Progress In Electromagnetics Research M, Vol. 36, 101–108, 2014

Design, Simulation and Fabrication of an Optimized Microstrip Antenna with Metamaterial Superstrate Using Particle Swarm Optimization

Nooshin Feiz[1, *], Farzad Mohajeri[1], and Davoud Zarifi[2]

Abstract—In this paper, a novel near zero refractive index metamaterial is designed and used as a superstrate of a microstrip antenna. In order to decrease the return loss, particle swarm optimization (PSO) is used to optimize the metamaterial structure. One of the important factors in the antenna designing, which influences the radiation efficiency, is to determine the accurate position of the feed, and PSO is used to find a precise location of the feed with minimum return loss. The simulation and fabrication of the microstrip antenna using the optimized metamaterial structure is also presented. The performance of the antenna is improved, and the gain is increased up to 4.5 dB. Moreover, a very good agreement is observed between simulation and measurement results.

1. INTRODUCTION

Microstrip antennas (MAs) have been widely used in microwave systems because of their attractive features, such as low profile and low cost [1, 2]. Although MAs have been considered significant advances in antenna technology, they suffer from a number of serious drawbacks such as very narrow bandwidth and low gain. In order to improve the antenna characteristic, metamaterials (MTM) are used as a superstrate [3, 4]. In order to achieve gain enhancement, MTMs, structural sizes of which are much smaller than the wavelength in free space are used in many papers [5–7]. MTM superstrates are practically useful to enhance the directivity of different radiation sources [8]. In addition, MTM superstrates are also used to improve the radiation performance of an antenna, which is interpreted by the theory of near-zero refraction index materials [9, 10]. The challenge in designing MA is to determine the feed position which is an important parameter in the radiation pattern and efficiency. In most cases, trial and error is used which is not accurate. Recently, the particle swarm optimization (PSO) is used to accommodate this challenge. PSO starts by designating each position in the solution space as a potential design. A fitness function is then defined to quantify the performance of each candidate design [11]. All the encountered positions are evaluated by this fitness function to represent how well the design criterion is satisfied. Finally, toward the end of the optimization, most particles converge to the global optimum, which expectedly results into the best design [12]. In this paper, a novel near-zero refractive index MTM unit cell used as a superstrate of the MA is introduced. In order to improve the antenna characteristic, PSO is applied to determine the best position of the coaxial cable and optimize the MTM structure which increases the gain and directivity of the MA and decreases the back lobe that plays an important role in enhancement of antenna efficiency. The proposed MTM structure is printed on a Rogers RT Duroid 5880 substrate with permittivity $\varepsilon_r = 2.2$ and loss tangent 0.0009. The unit cell structure is simulated by Ansoft High Frequency Structure Simulator (HFSS) and MATLAB. The results are presented and show that, in antenna with 12 MTM unit cells, the size reduction is about 15%. Measured and simulated results are compared. Accordingly, it can be concluded that these results are very close to each other.

Received 2 January 2014, Accepted 16 May 2014, Scheduled 22 May 2014

* Corresponding author: Nooshin Feiz (nooshin.feyz@gmail.com).

[1] Department of Electrical and Communication Engineering, Shiraz University, Shiraz, Iran. [2] Antenna and Microwave Research Laboratory, School of Electrical Engineering, Iran University of Science and Technology, Tehran, Iran.

2. BASIC STRUCTURE OF PSO

The general algorithm of PSO consists of three steps. First, positions and velocities of particles are generated; after that, the velocity of each particle is calculated, and finally, the position of the particle is updated. Here, each particle is defined as a point in the design space, and the position of which changes from one iteration to another based on velocity updates. After the position and velocity of each particle are initialized, the second step is to update the velocity of each particle using the particles objective or fitness values which are functions of the particle current position in the design space. The fitness function value of a particle determines which particle has the best global value in the current swarm called p_g and also determines the best position of each particle over time shown by p_i in current and all previous movement. The velocity update formula uses these two pieces of information for each particle in the swarm along with the effect of current velocity (v_i) to provide a search direction for the next iteration. The velocity update formula includes some random parameters, represented by the uniformly distributed variables which are shown by *rand*. The reason of using this parameter is to ensure good coverage of the design space and avoid entrapment in local optima. The algorithm of PSO can be used in d-dimensional space, and particle number i and position in each dimension is x_{id}. The velocity and position of each particle are updated by Equations (1)–(4), respectively [13, 14]

$$v_{id} = k * [v_{id} + c_1 * rand() * (p_{id} - x_{id}) + c_2 * rand() * (p_{gd} - x_{id})] \tag{1}$$

$$K = \frac{2}{\left|2 - \varphi - \sqrt{\varphi^2 - 4}\right|} \tag{2}$$

$$\varphi = c_1 + c_2 \tag{3}$$

$$x_{id} = x_{id} + v_{id} \tag{4}$$

where K is constriction factor set to 0.729; so, φ is 4.1. c_1 and c_2 are acceleration constants that represent the weighting of the stochastic acceleration terms, which pulls each particle toward the best position and global best position, respectively. This algorithm continues until the criterion, which is defined as a sufficiently good fitness or maximum number of the iteration, is met. Velocity of particles is limited to a constant parameter which is called $V_{\max}$ and is often set to about 10–20% of dynamic range of the variable on each dimension [13].

3. SIMULATION RESULTS

3.1. Metamaterial Unit Cell

In this work, a novel index MTM unit cell is employed. This unit cell is designed to have a near-zero value for the refractive index at the resonance frequency. Figure 1 illustrates the geometry of the MTM unit cell. Open, electric, magnetic and periodic boundary conditions are used in the simulation. In order to excite the permittivity and permeability behaviors, the perfect electric conductor (PEC) and perfect magnetic conductor (PMC) boundary conditions and feed port are employed on the x-axis and y-axis and z-axis, respectively [15].

An important parameter impacting the return loss and antenna gains consequently is the gap between sheets indicated as g in Figure 1. The simulation is made on a frequency band for the structure between 5 GHz and 12 GHz with a 0.01 GHz increment. In order to improve the return loss of the unit cell, PSO is used to optimize the MTM structure.

3.2. PSO Optimization

In order to find the best value for g, PSO is used as follows. First, the numbers of the iterations and particles are chosen 20 and 15, respectively. The fitness function is defined as a minimum value of the reflection coefficient which decreases the return loss and increases the efficiency of the MTM unit cell. In this case, MATLAB and HFSS are simultaneously applied, and Visual Basic Script (VBS) is used as an interface between the two softwares. The procedure of this algorithm is shown in Figure 2.

First, the initial value for g is considered 0.7 mm in MATLAB code, and VBS is used to link HFSS and MATLAB. In order to find the reflection coefficient, the structure is simulated by HFSS.

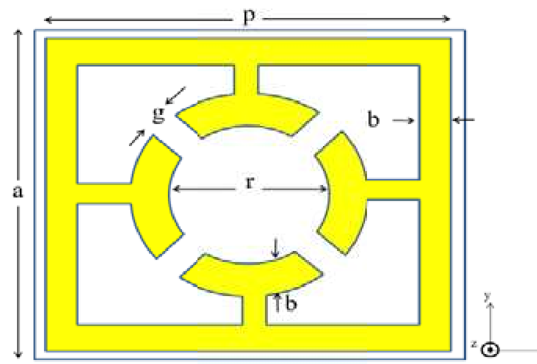


Figure 1. Structure of the unit cell of metamaterial ($a = 4.5\,\mathrm{mm}$, $p = 4.3\,\mathrm{mm}$, $b = 0.3\,\mathrm{mm}$, $r = 1.43\,\mathrm{mm}$).

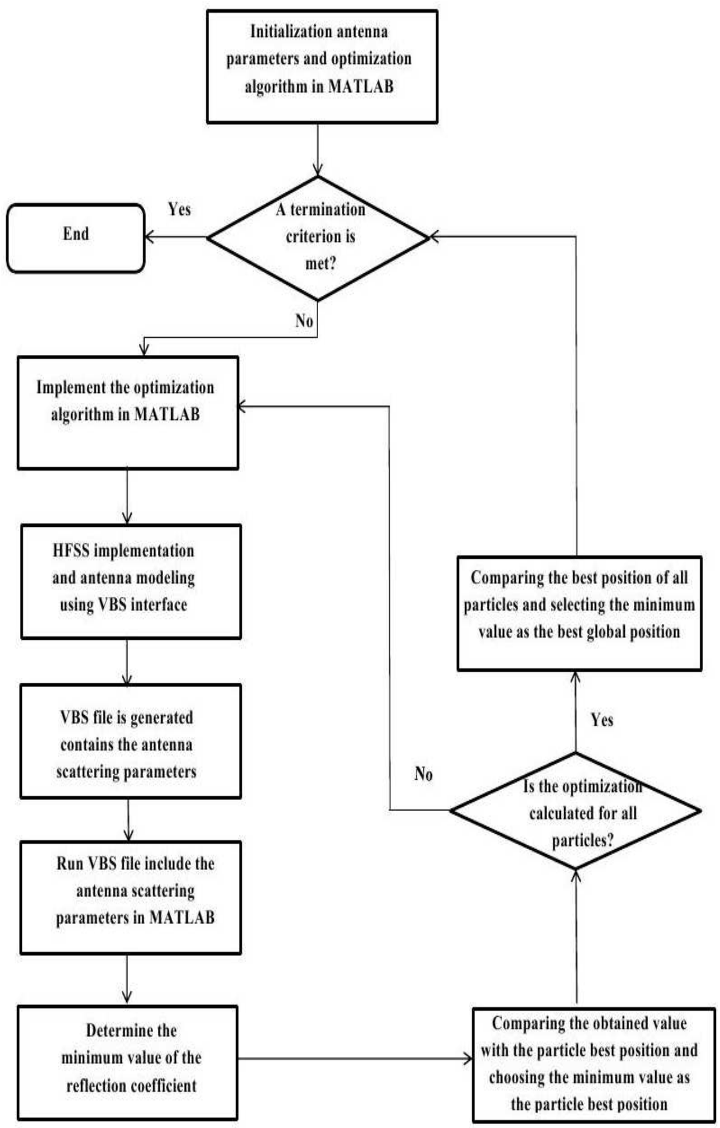


Figure 2. Flow chart of the PSO algorithm in electromagnetic problems.

So, HFSS is opened by the command code of MATLAB. Then, the structure of the near-zero refractive index MTM is drawn and run in HFSS by MATLAB codes in the frequency range defined in MATLAB. After that, to achieve the minimum value of the reflection coefficient, VBS is used to transfer the data of S parameter from HFSS to MATLAB.

Then, the structure of the near-zero refractive index MTM is drawn and run in HFSS by MATLAB codes in the frequency range defined in MATLAB. After that, to achieve the minimum value of the reflection coefficient, VBS is used to transfer the data of S parameter from HFSS to MATLAB. This value is compared with previous values, and the minimum value is chosen as P_i by PSO.

In each iteration, this process is done for each particle. Finally, in the end of the procedure the appropriate value is selected as P_g which is shown in MATLAB command window as the optimum location.

This process is repeated until the iteration meets the maximum number. In this case, HFSS runs 300 times and lasts for 17 hours. The gain of the MA, which uses arrays of unit cells as a superstrate, is increased by PSO. The optimized value of g is 0.4 mm.

This algorithm significantly reduces the return loss. As shown in Figure 3, a 10 dB reduction of the reflection coefficient is observed.

3.3. A Retrieval Method

A MTM superstrate was also used to improve the radiation performance of a MA, which was interpreted by the theory of near-zero refraction index materials [8–10]. In order to determine the reflective index of the optimized MTM unit cell, a retrieval algorithm, which uses reflection and transmission coefficients of a wave normally incident on a slab of the MTM, is applied [16]. From Figure 4, it can be observed that the refractive index of optimized structure is near-zero in 11 GHz. Thus, antenna gain due to the ultra-refraction phenomenon is significantly increased.

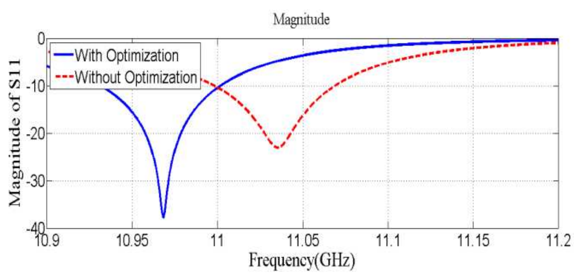


Figure 3. The simulated S_{11} of the optimized and primary MTM structure with respect to the frequency.

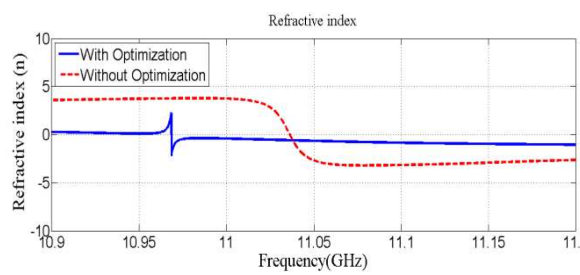


Figure 4. The extracted refractive index of the optimized and primary MTM structure with respect to the frequency.

Figure 5(a) shows the calculated effective permittivity of the optimized metamaterial extracted from the simulated S parameters [16]. As shown in Figure 5(b), the effective magnetic permeability is very close to zero around 11 GHz.

3.4. Antenna Design

The antenna dimensions are calculated based on the resonance frequency of the optimized MTM. An accurate determination of the coaxial cable position is the most important step in antenna design. The best place is at the point where the input impedance is 50 Ω. A Computer Aided Design (CAD) formula is used as a conventional way to determine the feed position. The disadvantage of this method is that it does not provide a precise response. In order to accurately determine the feed location, PSO is used to find the best position. The initializing parameter is the first step of PSO. In this paper, the CAD formula is used to preliminarily estimate the feed position. Then, the particles move toward the solution space for finding the best position with maximum matching to the fitness function. The fitness function is defined as a minimum value of the reflection coefficient. Consequently, this will lead to increase the antenna gain and radiation efficiency.

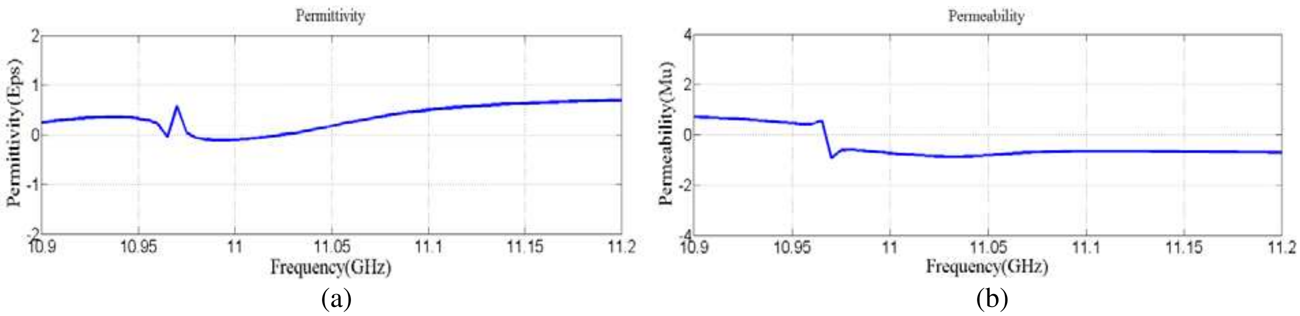


Figure 5. The extracted constitutive parameters of the optimized MTM structure with respect to the frequency. (a) Permittivity. (b) Permeability.

The simulated MA presents a return loss −27 dB around 9 GHz, and the gain is 9.2 dB which shows 4.5 dB growth rate.

After 8 hours and 300 times runs, the optimal value of the feed position is displayed in the MATLAB command window. The result of the optimization algorithm is 7.9 mm from the starting point of the substrate.

Figure 6(a) shows the top view of the optimized antenna with MTM superstrate. The top view of the antenna, which uses a 4×3 array of the optimized MTM as a superstrate, is presented in Figure 6(b).

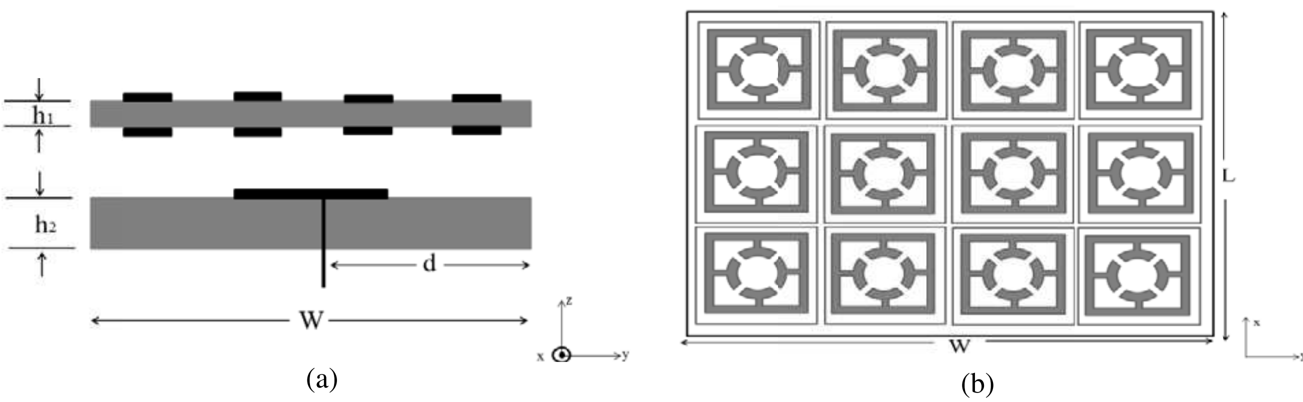


Figure 6. Configuration of the antenna using the optimized metamatrial structure. (a) Side view. (b) Top view. ($W = 21.6$ mm, $L = 19.7$ mm, $d = 7.9$ mm, $h_1 = 0.8$ mm, $h_2 = 1.6$ mm).

As shown in Figure 7, the gain of the optimized MA, which uses the optimized MTM structures as a superstrate, is increased significantly. It is apparent that the directivity of the optimized MA with MTM superstrate is increased. The gain of microstrip patch antenna incorporated with metamaterial unit cells and the single patch antenna is 9.18 (dB) and 4.68 (dB), respectively.

By comparing this figure, it can be concluded that using PSO for optimizing the MTM structure and determining the feed position could enhance the gain, significantly.

4. FABRICATION AND MEASUREMENT RESULTS

Figure 8(a) shows the side view of the fabricated optimized MA incorporated with the MTM structure. The top view of the fabricated MA, which shows the MTM structure, is shown in Figure 8(b). In order to compare results clearly, values obtained from both simulation and measurement are listed in Table 1.

The antenna is measured at a frequency range between 8.5 GHz–9.5 GHz. Figure 9(a) shows the comparison of reflection coefficient between the simulated and measured results.

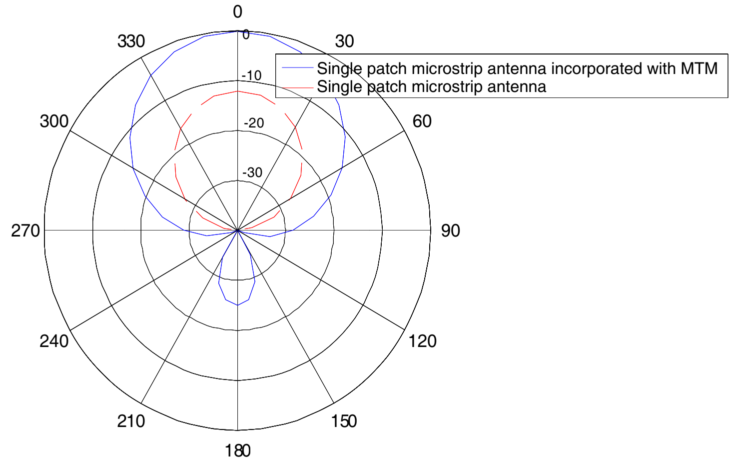
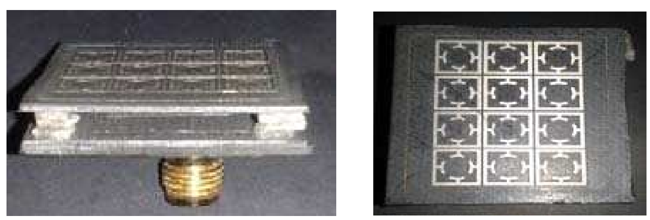
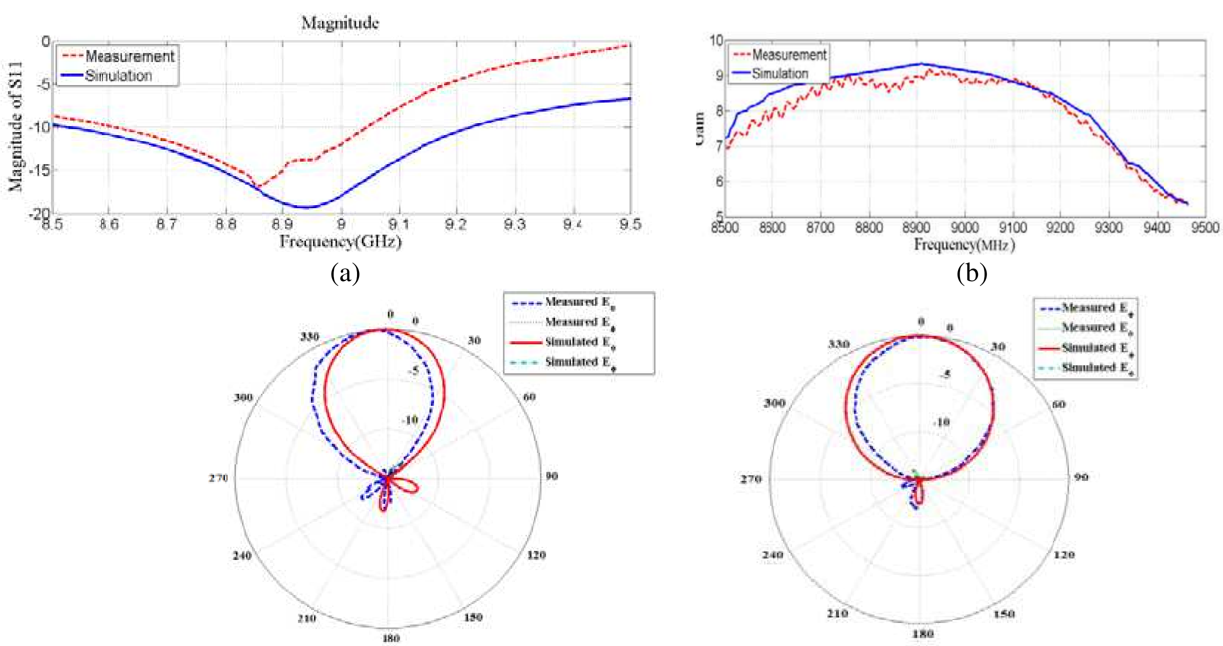


Figure 7. The simulated gain of the microstrip patch antenna with the MTM superstrate structure (solid line) and without MTM (dashed line).



(a) (b)

Figure 8. Fabricated antenna. (a) Side view. (b) Top view.



(a) (b)

(c) (d)

Figure 9. Comparison simulation and measurement results. (a) S_{11}. (b) Gain. (c) E-plane pattern. (d) H-plane pattern.

Table 1. Comparison between simulated and measured optimized microstrip antenna with MTM.

Antenna Parameter	Measurement Results	Simulation Results
Gain	9.18 dB	9.2 dB
S_{11}	−16 dB	−19 dB
Bandwidth	0.5 GHz	0.7 GHz

From this figure, it can be deduced that the measurement and simulation results are in a very good agreement. As shown in Figure 9(b), the simulation and measurement results are similar in terms of gain.

For comparison, the gains of the fabricated and simulated antennas are 9.18 dB and 9.20 dB, respectively.

Figure 9(c) shows the radiation pattern in E-planes for both simulated and measured antennas incorporated with MTM.

The comparison of the simulated and measured antennas in H-plane is shown in Figure 9(d).

From these figures, it can be concluded that the shape of the simulated radiation pattern is approximately similar to that of the measured radiation pattern.

5. CONCLUSION

In conclusion, the performance of the microstrip antenna has been improved through incorporation with the MTM structure. In this paper, a new structure of metamaterial with characteristic of near-zero refractive index is designed and simulated. This phenomenon enhances the antenna gain significantly because the radiated energy will be concentrated in a direction close to the normal of the MTM superstrate. In order to decrease the return loss of the MTM structure, PSO is used to achieve the minimum value of the reflection coefficient. To perform the optimization, HFSS and MATLAB should be run simultaneously. So, VBS is applied as an interface between these softwares. One of the major challenges in designing the antenna is to determine the exact location of the coaxial cable. PSO is again used to find the feed position accurately, with the minimum value of reflection coefficient. An improvement of 4.5 dB gain in simulation and measurement is obtained when MTM is used as a superstrate of the MA. Microstrip antenna which uses the optimized MTM as a superstrate is fabricated and tested. In conclusion, simulation and measurement results are in a very good agreement.

REFERENCES

1. Howell, J. Q., "Microstrip antennas," *IEEE Trans. Antennas Propagation Magazine*, Vol. 23, 90–93, 1975.
2. Guney, H. K. and N. Sarikaya, "A hybrid method based on combining artificial neural network and fuzzy inference system for simultaneous computation of resonant frequencies of rectangular, circular, and triangular microstrip antennas," *IEEE Trans. Antennas Propagation Magazine*, Vol. 55, 659–668, 2007.
3. Maslovski, S., P. Ikonen, I. Kolmakov, and S. Tretyakov, "Artificial magnetic materials based on the new magnetic particle: Metasolenoid," *Progress In Electromagnetics Research*, Vol. 54, No. 9, 61–81, Sep. 2005.
4. Yousefi, L. and O. M. Ramhi, "New artificial magnetic materials based on fractal hilbert curves," *Proc. IEEE Int. Workshop Antenna Technol.: Small Smart Antennas Novel Metamater.*, 237–240, Cambridge, UK, Mar. 2007.
5. Foroozeshand, A. and L. Shafai, "Investigation into the effects of the reflection phase characteristics of highly-reflective superstrates on resonant cavity antennas," *IEEE Transactions on Antennas and Propagation*, Vol. 58, No. 10, 3392–3396, 2010.

6. Weily, A. R., L. Horvath, K. P. Esselle, B. C. Sanders, and T. S. Bird, "A planar resonator antenna based on a woodpile EBG material," *IEEE Transactions on Antennas and Propagation*, Vol. 53, No. 1, 216–223, 2005.
7. Zarifi, D., H. Oraizi, and M. Soleimani, "Improved performance of circulary polarized antenna using semi planar chiral metamaterial covers," *Progress In Electromagnetics Research*, Vol. 123, 337–354, 2012.
8. Liu, H., S. Lei, X. Shi, and L. Li, "Study of antenna superstrates using metamaterials for directivity enhancement based on fabry-perot resonant cavity," *International Journal of Antenna and Propagation*, Vol. 2013, 209714–209715, 2013.
9. Li, B., B. Wu, and C. H. Liang, "Study on high gain circular waveguide array antenna with metamaterial structure," *Progress In Electromagnetics Research*, Vol. 60, 207–219, 2006.
10. Li, B., X. J. Dang, and C. H. Liang, "High gain circular waveguide antenna using 1-delectromagnetic band-gap structure," *Chinese Journal of Radio Science*, Vol. 20, No. 6, 879–884, 2006.
11. Robinson, J. and Y. Rahmat-Samii, "Particle swarm optimization in electromagnetics," *IEEE Transactions on Antennas and Propagation*, Vol. 52, No. 2, 397–407, Feb. 2004.
12. Jin, N. and Y. Rahmat-Samii, "Parallel particle swarm optimization and finite difference time domain (PSO/FDTD) algorithm for multiband and wide-band patch antenna designs," *IEEE Transactions on Antennas and Propagation*, Vol. 53, No. 11, 3459–3468, 2005.
13. Eberhart, R. C. and Y. Shi, "Particle swarm optimization: Developments, applications and resources," *Proceedings Congress Evolutionary Computation*, 81–86, 2001.
14. Clerc, M., "The swarm and the queen: Towards a deterministic and adaptive particle swarm optimization," *Proceedings, ICEC*, 1951–1957, Washington, DC, 1999.
15. Ziolkowski, R. W., "Design, fabrication, and testing of double negative metamaterials," *IEEE Transactions on Antennas and Propagation*, Vol. 51, No. 7, 1516–1529, 2003.
16. Chen, X., T. M. Grzegorczyk, B. I. Wu, J. Pacheco, and J. A. Kong, "Robust method to retrieve the constitutive effective parameters of metamaterial," *Phys. Rev. E*, Vol. 70, No. 016608, 1–7, 2004.