phase-h curves for different patch widths.

In the next step, we should consider an error tolerance for desired beam rotation angle (θ_b). The tolerance allows designing a nonuniform reflectarray. The tolerance $\theta_b = 7.2^\circ \pm 0.8$ is assumed acceptable for present work. Therefore, from Equation (2) the phase range is restricted between 220 and 270 degrees for assumed tolerance. Also, according to Fig. 5 the corresponding patch width of this range is $5.8 < w < 6.2$ mm. It means that if we set the constituent elements in $5.8 < w < 6.2$ mm region, we could design a nonuniform reflectarray in which its pattern rotates by tilting the ground.

The desired "w" region relates to the phase region between -100° and 80° as can be extracted from Fig. 4. Therefore, we should design a reflectarray whose required phase of most elements is restricted in this phase range. The required phase distribution of a reflectarray could be controlled by its size and feed location. We consider 27×27 element arrays and place the feed antenna in 180 cm high above center of the reflectarray surface. These parameters are replaced in Equation (1), and required phase distribution has been calculated, which is shown in Fig. 6(a). White point in the center shows the feed location in two dimensions of the coordinate system.



(a) (b)

Figure 6. Phase distribution on the antenna aperture. (a) The required phase distribution on reflectarray antenna surface. (b) The required phase restricted between -100° to 80°.

Although Fig. 6(a) illustrates that the most constituent elements of reflectarray are in our desired phase region, we could restrict the phase of elements in exactly desired range as shown in Fig. 6(b). As a result, we have theoretically estimated that the presented narrow beamwidth reflectarray is rotated about 14.4° (±7.2°). This is proved by full-wave simulation and fabrication in the next section.

3. RESULTS AND DISCUSSION

The proposed reflectarray is simulated in two states by CST microwave studio [24], with non-tilted and maximally tilted ground. Also, it is fabricated, and its radiation pattern is measured in both states. The antenna is installed on a pedestal and is fed by a standard X-band horn antenna. The fabricated reflectarray and test environment are depicted in Fig. 7.

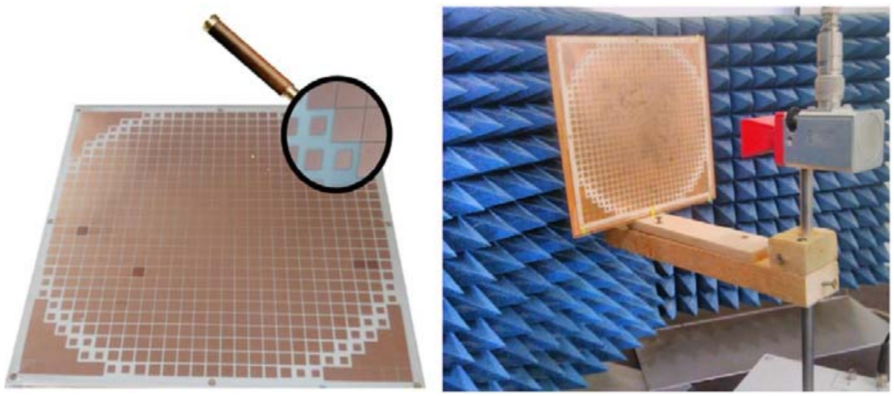
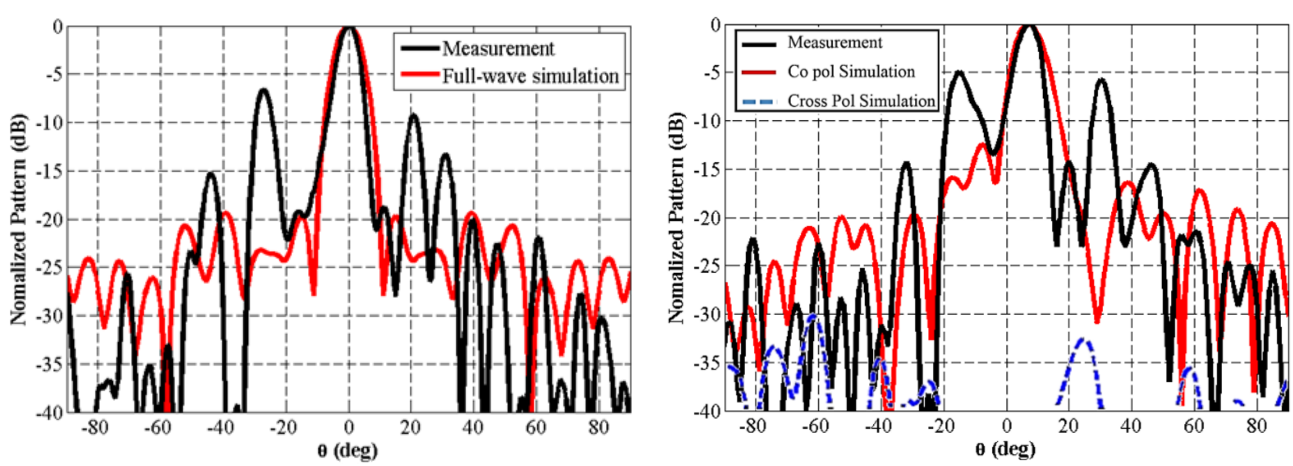


Figure 7. Prototype of fabricated reflectarray and test setup.

The radiation pattern of fabricated nonuniform reflectarray is compared with simulation in Fig. 8(a) under horizontal ground condition. It shows that the measured HPBW and first SLL are in good agreement with simulation results. The radiation of the maximum ground tilting states is depicted in Fig. 8(b). As can be seen from this figure, measurement results agree with simulation for the HPBW amount and main beam rotation.



(a) (b)

Figure 8. Simulation and measurement of normalized radiation patterns. (a) Horizontal ground condition, (b) maximum tilted condition.

The second SLL is however different between simulation and measurement graphs. This abnormal SLL of measurement comes from undesired reflections from the metal holder of reflectarray antenna.

The reflectarray cross polarization pattern has too low level when the ground is totally horizontal, and it is ignored in Fig. 8(a), but when the ground plane tilts maximally, the cross polarization pattern rises significantly, shown in Fig. 8(b). As can be seen from this figure, the cross polarization is not considerably relative to co-polarization pattern.

In the following, the simulation achievements of the present work are compared with two similar works in Table 1. It should be noted that the given HPBW and SLL results are measured in the horizontal ground condition.

Table 1. Comparison between recent passive beam steering works.

Reference	Our work	[20]	[25]
HPBW (deg)	9	24	10
Beam scanning (deg)	± 7.5	± 10	± 8
SLL (dB)	20	11.5	13
Ground movement	0.05λ	0.05λ	0.01λ
Size	$5.5\lambda \times 5.5\lambda$	$5.5\lambda \times 5.5\lambda$	$2.6\lambda \times 2.6\lambda$

It can be seen that the HPBW and SLL respectively improve 15° and 8.5 dB in the present work compared to [20]. The amount of scan angle, however, is reduced by 2.5°. Compared with [25], the SLL of our proposed nonuniform reflectarray is improved about 7 dB, but it does have improvement in HPBW proportional to their sizes. Here, we should note that our work is more similar to [20], in the movement mechanism of ground structure, whereas the authors in [25] have used more complex movable ground structure.

Antenna bandwidth is one of the most important parameters of any antennas. The antenna bandwidth is usually defined by its impedance; however, more other parameters like gain, HPBW, and SLL should be investigated in the reflectarray. The antenna bandwidths in terms of impedance, gain, SLL, and HPBW are simulated and depicted in Fig. 9. As can be seen from Fig. 9, the impedance bandwidth of the antenna is 9.3 GHz to 9.65 GHz. Designing a reflectarray is done at the center of impedance bandwidth, 9.5 GHz. Across the impedance bandwidth, the gain flatness is 1 dB, and the SLL and HPBW are about 19 dB and 9°, respectively. The antenna SLL reaches its maximum value at the center frequency (9.5 GHz), and it generally decreases when we get far from 9.5 GHz. Moreover,

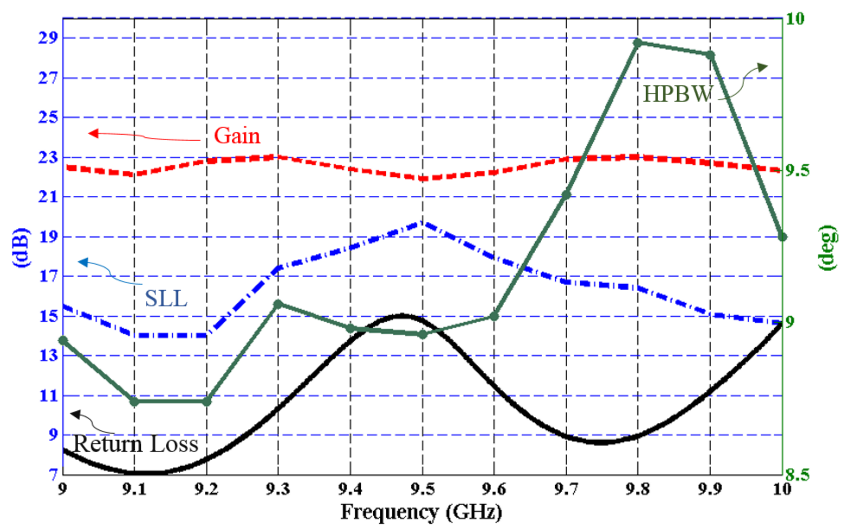


Figure 9. Antenna gain, HPBW and SLL as a function of frequency.

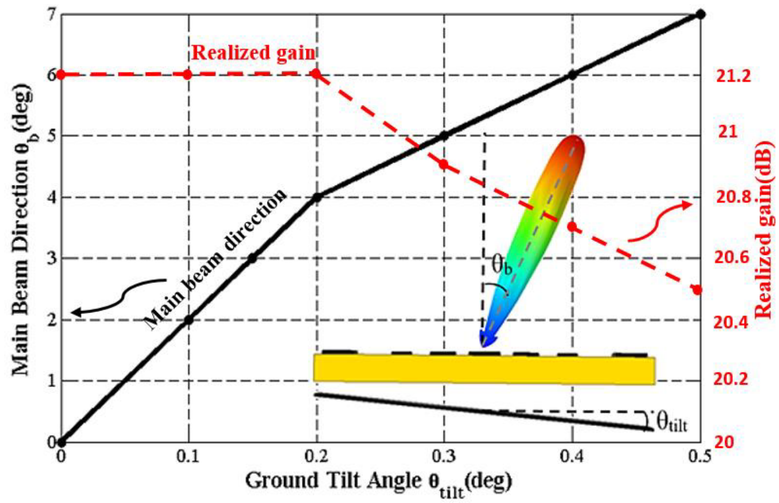


Figure 10. The linearity of beam scanning as a function of ground tilting angle.

the HPBW has small changes across antenna bandwidth.

Another important issue in the practical reflectarrays with beam steering capability is the linearity of beam scanning as a function of variable built in phase shifter. It matters for two reasons: first, we tend to have a uniform spatial scanning system, and the non-linearity of beam scanning causes that the beam steers at different speeds which is not desired in tracking systems. The second reason turns to the fact that a simple linear relation between beam direction and scanning propellant leads to less time requirement for setting the beam in the desired direction. In Fig. 10 it can be seen that the beam direction is a linear piecewise function of ground tilting angle. This simple relation gives a practical property to presented reflectarray.

In order to know the gain degradation with steering beam, the realized gain is shown in Fig. 10 as a function of ground rotation angle. The antenna realized gain is 21.2 dB in horizontal ground condition, and it degrades 0.7 dB when the main beam steers maximally.

As seen, the beam scanning range of presented antenna is restricted to $\pm 7.5^\circ$. One way to extend scanning range several times is segmenting the antenna ground plane [20, 25]. Segmenting technique is not applied in this paper for the complexity of implementation and measurement. It should be investigating in future works.

One of the interesting future works following this paper is using the presented idea in OAM application. It seems that by proper design of element distribution, the reflectarray can be used for generating different orders of OAM modes [26, 27]. In other words, the reflectarray antenna is an efficient apparatus to generate and manipulate OAM carrying beams at RF. However, the power considerations for generating higher order modes should be investigated carefully.

However, we have tried to take a step toward creating a more practical product, but several issues need to be addressed before commercialization of the proposed antenna: Finding an element with optimized phase behaviour, investigating the frequency bandwidth, etc.

4. CONCLUSION

An X-band beam steerable nonuniform reflectarray antenna is proposed. By using nonuniform elements, the HPBW decreases by 9°, and SLL increases to 20 dB that is significant improvement proportional to similar previous works. The positioned gap between the substrate and ground allows tilting the antenna ground. The influence of gap and patch size on reflected phase are investigated, and it is shown that the main beam of proposed reflectarray is steerable with controlling these two parameters. The full-wave simulation illustrates that the SLL reaches 20 dB and 12.5 dB respectively for 0° and 0.5° ground tilting angles. Low SLL and narrow beamwidth make the proposed antenna a good choice for many applications' need for beam steerable reflectarrays.

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