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A HIGH-DIRECTIVITY MICROSTRIP PATCH ANTENNA DESIGN BY USING GENETIC ALGORITHM OPTIMIZATION

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Abstract—A high-directivity patch antenna with broadside directivity is attractive, since a narrow beam can be obtained without the need of using an array of antennas. Therefore, the solution becomes simpler as there is no need for a complicated feeding network. In this sense, this paper presents a novel patch antenna design with high directivity in the broadside direction by using genetic algorithms (GA). The proposed GA method divides the overall patch area into different cells taking into account that cells have a small overlap area between them. This avoids optimized geometries where cells have only an infinitesimal connection. Therefore, the proposed method is robust for manufacturing. The antenna operates in a higher-order mode at 4.12 GHz and the geometry fits inside a patch of 40 mm × 40 mm on a substrate with a relative permittivity of 3.38 and a thickness of 1.52 mm resulting in a directivity of 10.5 dBi. The specialty of this design is the use of GA to select the optimized shape and the feeding position instead of a known shape and a fixed feeding position. The antenna has been fabricated and the simulation results are in good agreement with the measurements. This results in a simpler design of a single high-directivity patch, which can substitute an array of two elements operating in the fundamental mode.

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1. INTRODUCTION

Conventional single element microstrip patch antennas have a low directivity (6–7 dBi) [1]. Therefore, the design of high-directivity microstrip patch antennas is a challenging task. A classical patch, such as a square shaped patch, presents a single lobed broadside pattern in its fundamental mode (TM_{10} or TM_{01}) with a low directivity. Another broadside pattern can be found at a higher order mode (TM_{30}), but the directivity is again limited because the pattern presents high secondary lobes. In order to increase the directivity, an array of microstrip patches can be used, but this approach may add some complexity due to the feeding network. Moreover, the feeding network may deteriorate the radiation properties due to losses and/or distort the radiation pattern.

Various methods to improve the directivity of patch antennas have been reported in the literature, e.g., Sierpinski fractal patch [2], Koch island fractal patch [3, 4] and Koch island fractal boundary patch [5]. Design of patch antennas based on the Sierpinski fractal method has kept the size of the antennas small with a patch size of 40 mm × 40 mm to achieve a directivity of 10.9 dBi at 3.866 GHz [2]. Koch island fractal antenna presented in [3] shows a directivity of 13 dBi with an air gap so that the total height of the antenna is 3.5 mm. Both techniques rely on the use of a higher order mode supported by fractal-like structures called localized modes. Another technique to increase the directivity is the use of stacked patch antennas [6, 7]. Apart from that, high-directivity antennas based on superstrates [8–10], zero-index metamaterial [11], electromagnetic band gap resonator [12], modified peano space-filling curve [13], and photonic band-gap materials [14] have also appeared in the literature. In contrast, to obtain high-directivity, this paper proposes genetic algorithms (GA) to find the most suitable patch geometry and feed position instead of using a known geometry while keeping the substrate height small ($\sim 0.2\lambda$).

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 in [15]. Shape synthesis of patch antennas based on GA was presented few years later in [16]. In particular, GA has been applied to design broadband patch antennas [17–23], multiband patch antennas [22–29], and miniature patch antennas [30, 31]. However, no references have been found to optimize the shape of a single element to obtain a high-directivity broadside pattern. In this paper, GA is used to design a high-directivity patch antenna by optimizing the patch geometry and the feed position. Designs are simulated in the High Frequency Structure Simulator (HFSS) environment in combination with a home-made GA code. The GA operation is written using Visual Basic Script (VBS) Writer and the VBS file is called into HFSS environment to perform simulations.

This paper consists of four sections, where Section 2 presents the antenna configuration and GA. Section 3 presents the performance of the optimized design using simulated and measured results. The performance of a 1×2 patch array and the optimized patch antenna are also compared. Finally, Section 4 summarizes the paper.

2. ANTENNA CONFIGURATION AND GA

The patch size is fixed to fit in an area of $40\,\mathrm{mm} \times 40\,\mathrm{mm}$. The objective is to maximize the directivity within that area. The patch antenna 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 $50\,\Omega$ coaxial cable with a probe diameter of 1 mm.

2.1. Square Shaped Patch

Before starting the GA optimization process, a square shaped patch of $40\,\mathrm{mm} \times 40\,\mathrm{mm}$ in size is briefly analyzed since a square shaped patch operating in its fundamental mode is used in this paper for comparison purposes (Fig. 1(a)). When the feeding position is placed 7 mm from the center of the patch, the antenna resonates at 1.98 GHz (fundamental TM_{10} mode) with a reflection coefficient of $-13\,\mathrm{dB}$ (Fig. 1(b)). Also it resonates in a higher order mode at 3.95 GHz with a reflection coefficient of $-8\,\mathrm{dB}$.

The radiation patterns and the current distribution of the square shaped patch are shown in Fig. 2. At the fundamental mode the directivity is only 6.5 dBi along $\theta = 2°$, where θ is the angle measured from the z axis in usual spherical coordinates. At the second mode, the directivity is 6.5 dBi along $\theta = 66°$, which is not broadside.

In order to increase the directivity, an array of microstrip patches operating in the fundamental mode can be used. However, since this requires a feeding network, which adds complexity, the purpose here is to find out a single patch with a single feeding point that presents a high-directivity. In order to have a high-directivity, the microstrip patch needs to be electrically larger than the size of a square shaped microstrip patch in its fundamental mode, that is, the microstrip patch needs to operate in a higher-order mode. Unfortunately, higher-

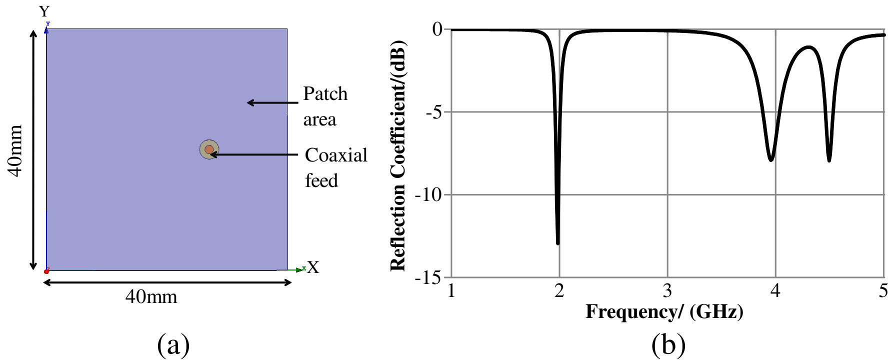


Figure 1. Simulation results of a square shaped patch. (a) Patch geometry. (b) S_{11} Plot.

order modes do not have a high-directivity with broadside behavior. Therefore, the GA procedure is employed to search for the right geometry to increase the directivity in the broadside direction.

In order to see the benefits of the proposal, a microstrip patch array having the same area as the patch to be optimized with the GA, is designed to obtain a high-directivity patch. An array of two elements, operating in their fundamental mode, fed in phase and spaced around 0.82λ to minimize the appearance of grating lobes, provides a directivity of 9.6 dBi at 4.12 GHz (Fig. 3). The patch area without taking into account the quarter wave length transformer, is $2388\,\mathrm{mm}^2$.

Therefore, the question is whether it is possible, within a single patch area of $1600\,\mathrm{mm}^2$, to obtain a similar directivity without using a feeding network. In this sense, the next section explains the optimization procedure in order to find a microstrip patch having a footprint of $40\,\mathrm{mm} \times 40\,\mathrm{mm}$ (the electrical patch size is 0.55λ at the operating frequency of 4.12 GHz).

2.2. GA Procedure

The patch area ($40\,\mathrm{mm} \times 40\,\mathrm{mm}$) is divided into 80 cells so as to overlap between adjacent cells (Fig. 4). 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". The purpose of having overlaps between adjacent cells is to avoid cells contacting each other by infinitesimal points, as this may pose a connection problem when manufacturing the microstrip patch due to the tolerances of the chemical etching. Also the proposed technique is suitable for

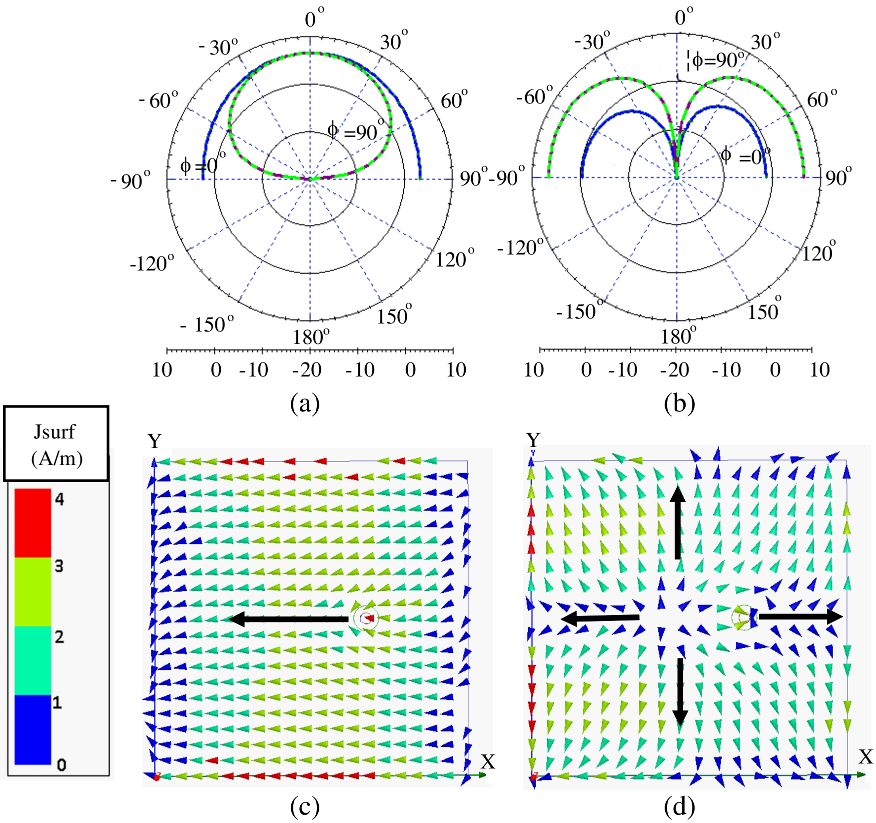
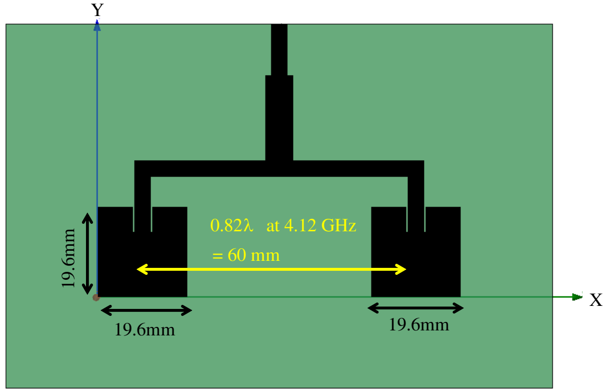


Figure 2. Simulation results of a square shaped patch. (a) Main radiation cuts at 1.98 GHz. (b) Main radiation cuts at 3.95 GHz. (c) Current distribution at 1.98 GHz. (d) Current distribution at 3.95 GHz. (The black arrow indicates the direction of current).

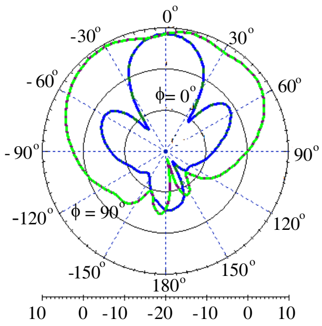
other fabrication methods such as stamping a metal used for the patch antenna in a plastic support. Therefore, the proposed method simplifies the fabrication of the patch antenna obtained through GA optimization (Fig. 5).

The first 80 genes in the chromosome define the patch geometry and five more genes are used to define the feed position. The possible feed positions are separated from each other by distances of 1 mm and 0.5 mm along x and y axes respectively. Therefore the chromosome consists of 85 genes as shown in Table 1. The solution space consists of 2^{85} solutions (nearly 3.8×10^{25}).

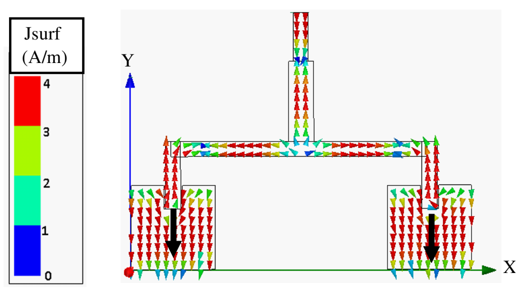
The fitness function includes the reflection coefficient and the



(a)



(b)



(c)

Figure 3. (a) An array of two microstrip patches. (b) Main radiation cuts at 4.12 GHz. (c) Current distribution at 4.12 GHz. (The black arrow indicates the direction of current).

Table 1. Format of the chromosome.

parameter	patch geometry	Feed position				
Corresponding genes	0, 1, 2, ..., 79	80	81	82	83	84

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.

$$F = D - L, \tag{1}$$

where D is the directivity perpendicular to the patch in dBi, and L is

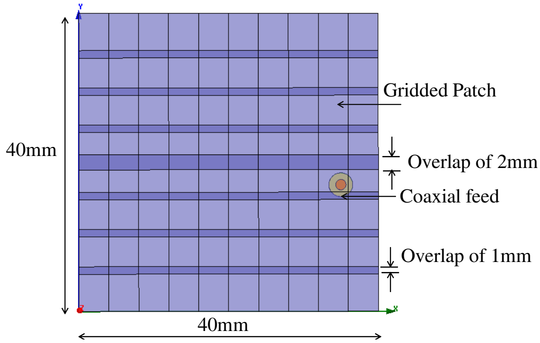


Figure 4. Cell distribution of the patch.

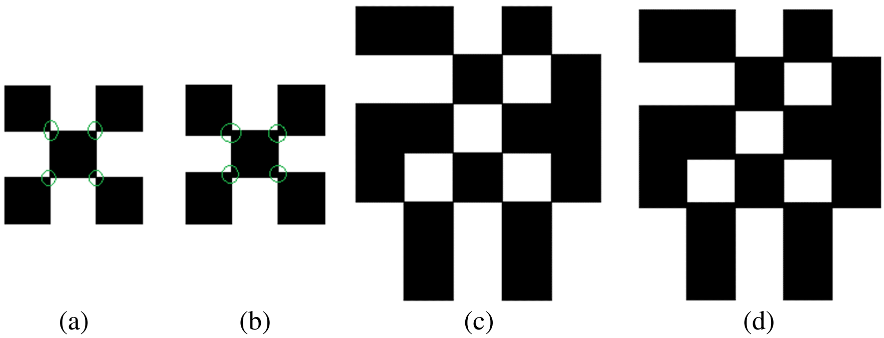


Figure 5. (a) Traditional on/off building blocks with infinitesimal connections. (b) Proposed overlapping scheme based on shifting of cells along the vertical axis. (c) A possible structure with infinitesimal connections. (d) A possible structure with overlapping as proposed in this paper.

defined as

$$L = \begin{cases} \rho & \rho \geq -10\,\mathrm{dB} \\ -10\,\mathrm{dB} & \rho < -10\,\mathrm{dB} \end{cases}, \tag{2}$$

where ρ is the reflection coefficient in dB at the resonant frequency. As per the objective of this paper, this fitness function is maximized for a solution with the highest possible directivity at the resonant frequency. Increasing both the directivity and bandwidth may be considered by modifying the fitness function and this topic is underway.

In the GA procedure, 20 individuals are included in a generation and single point crossover method is used with a 100% probability of crossover. One bit is mutated in 60% of the individuals within a generation. Tournament selection method is used for generation replacement and thus preservation of higher fitness values is guaranteed. The simulations are carried out until convergence is achieved.

3. HIGH-DIRECTIVITY ANTENNA

3.1. Simulation Results

For simulations, an Intel Core i7 processor with 2 GHz speed and a RAM with 6 GB capacity have been used. The optimized design is obtained after about 250 generations and it is checked for another 50 generations to confirm the convergence (Fig. 6). It consumed about 100 hours for convergence. It is 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 s, it would take approximately 19×10^{15} years to search all the antenna geometry space!

The optimized design is shown in Fig. 7(a). It resonates at 4.12 GHz with a reflection coefficient of -11.5 dB (Fig. 8(b)). Directivity over 10 dBi could be obtained in the frequency band from 4.08 GHz to 4.15 GHz (Fig. 7(b)). The design has a broadside radiation pattern with a maximum directivity of 10.5 dBi at 4.12 GHz. (Fig. 7(c)). The current distribution of the GA optimized patch is mainly parallel to y axis and some areas have in-phase currents, which is the reason for the broadside radiation (Fig. 7(d)). The radiation efficiency (η_r) at 4.12 GHz is about 67%.

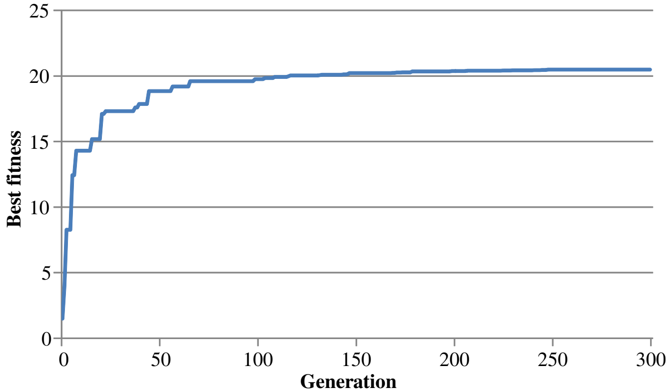


Figure 6. Convergence rate of the best fitness.

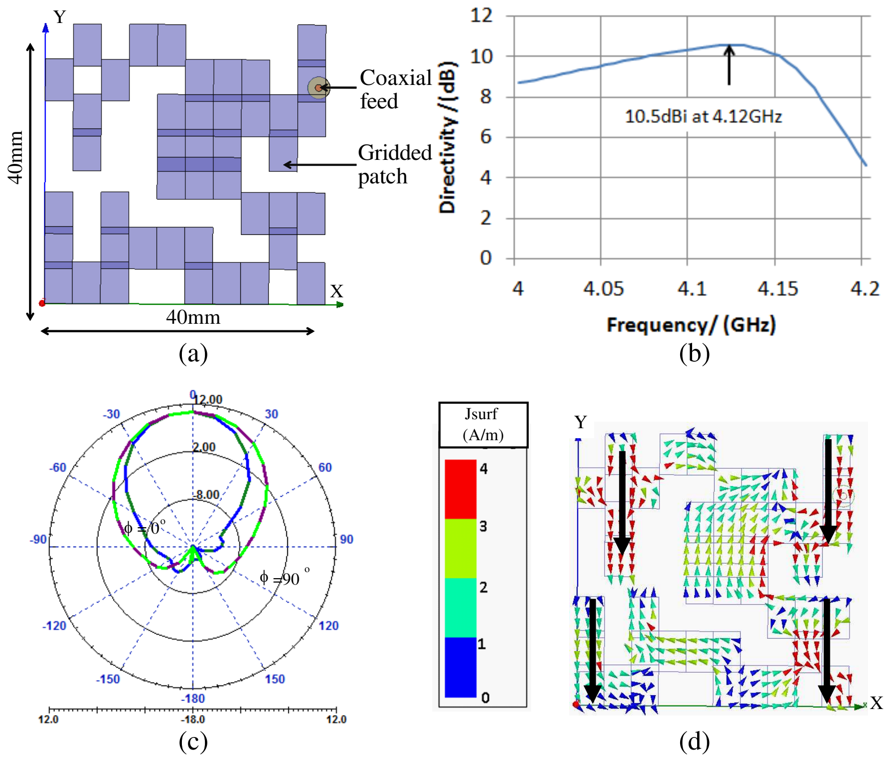


Figure 7. Simulation results of the optimized patch. (a) Patch geometry. (b) Directivity Vs Frequency. (c) Main radiation cuts at 4.12 GHz. (d) Current Distribution at 4.12 GHz showing the in-phase portions. (The black arrow indicates the direction of current).

3.2. Fabrication Results

The designed antenna has been fabricated on a substrate with dimensions of 100 mm × 100 mm. The ground plane extends beyond the patch and has the same dimensions as the substrate (Fig. 8(a)). The reflection coefficient of the antenna is measured by an *Agilent* vector network analyzer. The simulated and measured reflection coefficient values are in good agreement as can be seen in Fig. 8(b). The patch antenna operates from 4.10–4.12 GHz with $S_{11} < -10$ dB. It resonates at 4.12 GHz with a reflection coefficient of -13 dB. The measured radiation efficiency (η_r) at 4.12 GHz is about 67%.

The GA optimized patch is compared with an array of two patches occupying the same area (1600 mm^2) for the same frequency of

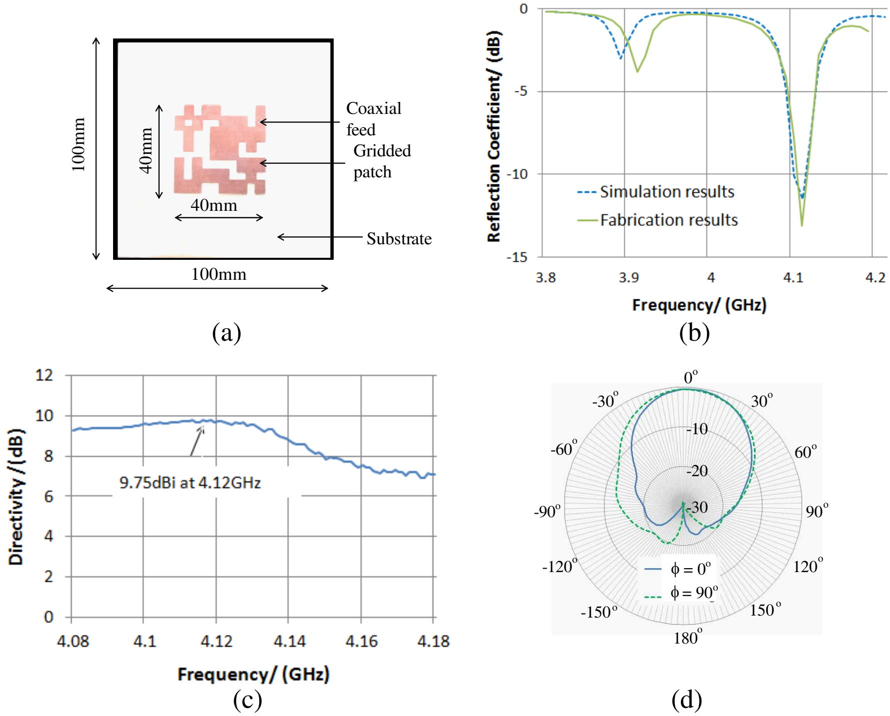


Figure 8. Fabrication results. (a) Photo of the antenna. (b) S_{11} plots. (c) Measured directivity Vs Frequency. (d) Normalized measured main radiation cuts.

Table 2. Performance of 1×2 patch array and the GA optimized patch antenna.

Parameter	1×2 patch array	Optimized single patch element	
		Simulated	Measured
Total area [mm^2]	> 2388	$40 \times 40 = 1600$	$40 \times 40 = 1600$
Resonant freq./ (GHz)	4.12	4.12	4.12
Directivity/ (dBi)	9.6 along $\theta = 0°$	10.5 along $\theta = 0°$	9.8 along $\theta = 0°$

operation. Results show that for the same electrical area of the array and the GA patch, almost the same directivity is obtained (Table 2). However, the GA patch does not need a feeding network. Therefore, the GA design presents a simpler construction while occupying less space. However, the impedance bandwidth is larger for the array than for the GA design. Therefore, a trade-off between compactness of the solution and bandwidth should be taken into account depending on the particular application.

4. CONCLUSION

The GA optimization has been successfully used to design a high-directivity patch antenna with a size of 0.55λ, obtaining a measured directivity of 9.8 dBi in the broadside direction. Simulation and measured results show that similar performance could be obtained. Comparison of the GA design with an array of two square shaped microstrip patches operating in its fundamental mode shows that for the same electrical area of both types, almost the same directivity is obtained. The GA design has the advantage that it is simpler, since it does not require a feeding network, which increases the total area of the antenna array.

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