Progress In Electromagnetics Research C, Vol. 32, 139–149, 2012

A COMPACT TRI-BAND ANTENNA DESIGN USING BOOLEAN DIFFERENTIAL EVOLUTION ALGORITHM

D. Li[1,*], F.-S. Zhang[1], and J.-H. Ren[2]

[1]National Key Laboratory of Antennas and Microwave Technology, Xidian University, Xi'an, Shaanxi 710071, P. R. China

[2]Shenzhen, Guangdong 518001, P. R. China

Abstract—A compact tri-band slot antenna based on a mesh-grid structure, which is suitable for WLAN/WiMAX applications, is presented. The proposed antenna is optimized by a Boolean differential evolution algorithm (BDE). Then an experimental prototype is fabricated and measured. Results of simulation and measurements indicate that the proposed antenna has $|S_{11}| < -10\,\mathrm{dB}$ in the three chosen frequency bands from 2.35 to 2.85 GHz, from 3.1 to 4.4 GHz and from 4.8 GHz to 5.85 GHz, which covers WLAN bands (2.4/5.2/5.8 GHz) and the WiMAX bands (2.5/3.5/5.5 GHz), respectively. In addition, good radiation performances such as omnidirectional and doughnut-shaped directivity and reasonable gain over the operating bands have been obtained. This example also demonstrates the applicability of the BDE/MOM optimization algorithm to efficient and in potential automated method for the antenna design.

1. INTRODUCTION

Recently, with the widespread deployment of short distance wireless communications, such as Wireless Local Area Networks (WLANs), the demand for compact, low cost, multiband and broadband antennas has increased rapidly. The two commonly used protocols of WLANs are WiFi and WiMAX. WiFi, which relays data and promises higher data rates and increased reliability based on access point, is designed to operate in 2.4 GHz (2.40–2.48 GHz) band and 5 GHz bands (5.15–5.35 GHz, 5.725–5.825 GHz in the United States and 5.15-5.35 GHz,

Received 2 July 2012, Accepted 27 August 2012, Scheduled 9 September 2012

* Corresponding author: Dong Li (sea20060902@163.com).

5.47–5.725 GHz in Europe). There is also another low cost and easily deployable broadband wireless access technology commonly named WiMAX (Worldwide Interoperability for Microwave Access), which is allocated the 2.5–2.69/3.4–3.69/5.25–5.85 GHz bands. According to the requirements of miniaturization and integration of modern communication system, it is necessary for an antenna to cover all these bands [1].

Differential evolution (DE) as a new algorithm was proposed by Price and Storn [2–4]. It is an effective, robust, and simple global optimization algorithm, which only has a few control parameters. DE has been successfully applied to many EM problems, such as array synthesis [5], electromagnetic imaging [6], and synthesis of coplanar strip lines [7]. Meanwhile, to solve binary optimization problems, some binary versions of DE have been proposed [8, 9]. In [9], a novel binary version of DE, namely Boolean differential evolution (BDE), has been applied to thinned array design, and it is observed that DE is also a powerful tool for binary optimization problems. Genetic algorithm (GA) optimized mesh-grid structure has been widely used in electromagnetic design, problems, such as microstrip patch antenna [10], planar monopole antenna [11], and frequency selective surface (FSS) [12] design ones.

In this paper, a tri-band slot antenna with a mesh-grid structure is introduced. The grids as well as the dimensions of the feed line are coded into a single binary chromosome and optimized simultaneously. Instead of GA, the recently proposed BDE algorithm is utilized as the binary optimizer [9]. By optimizing the mesh-grid structure, an appropriate slot shape, which has significantly enlarged the antenna's impedance bandwidth, is obtained. And the effectiveness of the BDE/MOM algorithm (combine BDE with the method of moment (MOM)) for antenna design is demonstrated. The optimized antenna is fabricated and measured. The measured results show good agreement with the simulated ones. Details of the antenna design and both the simulated and measured results are presented and discussed.

2. ANTENNA DESIGN

2.1. Boolean Differential Evolution (BDE)

Like other evolutionary algorithms, DE is a population-based stochastic optimizer that starts to explore the search space by sampling a multiple, randomly chosen initial point [2–4]. BDE follows the general procedures of the classic DE, except that the mutation operation is implemented using Boolean algebra. Assume that $\overrightarrow{X_{i,G}}$

$(i = 1, 2 \ldots NP)$ are solution vectors at generation G, which are represented by D-bit binary strings $(X_{1,i,G}, X_{2,i,G}, \ldots, X_{D,i,G})$, where NP is the population size and D the problem dimension. Successive populations are generated by adding the weighted difference of two randomly selected vectors to a third randomly selected vector. For classical BDE (BDE/best/1), the mutation, crossover, and selection operators are straight forwardly defined as follows.

2.1.1. Mutation

In the BDE algorithm, for each generation G of vectors $\overrightarrow{X_{i,G}}$, the mutation generation produces a set of mutation vectors $\overrightarrow{V_{i,G}} = (V_{1,i,G}, V_{2,i,G}, \ldots, V_{D,i,G})$ as follows:

$$\overrightarrow{V_{i,G}} = \overrightarrow{X_{best,G}} + \overrightarrow{F} \cdot \left(\overrightarrow{X_{r_1,G}} \oplus \overrightarrow{X_{r_2,G}}\right) \tag{1}$$

where r_1 and r_2 are mutually different integer indices randomly selected from $[1, 2 \ldots NP]$. 'AND', 'OR' and 'XOR' operators are denoted by symbols $(\cdot)$, $(+)$ and $(\oplus)$, respectively. $\overrightarrow{F}$ is a random D-bit binary string, which is not a control parameter in contrast to the classic DE algorithm. $\overrightarrow{X_{best,G}}$ is the best individual with the best fitness value in the population at generation G.

2.1.2. Crossover (Mating)

After the mutation phase, where NP mutant vectors $\overrightarrow{V_{i,G}}$ $(i = 1, 2 \ldots, NP)$ are calculated, the "binominal" crossover operation is applied to each pair of the generated mutant vector $\overrightarrow{V_{i,G}}$ and its corresponding target vector $\overrightarrow{X_{i,G}}$ to generate a trial vector

$$\begin{aligned} \overrightarrow{U_{i.G}} &= (U_{1,i,G}, U_{2,i,G}, \ldots, U_{D,i,G}) \\ U_{j,i,G} &= \begin{cases} V_{j,i,G} & \text{If } \mathrm{ran}(0,1) \le CR \text{ or } j = j_{rand} \\ X_{j,i,G} & \text{Otherwise} \end{cases} \end{aligned} \tag{2}$$

where CR is the crossover constant in the range [0, 1], which is the only control parameter of BDE. j_{rand} is a randomly chosen integer in the range $[1, D]$ which ensures $U_{j,i,G}$ to get at least one parameter from $V_{j,i,G}$. $\overrightarrow{V_{i,G}}$ and $\overrightarrow{X_{i,G}}$ are the chosen mating pairs.

2.1.3. Selection

To decide whether or not it should become a member of the next generation, each child (trial vector $\overrightarrow{U_{i,G}}$) competes with its parent

($\overrightarrow{X_{i,G}}$), and survives only if its fitness value is better. The fitness value depends on specific problems, which is also the minimized VSWR or the maximized gain in antenna design. The selection operation selects the better one from the parent vector $\overrightarrow{X_{i,G}}$ and the trial vector $\overrightarrow{U_{i,G}}$ according to their fitness values. For example, if we have a minimization problem, then $f(x)$ is the fitness function, and fitness value is $\mathrm{Min}(f(x))$. The selected vector is given by

$$\overrightarrow{X_{i,G+1}} = \begin{cases} U_{i,G} & \text{If } f\left(\overrightarrow{U_{i,G}}\right) < f\left(\overrightarrow{X_{i,G}}\right) \\ \overrightarrow{X_{i,G}} & \text{Otherwise} \end{cases} \tag{3}$$

And the selected one is used as a parent vector in the next generation.

In this design, the antenna structure is decided by the BDE algorithm, and the electrical characteristic of the antenna is calculated using the method of moment (MOM). By combining BDE with MOM, an efficient method for antenna design and optimization is presented [9]. The flow chart of a typical BDE/MOM is show in Figure 1.

2.2. Antenna Structure

The antenna is printed on a $24.2 \times 32.2\,\mathrm{mm}^2$ substrate with a thickness of 1 mm and dielectric constant of 2.65. As previously mentioned, the upper part of the ground plane consists of a 9 by 12 grid of

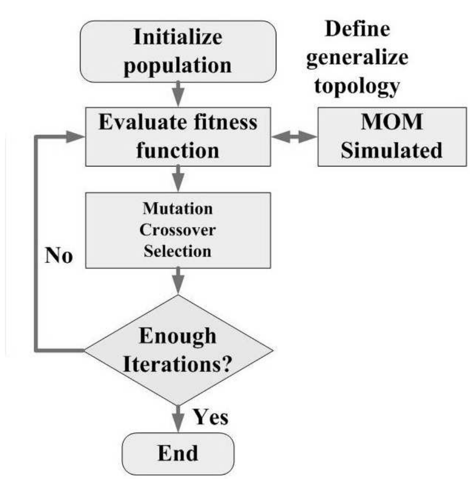

Figure 1. Flow chart illustrating the steps of a BDE/MOM algorithm.

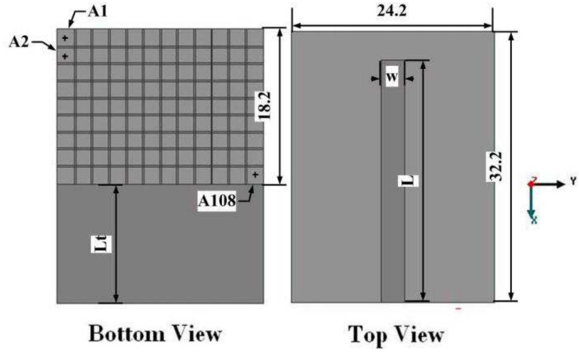

Figure 2. Geometry of the proposed antenna.

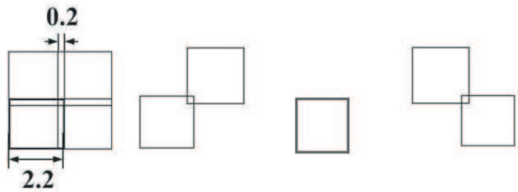

Figure 3. Geometry of the overlapping sub-patches.

metallic sub-patches. The overall dimension of the grid structure is 24.2 mm $\times$ 18.2 mm, and $Lt = 14$ mm. Each metallic subpatch of the grid structure can be switched "on" or "off" by the BDE algorithm. Figure 2 shows all sub-patches switched "on." Each sub-patch is a $2.2 \times 2.2\,\text{mm}^2$ square, and they are overlapped by 0.2 mm to ensure electrical contact in such constellations where two subpatches are touching only at the corner. This structure is to avoid impractical one-point sub-patch contacts [13]. The geometry of the overlapping sub-patches is shown in Figure 3.

2.3. BDE/MOM Optimization for Antenna Design

In the present design, the goal is to obtain a tri-band slot antenna, covering the WLAN and WiMAX bands. In the optimization process, no constraints placed upon how sub-patches can be set, so various slot shapes may be created, and some sub-patches separated from others may be created as a coupling structure. Thus, a 108-bit binary string ($A_1A_2 \ldots A_{108}$) is used and the on/off status of the ith sub-patch represented by A_i ($A_i = 1$ if the status is on, else $A_i = 0$). Besides the grid of sub-patches, the dimensions of the feed line which depends on the values of L and W should also be optimized. These parameters are encoded with an 8-bit binary code, respectively. As a result, the structure of the antenna is represented by a 124-bit long binary code, in which the grid structure is represented by the anterior 108-bit, and the remaining 16-bit, divided into 2 parts, represents the values of L and w.

A simple GA optimizer is developed in [14] and used to optimize the tri-band performance of the proposed antenna. The BDE can be broken down into a series of procedures as follows.

2.3.1. Creating an Initial Population

As previously mentioned, the configuration of the antenna is represented by a vector consisting of 124 bit code. Each vector just like a chromosome and each code of the vector like a gene. A diverse population of 30 solutions is generated by randomly setting each code to 0 or 1. The maximum number of fitness function iteration is set to 3000.

2.3.2. Evaluating Fitness Value of the Solutions

The fitness value of the solutions is evaluated by using IE3D software based on method of moment (MOM) [15]. The fitness function for the antenna design is given by:

$$\text{Fitness Value} = \min\left(Y_1 - Y_2\right)$$

$$\begin{aligned} Y_1 &= \frac{1}{M}\sum_{2.3\,\text{GHz}}^{2.9\,\text{GHz}} S_1(f) + \frac{1}{N}\sum_{3\,\text{GHz}}^{4.1\,\text{GHz}} S_1(f) + \frac{1}{L}\sum_{5\,\text{GHz}}^{6\,\text{GHz}} S_1(f) \\ Y_2 &= \frac{1}{P}\sum_{2.9\,\text{GHz}}^{3\,\text{GHz}} S_2(f) + \frac{1}{Q}\sum_{4.1\,\text{GHz}}^{5\,\text{GHz}} S_2(f) \end{aligned} \tag{4}$$

$$\begin{aligned} S_1(f) &= \begin{cases} |S_{11}(f)| & |S_{11}(f)| \geq -13 \\ -13 & |S_{11}(f)| < -13 \end{cases} \\ S_2(f) &= \begin{cases} |S_{11}(f)| & |S_{11}(f)| \leq -10 \\ -10 & |S_{11}(f)| > -10 \end{cases} \end{aligned} \tag{5}$$

In formula (4), M, N, L, P and Q are the numbers of the sample points within each band, where $M = 3$, $N = 4$, $L = 4$, $P = 1$ and $Q = 3$ have been used, so we sample 15 frequency points within the corresponding three bands. Y_1 represents the average of the $|S_{11}|$ through all bands and Y_2 the average of the $|S_{11}|$ outside the chosen bands.

2.3.3. Choosing the Mating Pairs

There exist a variety of techniques to choose from whose solutions should mate together to create a new generation. Here, the binary tournament selection, regarded as the most successful one, is used. This technique picks two solutions out of the population at random and adds the solution with better fitness to the mating pool.

2.3.4. Mating the Solutions Together

In our BDE, a crossover probability of 80% is used, $CR = 0.2$. To avoid the gene pool stagnation, a multipoint crossover technique is implemented. Each chromosome is randomly split up into five segments. The offspring solutions are then generated using alternate segments of their parents. In a final effort to maintain variation within the gene pool, each gene in every chromosome is given a 1% chance of mutation, causing it to switch from a 0 to a 1 or vice versa.

3. RESULTS AND DISCUSSION

The fitness value of the designed antenna after the fitness function iteration over 3000 times is plotted in Figure 4. Because of the complexity of the solution space, the best design is obtained after the 1800th iteration in each optimization. Through BDE/MOM process, it is observed that the obtained optimal fitness value is less than -18 dB. However, it should be noted that a better solution may exist as such algorithms do not guarantee a selection of absolute best solution, but one of possible, fitting the fitness requirements.

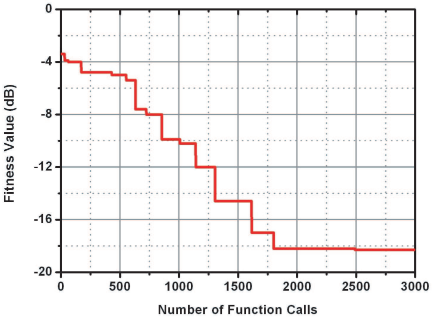

Figure 4. Convergence characteristic of the BDE/MOM.

Figure 5. Best antenna made using the result of optimization.

The optimum value of L is 18.87 mm, w is 2.8 mm and the optimized 108-bit binary on/off matrix is

$$[A_n] = \begin{bmatrix} 1 & 1 & 1 & 0 & 1 & 1 & 0 & 0 & 1 & 1 & 1 & 0 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 1 & 1 & 1 & 0 \\ 1 & 0 & 1 & 1 & 1 & 1 & 0 & 0 & 1 & 0 & 1 & 0 \\ 0 & 1 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 \\ 1 & 0 & 1 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 0 & 1 \\ 1 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 1 & 1 & 1 \\ 0 & 0 & 1 & 0 & 1 & 0 & 1 & 1 & 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 1 \end{bmatrix}$$

The best antenna made using the result of optimization is shown in Figure 5 and has been successfully fabricated to test the accuracy of the BDE/MOM algorithm in practical antenna designs. The return losses of the optimized tri-band antenna are simulated using Zealand's IE3D software package and measured using WILTRON37269A vector network analyzer.

Figure 6 shows a comparison of the simulated and measured results, and a good agreement between the simulated and measured results is observed. Three bandwidth ranges of 2.35–2.85 GHz, 3.1–4.4 GHz and 4.8–5.85 GHz of antenna operation with $|S_{11}| < -10$ dB have been achieved. The results show that the designed antenna is quite attractive for WLAN and WiMAX applications.

The normalized radiation patterns of the proposed antenna measured at 2.5, 3.55, and 5.5 GHz are shown in Figure 7. The co-polarization radiation patterns are measured results, but the cross-polarization radiation patterns are simulated results. It can be seen

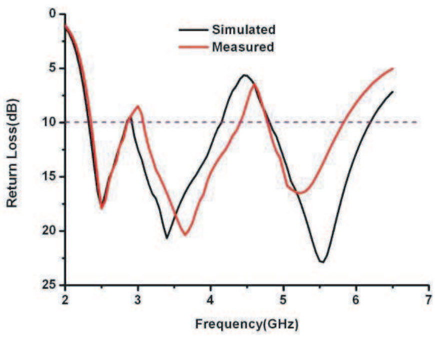

Figure 6. Simulated and measured return loss of the optimized antenna.

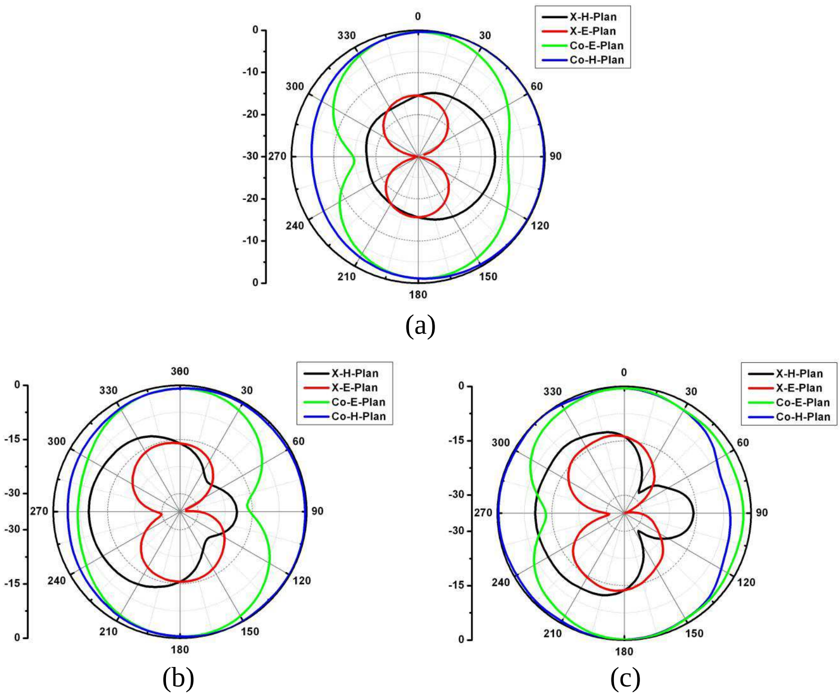

Figure 7. Radiation patterns of the proposed antenna at (a) 2.5 GHz, (b) 3.55 GHz, (c) 5.5 GHz.

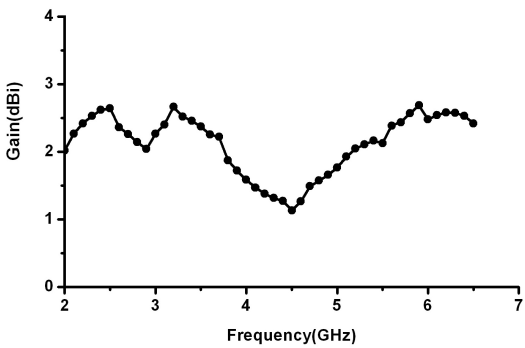

Figure 8. Frequency dependence of the gain for the proposed antenna.

that the antenna exhibits a nearly omnidirectional radiation pattern in the H-plane (x-y plane) and a dipole-like radiation pattern in the E-plane (x-z plane). It is also noted that the E-plane and H-plane patterns show relatively low cross-polarization radiation, which is determined by the configuration of the optimized antenna.

Finally, the frequency dependence of the antenna gain was measured. As shown in Figure 8, the antenna gain was measured about 2–3 dBi in the operating frequency bands with the peak value of 3 dBi at 5.6 GHz.

4. CONCLUSION

The optimization of a compact tri-band slot antenna has been implemented using Boolean differential evolution algorithm (BDE). A flow chart and descriptions illustrating the steps the BDE/MOM method are presented. The optimized antenna has a compact size of 24.2 mm 32.2 mm and is fabricated and measured. Measured results show that the optimized antenna has $|S_{11}| < -10\,\text{dB}$ in the three chosen frequency bands from 2.35 to 2.85 GHz, from 3.1 to 4.4 GHz and from 4.8 GHz to 5.85 GHz and nearly omnidirectional radiation patterns. The designed antenna is quite suitable for wireless communication applications. This example also demonstrates the applicability of the BDE/MOM optimization algorithm to efficient and in potential automated method for the antenna design. It also illustrates the potential of the BED/MOM optimization approach to solving the optimization problems in electromagnetics.

REFERENCES

1. Li, D., F.-S. Zhang, Z.-N. Zhao, L.-T. Ma, and X. N. Li, "A compact CPW-FED koch snowflake fractal antenna for WLAN/WiMAX applications," *Progress In Electromagnetic Research C*, Vol. 28, 143–153, 2012.
2. Storn, R. and K. Price, "Differential evolution — A simple and efficient adaptive scheme for global optimization over continuous spaces," Technical Report TR-95-012, Berkeley, CA, 1995.
3. Storn, R. and K. Price, "Differential evolution — A simple and efficient heuristic for global optimization over continuous spaces," *J. Global Optim.*, Vol. 11, 341–359, 1997.
4. Price, K., R. Storn, and J. A. Lampinen, *Differential Evolution: A Practical Approach to Global Optimization,* 1st Edition, Springer, New York, 2005, ISBN: 3540209506.
5. Kurup, D. G., M. Himidi, and A. Rydberg, "Synthesis of uniform amplitude unequally spaced antenna arrays using the differential evolution algorithm," *IEEE Trans. Antennas Propag.*, Vol. 51, 2210–2217, 2003.

6. Michalski, K. A., "Electromagnetic imaging of elliptical-cylindrical conductors and tunnels using a differential evolution algorithm," *Microwave Opt. Technol. Lett.*, Vol. 28, 164–169, 2001.
7. Yidiz, C., A. Akdagli, and M. Turkmen, "Simple and accurate synthesis formulas obtained by using a differential evolution algorithm for coplanar strip lines," *Microwave Opt. Technol. Lett.*, Vol. 48, 1133–1137, 2006.
8. Greenwood, G. W., "Using differential evolution for a subclass of graph theory problems," *IEEE Trans. Evol. Comput.,* Vol. 13, 190–1192, 2009.
9. Zhang, L., Y. C. Jiao, Z. B. Weng, and F. S. Zhang, "Design of planar thinned arrays using a Boolean differential evolution algorithm," *IET Microwave Antennas Propag.*, Vol. 4, 2172–2178, 2010.
10. Choo, H. and H. Ling, "Design of broadband and dual-band microstrip antennas on a high-dielectric substrate using a genetic algorithm," *IEE Proc. Microwave Antennas Propag.*, Vol. 150, 137–142, 2003.
11. Kerkhoff, A. J., R. L. Rogers, and H. Ling, "Design and analysis of planar monopole antennas using a genetic algorithm approach," *IEEE Trans. Antennas Propag.*, Vol. 52, 2709–2718, 2004.
12. Ohira, M., H. Deguchi, M. Tsuji, and H. Shigesawa, "Multiband single-layer frequency selective surface designed by combination of genetic algorithm and geometry-refinement technique," *IEEE Trans. Antennas Propag.*, Vol. 52, 2925–2931, 2004.
13. Johnson, J. M. and V. Rahmat-Samii, "Genetic algorithms in engineering electromagnetics," *IEEE Antennas and Propagation Magazine*, Vol. 39, No. 4, 7–21, 1997.
14. Johnson, J. M. and V. Rahmat-Samii, "Genetic algorithms in engineering electromagnetics," *IEEE Trans. Antennas Propag.*, Vol. 39, 7–21, 1997.
15. Liu, X. F., Y. B. Chen, Y. C. Jiao, and F. S. Zhang, "Modified particle swarm optimization for patch antenna design based on IE3D," *Journal of Electromagnetic Waves and Applications*, Vol. 21, No. 13, 1819–1828, 2007.