Pattern Synthesis of Dual-band Shared Aperture Interleaved Linear Antenna Arrays

Hua GUO, Chenjiang GUO, Jun DING

School of Electronics and Information, Northwestern Polytechnical University, Xi'an 710129, China

xdguohua@163.com, cjguo@nwpu.edu.cn, dingjun@nwpu.edu.cn

Abstract. *This paper presents an approach to improve the efficiency of an array aperture by interleaving two different arrays in the same aperture area. Two sub-arrays working at different frequencies are interleaved in the same linear aperture area. The available aperture area is efficiently used. The element positions of antenna array are optimized by using Invasive Weed Optimization (IWO) to reduce the peak side lobe level (PSLL) of the radiation pattern. To overcome the shortness of traditional methods which can only fulfill the design of shared aperture antenna array working at the same frequency, this method can achieve the design of dual-band antenna array with wide working frequency range. Simulation results show that the proposed method is feasible and efficient in the synthesis of dual-band shared aperture antenna array.*

Keywords

Pattern synthesis, linear arrays, dual-band, shared aperture, Invasive Weed Optimization.

1. Introduction

Design of the multifunctional antenna array is a key issue in the case of communication, remote sensing and electronic warfare, etc. Shared aperture antenna is one way to fulfill the multifunction of antenna array [1]. Two or more antenna subarrays that occupy the same area are known as shared aperture antennas or common aperture antennas [2]. If elements dedicated to different subarrays are interleaved in a shared aperture, the array is called interleaved or interlaced antenna array. Interleaving non-periodic subarrays provides a powerful and versatile tool to implement multifunctionality in antenna arrays [3].

The design of interleaved antenna array has been paid increasing attention in recent years. Many methods have been developed. In [1], a consistent strategy for the design of finite antenna arrays consisting of differently sized radiating elements is discussed. An effective and robust strategy for concurrently designing the transmitting and receiving antennas of a frequency modulated, continuous wave radar is discussed in [3]. A new method is described in [4] for adjusting the far-field polarization of an electronically steered phased-array antenna array. Three approaches to improving the efficiency of an array aperture by interleaving two arrays in the same aperture area is presented in [2]. The effect of allowing shared elements in interleaved thinned antenna arrays is investigated in [5]. An analytical technique based on almost difference sets (ADSs) for the design of interleaved linear arrays with well-behaved and predictable radiation features is proposed in [6].

However, the antenna arrays proposed above can only work at the same or similar frequencies. The working frequency range of the antenna arrays is narrow. Therefore, pattern synthesis of two interleaved linear arrays working at different frequencies is presented in this paper. The element positions are optimized by IWO and low PSLLs of the radiation patterns are obtained. IWO has been effectively used into the design of antennas [7], [8]. Usually, IWO outperforms the other optimization methods in the convergence rate as well as the final error level [9]. The rest of the paper is organized as follows. In Section 2, the mathematical model and the fitness function are given. How to determine the element positions of antenna arrays is depicted in Section 3. Section 4 describes the principles of IWO and the optimization procedure. Section 5 gives the simulation results and discussions. Finally, summary and conclusions are presented in Section 6.

2. Optimization Model

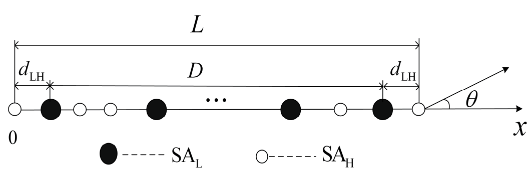

Fig. 1. Structure of a linear shared aperture antenna array.

The configuration of a linear shared aperture antenna array is as shown in Fig. 1. The length of the antenna array is L. The interleaved two subarrays are referred to as SA_L and SA_H, where the subscripts "L" and "H" indicate the lower and higher frequency subarrays. The normalized array factors of both subarrays can be given by

$$AF_L(\theta) = \frac{1}{N_L}\sum_{n=1}^{N_L}\exp(jk_L x_n^L \cos\theta) \ , \qquad (1)$$

$$AF_{\mathrm{H}}(\theta)=\frac{1}{N_{\mathrm{H}}}\sum_{n=1}^{N_{\mathrm{H}}}\exp(jk_{\mathrm{H}}x_n^{\mathrm{H}}\cos\theta) \quad (2)$$

where N_{L} and N_{H} are the element number of the lower and higher frequency subarrays, x_n^{L} and x_n^{H} are the nth element positions of both subarrays, $k_{\mathrm{L}} = 2\pi/\lambda_{\mathrm{L}}$ and $k_{\mathrm{H}} = 2\pi/\lambda_{\mathrm{H}}$ are wave numbers, λ_{L} and λ_{H} are wavelengths of the lower and higher working frequencies, θ is the angle measured from x-axis. The peak side lobe level of the radiation patterns can be calculated from

$$\mathrm{PSLL}=\max\left\{\max\left|AF_{\mathrm{H}}(\theta)\right|_{\theta\in S_{\mathrm{H}}},\max\left|AF_{\mathrm{L}}(\theta)\right|_{\theta\in S_{\mathrm{L}}}\right\} \quad (3)$$

where S_{L} and S_{H} are the side lobe areas for the radiation patterns of both subarrays.

The objective is to find the best element positions of both subarrays that can minimize the PSLL of the radiation patterns. In order to eliminate the effect of mutual coupling, the adjacent array elements have a minimum spacing. As both subarrays work at different frequencies, the minimum spacing constrains of adjacent elements will be different. The minimum element spacings for both subarrays are given by d_{L} and d_{H}, respectively. The minimum spacing of the elements that belong to different subarrays is depicted by d_{LH}. So, the objective function can be depicted by

$$\begin{cases}\min\{\mathrm{PSLL}\}\\ s.t.\ \min\left|x_i^{\mathrm{L}}-x_j^{\mathrm{L}}\right|\ge d_{\mathrm{L}}\\ \min\left|x_m^{\mathrm{H}}-x_n^{\mathrm{H}}\right|\ge d_{\mathrm{H}},\min\left|x_i^{\mathrm{H}}-x_m^{\mathrm{L}}\right|\ge d_{\mathrm{LH}}\\ i,j=1,2\cdots N_{\mathrm{L}};m,\mathrm{n}=1,2\cdots N_{\mathrm{H}}\\ i\ne j,m\ne n\end{cases} \quad (4)$$

In the following procedure, the problem is changed into a maximization problem. So, the fitness function is defined by

$$f=\max\{|\mathrm{PSLL}|\}. \quad (5)$$

3. Interleaving of Array Elements

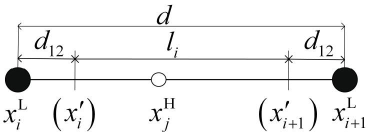

Fig. 2. Configuration of a segment of the array.

In this section, how to determine the array element positions of the two subarrays that satisfy those constrains given in (4) is proposed. Firstly, the element positions of the lower frequency subarray are determined. In order to efficiently use the whole array aperture, two elements are fixed at both sides of the antenna array. The positions of the first and last elements of the lower frequency subarray are d_{LH} and $D+d_{\mathrm{LH}}$, respectively. Only $N_{\mathrm{L}}-2$ element positions need to be determined. As shown in Fig. 1, the aperture length of lower frequency subarray is D. As depicted in [10], the remaining region over the array aperture is given by

$$SP_{\mathrm{L}}=D-(N_{\mathrm{L}}-1)d_{\mathrm{L}}\,. \quad (6)$$

Then, $N_{\mathrm{L}}-2$ random real numbers among the range of $[0, SP_{\mathrm{L}}]$ are calculated by

$$c_i^{\mathrm{L}'}=SP_{\mathrm{L}}\times r_i^{\mathrm{L}},i=1,2,\cdots,N_{\mathrm{L}}-2 \quad (7)$$

where r_i^{L} , $i = 1, 2,\cdots, N_{\mathrm{L}}-2$, are random numbers among the range of [0,1]. Then, $c_i^{\mathrm{L}'}$, $i = 1, 2,\cdots, N_{\mathrm{L}}-2$, are sorted in ascending order and a new vector $\mathbf{C}^{\mathrm{L}} = [c_1^{\mathrm{L}}, c_2^{\mathrm{L}},\cdots, c_{N_{\mathrm{L}}-2}^{\mathrm{L}}]$ is obtained, where $c_1^{\mathrm{L}}\le c_2^{\mathrm{L}}\le,\cdots,\le c_{N_{\mathrm{L}}-2}^{\mathrm{L}}$. Then, the element positions of lower frequency subarray can be obtained by

$$\begin{bmatrix}x_2^{\mathrm{L}}\\ x_3^{\mathrm{L}}\\ \cdots\\ x_{N_{\mathrm{L}}-1}^{\mathrm{L}}\end{bmatrix}=d_{\mathrm{LH}}+\begin{bmatrix}c_1^{\mathrm{L}}+d_{\mathrm{L}}\\ c_2^{\mathrm{L}}+2\cdot d_{\mathrm{L}}\\ \cdots\\ c_{N_{\mathrm{L}}-2}^{\mathrm{L}}+(N_{\mathrm{L}}-2)\cdot d_{\mathrm{L}}\end{bmatrix}. \quad (8)$$

It can be proved that the element spacing between x_i^{L} and x_{i+1}^{L} is $d_{\mathrm{L}}+(c_{i+1}^{\mathrm{L}}-c_i^{\mathrm{L}})$, $i = 2, 3,\cdots, N_{\mathrm{L}}-2$, which can satisfy the constrain of (4).

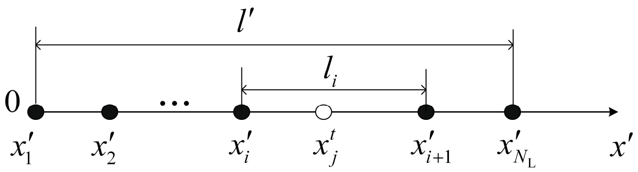

Fig. 3. Structure of the new coordinate system.

After the element positions of lower frequency subarray are calculated, the element positions of higher frequency subarray can be determined. As is shown in Fig. 2, if the adjacent element spacing of lower frequency subarray is less than $2d_{\mathrm{LH}}$, no array elements of higher frequency subarray can be disposed between them. So, the length that can arrange the elements of higher frequency subarray among the range of x_i^{L} and x_{i+1}^{L} can be determined by

$$l_i=\begin{cases}0, & x_{i+1}^{\mathrm{L}}-x_i^{\mathrm{L}}\le 2d_{\mathrm{LH}}\\ x_{i+1}^{\mathrm{L}}-x_i^{\mathrm{L}}-2d_{\mathrm{LH}}, & \text{else}\end{cases},\ i=1,2,\cdots,N_{\mathrm{L}}-1. \quad (9)$$

The total length of the array aperture that can dispose higher frequency elements is given by

$$l'=\sum_{i=1}^{N_{\mathrm{L}}-1}l_i\,. \quad (10)$$

In order to determine the element positions of higher frequency subarray, a new coordinate system is determined (Fig. 3). The coordinate value of x_i', $i = 1, 2,\cdots, N_{\mathrm{L}}$, can be determined by

$$x_1' = 0,\ x_{N_L}' = l',\ x_i' = \sum_{n=1}^{i-1} l_n,\quad i = 2,3,\cdots,N_L - 1\,. \quad (11)$$

There are N_H–2 elements of higher frequency subarray will be arranged in the length of l'. Similar to be shown above, a new parameter is given by

$$SP_H = l' - (N_H - 3)d_H\,. \quad (12)$$

Then, N_H–2 real random numbers among the range of [0, SP_H] are calculated by

$$c_i^{H'} = SP_H \times r_i^H,\ i = 1,2,\cdots,N_H - 2 \quad (13)$$

where r_i^H , $i = 1, 2,\cdots, N_H–2$, are random numbers among the range of [0,1]. Then, $c_i^{H'}$, $i = 1, 2,\cdots, N_H–2$, are sorted in ascending order and a new vector $\mathbf{C}^H = [c_1^H, c_2^H,\cdots, c_{N_H-2}^H]$ is obtained, where $c_1^H \le c_2^H \le\cdots\le c_{N_H-2}^H$. Then, the element positions of higher frequency subarray in coordinate system x' can be calculated by

$$\begin{bmatrix} x_1^t \\ x_2^t \\ \cdots \\ x_{N_H-2}^t \end{bmatrix} = \begin{bmatrix} c_1^H \\ c_2^H + d_H \\ \cdots \\ c_{N_H-2}^H + (N_H - 3)\cdot d_H \end{bmatrix}. \quad (14)$$

It can be proved that the element spacing between x_i^t and x_{i+1}^t is $d_H+(c_i^H-c_{i-1}^H)$, $i = 2, 3,\cdots, N_H–2$, which also satisfies the constrain proposed in (4). In order to fully utilize the whole array aperture, as is shown in Fig. 1, the first and last array element positions of higher frequency subarray are fixed to 0 and L, respectively. As is shown in Fig. 2, the rest element positions can be calculated by

$$\begin{cases} x_m^H = d_{LH} + x_i^L + (x_{m-1}^t - x_i'),\ x_i' \le x_{m-1}^t < x_{i+1}' \\ \quad i = 1,2,\cdots,N_L - 1,\ m = 2,3,\cdots,N_H - 1 \end{cases}. \quad (15)$$

4. Optimization Strategy using IWO

4.1 Introduction to IWO

IWO is a numerical stochastic search algorithm that simulates the natural behavior of weed colonizing in the opportunity spaces for optimizing the function. This algorithm is simple. However, it has been shown to be effective in converging to an optimal result [11]. There are four steps of the algorithm which are described below:

1) Initialization

A certain number of weeds are randomly spread over the entire search space (K-dimension). The initial population of each generation is $\mathbf{X} = \{\mathbf{x}_1, \mathbf{x}_2,\cdots, \mathbf{x}_K\}$. Each search space has N elements.

2) Reproduction

Each number of the population $\mathbf{X}$ is allowed to produce weed seeds within a specified region centered at its own position. The number of seeds that are produced by $\mathbf{x}_k$, $k = 1, 2,\cdots, K$, depends on its relative fitness value in the population with respect to the best and worst fitness. The formula of weeds producing seeds is given by

$$weed_k = \left\lfloor \frac{f - f_{\min}}{f_{\max} - f_{\min}}(s_{\max} - s_{\min}) + s_{\min} \right\rfloor \quad (16)$$

where $\lfloor q \rfloor$ denotes the integer part of q, f is the current weed's fitness, $f_{\max}$ and $f_{\min}$ represent the best and worst fitness value of the current population, $s_{\max}$ and $s_{\min}$ are the maximum and minimum number of seeds that current population can produce, respectively.

3) Spatial distribution

The generated seeds are randomly distributed over the K-dimensional search space by normally distributed real random numbers which have zero mean and variance σ^2. The standard deviation σ is made to decrease over the generations in the following manner.

$$\sigma_{cur} = \sigma_{\min} + \left(\frac{iter_{\max} - iter}{iter_{\max}}\right)^{nmi}(\sigma_{\max} - \sigma_{\min}) \quad (17)$$

where $\sigma_{\min}$ and $\sigma_{\max}$ are the minimum and maximum standard deviation, σ_{cur} is the standard deviation at the present time step, nmi represents the nonlinear modulation index. The maximum iteration number is $iter_{\max}$.

4) Competitive exclusion

Some kind of competition between plants is needed for limiting the maximum number of plants in a colony. Initially, the plants in a colony will reproduce fast and all the produced plants will be included in the existing colony, until the number of plants in the colony reaches a maximum value p_max. However, it is expected that by this time the fitter plants have reproduced more seeds when compared to weaker plants. From then on, only the fittest plants up to p_max, among the existing ones and the reproduced ones, are taken in the colony and steps 2 to 4 are repeated until the maximum number of iterations have reached. So, the population size in each generation must be less than or equal to p_max. This method is known as competitive exclusion and is also a selection procedure of IWO.

4.2 Optimization Steps

In order to optimize the positions of the array elements by using IWO, the optimization procedure can be expressed as follows:

Step 1. The parameter values of the antenna arrays and IWO are given. A $N\times K$-dimensional matrix is chosen as the initial population to be optimized. Each dimension of the population can be depicted by r_i, $i = 1, 2,\cdots, N$, where $N = N_L+N_H–4$ and $r_i\in[0,1]$. The first N_L–2 values are used to generate the element positions of lower frequency subarray while the rest N_H–2 values are used to generate the element positions of higher frequency subarray. Let $iter$ =1.

Step 2. The positions of the array elements are calculated by (8) and (15).

Step 3. The radiation patterns of the subarrays are calculated by (1) and (2). The peak side lobe level of the radiation patterns are determined by (3). The fitness value is defined by (5), which increases with the decrease of PSLL. The optimized parameters that can produce the best fitness are preserved as the ultimate result.

Step 4. The optimization parameters r_i, $i = 1, 2,\cdots, N$, are updated by IWO which has been introduced in Section 4.1.

Step 5. Let $iter = iter+1$, if $iter < iter_{\max}$, go to step 2, otherwise, terminate iteration.

5. Optimization Results

In this section, several simulation results are given to show the feasibility and effectiveness of the proposed algorithm. The parameters used in above equations are given in Tab. 1. The minimum spacing constrains for the adjacent array elements of the two subarrays are chosen as follows: $d_L = \lambda_L/2$, $d_H = \lambda_H/2$, $d_{LH} = (\lambda_H+\lambda_L)/4$.

$s_{\min}$	$s_{\max}$	$\sigma_{\min}$	$\sigma_{\max}$	K	$p\_\max$	$iter_{\max}$	nmi
0	10	10^{-3}	0.1	10	30	3000	3

Tab. 1. IWO parameter values.

Pattern Parameters	S-band	Ku-band	X-band	Ka-band
PSLL (dB)	−17.53	−17.56	−19.01	−19.03
MBW (^{0})	11.0	9.0	9.0	9.0
3dB BW (^{0})	3.62	0.72	3.08	0.88

Tab. 2. Parameters of the radiation patterns.

In order to demonstrate the effectiveness of IWO, the optimization results are compared with the results optimized by Particle Swarm Optimization (PSO) [9]. In case of PSO, as suggested in [9], both the cognitive rate (c_1) and the social rate (c_2) are set to 2.0 and the inertial weight is varied from 0.9 to 0.2. The number of sampling points for θ is 359. In order to obtain radiation patterns with low side lobe levels, the positions of the array elements are optimized. The algorithm is calculated 20 times and the best result is preserved as the ultimate result. A normal personal computer Intel Core i3 530 @2.93GHz CPU and 2GB of RAM is used and the algorithm is programmed by using MATLAB version 7.1.

5.1 *S*-band and *Ku*-band

In the first example, synthesis of *S*-band and *Ku*-band shared aperture antenna array is proposed. The central wavelengths of *S*-band and *Ku*-band are $\lambda_L = 10$ cm and $\lambda_H = 2$ cm, respectively. The element numbers of the two subarrays are chosen as $N_L = 20$ and $N_H = 45$. The total length of the whole array aperture is selected as $35\lambda_L/2$. The central frequency ratio of the two working frequencies is $\mu = \lambda_L/\lambda_H = 5.0$ which is an integer.

For the best optimization result of the 20 calculations, the performance of IWO compared with Particle Swarm Optimization (PSO) is shown in Fig. 4. It can be seen that

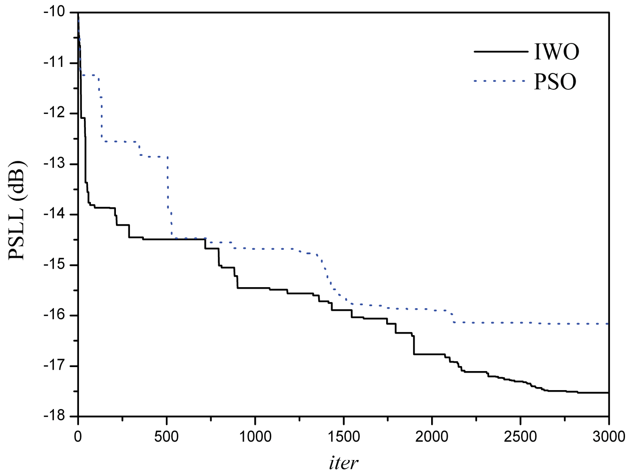

Fig. 4. PSLL versus iteration (*S*-band and *Ku*-band).

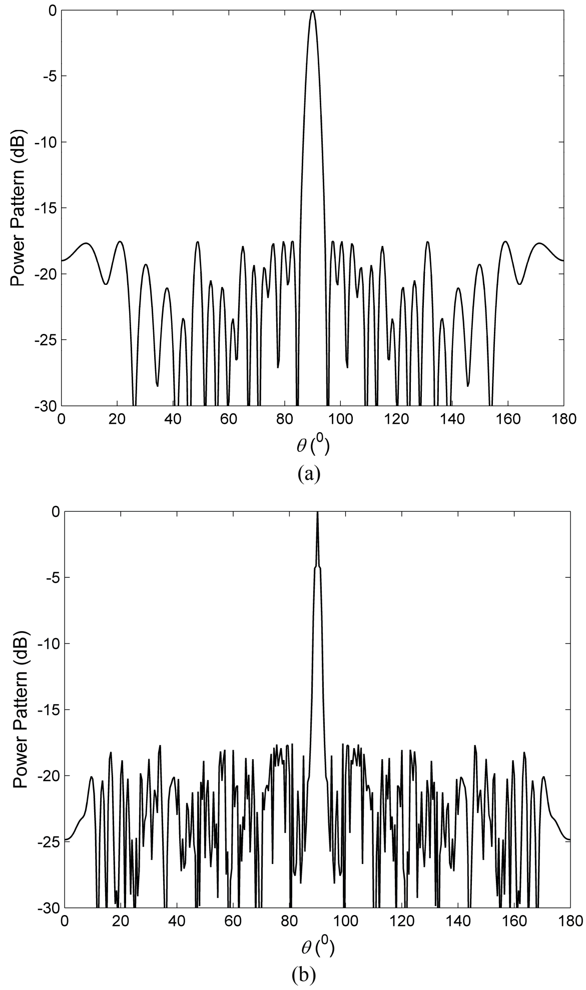

Fig. 5. Radiation patterns of the antenna array. (a) *S*-band; (b) *Ku*-band.

IWO can achieve a lower PSLL than PSO in this problem. The best results are PSLL = −17.53 dB optimized by IWO and PSLL = −16.16 dB synthesized by PSO. The radiation patterns of *S*-band subarray and *Ku*-band subarray are given in Fig. 5. The parameters of the radiation patterns, such as PSLL, main beam width (MBW) and 3 dB beam width (3 dB BW), are shown in Tab. 2. The element positions of both subarrays are given in Tab. 3 and Tab. 4. From Tab. 3 and Tab. 4, we can find that the minimum spacing of the adjacent elements for *S*-band subarray is 5.06 cm and which is 1.008 cm for *Ku*-band subarray. The minimum element spacing between *S*-band subarray and *Ku*-band subarray is 3.0 cm. They all fulfill those minimum spacing constrains given in (4). In order to show the advantage of the proposed method, the worst and average results of the 20 calculations are given. The worst and average results synthesized by IWO are PSLL = −16.60 dB and PSLL = −17.18 dB, respectively. The worst and average results synthesized by PSO are PSLL = −13.74 dB and PSLL = −15.44 dB. The computation time for a single optimization trail by IWO is about 3900 s while which is about 6100 s for PSO. From the results given above, it can be found that IWO is more effective and stable than PSO. Moreover, IWO is more timesaving than PSO.

Element Number	Element Positions (cm)				
1-5	3.000	50.637	58.511	66.030	73.243
6-10	80.359	88.063	93.759	98.819	105.040
11-15	111.466	117.259	123.243	128.447	133.794
16-20	138.865	144.926	154.303	164.937	172.000

Tab. 3. Positions of *S*-band subarray elements.

Element Number	Element Positions (cm)				
1-5	0.000	6.316	7.824	9.151	10.941
6-10	12.304	13.842	15.359	17.049	18.587
11-15	19.690	20.986	21.996	23.162	24.692
16-20	25.944	27.053	28.390	29.493	30.578
21-25	31.636	32.691	33.743	34.787	35.795
26-30	37.083	38.521	39.612	40.656	42.424
31-35	43.437	44.594	45.812	47.609	55.441
36-40	62.510	76.293	83.479	108.417	149.808
41-45	150.897	159.247	160.563	168.673	175.000

Tab. 4. Positions of *Ku*-band subarray elements.

5.2 *X*-band and *Ka*-band

In this example, the synthesis result of *X*-band and *Ka*-band shared aperture antenna array is presented. The central working wavelengths of *X*-band and *Ka*-band are $\lambda_L = 3$ cm and $\lambda_H = 0.8$ cm. The element numbers of both subarrays are selected as $N_L = 25$ and $N_H = 50$. The length of the whole array aperture is selected as $45\lambda_L/2$. The central frequency ratio of the two working frequencies is $\mu = \lambda_L/\lambda_H = 3.75$.

Fig. 6 gives the convergence curves of the best result for IWO and PSO. From Fig. 6, we can observe that IWO

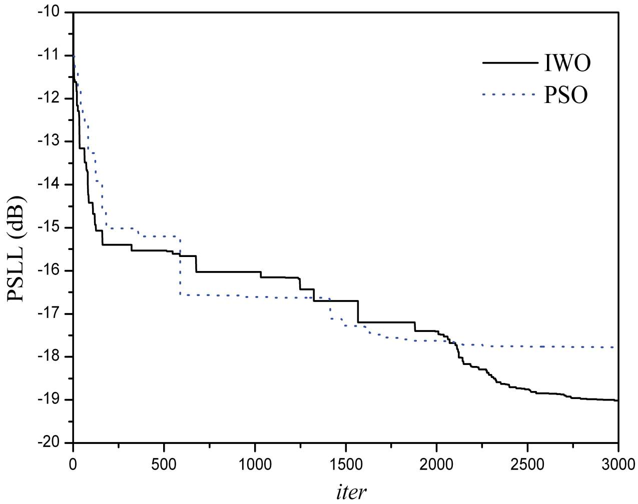

Fig. 6. PSLL versus iteration (*X*-band and *Ka*-band).

Element Number	Element Positions (cm)				
1-5	0.950	20.308	24.869	26.862	28.962
6-10	31.066	33.085	35.019	36.779	38.349
11-15	40.116	41.623	43.138	44.665	46.206
16-20	47.755	49.278	50.805	52.508	54.266
21-25	56.339	58.843	61.672	64.433	66.550

Tab. 5. Positions of *X*-band subarray elements.

Element Number	Element Positions (cm)				
1-5	0.000	1.908	2.650	3.380	3.993
6-10	4.523	5.154	5.787	6.236	6.711
11-15	7.130	7.623	8.080	8.587	9.027
16-20	9.628	10.030	10.441	11.016	11.516
21-25	12.049	12.452	12.873	13.344	13.751
26-30	14.166	14.571	14.976	15.384	15.888
31-35	16.447	16.950	17.350	17.759	18.256
36-40	18.688	19.173	21.484	21.912	22.465
41-45	22.952	23.486	23.892	30.106	57.506
46-50	59.818	60.415	62.819	63.411	67.500

Tab. 6. Positions of *Ka*-band subarray elements.

has better performance than PSO. The best results for IWO and PSO are PSLL = −19.01 dB and PSLL = −17.78 dB, respectively. The parameters of the radiations are given in Tab. 2. Tab. 5 and Tab. 6 provide the element positions of *X*-band subarray and *Ka*-band subarray, respectively. From Tab. 5 and Tab. 6, we can find that the minimum element spacings of *X*-band subarray and *Ka*-band subarray are 1.01 cm and 0.4 cm, respectively. The minimum element spacing between *X*-band subarray and *Ka*-band subarray is 0.95 cm. The element spacings satisfy the distance constrains proposed in (4). The worst and average results of the 20 calculations for IWO are PSLL = −17.75 dB and PSLL = −18.18 dB. The worst and average results for PSO are PSLL = −16.73 dB and PSLL = −17.23 dB, respectively. In this example, it takes about 4600 s and 6800 s for a single trail by IWO and PSO, respectively. So, IWO can get a lower peak side lobe level and takes less algorithm time than PSO.

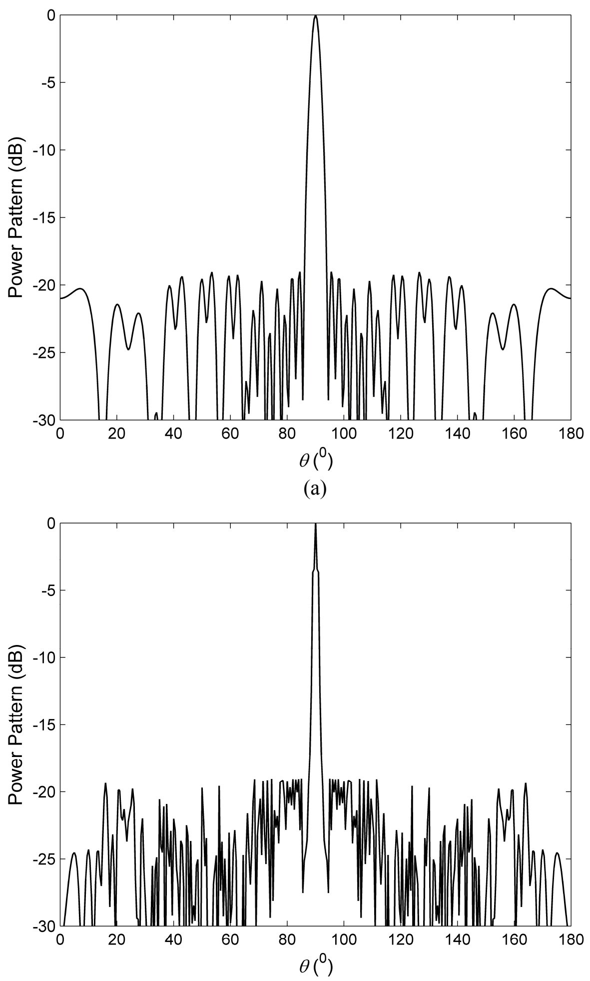

Fig. 7. Radiation patterns of the antenna array. (a) *X*-band; (b) *Ka*-band.

6. Conclusions

IWO is used in the synthesis of dual-band antenna arrays. The shared aperture interleaved linear antenna arrays working in a wide frequency range are considered here. In order to get radiation patterns with low side lobe levels, the element positions are optimized. The simulation results show that the PSLLs of the radiation patterns optimized by IWO are lower than those optimized by PSO. The PSLLs of the radiation patterns optimized by IWO are lower than −17 dB. Also, the minimum element spacing of the antenna arrays satisfies the designing constrains which will reduce the cross coupling effect of the adjacent elements.

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About Authors ...

Hua GUO was born in 1981. He received his B.S. degree in Applied Physics from Xidian University (XDU) in 2004. In 2007, he obtained his M.S. degree in Radio Physics from XDU. He is now working towards the Ph.D. degree in Electromagnetic Fields and Microwave Techniques at Northwestern Polytechnical University (NWPU). His research interests include electromagnetic theory and calculation, array antenna design, phased arrays and radars.

Chenjiang GUO was born in 1963. He received his B.Eng. degree in Electronic Engineering in 1984 from Northwestern Polytechnical University (NWPU). He obtained his M.S. degree in Electromagnetic Fields and Microwave Techniques in 1987 from the NWPU. In 2007, he received his Ph.D. degree in Circuits and Systems from

the NWPU. He is now a professor of Electromagnetic Fields and Microwave Techniques in the NWPU. His research interests include electromagnetic theory, antenna theory and design, microwave circuit design and electromagnetic compatibility (EMC).

Jun DING was born in 1964. She received her B.Eng. degree in Electronic Engineering in 1986 from Northwestern Polytechnical University (NWPU). She obtained her M.S. degree in Electromagnetic Fields and Microwave Techniques in 1989 from the NWPU. In 2005, she received her Ph.D. degree in Circuits and Systems from the NWPU. She is now a professor of Electromagnetic Fields and Microwave Techniques in the NWPU. Her research interests include electromagnetic calculation, antenna theory and design, microwave circuit design and electromagnetic compatibility (EMC).