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Wideband Single-Layer Reflectarray Antenna Using Planar Monopole Elements for mm-Wave Applications

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***Abstract*—In this paper, a single-layer wideband reflectarray antenna is proposed. Inspired by the ultra-wideband printed monopole antenna, a honeycomb wideband planar monopole unit cell is designed and employed to constitute a reflectarray antenna. The proposed unit cell takes advantage of the length of co-planar waveguide and the size of trapezoidal ground to realize the required phase delay for reflected waves. The experimental results show that the phase shifting curves at different frequency points within the working frequency band are relatively parallel, and the phase shifting range exceeds 360°. By arranging the elements in a honeycomb array form, the array size is reduced and the aperture efficiency is improved. To evaluate the array performance, a reflectarray consisting of 211 elements is designed and simulated. The simulation results demonstrate that a stable high gain and low sidelobe level are achieved simultaneously from 19 GHz to 34 GHz, indicating a relative operating bandwidth of 56.6%. Moreover, the 3-dB gain bandwidth is 40.89%, and a peak gain of 27.12 dBi occurs at 26 GHz, with a maximum aperture efficiency of 49.15%.**

***Index Terms*—Hexagonal unit cell, mm-wave antenna, planar monopole, wideband reflectarray antenna**

I. Introduction

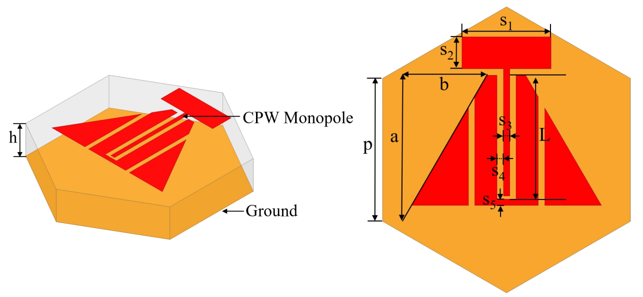
With the rapid development of satellite communication and radar systems, there is a growing demand for high aperture efficiency and wideband antennas. Reflectar- ray antennas combine the advantages of parabolic antennas and phased array antennas. Compared to parabolic antennas, reflectarray antennas use printed circuit boards to achieve a planar array while being easily processed. In contrast to phased array antennas, space-fed array antennas do not require a large number of transmit/receive (T/R) components [1], significantly reducing the production costs.

Nevertheless, traditional single-layer reflectarray antennas often suffer from narrow bandwidth and low aperture efficiency due to the use of microstrip patch antennas as array unit cells. Wideband and high aperture efficiency array antennas have been extensively investigated, but most studies have struggled to address the cost concerns. In [4], a dipole reflectarray antenna operating in the 10 - 30 GHz frequency range was proposed based on tightly coupled elements. The reflectarray antenna maintains a stable high gain pencil beam and low sidelobe levels within the operating frequency band. However, the antenna structure is complex and entails high manufacturing costs. In [5], a novel wideband S-shaped phasing element was introduced, which was printed on a single-layer PCB with an underlying reflective ground plane. This simple structure achieves high aperture efficiency and wideband performance while reducing production costs. Another study proposed a slot patch reflectarray element [6]. This single-layer element achieves broadband effect by adding parasitic patches on both sides of the slot patch to introduce additional resonances. Ultimately, the single-layer structure attains both wide bandwidth and high gain performance.

In order to enhance the bandwidth of single-layer patch array antennas, this design is based on ultra-wideband printed monopole antennas [2], [3]. A honeycomb single-layer broadband monopole reflectarray unit cell is introduced in this work, and the resulting reflectarray achieves characteristics such as wide bandwidth and high aperture efficiency. It is anticipated that this design could find applications in fields such as satellite communication, radar systems and mm-Wave applications.

II. Unit cell design

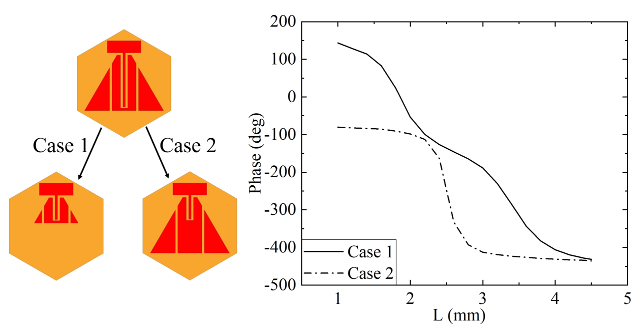
Inspired by the ultra-wideband printed monopole antenna, a single-layer broadband planar monopole reflectarray unit is designed based on the wideband characteristics of this structure. The unit structure is shown in Fig.1 and consists of a coplanar waveguide (CPW) monopole, a dielectric substrate, and a metal ground plane. The array adopts a regular hexagonal shape, allowing for a more compact arrangement of units in the array to enhance aperture efficiency. The dielectric substrate is made of Rogers 5880 with a dielectric constant of 2.2 and a loss tangent of 0.0009. At the end of the coplanar waveguide transmission line, an open circuit is introduced. When the electromagnetic wave reaches the open circuit, it reflects



(a) (b)

Fig. 1. Unit cell structure. ($p = 4.5mm, a = 6.1mm, b = 3.55mm, s_1 = 2.8mm, s_2 = 1mm, s_3 = s_4 = s_5 = 0.2mm, h = 1.524mm$)

back, allowing the phase of the reflected electromagnetic wave to be altered by adjusting the length of the transmission line L. However, due to the small size of the array elements, the spatial variation of the transmission line is limited, as shown in Fig.2 Case 2. If the trapezoidal ground plane size is kept unchanged and only the length of the transmission line is adjusted, it is not enough to realize the phase shift above 360° and the phase shift curve is not linear. To meet the phase shift requirements, this design



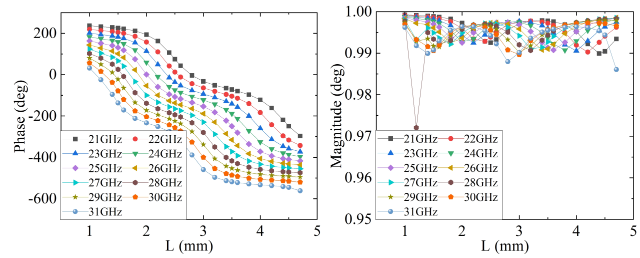
(a) (b)

Fig. 2. (a) Two cases of phase shifting. (b) Comparison of phase shift curves between case 1 and case 2 arrays at 26 GHz.

simultaneously varies the trapezoidal ground plane with the transmission line. The phase shift curves for the two different approaches are shown in Fig.2 (b). This design achieves a phase shift of 520° when the length L varies between 1 mm and 4.5 mm. By optimizing and simulating the parameters of the array unit cell, as shown in Fig.3 (a), the wideband phase shift characteristics of the proposed single monopole reflectarray unit are illustrated. It can be observed that within the operating frequency range of 21 GHz to 31 GHz, the phase shift curve exhibits a relatively linear and parallel trend at different frequencies. In Fig.3 (b), the amplitude characteristics of this designed unit are displayed, revealing that within the operating frequency band, the reflection amplitude remains above 0.97.

III. Array Design

This design employs a honeycomb arrangement for the array, comprising 211 elements forming a circular array.



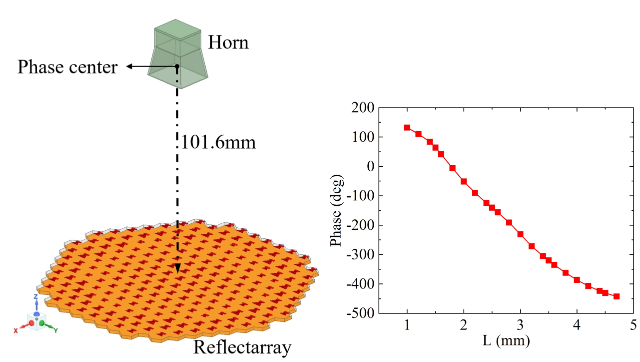
(a) (b)

Fig. 3. The proposed unit cell reflection characteristic. (a)Reflection phase (b)Reflection magnitude

The average beamwidth of the standard feed source within the operating frequency band is 75°, and the optimal distance from the feed source to the array surface is calculated to be 101.6 mm. Fig.4 (a) shows the overall configuration of the array. To achieve a larger bandwidth and reduce phase shift errors at different frequency points, the phase shift curves for the 21 GHz- 31 GHz range are averaged. For each frequency point, the phase shift curve is divided by the corresponding beamwidth factor k, averaged, and then multiplied by the beamwidth factor k_0 at the center frequency of 26 GHz. The average phase shift curve for the array elements is depicted in Fig.4 (b). Using the equation:

$$\Phi_u(x_i, y_j) = -k_0 \sin\theta_u(x_i \cos\theta_u + y_j \sin\phi_u) + k_0 R_{ij} + \phi_{u0} \quad (1)$$

the phase compensation required for each element when the beam is directed to $(\theta, \phi) = (0°, 0°)$ is calculated. The corresponding length L for each array element is then determined based on the relationship with the average phase shift curve. The calculated phase compensation for each array element is shown in Fig.5 (a), and the corresponding L length for each element is illustrated in Fig.5 (b).



(a) (b)

Fig. 4. (a)Reflectarray configuration. (b)Unit cell average phase shift curve.

IV. Results and Discussions

Using ANSYS HFSS for simulation, the results of the reflectarray antenna design are presented in Fig.6 (a) -

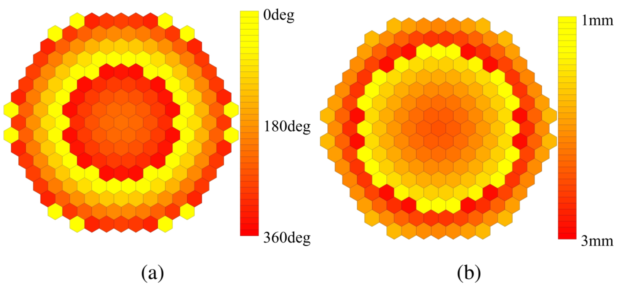


Fig. 5. Phase compensation and L distribution for different unit cells.

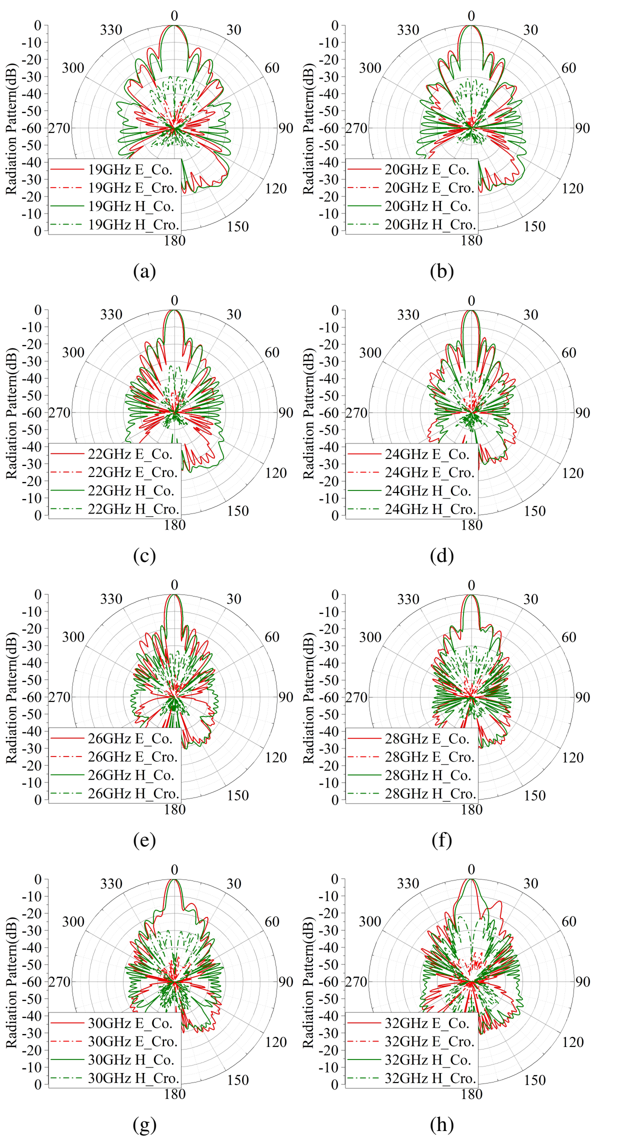


Fig. 6. Radiation patterns at different frequency points. (a) 19 GHz (b) 20 GHz (c) 22 GHz (d) 24 GHz (e) 26 GHz (f) 28 GHz (g) 30 GHz (h) 32 GHz

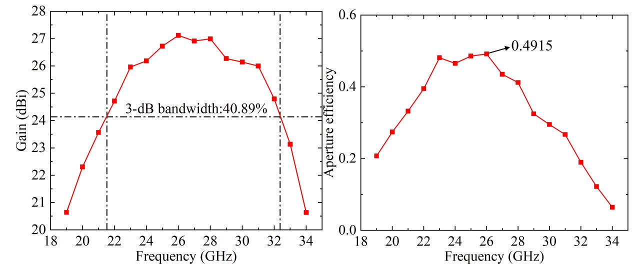


Fig. 7. Reflectarray antenna gain and aperture efficiency.

(h). The radiation patterns at different frequency points are shown, and within the 19 GHz - 34 GHz bandwidth, the antenna maintains a stable pencil beam, with the beam direction consistently pointing towards (0°, 0°), and maintaining low sidelobe levels. The gain curve is illustrated in Fig.7, with the highest gain reaching 27.12 dBi at 26 GHz. The maximum aperture efficiency is 49.15%, and the 3-dB gain bandwidth is 40.89%.

V. Conclusion

This paper presents a hexagonal broadband monopole reflectarray element. By arranging 211 elements in a honeycomb pattern, a wideband reflectarray antenna with high aperture effifency is realized. Simulation results verify that the propsoed design exhibits advantages such as wide bandwidth, high aperture efficiency, and stable radiation patterns. With these merits, the presented antenna could find applications in satellite communications, radar systems, and mm-Wave systems.

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