A High Efficiency Reflectarray Antenna Design Based on Incident Field

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Abstract—A single-layer reflectarray antenna operating at Ku band with Phoenix elements is presented. The element is optimized by parameter study to achieve a linear phase shift curve and sufficient phase variation range. And then, a 941-element array with linear polarization is designed. Differing from calculating wave path difference directly, the phase distribution on the reflectarray plane is calculated by exacting the phase of incident field, which indicates a more accurate phase compensation. At the configurable design stage, an off-set horn with multimode is installed and its position is optimized. The simulated results show 3-dB gain bandwidth of 28% and a maximum aperture efficiency of 64% at 13.5 GHz center efficiency.

Index Terms—Reflectarray, linear polarization, high efficiency, 3-dB bandwidth, incident field

I INTRODUCTION

A reflectarray antenna is the array antenna system that consists of a reflective aperture and feed antenna. This conception was first proposed in 1960s [1], waveguides with different lengths were used to provide different phase. However, it was bulky and nonplanar, making the fabrication very troublesome. Later, in [2], a planar microstrip patch-type reflectarray, which consisted of microstrip patch elements of different sizes, was proposed. Its advantages such as flat reflecting surface, light in weight, and ease of manufacture made the reflectarray become the study interests to many microwave engineers.

Recent years, to meet the more and more challenging requirements for long distance communication e.g. radars, satellites, remote sensing, space exploration systems etc., high gain antenna with pencil beam are extremely demanding. Traditionally, the reflector and phase array antenna are designed for these systems. However, their drawbacks could not be ignored as the demand becomes more rigorous. For example, parabolic reflectors with non-planar curved reflector surface are too bulky to be installed on some compact radar systems. Traditional arrays need complex feeding network to control the phase, and it really costs especially at high frequencies. With combining advantages of both array antenna and reflector [3], reflectarray antenna is free from these problems.

The basic mechanism of reflectarray is to convert incident wave with spherical wave front transmitted from feed at focal point to a planar wave through phase compensation by adjusting their geometrical parameters. Several methods are usually utilized to fulfill this job, such as the varying patch size, rotating circular or square rings, changing effective dielectric constant of the substrate by drilling holes and et al. [4-5].

However, the main limitation to printed reflectarray antenna is the low aperture efficiency and narrow bandwidth inheriting the narrow bandwidth of elements. There are some means available to overcome bandwidth limitation, such as stacked patches of variable size [6], true-time delay [7], and sub-wavelength techniques [8]. As far as high aperture efficiency design, there is no mature method. But the guidance principle is obvious that the better compensation for each position is done, the more collected the pencil beam will be. In [9-11], researchers use ray theory to calculate the phase distribution and then match the needed phase with element parameters, a reflectarray is realized with aperture efficiency of 59% and 3-dB gain bandwidth of 17.3% using a single layer air via in [9]. A dual-band reflectarray with aperture efficiency over 60% is introduced in [10] by combining four commonly used wideband design approaches: the sub-wavelength spacing, multiresonance structures on an electrically thick layer, multitype elements, and the dual-frequency phase synthesis. A one-bit digital coding reflectarray based on fuzzy phase control is designed in [11], achieving 1-dB bandwidth of 25% while the aperture efficiency is only 30%. Obviously, it is not an easy work to design a reflectarray with good performance in both efficiency and bandwidth.

In this paper, a Ku-band linear polarization microstrip reflectarray is designed. The single element is optimized in CST with unit cell periodic environment, achieving a smooth linear phase curve with a more than 360 °variation range. A multimode horn with linear polarization is used as the excitation source. To obtain the phase distribution accurately, instead of using wave path-difference to exact phase needed, phase calculation is based on illuminating field in this design. To start, the structure of the proposed element is shown in Part II. The Floquet method has been adopted for simulating the reflection performances of the proposed element. In Part III, design procedure of the high efficiency reflectarray will be given. At the same time, simulated results is provided and discussed in part IV.

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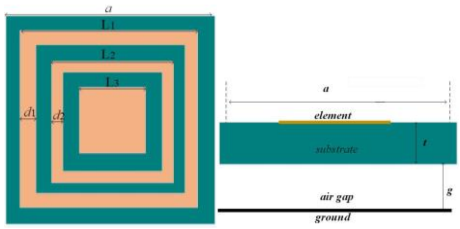


(a) (b)

Fig. 1. Geometry of the Phoenix element (a) top view (b) side view.

II UNIT CELL DESIGN

The proposed element configuration is shown as Fig. 1, which consists of four parts, they are radiation microstrip patch, substrate, air gap and the ground. The radiation patch is composed of dual loops and an inner square patch.

Phase shift is realized by changing the size of second loop while keeping the outer loop a constant size to minimize coupling between elements. Meanwhile, the air gap is contributed to a lower phase deviation and make the phase shift curve smoother. A smaller phase deviation to element size means a relatively low demand for machining accuracy, since phase shift is less sensitive to patch parameters. A substrate with permittivity 2.65 is selected and an element spacing 8mm (0.36λ) is set to avoid grating lobes.

To derive phase curve and study the characteristic of element, the commercial software CST is operated. Unit cell conditions are placed around a single element while the Floquet wave incidents from the top of element to simulate the two dimensional infinite array environment.

By adjusting the polarization angle, illuminating angle could be changed as needed.

Parameter study is carried out to optimize the element structure to obtain a phase curve with gentle change and sufficient phase range. The square patch is designed to cooperate the metal loops to arouse resonance, therefore, changing its length L_3 singly within a range does not influence the phase shift. As shown in Fig. 2, phase curves with several different L_3 values are almost overlapped. In this design, L_3=0.8mm is chosen to make sure that the inner loop could change parameters in a proper range.

Followed by study on width of two loops shown as Fig. 3. It can be seen from Fig. 3 (b) that setting loop width as 0.4mm can make the deviation smallest, while the length of inner loop L_2 varies from 1.4 to 7.8mm.

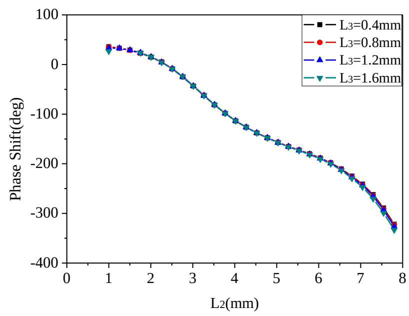
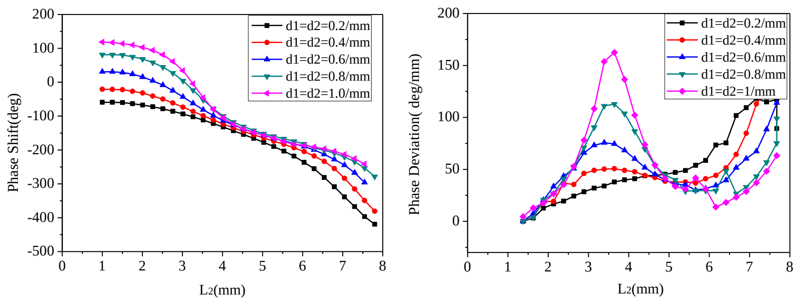
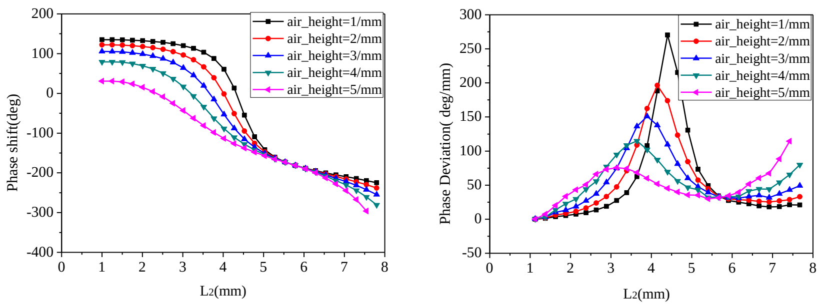


Fig. 2. Phase variation for different inner patch size



(a) (b)

Fig. 3. Parameter study on width of metal loops at the center 13.5GHz frequency (*a*) Phase variation versus loop width (b) Phase deviation versus loop width.



(a) (b)

Fig. 4. Parameter study with thickness of air gap at 13.5GHz (*a*) Phase variation versus gap thickness (*b*) Phase deviation versus gap thickness.

Except that, the thickness of air gap is optimized, Fig. 4 shows that g=5mm promising a best linear phase curve wicarantee both phase range and linearity, g=5mm is set while the thickness of the substrate is set as 2mm.

Finally, the phase shift against L_2 for several different frequencies is studied. From Fig. 5, a good parallel between phase curves at different working frequencies could be seen, promising a wide bandwidth. What has to be illustrated specially is that the conception of bandwidth in the design of a reflectarray antenna is different from that in common microwave antenna design. It concerns with phase rather than S parameters. That is to say, when the antenna works in a broad frequency range, the phase shift curves in this range are expected to be coincide to supply a nearly constant phase reference. Fig. 5 shows a bunch of nearly parallel curves, thus it supplies a relatively accurate phase reference for the array design in proceeding study.

To conclude, the element design combines the following four method to improve its performance: multi-resonance loops to obtain sufficient phase shift range, subwavelength spacing to minimize the coupling and air gap to smoothen the phase curve at the same time to lighten the structure. It is worthy to spend time on element deign since that, in some degree, its performance determines the potential character of the whole reflectarray antenna.

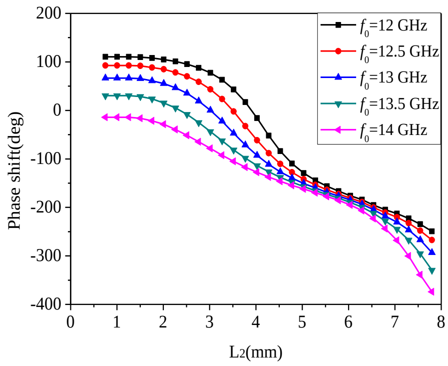


Fig. 5. Phase shift at different frequencies

III Reflectarray Design

A. Reflectarray Structure Layout

Using the proposed element, an offset reflectarray antenna is designed. It is composed of 941 unit cells, which are set on a flat circular plane with diameter of 286mm. The reflective plane is illuminated by a multimode horn with good uniformity in both E and H plane. The radiation character of the horn could be well approached with $\cos^q\theta$, and $q = 6.5$ in this case. As we expected, the out beam should orient to 15° shifting away from the boresight of the reflectarray aperture (E plane). According to the study in [12], the angle of the feed source towards to the reflective plane should be also be install as 15°. It illustrates that radiation loss is introduced by reflected wave that is not in the same direction as main beam and radiation by ground plane. In this case, offset setting properly can lower the loss due to specular reflection from the ground plane which is not at the same direction with the main orientation. It means that the main beam direction and the angle of incident beam is mirror symmetrical. At the same time, offset of horn introduces the illuminating loss in theory, and it will be involved into a complex discussion to consider the effect of off-angle to elements in different regions. As [13] studied, the aperture efficiency of an offset feed reflectarray maintains almost constant with offset angle increasing until the angle of 25° is achieved, in which the efficiency drops about 1%. Therefore, at present, the loss introduced by oblique incidence is not considered in this design. What we focused presently is the layout of feed source, the related position to reflective plane, and the accurate way to exacting phase difference. According to [13], which studied factors influencing spilling efficiency and illuminating efficiency and the relationships, the horn is set as H/D=0.75, towards to the plane in the angle of 15° , where D is the antenna diameter and H is the height of horn feed. The horn is designed with radiation pattern $q = 6.5$, to provide an illumination with -10dB taper cooperatively, which refers to the design rule of parabolic reflector. To sum up, the optimization above achieves a compromise between illuminating efficiency and spilling efficiency, having the potential to achieve a high aperture efficiency.

B. Phase Compensation Based on Incident Field

Phase difference distribution of each element is one of the directions for designers to decide parameters of each unit. It is necessary to exact phase differences in an accurate way. In most existed design, calculating the wave path differences between the feed and element positions is the common method to get the series of value, the relative value. It is enough and easily available when the design is not aimed for a high radiation efficiency. However, the master systems such as radar, satellite etc. call for planar antennas with better performance, and aperture efficiency is one of the demand. To return to the initial principles, as illustrated in part I, if we make up the reflective plane in a more accurate way, the reflected wave would be more concentrated and radiation would be more efficient. Therefore, this part aims for finding another method to calculate phase difference and then verify it in the next part.

At the phase compensation stage, a method based on in-field phase is utilized to calculate the phase distribution on the aperture surface [14]. This method could calculate the needed phase by exacting the illuminate field according to simulation or measurement of the single feed and then including the extra phase needed to meet the required beam orientation.

As Fig. 6 shown, set the reflective plane as the reference plane, and then exact income filed ϕ_i^{inc} at each element position from the horn. It can be done by simulation or measurement.

Phase differences between each element could be compensated with $-\phi_i^{inc}$, leading reference plane to a zero phase plane. And then, calculate the required phase distribution ϕ_i^{ref} on the expected beam direction as Fig. 7

shown, it can be calculated with array theory assuming that the array is illuminated by a broadside field. At this stage, it does not involve the phase center of horn antenna, wave path difference could be used.

Finally, add the above two components to get the value of phase needed to make up, as equation (1),

$$\phi_i = -\phi_i^{inc} + \phi_i^{ref} = -\phi_i^{inc} - k_0 \vec{r_i} . \vec{r_0} \tag{1}$$

Therefore, phase difference is separated into two parts, one is from the phase distribution of incident field, another is from the wave path difference from elements to radiation plane.

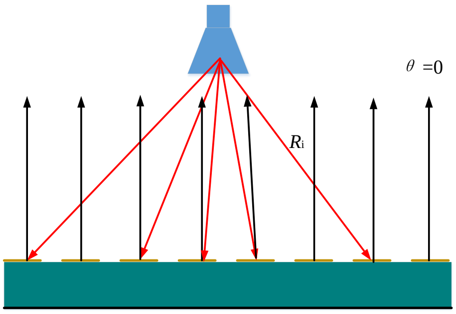


Fig. 6. Phase compensation for ϕ_i^{inc} when beam orientation θ = 0

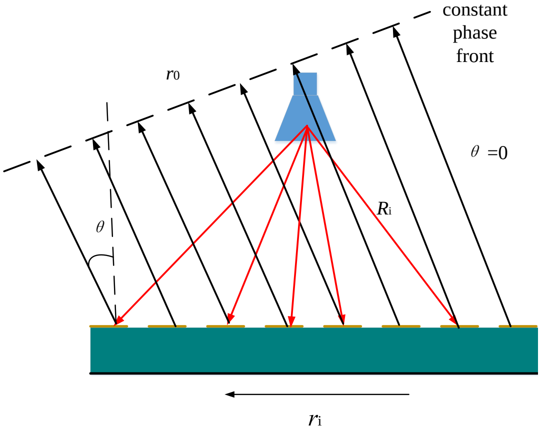


Fig. 7. Phase compensation for $\phi_i^{inc} + \phi_i^{ref}$ when beam orientation θ ≠ 0

Although, it looks similar with classical path wave difference method, it comes back to the mechanism intrinsically. The main difference between wave path difference (the method is usually used) and incident field is the first step. Since that phase delay caused by path delay is essentially presented as the difference on income field at each element, exacting phase distribution does not rely on the position of phase center. With incident field, phase can be calculated easily. And then, optimization on structural level could be done independent from phase center. It is different from calculating wave path, the later assumes that beam is radiated from one point (phase center) to the reflective plane. Therefore, calculation based on income field is more practical and accurate.

Obviously, phase calculation based on incident field is independent on the phase center of feed since the phase needed is divided into two components, and the phase difference resulted from the feed radiation is calculated straightly by extracting the incident field rather than calculating wave path difference which relies on accurate phase center. This method could be implied in more cases than ray theory usually used in current designs. Also, it could be used to calculate phase distribution in the case where an irregular aperture is designed or when the elements is incited by near field.

C. Results And Discussion

Putting the above method into a numerical code, phase compensation needed at each element position could be easily obtained. And then, matching the phase with geometric dimension according to the phase shift curve exacted by unit design. With the help of VBA auto-modeling function, the proposed reflectarray could be modeled and simulated using the full-wave integrated-domain solver of CST Microwave Studio. At this stage, full structures with feeding network, horn feed antenna and reflective plane are concluded in one project. Although it consumes more time than separated simulation, it works out the results in a more accurate way.

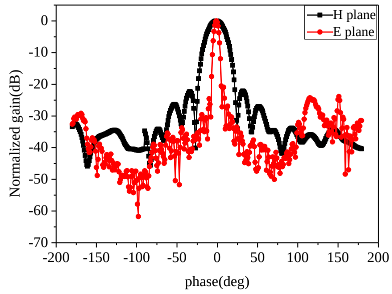


Fig. 8. Normalization radiation pattern of reflectarray with E plane and H plane components

Simulated by CST, radiation characters have been obtained. The maximum gain in far-field at central frequency 13.5GHz is 30.2 dBi without normalization, and the main beam is orienting 15 °accurately as expected.

In order to compare the performance in E plane and H plane, and study its radiation characters, we normalize the initial results into vertical direction. As Fig. 8. Shows, normalized gain in both E and H plane is obtained, it can be seen the side lobe levels are both below -22 dB, proving a well-defined radiation pattern with concentrated main beam. It owes to both element performance, layout of the whole structure, and accurately calculation on phase distribution of each element.

According to equation (2), aperture efficiency could be calculated with gain values at different frequencies. A maximum aperture efficiency of 64% is obtained.

$$G = \frac{4\pi A}{\lambda^2}\eta_\alpha \tag{2}$$

where G is the realized gain of the reflectarray and A is the area of the reflective plane.

The bandwidth is then studied in frequencies between 12 GHz and 16 GHz which includes both up and down band of Ku working band. Fig. 9 shows normalized gain and corresponding aperture efficiency. It can be seen 3-dB bandwidth is 28% and maximum aperture efficiency reaches to 64% at the central efficiency. Compared with the existed studies, the reflectarray designed achieves good performance in both bandwidth and aperture efficiency. As listed in part I, they usually concentrate on only one expect, which is not practical. Since both two characters are demanding in application.

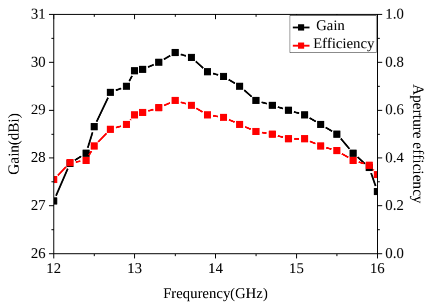


Fig. 9. Radiation gain and aperture efficiency of antenna vs. frequency at 13.5 GHz

In fact, the maximum aperture efficiency is about 74% with numerical calculation with element radiation pattern. The realized efficiency is much less than expected, the loss unexpected may be introduced by less efficient reflection at the edge of reflective plane which is hard to be avoided.

IV Conclusion

An optimized Phoenix element is used to the high efficiency reflectarray antenna design with a smooth linear phase curve and more than 360° variation range at Ku-band. To improve the gain of reflectarray antenna, offset horn, parameter optimization and a more accurate phase calculation method are synthetic in design procedure. The simulated results show that the maximum aperture efficiency is 64% and 3-dB bandwidth is more than 28%, which is better than most of published research results. However, an important work waiting to do next is to include the difference from different illuminate angles to optimize the geometrical dimension at the edge of aperture plane, which will improve the antenna gain further.

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