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A single objective approach for suppressing sideband radiations of ultra-low side lobe patterns in time-modulated antenna arrays

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In this paper, a novel optimization method based on single objective, that is, minimization of sideband radiation (SBR) of ultra-low side lobe, narrow beam patterns in time modulated antenna arrays (TMAAs) is proposed. The proposed method utilizes the weighting vectors of the low side lobe Dolph-Chebyshev/Taylor series patterns as the dynamic excitation coefficients of the desired pattern at fundamental radiation. Differential evolution algorithm is employed to distribute the static amplitudes and switch-on time durations in such a way that in the optimization process, dynamic excitation distribution remains the same. Static amplitudes are perturbed in a predefined search range of (0.25, 1), whereas the weighted values of switch-on time durations are obtained by dividing dynamic excitation coefficients by static amplitudes. The technique greatly simplifies the difficulties of multi-objective TMAA synthesizing problem by reducing it to a single-objective optimization problem. Numerical examples for a 32-element linear array are presented to produce ultra low side lobe Taylor $\bar{n}$ and Dolph-Chebyshev pattern with low value of maximum sideband radiation (SBR_{max}). The optimization results of the proposed method are also compared with those obtained by other optimization techniques, which have been reported previously.

1. Introduction

Low side lobe-phased array antennas are very important in high-performance electronic systems, mainly which are operated in heavy clutter and/or jamming environments. Theoretically, the weighting vector of the element excitation distribution to generate low/ultra-low side lobe pattern can be obtained by using the well-known numerical techniques such as Chebyshev/Taylor distribution.[1] But, due to high dynamic range ratio (DRR) of static amplitude, it is very difficult to achieve low/ultra-low side lobe pattern in practical arrays. Because, high value of DRR produces various errors such as systematic error, random errors which degrade side lobe level (SLL) from its desired value.[2]

The time modulation technique to antenna array [3] provides an additional degree of freedom "time" to control the far-field pattern of the array. In its simplest form, the technique utilizes a simple switching circuit in the feed network of the array. The main advantage of this technique is that electronically, the relative on-time durations of the array elements can be organized properly to realize time-averaged radiation patterns of

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stipulated low side lobe level.[4] However, the undesired sideband radiations (SBRs) in time-modulated arrays reduces the radiation efficiency and directivity of the antenna array.[5,6] In 2002, Yang et al. [7] first reported an optimization method based on differential evolution (DE) to suppress the SBRs in time-modulated linear antenna arrays (TMLAAs). After that during the last decade including DE,[8–10] different evolutionary algorithms like genetic algorithms,[11] simulated annealing,[12–13] particle swarm optimization[14–18] and multi-objective evolutionary algorithm based on objective decomposition with DE operator (MOEA/D-DE) [19–20] have been applied to reduce the maximum of SBR (SBR_{max}) for the desired pattern at the operating frequency. Recently, in order to suppress the SBR_{max}, side band power of time-modulated antenna array (TMAA) is filtered out by using a modified switching circuit and the limited bandwidth of the practical radiating elements.[21]

Basically, TMAA synthesis problems are multi-objective optimization problems where the multiple objectives are low SLL and narrow beam width (BW) of the main beam at operating frequency and low value of SBR_{max}. In [19], it is shown that these specifications of the multiple objectives always conflict with each other. On the basis of the optimization techniques used so far to synthesize TMAAs, the optimization techniques can be classified in two categories as – (I) single objective optimization methods and (II) multi-objective optimization methods. In the first category, the TMAA synthesizing problems have been solved by applying a single objective optimization method where all the objectives are added with different weighting factor to form a single cost function and the cost function is minimized.[7–18] In such techniques, it is tedious and difficult to select proper weighting factors for the optimal solution as the values of the weighting factors are obtained by trial and error method.[8] On the other hand, in the second category, all the objectives are treated as distinct objectives and a multi-objective optimization tool such as MOEA/D-DE [19–20] has been applied to achieve all the objectives simultaneously. Usually, the first category of the optimization method has been applied in most of the TMAA synthesis problems whereas the second method has been used rarely.

In this paper, we introduce a method to realize low side lobe, narrow beam patterns in TMAAs with reduced SBR power. The proposed method utilizes the combined effectiveness of a single objective DE-based optimization method and well known analytical techniques like Dolph-Chebyshev/Taylor series. The analytical technique is used to provide the dynamic excitation coefficients of the low side lobe, narrow beam pattern whereas DE is applied to determine the appropriate combination of static amplitudes and switch-on time durations that suppress SBR without affecting the distribution of dynamic excitations. The proposed method is demonstrated by considering a 32-element TMLAA and reducing SBR_{max} of -50 dB SLL Taylor pattern and -58.5 dB SLL Dolph-Chebyshev pattern to below -32 dB.

2. Theory

Assume a broadside TMLAA of N mutually uncoupled, equally spaced isotropic radiators. Let at each modulation period T_m, all the radiators be periodically excited by a sinusoidal signal of frequency $\omega_0 = 2\pi f_0$ with on-time sequence $t_p^{on} (0 \leq t_p^{on} \leq T_m)$ $\forall p \in [1, N]$. The periodical excitation of the array elements can be decomposed by applying Fourier series technique and the resulting array factor at k-th harmonics can be written as in (1), [5].

$$AF_k(\theta, t) = e^{j(\omega_0 + k\omega_m)t} \sum_{p=1}^{N} A_p \tau_p \frac{\sin(k\pi\tau_p)}{k\pi\tau_p} e^{-j[k\pi\tau_p - (p-1)\beta d_0 \cos\theta]} \tag{1}$$

where $\omega_m = 2\pi/T_m = 2\pi f_m$ is the modulation frequency, $\{A_p\}$ and $\{\tau_p\} = t_p^{on}/T_m$ $\forall p \in [1, N]$ stand for the normalized static amplitudes and on-time durations of the array elements. From (1), it is seen that the array factor expression at the fundamental component, AF_0 (with $k=0$), provides the radiation pattern at the operating frequency. For the fundamental pattern of specific SLL and BW, the corresponding dynamic excitation distributions, $\{E_p\} = A_p\tau_p$ $\forall p \in [1, N]$ can be obtained by using any of the well-known weighting methods, namely Dolph-Chebyshev/Taylor series. For a specific fundamental pattern, the proposed approach utilizes DE to distribute $\{A_p\}$ and $\{\tau_p\}$ in such a way that their element wise products are equal to E_p $\forall p \in [1, N]$. As in the optimization process dynamic excitation distribution is remained same, the redistribution of the static amplitudes and switch-on time durations will not affect the SLL and the BW of the main beam at the operating frequency. Thus, the approach reduces the multiple objectives (simultaneous minimization of SLL, BW of the main at the operating frequency and SBR level) of TMLA to a single objective that is minimization of $\mathrm{SBR}_{\max}$ only.

3. Optimization via DE

3.1. Differential evolution

The DE algorithm [22–24] is a stochastic, efficient evolutionary computational method. Due to the superior search ability and faster convergence profile, it has been successfully applied to solve many antenna,[7–10] inverse scattering,[22] engineering [23] and electromagnetics [24] problems. DE starts the searching process by randomly generating an initial population of N_{POP} number of D dimensional parameter vectors as

$$\begin{bmatrix} V_1 \\ \vdots \\ V_{N_{POP}} \end{bmatrix} = \begin{bmatrix} v_{11} & v_{12} & \ldots v_{1D} \\ \vdots & \vdots & \vdots \\ v_{N_{POP}1} & v_{N_{POP}2} & \ldots v_{N_{POP}D} \end{bmatrix}. \tag{2}$$

where v_{ij} with $i = 1, 2, \ldots, N_{POP}$, $j = 1, 2, \ldots, D$; is the jth parameter value of the ith parameter vector. To generate the new vectors for the next generation, iteratively three genetic operators, mutation, crossover and selection are executed sequentially.

In mutation operation, corresponding to each primary parent vectors $\vec{V}_s^g$, $s = 1, 2, \ldots, N_{POP}$, of the current generation 'g', a mutant vector ($\vec{X}_s^g$) is produced as

$$\vec{X}_s^g = \vec{V}_\alpha^g + F.\left(\vec{V}_\beta^g - \vec{V}_\gamma^g\right) \tag{3}$$

where the vector indexes α, β and γ are mutually exclusive to each other and randomly chosen from the range [1, N_{POP}] such that these are different from the primary vector index 's'. F is a scalar number, known as mutation constant and its typical value lies between [0.4, 1].

The binomial crossover method is applied to enhance the potential diversity of the population. In this operation, new children vectors $\vec{Y}_s^g$ are formed by exchanging the components of the parent vectors and the mutant vectors. The components of the children vector are given by

$$y_{z,s}^{g} = \begin{cases} v_{z,s}^{g} & \text{if } (rand_{z,s}(0,1) \leq \eta_c \text{ or } z = z_{rand}) \\ x_{z,s}^{g} & \text{otherwise} \end{cases} \tag{4}$$

where $rand_{z,s}$ (0,1) is a randomly generated number between $(0,1)$ and the randomly chosen index, $z_{rand} \in [1,2,\ldots,D]$. The parameter $\eta_c \in (0,1)$ is known as crossover constant.

In the selection operation, to keep the population size constant at each consecutive generation of the optimization process; either parent vector of the current generation ($\vec{V}_s^g$) or the corresponding children vector ($\vec{Y}_s^g$) is selected as the parent vector for the next generation. The selection mechanism is

$$\begin{aligned} \vec{V}_s^{g+1} &= \vec{Y}_s^g \quad \text{if } \psi(\vec{Y}_s^g) \leq \psi(\vec{V}_s^g) \\ &= \vec{V}_s^g \quad \text{if } \psi(\vec{Y}_s^g) > \psi(\vec{V}_s^g). \end{aligned} \tag{5}$$

3.2. Optimization method

In order to suppress $\mathrm{SBR}_{\max}$ of the desired pattern at the operating frequency, DE is used in the following way. In the optimization process, to redistribute A_p and τ_p, only A_p $\forall p \in [1,N]$ are taken as optimization parameters for the DE algorithm. The algorithm perturbs A_p $\forall p \in [1,N]$ in the search range (0.25, 1). Then, to obtain τ_ps, E_ps are divided by A_ps as $\tau'_p = E_p/A_p$ $\forall p \in [1,N]$. For the given pattern E_ps are invariable, whereas A_ps may take any value from the search range (0.25, 1). Therefore, τ'_p may be greater than unity; particularly for the centre elements where E_p values are close to 1 whereas for A_p it may be less. For a particular distribution of A_p, let ξ be the maximum value of τ'_p which is obtained by dividing E_p by A_p $\forall p \in [1,N]$. Without loss of generality, ξ is used to normalize τ'_p and finally τ_ps are obtained as $\{\tau_p\} = \tau'_p/\xi$ $\forall p \in [1,N]$. ξ can be multiplied with A_p to get back the exact values of E_p but this is not required. Since the distribution of E_p or A_p normalized to its maximum will remain unchanged when these are multiplied or divided by a real number ξ.

3.3. Cost function

The DE is used to reduce the cost function value as low as possible. The cost function is defined as

$$\Psi(A_p, \tau_p) = \mathrm{SBR}_{\max} \tag{6}$$

where $\mathrm{SBR}_{\max}$ is the maximum sideband level (SBL) among all the SBR obtained during the optimization method. Since, first few harmonics contain a significant amount of power. In Section 4, we have considered the maximum value of SBL among the first five SBRs and numerical results show that in the higher harmonics the sideband level decrease automatically below the maximum value. Since at f_0, the SLL and BW of the main beam are determined by the predetermined dynamic excitation distribution of the pattern and are remained same during the optimization process. Hence, in this approach, the simultaneous optimization of multiple objectives like minimization of SLL, BW of the main at the operating frequency and $\mathrm{SBR}_{\max}$ are not required. Only one objective of the optimization problem based on the minimization of $\mathrm{SBR}_{\max}$ will suffice.

4. Results and discussion

To demonstrate the proposed approach, the following examples are presented. A symmetric TMLAA with $N = 32$ and $d_0 = 0.5\lambda$ is considered. As a first example, the weighting vector of -50 dB SLL Taylor $\bar{n}$ ($\bar{n} = 8$) pattern is selected. For this pattern, we want to suppress SBR_{max} as low as possible. Due to symmetry, the number of optimization parameters becomes half, i.e. 16. The control parameters of DE are set as $N_{POP} = 5D$, $F = 0.4$ and $\eta_c = 0.8$. After the preset 200 number of iterations, the DE reduced the cost function value to -32.87. It implies that corresponding to -50 dB SLL Taylor pattern; DE suppresses SBR_{max} to -32.87 dB. Figure 1 shows the DE-optimized power patterns at f_0 and first two sidebands, $f_0 + f_m$ and $f_0 + 2f_m$. The BW between the first null (FNBW) of the main beam of the Taylor pattern at f_0 is obtained as 15.62°. The optimized values of static amplitudes and on-time durations which are used to plot Figure 1 are shown in Figure 2. The search range of on-time durations is observed as [0.0484, 1].

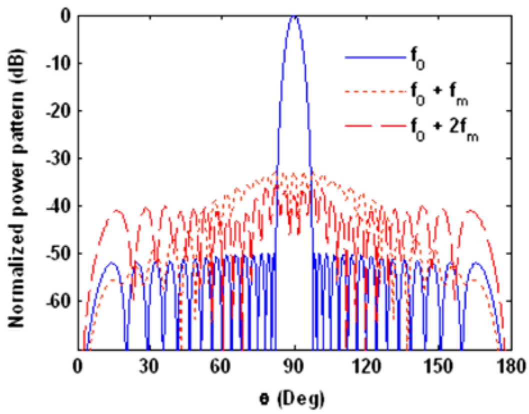

Figure 1. -50 dB SLL Taylor $\bar{n}$ ($\bar{n} = 8$) pattern at f_0 by suppressing SBL at $f_0 + f_m$ and $f_0 + 2f_m$ to -32.87 and -35.66 dB respectively.

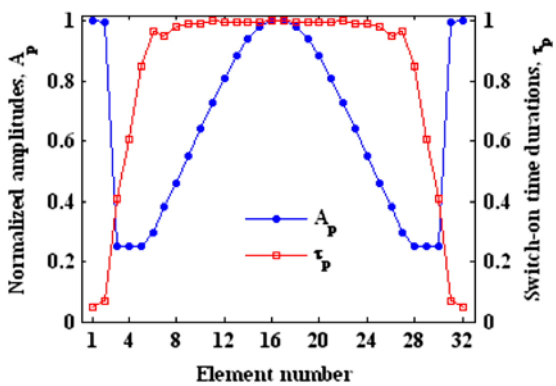

Figure 2. DE-optimized static amplitudes and related on-time durations of the power pattern shown in Figure 1.

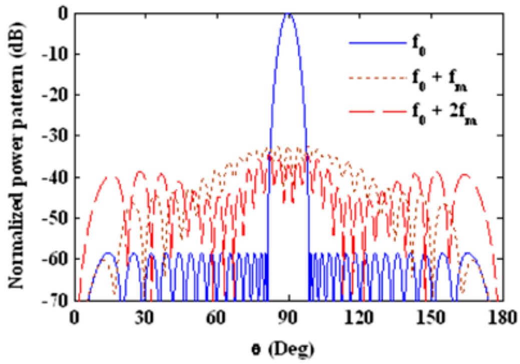

Figure 3. −58.5 dB SLL Chebyshev pattern at f_0 by suppressing SBL at $f_0 + f_m$ and $f_0 + 2f_m$ to −32.55 and −34.55 dB, respectively.

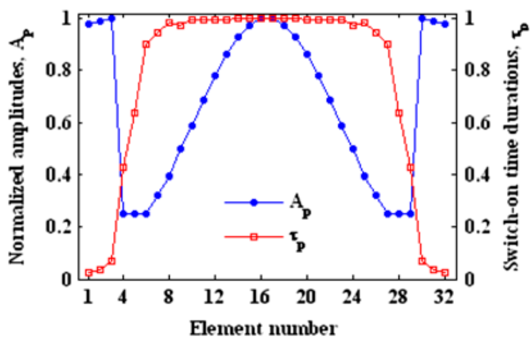

Figure 4. DE-optimized static amplitudes and related on-time durations of the power pattern shown in Figure 3.

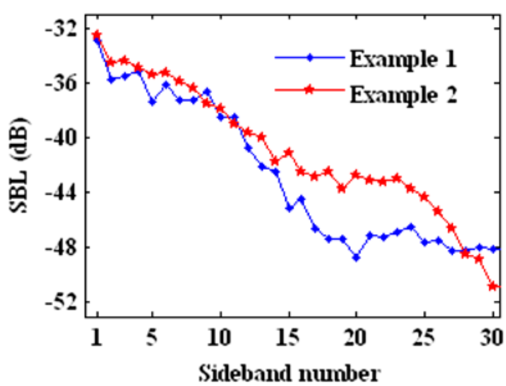

Figure 5. SBL at first 30 sideband of the DE-optimized 32 element TMLAA as considered in examples 1 and 2.

In [7], the category-I optimization technique based on DE is used to realize a pattern of same SLL by reducing SBR_{max} to −32.2 dB. However, FNBW of the fundamental pattern is almost 20° which is 3.38° higher than that of Figure 1.

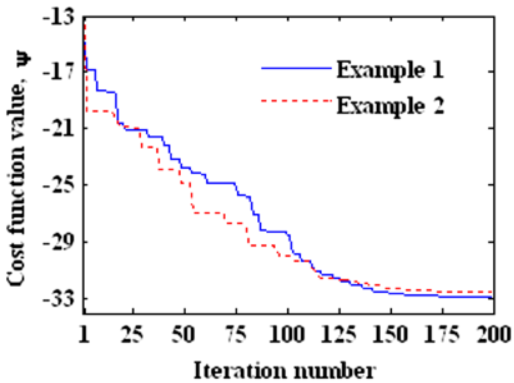

Figure 6. Variations of the cost function, Ψ during the optimization process of examples 1 and 2.

In [19], the category-II optimization technique based on MOEA/D-DE is used to synthesize the same TMLAAs as considered in the first example and Ref. [7]. There, it is also shown that the MOEA/D-DE-based optimization technique outperforms over the DE-based single objective optimization technique [7] by reducing SLL and SBR_{max} to −58.5 and −32.2 dB, respectively, with FNBW of almost 20°. To illustrate the effectiveness of our proposed approach, the weighting vector of −58.5 dB SLL Dolph-Chebyshev pattern is chosen as the second example. Since the Dolph-Chebyshev method provides the optimum pattern, i.e. the pattern with minimum BW for a specific value of SLL or, vice versa. In this case also, same values of DE control parameters are used. After 200 iterations, DE reduces the cost function value to −32.54. Thus, for the −58.5 dB SLL Dolph-Chebyshev pattern, SBR_{max} is reduced to −32.54 dB. To observe the power pattern with suppressed SBR, the normalized power pattern at f_0, $f_0 + f_m$ and $f_0 + 2f_m$ are plotted in Figure 3. The corresponding optimized static amplitudes and on-time durations are compiled in Figure 4. Figure 3 shows a really optimized pattern where a −58.5 dB SLL is obtained with narrowest FNBW of 17.78° as well as low value of SBR_{max}. The search range for the on-time durations are obtained as [0.0223, 1].

Figure 5 shows the SBL of first 30 harmonics produced by 32 elements TMLAA with the DE-optimized static amplitudes and on-time durations as shown in Figures 2 and 4 for the examples 1 and 2, respectively. From Figure 5, it is seen that the proposed approach successfully suppresses SBLs of all other harmonics to below SBR_{max}. For the above two examples, total sideband power losses and directivity of the array are evaluated by using the formula given in [Ref. [5], Equation (33)] and [Ref. [6], Equation (9), and Table 1], respectively. These values are obtained as 0.338 and 13.383 dB for example 1, and 0.350 and 13.231 dB for example 2.

Figure 6 shows the convergence characteristics of the DE for the two examples. It can be seen that in both the examples, DE successfully reduces the cost function value below −30 before 200 iterations. The proposed approach is also tested on the patterns of SLL up to −100 dB. The simple and robust method successfully reduces SBR_{max} to below −30 dB in all the cases. However, when the SLL is very low, the switch-on time durations for the edge elements become so low that it is practically very difficult to realize in practical switching circuits.

5. Conclusions

A single objective optimizing technique, based on DE is presented to minimize the SBR in TMLAs. The technique suppresses the sideband level by redistributing the static amplitudes and switch-on time durations of the predetermined dynamic excitation distribution of the fundamental pattern. Without affecting the fundamental power pattern, this straightforward single objective optimization method successfully reduces the sideband level to a significantly low value. The technique prevents the difficulties of providing weighting factors to the different objectives in TMLA synthesizing problem.

References

[1] Balanis Constantine A. Antenna theory analysis and design. 3rd ed. New Delhi: John Wiley & Sons; 2010.
[2] Schrank HE. Low sidelobe phased array antennas. IEEE Antennas Propagat. Society Newslett. 1983;25:4–9.
[3] Shanks HE, Bickmore RW. Four dimensional electromagnetic radiators. Canad. J. Phys. 1959;37:263–275.
[4] Kummer WH, Villeneuve AT, Fong TS, Terrio FG. Ultra-low side-lobes from time-modulated arrays. IEEE Trans. Antennas Prop. 1963;1:633–639.
[5] Bregains JC, Fondevila–Gomez J, Franceschetti G, Ares F. Signal radiation and power losses of time-modulated arrays. IEEE Trans. Antennas Prop. 2008;56:1799–1804.
[6] Yang S, Gan YB, Tan PK. Evaluation of directivity and gain for time modulated linear antenaa arrays. Microw. Opt. Technol. Lett. 2004;42:167–171.
[7] Yang S, Gan YB, Qing A. Sideband suppression in time-modulated linear arrays by the differential evolution algorithm. IEEE Antennas Wireless. Prop. Lett. 2002;1:173–175.
[8] Mandal SK, Mahanti GK, Ghatak Rowdra. Differential evolution algorithm for optimizing the conflicting parameters in time-modulated linear array antennas. Prog. Electromagnet. Res. B 2013;51:101–118.
[9] Aksoy E, Afacan E. Thinned nonuniform amplitude time-modulated linear arrays. IEEE Antennas Wireless Propag. Lett. 2010;9:514–517.
[10] Zhu Q, Yang S, Zheng L, Nie Z. Design of a low side lobe time modulated linear array with uniform amplitude and subsectional optimized time steps. IEEE Trans. Antennas Prop. 2012;60:4436–4439.
[11] Yang S, Gan YB, Qing A, Tan PK. Design of uniform amplitude time modulated linear array with optimized time sequences. IEEE Trans. Antennas Prop. 2005;53:2337–2339.
[12] Fondevila J, Bregains JC, Ares F, Moreno E. Optimizing uniformly excited linear arrays through time modulation. IEEE Antennas Prop. Lett. 2008;56:1799–1804.
[13] Fondevila J, Brégains JC, Ares F, Moreno E. Application of time-modulation in the synthesis of sum and difference patterns by using linear arrays. Microw. Opt. Technol. Lett. 2006;48:829–832.
[14] Poli L, Rocca P, Manica L, Massa A. Handling sideband radiation in time-modulated arrays through particle swarm optimization. IEEE Trans. Antennas Prop. 2010;58:1408–1411.
[15] Poli L, Rocca P, Manica L, Massa A. Sideband radiation reduction exploiting pattern multiplication in directive time-modulated linear arrays. IET Microwaves Antennas Propag. 2012;6:214–222.
[16] Poli L, Rocca P, Manica L, Massa A. Pattern synthesis in time-modulated linear arrays through pulse shifting. IET Microw. Antennas Propag. 2010;4(9):1157–1164.
[17] Rocca P, Poli L, Oliveri G, Massa A. Synthesis of time-modulated planar arrays with controlled harmonic radiations. J. Electromagn. Waves Appl. 2010;24:827–838.
[18] Rocca P, Manica L, Poli L, Massa A. Synthesis of compromise sum-difference arrays through time-modulation. IET Radar Sonar Nav. 2009;3:630–637.
[19] Chen Y, Yang S, Nie Z. Improving conflicting specifications of time-modulated antenna arrays by using a multiobjective evolutionary algorithm. Int. J. Numer. Model, Wiley online, library. 2012;25:205–215.
[20] Pal S, Das S, Basak A. Design of time-modulated linear arrays with a multi-objective optimization approach. Prog. Electromagnet. Res., B. 2010;23:83–107.

[21] Y. Tong, Tennant A. Sideband level suppression in time modulated linear arrays using modified switching sequences and fixed bandwidth elements. Electron. Lett. 2012;48:10–11.
[22] Rocca P, Benedetti M, Donelli M, Franceschini D, Massa A. Evolutionary optimization as applied to inverse scattering problems. Inverse Prob., Topical Rev. 2009;25:1–41.
[23] Das S, Suganthan PN. Differential evolution: a survey of the state –of-the-art. IEEE Trans. Evol. Comput. 2011;15(1):4–31.
[24] Rocca P, Oliveri G, Massa A. Differential evolution as applied to electromagnetics. IEEE Antennas Propag. Mag. 2011;53(1):38–49.