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Phase-Only Optimization of Asymmetric Multiple Beams Reflectarray with Single Feed Using the Invasive Weed Optimization

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Abstract

Phase-only optimization of asymmetric multiple beams reflectarray with single feed is investigated in this paper. The conventional design approaches are first reviewed. Secondly, for design of asymmetric multiple beams reflectarray with arbitrary gain levels and beam directions, a general method based on invasive weed optimization is proposed. Then, practical considerations for applying the proposed method to design multiple beams reflectarray are talked over. For illustrating the effectiveness of the proposed method, several multiple beams design cases with different design requirements are optimized through this method, and the optimized results are analyzed through simulation approach based on array theory. The simulation results show that the optimized cases demonstrate the satisfactory multiple beams performance.

Keywords: *Multiple beams, Reflectarray, Array theory, Invasive weed optimization, Intersection approach, Iterative Fourier Techniques*

1. Introduction

Due to combination of the favorable features of reflectors and phased arrays, printed reflectarray antenna has received notable attentions over years and been applied in various applications, such as satellite communications, radars systems, and commercial usages [1-2]. The outstanding feature of the reflectarray antenna is the individual phase control of each element without complex feeding network and high manufacturing cost [1]. In comparison with phased arrays with complex feeding network and reflectors with high manufacturing cost, this feature can help the reflectarray to achieve shaped or even multiple beams without additional complexity and cost [3-4].

High gain multiple beams antennas have numerous applications in electronic counter measures, satellite communications, and multiple target radar systems [5].These multiple beams antennas are typically based on reflectors with feed-horn clusters [6] or large phased arrays [7]. Considering the complex processing technologies of these antennas, the manufacturing cost of these multiple beams antennas are typically high. However, low-cost feature of reflectarray antenna makes it a suitable antenna candidate for the multiple beam applications with cost reduction.

Multiple beams performances can be achieved by the reflectarray antennas with single or multiple feeds. Several designs of single feed multiple beams have been demonstrated over years. A single-feed two beams reflectarray design was demonstrated in [4] while [8-10] presented a single feed four beams reflectarray design. Multiple feed multiple beams

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reflectarray design with shaped patterns was studied in [11]. It should be noted that different approaches in these papers have been introduced to achieve the multiple beams performance, however, all reported designs are concentrated on symmetric multiple beams performance. As design of a single feed asymmetric multiple beams reflectarray is a quite challenging task with high complexity, the conventional approaches implemented to obtain the required aperture phase distribution fail to achieve a satisfactory performance [12].

The major focus of this paper is on the optimization design of asymmetric multiple beams reflectarray with single feed. Firstly, the available design approaches are reviewed. Then, for designing asymmetric multiple beams reflectarray with arbitrary gain levels and beam directions, a general method is proposed. This method is based on implementing a novel numerical optimization algorithm named invasive weed optimization (IWO) [13-14], inspired from weed colonization, for phase optimization of reflectarray elements. Practical considerations for implementing the proposed method are discussed in this paper. In order to demonstrate the effectiveness of the proposed method for designing the asymmetric multiple beams reflectarray with a single feed, several multiple beams cases with different design requirements are optimized and the performances of the optimized multiple beams reflectarray are analyzed numerically.

2. Optimization Methods for Single Feed Multiple Beams Reflectarray

It is important to point out that the element amplitude on the reflectarray aperture has been fixed by the property and relative position of feed and element. Therefore, in order to achieve the multiple beams performance with a single feed, the only adjustable parameter is the element phase on the reflectarray aperture. As it is known, the reflected phase of element can be adjusted by controlling the geometrical parameters of the elements. Owing to this feature, arbitrary element phase distribution on the aperture can be realized, which provides the capability for the reflectarray to achieve simultaneous multiple beams performance with a single feed. However, the challenge is the determination of the element reflected phase required for the multiple beams performance. In other words, the design of multiple beams reflectarray becomes a basic phase-only array synthesis problem.

In general, to achieve multiple beams performance with single feed, the element phase distribution on the reflectarray aperture can be calculated through two different methods: one is direct analytical method, and the other is optimization method. While having an analytical expression for the required aperture phase is advantageous, it has been studied that the achieved performance of those analytical approaches cannot be satisfactory in most cases, and in order to achieve a desirable performance, it is necessary to apply some optimization procedure [10]. In optimization methods, an optimum element phase distribution on the reflectarray aperture for achieving desired multiple beams performance can be obtained through a phase-only optimization technique. It should be noted that the optimization techniques are typically categorized into two major groups, *i.e.* local and global search techniques. Although both search techniques are model-based optimization routines, the essential difference between these two techniques is the solution hyperspace that the algorithm searches. For a local search algorithm, it can only search for the solution in a limited hyperspace determined by the initial values. On the other hand, a global search algorithm can search the entire solution hyperspace. In other words, a local search algorithm can only find the optimal solution if it is discoverable from the starting searching points. Otherwise, this search algorithm could get trapped in the local minima and will not converge. In contrast, a global search algorithm can find the optimum solution from any starting searching point; however, the major drawback is very high computation cost.

Currently, the primary optimization approach applied for multiple beams reflectarray designs is the intersection approach also known as the iterative Fourier techniques (IFT) [15]. This approach is a very robust local search algorithm which searches for the solution with an iterative procedure. It is worthwhile to point out that the initial values for element phase distribution are typically obtained from the direct analytical solution. While several multiple beams reflectarray have been successfully demonstrated using this approach [9-11], for some complex cases, this algorithm can only converge to local minima rather than the optimum solution because of the non-convexity of the optimization problem on hand. It is worthwhile to point out that for multiple beams designs, if the initial radiation patterns generated by the initial phase distribution are with high side lobes in the visible range, this method usually cannot optimize this design. However, this problem becomes more challenging when the asymmetric multiple beams performance is required. Therefore, it is necessary to introduce a global and more powerful optimization approach into the design of multiple beams reflectarray.

As discussed earlier, global search techniques search for the solution in the entire hyperspace. Therefore, an efficient and high performance algorithm is necessary for optimization. The IWO, a numerical stochastic optimization inspired from weed colonization, is first introduced by Mehrabian and Lucus in 2006 [13], and applied to the electromagnetic problems by Karimkashi and Kishk in 2010 [14]. It is shown that in certain cases the IWO outperforms the genetic algorithm (GA) and particle swarm optimization (PSO) in convergence rate as well as the final error level with less computational bookkeeping. Moreover, the performance of IWO is more stable and efficient against different boundary conditions and tuning parameters. Hence, the IWO is selected for the optimization design of multiple beams reflectarray. It is significant to point out that while IWO has been implemented for array optimization, for most cases, the number of elements is usual around 100, which implies that a main challenge in practically implementing a global search for a reflectarray is the very large solution hyperspace due to the several hundreds of elements on the reflectarray aperture.

3. Practice Considerations for Implementing Invasive Weed Optimization in Multiple Beams Reflectarray Design

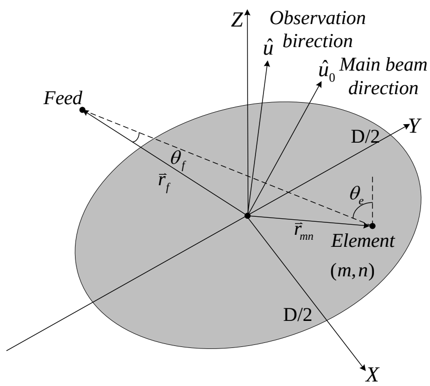

Figure 1. Geometrical Model of the Reflectarray System

IWO is a powerful global search algorithm which is well suit for array synthesis problems. While this optimization method is very robust, the major computational expensive part focuses on the evaluation of fitness function. For the reflectarray synthesis design, the calculation of the radiation pattern is required for the fitness evaluation each iteration. Therefore, the efficient computation of the radiation pattern becomes the key point in the optimization. It has been shown that the radiation pattern of a reflectarray can be computed using two different approaches, namely array theory and aperture field methods [1]. While the analysis principles for the two methods are completely different, numerical investigations have shown that the co-polarized radiation patterns computed by both methods are in well agreement with each other [16]. However, from the viewpoint of computational time, the array theory technique is much faster, and therefore it is more suitable for the optimization problem discussed in this paper. It should be pointed out that a further computational speed up for the calculation of radiation pattern can be achieved through replacing the double summations by a 2-D Fourier transform [16]. A geometrical model of the reflectarray system and vector coordinates is illustrated in Figure 1.

It should be noted that in order to implement special transforms in the array theory formulation, a direct relationship between the angular coordinates (u = sinθcosφ, v = sinθsinφ) and array elements (m, n) is required. Then, the Fourier transforms are used to directly relate the complex coefficients between the angular coordinates and the array elements. Finally, the radiation pattern of a reflectarray system can be calculated quite efficiently using the following equation

$$E(u,v)=\mathrm{Cos}^{q_e}(u,v)\times 2DFFT\left\{\frac{\mathrm{Cos}^{q_f}\theta_f(m,n)}{\left|\bar{r}_{mn}-\bar{r}_f\right|}\cdot\mathrm{Cos}^{q_e}\theta_e(m,n)\cdot e^{-jk\left(\left|\bar{r}_{mn}-\bar{r}_f\right|+\bar{r}_{mn}\cdot\hat{u}\right)}\cdot e^{j\phi_{mn}}\right\} \quad (1)$$

The first term in the above equation is the transmit mode pattern of the element which can be multiplied with the array factor after implementing the Fourier transform. It should be noted that in the above equation, every term except the exponential term $e^{-jk\bar{r}_{mn}\cdot\hat{u}}$ is calculated before implementing the Fourier transform, and only this exponential term is directly relating the aperture fields to far fields. Moreover, it is necessary to point out that the term ϕ_{mn} in equation is consisted of two parts: one is the compensation for the spatial delay, and the other is the element aperture phase shift for reflectarray element. As the spatial delay for each element is a fixed value, only the element aperture phase shift need to be adjusted in the optimization.

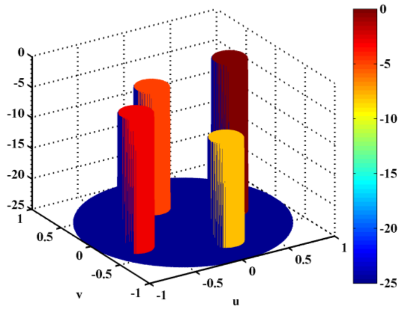

Figure 2. Upper Bound Mask (M_U) Model for an Asymmetrical Multiple Beams Reflectarray

In the next stage, the IWO approach is implemented to optimize the element aperture phase shift within the range from 0 to 2π. In order to achieve multiple beams performance, a far field mask based on the design requirements should be defined for the optimization. The required far field mask for multiple beams radiation patterns are typically circular contours defined in the direction of each beam with required beam level [9-10]. Moreover, it also should be noted that the far field mask usually requires defining the upper (M_U) and lower (M_L) bound according to the desired pattern performance in the entire angular range. A 3-D figure of the upper bound mask model for a multiple beams design with different beam levels in asymmetric beam directions is shown in Figure 2.

The fitness function, cost measure to be minimized, defined for this optimization is as following equation

$$Fitness = \sum_{\substack{(u,v)\notin \text{mainbeam} \\ \text{and}|E(u,v)|>M_U(u,v)}} \left(|E(u,v)| - M_U(u,v)\right)^2 + \sum_{\substack{(u,v)\in \text{mainbeam} \\ \text{and}|E(u,v)|<M_L(u,v)}} \left(|E(u,v)| - M_L(u,v)\right)^2$$
$$+ P \times \sum_{\substack{(u,v)\in \text{mainbeam} \\ \text{and}|E(u,v)|>M_U(u,v)}} \left(|E(u,v)| - M_U(u,v)\right)^2 \quad (2)$$

The above equation shows that the fitness function takes into account the performance of every point in the visible range, *i.e.* $u^2 + v^2 \leq 1$. The first term in the fitness function evaluates the side lobe performance of the pattern for every point which does not belong to the main beam area. The last two terms evaluate the main beam performance of the pattern. It is important to point out that for a multiple beams design with same beam level the value of coefficient P can be 0, however, for the different beam levels case it should be 1 for considering the effect of different beam levels on the main beam performance.

4. Numerical Results

4.1. Optimized Multiple Beams Performance for IWO

In order to illustrate the feasibility and robustness of this global optimization technique for general multiple beams reflectarray design, four different multiple beams design cases with working frequency of 12.5 GHz are investigated. For these design cases the reflectarray aperture is a circular plate with a diameter of 10λ, and the element located on the aperture is with the spacing of $\lambda/2$. The feed is prime focus with the f/D = 0.75. The power q_e of the element pattern model is 1. The power q_f of the feed pattern model is 6.5, which generates an edge taper below -13 dB.

Table 1. Design Requirements for Multiple Beams Performance (Beam Direction (θ_n, φ_n) and Normalized Gain Level)

Design	Beam 1	Beam 2	Beam 3	Beam 4
Case I	(30°, 0°) 0 dB	(30°, 90°) 0 dB	(30°, 180°) 0 dB	(30°, 270°) 0 dB
Case II	(30°, 0°) 0 dB	(25°, 100°) 0 dB	(45°, 200°) 0 dB	(35°, 280°) 0 dB
Case III	(30°, 0°) 0 dB	(30°, 90°) -5 dB	(30°, 180°) -3 dB	(30°, 270°) -8 dB
Case IV	(30°, 0°) 0 dB	(25°, 100°) -5 dB	(45°, 200°) -3 dB	(35°, 280°) -8 dB

The design requirements for these multiple beams design cases are summarized in Table 1. It is worthwhile to point out that while the beam width and gain level of the multiple beams antennas are generally determined based on the task requirements, for the design cases investigated in this paper all beams are set to have the same beam width of the reference single beam design with the same configuration of the design cases. In addition, the side lobe level of the upper mask for all design cases is set to -25 dB. The contour figures of the upper bound mask model for these four design cases are exhibited in Figure 3.

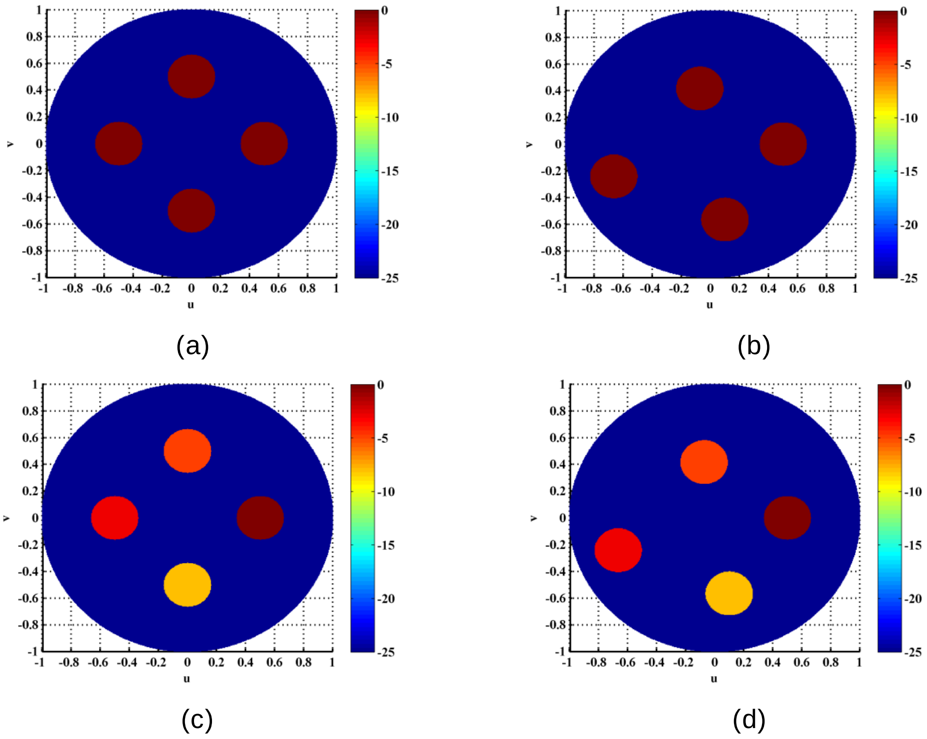

Figure 3. Contour Figures of the Upper Bound Mask Model for these Four Designs: (a) Case I, (b) Case II, (c) Case III, (d) Case IV

With the design requirements specified, the task is then to initialize the parameters of IWO for the optimization problem. The initial standard deviation (SD) is set equal to 5 percent of the range $[0, 2\pi]$ of each element phase shift, and the final SD is set equal to 5e-5. It is suggested that the best choice for the value of nonlinear modulation index is 3, moreover, it has been concluded that the maximum and minimum numbers of seeds are respectively set to 5 and 1, which can lead to a good performance of the optimizer [14]. The maximum number of plant is set to 30, and the restricted boundary condition is selected. For each design case, 100,000 iterations are performed. It should be noted that in equation (1), the computation time for radiation pattern calculation is mainly depending on the far field resolution. For arrays with about 400 elements, a far field pattern with 400×400 points evenly spaced in the angular coordinates is usually adequate, and therefore this value is used for all design cases in this paper. With our developed radiation pattern analysis code, the computation time for each radiation pattern calculation is about 3 milliseconds on a 3.06 GHz Intel Xeon W3350 Think Station. For each design case, the total computation time is about 23 hours. The convergence curves for the four design cases are exhibited in Figure 4. From the Figure 4, it can be seen that in all four design cases, although the solution doesn't convergence initially, it eventually escapes the optimization traps.

For the four design cases investigated in this paper, the first two cases have multiple beams with equal gain level. Case I is a symmetric four beams reflectarray design, which is similar to the case reported in [9-10]. Case II is an asymmetric four beams reflectarray design. From the convergence curves, it can be observed that with the fixed iteration numbers, the fitness improvement for Case I is more obvious than that for Case II, which is good indicator for the complexity of the asymmetric design. Designs of multiple beams with different gain levels are investigated in the last two cases. The same fact that the asymmetric design is more complex than the symmetric design is observed. The optimized phase distribution and radiation patterns for these four design cases are shown in Figure 5 and Figure 6, respectively. From Figure 6, it can be observed that the four multiple beams design cases investigated in this paper achieve the design requirements, which demonstrates the effectiveness and robustness of the invasive weed optimization for the multiple beams designs. It is worthwhile to point out that according to the design requirements it is possible to use the symmetry of the optimization problem to reduce the dimension of the problem. However, the focus of this paper is on asymmetric multiple beams design, therefore no symmetry boundary is utilized in the optimization process.

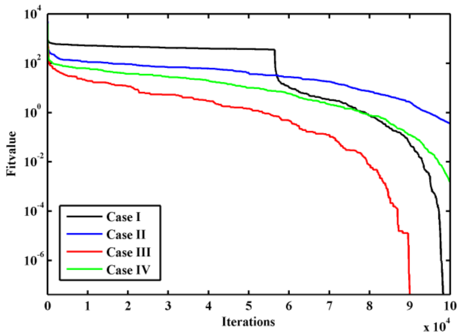

Figure 4. Convergence Curves of the Invasive Weed Optimization for Multiple Beams Reflectarray Design Cases

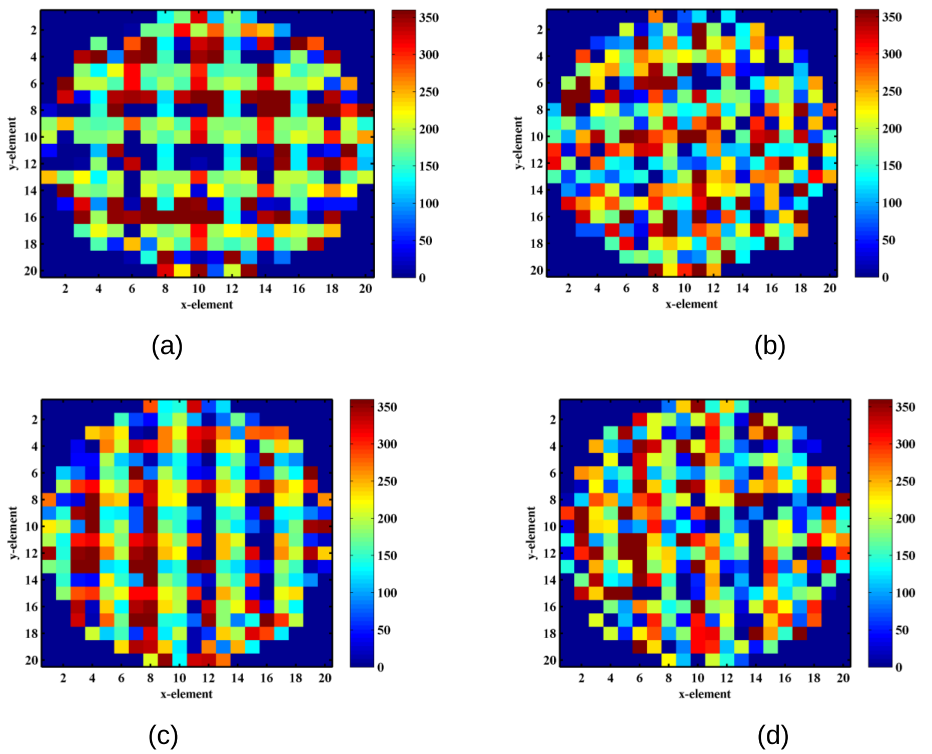

Figure 5. Optimized Element Phase Distribution: (a) Case I, (b) Case II, (c) Case III, (d) Case IV

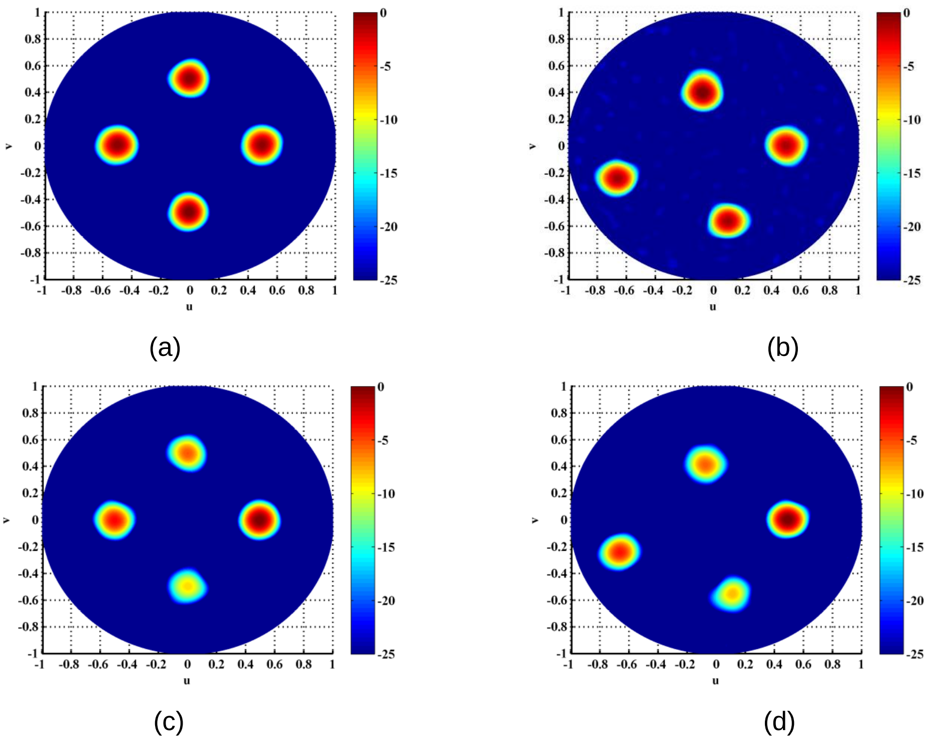

Figure 6. Radiation Patterns for the Optimized Multiple Beams Reflectarray: (a) Case I, (b) Case II, (c) Case III, (d) Case IV

4.2. Comparison between the IWO and the IFT

To illustrate the significance of implementing a global search technique for asymmetric multiple beams designs and the limitation of the local search techniques, the IFT is applied for phase optimization of Case II with the same design requirements. The optimized phase distribution and radiation pattern obtained by using the IFT are shown in Figure 7. There are to be compared with Figure 5 (b) and Figure 6 (b), respectively. From comparison, it can be observed that for this design case, the obtained radiation performance by the IFT is not satisfactory. Gain levels, side lobe levels and beam direction are obviously not satisfying with design requirements. In particular, some undesired lobes with a larger than -10 dB normalized magnitude are generated in visible range. In addition, the normalized gain level difference between beams is larger than 3dB.

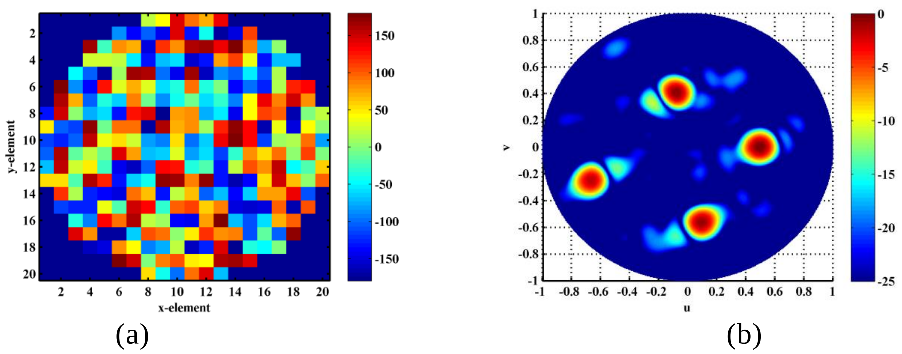

Figure 7. Optimized Element Phase Distribution and Radiation Patterns for Case II Using the IFT: (a) Phase Distribution, (b) Radiation Patterns

In general, the IFT is quite advantageous for simple design case such as Case I. However, for asymmetric design case, the optimization problem is quite challenging, and a satisfactory multiple beams performance cannot be achieved with this technique. In addition, while in comparison with the IFT, the IWO requires much higher computation time, the major strength of this global search technique is the capability to escape the traps in the optimization procedure.

5. Conclusion

Phase-only optimization of asymmetric multiple beams reflectarray with single feed has been investigated in this paper. At first, conventional approaches for designing multiple beams reflectarray are reviewed, and the shortcomings of these approaches are discussed. After that, a general approach based on the invasive weed optimization to design asymmetric multiple beams reflectarray is proposed and practice considerations of implementation of this approach are discussed. Different design cases of multiple beam reflectarray with asymmetric beam directions and gain levels are optimized by the proposed approach. The satisfactory multiple beams performances achieved by the proposed approach demonstrate the effectiveness and robustness of this approach, which makes this method a more universal approach for any multiple beams performance design.

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References

[1] J. Huang and J. A. Encinar, “Reflectarray Antennas”, John Wiley & Sons, New Jersey, **(2008)**.
[2] D. M. Pozar, S. D. Targonski and H. D. Syrigos, “Design of millimeter wave microstrip reflectarray”, IEEE Trans. Antennas & Propag., vol. 45, no. 2, **(1997)**, pp. 287-296.
[3] D. M. Pozar, S. D. Targonski and R. Pokuls, “A shaped-beam microstrip patch reflectarray”, IEEE Trans. Antennas & Propag., vol.47, no. 7, **(1999)**, pp. 1167–1173.
[4] J. A. Encinar and J.A. Zornoza, “Three-layer printed reflectarray for contoured beam space applications”, IEEE Trans. Antennas & Propag., vol. 52, no. 5, **(2004)**, pp. 1138–1148.
[5] R. C. Hansen, “Phased Array Antennas”, John Wiley & Sons, New Jersey, **(1998)**.
[6] P. Balling, K. Tjonneland, L. Yi and A. Lindley, “Multiple contoured beam reflector antenna systems”, IEEE Antennas and Propagation Society International Symposium (APSURSI), Michigan, U.S.A, **(1993)**, pp. 1354-1357.
[7] L. Schulwitz and A. Mortazawi, “A compact dual-polarized multi beam phased-array architecture for millimeter-wave radar”, IEEE Trans. Microw. Theory Tech., vol. 53, no. 11, **(2005)**, pp. 3588–3594.
[8] J. Lanteri, C. Migliaccio, J. A. Laurinaho, M. Vaaja, J. Mallat and A. V. Raisanen, “Four-beam reflectarray antenna for Mm-waves: design and tests in far-field and near-field ranges”, European Conference on Antennas and Propagation (EUCAP), Berlin, Germany, **(2009)**, pp. 2532-2535.
[9] P. Nayeri, F. Yang and A. Z. Elsherbeni, “Design and experiment of a single feed quad beam reflectarray antenna”, IEEE Trans. Antennas & Propag., vol. 60, no. 2, **(2012)**, pp. 1166-1171.
[10] Y. Qu, C. J. Guo, H. Guo and J. Ding, “Design of single-feed multi-beam reflectarray using iterative Fourier techniques”, International Journal of Smart Home, vol. 9, no. 4, **(2015)**, pp. 187-195.
[11] M. Arrebola, J. A. Encinar and M. Barba, “Multifed printed reflectarray with three simultaneous shaped beams for LMDS central station antenna”, IEEE Trans. Antennas Propag., vol. 56, no. 6, **(2008)**, pp. 1518-1527.
[12] P. Nayeri, F. Yang and A. Z. Elsherbeni, “Design of single feed reflectarray with asymmetric multi-beams”, IEEE Antennas and Propagation Society International Symposium (APSURSI), Illinois, U.S.A **(2012)**, p. 1-2.
[13] A. R. Merabian and C. Lucas, “A novel numerical optimization algorithm inspired from weed colonization”, Ecological Informatics, vol. 1, no. 4, **(2006)**, pp. 355-366.
[14] S. Karimkashi and A. A. Kishk, “Invasive weed optimization and its features in electromagnetics”, IEEE Trans. Antennas Propag., vol. 58, no. 4, **(2010)**, pp. 1269-1278.
[15] R. Fletcher, “Practical Methods of Optimization, 2nd edition”, John Wiley & Sons, New Jersey, **(2007)**.

[16] O. M. Bucci, G. Franceschetti, G. Mazzaralla and G. Panariello, “Intersection approach to array pattern synthesis”, IEE Proceedings, vol. 137, no. 6, **(1990)**, pp. 349-357.
[17] R. Vescovo, “Re-configurability and beam scanning with phase-only control for antenna arrays”, IEEE Trans. Antennas Propag., vol. 56, no. 6, **(2008)**, pp.1555-1565.
[18] W. P. M. N. Keizer, “Low side-lobe patterns synthesis using iterative Fourier techniques coded in MATLAB”, IEEE Antennas & Propag. Mag., vol. 51, no. 2, **(2009)**, pp. 137-150.
[19] Y. Qu, C. J. Guo, H. Guo and J. Ding, “Fast analysis for aperture efficiency and radiation patterns of reflectarray antennas”, International Journal of Signal Processing, Image Processing and Pattern Recognition, vol.7, no.4, **(2014)**, pp. 243-254.
[20] P. Nayeri, A. Z. Elsherbeni and F. Yang, “Radiation analysis approach for reflectarray antennas”, IEEE Trans. Antennas & Propag., vol. 55, no. 1, **(2013)**, pp.127-134.

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