Genetic Algorithm Optimization of a High-Directivity Microstrip Patch Antenna Having a Rectangular Profile

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Abstract. *A single high-directivity microstrip patch antenna (MPA) having a rectangular profile, which can substitute a linear array is proposed. It is designed by using genetic algorithms with the advantage of not requiring a feeding network. The patch fits inside an area of 2.54λ x 0.25λ, resulting in a broadside pattern with a directivity of 12 dBi and a fractional impedance bandwidth of 4 %. The antenna is fabricated and the measurements are in good agreement with the simulated results. The genetic MPA provides a similar directivity as linear arrays using a corporate or series feeding, with the advantage that the genetic MPA results in more bandwidth.*

Keywords

Directive antennas, genetic algorithms, linear antenna arrays, microstrip patch antennas, optimization.

1. Introduction

Microstrip patch arrays are used to obtain high-directivity by grouping several microstrip elements operating basically in their fundamental mode [1], [2]. In addition, they have been used to obtain wideband [3]–[5] and multiband [6], [7] operations and also in radiation pattern synthesis [8]. Other approaches use arrays with microstrip elements operating in higher-order modes, while keeping broadside patterns by exploiting the benefits of localized modes of certain fractal-inspired antennas [9], [10]. However, all these approaches may add some complexity due to the feeding network, which may also deteriorate the radiation properties due to losses and/or distort the radiation pattern.

Antennas for base stations or hot-spots present a narrow beam in the vertical plane and a wider beam in the horizontal plane, in order to provide coverage in a particular spatial sector. This kind of pattern is achieved by linear array of antennas, which require a feeding network to feed each element. As an alternative to this classical solution, a single element MPA with the advantage of not requiring a feeding network is proposed in this paper by means of genetic algorithm (GA).

Achieving high-directivity by using single element MPAs is a challenging task, as conventional MPAs have moderate directivity (6-7 dBi) [11]. A classical patch, such as a square patch, presents a broadside pattern at its fundamental mode (TM_{10} or TM_{01}), with a low directivity. A broadside pattern can also be found at a higher order mode (TM_{30}), but the directivity is again limited, as the radiation pattern presents high secondary lobes.

Various methods to improve the directivity of MPAs have been reported in the literature, e.g.:- Sierpinski fractal-inspired patch [12], Koch island fractal patch [13]–[15], electromagnetic band gap (EBG) resonator [16], superstrates [16], [17], zero-index metamaterial [18], modified Peano space-filling curve [19], photonic band-gap materials [20] and partially reflective surfaces [21]. Higher orders of fractals increase the length of the current line, which leads to a higher radiation resistance and a higher gain [22]. Koch island fractal antenna presented in [13] shows a directivity of 13 dBi thanks to the excitation of a higher-order mode. An MPA designed based on the Sierpinski fractal method achieves a directivity of 10.9 dBi with a broadside pattern following the same principle [12]. In contrast, this paper proposes a high-directivity MPA, where GA is employed to find the most suitable patch geometry and feed position instead of using a known geometry. The proposed antenna has a thin profile (~0.02λ).

GA is a powerful optimization technique that has been shown to be useful in a wide area of electromagnetics [23]. In particular, GA has been applied to design broadband [24]–[29], multiband [28]–[36], miniature [37]–[38], and circularly polarized [39] MPAs. In [40], GA is used to design a high-directivity (10 dBi) MPA with a foot print of 0.55λ × 0.55λ. It is a narrowband broadside antenna with similar beam-widths at the main radiation planes (E and H planes). In contrast, in this paper, a high-directivity (12 dBi) MPA having a rectangular profile is designed with the objective of obtaining a narrow beam in one plane (E plane) and a wide beam in the perpendicular plane (H plane) with an improved bandwidth. 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 six sections, where Section 2 presents the performance of different linear arrays fed by coaxial probes, corporate and series-fed schemes for comparison purposes. All of them have the same electrical area as the genetic MPA. In Section 3, the performance of a third iteration Koch line is presented also for comparison purposes. Section 4 explains the antenna configuration and GA procedure. Section 5 shows the performance of the optimized design using patch geometry, reflection coefficient, radiation patterns, current distribution and directivity. Finally, Section 6 summarizes the paper.

2. Microstrip Patch Arrays

In order to see the benefits of the proposal, a 1 × 4 patch array of 20 mm × 20 mm elements with a separation of 60 mm (0.78 λ) to minimize the grating lobes is considered first (Fig. 1a). The array has no combined feeding network and elements are separately coaxially-fed with uniform amplitude and phase. A thin substrate with a thickness of 1.52 mm, a relative permittivity of 3.38, and a loss tangent of 0.0027 is used.

The array is broadside and has a high-directivity of 12.9 dBi (Fig. 2a) at 3920 MHz. It has a fractional bandwidth of 1.7 % ($S_{11} \leq$ -10 dB) in the range 3900 MHz to 3970 MHz (Fig. 3). A side of each square patch is approximately half wavelength long at 3920 MHz and therefore is operating at the fundamental mode (TM_{10}). However, this antenna array is complex, since another layer is needed for the feeding network and vias are needed to connect the feeding network to each patch at its excitation point.

Therefore, a corporate-fed network printed in the same layer is also considered to feed the array as shown in Fig. 1b. For matching purposes, each element is inset fed by a feeding line with a notch width of 3.5 mm and an inset length of 5.5 mm. The total area occupied by the array and the feeding network is approximately 5400 mm^2. The corporate-fed array provides a directivity of 12.2 dBi with a broadside pattern (Fig. 2b). The array has fractional bandwidth of 1 % ($S_{11} \leq$ -10 dB) operating from 3910 MHz to 3950 MHz (Fig. 3).

In the corporate-fed array, the previous problem of complexity in the feeding is removed. However, the directivity decreases from 12.9 dBi to 12.2 dBi (Fig. 2b) as the feeding network perturbs the pattern.

Fig. 1c shows a series-fed array. The series feed scheme minimizes the area of the feeding network. In order to have the same excitation phase for each element, the distance between centers of patches is kept at one wave length (λ_g) [41]. Therefore, five elements could be accommodated to have the same total length of 200 mm (the same electrical length) in the array.

The series-fed scheme is the best of the three in the sense that it is very compact and has a directivity of 13.2 dBi. (Fig. 2c). However, the array has a low fractional bandwidth of 1 % ($S_{11} \leq$ -10 dB) operating from 3890 MHz to 3930 MHz (Fig. 3).

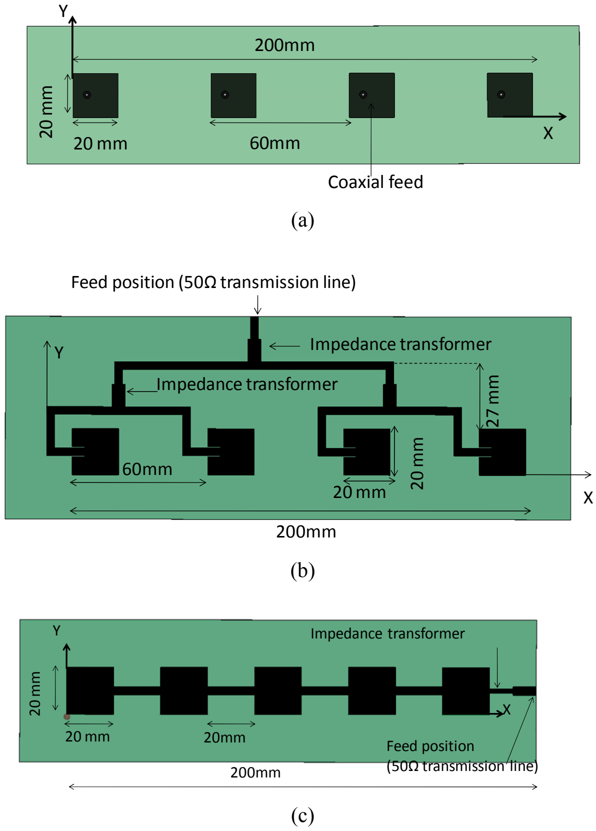
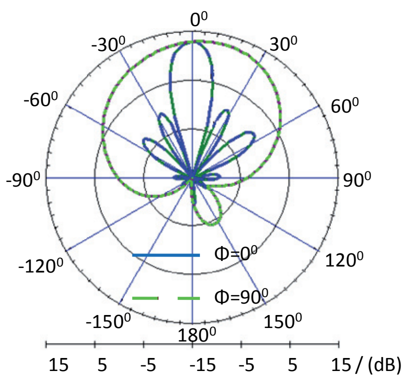
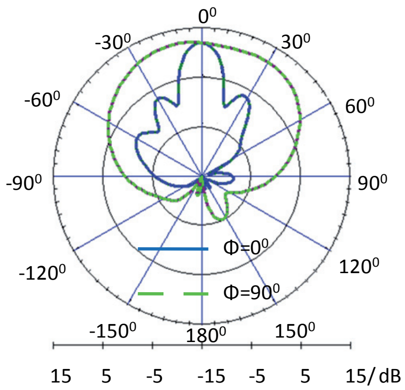


Fig. 1. Antenna configurations: (a) Coaxial-fed antenna array. (b) Corporate-fed microstrip array. (c) Series-fed microstrip array.

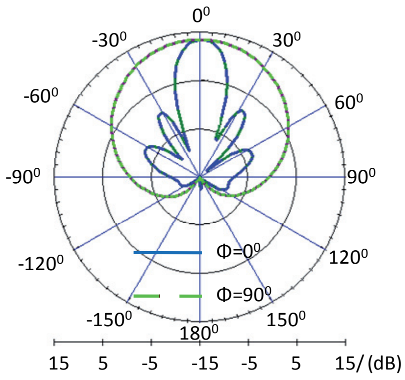
The simulated current distribution of each element in all three arrays is mainly parallel to x axis, showing that each patch is excited in the TM_{10} mode.



(a)



(b)



(c)

Fig. 2. Simulated main radiation cuts at 3920 MHz: (a) Coaxial-fed antenna array. (b) Corporate-fed microstrip array. (c) Series-fed microstrip array.

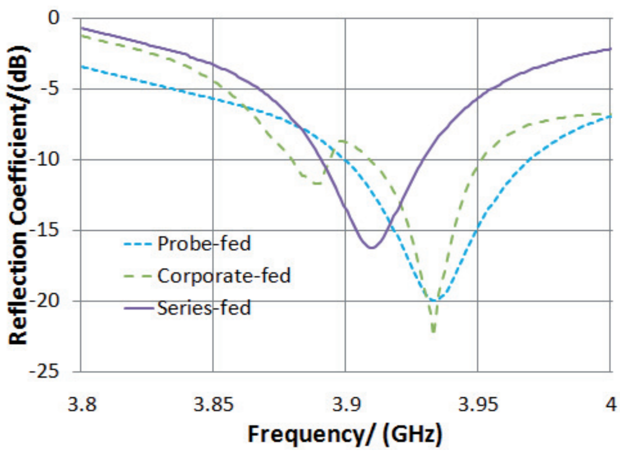
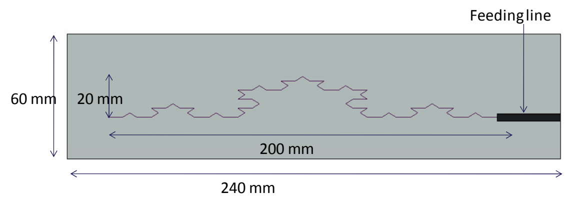


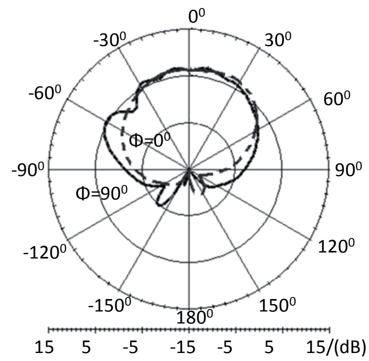
Fig. 3. Simulated reflection coefficient plots.

3. Comparison with a Fractal-Shaped Antenna

In order to compare the results further, performance of a third iteration Koch curve, which occupies the same patch size (20 mm × 200 mm) on the same substrate (Fig. 4) is evaluated. The said antenna is operating in a higher order mode, since its length of 448 mm is approximately 6 λ. Although a broadside pattern is obtained, the directivity is only 6.3 dB which is lower than the arrays.



(a)



(b)

Fig. 4. Simulation results of the Koch curve. (a) Patch geometry. (b) Main radiation cuts at 3920 MHz.

This brief exercise is however under further investigation, since some fractal-shaped antennas feature high-directive thanks to the excitation of localized modes called fracton and fractino modes [10], [12]–[15].

4. Antenna Configuration and GA Procedure

The performance of arrays and fractal raises the need for having a compromise between simplicity of the feeding network, directivity and bandwidth. Therefore, the question is whether it is possible to obtain similar or higher directivity and bandwidth within a single patch area of 200 mm × 20 mm, without using a feeding network. In this sense, this section explains the optimization procedure, in order to find an MPA instead of arrays, to obtain similar performance, by having a footprint of 200 mm × 20 mm.

The patch area of 200 mm × 20 mm is divided into 100 cells, so as to overlap between adjacent cells (Fig. 5). The purpose of the overlap (1 mm) is to avoid having cells contacting by an infinitesimal point which may pose a connection problem when manufacturing the MPA, due to the tolerances of the chemical etching. Therefore, the proposed method simplifies the fabrication of MPA obtained through GA optimization. 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”.

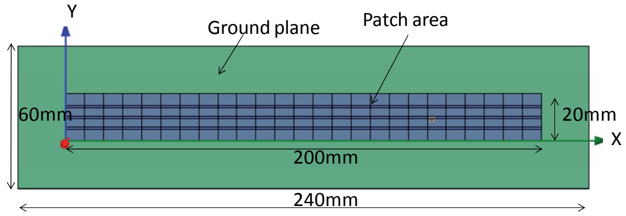


Fig. 5. Cell distribution avoiding infinitesimal connections.

The first 100 genes in the chromosome define the patch geometry and seven more genes are used to define the feed position. Therefore the chromosome consists of 107 genes as shown in Tab. 1. The solution space consists of 2^{107} solutions which is nearly 2×10^{62} solutions.

Parameter	Patch geometry	Feed position
Corresponding genes	0, 1, 2, -----------, 99	100,----, 106

Tab. 1. Format of the chromosome.

The fitness function includes the directivity perpendicular to the patch, impedance matching in the resonance and the $S_{11} \leq$ -10 dB impedance bandwidth. The fitness function F is organized as shown in equation (1) to maximize the directivity, the value of the impedance matching in the resonance and the bandwidth. As these objectives are conflicting, they are merged into a single-objective function. However, the preferences of each objective are set by weighting coefficients of partial criteria in the aggregating objective function [42], [43].

$$F = D + \frac{B}{10} \tag{1}$$

where D (in dBi) is the directivity perpendicular to the patch, at the frequency with maximum resonance. B is the bandwidth measured in MHz. For a given chromosome (antenna), the S_{11} is computed from 3800 to 4200 MHz. Then, B in MHz is computed. For the resulting B comprising a frequency range from $f_{\min}$ to $f_{\max}$, D is computed at f_D having $\min(S_{11}(f_D))$ where $f_D \in [f_{\min}, f_{\max}]$. As we require a bandwidth of at least 100 MHz, which is greater than that of arrays, $B/10$ is considered to calculate the fitness. (e.g. if a design has a directivity of 12 dBi and bandwidth of 100 MHz, then $D = 12$, $B = 100$ and $F = 22$). Therefore, the fitness function put a similar force on both D and $B/10$ to increase.

In the GA procedure, the probability of crossover is 100% and single point crossover method is used. The probability of mutation is 1.5 %. A generation consists of 20 individuals. 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.

5. Synthesis of the Antenna Geometry by GA Optimization

For simulations, an Intel Core i7 processor with 2 GHz speed and a RAM with 6 GB capacity have been used. It consumed about 50 hours to converge. The optimized design has been achieved in about 60 generations and simulations have been carried out for another 30 generations to confirm convergence (Fig. 6).

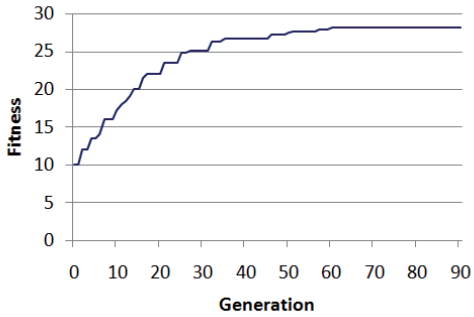


Fig. 6. Fitness convergence rate over iterations. Each generation takes about one minute.

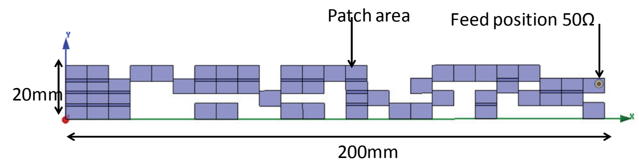
The best fitness of the first generation was 9.9 and it reached 28.1 when converged. However, achievement of three aforementioned objectives in the best individual (best fitness) is questionable. Therefore, at the end of the optimization process, a set of ten best solutions (Pareto optimal set) was checked for the performance, so as to select a single solution considering preferences in the objectives [42]. The first preference is impedance matching in the resonance. The second preference is having a bandwidth larger than 100 MHz. The third preference is the directivity at resonance as high as possible.

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 4×10^{22} years to search all the antenna geometry space.

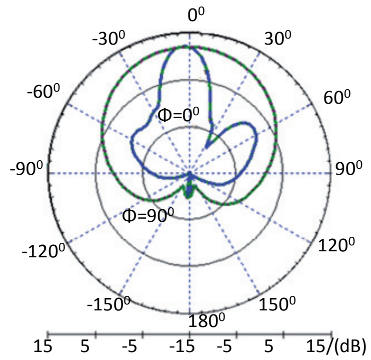
The optimized design on a finite ground plane of 240 mm × 60 mm is shown in Fig. 7a. The directivity at 3920 MHz is 12.1 dBi. The current distribution of the GA optimized patch is mainly parallel to x axis having hot-spot areas with in-phase current (Fig. 7b). Since the area is electrically large, the radiation pattern is directive and pointing to the broadside direction, thanks to the in-phase radiation of each small area marked in big arrows (Fig. 7c). In contrast to the corporate-fed array and series-fed array, the optimized design shows a radiation pattern with less side lobes.

Fig. 8 shows how directivity changes with frequency for each architecture showing a similar directivity compared to a corporate-fed array and probe-fed array at the resonance. The GA design shows a directivity 1 dB less than the series array. However, all the arrays present narrower impedance bandwidths than the GA design.

The cross-polarization discriminations (XPD) of the patch arrays and the GA design are shown in Fig. 9. In the broadside direction, the series array and GA path present a similar XPD (~20 dB) whereas the corporate array is 17 dB. The XPD of corporate array degrades faster for angles near the broadside direction than the series array and GA patch. Thus, all the designs show linear polarization aligned with the longest dimension of the patch.



(a)



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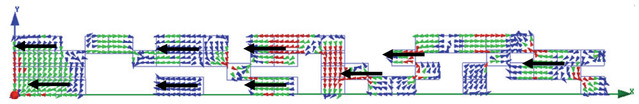

(c)

Fig. 7. Simulation results of the optimized patch. (a) Patch geometry. (b) Main radiation cuts. (c) Current distribution at 3920 MHz. (The big arrows qualitatively represent the current distribution).

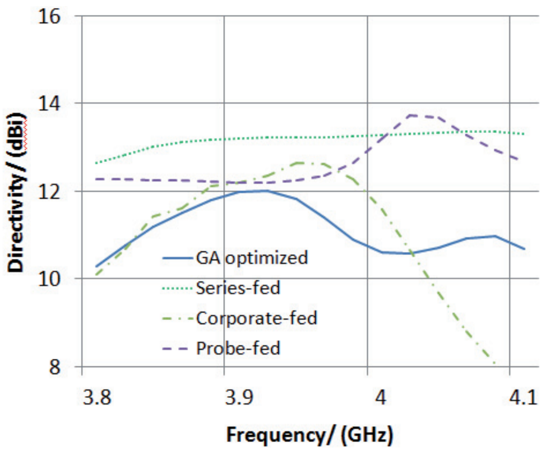

Fig. 8. Simulated directivity vs frequency.

The GA design is fabricated on a substrate with dimensions of 240 mm × 60 mm, which are the same dimensions of the ground plane (Fig. 10a). The normalized main radiation cuts and directivity are measured in an anechoic chamber (Fig. 10b,c). The maximum directivity is 12 dBi at 3820 MHz giving a broadside radiation pattern. The maximum realized gain is 11.1 dBi (at 3820 MHz), which results in a total efficiency of 81 %. The cross-polar discrimination is 20 dB at the broadside direction ensuring linear polarization aligned with the longest dimension of the patch.

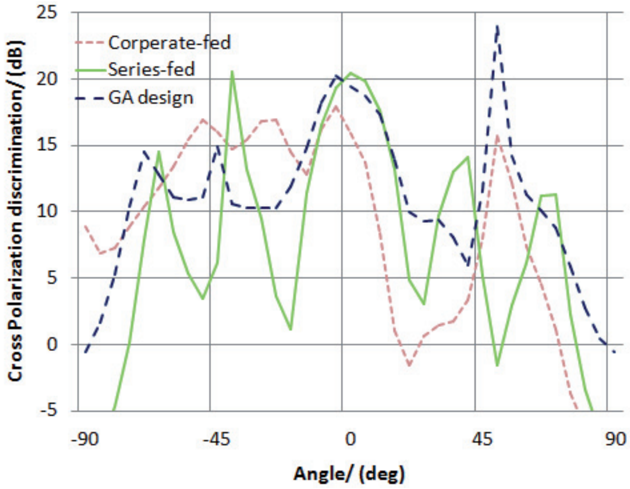

Fig. 9. Simulated XPD at φ=0º.

The reflection coefficient is measured from a vector network analyzer using a SMA connector underneath the ground plane. The optimized design operates from 3820 MHz to 3950 MHz with fractional bandwidth of 4 % (Fig. 10d). A shifting to lower frequencies of about 2.5 % can be observed, which is acceptable. It may be due to small tolerances of the patch geometry occurring during the chemical etching process. The shapes of the measured reflection coefficient, directivity, and main radiation cuts are in good agreement with the simulations.

The GA optimized patch is compared with probe-fed (ideal case without feeding network), corporate-fed, and series-fed arrays occupying the same area (4000 mm^2), for the same frequency. Results show that for the same electrical area of the arrays and the GA patch, almost the same directivity is obtained (Tab. 2). However, the GA patch does not need a feeding network. Further, the impedance bandwidth is larger for the GA design than the classical arrays.

6. Conclusions

The GA optimization has been successfully used to design a high-directivity MPA having rectangular profiles, obtaining a measured directivity of 12 dBi in the broadside direction. Simulated and measured results are in good agreement. Comparison of the GA design with arrays of square shaped microstrip patches operating in its fundamental mode shows that for the same electrical area, almost the same directivity is obtained. Moreover, the GA design has the advantages that result in a larger bandwidth of a factor around 2 compared to a corporate-fed array and a factor around 3 compared to a series-fed and probe-fed arrays. The GA antenna is attractive for antennas with moderate directivity as those used in hot-spots.

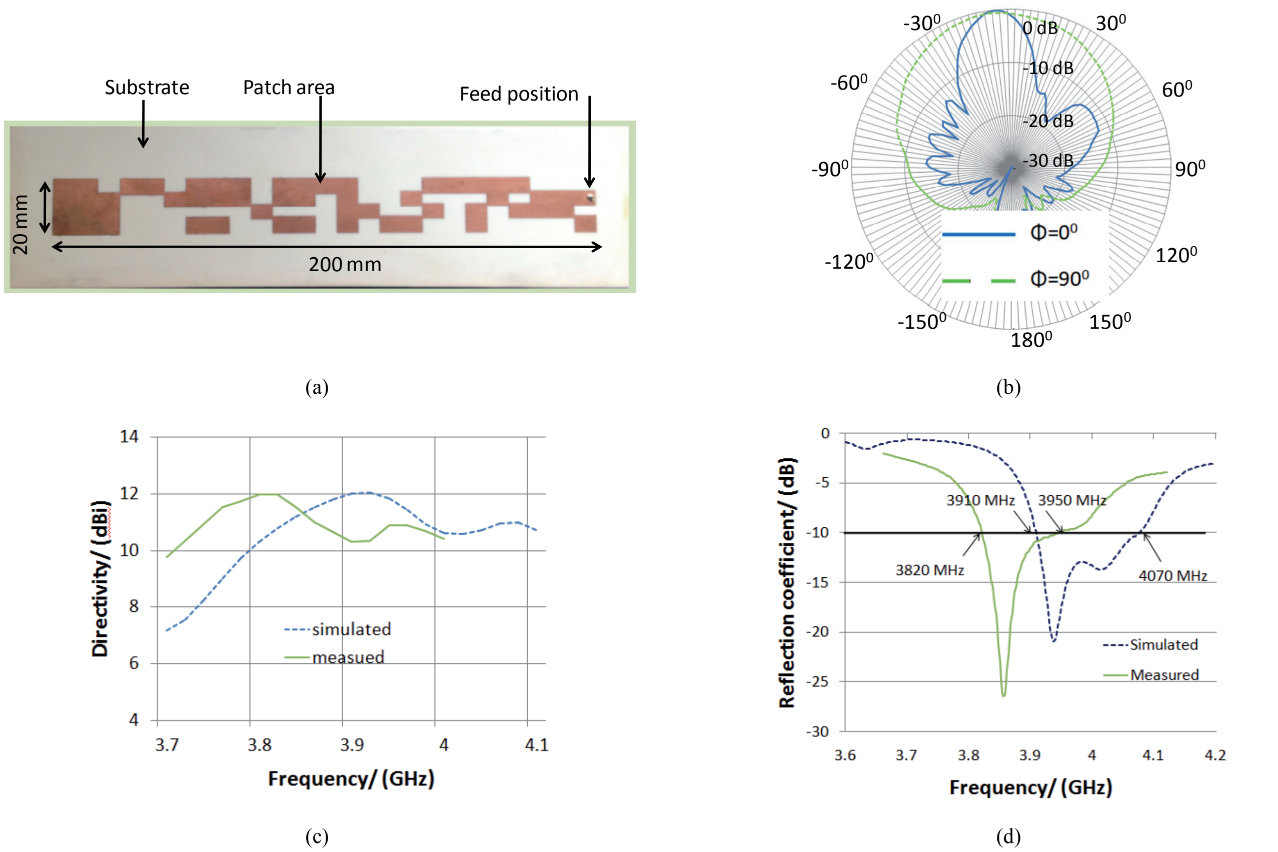

Fig. 10. Fabrication results of the optimized patch. (a) Photo of the antenna. (b) Normalized measured main radiation cuts at 3820 MHz (φ=0° corresponds to the E plane). (c) Directivity vs. frequency. (d) S11 plots.

Parameter	1 × 4 patch array (simulated)			GA Optimized single patch element	
	Probe-fed	Corporate-fed	Series-fed	Simulated	Measured
Total area/ (mm^2)	4000	5400	4000	4000	4000
Freq. of max. directivity / (MHz)	3930	3930	3910	3920	3820
Bandwidth/ ($S_{11} \leq$ -10 dB, %)	1	1.7	1	3.3	4
Directivity along $\theta = 0^0$/ (dBi)	12.9	12.2	13.2	12.1	12
Gain along $\theta = 0^0$/ (dBi)	11.9	10.6	12.5	11.1	11.1
Antenna efficiency/ (%)	79	69	85	79	81

Tab. 2. Performance of 1 × 4 patch array and the GA optimized patch antenna.

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