Frontiers of Information Technology & Electronic Engineering
www.zju.edu.cn/jzus; engineering.cae.cn; www.springerlink.com
ISSN 2095-9184 (print); ISSN 2095-9230 (online)
E-mail: jzus@zju.edu.cn

Optimal array factor radiation pattern synthesis for linear antenna array using cat swarm optimization: validation by an electromagnetic simulator[*]

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Received Oct. 30, 2015; Revision accepted Feb. 16, 2016; Crosschecked Mar. 14, 2017

Abstract: In this paper, an optimal design of linear antenna arrays having microstrip patch antenna elements has been carried out. Cat swarm optimization (CSO) has been applied for the optimization of the control parameters of radiation pattern of an antenna array. The optimal radiation patterns of isotropic antenna elements are obtained by optimizing the current excitation weight of each element and the inter-element spacing. The antenna arrays of 12, 16, and 20 elements are taken as examples. The arrays are designed by using MATLAB computation and are validated through Computer Simulation Technology-Microwave Studio (CST-MWS). From the simulation results it is evident that CSO is able to yield the optimal design of linear antenna arrays of patch antenna elements.

Key words: Patch antenna; Linear antenna array; Cat swarm optimization (CSO); Side lobe level (SLL)
http://dx.doi.org/10.1631/FITEE.1500371 **CLC number:** TN957.2; TP391

1 Introduction

The antenna is a far-reaching element here and now with the constantly progressive technology. Antenna plays an imperative role in short or long distance wireless communication. The contemporary research is going on for the development of antenna with accuracy and efficiency. For long distance communication, the antenna should be highly directive with high gain and less interference. However, the radiation characteristics of a single type antenna will be of low directivity, low gain, and low efficiency (Krous, 1950; Simon *et al.*, 1994; Stutzman and Thiele, 1998; Balanis, 2005; Blank and Hutt, 2005). To accommodate these characteristics, the single type antenna will have to have a large size, which is essentially impractical and battens high inordinate. To overcome this problem, identical antennas are arranged in an array of identical elements. The geometric arrangements of the arrays may be of different configurations according to the areas of applications (Haupt, 1997; Güney and Akdağli, 2001; Haupt and Werner, 2006; Hardel *et al.*, 2011; Guo *et al.*, 2015). The different array structures may be of linear (Panduro *et al.*, 2009a), circular (Mandal *et al.*, 2009; Panduro *et al.*, 2009b), planar (Balanis, 2005), or conformal (Balanis, 2005) type, or hybridization of these structures. The reduction of side lobe levels (SLLs) is an important issue for the antenna research community.

The optimal uniform and nonuniform inter-element spacing and current excitations, respectively, allow an accelerated and flexible design. All these procedures control both the peak and average SLLs (Mouhamadou and Vaudon, 2007; Yallaparagada *et al.*, 2011; Ram *et al.*, 2012; Liu *et al.*, 2015). If the

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[*] Project supported by SERB, Department of Science and Technology, Government of India (No. SB/EMEQ-319/2013)

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array elements are placed symmetrically along the *Z*-axis about the center of the array, both the number of optimizing parameters required and the estimation time are reduced by approximately 50%. Amplitudes and inter-element spacing are simple to implement and are less sensitive to the quantization error (Ram *et al*., 2015a).

Patch antennas are of low cost, have a low profile, and are easily fabricated. Due to its simple structure, it has been widely used in telecommunication and cellular mobile communication. Microstrip patch antennas have attractive features and advantages, e.g., robustness, ease of fabrication, small size, low cost, and ease of installation and integration with feed networks (Ansari *et al*., 2010). One of the limitations of this type of antenna is its limited bandwidth of operation characteristics at which the antenna can perform comfortably. These characteristics influence the design of the antenna (Aslam and Bhatti, 2009). Patch antenna contains a substrate and a ground plane at the bottom of the substrate. A patch antenna is placed on the top of the substrate and the patch is connected to the feed line by which the patch gets excited. The substrate is made up of a perfect electric conductor. There are many methods to operate the antenna in multiple bands (Park *et al*., 2005; Joshi *et al*., 2012; Koziel and Ogurtsov, 2015). One way is by using the perturbation of the slots in the patch, and the other is the fractal approach.

Due to the upcoming improved technology, the enabled communication devices have to have smaller size. The size of the antenna is a serious constraint for the design of any communication device or any antenna enabled device. Due to this, the small size antenna has been highly demanded. Wireless local area network (WLAN) and Worldwide Interoperability for Microwave Access (Wi-MAX) are two most rapidly growing technologies in modern wireless communication (Park *et al*., 2005; Aslam and Bhatti, 2009; Ansari *et al*., 2010; Joshi *et al*., 2012; CST, 2013; Koziel and Ogurtsov, 2015). These technologies give more freedom and flexibility for the devices to move around the wide coverage area with all-time connectivity with the network.

There are several studies on the improvement of particular antenna elements (Singh *et al*., 1971; Park *et al*., 2003; Sun *et al*., 2005; Hoivik and Ramadoss, 2009; Hassan and Ragheb, 2012; Artemenko *et al*., 2015; Haraz *et al*., 2015). Various applications of the evolutionary algorithm have been presented in different fields of engineering (Mangaraj *et al*., 2013; Ghatak *et al*., 2015).

Nature-inspired algorithms have brought great revolution in all fields of electromagnetics, where the optimization of certain parameters is highly complex and nonlinear. With the help of a properly designed cost function (or fitness function) and optimizing parameters, any type of problem can be effectively solved. Nature-inspired algorithms play an important role in the optimal design of the antenna array for better radiation characteristics.

Different evolutionary optimization algorithms, e.g., genetic algorithm (GA) (Mandal *et al*., 2009; Panduro *et al*., 2009a; 2009b), particle swarm optimization (PSO) (Mandal *et al*., 2009; Panduro *et al*., 2009b), and differential evolution (DE) (Panduro *et al*., 2009b), have been widely used for the synthesis of radiation patterns of various antenna arrays. PSO (Eberhart and Shi, 2001; Kennedy and Eberhart, 2001) is simple to implement and its convergence may be controlled via few parameters. The major drawbacks of GA, PSO, and DE are premature convergence and entrapment to a suboptimal solution. With growing interest in applications of multi-objective optimization methods to real-world problems, it is essential to develop efficient algorithms for a better performance in engineering design and resource optimization. An efficient algorithm for multi-objective optimization based on swarm intelligence principles was presented in Reddy and Kumar (2007).

Various purposes of communication require different types of antennas to improve the performances of transmission and reception of the desired signal. In this study, a single band microstrip patch antenna resonating at 5.85 GHz for the Wi-MAX application is designed and simulated. A broadside linear array of elements is considered for the microstrip patch antenna. The excitation phase of each element is null. A cost function is defined, which keeps the SLL low, and the excitation of the each element and inter-element spacing are optimized by using cat swarm optimization (CSO) (Ram *et al*., 2015b; 2015c).

For the practical implementation of any antenna, the consideration of parameters is very important. The optimal results obtained by extensive MATLAB simulations using CSO are validated through the Computer Simulation Technology-Microwave Studio

(CST-MWS), which is a computing package established on a finite integration technique (CST, 2013). CST-MWS is a simple and widely used electromagnetic field simulation software. It overtures discriminative, effectual simulation explication for electromagnetic design and analysis. After designing a structure, an automatic meshing procedure is applied before the simulation starts. CST-MWS is a method on demand, giving the choice of simulation or mesh type suitable for a particular problem (Ansari *et al.*, 2010). Also, it is useful in designing different types of array such as linear, circular, and planar.

2 Design equations

A symmetric linear antenna array is arranged in the broadside direction with $2M$ equally spaced isotropic elements (Fig. 1a). The linear array of isotropic sources is placed along the Z-direction, and the projection P is placed in the positive X-Z plane. The direction of the maximum radiation is along the Y-direction. Similarly, for the patch antenna design, the substrate is placed in the X-Z plane. The radiation of the patch antenna is along the Y-axis. According to the pattern multiplication concept, i.e., the total field of the array is the product of the radiation pattern of a single element and the array factor (Balanis, 2005), the radiation direction of the patch element pattern and the array pattern radiation direction should be along the same axis.

The array factor (AF) for the broadside direction is given by

$$\mathrm{AF}(\theta) = 2\sum_{n=1}^{M} I_n \cos\left[\left(\frac{2n-1}{2}\right)kd\cos\theta\right], \tag{1}$$

where θ is the elevation angle, I_n (n=1, 2, …, M) the current excitation coefficients, d the inter-element spacing, k the propagation constant, $2M$ the number of elements in the array.

The cost function (CF) for reducing SLL is given as

$$\mathrm{CF} = \frac{|\mathrm{AF}(\theta_{\mathrm{msl}}, I_n)|}{|\mathrm{AF}(\theta_0, I_n)|}, \tag{2}$$

where θ_0 is the angle of the elevation plane of the maximum of radiation pattern in range $[0, \pi]$, θ_{msl} the angle of the elevation plane of the maximum side lobe, $\mathrm{AF}(\theta_{\mathrm{msl}}, I_n)$ is obtained on either side of the main beam. The CSO technique is used to optimize non-uniform amplitude excitation and uniform inter-element spacing.

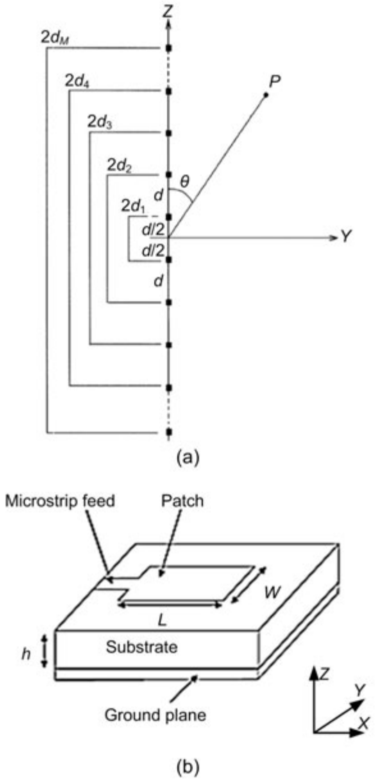


Fig. 1 Geometry of a 2*M*-element linear antenna array of microstrip patch antennas placed along *Z*-axis (a) and structure of a single microstrip patch antenna (b)

The discussions presented so far have considered only an array consisting of isotropic radiators, or mainly the array factor. However, an array with a more directive element pattern, such as a patch antenna, is considered for this design, and then the principle of pattern multiplication is used. Assuming there is no mutual coupling between the patch antenna elements. The resultant radiation pattern at the fundamental frequency is computed as the product of the conventional array factor and the element pattern of the patch antenna.

For the design of a microstrip antenna (Fig. 1b), the following have been considered. In this antenna, the substrate has a thickness h=1.6 mm and a relative permittivity ε_{r}=4.4. Suppose c is the speed of light, f_{r}

the operating frequency (5.85 GHz for Wi-MAX applications), ε_0 the permittivity in vacuum, and μ_0 the permeability in the free space. Based on the above numerical values, various patch parameters can be calculated using Eqs. (3)–(12) (Balanis, 2005).

The width of the pitch is determined by

$$W=\frac{1}{2f_{\mathrm{r}}\sqrt{\mu_0\varepsilon_0}}\sqrt{\frac{2}{\varepsilon_{\mathrm{r}}+1}}. \tag{3}$$

The effective permittivity is given by

$$\varepsilon_{\mathrm{eff}}=\frac{\varepsilon_{\mathrm{r}}+1}{2}+\frac{\varepsilon_{\mathrm{r}}-1}{2}\left(1+12\frac{h}{W}\right), \tag{4}$$

where h is the thickness of the substrate. The relationship between the extended incremental length of the patch and the substrate thickness is

$$\frac{\Delta L}{h}=0.412\frac{\varepsilon_{\mathrm{eff}}+0.3}{\varepsilon_{\mathrm{eff}}-0.258}\frac{\frac{W}{h}+0.264}{\frac{W}{h}+0.8}. \tag{5}$$

The length of the patch is given by

$$L=L_{\mathrm{eff}}-2\Delta L, \tag{6}$$

where L_{eff} is the effective length. L_{g} and W_{g} are the length and width of the ground plan, respectively, and are calculated as

$$L_{\mathrm{g}}=6h+L, \tag{7}$$

$$W_{\mathrm{g}}=6h+W. \tag{8}$$

The inset feed is calculated as follows (Balanis, 2005):

$$G_1=\frac{-2+\cos(k_0W)+k_0WS_{\mathrm{i}}(k_0W)+\dfrac{\sin(k_0W)}{k_0W}}{120\pi^2}, \tag{9}$$

$$G_{12}=\frac{1}{120\pi^2}\cdot\int_0^{\pi}\left[\frac{1}{\cos\theta}\sin\left(\frac{k_0W}{2}\cos\theta\right)\right]^2\mathrm{J}_0(k_0L\sin\theta)\sin^3\theta\mathrm{d}\theta, \tag{10}$$

$$R_{\mathrm{in}}=\frac{1}{2(G_1+G_{12})}, \tag{11}$$

$$y_0=\frac{L}{\pi}\arccos\left(\sqrt{\frac{Z}{R_{\mathrm{in}}}}\right), \tag{12}$$

where $\mathrm{J}_0(\cdot)$ is the zero-order Bessel function of the first kind, $S_{\mathrm{i}}(\cdot)$ the sine integral function, k_0 the propagation constant, R_{in} the resonant input resistance, Z the characteristic impedance, G_1 the conductance of feed line, and G_{12} the mutual conductance.

3 Numerical results and discussions

This section shows the numerical results for the three sets of linear arrays of microstrip patch antenna elements obtained by using the CSO technique. The applied CSO algorithm for the purpose of optimization is not described here although CSO has been applied for the first time to solve this problem. The description of CSO has been given in Ram *et al.* (2015b; 2015c). For each antenna array, constraints of the optimization variables are maintained. CSO yields the optimal normalized uniform and nonuniform inter-element spacing ($d\in[\lambda/2, \lambda]$) and the amplitude excitation weights, respectively, for the sets of linear arrays of microstrip patch antenna elements. The sets of arrays considered are of 12, 16, and 20 elements. Table 1 lists the maximum SLL and first null beamwidth (FNBW) of a uniformly excited linear array of microstrip patch antenna elements, and Table 2 shows the optimal results obtained by using CSO.

Table 1 Initial values of the maximum SLL and FNBW for uniformly excited (I_n=1, n=1, 2, …, M) and λ/2 inter-element spacing linear arrays of isotropic and microstrip patch antenna elements

Set	Number of elements	Maximum SLL (dB)	FNBW (degree)
I	12	−13.07	19.80
II	16	−13.15	14.40
III	20	−13.19	11.88

SLL: side lobe level; FNBW: first null beamwidth

3.1 Analysis of radiation patterns

Fig. 2 illustrates the optimal radiation characteristics of 12-, 16-, and 20-element linear arrays of microstrip patch antenna elements, obtained by using

Table 2 Optimal current excitation coefficients, optimal inter-element spacing, and the corresponding maximum SLL and FNBW for three linear arrays of microstrip patch antenna elements

Set	Current excitation coefficients	Inter-element spacing	Maximum SLL (dB)	FNBW (degree)
I	I_1=0.8639 I_2=0.7692 I_3=0.6081 I_4=0.4156 I_5=0.2395 I_6=0.1156	0.8565λ	−37.91	19.80
II	I_1=0.8909 I_2=0.8333 I_3=0.7244 I_4=0.5874 I_5=0.4363 I_6=0.2932 I_7=0.1722 I_8=0.0976	0.8883λ	−39.97	15.12
III	I_1=0.9196 I_2=0.8797 I_3=0.8041 I_4=0.7004 I_5=0.5798 I_6=0.4549 I_7=0.3324 I_8=0.2255 I_9=0.1370 I_{10}=0.0899	0.9084λ	−41.72	11.88

SLL: side lobe level; FNBW: first null beamwidth

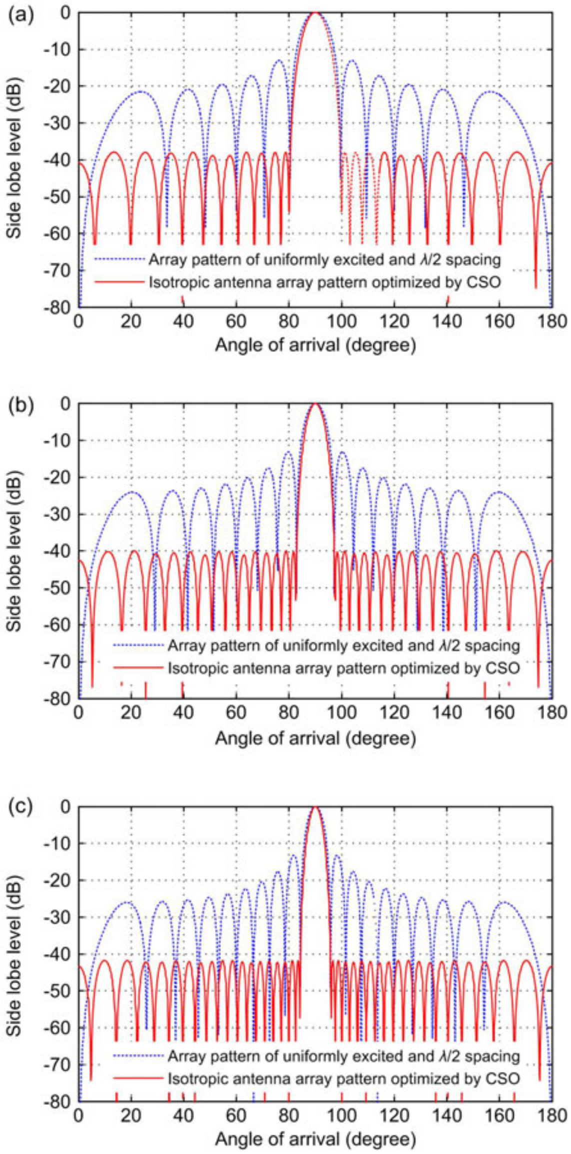


Fig. 2 Optimal radiation pattern obtained by using cat swarm optimization for a linear array of microstrip patch antennas with 12 (a), 16 (b), and 20 (c) elements

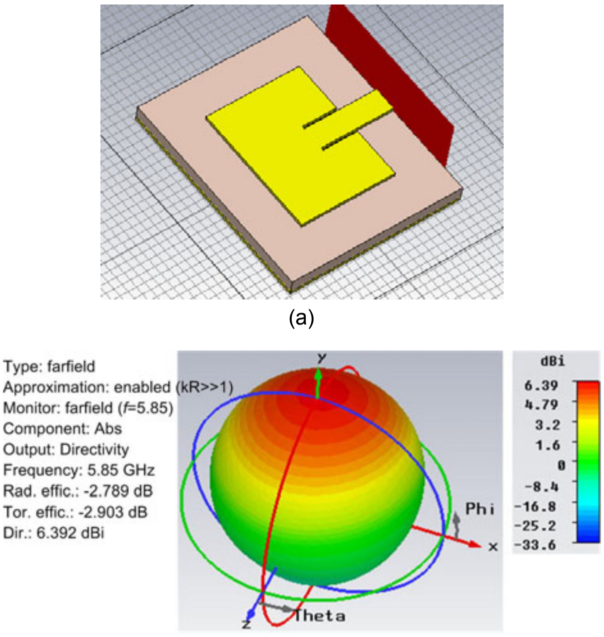
CSO. It is clear that besides a noticeable reduction of SLL, FNBW is restricted upon optimization. Table 2 indicates that, for optimal nonuniformly exited and optimal uniformly spaced symmetric 12-, 16-, and 20-element linear antenna arrays, SLLs reduce to −37.91, −39.97, and −41.72 dB, respectively, from −13.07, −13.15, and −13.19 dB, respectively. The MATLAB simulation results justify that for all the array arrangements, additional nulls are obtained, which is an extra advantage for the jamming of signal.

3.2 Validation of results by CST-MWS

A simple patch antenna designed to operate at 5.85 GHz with a bandwidth of 335 MHz has been simulated by the transient solver in CST. The substrate material used in this design is normal FR-4 with a thickness of 1.6 mm and a relativity permittivity of 4.4. The detailed geometry of the patch antenna and its bottom view are as shown in Fig. 1b. The design parameters of the microstrip patch antenna are listed in Table 3. The scattering parameters are often used to describe the antenna performance. The reflection coefficient Γ of an antenna is defined by the ratio between the power reflected back and the total input power (Balanis, 2005). The reflection coefficient in dB is expressed as $20\log|\Gamma|$. Fig. 3a shows the designed microstrip patch antenna, and Fig. 3b shows the far-field pattern of directivity of the designed microstrip patch antenna. The directivity obtained for the patch antenna is 6.392 dBi. Fig. 4 shows the

Table 3 Calculated values of the patch parameters

Parameter	Description	Numerical value obtained
W	Width of the patch antenna	15.5940 mm
$\varepsilon_{\mathrm{eff}}$	Effective permittivity	3.8381
L_{eff}	Effective length	13.0881 mm
ΔL	Extended incremental length of the patch	0.7232 mm
L	Length of the patch antenna	11.6417 mm
L_{g}	Length of the substrate/ground plane	21.2417 mm
W_{g}	Width of the substrate/ground plane	25.1940 mm
H	Thickness of the substrate	1.6 mm
m_{t}	Thickness of the ground plane and patch antenna	0.4 mm
G_{p}	Gap between feed line and the patch	0.3 mm
M_{f}	Width of the patch	0.31 mm


(a)

Type: farfield
Approximation: enabled (kR>>1)
Monitor: farfield (f=5.85)
Component: Abs
Output: Directivity
Frequency: 5.85 GHz
Rad. effic.: -2.789 dB
Tot. effic.: -2.903 dB
Dir.: 6.392 dBi

(b)

Fig. 3 Microstrip patch antenna designed (a) and far-field radiation pattern for the directivity of the designed microstrip patch antenna (b) (References to color refer to the online version of this figure)

far-field pattern of the gain of the microstrip patch antenna designed, and the measured gain is 3.603 dB.

In this example, the transmission line impedance is set to 50 Ω. Fig. 5a shows the voltage standing wave ratio (VSWR) for the example antenna, and Fig. 5b shows its bandwidth curve (return loss curve).

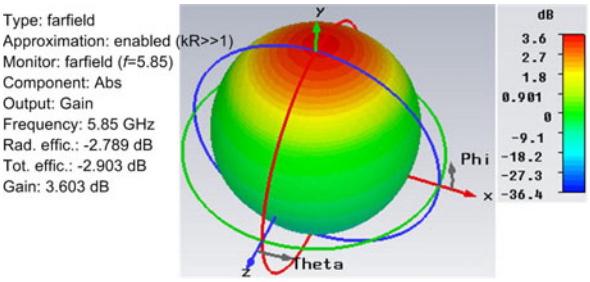

Type: farfield
Approximation: enabled (kR>>1)
Monitor: farfield (f=5.85)
Component: Abs
Output: Gain
Frequency: 5.85 GHz
Rad. effic.: -2.789 dB
Tot. effic.: -2.903 dB
Gain: 3.603 dB

Fig. 4 Far-field radiation pattern for the gain of the microstrip patch antenna designed (References to color refer to the online version of this figure)

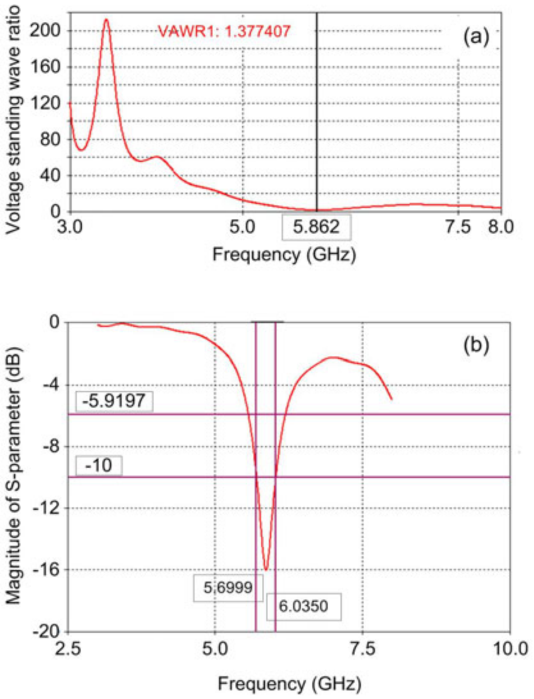


Fig. 5 Voltage standing wave ratio (VSWR) for the designed microstrip patch antenna (a) and bandwidth curve for the designed microstrip patch antenna (b)

The VSWR obtained is 1.377 dB, and the bandwidth is 0.3357 GHz. For an ideal matching, there should be no reflection and return loss, i.e., VSWR=1. This is impractical in real-life scenarios, so it is defined that VSWR<2 gives rise to a good matching system. Fig. 5b shows that the patch antenna designed operates at 5.85 GHz and the return loss is −15.541 dB.

Fig. 6 shows the far-field radiation pattern for the directivity of a 12-element linear array of microstrip patch antenna elements designed. The calculated directivity of the linear array of microstrip patch antenna elements is 17.39 dB. Fig. 7a shows the polar plots for the elevation angles of the 12-element linear

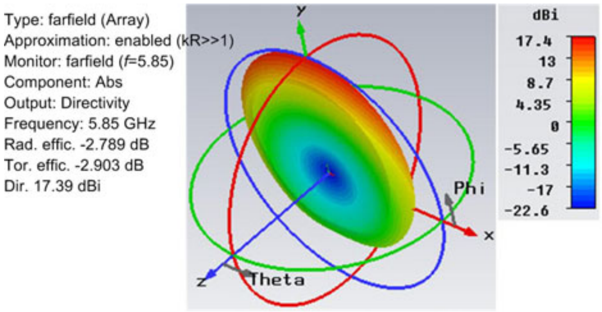


Fig. 6 Far-field radiation pattern for the directivity of the designed 12-element linear array of microstrip patch antennas (References to color refer to the online version of this figure)

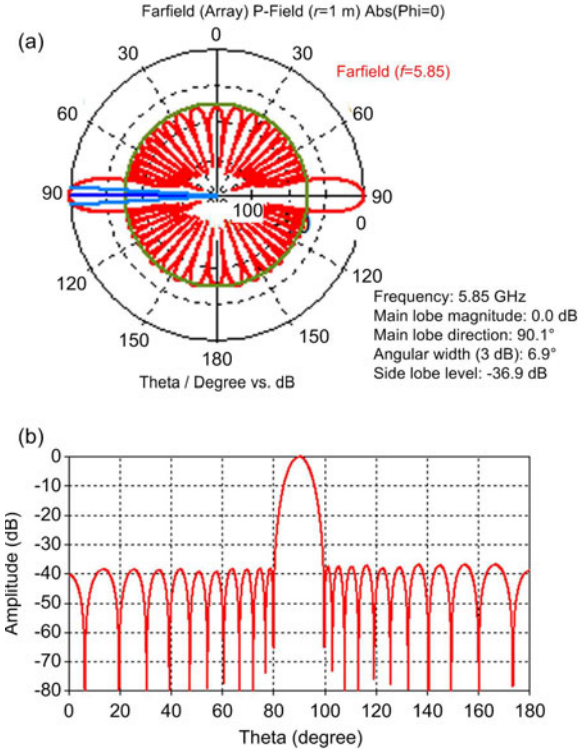


Fig. 7 Polar plot for the elevation angle of the designed 12-element linear array of microstrip patch elements (a) and array pattern of the linear array of microstrip patch antenna (b) obtained in CST-MWS

array of microstrip patch antenna elements designed and Fig. 7b the corresponding array pattern obtained by CST-MWS. From Fig. 7b, it is clear that the radiation pattern of a CSO optimized 12-element linear array of microstrip patch antenna elements matches approximately that of the linear array simulated (Fig. 2a). Thus, CST-MWS validates the optimized simulation results obtained by CSO.

4 Conclusions

The optimal designs of linear arrays of microstrip patch antenna elements with uniform and nonuniform inter-element spacing and current excitations have been carried out using an evolutionary optimization technique called cat swarm optimization (CSO). Simulation results justify that the optimal design of a nonuniformly excited linear antenna array with optimal inter-element spacing offers a considerable side lobe level (SLL) reduction with respect to the corresponding uniform linear array with a uniform inter-element spacing of $\lambda/2$. From the simulation results, it is clear that, for the arrays with 12, 16, and 20 elements, the SLLs have been reduced much more as compared with the corresponding uniform linear arrays of microstrip patch antenna elements, with a very little change in first null beamwidth (FNBW). The FNBWs of the elementary and concluding radiation patterns are almost the same.

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