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Abstract

This paper presents a single layer multi-band reflectarray antenna with circular polarization. The antenna geometry and operation principles are described. The reflectarray design procedure, including antenna elements and offset feed, is illustrated in details. An X band reflectarray prototype is fabricated and measured in the near field system, which realizes a 30.4 dB gain, 53.7% efficiency, and a 6% bandwidth

1. Introduction

High gain antennas are desired in various applications, such as radar, radio astronomy, satellite communications, remote sensing, and deep space explorations. One way to increase the antenna gain is to construct an antenna array with hundreds or thousands of elements. However, it usually suffers from a noticeable power loss in the feeding network. In contrast, a large aperture reflector antenna that avoids the usage of a feeding network can achieve a higher efficiency and hence is widely used in many communication systems. The conventional parabolic reflectors are generally bulky in size and large in mass due to the curved reflecting surfaces. Recently, planar reflectarray has been proposed, which has numerous advantages such as light weight, low cost, and conformability with installation platforms [1].

The bandwidth performance of a reflectarray is limited by the narrow bandwidth of microstrip antenna elements and the differential spatial phase delay in a large aperture. Multi-layer structure has been used to improve the bandwidth performance. For example, a stack-patch element was proposed in [2] to broaden the reflectarray bandwidth, and a two-layer structure with angular rotated rings was successfully demonstrated in [3] for dual band operation. In this paper, a single-layer reflectarray antenna is designed to realize tri-band (C/X/Ka) operation with circular polarization (CP). A modified element rotation technique is proposed to compensate the spatial phase delay. To demonstrate the proposed antenna concept, an X-band reflectarray prototype was fabricated and tested, which has a gain of 30.4 dB and an aperture efficiency of 53.7%.

2. Reflectarray Geometry for Multi-Band CP Operation

The reflectarray antenna, as sketched in Fig. 1, consists of three different types of elements: split circular rings, split square loops, and cross-dipole elements. All three types of elements are mounted on a 62 mil thick RT/Duroid 5870 substrate (\(\varepsilon_r=2.33\)). This single-layer design is significantly simpler to fabricate and lower cost than the multi-layer design.

A split circular ring with a vertical bar [4] is designed to reflect CP wave with the same polarization state at Ka band (32 GHz). The element spacing is half wavelength. Since the substrate thickness is relative thick in term of the wavelength at Ka band, the element will provide a broad operating bandwidth. In order to realize a planar wavefront, the angular rotation technique [5] is used for each element to compensate the spatial phase delay.

A split square loop is designed to reflect the CP wave with the same polarization state at X band (8.4 GHz). The element spacing is four times of the element spacing at Ka band. Since the substrate thickness is relative thin in term of the wavelength at C band, the operational bandwidth becomes narrower. The conventional angular rotation technique cannot be used here for the X-band elements because the rotation of square rings will collide with the split ring elements. To solve this problem, a modified approach is to move the position of slots along the perimeter of the
square loop. It is observed that when the slot position is moved along the perimeter of the square loop, the resonant frequency of the structure will shift due to the corner effect. To maintain the same operating frequency, the slot width needs to be adjusted. Furthermore, it is important to point out that the phase variation is no longer a linear function of the rotation angle as the conventional method.

Fig. 1: Geometry of a single-layer tri-band reflectarray design.

A cross dipole is designed to operate at C band (7.1 GHz), which has the same element spacing as the square loop but shifts half periodicity in space. In contrast to the previous two designs, this cross dipole reflects the incident CP wave with the opposite polarization state because of the symmetric geometry. This design will help to avoid the coupling effect between two close frequencies (7.1 GHz and 8.4 GHz). To compensate for the spatial phase delay, the C band design uses variable element size method [6]. The length of the cross dipole is adjusted to obtain the required reflection phase.

3. Reflectarray Design Procedure

The reflectarray design procedure consists of two steps: (1) antenna element design and (2) optimum feed location design. In the element design, the antenna dimensions are determined and the relation between the rotation angle and the phase variation is derived. In the feed design, an optimum feed location (f/D) is searched to maximize the antenna efficiency. In this paper, the X-band antenna is developed as an example to illustrate the design procedure.

3.1 Antenna element designs

The full wave solver Ansoft Designer is applied in the element designs. Periodic boundary conditions (PBC) are placed around a single antenna unit to model an infinite array environment while a plane wave is launched to illuminate upon the unit cell. The array grid is uniform and square shaped, with a period p=18.75 mm between adjacent cells.

Figure 2(a) demonstrates the magnitudes of the reflected co-polarized (right hand circularly polarized, RHCP) and the cross-polarized (left hand circularly polarized, LHCP) components, with different angles of incidences. By rotating the slots around the perimeter of the square loop, different reflection phases can be obtained to compensate the spatial phase delay of elements at different locations on the reflecting surface. Compared with the conventional element rotation technique, this slot rotation technique exhibits two distinctions. First, the phase variation is no longer a linear function of the rotation angle. As illustrated in Fig. 2(b), a curve fitting technique is used to derive an empirical formula of the phase variation for later array design. Secondly, the slot width needs to be adjusted during rotation to compensate for the effect of the square corner.
3.2 Optimum position of the offset feed

The antenna elements are aligned on a circular aperture with the diameter $D = 500$ mm. The feed is located at a distance $f$ from the array plane, as depicted in Fig. 3(a). To minimize the feed blockage, an offset feed structure is used with a distance $d$ to the edge of the aperture. A tilted beam is designed with $\theta_1 = \theta_2 = 25^\circ$ aside from the normal to the reflector plane.

Similar to the conventional reflector design, the ratio $f/D$ is optimized to achieve the maximum aperture efficiency. As shown in Fig. 3(b), when $f/D$ increases, the spillover efficiency decreases but the illumination efficiency increases. The maximum total efficiency is obtained at $f/D=0.68$ for the horn antenna with a $\cos^q$ pattern ($q=6$). The magnitude and phase distributions over the array plane are then computed.

4. Near Field Measurements of the Reflectarray

To verify the antenna concept and the modified element rotation technique, an X-band reflectarray prototype was fabricated. The array plane was divided into four quadrants for easy fabrication. Then they were assembled together on a solid aluminum ground plane. Wooden frames were incorporated to support both the array plane and the feed
horn that was specially designed to achieve circularly polarized patterns in X-band. The performance of the prototype was obtained through near field measurement, accomplished in the NSI Inc. Figure 4(a) is a photo of the reflectarray antenna set in the near field measurement system at The University of Mississippi.

Figure 4(b) shows the far field patterns at 8.4 GHz, which is transformed from the near field data. In the $yz$ plane, an offset main beam is obtained, as expected from the offset feed. The side-lobe levels are below -20 dB in both planes, as well as the cross-polarization level. The 3 dB beam widths are 4.8° and 4.3°, respectively. Through the comparison with a standard horn, the gain of the reflectarray antenna is 30.4 dB and the aperture efficiency is 53.7%. The fractional axial ratio bandwidth is 6%, while the 3 dB gain bandwidth is 7%.

Fig. 4. Near field measurement of the reflectarray prototype: (a) setup of the reflectarray in a near field system and (b) measured radiation pattern.

5. Conclusions

This paper presents a single-layer tri-band reflectarray with circular polarization. Circular ring, square loop, and cross dipole are designed to operate at Ka band, X band, and C band, respectively. The reflectarray design procedure is summarized and a modified element rotation technique is proposed to solve the difficulty of incorporating three elements on the same reflecting surface. To demonstrate the antenna design procedure and the new phase compensation technique, a reflectarray prototype was fabricated and tested in the near field measurement system, which realizes a 30.4 dB gain and a 6% bandwidth.

6. References