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RESEARCH ARTICLE

Optimization of the performance of patch antennas using genetic algorithms

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Abstract: Patch antenna is a widely used antenna type in many applications. These antennas are low-profile, cheap, conformable to planar and non planar surfaces, simple to fabricate using printed circuit technology and compatible with monolithic microwave integrated circuit (MMIC) designs. However, their narrow bandwidth and low efficiency are the major drawbacks. In this study, genetic algorithm optimization (GAO) method was used to design the shape of the patch, feed position, thickness of the dielectric substrate and the substrate material simultaneously in order to optimize both bandwidth and gain. It was found that thin broadband fragmented single probe feed patch antennas with -10 dB impedance bandwidths up to almost 2:1 can be easily designed using GAO. The antennas were simulated using high frequency structure simulator (HFSS) and the results were validated using measurements.

Keywords: Antenna radiation patterns, bandwidth, gain, genetic algorithm optimization, patch antennas.

INTRODUCTION

A patch antenna is a metallic strip or a patch mounted on a dielectric layer (substrate), which is supported by a ground plane. The radiating patch and the feed lines are usually photo-etched on the dielectric substrate (Howell, 1975; Karver & Mink, 1981; Pozar, 1992; Balanis, 1997). Patch antennas are becoming popular in wireless applications due to their low-profile structure. They are extremely compatible for embedded antennas in handheld wireless devices such as cellular phones and pagers. Other areas where they have been used successfully are satellite communication, radar systems and missiles. They are simple, robust, inexpensive, light in weight and integrable with microwave circuits. The major disadvantages of the patch antennas are narrow bandwidth and low efficiency.

Design of wideband and efficient patch antennas is an interesting problem for the antenna research community. In the initial stage, analysis was confined to basic shapes such as rectangular, circular and elliptical. Antenna parameters were theoretically calculated and fabricated so as to suit for a specific application. Later, research was expanded to different configurations in order to obtain better performance in wideband applications (Aanandan & Nair, 1986; Pues & Van de capelle, 1989; Ali *et al*., 2005; Guo *et al*., 2007). Insertion of slots, slits, parasitic elements and capacitive loading are some of the standard techniques used to obtain bandwidth improvements and multiband operations (Wong, 2003). Design of patch antennas with complex geometries was made possible with the availability of advanced simulation software and developments in the fabrication technology.

The performance of patch antennas can be optimized *via* changing antenna parameters such as patch geometry and substrate thickness. Therefore, optimization techniques can be applied to enhance the performance of patch antennas (Johnson & Rahmat-Samii, 1997; Villegas *et al*., 2004; Thors *et al*., 2005; Polivka *et al*., 2006; Jin & Rahmat-Samii, 2008; Su *et al*., 2008; Jayasinghe & Uduwawala, 2010; Jayasinghe & Uduwawala, 2012). Genetic algorithm is one such powerful optimization technique used in patch antenna design. It is a robust, stochastic-based search technique, which can handle the common characteristics of electromagnetic optimization problems that are not readily handled by other traditional optimization methods.

In this study, genetic algorithms were used to design the patch geometry, feed position, substrate thickness and permittivity in order to optimize the bandwidth and gain

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of the antenna. Broadband (Johnson & Rahmat-Samii, 1997; Jayasinghe & Uduwawala, 2010) and multiband (Villegas *et al*., 2004; Polivka *et al*., 2006; Su *et al*., 2008; Jayasinghe & Uduwawala, 2012) patch antenna designs using genetic algorithm optimization (GAO) procedure has been reported in the literature. In the publications by Jayasinghe & Uduwawala (2010) and Johnson & Rahmat-Samii (1997), only the patch geometry is considered for optimization, and fractional bandwidth values of 51 % and 20 % were achieved. In both papers, the feed position is fixed and in Jayasinghe & Uduwawala (2010) the antenna is center fed. In addition, both papers have optimized only the bandwidth; but the gain has not been considered. In 2012, Jayasinghe & Uduwawala reported a quad-band patch antenna that has been designed taking both the patch geometry and the feed position as optimization parameters. Again the radiation patterns have not been considered in the optimization process. In Thors *et al*. (2005) the research was conducted on infinite phased arrays.

In contrast, the analysis in this paper covers different antenna parameters simultaneously to obtain the optimized performance in a single element patch antenna in terms of both the bandwidth and gain. The analysis of the patch antennas was carried out by using high frequency structure simulator (HFSS), which is a highly accurate commercially used electromagnetic solver. The simulations were validated by taking measurements on a fabricated patch antenna.

SIMULATION AND DESIGN

The antenna is a symmetrical fragmented patch, fed by a 50 Ω coaxial line. It is optimized in the frequency range 3.5 − 4.5 GHz. In order to search for the optimum solution of conducting regions, the patch area ($l \times w$) is divided into small cells as shown in Figure 1 where each cell can be assigned either conducting or non-conducting properties. The size of a cell was taken equal or less than 3 mm for all the designs in order to achieve better results.

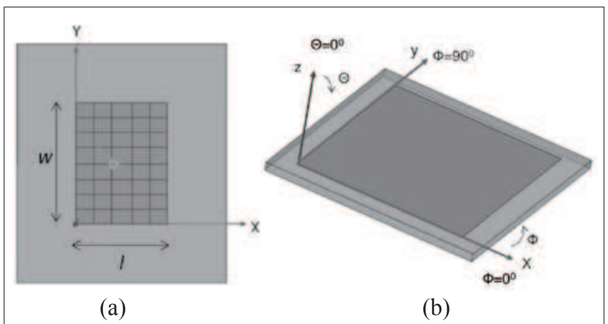


Figure 1: Antenna geometry (a) front view; (b) coordinate system

When the antenna is fed at the centre point, it is assumed to be symmetrical about its centre axes parallel to the x axis and y axis. When it is fed off-centered, it is assumed to be symmetrical about the centre axis parallel to the x axis. Therefore, only a quarter or a half of the patch is coded accordingly into genes in GAO procedure. Since only two values are possible for each cell, binary coding was used. The chromosomes describe the entire fragmented patch. When more parameters are included in the design such as the feed position, relative permittivity and substrate thickness, the corresponding genes are added into the chromosome subsequently.

Since the main objective was to design broadband patch antennas, the fitness function was defined by summing the magnitudes of the reflection coefficient ρ taken at 10 MHz intervals over the range of 1 GHz from 3.5 GHz to 4.5 GHz. In order to avoid the solutions of narrow bandwidth with very low reflection coefficient values and to increase the bandwidth as much as possible, reflection coefficient values less than -10 dB were considered as -10 dB. In later designs, the gain at 4 GHz was also included in the fitness function. Therefore, the fitness function F, which is maximized in the search for the optimum solution can be written as

$$F = kG - \sum_{n=1}^{n=101} L(n) \qquad ...(1)$$

where k is a weighting factor, G is the gain (in dB) at 4 GHz and L is defined as

$$L = \begin{cases} \rho & \rho \geq -10dB \\ -10dB & \rho < -10dB \end{cases} \qquad ...(2)$$

The population size is 20 chromosomes per generation in all designs. The probability of crossover is 100 % and the single point crossover method was used. One bit is mutated in 60 % of the individuals within a generation. The next generation is formed from the best 20 individuals in the current generation and its siblings in order to ensure the preservation of the fittest.

The simulation along with GAO was programmed using HFSS scripts. The programme was run over iterations until the expected value of the fitness function is reached or until the best value of the fitness function remained unchanged for 20 generations.

RESULTS

The simulations were carried out under four categories based on the number of antenna parameters optimized using genetic algorithms. They are the geometric shape, feed position, substrate thickness and the substrate permittivity.

Figure 2 shows the simulation results of reflection coefficient and radiation patterns of a conventional rectangular patch antenna. The relative permittivity of the substrate is 3.2 and the thickness of the substrate is 6 mm. The dimensions of the antenna are l = 17.5 mm and w = 26 mm, which make it resonant at 4 GHz in the fundamental mode (Balanis, 1997). The antenna is narrowband with a -10 dB fractional bandwidth [voltage standing wave ratio (VSWR) < 2] of 9 %. The operating frequency range is 3.84 − 4.20 GHz. The radiation patterns are obtained on two vertical planes $\phi = 0^{\circ}$ and $\phi = 90^{\circ}$ as shown in the Figure 2b. The maximum radiation is along $\theta = 22^{\circ}$ with a gain of 6.41 dB in $\phi = 0^{\circ}$ plane and 5.36 dB in $\phi = 90^{\circ}$ plane. The aim of this study was to improve this bandwidth and gain perpendicular to the patch plane as evident in the following sections.

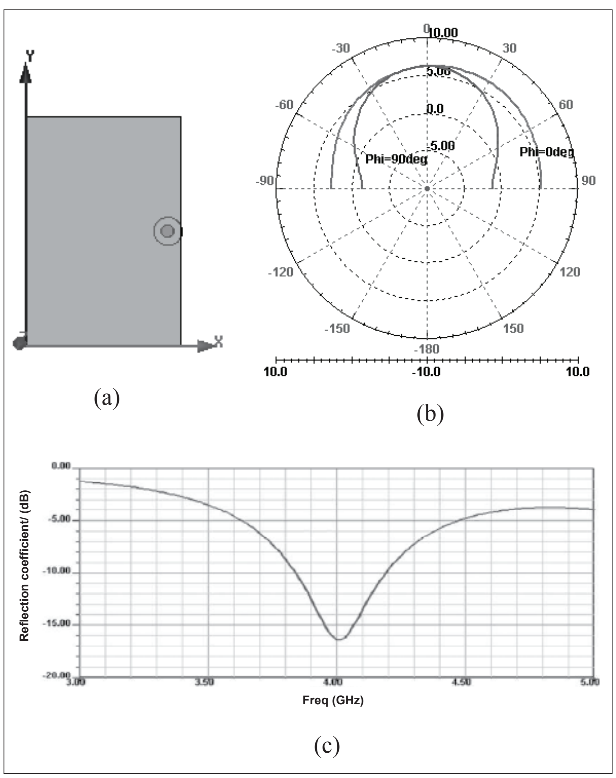


Figure 2: Simulation results of a rectangular shaped patch with a substrate thickness of 6 mm

A. Geometric shape as the only parameter

The antenna was fed at the centre when the geometrical shape is the only parameter considered for optimization and the antenna was assumed to be symmetrical about its centre axes parallel to the x axis and y axis. Therefore, the patch area was gridded into 100 cells and only a quarter of the patch was coded as a chromosome with 25 genes. The dimensions of the antenna were l = 17.5 mm and w = 26 mm, which are the same as that of the rectangular patch described earlier. The permittivity ε_r was 3.2 and the substrate thickness was 6 mm.

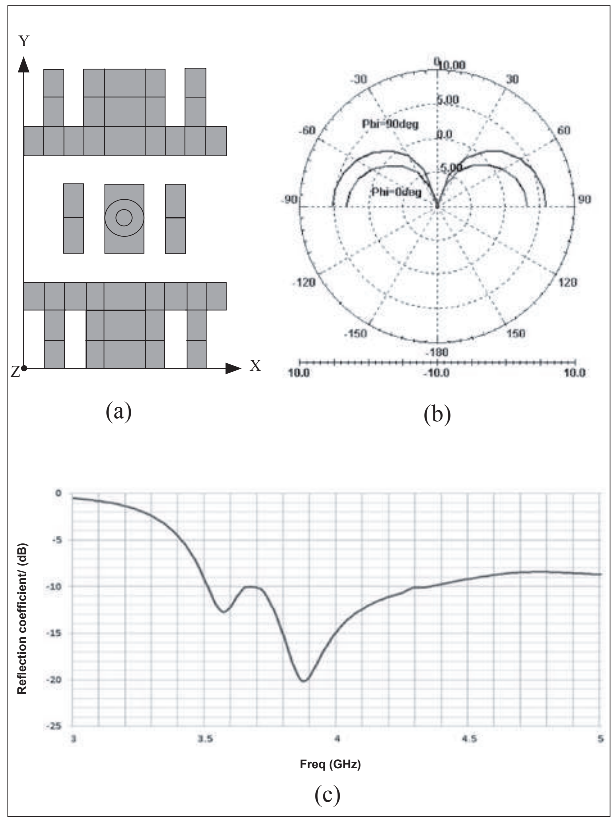


Figure 3: Design results of the antenna with optimized patch shape (a) patch antenna; (b) radiation pattern; (c) reflection coefficient

The fractional impedance bandwidth (VSWR < 2) of the optimized design was 20 % from 3.51 – 4.29 GHz. Comparison of Figure 2 and Figure 3 shows an improvement of bandwidth from 1.1 : 1 to 1.2 : 1 after optimizing the patch shape, while maintaining the same patch size. The maximum radiation is along the antenna plane with 5.48 dB in $\phi = 90^{\circ}$ plane and 3.05 dB in $\phi = 0^{\circ}$ plane.

B. Geometric shape and feed position as parameters

The genetic algorithm optimization method was used to design the patch shape and the feed position of a fragmented patch antenna while keeping the relative permittivity and the thickness of the substrate constant at the same values as in section A. The dimensions of the antenna were $l = 17.5$ mm and $w = 26$ mm. The patch area was gridded into 50 cells and the first 25 genes of the chromosome were used to define the shape. The next four genes were used to define the feed position, allowing it to take 16 discrete values from the center of the patch to the edge along the x axis. Figure 4 shows the optimized design, radiation pattern and reflection coefficient plot. In the optimized design, the maximum radiation is perpendicular to the patch with a gain of 6.07 dB. The bandwidth was improved to operate in 3.50 − 4.53 GHz range, which is 1.3 : 1. The fractional bandwidth shows an improvement from 9 % to 25.7 % when Figures 2 and Figure 4 are compared.

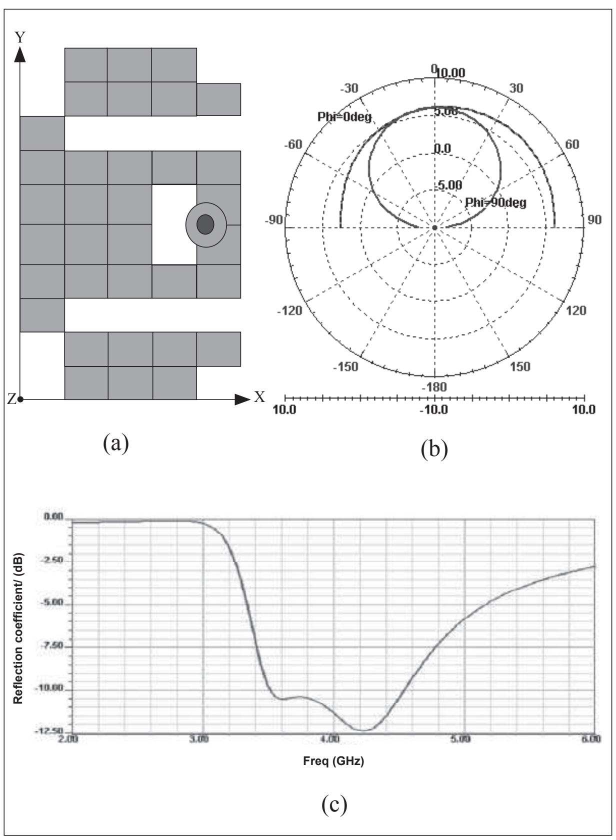


Figure 4: Design results of the antenna with optimized patch shape and feed position (a) patch antenna; (b) radiation pattern; (c) reflection coefficient

In order to validate the simulation results, a patch antenna designed using GAO was fabricated (Figure 5a). The same material was used but with a thickness of 0.762 mm. The optimized design operates in a -10 dB bandwidth of 170 MHz as shown in Figure 5b. The printed antenna was tested by using a vector network analyzer (Figure 5b) for comparison. The measurement results agree well with the simulation results.

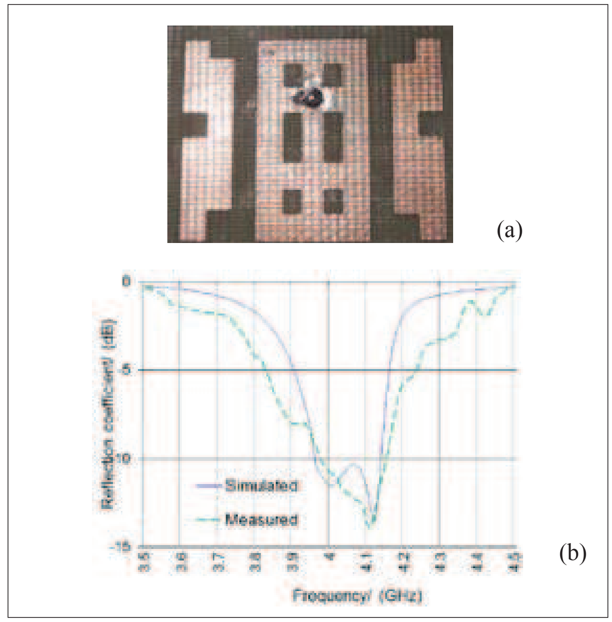


Figure 5: Comparison of simulated and measured results of the optimized antenna with the 0.762 mm thick substrate (a) fabricated antenna; (b) reflection coefficient

C. Geometric shape, feed position and substrate thickness as parameters

The substrate thickness was also included in the GAO procedure in addition to patch shape and feed position. The permittivity ε_r was kept as 3.2 and the dimensions of the antenna were $l = 21$ mm and $w = 26$ mm. In Figure 6, the results of the optimized design are presented when the substrate thickness was allowed to take sixteen discrete values between 1 – 16 mm. In the optimized design, the thickness was 13 mm and a fractional bandwidth of 47.9 % could be obtained. The bandwidth was improved to operate in 3.03 − 4.98 GHz range (1.6 : 1). The maximum gain is in the direction $\theta = 30^\circ$ with 2.58 dB in $\phi = 90^\circ$ plane and 3.76 dB in $\phi = 0^\circ$ plane. Although the bandwidth is quite improved, the gain has decreased when compared to previous designs.

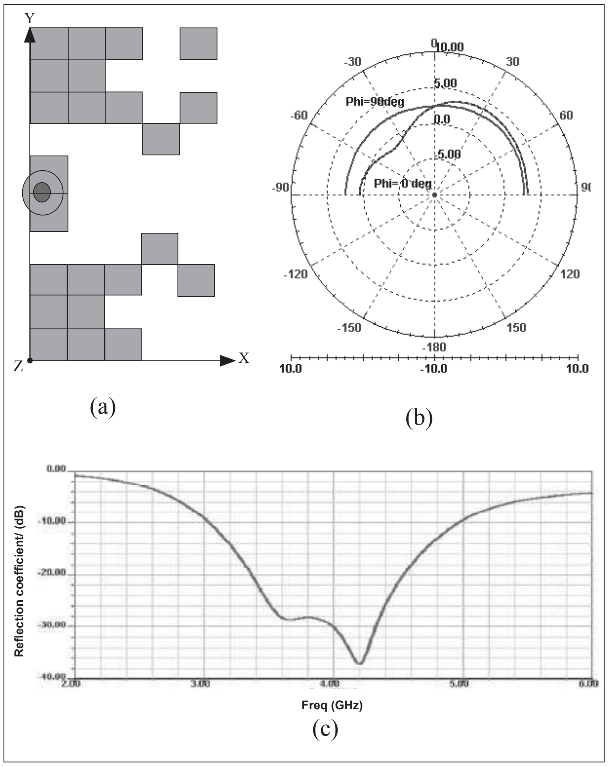


Figure 6: Design results of the antenna with optimized patch shape, feed position and substrate thickness. (a) Patch antenna; (b) radiation pattern; (c) reflection coefficient

D. Geometric shape, feed position, substrate thickness and substrate material as parameters

The substrate material was also included in the optimization by taking eight discrete permittivity values, which were 2.08, 2.5, 2.94, 3.2, 4.5, 6, 9.2 and 10.2. The substrate thickness was changed from 1 – 16 mm. The format of the chromosome is shown in Table 1.

Table1: Format of the chromosome

Geometric shape	Feed position	Substrate thickness	Substrate material
0, 1 ---- 24	25 26 27	28 29 30 31	32 33 34

In addition to the summation of reflection coefficient values, the gain at 4 GHz was also included in the fitness function with a weighting factor of 10. The dimensions of the antenna were l = 21 cm and w = 26 cm. The thickness of the optimized design was 12 mm and the permittivity was 2.94. The fractional bandwidth of the optimized design was 60 % (nearly 2:1) and the maximum gain was 6.48 dB perpendicular to the plane of the patch as shown in Figure 7. In this design, it was possible to improve both bandwidth and the gain.

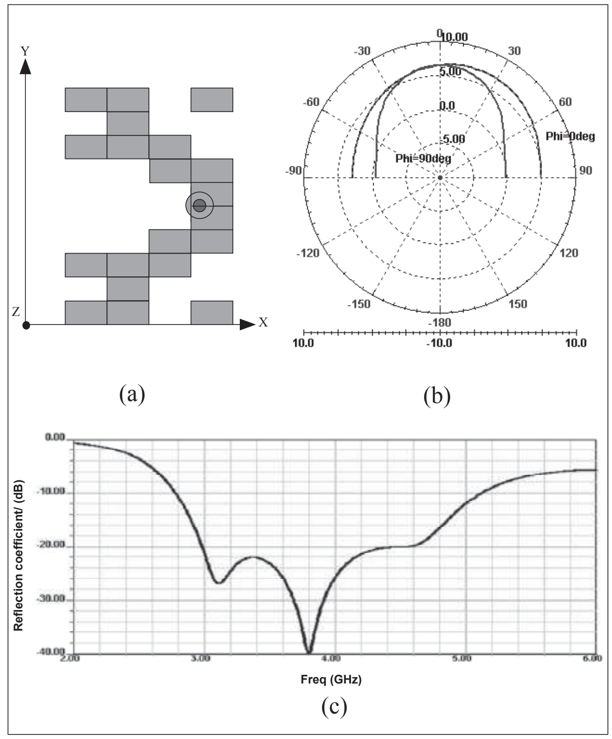


Figure 7: Design results of the antenna with optimized patch shape, feed position, substrate thickness and substrate material. (a) Patch antenna; (b) gain plot; (c) reflection coefficient

Convergence rate of the best fitness value for the design in Figure 7 is shown in Figure 8.

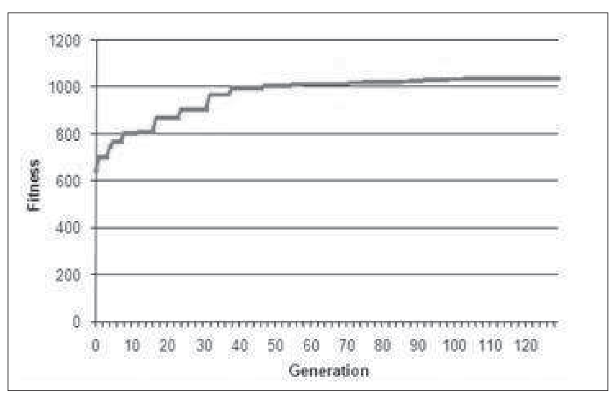


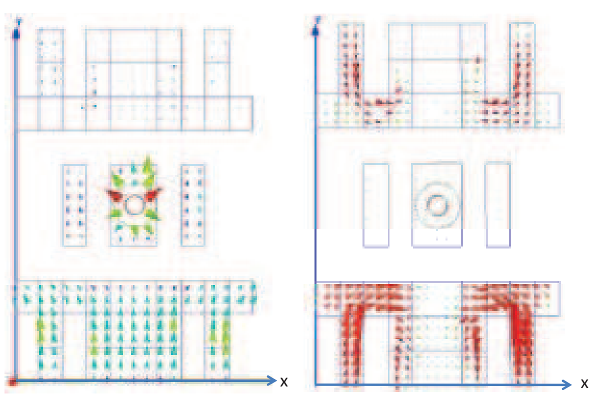
Figure 8: Convergence rate of the best fitness value for the design in Figure 7

EVALUATION

The results (Table 2) show that the drawbacks of the patch antennas can be overcome by optimizing the patch antenna parameters. The bandwidth and the gain can be improved successfully by using one or more antenna parameters for the optimization process. Increasing the bandwidth of a rectangular patch can be acheived by inserting slots, slits and parasitic elements. They provide several resonant current paths and thus make the antenna resonant at several frequencies. If the dimensions are selected such that these frequencies are close to each other, their resonant bands can overlap to give an increased single bandwidth to the antenna. In GAO procedure, these slots and parasitic elements are generated as part of the solution to give the desired results. Figure 9 shows how different resonant current paths are created in the antenna designed in section A.

Table 2: Bandwidth and gain of antennas designed by optimizing different parameters

	Optimized parameters	Fractional bandwidth	Gain
1	Geometric shape	20 %	5.48 dB in = 90^0 plane and 3.05 dB in = 0^0 plane
2	Geometric shape and feed position	25.7 %	6.07 dB perpendicular to the patch
3	Geometric shape, feed position and substrate thickness	47.9 %	2.58 dB in = 90^0 plane and 3.76 dB in = 0^0 plane
4	Geometric shape, feed position, substrate thickness and substrate material	60 %	6.48 dB perpendicular to the plane



(a) (b)

Figure 9: Current patterns of the antenna in section A (a) at 3.6 GHz; (b) at 3.9 GHz

Although the operating frequency was selected in the range 3.5 − 4.5 GHz for all the simulations in this paper, the given results are applicable to other frequencies by scaling the design. For example, the optimized design in Figure 7 was resized by a factor of 0.8 to obtain broadband performance around 5 GHz. All factors other than the patch size, such as patch shape, substrate thickness and permittivity were kept unchanged. The resulted fractional bandwidth was 57.5 % and gain was 5.38 dB as shown in Figure 10 and they were quite close to the results in Figure 7. But more accurate designs can be obtained if the optimization is done for the required frequency range. This is especially needed at low frequencies as if the antenna is resized to obtain broadband performance at low frequencies, the bandwidth reduces as the ground plane constitutes a bandwidth limiting factor at low frequencies.

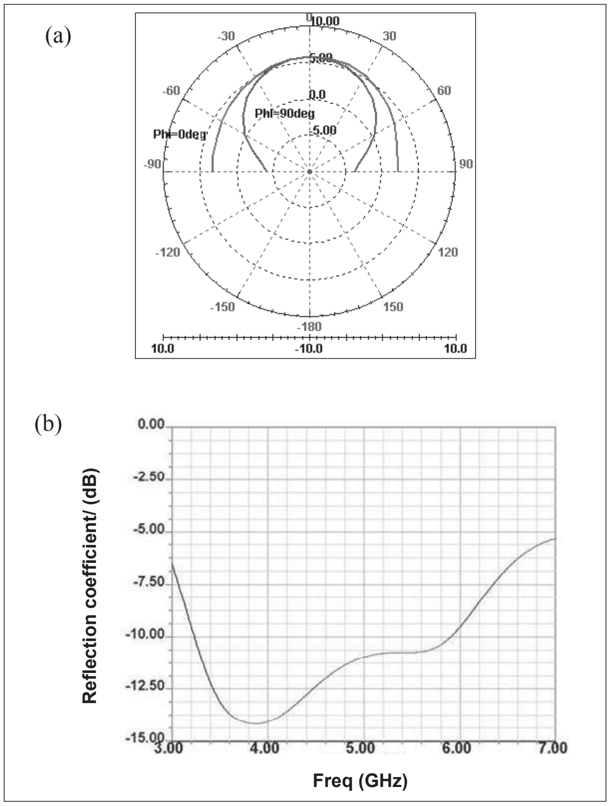


Figure 10: Design results of the antenna in section D when it is resized to operate around 5 GHz (a) gain plot; (b) reflection coefficient

CONCLUSION

In this study, genetic algorithm optimization method has been used to synthesize broadband fragmented probe feed patch antennas with increased impedance bandwidth and gain. The patch geometry, feed position, substrate thickness and permittivity of the patch antennas have been optimized to achieve fractional bandwidths up to nearly 60 % and gains up to 6.5 dB. The simulations have been carried out by using HFSS and validated by taking measurements of a fabricated antenna.

The simulation results show that thick substrates with low permittivity are suitable for patch antennas to achieve wider bandwidths. But thick substrates are undesirable if the antenna is to be integrated with microstrip circuits. Then a compromise has to be reached between good antenna performance and circuit design.

Extending this study to array antennas would be of interest in forthcoming research.

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