Design and Optimization of Broadband Single-Layer Reflectarray

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***Abstract*—A novel broadband single-layer reflectarray for satellite communications has been presented. The design and simulation results are obtained and discussed. The element in the reflectarray provides a nearly 360° linear phase range. The reflectarray is fed by a printed microstrip log-periodic dipole antenna. The broadband characteristic of the reflectarray is obtained due to the sub-wavelength of the element space. In order to increase the gain bandwidth of this reflectarray further, an optimization technique was utilized to minimize the frequency dispersion. Finally, a prime-focus 256-element reflectarray at C band is designed and simulated. The obtained 3-dB gain bandwidth reaches 30.8% (from 4.4 to 6.0GHz).**

Keywords—broadband reflectarray; log-periodic dipole antenna; single-layer; satellite communication

I. INTRODUCTION

Microstrip reflectarray antennas have been widely investigated because of their potential advantages over microstrip arrays and parabolic reflectors [1]. The radiation element in the reflectarray can scatter the incident field with a designated phase to achieve a specific shaped beam. It is well known that printed reflectarray have some advantages such as low profile, low cost, easy fabrication and possibilities integrated with electronic beam control circuits. These characteristics make the reflectarray technology a suitable choice for satellite and wireless communication systems. However, the most severe drawback of the microstrip reflectarray is its limited bandwidth performance. This shortcoming is apparent for single-layer microstrip reflectarrays especially. The bandwidth performance of a microstrip reflectarray is limited primarily by two factors. One is inherent narrow bandwidth behavior of microstrip elements themselves. Another one is differential spatial phase delay [1]. In order to extend the range of linear phase-frequency response as wide as possible, several novel element structures, including multi-resonant loop element [2], square cross and modified Malta cross [3], multi-dipole element [4], windmill-shaped element [5], disk element with attached phase-delay line [6], circular rings with open-circuited stubs [7], have been proposed in the literature. The objectives of these methods are to obtain linear phase-frequency response in a phase shift range larger than 360°, which can be used as an additional degree of freedom for a further improvement of bandwidth. However, these methods can only address the first factor of the bandwidth limitation. The second factor is more significant for large reflectarrays. One effective technique to compensate for the spatial phase delay is using sub-wavelength coupled-resonant elements [8] instead of conventional $\lambda/2$ ones. It has been shown that this method can realize a similar S-shape reflection phase response by reducing the phase error at different frequencies. Another method was introduced in [9] to overcome the bandwidth limitation of large reflectarrays by using an optimization routine to adjust the parameters of the radiation element to minimize the frequency dispersion.

In this paper, the combination of square patch and ring with thin loop boundary is adopted as the essential reflectarray element structure. The geometry of this element exhibits a cycle evolutionary characteristic [10]. The inter-element space of unit-cell is investigated using commercial software HFSS [11]. In order to increase the gain bandwidth further, the optimization method is also adopted in this paper. The advantages of this method are demonstrated in the design of a prime-focus 256-element reflectarray operating at C-band. Compared to other single layer reflectarray designs in Table 1, the gain bandwidth of reflectarray in this paper show a significant improvement across the band. Its 3-dB gain bandwidth (BW) can reach 30.8%.

TABLE I. PERFORMANCE OF DIFFERENT BROADBAND SINGLE LAYER REFLECTARRAY

Ref.	[2]	[3]	[4]	[5]	[6]	[7]	[8]
1-dB Gain BW (%)	9	19	NAN	20	NAN	NAN	17
3-dB Gain BW (%)	NAN	NAN	14.1	NAN	18	17.8	NAN

II. ANALYSIS OF REFLECTARRAY ELEMENT

The structure of individual radiation element is presented in Fig. 1. It is built from a square ring slot of length L_S and width W_S. A metallic ring is inserted into the slot, and its length and width are L_R, W_R respectively. The required phase shift reflected by the element is obtained by changing the position parameter L_R of the metallic ring. L_R changes from $L_{R\min} = L_P$

to $L_{R\max} = L_S + 2W_R$. In the following simulations, the default inter-element space L_S is 20mm, which is $\lambda_0/3$ (λ_0 is the wavelength in vacuum at the center frequency $f_0 = 5\text{GHz}$). The radiation element is fabricated on a 1.6 mm thickness dielectric substrate (FR4) of $\varepsilon_{r1} = 4.4$ and $\tan\delta_1 = 0.02$. The substrate is suspended above ground plane with a distance of $h = 18\text{mm}$. The substrate layer and the ground plane are separated by Rohacell foam ($\varepsilon_{r2} = 1.06$). The width of metallic ring is $W_R = 0.5\text{mm}$. The sidelength of the center square patch is $L_P = 6\text{mm}$.

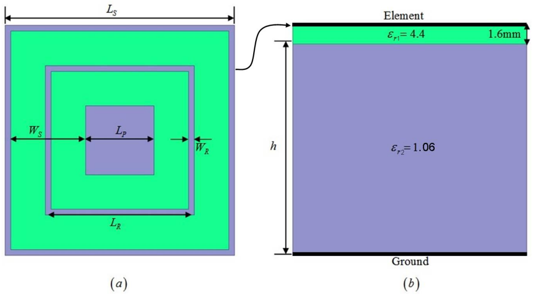


Fig. 1. (a) Geometry of the radiation element. (b)Side view of the element.

In general, the reflection phase characteristics of radiation elements are angle-dependent, which can be observed in Fig. 2. It shows phase of the reflected wave with respect to L_R for different incident angles in the range of 0°~40°. The maximum phase discrepancy with respect to normal incident is 70° at θ=40°. Hence, oblique incidence for each element is needed to take into account in the design procedure. To obtain the phase response, periodic boundary conditions are introduced to consider the mutual coupling between the identical neighbor elements in HFSS. The element is excited by the Floquet port with linear polarized electric field.

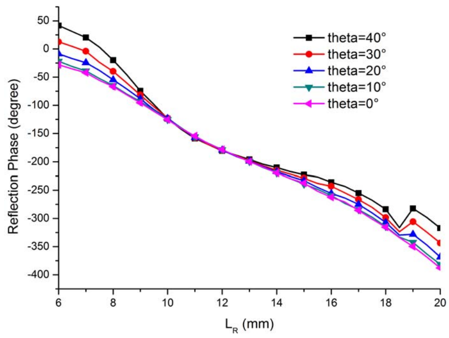
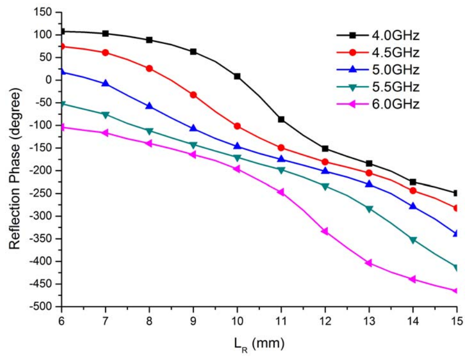
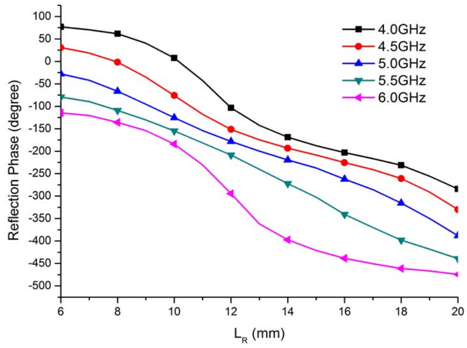


Fig. 2. Phase responses of the radiation element with respect to L_R for different incident angle.

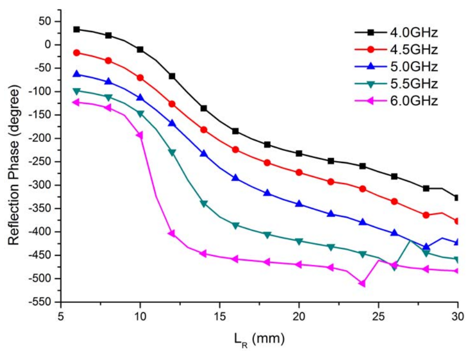
According to the reflectarray design method, the position of the metallic ring in the radiation element is calculated to produce the required reflection phase at the center frequency. However since the reflection phase of the elements is a function of frequency, as the frequency changes, phase errors are introduced in the array and results in bandwidth limitation of the reflectarray. The phase variation corresponding to the inter-element space is shown in Fig. 3. On the one hand, it can be seen that the sub-wavelength unit cells can almost achieve the same phase range as half wavelength unit cell which is typically around 360° for single layer designs. This factor will not deteriorate the bandwidth of reflectarray. On the other hand, a set of phase curves with better parallelism over a wide frequency range can be achieved by adjusting sub-wavelength element spacing. It is well known that this can result in an improved antenna bandwidth. Although there is no theoretical limit on using smaller unit cells in reflectarray designs, the fabrication tolerance of the elements becomes a critical factor. In this paper, the inter-element space is chosen as $\lambda_0/3$.



(a) $L_s = \lambda_0/4$



(b) $L_s = \lambda_0/3$



(c) $L_s = \lambda_0/2$

Fig. 3. Phase of the reflected wave with respect to L_R for different values of L_s.

III. FEED DESIGN

Conventionally, most of the reflectarrays are excited by a horn antenna. In order to minimize the aperture blockage effect in the center-feed reflectarray, a broadband printed log-periodic dipole arrays (PLPDA) is designed as the feed. In this paper, a printed LPDA is designed and shows better performances. Actually, in the range of 3GHz ~ 9 GHz, its gain is remarkably constant versus frequency. The array structure is based on a pair of parallel balanced printed transmission lines on the two sides of a thick 0.8mm dielectric slab (FR4). The array dipoles are connected to the two printed lines in an alternate way. A coaxial infinite balun is used to feed the parallel lines and enlarge the impedance bandwidth. The outer conductor of the coaxial cable is soldered to one of the parallel line, and the inner pin is bent and welded to the opposite parallel line. The characteristic impedance of the balanced feeding line is selected as 50Ω. In order to improve the impedance matching in the whole operating bandwidth, the feed line is terminated with a 187Ω resistor load. All the details are shown in Fig. 4.

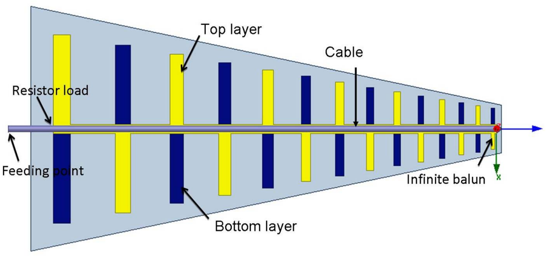


Fig. 4. Printed LPDA layout.

The simulated results of return loss and gain of the PLPDA are revealed in Fig. 5. It is demonstrated that the overlap between impedance bandwidth ($S_{11} \le -10\text{dB}$) and 1-dB gain bandwidth is 3.1GHz~8.6GHz. The relative bandwidth of the proposed antenna is more than 94%. The simulated radiation patterns also show that the 10-dB beam width in E- and H-planes are almost the same around 60°. This kind of antenna is suitable for use as the feed of reflectarray. The beam-width of 10-dB gain-drop can used to determine the ratio of focus to diameter.

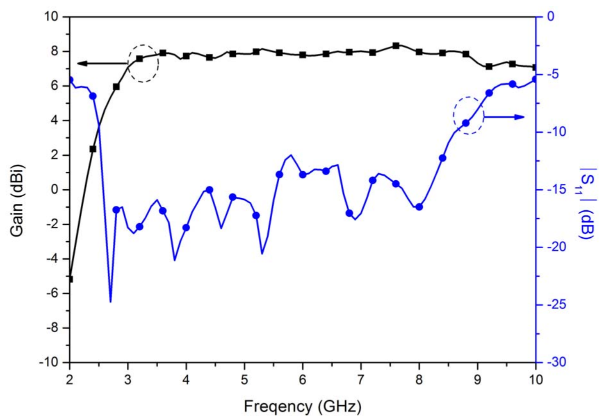


Fig. 5. Simulated S11 and gain.

IV. FULL ARRAY DESIGN AND OPTIMIZATION

In order to produce a beam in the given direction (θ_b, φ_b), the phase shift required at each element is expressed as:

$$\phi_{Ref}^{\text{required}}(x_i, y_i, f) = \phi_{Inc}(x_i, y_i, f) - k_0(f)\sin\theta_b(\cos\varphi_b x_i + \sin\phi_b y_i) \quad (1)$$

where $k_0(f)$ is the propagation constant in vacuum at frequency f, and (x_i, y_i) is the coordinate of element i, $\phi_{Inc}(x_i, y_i, f)$ is the phase of incident field on element i at frequency f, $\phi_{Ref}^{\text{required}}(x_i, y_i, f)$ is the phase of the coefficient for element i at frequency f. Generally, the phase of incident field is calculated as:

$$\phi_{Inc}(x_i, y_i, f) = -k_0(f)d_i \quad (2)$$

where d_i is the distance between the phase center of the feed and the cell i. For the horn feed, the phase center is in the vicinity of radiation aperture. But for the PLPDA feed, it is difficult to determine the phase center accurately. In order to avoid this problem, the phase of incident field on the element's surface can be calculated directly using HFSS.

In order to minimize the frequency dispersion, the following error function can be defined firstly [9]:

$$e(x_i, y_i) = \sum_{m=l,c,u} \left| \phi_{Ref}^{\text{required}}(x_i, y_i, f_m) - \phi_{Ref}^{\text{achieved}}(x_i, y_i, f_m) \right| \quad (3)$$

where $\phi_{Ref}^{\text{required}}(x_i, y_i, f)$ and $\phi_{Ref}^{\text{achieved}}(x_i, y_i, f_m)$ are the required and achievable phase delay, respectively, for the ith element at the frequencies f_c, f_l and f_u. f_c, f_l and f_u are center, lower and upper band edge frequencies, respectively. In practice, the error function introduced in (3) is calculated for all elements within the cell parameters search space. The element with the lowest error function is selected as the optimum element from the point of view of bandwidth performance.

Based on the above considerations, a C-band center-fed pencil beam microstrip reflectarray is designed for center operating at 5GHz. The lower and upper band edge frequencies are 4GHz and 6.5GHz respectively. As shown in Fig. 6, the prime-focus reflectarray antennas have a rectangle aperture. The dimension of this array is 32cm×32cm and the total number of radiating elements is 256 (16×16). The distance between the feed (LPDA) and the reflectarray aperture surface is 160mm (the ratio of focus F to diameter D is $F/D = 0.5$). The reflectarray is analyzed by using HFSS. Fig. 7 shows the phase of incident field on the designed reflectarray with PLPDA feed by changing the material of the whole reflectarray to vacuum.

The simulated radiation patterns at 5GHz are shown in Fig. 8, where the gain is 21.5dBi and the side lobe level is below -18.1dB and -20.2dB in E- and H-plane, respectively.

The simulated gain from 4GHz to 6.5GHz for reflectarray is shown in Fig. 9. It is indicated that the maximum gain is 22dBi at 5.2GHz. The 3-dB gain bandwidth of the reflectarray antenna is about 30.8%.

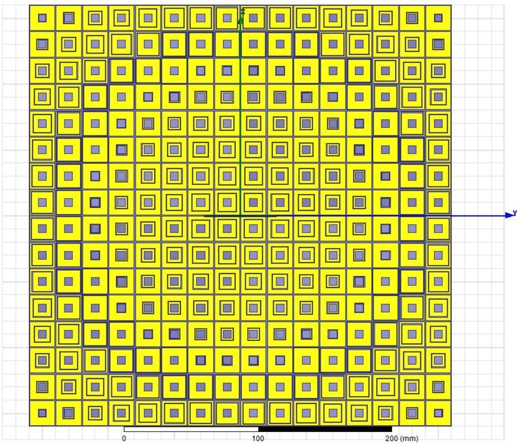


Fig. 6. Geometry of PLPDA feed reflectarray.

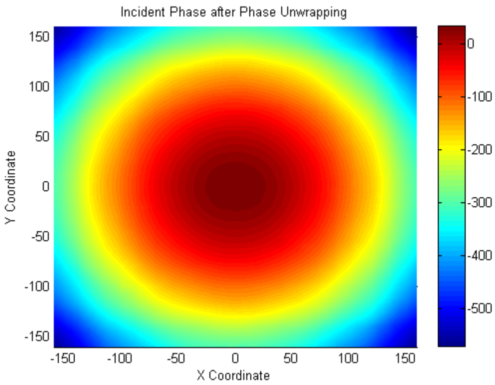


Fig. 7. Phase of incident field in degree.

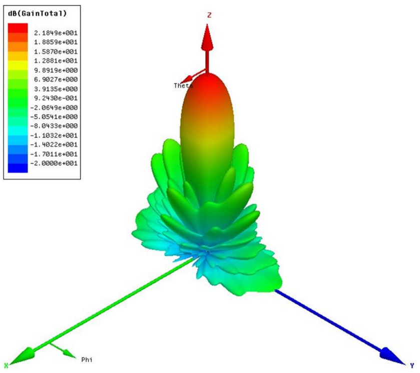


Fig. 8. Simulated radiation pattern at 5GHz.

V. Conclusions

A single-layer microstrip reflectarray has been designed and analyzed in this paper. This reflectarray was designed for broadband satellite communications at C-band. In order to reduce the blockage effects and increase aperture efficiency, a printed broad-band log-periodic dipole arrays is adopted as the feed. By using sub-wavelength radiation element and optimized method, the frequency dispersion on the level of gain is minimized. The performance of a prime-focus 256-element reflectarray was verified using HFSS. The simulated results have a significant improvement in bandwidth of the reflectarray. The 3-dB gain bandwidth of 30.8% was achieved.

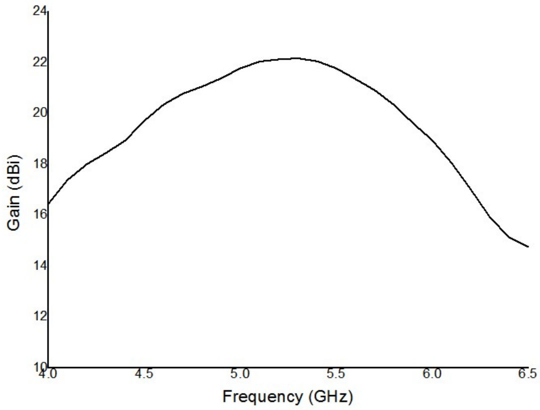


Fig. 9. Simulated gain against frequency.

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