

A Broadband Reflectarray Antenna Using Dual-Resonance Phase-Delay-Line Unit Cell

Sen Liu, Qiang Chen (Graduate School of Engineering, Tohoku University)

Abstract: A broadband linearly polarized single-layer reflectarray antenna constructed by the element cells of sub-wavelength dual-resonance with phase delay line is presented in this paper. The novel element is composed of circle split patch together with split ring, and two identical phase delay line are attached to each half of the outer ring. With this novel structure, a linear phase response ranging about 550° is achieved by varying the length of the phase delay line. An offset-fed reflectarray antenna composed of 225 elements forming a square-shape aperture is designed and simulated. Simulation results show that 22% 0.5° main beam direction bandwidth with 1-dB gain varying is achieved. Meanwhile, the gain at 10GHz is about 24.8 dB, which results in about 53.5% aperture efficiency is realized. At the same time, the side-lobe level and cross polarization for E-plane are also simulated which are below -20.4 and -30 dB, respectively.

Keyword: broadband, sub-wavelength, dual-resonance, phase-delay-line, reflectarray antenna, single-layer unit cell

1. Introduction

Microstrip reflectarray technology has attracted wide attention in many applications, such as communication and radar, due to its alluring advantages of low profile, lightweight, and low cost [1]. However, there are also some disadvantages for microstrip reflectarray antennas, especially the narrow bandwidth. Reflectarray bandwidth is mainly limited by two different factors. The first one is the narrow band of the radiating elements, and the second one is the differential spatial phase delay resulting from the different lengths from the feed to each point on the wave front of the radiated beam.

Numerous methods were presented to enhance the bandwidth performance of the radiating unit cells for reflectarray antennas in recent years, among which by applying unit cells with wide-range linear phase responses is a very effective one [2]. There are several approaches to achieve linear-phase responses, such as using multilayer structures [3], thickening substrate, and attaching phase-delay lines [4]. In order to reduce the fabrication errors and the cost, single-layer broadband

reflectarrays have been proposed by using multiresonant elements, and 24% 1-dB gain bandwidth was achieved [5]. However, this approach needs thick substrate to obtain linear-phase responses, so the increase of mass as well as cost is unavoidable. Besides, thick substrate also leads to smaller linear phase range. Therefore, the dimension sizes of the elements have to be largely varied in order to achieve wide enough range of linear-phase responses, and, thus, potential phase error is unavoidable due to the mutual couplings become much complicated as well as the fabrication errors are hard to control.

In this paper, a linear-polarized single-layer unit cell structure is proposed to enhance the bandwidth performance of reflectarray antennas. The proposed element structure is constructed by circle split patch together with split ring, which form the dual-resonance configuration. A 225-element offset-fed reflectarray forming a square-shape aperture operating at X-band is designed and simulated using full-wave simulation technology to validate the broadband characteristic of the proposed unit-cell structure. Simulation results show that 0.5° main beam direction bandwidth within 1-dB gain varying reaches 22%. The simulated gain at 10GHz is about 24.8dB, which results in about 53.5% aperture efficiency.

2. Unit-Cell Design

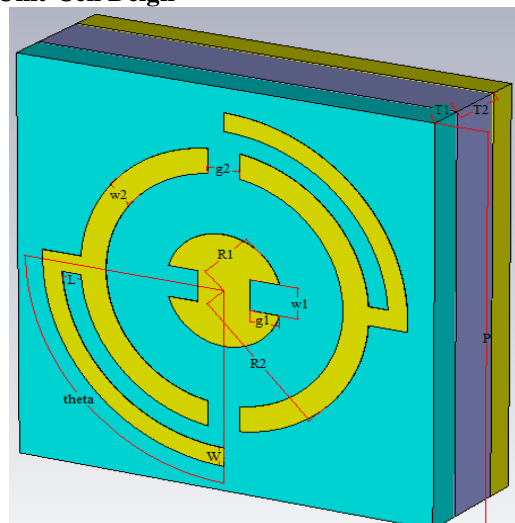


Fig. 1 Unit-cell structure for reflectarray antenna

Fig. 1 depicts the designed single-layer unit-cell structure. The proposed unit cell consists of a circle split

patch and a split ring, each with a pair of gaps orthogonally placed, and two identical phase delay line are attaching to the outer ring for phase shifts. R1, w1 and g1 are the circle patch radius, patch split width and patch split length. R2, w2 and g2 represent the ring outer radius, ring width and gap width, respectively. L and W are the length and the width of the stubs that connect the phase delay lines to the ring, which ensure the matching between phase delay lines and resonance structure. The length of the identical phase delay lines is represented by its rotation angle θ in degrees. P denotes the unit-cell period. Unit cells are etched on a dielectric substrate (T1) of 1.2 mm thickness with relative permittivity of 3.24 and dielectric loss tangent of 0.006 at 10 GHz, and a 2-mm-thick air layer (T2) separates the substrate layer and the metallic ground for smoother phase response.

To investigate the phase response of the unit cell and perform optimization for structure geometry parameters, an infinite array model is built in the simulation software of CST, in which Floquet port excitation and unit cell boundary condition are adopted. In order to get smooth phase response and magnitude response, the geometric parameters of the patch and ring, together with the period of the unit cell are optimized, which is designed to resonate at 10GHz. Furthermore, the width (W) and length (L) of the stub should also be optimized to realize good matching between phase delay line and resonance structure. In this way, the reflecting phase curves versus the lengths of the phase delay lines at different frequencies will have a great chance to maintain parallel, and, thus, wideband performance can be achieved. Table I lists the final designed element parameters for the elements.

Table I

Reflectarray Element Geometry Parameters

Quantity	Value
θ (theta)	4:1:172
P	13($\approx 0.43\lambda_0$ at 10 GHz)
R1	1.8 mm
w1	1 mm
g1	1 mm
R2	4.5 mm
w2	0.8 mm
g2	1 mm
W	0.6 mm
L	0.6 mm

The magnitude response curves and phase response curves against the length of the phase delay line at different frequencies of 9, 10, 11 and 12 GHz are plotted in Fig. 2 and Fig. 3, respectively, in which the value of rotation angle is the length of the phase delay lines. As one can see, a linear and smooth reflecting phase curve ranging about 550° is achieved at frequency of 10 GHz. Parallel phase curves among different frequencies are also obtained to ensure the broadband design. Meanwhile,

reflection loss less than 1dB can be obtained at 10 GHz. It is worth noting that although there are elements of reflection loss above 1dB, the effect of these elements can be ignored when the array is large.

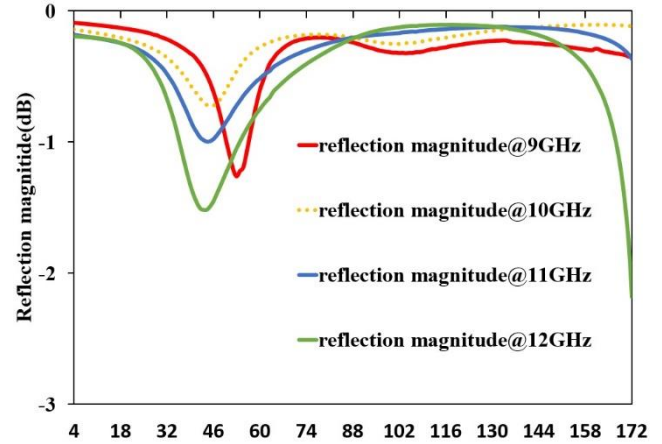


Fig. 2 Reflection phase curve versus the length of phase delay line

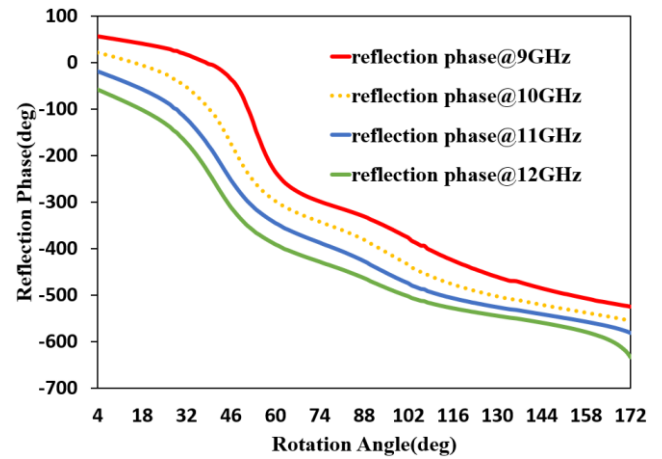


Fig. 3 Reflection magnitude curve versus the length of phase delay line

3. Reflectarray antenna with the proposed unit cell

In this section, an X-band offset-fed reflectarray antenna with 225 (15 × 15) elements is designed, and simulated to numerically validate the broadband feature of the novel unit-cell structure.

The required reflecting phases for all unit cells on the reflectarray aperture are calculated at 10 GHz, according to

$$\phi_R = k_0 \cdot (d_i - (x_i \cos \varphi_0 + y_i \sin \varphi_0) \sin \theta_0)$$

where k_0 represents the propagation constant in free space, d_i is the distance between the phase center of the feed source and the center of the i th unit cell on the reflectarray aperture, and (θ_0, φ_0) is the designed main beam radiation direction. Here, to avoid feed blockage, a 10° offset-fed design is selected for the reflectarray antenna to produce a main beam in $(20^\circ, 0^\circ)$ direction. An X-band standard gain horn of linear polarization is

utilized as the feed source, and the path between the feed source and the reflectarray center is designed to be 300 mm, which is optimized to -10dB edge taper. The unit-cell phase responses are designed to compensate for the spatial phase delays between the feed source and reflectarray unit cells.

Fig. 4 shows the designed phase distribution on the aperture at 10 GHz, and Fig. 5 shows the reflectarray aperture that is composed of 225 unit cells forming a square-shape aperture. One can further see from Fig. 5 that the unit cells are placed in a mirror symmetric arrangement in order to decrease the cross polarization [6]. Fig. 6 shows the setup for the full wave simulation configuration.

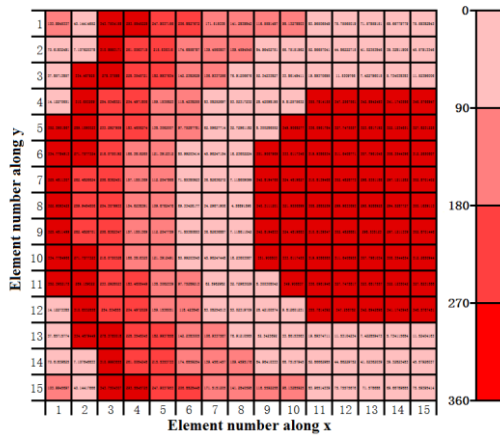


Fig. 4 Phase distribution of the designed reflectarray aperture

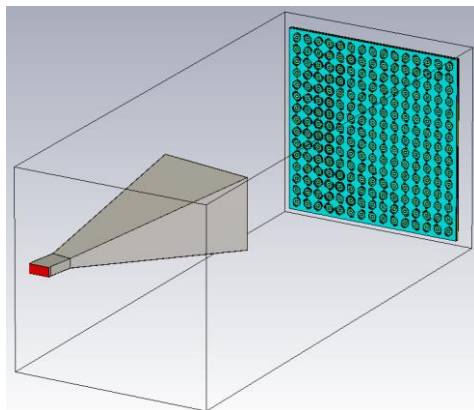


Fig. 6 Simulation setup of the designed reflectarray antenna

Fig. 7 and 8 show the simulated radiation patterns of co-polarization and cross-polarization at frequencies among 0.5° main beam direction band within 1-dB gain varying in E-plane and H-plane, respectively. As can be seen, a gain of about 24.8 dB at 10 GHz is achieved, which means about 53.5% aperture efficiency is realized. The simulated cross-polarization levels of both principal planes (E-plane and H-plane) are suppressed below -30

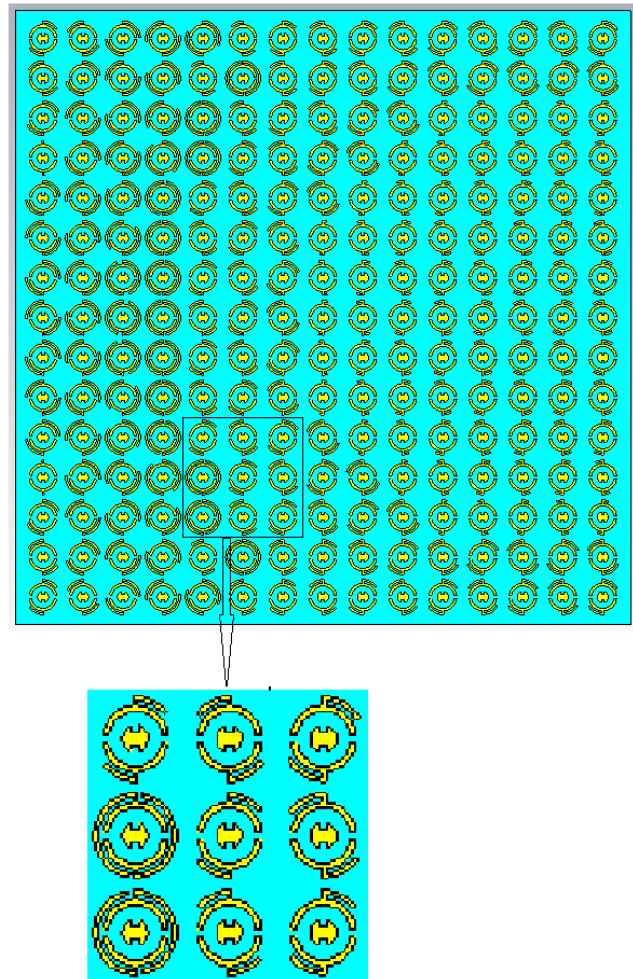


Fig. 5 Layout and element arrangement of the designed reflectarray

dB among the working frequency band benefited from the special element arrangement design. Moreover, the realized side-lobe levels for both principal planes are -20.4 dB and -17.6 dB at 10 GHz, respectively. Both Fig. 7 and 8 demonstrate the broadband performance well because the simulated radiation patterns within the 0.5° main beam direction bandwidth with 1-dB gain varying remain stable.

Fig. 9 and Fig. 10 plot the simulated main beam direction curve and simulated gain curve against frequency, from which one can see that main beam direction change within 0.5° can be achieved from 9.1 GHz to 11.3 GHz. At the same time, 1-dB gain varying can also be achieved within this band. It should be mentioned that the gain become larger with increasing frequency. It is almost caused by the increasing electric aperture size. However, the main beam direction become unacceptable as frequency increases.

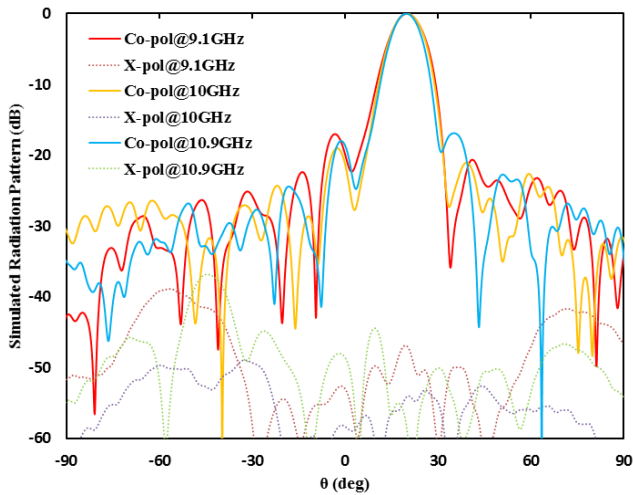


Fig. 7 Simulated H-plane Radiation Patterns at different frequencies

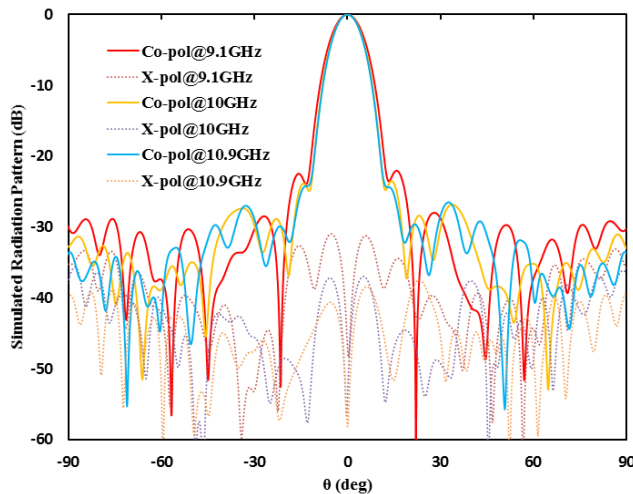


Fig. 8 Simulated E-plane Radiation Patterns at different frequencies

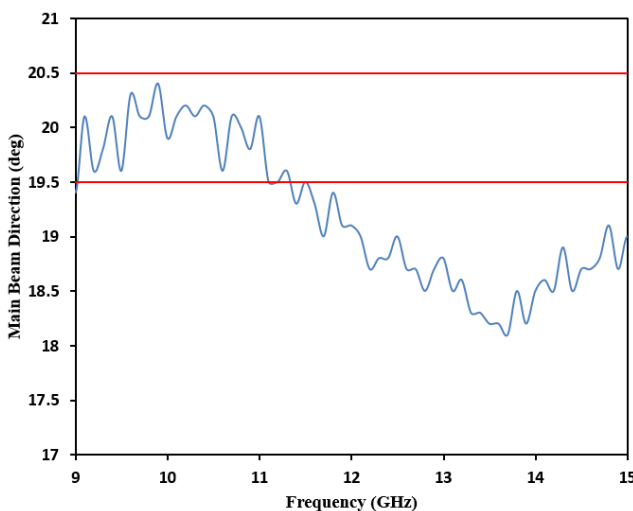


Fig. 9 Main Beam Direction vs. Frequency

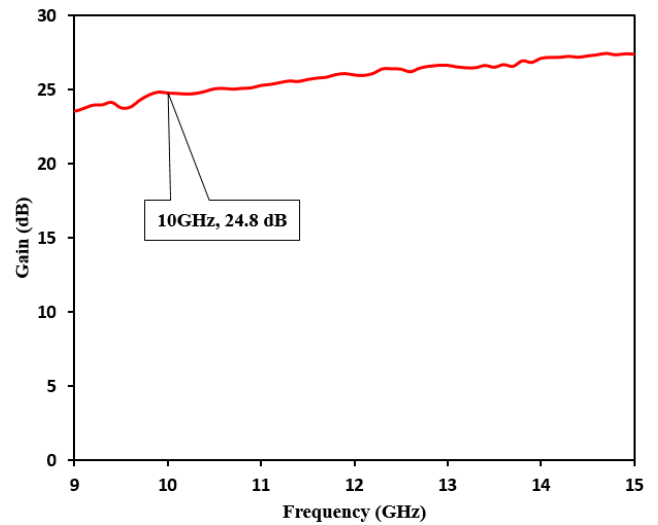


Fig. 10 Gain vs. Frequency

4. Conclusion

A novel single-layer unit cell with phase-delay lines is proposed for reflectarray antennas with enhanced bandwidth performance. The geometry dimensions of split patch and split ring as well as the lengths of phase-delay lines are optimized to realize parallel-phase responses in a wide frequency range. A 225-element offset-fed reflectarray with square-shape aperture operating at X-band is designed and simulated. From the simulation results, the 22% (9.1-11.3 GHz) 0.5° main beam direction bandwidth within 1-dB gain varying is obtained.

Reference

- [1] J. Huang, J. A. Encinar, Reflectarray Antennas. New York, NY, USA: Wiley, 2007.
- [2] E. Carrasco, M. Barba, and J. A. Encinar, "Reflectarray element based on aperture-coupled phases with slots and lines of variable length," *IEEE Trans. Antennas Propag.*, vol. 55, no. 3, pp. 820-825, Mar. 2007.
- [3] J. A. Encinar and J. A. Zornoza, "Broadband design of three-layer printed reflectarrays," *IEEE Trans. Antennas Propag.*, vol. 51, no. 7, pp. 1662-1664, Jul. 2003.
- [4] H. Hasani, M. Kamyab, and A. Mirkamali, "Broadband Reflectarray Antenna incorporating disk elements with attached phase-delay-lines," *IEEE Antennas Wireless Propag. Lett.*, vol. 9, pp. 156-158, 2010.
- [5] M. R. Chaharmir and J. Shaker, "Broadband reflectarray with combination of cross and rectangle loop elements," *Electron. Lett.*, vol. 44, no. 11, pp. 658-659, May 2008.
- [6] H. Hasani, M. Kamyab, and A. Mirkamali, "Low cross-polarization reflectarray antenna," *IEEE Trans. Antennas Propag.*, vol. 59, no. 5, pp. 1752-1756, May 2011.