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RESEARCH ARTICLE

Increasing the directivity of a microstrip patch array by genetic optimization

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Abstract: Conventional single element microstrip patch antennae have a low directivity (6 − 8 dB). In order to increase the directivity, an array of microstrip patches can be used. It may be possible to further improve the performance of arrays by applying genetic algorithms (GA). This paper presents a method to increase the directivity of a 2 × 1 patch array with broadside radiation using GA. The proposed GA method divides the patch area into different cells, taking into account that cells have a small overlap area between them. The patch array is etched on a substrate with a relative permittivity of 3.38 and a thickness of 1.52 mm. The antenna operates at 4 GHz resulting in a directivity of 10.9 dB. The specialty of this design is the use of GA to select the inter-element spacing, optimized shape and the feeding position instead of a known shape and a fixed inset length of feeding. The results show that the directivity of the genetic array is larger than that of the conventional array with the same overall dimensions, which resonates at the same frequency.

Keywords: Genetic algorithms, microstrip arrays, microstrip patch antenna.

INTRODUCTION

Conventional single element microstrip patch antennae have a moderate directivity of about 6 − 8 dB (Balanis, 2005). The design of a high-directivity microstrip patch antenna is a challenging task because a classical patch such as the square patch presents a broadside pattern at its fundamental mode (TM_{10} or TM_{01}) with a low directivity. At the TM_{20} or TM_{02} there is a null in the broadside direction. A broadside pattern can be found at a higher order mode (TM_{30}), but the directivity is again limited, as the pattern presents high secondary lobes.

Various methods to improve the directivity of a patch antenna have been reported in literature. One such method is the use of higher order modes of fractal-like antennae such as Sierpinski (Anguera *et al.*, 2001; 2003a), Koch (Borja *et al.*, 2000; Romeu *et al.*, 2000; Anguera *et al.*, 2008), and Hilbert (Anguera *et al.*, 2003b). Another technique to increase the directivity is the use of stacked patch antennas (Anguera *et al.*, 2004). In addition to the above, high-directivity antennae based on superstrates (Foroozesh & Shafai, 2012; Pirhadi *et al.*, 2012), zero-index metamaterial (Zhou *et al.*, 2009), electromagnetic band gap resonator (Cheype *et al.*, 2002), modified peano space-filling curve (El-Khouly *et al.*, 2007), photonic band-gap materials (Yang *et al.*, 1997) and partially reflective surfaces (Weily *et al.*, 2005) have also appeared in the field. Moreover, publications by Jayasinghe *et al.* (2013a;b) propose the design of a high-directivity microstrip patch antenna to replace a 2 × 1 and a 4 × 1 conventional patch arrays by avoiding feeding networks. In contrast, the present study proposes applying genetic algorithms (GA) on an array, and in particular, to each of the elements of a 2 × 1 array. The objectives of this study are to find the most suitable patch geometry, inset feeding length and inter-element spacing of a 2 × 1 array, while keeping the substrate height small (~0.02 λ) in order to further improve the directivity compared to a square element array having the same dimensions.

GA is a powerful optimization technique that has been shown to be useful in a wide area of electromagnetics. Nearly 20 years ago, the genetic optimization of a set of metallic strips to obtain desired radiation parameters was discussed by Haupt (1995). GA has been used to

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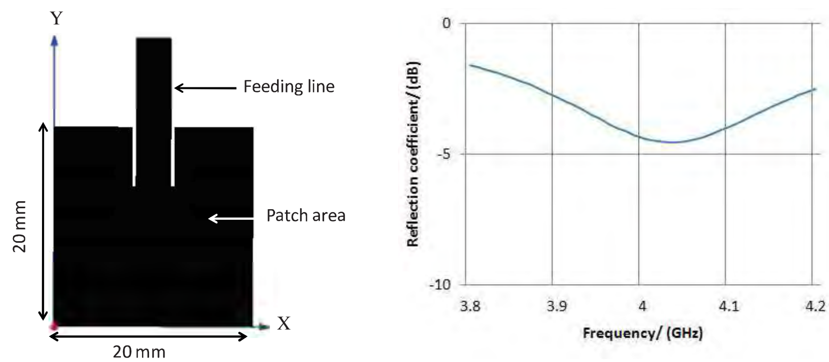
design compact and multiband arrays (Paras & Gangwar, 2011), high-gain and wideband arrays (Feng *et al*., 2013), thinned arrays (Jain & Mani, 2011), switched beam antenna arrays (Mitilineos *et al.*, 2004) and low radar cross section arrays (Zhu *et al.*, 2012). Further, GA has been incorporated in arrays to reduce side lobe levels (Laseetha & Sukanesh, 2011; Patel & Alad, 2013) to increase directivity (Siakavara, 2010), locate defective elements (Rodríguez *et al.*, 2000) and for beam scanning (Tokan & GÄunes, 2009). Moreover, the design of radiation characteristics of a patch array in terms of side-lobe level, main-lobe half-power beamwidth and dynamic range is also available in literature (Coevorden *et al.*, 2005).

However, to the authors' knowledge no references have been found regarding optimizing the antenna geometry of a microstrip patch array, to improve the directivity in comparison to the same array using square elements. In this study, GA is used to design a high-directivity patch array by optimizing the inter-element spacing, patch geometry and feed position. The designs have been simulated in the high frequency structure simulator (HFSS) environment in combination with a home-made GA code in MS Windows operating system. The GA operation is written using Visual Basic Script (VBS) Writer and the VBS file is called into the HFSS environment to perform simulations. The designs are checked for their fitness continuously until the termination criteria as set in the VBS code is reached.

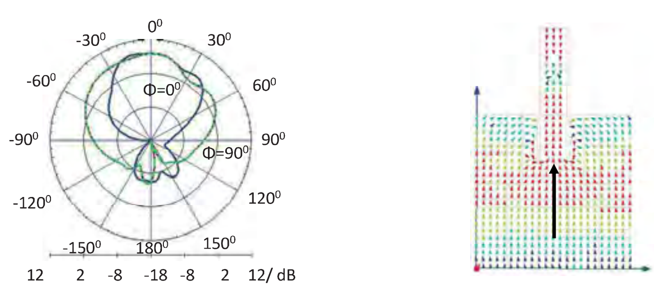
ANTENNA CONFIGURATION AND GA

The patch array consists of two elements, where the size of a single element is fixed to fit in an area of 20 × 20 mm^2. The objective is to maximize the directivity within that area. The patch array is etched on a thin substrate with a thickness of 1.52 mm. The substrate material is Rogers RO4003 (tm), which has a relative permittivity of 3.38 and a loss tangent of 0.0027. The antenna is fed by a 50 Ω coaxial cable with a probe diameter of 1 mm.



(a) (b)

Figure 1: Simulation results of a single patch element. (a) Patch geometry; (b) S_{11} Plot



(a) (b)

Figure 2: Simulation results of a square shaped patch. (a) Main radiation cuts at 4GHz; (b) current distribution at 4 GHz (the black arrow indicates the direction of current)

Single patch element

Before starting the GA optimization process, a single patch element (size of 20 × 20 mm^2) is briefly analyzed for comparison purposes (Figure 1a). When the inset feeding length is 5.5 mm, the antenna resonates at 4 GHz in the fundamental mode (Figure 1b).

The radiation patterns and the current distribution of the square shaped patch are shown in Figure 2. At the fundamental TM_{01} mode, the directivity is only 7.1 dB in the broadside direction.

The basic method to improve the directivity is to use arrays. In this paper instead of using a conventional array, an optimized array is introduced. The next section explains the GA procedure employed to search for the right geometry to increase the directivity in the broadside direction.

GA procedure

To show the potential advantages of the proposed method, an array consisting of two identical elements is optimized in terms of element geometry, feeding position, and inter-element spacing. With this illustrative example, the method can be expanded to arrays with a large number of elements. The patch area in each element (20 × 20 mm^2) is divided into 23 cells so as to overlap between adjacent cells (Figure 3). The conducting or non-conducting property of each cell is defined using binary encoding. If a cell is conducting, then the corresponding gene is assigned '1' and if a cell is non-conducting, it is assigned '0'.

Thus, the first 23 genes in the chromosome define the patch geometry and three more genes are used to define the inset feeding length. Different inset feeding lengths are used to select the best length for impedance matching. The final two genes define the inter-element spacing. The inter-element spaces are 4, 5, 6 and 7 cm, which are 0.53, 0.66, 0.8 and 0.93 λ, respectively with regard to 4 GHz. Therefore, the chromosome consists of 28 genes as shown in Table 1. For example, considering the genes for inter-element spacing, if they are 00, 01, 10, and 11, the element spacing is 0.53, 0.66, 0.8 and 0.93 λ, respectively. Larger values are not recommended to avoid grating lobes.

The solution space consists of 2^{28} solutions (nearly 268 × 10^6) that would take a long time for a brute force method to analyze all the solution space. For example, if 1 minute is needed to simulate one solution, the overall time to analyze the whole solution space would be 510 years, where the GA takes only hours to find a solution.

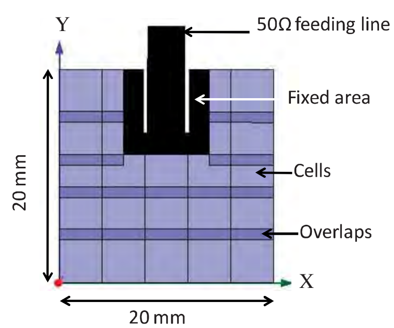


Figure 3: Cell distribution of the patch

Table 1: Format of the chromosome

Parameter	Patch geometry	Inset feeding length	Inter-element spacing
Corresponding genes	0, 1, 2, --------, 22	23 24 25	26 27

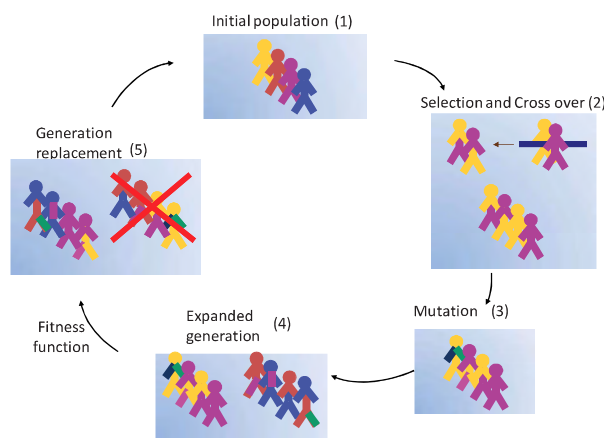


Figure 4: GA antenna design procedure

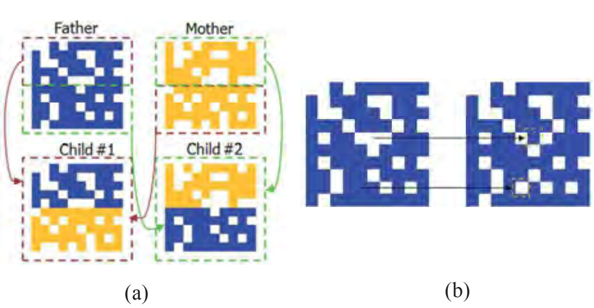


Figure 5: GA operations (a) Crossover (two children are generated from their parents); (b) Mutation (few bits are mutated)

In the GA optimization procedure, the chromosomes go through three phases; initiation, reproduction and generation replacement (Figure 4). During initiation, 20 chromosomes are created randomly as the population size should be large enough to effectively create the next generation, and on the other hand, it should be small enough to handle practically. Reproduction phase produces a new generation, which consists of 20 chromosomes from the current generation. A pair of individuals from the current population is selected to act as parents through random pairing. Then the operations called crossover and/or mutation are applied on the parents to produce the new generation. In the generation replacement phase, the new generation replaces the previous generation as the least fit individuals are removed from the expanded generation until it reduces to the normal population size (20). Thus the new generation is formed from the best individuals in the new generation and parent generation.

Table 2: Performance of Square patch array and the GA optimized patch array

Parameter	Square patch array	GA optimized patch array
Resonant freq./ (GHz)	4	4
Directivity along = 0^0/ (dB)	9.6	10.9

The GA optimization procedure consists of three natural inspired operations; selection, crossover and mutation (Figure 5). The selection method used in this study is the binary tournament selection. During crossover, genes of a randomly selected pair of individuals are exchanged in order to create the individuals of the next generation. Thus, two members of the new generation are created from two parents. In the GA procedure, the probability of crossover is 100 %, and single point crossover method is used. The crossover point is selected randomly. In binary representation, mutation operator changes a '0' to '1' and *vice-versa*. This operator allows the introduction of new chromosomes to the population and it assures that the entire search space is connected. The probability of mutation is 3 % and the mutating genes are selected randomly. The simulations are carried out until convergence of fitness is achieved.

The fitness function includes the reflection coefficient and the directivity perpendicular to the patch at the resonant frequency. As the reflection coefficient is negative, while the directivity is positive, the fitness function F is organized as shown in equation (1) to make this a maximization problem.

$$F = D - L , \qquad ...(1)$$

where D is the directivity perpendicular to the patch in dB and L is defined as

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

where ρ is the reflection coefficient in dB at the resonant frequency. As per the objectives of this study, this fitness function is maximized for a solution with the highest possible directivity at the resonant frequency.

HIGH-DIRECTIVITY ARRAY

Optimized patch array

For the simulations, an Intel Core i7 processor with 2 GHz speed and a RAM with 6 GB capacity was used. The optimized design is obtained after about 40 generations and it is checked for another 20 generations to confirm the convergence of fitness. It consumed about 50 hours to run all 60 generations. As mentioned above, it was interesting to note that using an exhaustive method such as considering all the possible simulations without using GA, would be impractical. If each simulation takes 1 minute, it would take approximately 500 years to search all the antenna geometry space. Future work may be focused on running this procedure in UNIX machines.

The optimized design has an inter-element spacing of 0.8 λ and resonates at 4 GHz (Figure 6). It is worth noting that the inter-element spacing is not the largest among the four possible values, which is 0.93 λ. The reason is that the GA has found a solution that minimizes grating lobes. Naturally, the method can be expanded to include more inter-element values. However, for the sake of showing the potential of the method, only four inter-element values have been proposed here.

The -10 dB impedance bandwidth is 50 MHz. At the resonance frequency it has a broadside directivity of 10.9 dB (Figure 7a). The current distribution of the GA optimized patch is mainly parallel to the x axis and some areas have in-phase currents, which is the reason for the broadside radiation (Figure 7b).

Conventional patch array

In order to determine the benefits of the aforementioned design, a conventional 1 × 2 microstrip patch array was designed (Figure 8). The array, operating in its fundamental mode, fed in phase and spaced around

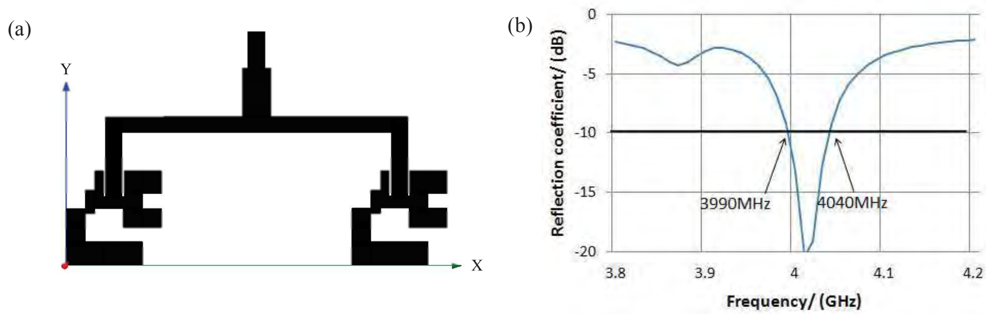


Figure 6: Performance of the optimized patch. (a) Patch geometry; (b) S_{11} plot

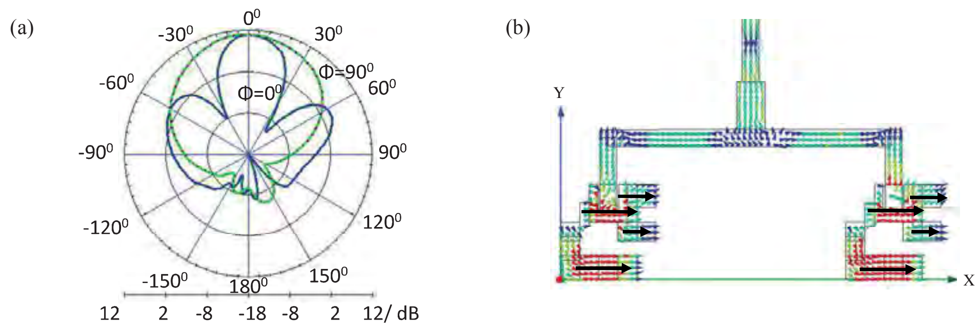


Figure 7: Performance of the optimized patch. (a) Main radiation cuts at 4 GHz; (b) current distribution at 4 GHz showing the in-phase portions (the black arrow indicates the direction of current)

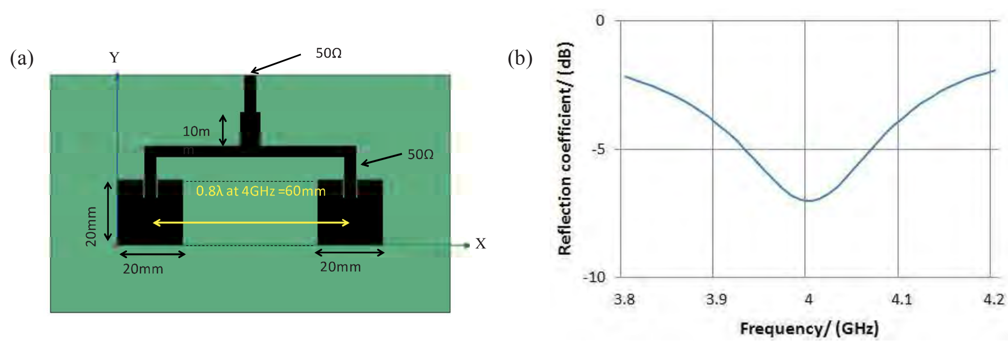


Figure 8: Performance of the 1× 2 microstrip patch array. (a) Patch geometry; (b) S_{11} plot

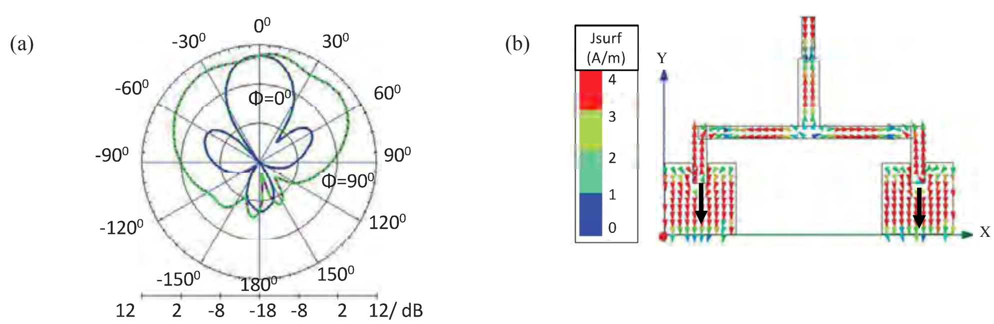


Figure 9: Performance of the 1× 2 microstrip patch array. (a) Main radiation cuts at 4 GHz; (b) current distribution at 4 GHz (the black arrow indicates the direction of current)

0.8 λ, provides a directivity of only 9.6 dB at 4 GHz (Figure 9).

The GA optimized patch array is compared with an array of two square patches occupying the same area for the same frequency of operation. The results show that the genetic array has a larger directivity (1.3 dB more) and a better resonance behaviour (Table 2) indicating that it is possible to obtain a higher directivity by optimizing the patch geometry.

CONCLUSION

The GA optimization technique has been successfully used to improve the directivity of a patch array by having a directivity of 10.9 dB in the broadside direction. Comparison of the GA design with a conventional array of two square shaped microstrip patches showed that for the same area, the GA design achieves a 1.3 dB increment in the directivity. The method proposed here can be expanded to arrays with large number of elements.

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