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Novel Phase Distributions for Large Beam-Scanning Reflectarrays

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Abstract—In this paper, the hybrid combination of genetic algorithm and particle swarm optimization (GAPSO) is used to optimize the phase distribution (PD) of beam-scanning reflectarray. The GAPSO takes advantage of both conventional algorithms and it could cover their weaknesses. Two novel PDs are proposed in this paper. Constant phase elements (CPEs) and ordinary elements (OEs) are two basic kinds of elements used in these two novel PDs. The phases of CPEs are fixed and it is not changed during beam scanning and only OEs' phase could be adjusted to scan the main beam. GAPSO and two novel PDs are applied to array factor PD of a 30*30 reflectarray antenna to displace the main beam electronically in the vertical plane from -40° to 40° . In these two novel PDs, 28.8% of total elements are selected as CPEs. In the first one with only CPEs, the phase of OEs (71.2% of total elements) could adjust, but in the second novel PD with CPEs and phase symmetry plane 35.5% of the total elements' phase could be changed to scan the beam. Optimization results show that the novel PD and hybrid algorithm have appropriate performance in the electronically beam scanning of reflectarrays.

Keywords: Beam scanning reflectarray Antenna, GAPSO, Constant Phase Element, Ordinary Element.

1. Introduction

Microstrip reflectarrays are a combination of reflectors and phased arrays. Because of their advantages over parabolic reflectors and phased arrays, they have attracted many researchers' attention in recent years ¹⁻⁴. Microstrip reflectarrays consist of a printed array that acts as a reflector and a space feed pointed at the focal point ⁵. The Beam-scanning capability of reflectarrays is the most important feature in wireless systems like satellites and radars ⁶. Feed tuning and aperture phase tuning are the two major methods that have been utilized for beam-steering in reflectarrays. To get the beam in the desired direction using the feed tuning method, the phase center of the feed antenna must be displaced and there is no need to change reflector surface features. On the other hand, in the aperture phase tuning method, the phase of each radiating element must be adjusted to achieve the desired beam direction ⁷. To scan the main beam electronically, there are two different ways of adjusting the phase of elements or phase distribution on reflectarray: 1. computing element phase analytically, 2. Optimizing phase distribution on reflectarray ⁸.

The iterative projection method for computing the phase distribution on reflectarray has been proposed in ⁹, where a varactor diode has been used to apply phase changes in the elements. While in ¹⁰, the nematic liquid crystals and analytically phase distribution have been taken into account to steer the beam. Authors in ¹¹ took advantage of RF MEMS to apply phase changes in the elements. The beam-scanning performances of 1-bit pin diode loaded elements are discussed in ¹². A multi-beam pattern is obtained in ¹³, where the PSO algorithm is employed for optimizing the phase distribution. The quad beam was obtained by using the alternating projection method for phase optimization in ¹⁴. In ¹⁵, the phase-only optimization technique (POT) is applied to design the reflectarray with the contoured beam. In the above-mentioned research works, all of the elements' phases are optimized or changed to synthesize the beam. Thus, on electronically reconfigurable reflectarrays, each element needs at least one phase-shifter. For large reflectarrays, this number of phase-shifters and biasing devices for active phase shifters will be very expensive and hard to implement.

In this paper, two novel phase distributions have been proposed to overcome the mentioned drawbacks. To achieve beam-scanning capability in these types of phase distributions, there is no need to optimize the phase of all elements and it will be enough to optimize a few of them. These structures consist of two kinds of basic elements: 1. Ordinary Element (OE). 2. Constant-Phase Element (CPE). A CPE is an element with a constant phase for all scanning values of the beam while OE is an element that its phase adjusts and changes. The hybrid GAPSO algorithm which is a combination of conventional genetic algorithm (GA) and particle swarm optimization (PSO) has been used for adjusting the phase of OEs in this paper.

This paper is organized as follows: The types and procedures of the GAPSO algorithm are described in detail in section 2. In section 3, the optimizing setup is described. The reflectarray setup is explained in section 4 and the concept of phase distributions for reflectarray is introduced and optimization results are demonstrated and illustrated in section 5. Finally, some important conclusions are summarized in section 6.

2. GAPSO Algorithm Procedure

GAPSO is a combination of GA and PSO algorithms. Various and different combinations of these two optimization methods have been presented in the form of a hybrid GAPSO algorithm so far. In the type of GAPSO algorithms, first, GA is utilized to optimize the problem. Afterward, at the end of the GA process, the obtained results from GA are entered as the initial values to the PSO algorithm and the optimization process is continued by it¹⁶. Another type of combination method is presented in¹⁷. According to this method, the crossover and mutation functions of the GA are used in the PSO algorithm to escape the local optimal points. One of the other GAPSO hybrid algorithms uses GA and PSO in parallel. In this method, half the initial generated population is optimized by GA, and the other half is optimized using the PSO algorithm in parallel^{18,19}. In¹⁶⁻¹⁹, it is shown that the hybrid GAPSO algorithm is more efficient, reliable, and faster than the conventional GA and PSO algorithms. Hence, in this paper, hybrid GAPSO is applied to optimize the phase distribution on reflectarray for beam-scanning capability. The type of GAPSO that is used in this research work is the parallel GA and PSO. In this method, half of the initial generated population with better fitness values is optimized by GA to avoid local optimal points and to search a wider area. The other half with worse fitness values is optimized by PSO due to the better convergence speed of this algorithm. The flowchart of a GAPSO algorithm is shown in Fig.1.

3. Optimizing Setup

The magnitude of elements in reflectarray antennas is depending on the features of the feed and is usually fixed. So, the only parameter that can be controlled to achieve the beam-scanning performance is the elements' reflection phase. As discussed in section 1, optimizing and calculating analytically, are the two approaches for adjusting the phase distribution on reflectarray. The GAPSO explained in section 2 is used in this paper to optimize the reflectarray array factor phase distribution. Array factor of M*N array is calculated using (1)²⁰.

$$AF(\theta, \varphi) = \sum_{m=1}^M \sum_{n=1}^N I_{m,n} e^{i(k_0(x'_{m,n} \sin(\theta) \cos(\varphi) + y'_{m,n} \sin(\theta) \sin(\varphi)) + \varphi_{m,n})} \quad (1)$$

Where the k_0 is the free space wavenumber and $I_{m,n}$, $x'_{m,n}$ and $y'_{m,n}$ are amplitude, x coordinate, and y coordinate of m,n th element respectively. $\varphi_{m,n}$ is the phase of m,n th element of (M row* N column) reflectarray and the only parameter that can be changed or adjusted to scan the beam in reflectarrays. The u-v mapping is needed to implement the angular transformation in array factor formulation, where $(u = \sin(\theta) \cos(\varphi), v = \sin(\theta) \sin(\varphi))$. After applying this transformation, the array factor formula is changed to below:

$$AF(u, v) = \sum_{m=1}^M \sum_{n=1}^N I_{m,n} e^{i(k_0(x'_{m,n} u + y'_{m,n} v) + \varphi_{m,n})} \quad (2)$$

Fig. 1. GAPSO Algorithm Structure

3.1 Fitness Function and Evaluating

The fitness function in each optimization algorithm is one of the most important functions required for the optimization process because this function evaluates the value of the proximity of the optimal response to the desired response. The fitness function that is used to optimize the array factor of reflectarray is:

$$Fitness(u, v) = (UM^2 - |AF|^2) * (LM^2 - |AF|^2) + |UM^2 - |AF|^2| * |LM^2 - |AF|^2| \quad (3)$$

Where UM and LM are the upper mask and lower mask on the u - v plane respectively. The upper mask is defined to adjust the sidelobe level (SLL) and beam-width, and the lower mask is set to adjust the half-power beam-width (HPBW). Also, both of them adjust the direction of the main beam. These masks are used in both horizontal and vertical planes. In (3) all parameters are normalized and if at a specific point, the array factor (AF) is placed between the upper and lower masks, the value of the fitness function is zero (zero error). Otherwise, the value of the fitness function will be greater than zero and a positive amount. Fig.2 shows the upper mask and lower mask amplitude over u or v .

3.2 Algorithm Function and Parameters Setup

The functions used in GAPSO are given in table 1.

Fig. 2 Upper and Lower Masks

The parameters of GAPSO are the sum of the GA and PSO parameters. The values of GAPSO parameters are expressed in table 2.

Table 1 Functions types for GAPSO

Functions	Type
Selection	Roulette wheel
Cross-over	Uniform
Selection for mutation	Random
Mutation	Random

Table 2 Values of GAPSO parameters

Parameters	Value
Number of total populations	200
Number of PSO population	100
Number of GA population	100
Range of variables changes	$[-2\pi, 2\pi]$
Range of variables speed change	$[-0.1\pi, 0.1\pi]$
W	From 1 to 0.4 linear decreasing
C1	2
C2	2
Percent of Cross-Over	80
Percent of Mutation	20

4. Reflectarray Setup

Reflectarray that used in this paper, contains a 30×30 ($M=30$, $N=30$) rectangular printed array and an axial symmetric feed with $\cos^{15}(\theta)$ radiation pattern model. Element spacing in the printed array is uniform and equals $\lambda_0/2$ at $f_0 = 10 \text{ GHz}$. The feed is pointed at the center of the printed array and perpendicular to it. The distance between the center of the printed array and the phase center of the feed is $21.5\lambda_0$. By using (4) and Fig.3, amplitude distribution on reflectarray is shown in Fig. 4.

$$|E_{Fn}| = \left(\frac{A_0}{d_{m,n}} \right) \cos^q(\theta_F) \quad (4)$$

In the above equation, $|E_{Fn}|$ is the amplitude of the electrical field that radiated from a source to the elements and $q = 15$. $d_{m,n}$ is the distance between the phase center of the feed and the center of each element and A_0 is the constant value. To compensate for the distance difference between the center of each element and phase center of the feed and to achieve beam in bore-sight of reflectarray without optimizing, each elements' phase is calculated by using:

$$\varphi_{m,n} = -k_0 d_{m,n} \quad (5)$$

Fig. 3 Feed and Elements Position in Reflectarray

Fig. 5 shows the bore-sight non-optimized normalized AF and as shown in this figure, SLL for the non-optimized array factor of the reflectarray is -20dB in the bore-sight beam direction.

5. Novel Phase Distributions and Optimization Results

5.1 Ordinary Phase Distribution

In the ordinary phase distribution that is used for all electronically beam-scanning reflectarrays before, the phase of all elements needs to be changed to displace the main beam at different angles. So, all the array elements need phase shifters except in arrays with an odd number of rows or columns. In large arrays (arrays with a large number of elements) the phase shifters cost and the complexities of implementation are the major disadvantages of this phase distribution. To overcome the mentioned drawbacks, two novel phase distributions are proposed in the following.

Fig. 4 Normalized amplitude distribution on reflectarray [dB] **Fig. 5** Bore-sight non-Optimized normalized AF

Fig. 6 Array structure with an odd number of rows or columns

5.2 Phase Distribution with Constant Phase Elements

Considering the array in Fig. 6 with an odd number of elements in the row (M) or column (N) and according to array theory, to scan the main beam in one of the principal planes (azimuth or vertical) there is no need to change the phase of elements in the middle row or column. So, these elements are constant phase elements in beam-scanning arrays. But in the reflectarrays with an even number of rows or columns, according to (6), there is no element that phase remains constant in the analytical phase synthesis method during the beam-scanning.

$$\varphi_R(x'_{m,n}, y'_{m,n}) = -k_0 \sin(\theta_b) \cos(\varphi_b) x'_{m,n} - k_0 \sin(\theta_b) \sin(\varphi_b) y'_{m,n} + k_0 d_{m,n} \quad (6)$$

Where $\varphi_R(x'_{m,n}, y'_{m,n})$ is the phase required for each element in the $(x'_{m,n}, y'_{m,n})$ to achieve the beam direction at (θ_b, φ_b) . Fig.7 shows the non-periodical analytical phase distribution for mentioned array setup in section 4 for different beam directions in the v -plane, where elements are horizontally numbered in the array. As shown in this figure there are no elements that phase remain constant during the beam-scanning performance.

So, to implement the constant phase elements of the phased array with odd rows or columns to reflectarrays, some elements have to select randomly from the mentioned array setup and considered as CPEs. CPEs have a constant phase during the beam-scanning and their phase will not have optimized or changed. CPEs' phases are fixed to the values that compensate the distance difference between the center of the elements and phase center of the feed and calculated using (5). To change the beam direction in this type of phase distribution, only the phase of ordinary elements (OEs) (Element could be changed or optimized). So, only these elements need phase shifters.

Fig. 7 Analytical phase distributions for 30*30 reflectarray with different values of beam-direction

5.3 Phase Distribution with CPEs and Phase Symmetry Plane

Other drawbacks of one plane electronically beam-scanning reflectarrays with active phase shifters are the biasing device design complexity and expensive cost. One way to solve these problems is to use CPEs, as explained in the previous section. Another proposed method is to create symmetry in the phase of elements. If the CPEs symmetry phase plane is used together, costs and implementation complexities will dramatically decrease. For simultaneous use of the advantages of both methods, in addition, to select some elements as CPEs, the phase of all elements (CPEs and OEs) in the array as follows:

$$\varphi_{m,n} = \varphi_{m,N-n+1} \quad (7)$$

In other words, according to Fig.9, the phases of the element on the right side of the red line are equal to the phase of elements on the left side of that line.

5.4 Optimizing and Results

GAPSO is applied to describe reflectarray with explained phase distributions to find appropriate phase distribution to move the main beam direction in the v -plane and in the u -plane main beam, the direction remains in $u=0$. In addition to beam-scanning in the v -plane, upper masks and lower masks are defined to fix the SLL below -24 dB and remain the HPBW without any changes in both u and v plane, compared to the non-optimized boresight beam shown in Fig. 5.

Fig. 8 (a) AF and Phase distribution synthesis diagram. (b) The main loop of MATLAB program

The AF of reflectarray is optimized in both u and v planes simultaneously and the total fitness value is the sum of the fitness values in the u plane and v plane. Fig.8(a) shows the AF and Phase distribution synthesis diagram and Fig.8(b) shows the main loop of optimizing program in MATLAB. To scan the main beam from $\theta_b = -40^\circ$ to $\theta_b = 40^\circ$ with almost 3dB AF gain reduction through the phase distribution with only CPEs, the 260 elements are the maximum possible number that can be randomly selected as CPEs. The white elements are shown in Fig. 9 are the CPEs and the black colored elements are the OEs. To change the beam direction in this type of phase distribution, only the phase of OEs (71.2% of total elements) could be changed or optimized. So, only these elements need phase shifters.

To implement phase distribution with CPEs and phase symmetry plane and desired beam scanning conditions in v -plane, CPEs must be selected symmetrical in array combination, one of the best choices for CPEs shape is the symmetric diagonal shape. Also, the phase symmetry plane is applied to explain the array setup. Fig. 10 demonstrated the array structure used in this kind of phase distribution. White-colored elements are the CPEs and black-colored elements are OEs.

Fig. 9 Array structure with only CPEs

Fig. 10 Array structure with CPEs and Phase symmetry plane

Because of the symmetric phase of all elements and 260 CPEs, only 35.6% of all existing elements in the described reflectarray setup are optimized and the phases of other elements are either constant (CPEs) or equal to the other elements. The normalized v -plane reflectarray AF patterns for describing phase distributions and array setup are shown in Fig. 11. As shown in this figure main lobe of the reflectarray AF pattern is moved from $\theta_b = -40^\circ$ to $\theta_b = 40^\circ$ in v -plane for all of the phase distributions. The SLLs of patterns for all of the phase distributions are nearly or below -24dB, as illustrated in Fig.12, and HPBW's of them are not significantly changed and it is almost equal to non-optimized pattern. Fig. 13, shows the maximum $|AF|$ over different values of beam direction in v -plane for three explained phase distributions. As shown in this figure, maximums of $|AF|$ for these phase distributions are close, and almost 3dB AF gain reduction is achieved for 80° beam-scanning range.

The total fitness values over different iterations of the optimization process for all phase distributions are demonstrated in Fig. 14. As shown in this figure the values of total fitness for all phase distributions and all beam directions are nearly zero. Hence, the reflectarray AF optimized patterns in both u and v -plane are meeting the optimization goals. Fig. 15 shows Optimized normalized AF in v plane over normalized frequency (f/f_0) for three described phase distributions. In all three phases distributions, the patterns in $\theta_b = -40^\circ$ and $\theta_b = 40^\circ$ are the limiting factors for frequency, bandwidth and the pattern in these beam angles decrease rapidly over frequency in comparison to the other beam angles.

Fig. 11 Optimized normalized AF in v -plane for (a) Ordinary phase distribution. (b) Novel phase distribution with CPEs and (c) Novel phase distribution with CPEs and phase symmetry plane

Fig. 12 SLL[dB] over different values of beam direction in v -plane for phase distributions

Fig. 13 Maximums of $|AF|$ over different values of beam direction in v -plane for phase distributions

So, according to Fig. 15, to achieve 80° beam-scanning range with only 3dB $|AF|$ compression over frequency, the fractional bandwidth is almost 11% for all three-phase distribution.

Fig. 14 Total fitness function over iteration for (a) Ordinary phase distribution. (b) Novel phase distribution with CPEs and (c) Novel phase distribution with CPEs and phase symmetry plane

Fig. 15 Optimized normalized AF in v plane over normalized frequency (f/f_0) for (a) Ordinary phase distribution. (b) Novel phase distribution with CPEs and (c) Novel phase distribution with CPEs and phase symmetry plane

6. Conclusion

Microstrip beam-scanning reflectarrays phase distribution synthesis methods have been studied in this paper. Hybrid GAPSO has been described for optimizing the phase distribution on reflectarrays. In addition to ordinary phase distributions, two novel phase distributions with constant phase elements and symmetry phase plane have been proposed to achieve beam-scanning capability in reflectarrays. The array factors of 30×30 reflectarray by using these three kinds of phase distributions have been optimized to displace the beam in the vertical plane from -40° to 40° . The optimized result shows that GAPSO has a good performance to optimize the phase distribution of beam-scanning reflectarrays.

Results obtained from optimizing two novel phase distributions demonstrates that for beam-scanning reflectarrays, it is not necessary to optimize the phase of all elements and by optimizing just a few numbers of them (71.2% of total elements in phase distribution with CPEs and only 35.6% in phase distribution with CPEs and phase symmetry plane) the reflectarray will have the same performance in Frequency bandwidth, Gain and Side Lobe Level compared to the ordinary phase distribution or optimizing phase of all elements. Hence, due to the absence of phase shifters in a large number of elements in these two novel phase distributions, the cost and complexities of designing and implementation of electronically beam-scanning reflectarray and its biasing devices will be decreased.

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