Digitized Reconfigurable Metal Reflectarray Surfaces for Millimeter-Wave Beam-Engineering

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Abstract: Digitized beam-forming metal reflectarray antennas are designed for the millimeter-wave region. The phase control of antennas has been implemented by the reconfiguration of rectangular grooves on a metal plate. The antenna has 1147 elements arranged in an aluminum metal plate. The depths of all metal grooves are manipulated for designed phase control of high-gain beam-aimed reflectors. We have demonstrated a digitized reconfigurable metal reflectarray to steer a re-radiated millimeter-wave field from the reflector in a two-dimensional scanning plane from $\pm 20^\circ$ to $20^\circ$. The far-field patterns show that the measured gain of the 2-bit reflectarray is only 1 dB lower than that of a non-digitized reflectarray antenna. The measured peak gain is higher than 31.7 dB, and the measurements show that the gain of the full $40^\circ$ scanned beam is 31.7 dB and well-defined scanned beams are obtained with a maximum scan gain loss of 0.2 dB. The proposed reconfigurable antennas can be a useful candidate for high-gain beam-aimed antennas for practical reflecting surfaces and a variety of wireless and satellite communication systems.

Keywords: reflectarray antenna; millimeter-wave; digitized antenna; beam-steering; metal-only antenna

1. Introduction

A reflectarray antennas is made of an array of reflected phase elements and a feeder, which efficiently re-radiate electromagnetic waves. Printed-patch reflectarray is becoming considerable a substitute to a curved reflector due to numerous advantages such as its ease of transportation and fabrication, and low profile and weight [1]. Despite of these advantages, the antennas suffer from the major drawbacks which inherently have substrate loss and narrow bandwidth characteristics. Recently, metal-only reflectarray antennas have been studied as promising antennas because the antenna does have any dielectric loss [2–4]. A metal reflectarray antenna is manufactured by the phase-controlled metallic unit cell. The reflection phases of unit cell are simply controlled by the depth or height at the end of each waveguide. The reflectarray is an alternative to a phased-array antenna, which can provide the possibility of utilizing reconfigurable beam-forming for many applications such as synthetic aperture radar, automotive radars, security and medical imaging systems, and satellite communications.

Technological advancement involved in millimeter-wave bands, expedited by upcoming solid-state sources and detectors, has attracted a great deal of interest in many different research areas and industrial applications. Thousands of phase elements of millimeter-wave reflectarray can be calculated for the meditated wave front focused at a desired location. The phase elements of a reflectarray antenna have been realized with MEMS switches [5], diodes [6,7], liquid crystal [8,9], dielectrics [10,11], and height of array [12,13]. Furthermore, research on reflective array antennas having a functional role such as low-profile dual circularly polarization [14] and intelligent reflecting surface [15] has been recently reported.
This paper describes the design of digitized beam-aimed metal reflectarray antennas in a millimeter-wave region. The phase of metal groove elements is digitized by the number of bits and also calculated by a conventional beam-forming method [16]. This paper has the advantage of being able to manufacture a beam-aimed antenna in a millimeter wave band by using a relatively simple machining method. In order to save the time and cost required for production, the phase adjustment value of each element is digitized. The research results of this paper can be directly utilized as practical examples such as functional reflective surfaces for the changing channel path and increasing channel distance in millimeter wave and 6G band communication and the choice for high-gain beam-steering antennas in millimeter-wave regions.

2. Reconfigurable Metal Reflectarray

A single unit groove in Figure 1a is shown as a metal reflectarray antenna building block. All waveguides are placed in a ground metal, an aluminum. The sizes of unit cell for the metal reflectarray are \( a = 1.8 \) mm, \( b = 1.4 \) mm, \( T_a = 2.3 \) mm, and \( T_b = 1.9 \) mm. The depth of a metal rectangular waveguide, \( d \), is changed for steered-beam metal reflectarray antennas. The period of unit cell is accepted by the minimization of mutual coupling between arrays. The mentioned isolated element analysis is valid when the distance between the edges of the adjacent patches is larger than 0.25\( \lambda \), also assuming the array elements spacing is larger than 0.6\( \lambda \) [17]. Thus, the mutual coupling between the elements can be neglected. Figure 1b shows simulated reflection phases of the unit cell in degree varying the depth of unit cell for some frequency components.

![Figure 1.](image)

The depth of phase element is tuned and the antenna frequency is also changed to confirm the sensitiveness of reflected phases from 80 to 110 GHz. The antenna frequency is selected by 95 GHz to reduce atmospheric propagation loss. The depth of each waveguide, \( d \), is changed for under half of the guided wavelength for the antenna frequency \( (0 \leq d < \lambda/2) \). The reflected phase can be fully satisfied from \(-\pi\) to \(\pi\) due to the ground-plane reflection, which is the round trip propagation in each metal waveguide. A perfect electric and magnetic conductor with a periodic boundary condition of a TM-polarized wave is used for electromagnetic full-wave simulation, CST Microwave Studio. Rectangular metal waveguide grooves are equally spaced arrays in an aluminum metal plate.

The required phase at the \( i \)th element for beam-steering reconfigurable metal reflectarray antennas to focus a beam in the direction \((\theta_b, \phi_b)\) with \( N \) elements in each column and \( M \) elements in each row is calculated [18]:

\[
\phi(m_i, n_i) = -k_0 \sin \theta_b \cos \phi_b m_i - k_0 \sin \theta_b \sin \phi_b n_i
\]  

where \( k_0 \) is the free space propagation constant and \((m_i, n_i)\) are coordinates of the element \( i \). The calculated phase shift on each reflectarray element can be expressed as:
\[ \phi_i^R = k_0 (d_i - (m_i \cos \phi_b + n_i \sin \phi_b) \sin \theta_b). \] (2)

\(d_i\) is the distance from the phase center of the feed to the element. For uniform amplitude distribution, four required phase patterns for millimeter-wave beam-steering metal reflectarray antennas from \(\theta = -20^\circ\) to \(20^\circ\) are shown in Figure 2. The required phases are calculated by the relation of each groove location and feed location. There are 1147 \((M \times N, 31 \times 37)\) elements constructed on 71.8 mm \(\times\) 70.8 mm \(\times\) 10 mm size aluminum metal plate.

Figure 2. Required phase patterns for reconfigurable millimeter-wave reflectarray antennas from \(\theta = -20^\circ\) to \(20^\circ\) (a) \(\theta = -20^\circ\); (b) \(\theta = -10^\circ\); (c) \(\theta = 10^\circ\), (d) \(\theta = 20^\circ\).

Figure 3 show the simulated far-field radiation characteristics when each main beam is independently directed from \(\theta = -20^\circ\) to \(20^\circ\). The radiation patterns at working frequency are an efficiently directed changing beam-steering angle in H-plane. The antenna maximum gains are rarely changed. The gain of bore-sight and \(-20^\circ\)-steered antennas are 33.44 and 33.41 dB and half-power beam width are 2.44° and 2.45° in the H-plane, respectively. There is no dramatic change when the beam-steering angle is changed. The designed reconfigurable metal reflectarray antennas rarely change the characteristics of bore-sight antennas.

Figure 3. Simulated far-field patterns in H-plane of reconfigurable millimeter-wave reflectarray antennas when observation angles are changed from \(\theta = -20^\circ\) to \(20^\circ\).
3. Digitized Reconfigurable Metal Reflectarray

The reflection phase of the rectangular groove element of a metal reflectarray antenna is generally designed to compensate the spatial phase delay from the feeder to that element, which is appropriately controlled by the manipulation of groove depth and the depth of each element is tuned by the phase matching condition by Equations (1) and (2). Afterwards, the ideally required reflection phase of the \( i \)-th groove, \( \phi_{i,o} \), is replaced with quantized phase sates, \( \phi_{i,q} = q \times (\phi_{i,o} \mod q) \), where \( q = 2\pi/2^n \) and \( n \) is the number of quantized phase-shift bits. We use different subscripts to simply explain required -either \( o \), original or \( q \), quantized-phase of each element.

Figure 4 shows the simulated radiation patterns of digitized reflectarray antennas when all required phases for high-gain antenna are quantized by the number of bits, \( n \). Increase the number of quantized bits higher than the gain of designed reflectarray antennas. The radiation characteristics of digitized metal reflectarray are comparable when the required phase of groove is quantized by four bits. This means that the 16-depth elements are sufficient for high-gain reflectarray. Moreover, the digitized metal reflectarray is easily constructed with only two bits in 1 dB-loss circumstance, which results in the reduction of the manufacturing time and cost [19]. Figure 5 shows the calculated four required phase patterns for digitized 20\(^\circ\)-steered metal reflectarray antennas for non-digitized cases and three different bits.

![Figure 4](image_url)

**Figure 4.** Simulated far-field patterns in H-plane of digitized reflectarray antennas when all required phases for high-gain antenna are quantized by the number of bits.

![Figure 5](image_url)

**Figure 5.** Required phase patterns for 20\(^\circ\)-steered digitized metal reflectarray antennas for a non-digitized case and three different bits, \( n = 1, 2, \) and 4.
Figure 6 shows the simulated radiation patterns of digitized reflectarray antennas when a re-radiation field is directed at $\theta = 20^\circ$. The metal reflectarray antennas are constructed for five different bits from 1 to 4 bits and infinite bits. Infinite phase bit is continuous phase. The radiation patterns at working frequency are efficiently directed changing quantized bits in H-plane. The main lobe of radiation fields are well directed at $\theta = 20^\circ$ for all quantized bits. The maximum gains of the reflectarray antennas are rarely changed over two bits. The gain of $20^\circ$-steered antenna is 32.42 dB and half-power beam width is 2.44° in the H-plane. There is no dramatic change when the number of quantized bits decreases. Here, two-quantized-bits is sufficient to construct digitized metal reflectarray.

4. Experimental Results and Discussion

Figure 7 is a picture of the reflectarray antenna measurement configuration in a near-field scanning probe chamber, and the inset shows the three-dimensional modeling of the designed antenna and a feeder. In order to measure the beam steering angle of the beam-steered antenna, a curved feeding part is manufactured. The experimental results of the fabricated antennas are compensated for the loss in the straight and curved waveguide.

Figure 8 shows experimental and simulated far-field radiation patterns of bore-sight and $-20^\circ$-beam reflectarray antennas for H-plane for a two-bit quantized phase. For the comparison, the experimental (solid) and simulated results (dashed) are shown in the same figure. The experiment was conducted in a near-field measurement system. The used feeder is a W-band rectangular pyramidal horn with 14.7 dB which has the minimum
reflection at antenna frequency. The constructed antenna was manufactured using a typical machining process with a vertical resolution of 30 µm. The maximum gain are 31.91 and 31.73 dB and a half-power beam width are 2.61° and 3.15° for bore-sight and −20°-aimed antennas in H-plane, respectively.

![Figure 8](image-url)

Figure 8. Experimental (solid) and simulated (dashed) far-field radiation patterns of proposed two-bit digitized reconfigurable reflectarray antennas when two different observation angles are applied. (a) θ = −20°; (b) θ = 0°.

The experimental results are similar to the simulated results. Between two results, the side lobe and measured gain have some differences due to the interference from the feeder support bar and the scattering fields at the edge of the conductor cells. In the case of a −20°-aimed antenna, the radiated filed is very similar to that of a bore-sight antenna. By these results, we can anticipate that wide angle tuning of a digitized metal reflectarray antenna is possible. The far-field radiation characteristics of measured and simulated results of reconfigurable metal reflectarray in H-plane are summarized in Table 1. The measured gain is lower than a simulated one under 0.7 dB due to the blockage by feeder flanges and struts.

| Angle (deg) | Gain (dB) | HPBW (deg) | Side Lobe Level (dB) |
|------------|-----------|------------|----------------------|
| 0°         | Sim. 32.39 | 2.42       | −18.47               |
|            | Exp. 31.91 | 2.61       | −11.15               |
| −20°       | Sim. 32.44 | 2.45       | −20.46               |
|            | Exp. 31.73 | 3.15       | −11.91               |

The measured −20°-aimed antenna gain and return loss for the frequency range of 80~110 GHz with the simulation results is shown in Figure 9. The measured gain below 95 GHz shows a good agreement with the simulated one, but the difference is increased at the higher frequency range due to the phase error of a blockage and a diffraction caused by the waveguide flange and the supporting strut. Nevertheless, the 1-dB gain bandwidths of a designed metal reflectarray antenna from experimental and simulated results are about 6.2 % (92.3~98.2 GHz) and 5.3 % (92.7~97.7 GHz), respectively and return loss was less than about −10 dB in 80~110 GHz.
5. Conclusions

In summary, we have designed digitized beam-steering metal reflectarray antennas composed of rectangular grooves on a metal plate for the millimeter-wave region. All depths of 1147 metal grooves in an aluminum plate are elaborately manipulated and quantized for designed phase control of high-gain reconfigurable reflectors. By the results of full-wave analysis and near-field experiments, there is no significant change of radiation patterns over two-quantized-bits. The radiation of designed digitized-steered-beam metal reflectarrays are well directed at $\theta = 20^\circ$ in a two-dimensional plane for a 2-bit quantized antenna. Remarkably, the radiation characteristics are almost the same as those of the non-quantized cases. The measured peak gain is higher than 31.7 dB for the full $40^\circ$ steered region and gain loss of well-steered beams are 0.2 dB. These beam-aimed antenna in a millimeter wave band can be made by a simple machining, and the phase value of each element is digitized to save the time and cost required for production. The research results can be directly utilized as practical examples such as functional reflective surfaces for a changing channel path and increasing channel distance in millimeter wave and 6G band communication and a variety of wireless communication systems.

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