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INNOVATIVE DESIGN OF A PLANAR FRACTAL-SHAPED
GPS / GSM / WI-FI ANTENNA

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Abstract – In this letter, the design of a microstrip three-band antenna working in GPS, GSM and Wi-Fi frequency bands is described. By considering a planar geometry printed on a dielectric substrate, the tuning of the antenna behavior in three non-harmonic frequency bands is obtained perturbing the patch perimeter according to a Koch-like fractal shape. The synthesis procedure is automatically performed by means of an iterative PSO-based optimization strategy where a fractal boundary generator is integrated with a MoM-based electromagnetic simulator. The feasibility of the approach as well as the reliability of the synthesized antenna is assessed through simulations as well as experimental results.

Introduction

The design of multi-band antennas has attracted the attention of several researchers due to the growing demand of radiating devices able to provide multiple reception and transmission functionalities in a limited volume. Such a task has proven to be trivial at all, since project guidelines usually require uncorrelated resonance frequencies instead of the harmonic behavior of classical antenna structures [1]-[3]. Concerning conventional techniques, the insertion of reactive loads in the radiating structure has been considered to

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obtain a non-harmonic radiating behavior. Such a solution has been employed in dealing with wire antennas and, recently, it has been also proposed using fractal geometries. As a matter of fact, fractals have been extensively studied because of their interesting electro-dynamical properties [4][5][6] that allow both miniaturization and multi-band behavior. Although standard pre-fractal shapes present harmonic relationships among resonance frequencies [7], suitable deformations of their building geometrical elements cause an increase of the degrees of freedom in the antenna frequency response. Accordingly, some interesting results have been obtained by assuming as reference geometry that of a standard monopole-like fractal (e.g., the Koch curve). Notwithstanding, the overall dimensions in the direction orthogonal to the reference ground plane usually prevent their use in applications where conformal shapes are required (e.g., automotive or aeronautical frameworks). For these applications, the adoption of conformal patches is an optimal choice, but a cavity-like resonance frequency behavior occur [10][11]. In order to fit both geometrical and electrical constraints, the exploitation of fractals in designing patch antennas has been studied [5].

In such a framework, this letter describes the synthesis of a patch antenna, which operates in three non-harmonic frequency bands, carried out by perturbing the boundaries of a reference rectangular patch according to a fractal-based erosion process. Numerical and experimental results are shown for assessing the effectiveness and reliability of the synthesized prototype.

Antenna Design

Starting from a rectangular patch, the perimeter of the antenna has been modified by determining the lengths of fractal segments in order to tune three resonant modes of the reference structure for satisfying the project constraints. A sketch of the antenna geometry, where the optimization parameters to be tuned are indicated, is shown in Fig. 1.

As far as the project guidelines are concerned, the following constraints have been taken into account: a) working bands: L1 GPS, GSM, and Wi-Fi centered at $f_1 = 1575.42\ MHz$, $f_2 = 1850.00\ MHz$, and $f_3 = 2440.00\ MHz$, respectively; b) Voltage Standing Wave Ratio (VSWR) values smaller than 2 at the resonance frequencies; c) hemispherical coverage with a main lobe width $\theta_{-9dB} = 70°$; d) maximum dimensions of $10 \times 10\ \left[cm^2\right]$; e) Arlon substrate (thickness $h = 0.8\ \left[mm\right]$, $\varepsilon_r = 3.38$, $tg\delta = 0.0025$ at $f = 10\ GHz$).

Because of the dimensionality (i.e., the number and range of values of the unknowns) of the problem at hand, the array of the unknowns

$$\underline{\chi} = \left[x_{input}; y_{input}; L_{1,2,m,i}; \Theta_{1,2,n,j}; L_{2,1,1,p}; \Theta_{2,1,1,q}\right] \tag{1}$$

where $m,i,n,p = 1,...,4$ and $j,q = 1,2$; $\left(x_{input}, y_{input}\right)$ being the location of the feed point, has been determined exploiting an iterative stochastic optimization strategy. In order to quantify the fitting of a trial solution to the project constraints, a suitable cost function has been defined. It was a two-term function

$$F\left(\underline{\chi}\right) = \Omega\left(\underline{\chi}\right) + \Gamma\left(\underline{\chi}\right) \tag{2}$$

taking into account VSWR requirements

$$\Omega(\underline{\chi}) = \sum_{t=0}^{T-1} \left\{ \max\left[0, \frac{\Phi(t\Delta f) - VSWR_{max}}{VSWR_{max}} \right] \right\} \tag{3}$$

as well as radiations properties

$$\Gamma(\underline{\chi}) = \sum_{u=0}^{U-1}\sum_{v=0}^{V-1}\sum_{z=0}^{Z-1} \left\{ \max\left[0, \frac{G_{min}(u\Delta\theta, v\Delta\varphi, z\Delta f) - \Lambda(u\Delta\theta, v\Delta\varphi, z\Delta f)}{G_{min}} \right] \right\} \tag{4}$$

$\Phi(f)$ and $\Lambda(\theta,\varphi,f)$ being the value of the VSWR and the value of the gain function computed in correspondence with the solution $\underline{\chi}$, respectively. Moreover, Δf is the sampling frequency step in the resonance bands, and $\Delta\theta$ and $\Delta\varphi$ are the angular steps when computing the gain function.

Concerning the iterative minimization of (2), a PSO strategy [12] has been used since it proved to be very effective and versatile in several antenna synthesis problems [8][9][13]. Towards this purpose, the fractal Kock-like boundary generator $\Im$ has been integrated with a MoM-based [14] electromagnetic simulator for computing the VSWR values $[\Phi(f) = VSWR\{\Im(\underline{\chi})\}]$ and the gain function $[\Lambda(\theta,\varphi,f) = G\{\Im(\underline{\chi})\}]$ in correspondence with every trial solution generated during the evolution of the optimization.

The iterative loop has been implemented as follow:

a. Generation of a set of trial solutions $\underline{\chi}_m^{(n)}$, $m = 1,...,M$ being the trial solution index and $n = 1,...,N$ being the iteration index;

b. Use of the pre-fractal generator for building the antenna shape $\alpha_m^{(n)}$ corresponding to the trial array $\underline{\chi}_m^{(n)}$, $\alpha_m^{(n)} = \Im\{\underline{\chi}_m^{(n)}\}$;

c. Computation of the values of electric parameters of each trial antenna through the MoM electromagnetic simulator $[\Phi_m^{(n)}(f) = VSWR\{\alpha_m^{(n)}\}$ and

$\Lambda_m^{(n)}(\theta,\varphi,f) = G\{\alpha_m^{(n)}\}$] and evaluation of the corresponding cost function value $F_m^{(n)} = F\{\underline{\chi}_m^{(n)}\}$;

d. Updating of the set of *M* trial solutions by means of the PSO strategy [12][13], $\{\underline{\chi}_m^{(n+1)}; m = 1,...,M\} = PSO\{\underline{\chi}_m^{(n)}; m = 1,...,M\}$;

e. Iterative repetition of steps (b.)-(d.) until a fixed heuristically-defined maximum number of iterations $n = N$ is reached.

Numerical Results and Experimental Validation

The process synthesis has been carried out by considering the following setup: $N = 250$ and $M = 10$. For illustrative purposes, Figure 2 shows the evolution of the trial shape as well as of the position of the feed point (white dot) up to the optimized one [Fig. 2(*f*)] whose patch support has a maximum dimension of $41.1 \times 45.5 [mm^2]$. For completeness, the plots of the VSWR values are reported in Figure 3. As it can be noticed and confirmed by the plot of the cost function $F(\underline{\chi})$ versus the iteration number (Fig. 4), the electric behavior of the trial solution evolves from an unsatisfactory compliance with the project constraints until an accurate fitting.

In order to complete the assessment with an experimental analysis, a prototype of the fractal-shaped patch antenna (Fig. 5) has been built by using a photolithographic printing circuit technology. Then, it has been equipped with an additional ground plane of dimensions $90 \times 140 [cm^2]$ for approximating the numerical modeling of the simulated structure (i.e., the patch over an infinite ground plane). For comparison purposes, simulated and measured (in an anechoic chamber) VSWR values are reported in Fig. 6. As

its can be observed, there is a good agreement that further points out the reliability of the numerical synthesis procedure.

Finally, for completeness, the radiation properties of the synthesized antenna are analyzed. In particular, the plots of the horizontal and vertical ($\phi = 0°$) gain patterns are shown in Fig. 7. As expected, the obtained results turn out compliant with the project specifications since an hemispherical coverage, suitable for both GPS and mobile communication systems, is obtained whatever the frequency band.

Conclusions

In this letter, the design of a three-band fractal-shaped patch antenna has been described. Starting from a set of design constraints, the perimeter of the rectangular reference structure has been iteratively modified by optimizing the descriptors of the fractal boundaries and the position of the input port through a PSO-based procedure. The synthesized structure has been analyzed both numerically and experimentally by considering an antenna prototype.

Acknowledgments

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Figure captions:

Fig. 1. Sample of a trial fractal-shaped patch antenna.

Fig. 2. Evolution of the trial geometry during the optimization process.

Fig. 3. Plots of the VSWR values at different iterations of the optimization process.

Fig. 4. Plot of the optimal value of the cost function versus iteration number.

Fig. 5. Photograph of the fractal-shaped antenna prototype.

Fig. 6. Three-band fractal-shaped patch antenna - Comparison between numerical and measured VSWR values.

Fig. 7. Three-band fractal-shaped microstrip antenna - Gain function at different frequencies: (*a*) horizontal plane and (*b*) vertical plane.
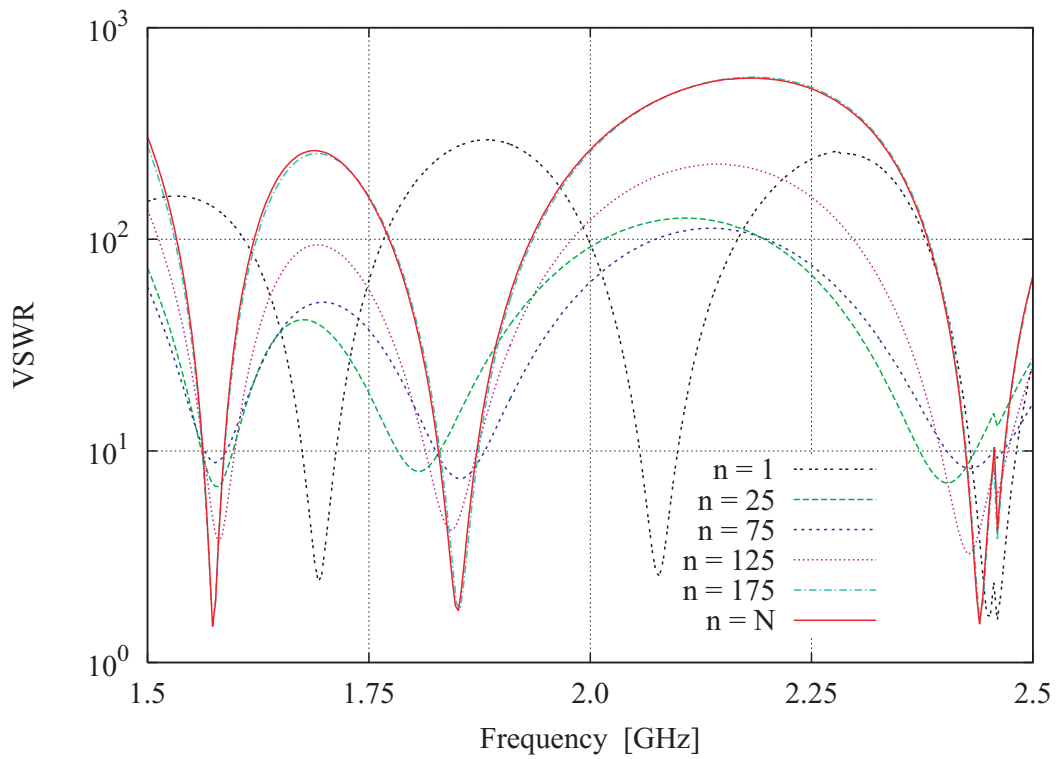
Fig. 1 - R. Azaro *et al.*, "Innovative design of a planar fractal-shaped ..."

(*a*) *n* = 1

(*b*) *n* = 25

(*c*) *n* = 75

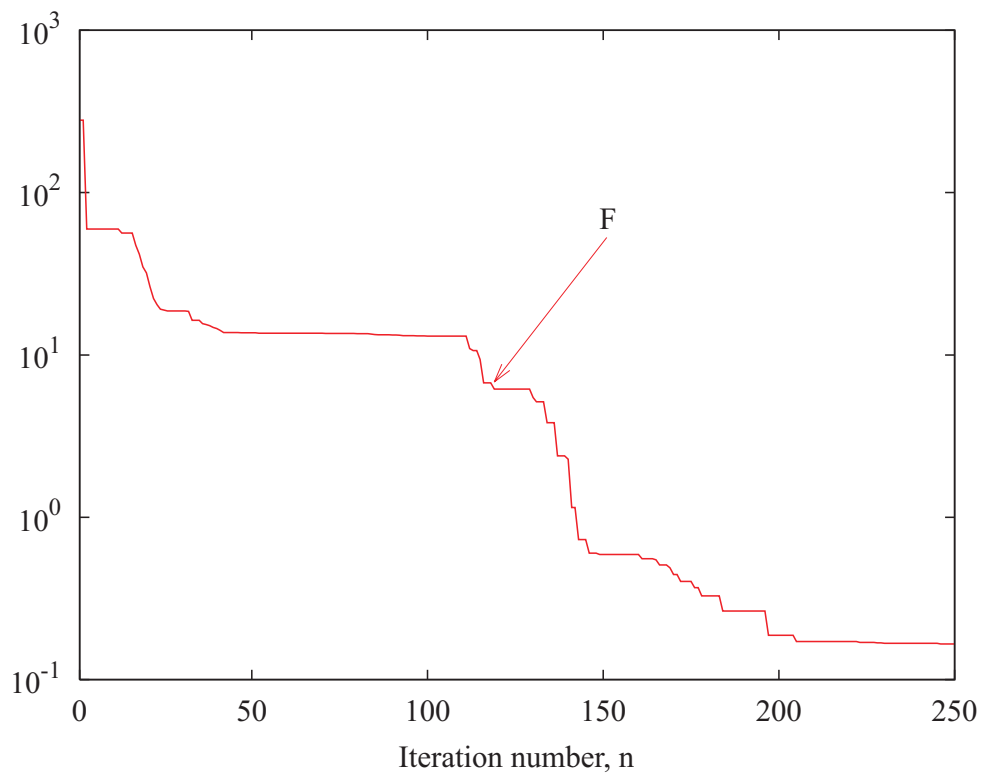(*d*) *n* = 125

(*e*) *k* = 175

(*f*) *n* = *N*
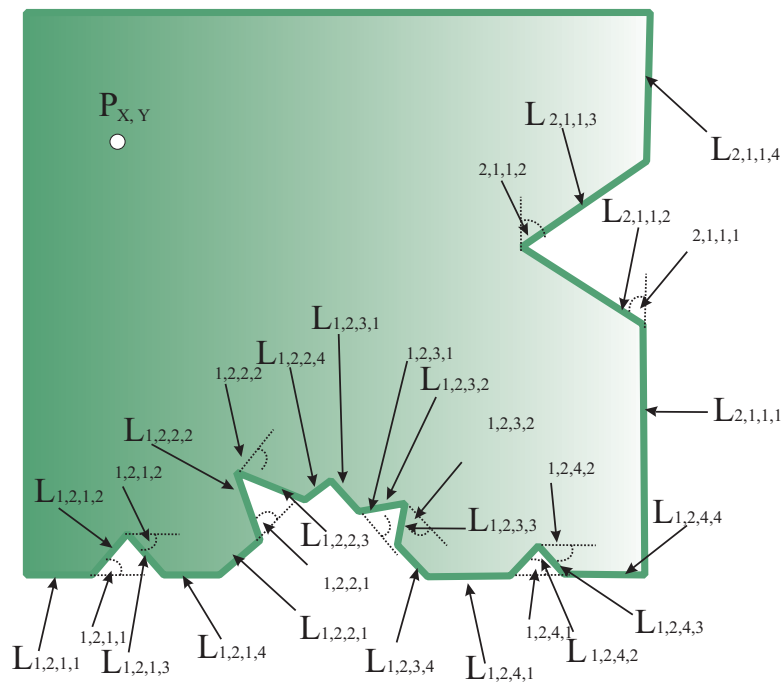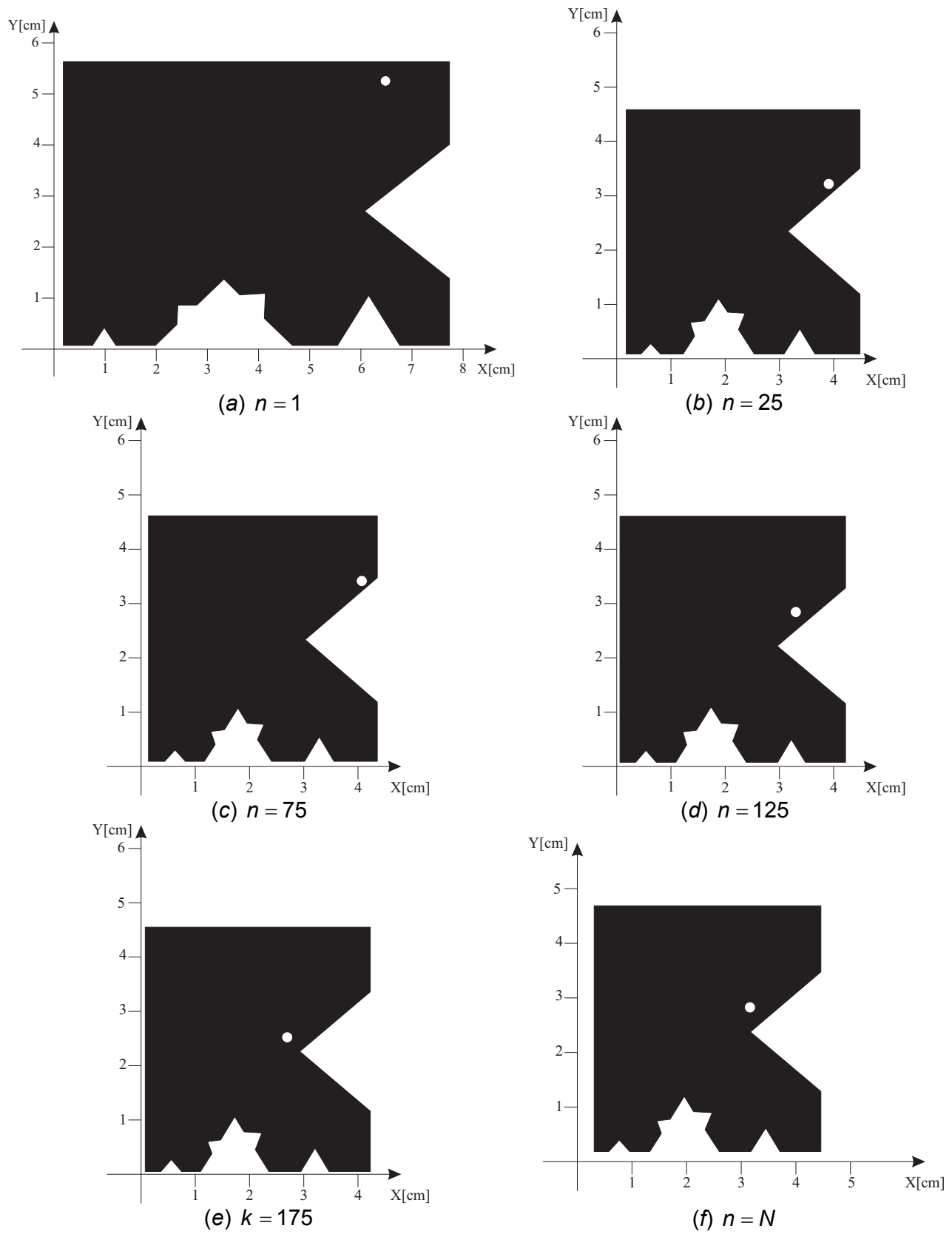
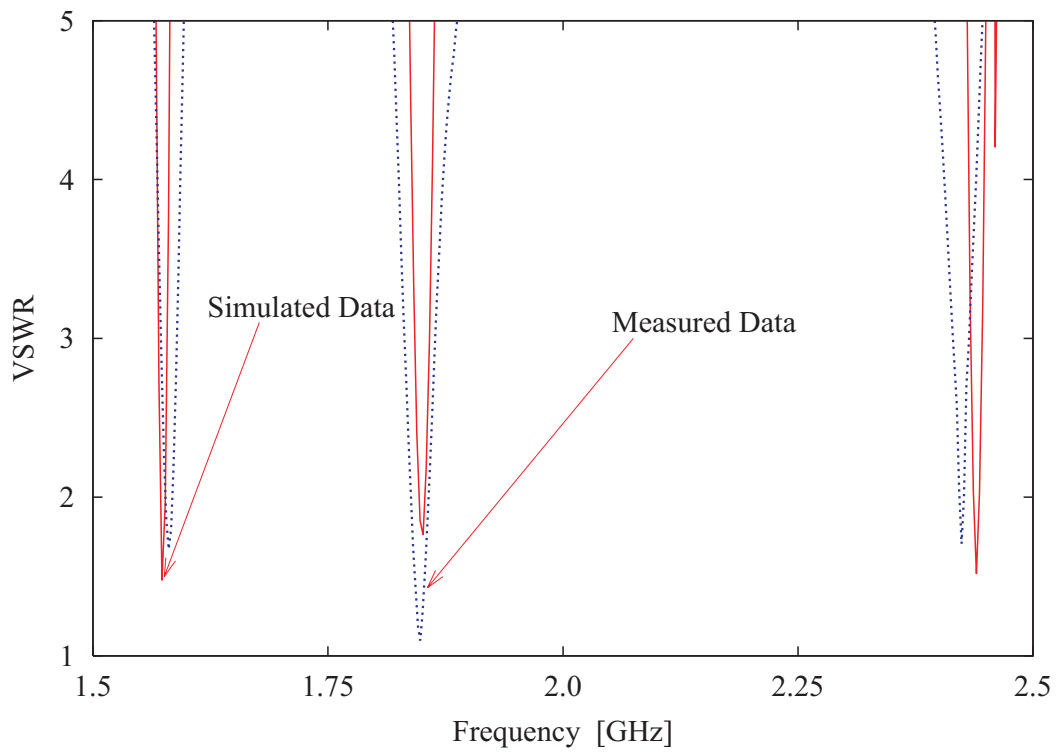**Fig. 2 - R. Azaro *et al.*,** "Innovative design of a planar fractal-shaped ..."

Fig. 3 - R. Azaro _et al._, "Innovative design of a planar fractal-shaped ..."

Fig. 4 - R. Azaro *et al.*, "Innovative design of a planar fractal-shaped ..."
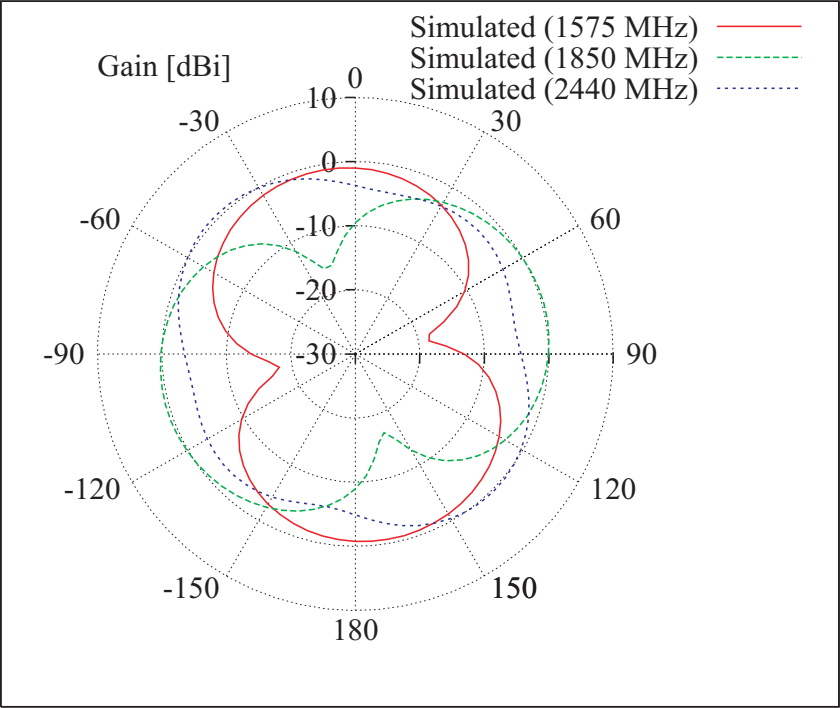
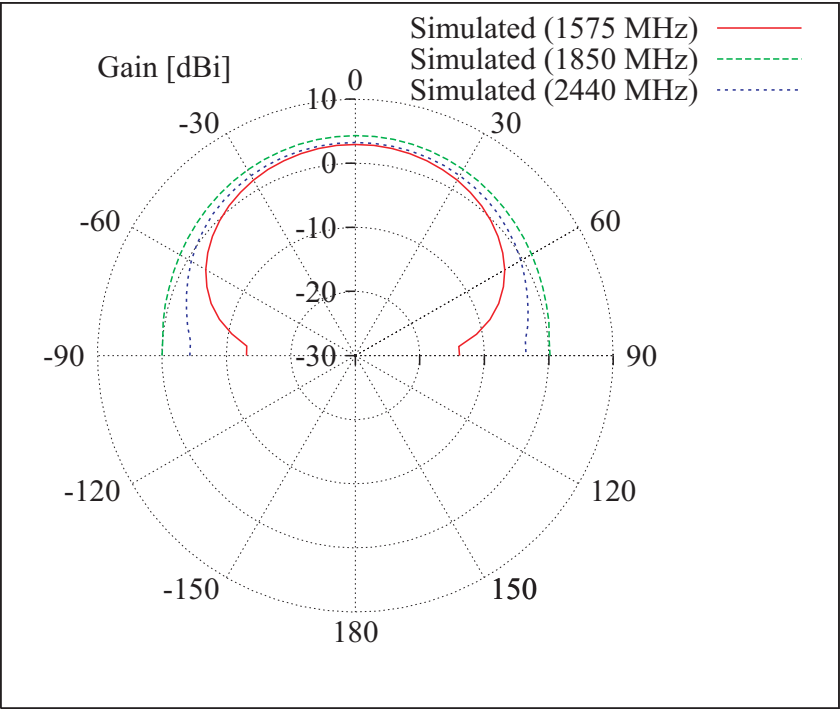**Fig. 5 - R. Azaro *et al.*,** "Innovative design of a planar fractal-shaped ..."

Fig. 6 - R. Azaro *et al.*, "Innovative design of a planar fractal-shaped ..."

(*a*)

(*b*)

Fig. 7 - R. Azaro *et al.*, "Innovative design of a planar fractal-shaped ..."