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Design of Single-Feed Multi-Beam Reflectarray Using Iterative Fourier Techniques

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Abstract

Reflectarray antenna with multiple simultaneous beams is a promising antenna candidate for the multiple beam applications. A comprehensive and systematic study on the design of single-feed multi-beam reflectarray antenna is presented in this paper. The traditional direct design method, called aperture field superposition method, is investigated first. It is demonstrated that although this method can generate a multi-beam pattern, it cannot provide satisfactory performances, mainly because of high side lobe level, gain loss and beam deviation. The iterative Fourier technique is then applied to optimize the performances of the multi-beam reflectarray antenna. The required mask and cost function for multi-beam design and the flow of the iterative Fourier techniques are represented. Finally, a Ku-band four beam reflectarray with a single feed is designed using the iterative Fourier techniques and the radiation performances are analyzed and compared with that of single beam, as reference case, and multiple beam designed by aperture field superposition. The numerical results show that a good four beam performance can be obtained by using the iterative Fourier techniques, which suggests that the iterative Fourier technique is suitable for the design of the multi-beam reflectarray antenna with a single-feed.

Keywords: *reflectarray antenna, multiple beams, aperture field superposition, iterative Fourier technique*

1. Introduction

As combining the favorable features of the reflectors and phased arrays [1-2], the reflectarray antennas have been received notable attentions over years and have been used in various applications, such as satellite communications, radars systems, and commercial usages [3-4]. Since the phase of each reflectarray element can be individually controlled, the reflectarray antennas can achieve shaped beam performances without the complex processing technology and high manufacturing cost [5]. Similarly, the reflectarray antennas can also realize multiple beams performances by adapting the phase of each element appropriately [1, 6].

High gain multi-beam antennas have numerous applications in electronic countermeasures, satellite communications, and multiple-target radar systems [7]. These multi-beam antennas are typically based on reflectors with feed-horn clusters [8] or large phased arrays [9]. For reflector antennas on communication satellite, the multiple beams with tailored earth coverage patterns can be generated by using horn clusters with feeding network. For phased arrays on multiple-target radar systems, multiple simultaneous beams can be generated by connecting the array to a beam forming network with multiple ports. Considering the complex processing technology of these antennas, the manufacturing cost of these multiple beam designs are relatively high. However, low-cost

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feature of reflectarray antenna makes it a suitable antenna candidate for the multiple beam applications with the cost reduction.

Multiple beams can be generated by the reflectarray antennas with single or multiple feeds. A two-beam reflectarray design using a single feed was shown in [6], while [10] present a four simultaneous beam reflectarray with a single feed. Multi-feed multi-beam reflectarray antennas with shaped patterns were studied in [11]. In addition, multi-feed single-beam reflectarray antennas were investigated in [12]. In this paper, a systematic investigation of the multi-beam reflectarray antenna with a single-feed is presented through a case study of a four beam design. A comprehensive design performance comparison between the traditional direct design method, called aperture field superposition (AFS) method, and an optimization method, called iterative Fourier techniques (IFT) method. The theory basic of both methods are discussed. Besides, the required mask and cost function for multi-beam design using IFT method are represented. From the design performance comparison, it suggests that the iterative Fourier technique is suitable for the design of the single-feed multi-beam reflectarray antenna with desired performance.

2. Aperture Field Superposition Method for Multiple Beam Reflectarray Antennas

2.1. Theory basics of the Aperture Field Superposition Method

Multiple beam performance of reflectarray antenna with a single feed can be obtained by using the superposition of aperture field associated with each beam on the reflectarray surface [1]. To generate *N* beams with a single feed, the aperture field on the reflectarray surface can be expressed as follows:

$$E_a(x_e, y_e) = \sum_{n=1}^{N} A_n(x_e, y_e)\exp(j\phi_n(x_e, y_e)) \tag{1}$$

In this equation, (x_e, y_e) are the position of each element on the reflectarray surface, and $A_n(x_e, y_e)$ and $\phi_n(x_e, y_e)$ are the required amplitude and phase of each element which will generate the n^{th} beam in the direction (θ_n, φ_n). As it is known that in a reflectarray the amplitude of each element is fixed by the position of feed and element, which are independent of the beam direction, therefore

$$E_a(x_e, y_e) = A(x_e, y_e)\sum_{n=1}^{N} \exp(j\phi_n(x_e, y_e)) \tag{2}$$

Where, the required element phase of each beam can be calculated as follow:

$$\phi_n(x_e, y_e) = -k_0 \sin\theta_n (x_e \cos\varphi_n + y_e \sin\varphi_n) \tag{3}$$

With the superposition of the aperture field in (2), the total required amplitude and phase distribution on the reflectarray surface can be obtained. The phase distribution corresponding to the multi-beam performances can then be realized by a mount of phased elements studied for reflectarray antenna design. It should be noted that although this method can generate multi-beam performance, there are a number of problems associated with this method. A basic problem exists here which is due to the fixed amplitude distribution imposed by the feed. Even though the required phase in equation (2) can be met by proper element designs, the amplitude requirement cannot be met for reflectarray, because of that in equation (2)

$$\left|\sum_{n=1}^{N} \exp(j\phi_n(x_e, y_e))\right| \neq 1 \tag{4}$$

As a result of this deviation of the amplitude distribution on the aperture field, reflectarray designed using this aperture field superposition (AFS) method may show a degenerated performance.

2.2 Results Analysis of the Aperture Field Superposition Method

To demonstrate the multi-beam design ability of the AFS method, a four-beam reflectarray antenna operating at 12.5 GHz, which has a circular aperture with a diameter of 15λ at the design frequency, is studied. The designed four beam is in the direction of ($\theta_{1,2,3,4}$ = 30°, φ_1 = 0°, φ_2 = 90°, φ_1 = 180°, φ_1 = 270°,) with symmetry property. The element space is 0.5λ and ideal elements are used here. A prime focus feed molded as (cos θ)$^{6.5}$ at the design frequency is used in this design and positioned with F/D ratio of 0.75 which generates an edge taper of -12 dB. The radiation patterns of the reflectarray are calculated using the aperture field method as described in [13], as follows:

$$E(u,v) = S\sum_{m=1}^{Ny}\sum_{n=1}^{Nx} E_a(nd_x, md_y)\exp[jk_0(nd_x u + md_y v)] \tag{5}$$

Where $S = 4\sin(0.5k_0ud_x)\sin(0.5k_0vd_y)/k_0^2uv$, $u = \sin\theta\cos\varphi$, $v=\sin\theta\sin\varphi$. d_x and d_y are the element spacing along x and y axis, respectively.

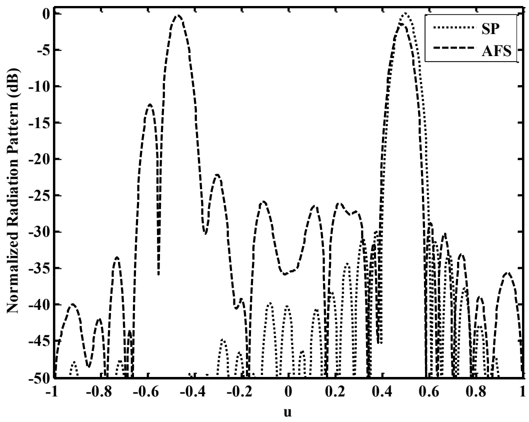


Figure 1. Normalized Radiation Patterns of the Single- and Four-beam Design

To compare the design performance of the AFS method, a single-beam (SB) reflectarray pointing in the direction of (θ = 30°, φ = 0°) is designed as a reference case. In Figure 1, the normalized radiation pattern of this single beam case is compared with the four beam case designed by AFS method. As the reference beam is in the v = 0 plane only this plane is given here, and a similar pattern was observed in the u = 0 plane. From Figure 1, it can be seen that AFS method can realize a four beam reflectarray with a single feed, however, the radiation pattern shows small beam deviation and gain loss compared with the reference beam. The radiation pattern of the reflectarray designed by AFS shows that the peak side-lobe level is -12.46 dB which is much higher than that of the reference reflectarray (-29.76 dB), which is mainly because of the amplitude deviation in equation (2). As it is known, the antenna directivity is an important parameter to evaluate the radiation performance. For a multi-beam reflectarray with a single feed, the power of each beam will theoretically be reduced by 1/N. In other words, it is ideally expected that a four beam will reduce the antenna directivity by 6 dB. However, the calculated numerical results show that the directivity for the reference case and four beam case designed by AFS are 26.69 dB and 19.35 dB, which exhibits a directivity reduction of 7.34 dB showing about 1.34 dB higher than the ideal directivity reduction. The higher directivity reduction is mainly due to the high side-lobe levels of the four beam case designed by AFS.

Finally, the shortcomings of the AFS method can be summarized as follows:

1) High side-lobe levels and small beam deviation because of amplitude error.

2) Directivity reduction because of high side-lobe level.

As a result of those shortcomings associated with the AFS method of multi-beam reflectarray design, it is necessary to achieve desirable performance through optimization routine.

3. Iterative Fourier Techniques Method for Multiple Beam Reflectarray Antennas

3.1 Theory Basics of the Iterative Fourier Techniques Method

Another method in multi-beam reflectarray design is as a general array synthesis problem. However, the synthesis of the reflectarray radiation pattern is restricted by the fact that the amplitude of element excitation is fixed by the feed property and distance between feed and element location. As a result, the synthesis of the reflectarray radiation pattern becomes a phase-only synthesis process. The iterative Fourier techniques (IFT) have been applied low side-lobe pattern of phase only synthesis [14]. This method uses the property that for an array with a uniform element spacing in the order of half-wavelength, an inverse Fourier transform relationship exists between the array factor and the element excitations. Because of this relationship, a direct Fourier transform performed on the array factor will yield the element excitations. The underlying method relies on the repeated use of both types of Fourier transforms. The flows of the iterative Fourier technique algorithm for the synthesis of four beam radiation patterns for a reflectarray with a single feed proceed as follows:

Step 1 Start the synthesis using a random initialization with range [$-\pi$, π] or a suitable starting point according to experience for $Ny \times Nx$ required phase of element.

Step 2 Calculate far field pattern $E(u,v)$ from aperture field $E_a(x, y)$ using a $Nfft \times Nfft$ point 2-D inverse FFT with $Nfft > \max(Nx, Ny)$ by applying zero padding, then calculate the cost function according to the obtained far field pattern $E(u,v)$.

Step 3 Adapt the amplitude of far field pattern $E(u,v)$ to the required mask M.

Step 4 Calculate aperture field $E_a(x, y)$ for the adapted far field pattern $E(u,v)$ using a $Nfft \times Nfft$ point 2-D FFT.

Step 5 Truncate aperture field $E_a(x, y)$ from $Nfft \times Nfft$ samples to $Ny \times Nx$ coupled to the rows and columns of the aperture.

Step 6 Make the amplitude of the truncated aperture field $E_a(x, y)$ equal to the amplitude fixed by the position of feed and element.

Step 7 Repeat steps 2 thru 6 until the solution is consider to be converged or the maximum number of iterations is reached

The key characteristic of this iterative synthesis method is very simple and highly robust, so that, it is very easy to implement in software. Comparing with other methods, the main advantage is high computational speed for convergence of the solution because of the core calculation based on direct and inverse fast Fourier transforms, which makes it suitable for reflectarray antenna.

3.2 Setup of the Iterative Fourier Techniques Method

In general, the pattern requirements for the design are defined by a required mask, such as two sets of bound values, between which the radiation pattern must lie. The general form of the radiation patterns that satisfy the required mask is set $M \equiv \{ E(u,v): M_L(u,v) \ll |E(u,v)| \ll M_U(u,v) \}$, where $|E(u,v)|$ is the amplitude of the radiation pattern. $M_L(u,v)$ and $M_U(u,v)$ are the upper and lower bound values of the required pattern in the total angular range. Before the IFT to be implemented, a required mask for multi-beam radiation patterns and a cost function for controlling the number of iterations must be defined. As it is known, the required masks for multi-beam radiation patterns are general circular contour defined in the direction of each beam. Since in multi-beam design the beam width, which is related to the antenna aperture size and aperture illumination, is not expected to change, the upper and lower mask bounds in beam area can be defined according to the reference single-beam design, as following:

$$\begin{array}{lll} \text{If } (u,v) \in \text{ main beam:} & & M_U(u,v) = 0 \text{ dB} \\ \text{If } (u,v) \in \text{ -3 dB beam width:} & & M_L(u,v) = \text{-3 dB} \end{array} \quad (6)$$

As it is known, the main objective of this multi-beam design is to minimize the peak side lobe level without beam width change. While it is possible to control the side lobe level by defining an M_U in side lobe area at certain value, in order to further minimize the side lobe level, both and in side lobe area are set to -200 dB. A 2D figure of the required mask model in v = 0 plane for four beam reflectarray is plotted in Figure 2, and a similar mask model is set in the u = 0 plane. It should be emphasized that in our simulation it was found that setting the level of the required mask in main beam area to zero or to a realizable value showed almost similar results.

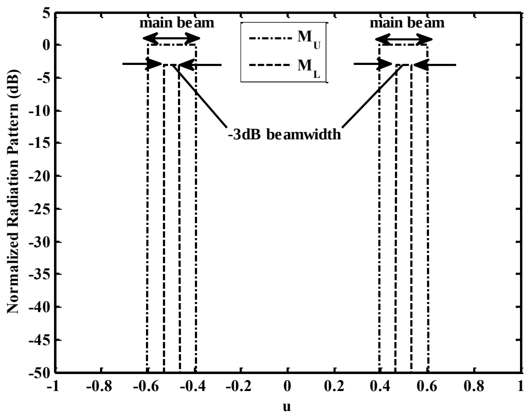


Figure 2. The Required Mask in *v* = 0 Plane

In the iteration process, it is necessary to define a cost function that can control the iteration number to the convergence solution. As in the iteration process the requirements in the main beam area will be satisfied according to Step 3, the cost function need only to consider the side lobe performance of the patterns. Thus, the cost function is evaluated over every point in the side lobe area of the (u,v) space using the following equation:

If $|F(u,v)| > M_U(u,v)$

$$\text{Cost} = \sum_{u^2+v^2 \le 1} (|F(u,v)| - M_U(u,v))^2 \quad (7)$$

After the required mask and cost function are defined, the optimized phase distribution of the reflectarray elements will be obtained by the iterative procedure. It should be noted that the iterative procedure is considered to be converged when the value of the cost function becomes stable. In general, for a random initialization with range [-π, π], the iterative procedure converges within only a few iterations; however, a suitable starting point can reduce the number of iterations. Thus, the phase distribution obtained by the AFS method is used as the starting point for the iterative procedure. The IFT method is then implemented to improve the performance of the patterns.

4. Numerical Results

In this four beam reflectarray design case, the both types FFT of 512×512 points evenly spaced in the angular coordinates are used to compute radiation patterns and element excitation. The 2D and 3D radiation patterns of the optimized four beam reflectarray are shows in Figure 3 and Figure 4, respectively. The optimized element phase distribution compared with the phase distribution obtained by the AFS method is plotted in the Figure 5. In Figure 3 and 4, a four beam performance is obviously obtained with the peak side lobe level of -28.72 dB, which is 16.26 dB lower than that of the AFS designed case and only 1.04 dB higher than that of the reference case, and the directivity of 21.61 dB, which is 2.26 dB higher than that of the AFS designed case and 5.08 dB lower than that of the reference case. From those results, it can be observed that the optimization implemented by the IFT method has corrected the amplitude error associated with the AFS method, which clearly demonstrates the effectiveness of the phase optimization process.

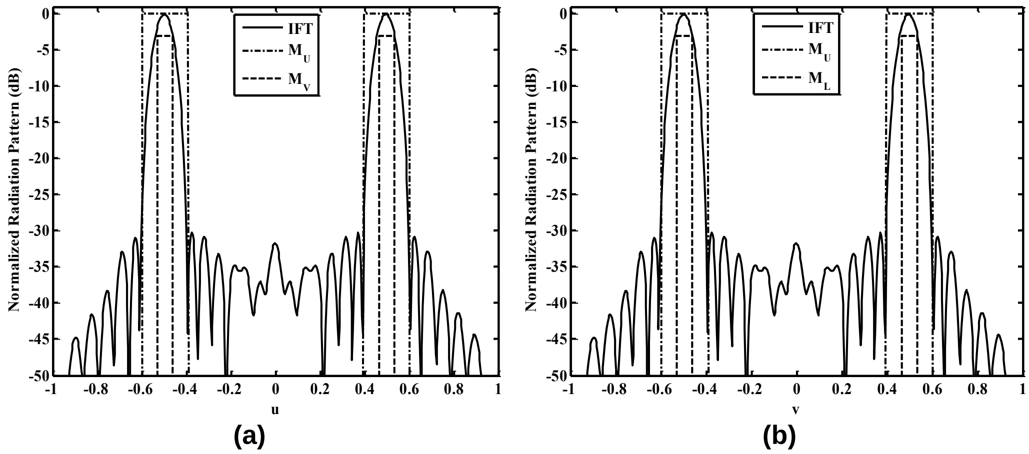


Figure 3. Calculated 2D Radiation Patterns of the Four Beam Reflectarray at 12.5 GHz: (a) v = 0 Plane, (b) u = 0 Plane

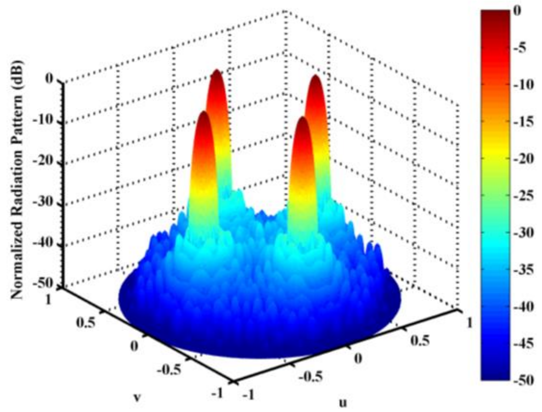
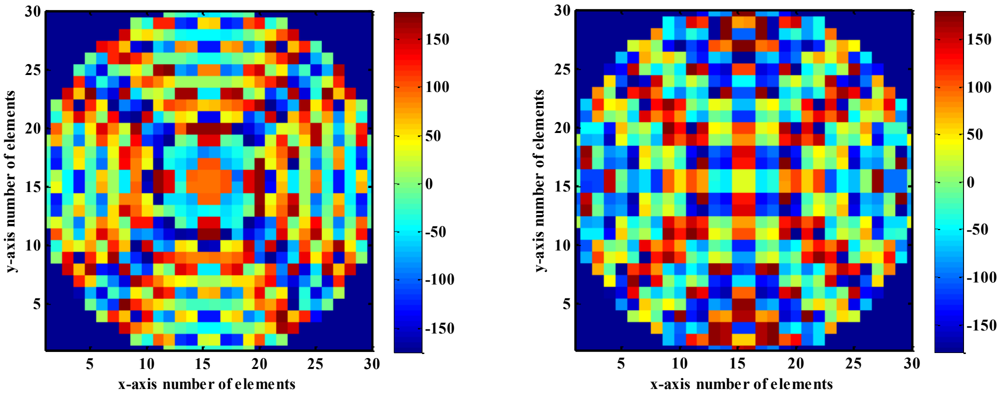


Figure 4. Calculated 3D Radiation Patterns of the Four Beam Reflectarray at 12.5 GHz

For this four beam design, the convergence curve for the iteration process is given in Figure 6, where it can be seen that the solution converges after 15 iterations. Although the convergence number of the iteration process generally depends on the problem at hand, in most cases the IFT method will converges within just a few iteration. It is important to point out that although IFT method is local search algorithm, in some cases the IFT method might converge to local minima, nevertheless, for the symmetric four beam design this method can get out traps and finally converge. Similar radiation pattern results can be obtained when a random initialization with range [-π, π] is used for starting point, which demonstrates that for the symmetric four beam design this method can get out traps and finally converge. However, for the asymmetric multi-beam cases, the local minima problem will more challenging, and an appropriate starting point should be chosen to circumvent the local minima problem or a more powerful global search algorithm, such as Invasive Weed Optimization (IWO), should be applied.



(a) (b)

Figure 5. Obtained Phase Distribution of the Reflectarray Element: (a) Obtained by IFT, (b) Obtained by AFS

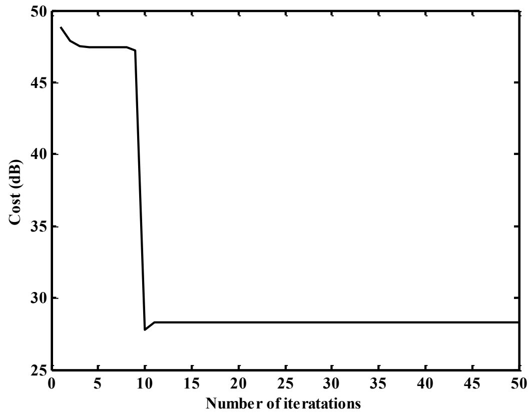


Figure 6. Convergence Curse for the Iteration Process

5. Conclusions

A systematic investigation of the multi-beam reflectarray antenna with a single-feed is presented in this paper through a case study of a four beam design. The traditional direct design method for multi-beam reflectarray with a single-feed named aperture field superposition method is studied first, and the design performances are compared with a reference single beam reflectarray. The deteriorated performances suggest that an optimization procedure on element phase distribution should be implemented to achieve a satisfied performance. The iterative Fourier techniques method is then applied to optimize the performance of the multi-beam reflectarray antenna. The required mask of multi-beam and the flow of the iterative Fourier techniques are represented. Based on that, a four beam reflectarray antenna is designed through this method, and the four beam performance is investigated and compared with that of the reference single beam reflectarray and that of the four beam reflectarray. The numerical results show that the iterative Fourier technique is suitable for the design of the multi-beam reflectarray antenna with a single-feed.

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