Design of a Compact GA-Optimized Annular-Slot Multiband Circular Microstrip Antenna

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Abstract: A compact size circular patch microstrip antenna having 270^0 annular slot with single feed has been proposed. Its structure has been optimized using a very simple and appropriate Genetic Algorithm (GA) tool. The reference antenna has been designed by calculating the structural parameters using the cavity model analysis. GA optimizes the structure of reference antenna for the optimum response in terms of Reflection coefficient, gain, axial ratio, directivity, and radiation pattern. The optimized antenna exhibits excellent characteristics in terms of these performance parameters as compared to the reference antenna.

Key words: circular patch microstrip antenna, annular slot, GA, cavity modal analysis

1. Introduction

Circular microstrip antennas having different circular geometrical radiating patches and slots are very attractive in the sense that they have several interesting properties that make it attractive for wireless applications [1-2]. The geometrical radiating patches have been used with different shapes like circular disk [3-4], half circular disk [5], annular ring patch [6-7], annular circular slot [8], elliptical patches/slots [9] and stacked patches [10]. The slot shapes may include circular ring slot, square ring slot, and elliptical slots. In the wireless band, the antennas have been designed for multiband operation [11]. The application of different optimization techniques has been employed for optimizing the performance of antennas in terms of gain, bandwidth and radiation patterns [12-18]. The methods include artificial neural networks, genetic algorithms, particle swarm optimization and central force optimization methods. Genetic Algorithms (GAs) have been extensively applied for the optimization of shapes for optimum performances due to its simple and global converging nature. In this paper, the simple analysis along with the genetic optimization algorithm is presented for the design of annular slot of 270^0 on a circular patch.

The method studied here is based on the cavity model and the optimization of the dimensions of height, radius and annular slot on the patch along with feed point location of the antenna is performed using the genetic optimization algorithm, to achieve an acceptable antenna operation having three bands.

2. Structure development of the proposed antenna

The structure of the proposed antenna element has been shown in Figure 1. The initial design parameters of the proposed antenna have been calculated using the cavity model analysis of a circular microstrip antenna [2], [19] as

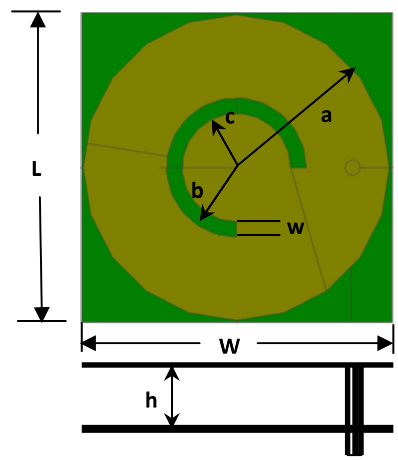

Fig. 1. Structure of the Proposed Antenna

$$a = \frac{F}{\left\{1+\frac{2h}{\pi\varepsilon_r F}\left[ln\left(\frac{\pi F}{2h}\right)+1.7726\right]\right\}^{1/2}} \quad (1)$$

where, $F = \frac{8.791\times10^9}{f_r\sqrt{\varepsilon_r}}$

ε_r = the relative permittivity of the dielectric material

f_r= the resonant frequency of the antenna

h = the height of the dielectric material.

Initial resonant frequency has been taken as 5 GHz, ε_r as 2.33 (ARLON CuClad) having negligible losses and height of the substrate has been chosen to be 5.0 mm. A finite ground plane has been chosen for the square shaped patch with side length of 20.0 mm. These data gave the radius of the patch to be 9.867 mm. When simulating the geometry on the IE3D Software [20] using a probe feed at a distance of 7.5 mm from the center, the resonant frequency obtained is 5.824 GHz with a bandwidth of 648 MHz and a Reflection coefficient (S11) of -24.578 dB (corresponding to a VSWR of 1.126).

The directivity obtained is 7.079 dBi at the resonant frequency. The total field gain of 3.04 dBi and an axial ratio of 1.143 dB have been obtained.

An annular ring slot of 270^0 with a width of 1.0 mm has been cut on the circular patch as shown in Figure 1. When simulating this antenna, the Reflection coefficient obtained is -13.05 dB at 5.446 GHz (corresponding to a VSWR of 1.57). Other parameters obtained are: directivity = 6.8 dBi, total field gain =2.356 dBi and axial ratio = 0.682 dB.

The performance of this antenna (reference antenna) has been optimized using the genetic algorithm (GA) optimization process.

3. General analysis of the proposed antenna

The antennas in the literature mostly employ circular patches with different forms like multilayered, U-slot, annular ring patch etc. A number of methods are available for the analysis of circular microstrip antenna given in [2]. These include cavity model, mode matching with edge admittance, generalized transmission line model (TLM) integral equation approach and FDTD. For the simplicity of analysis of the proposed antenna it has been considered to be a combination of three parts: first a circular patch of radius 'a', second, a 270^0 annular ring (arc) of width ranging from 'b' to 'c' and a 90^0 (arc).

The wave equation due to only circular patch of radius 'a' for electric field without any excitation current can be written as [2]

$$(\nabla^2 + k^2)\vec{E} = 0 \qquad k = 2\pi\sqrt{\varepsilon_r}/\lambda_0 \tag{2}$$

which has solution in cylindrical coordinates as

$$E_z = E_0 J_n(k\rho)\cos n\phi, \tag{3}$$

Where, $J_n(k\rho)$ are Bessel functions of n^{th} order.

The magnetic field components are

$$H_\rho = \frac{j}{\omega\mu\rho}\frac{\partial E}{\partial\phi} = -\frac{jn}{\omega\mu\rho}E_0 J_n(k\rho)\sin n\phi \tag{4}$$

$$H_\phi = -\frac{j}{\omega\mu}\frac{\partial E_z}{\partial\rho} = -\frac{jk}{\omega\mu}E_0 J_n(k\rho)\cos n\phi \tag{5}$$

The other field components are zero inside the cavity of dielectric material

$$E_\rho = E_\phi = H_z = 0 \tag{6}$$

The magnetic field boundary condition at the wall

$$H_\phi(\rho = a) = 0 \tag{7}$$

The radiation field in θ and ϕ planes are given by

$$E_\theta = -j^n\frac{V_a k_0}{2}\frac{e^{-jk_0 r}}{r}\cos n\phi J_n'(k_0 a\sin\theta).F_3(\theta) \tag{8}$$

$$E_\phi = nj^n\frac{V_a k_0}{2}\frac{e^{-jk_0 r}}{r}\sin n\theta\frac{J_n(k_0 a\sin\theta)}{k_0 a\sin\theta}\cos\theta.F_4(\theta) \tag{9}$$

Where, $F_3(\theta)$ and $F_4(\theta)$ are the correction factors included when effective substrate and ground plane are considered

The resonance frequency of TM_{nm} mode is given by

$f_{nm} = \dfrac{X_{nm}c}{2\pi a_e\sqrt{\varepsilon_r}}$, where X_{nm} is the m^{th} zero of $J_n'(ka)$

where c is the velocity of light in free space.

The input impedance of the circular patch(without losses) is given by

$$Z_{in} = -j\omega\mu_0 h\left\{\frac{1}{\pi a^2k^2} + \sum_{m=2}^{\infty}\frac{J_0^2(k_{0m}\rho_0)}{\pi a^2 J_0^2(k_{om}a)(k^2-k_{0m}^2)} + \frac{2}{\pi}\sum_{n=1}^{\infty}\sum_{m=1}^{\infty}\left(\frac{\sin n\Delta}{n\Delta}\right)^2\frac{J_n^2(k_{nm}\rho_0)}{J_n^2(k_{nm}a)}\frac{k_{nm}^2}{(k^2-k_{nm}^2)(k_{nm}^2a^2-n^2)}\right\} \tag{10}$$

For the part of annular ring patch the analysis of [7] can be used. The resonant frequency is obtained by

$$f_{nm} = \frac{X_{nm}c}{2\pi a\sqrt{\varepsilon_r}}. \tag{11}$$

The characteristic equation for the modes is given by

$$J_n'(kb)Y_n'(ka) - J_n'(ka)Y_n'(kb) = 0 \tag{12}$$

And the input impedance can be calculated by

$$Z_{in} = j\omega\mu_0 h\left\{\sum_{n=0}^{\infty}\sum_{m=1}^{\infty}\frac{\pi k_{nm}^2\left(\frac{\sin 2n\omega_f}{2n\omega_f}\right)^2}{2\varepsilon_0 n\left(k_{eff}^2-k_{nm}^2\right)}\times\frac{\left[J_n(k_{nm}\rho_0)Y_n'(k_{nm}a_e)-Y_n(k_{nm}\rho_0)J_n'(k_{nm}a_e)\right]^2}{\left[\frac{J_n'^2(k_{nm}a_e)}{J_n'^2(k_{nm}b_e)}\left(1-\frac{n^2}{(k_{nm}^2b_e^2)}\right)-\left(1-\frac{n^2}{(k_{nm}^2a_e^2)}\right)\right]}\right\}\cos^2 n\varphi_0 \tag{13}$$

Where, a_e and b_e are the effective radii defined as

$$a_e = a - 3h/4 \tag{14}$$

$$b_e = b + 3h/4 \text{ and } k_{eff} = k_0\sqrt{\varepsilon_{re}\left(1-j\delta_{eff}\right)} \tag{15}$$

The integer n denotes the azimuthal variation as per $\cos n\varphi$, while the integer m represents the mth zero of characteristic equation given by equation (12) and denotes the variation of fields across the width of the ring. The input impedance of the 90^0 angled annular sector patch between circular patch and the annular ring patch can be calculated using equation (13) for 90^0 variation of angle φ_0. And the total conductance of the proposed parch antenna can be calculated by adding the admittances of the three parts considered and hence input resistance can be calculated.

4. Application of genetic algorithm for optimization of proposed antenna

Genetic Algorithms (GAs) are an efficient class of evolutionary algorithms inspired by the biological processes like inheritance, mutation, selection and crossover. GA works with a population (generation) of possible solutions. Each solution is represented through a chromosome, an abstract representation of parameters involved in optimization problem. In each generation, the individuals (chromosomes) are decoded and evaluated according to a fitness function appropriately chosen for particular problem. A number of stochastically selected individuals based on their fitness, are modified using the processes of recombination and mutation to form a new population. This new population is then used in the next iteration of the algorithm. The GA can use coded or non-coded parameters. In this paper the non-coded values of optimization parameters have been used [17]. The crossover probability has been taken to be 0.3.Single point crossover and roulette wheel selection processes have been used as other genetic operators. GA runs for 10 generations and 10 individuals in first generation. The optimization program module uses the computing capabilities of the simulation software Zeland's IE3D. GA is quite simple and powerful tool to be applied for optimization of complex structures. The algorithm has steps as shown in Figure 2 [21].

The GA module uses the parameters calculated by the IE3D simulator. The reference antenna with the desired parameters has been first simulated. The geometry file (with extension *.geo*) has been changed and new structures obtained have been simulated. The fitness module of GA and IE3D has been shown in Figure 3.

After changing the geometry file the following codes has been used to start simulator [19]: c:\Program Files\Zeland\exe\Zeland.exe,ie3d.exe "pathname of *.sim* fie". The fitness module uses the parameters of each structure and calls simulator to calculate the electrical properties of each structure. These electrical properties (Reflection coefficient or VSWR) can be used to evaluate the fitness value of each structure. The design objective has been taken as to broaden the bandwidth with minimum Reflection coefficient by optimizing the structure. To achieve this goal the fitness function has been defined as the average of Reflection coefficient (S_{11}) values that goes below -10 dB over the given frequency band.

$$Fitness = \frac{1}{N}\sum_{n=1}^{N} S(f_i) \tag{16}$$

and

$$S(f_i) = \begin{cases} 10, & S_{11}(f_i) < -10 \\ |S_{11}(f_i)| & S_{11}(f_i) \geq -10 \end{cases}$$

Where, $S_{11}(f_i)$ is the Reflection coefficient calculated by simulator at the sampling frequency f_i.

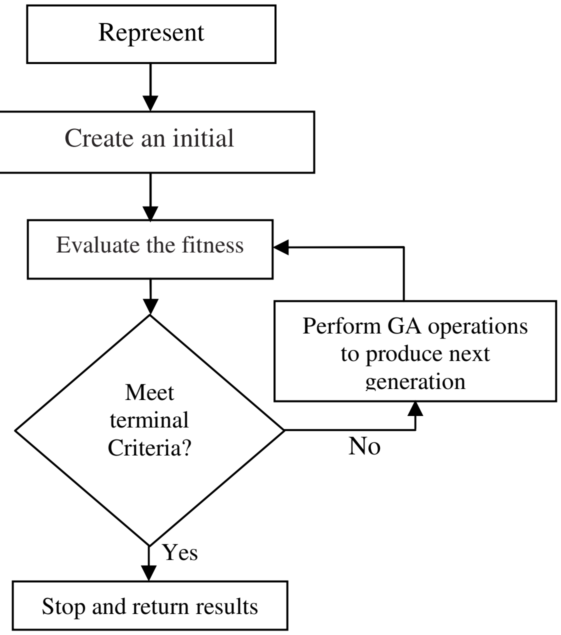

Fig. 2. The genetic algorithm module

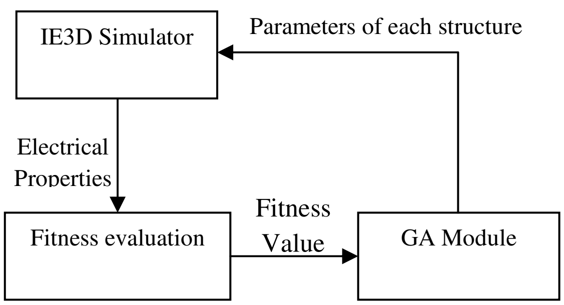

Fig.3. GA and IE3D fitness module

The optimization process has been carried out in step by step manner. First the ground plane size has been optimized. Then the height of substrate, radius of the patch, finally the slot position and its width has been optimized for optimum performance.

5. Results and discussion

The optimized values of the antenna structure parameters of Figure 1 have been shown in Table 1.

The performance parameters of the antenna are reflection coefficient (S_{11}), axial ratio, total field directivity, total field gain and elevation pattern gain for the reference antenna discussed in Section II and the optimized antenna. The variation of these parameters with frequency for both the antennas has been shown in Figure 4. It is obvious that the GA optimized antenna Reflection coefficient curve gets deep resonant peaks at points 4, 5 and 6 corresponding to points 1, 2 and 3 respectively for the reference antenna.

It enhances the number of bands from one to three around resonant frequencies at 5.27 GHz, 6.46 GHz and 7.89 GHz with bandwidths of 140 MHz, 400 MHz and 637 MHz, respectively.

Table 1. Optimized values of the antenna parameters

Sl. No.	Structure Parameter (As in Figure 1)	Optimized Value
1.	L, Length of the ground plane	20.093 mm
2.	W, width of the ground plane	20.093 mm
3.	a, radius of the circular patch	7.48 mm
4.	b, outer radius of annular slot	4.25 mm
5.	c, inner radius of annular slot	3.48 mm
6.	w, width of the annular slot	7.7 mm
7.	h, height of the substrate	3.28 mm

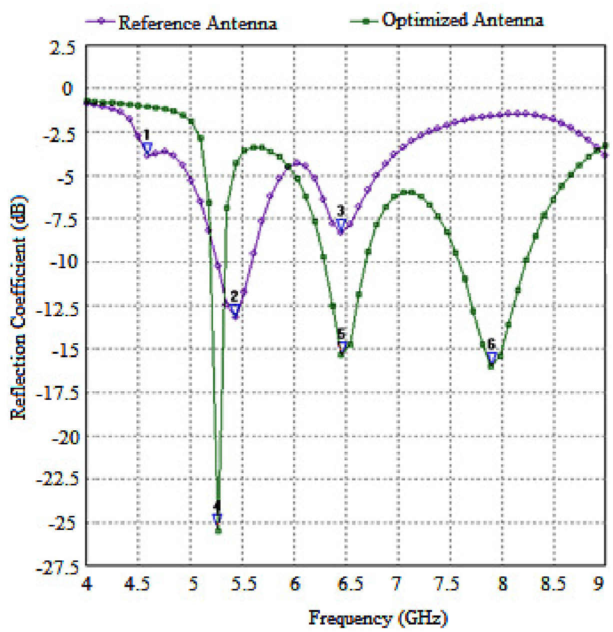

Fig. 4. Variation of reflection coefficient with frequency

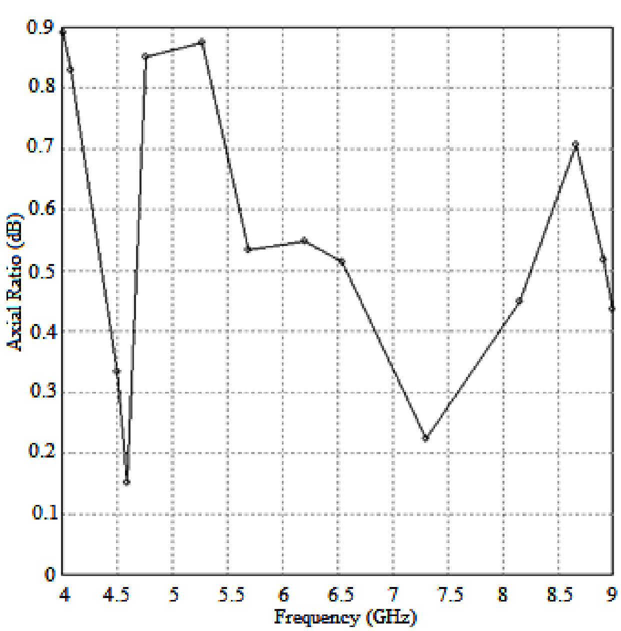

Fig. 5(a). Axial ratio of the Reference Antenna

Figure 5-7 show the axial ratio, directivity and total field gain curves versus frequency for the reference and optimized antenna respectively. The variation of axial ratio (Fig 5) in the optimized antenna has been decreased well below 3 dB value whereas the directivity (Fig 6) of the optimized antenna has been increased over the range of higher frequencies of the antenna operation. The total field gain of the antenna has been improved by a large amount and continuously in the higher frequency band where it decreases for the reference antenna (Figure 7).

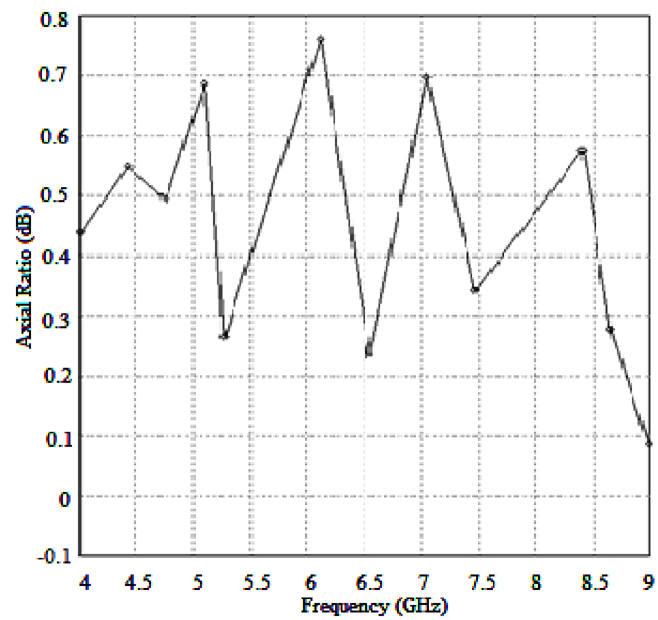

Fig. 5(b). Axial Ratio vs. Frequency curve of the Optimized antenna

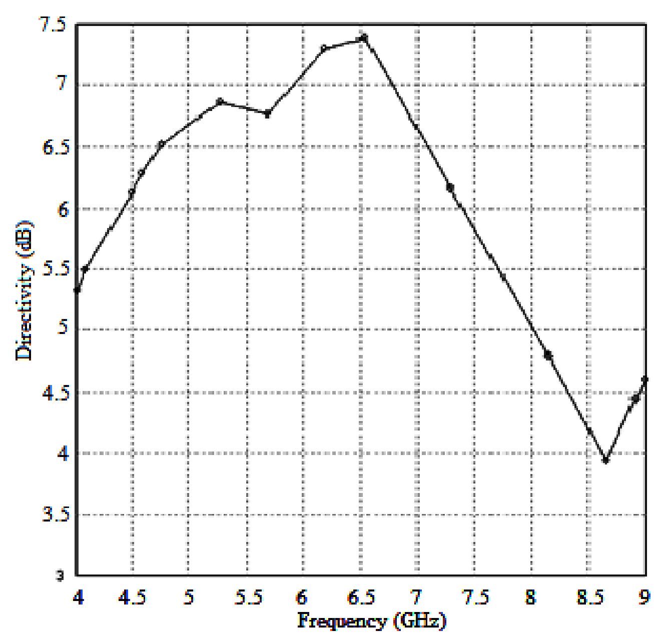

Fig. 6(a). Total field directivity vs. frequency curve of the reference antenna

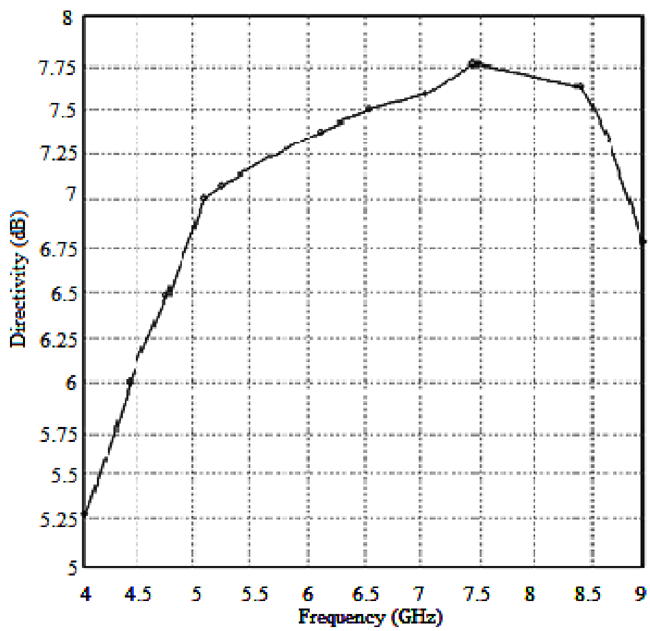

Fig. 6(b). Total field directivity vs. frequency curve of the optimized antenna

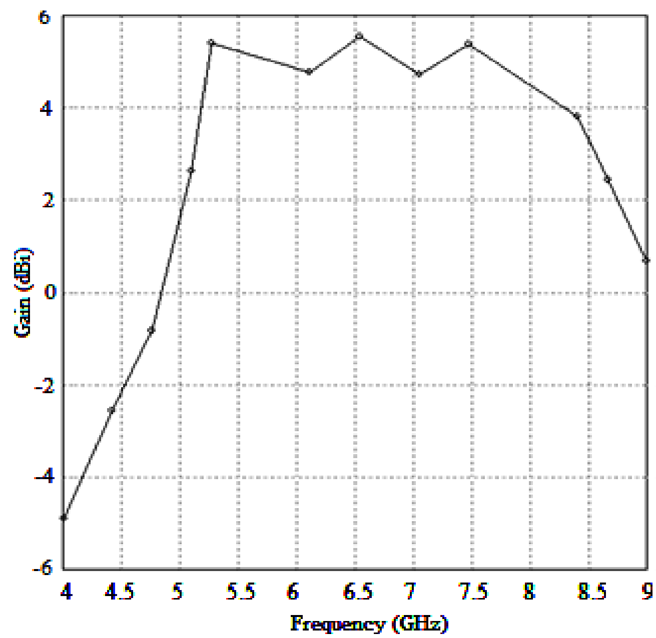

Fig. 7(b). Total field gain vs. frequency curve of the optimized antenna

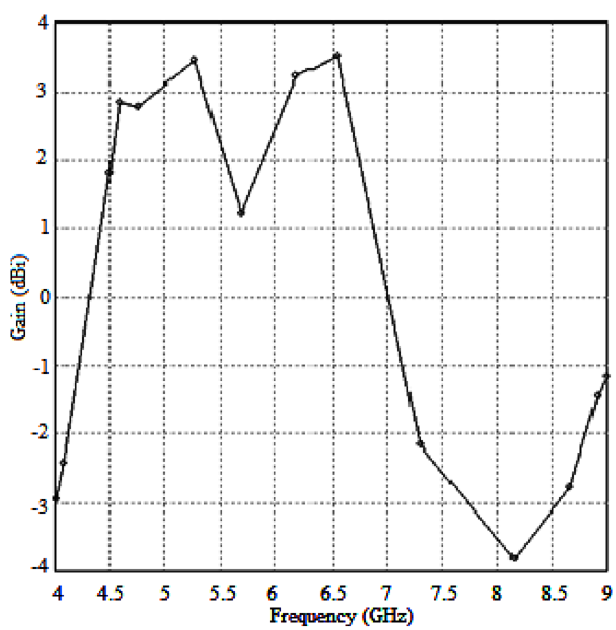

Fig. 7(a). Total field gain vs. frequency curve of the reference antenna

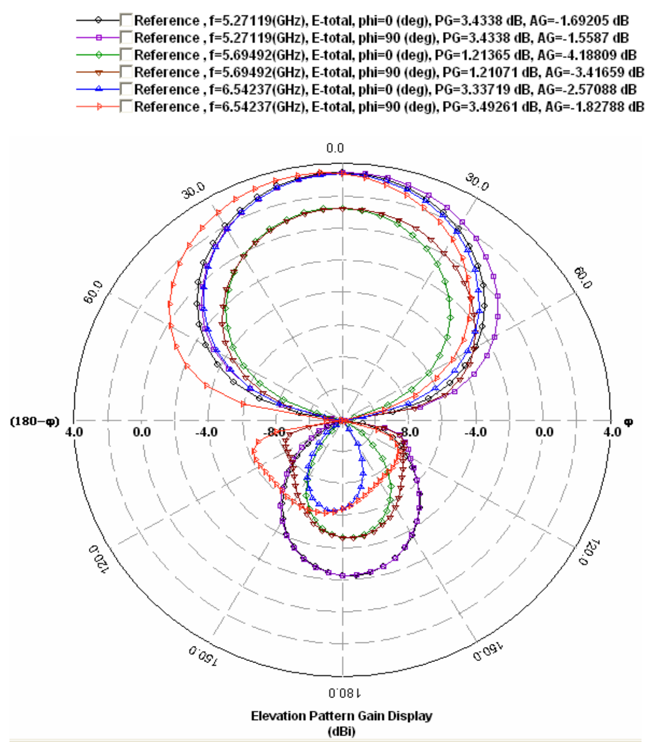

Fig. 8(a). Gain pattern of the reference antenna

In Figure 8, the elevation radiation patterns of the reference and the optimized antenna have been shown. The optimized one directive pattern in one side of the patch is shown.

6. Conclusion

The genetic algorithm has been applied for optimization of a circular microstrip antenna with 270^0 annular patch having probe feed. The results show that the compact size circular microstrip antennas with simple geometries can be designed for multiband operation with good radiation properties. The GA is a simple and very appropriate tool for optimizing structure to generate very good radiation pattern characteristics for single or multiband operations.

The designed antenna is very compact and can be used in the communication applications, WLANs as well as for the advanced frequency radars or scatterometers.

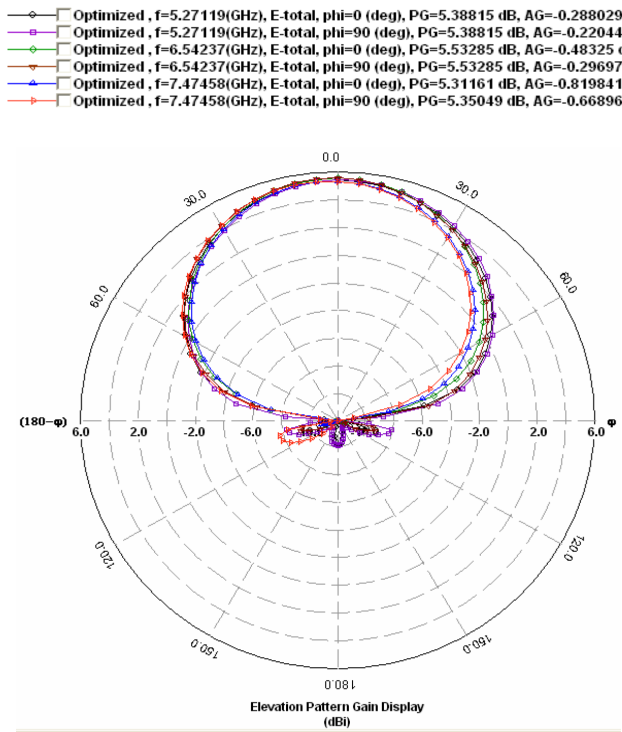

Fig 8(b). Elevation gain pattern of the optimized antenna**.**

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