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# Sierpinski Pyramidal Antenna Loaded With a Cutoff Open-Ended Waveguide

Sami Hebib, Hervé Aubert, *Senior Member, IEEE*, Olivier Pascal, Nelson J. G. Fonseca, *Member, IEEE*, Lionel Ries, and Jean-Marc E. Lopez

**Abstract**—A new pyramidal antenna for satellite application is presented. Sierpinski triangle antennas are chosen as radiating elements for their multiband features. The ground plane of the antenna is perforated and loaded with a cutoff open-ended waveguide: this original configuration leads to a good tradeoff between rear radiation and impedance matching. Ideal trap-loads are used to improve the multiband operation of the Sierpinski radiating elements. The antenna radiates circularly polarized electromagnetic fields with a large coverage at multiple operating frequencies. A specific application is given in this paper for a triband operation. Experimental results are reported and discussed.

**Index Terms**—Pyramidal antenna, multiband applications, Sierpinski triangle antennas, cutoff open-ended waveguide.

## I. INTRODUCTION

HERE is a constant rise of interest for multiband antennas, mainly driven by the objective to reduce the number of on-board and ground antennas by integrating several applications on a single radiating element. In a previous study [1], [2] a new triband circularly polarized antenna based on a pyramidal structure has been proposed by the authors. The present paper describes a new version of this pyramidal circularly polarized antenna with multiband Sierpinski radiating elements.

Contrary to generally accepted idea, fractal antennas are not generally suitable for the design of multiband antenna where operating frequency ratios are needed to be controlled. Moreover, the self-similarity of the radiation patterns at these frequencies is questionable [3]. For the well-known Sierpinski triangle antenna, the difficulties in obtaining self-similar radiation patterns is essentially due to the electromagnetic coupling between the multiple resonators that constitute the antenna. The insertion of distributed stop-band filters between these resonators may be advantageously used for removing this undesirable effect [4]. However the resulting radiating structure may be very large. Ideal lumped trap-loads are used here for minimizing the size of the Sierpinski triangle antenna and reinforcing the decoupling

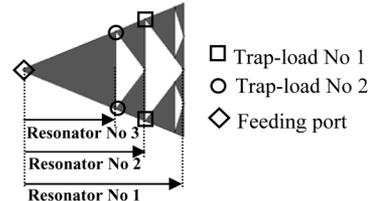


Fig. 1. Trap-loads locations in the Sierpinski radiating elements for a triband application.

between its multiple resonators. Previously, lumped trap-loads have been already used to design multiband antennas [2], [5]. Moreover the proposed antenna is back-loaded with a cutoff and open-ended metallic waveguide. This original configuration allows a good tradeoff between the rear radiation and the impedance matching of the antenna. Measurements presented in this Letter confirm the expected multiband behavior and the circular polarization of the proposed antenna.

## II. ANTENNA DESCRIPTION

The multiband behavior of the antenna is achieved by using Sierpinski radiating elements with appropriate integrated trap-loads or lumped band-stop filters. An elementary lossless lumped-element trap-load consists of a shunted capacitive element  $C$  with an inductive element  $L$ . This circuit is characterized by a rejected frequency band defined at the center frequency  $f_c = 1/(2\pi\sqrt{LC})$ . Conditions for impedance matching and finite available components values enable us to limit the choice to a few numbers of couple  $(L, C)$ . A triband (at operating frequencies  $f_1, f_2$  and  $f_3$ , with  $f_1 < f_2 < f_3$ ) Sierpinski triangle antenna with trap-loads is shown in Fig. 1. Two different types of trap-loads are used in this Sierpinski radiating element: trap-load No. 1 with resonant frequency sets at  $f_2$  and trap-load No. 2 with resonant frequency sets at  $f_3$ . These trap-loads do not reject the lowest frequency  $f_1$  and therefore allow the resonator No1 to operate at its resonant frequency  $f_1$ . Since the trap-load No. 1 is equivalent to an open-circuit at the intermediate frequency  $f_2$ , the monopole is equivalent to the resonator No. 2 and then, it operates at frequency  $f_2$ . Finally, at  $f_3$  the trap-load No. 2 is in the blocked state, and consequently, the monopole is equivalent to the shortest element (resonator No. 3) operating at  $f_3$ .

Two configurations can create circularly polarized radiating fields from this linearly polarized antenna element: the first configuration uses quadratic phase excitations placed at the center of the structure while for the second configuration, the quadratic

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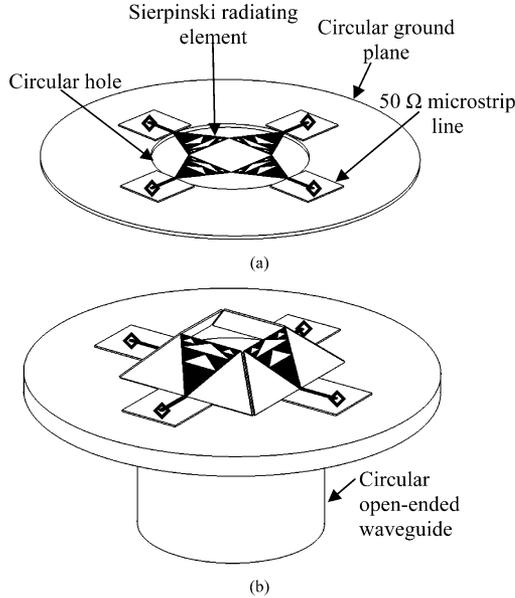


Fig. 2. Sierpinski antenna with border excitation: (a) the planar configuration, (b) the pyramidal configuration ( $\diamond$ : Feeding ports).

phase excitations are located at the border of the antenna [see Fig. 2(a)]. According to electromagnetic simulations (not shown here), it can be observed that the latter configuration provides higher directivity with wider bandwidth as compared to the first one. Furthermore, the four feeding ports in this second configuration are all disjointed, making it easier to feed in practice. However, this configuration suffers from undesirable interferences due to the array effect induced by the nonhomothetic shape of the antenna, this effect increasing with the frequency. In addition it may present relatively low radial directivity at high frequencies. The natural solution to overcome these two drawbacks consists of exploiting the axis perpendicular to the antenna surface. The resulting pyramidal antenna [see Fig. 2(b)] provides a better radial radiation, hence possible improvement in the radial directivity. Additionally, with this configuration, the feeding ports are brought closer to each other, leading to a reduction or even suppression of the abovementioned undesirable array effect. In many cases, pyramids with an inclination angle of  $45^\circ$  present a good tradeoff between the expected radial and axial radiation performance. The outer radius of the circular ground plane is chosen in order to reduce the edge radiation produced by the surface current on the ground plane.

We have observed, for the first time to our knowledge, that an excellent impedance matching at all operating frequencies is obtained when 1) a hole is made in the metallic ground plane just below the pyramidal antenna *and* 2) when the four feeding ports are located at the edge of this hole (see Fig. 2, where  $50\Omega$  -microstrip lines have been used to connect the excitation ports—e.g., SMA connectors—to the radiating elements). Without such perforation of the ground plane, a poor impedance matching is observed at many (if not all) operating frequencies. However the presence of the hole generates a rear electromagnetic radiation. In order to reduce this undesirable radiation, the ground plane is loaded with a cutoff and open-ended

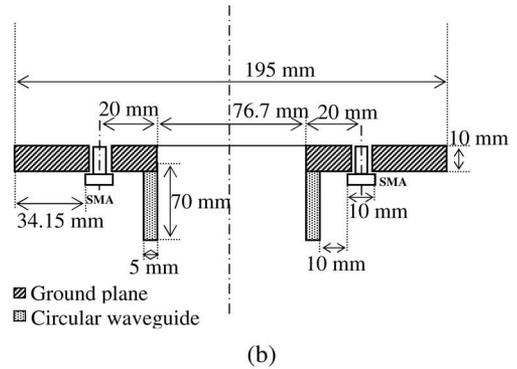
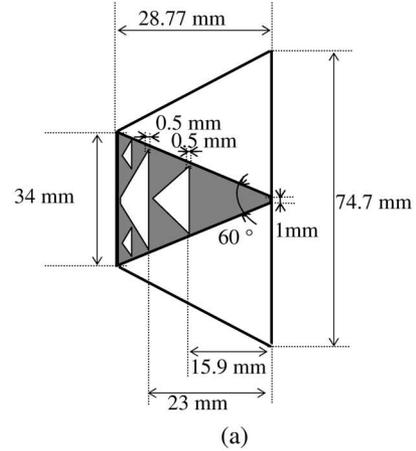
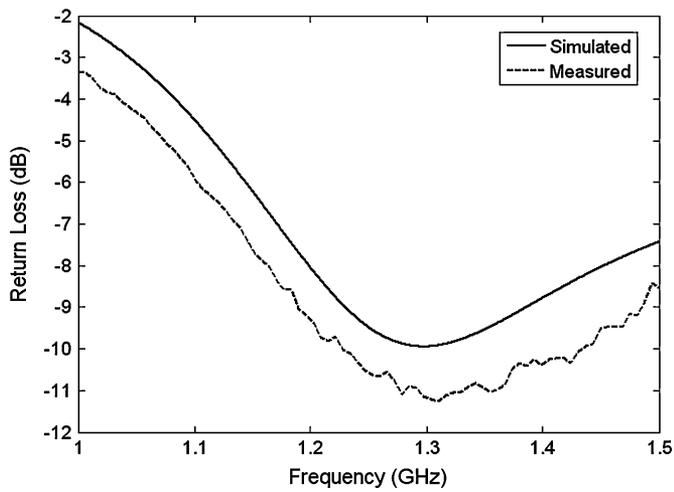
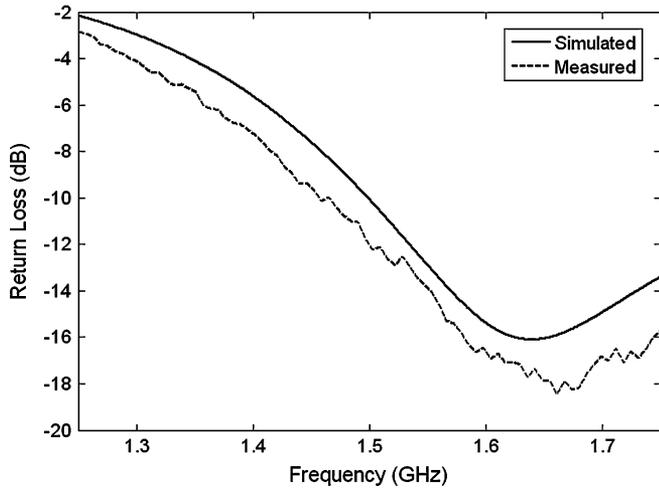


Fig. 3. (a) Dimensions of the radiating elements, (b) the ground plane and the waveguide dimensions, and (c) the manufactured antenna.

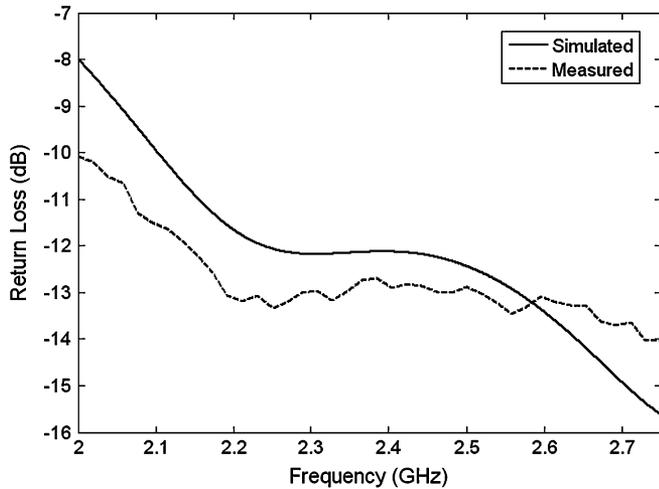
metallic waveguide. This metallic waveguide may be viewed as the continuation of the finite-thickness ground plane together with the hole. This waveguide is designed such that no modes are propagating inside at all the operating frequencies of the multiband antenna. Since all modes in the waveguide are attenuated, the longer the open-ended waveguide the lower the rear radiation. The maximum directivity of rear radiation (at elevation angle of  $180^\circ$ ) is expected at the highest operating frequency because the attenuation constant of the first cutoff mode is lower at this frequency than at the other frequencies. Nevertheless, we have observed that longer the waveguide, poorer the impedance matching of the antenna and the poorest impedance matching is found at the lowest operating frequency. Consequently varying the length of the cutoff open-ended waveguide allows achieving



(a)



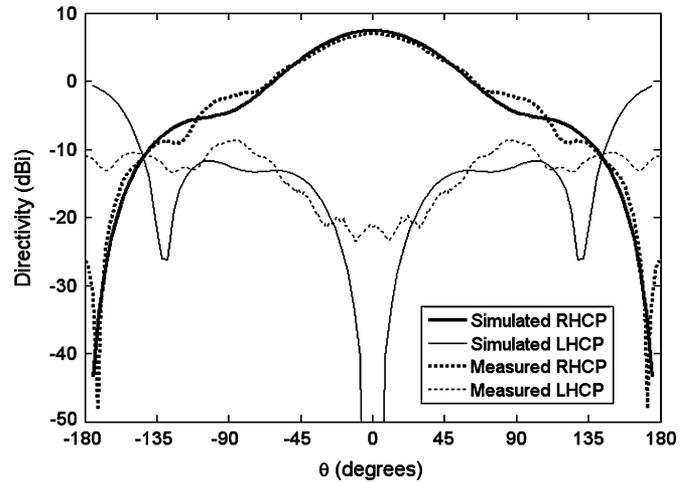
(b)



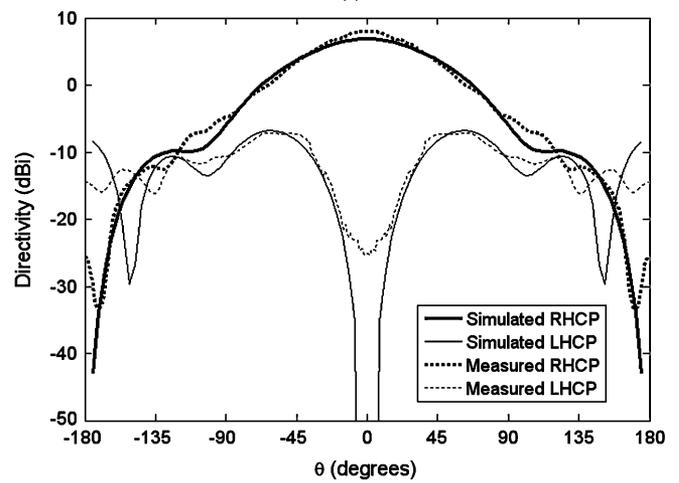
(c)

Fig. 4. The simulated and measured return loss for the Sierpinski multiband antenna in (a) the first band, (b) the second band, and (c) the third band.

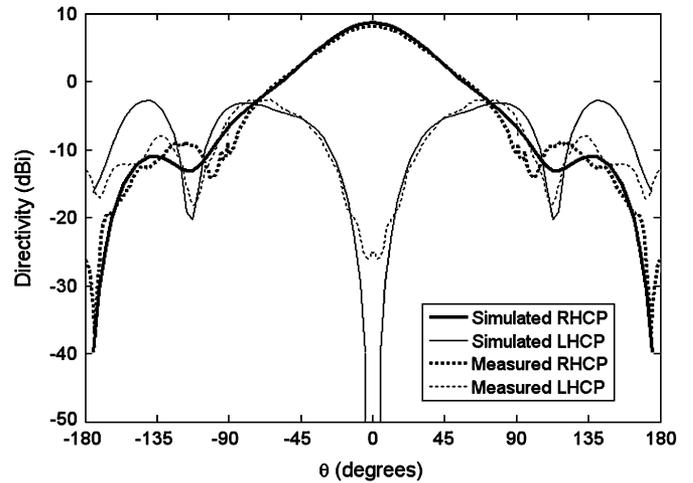
a good tradeoff between rear radiation and impedance matching at feeding ports.



(a)



(b)



(c)

Fig. 5. Measured and simulated radiation patterns for the multiband antenna at the three operating frequencies: (a) 1.3 GHz, (b) 1.6 GHz, and (c) 2.3 GHz.

### III. TRIBAND APPLICATION

In this section, a triband Sierpinski pyramidal antenna loaded with a cutoff waveguide is designed, simulated and finally measured. The trap-loads in this application are approximated as ideal ON/OFF switches both in simulation and measurement. The

desired central frequencies of the three operating bands are  $f_1 = 1.3$  GHz,  $f_2 = 1.6$  GHz and  $f_3 = 2.3$  GHz. The electromagnetic simulations are provided by means of a finite-difference time-domain (FDTD) method using CST Microwave Studio software [6]. The four Sierpinski radiating elements that constitute the antenna are printed with copper on a low-permittivity substrate (relative permittivity = 2.08 and thickness = 0.762 mm) [see Fig. 3(a)]. The same substrate is used for the realization of the  $50\Omega$ -microstrip lines. These microstrip lines have a width of  $w = 2.39$  mm and are printed on  $30\text{ mm} \times 30\text{ mm}$  boards. The dimensions of the building blocks of the antenna (in particular, the ground plane and the circular waveguide) are given in Fig. 3(b). The outer radius of the ground plane is 97.5 mm. Minor safety margins are added to the radius of the hole that perforates the ground plane in order to avoid any possible manufacturing defects. The cutoff open-ended metallic waveguide used for controlling the rear radiation and impedance matching has an inner radius of 38.35 mm and a length of 70 mm. This length is set to reduce the rear electromagnetic radiation. Finally, a pyramidal inclination of 45 degrees is selected as a good tradeoff between the radial and axial radiation performance. The final manufactured antenna is shown in Fig. 3(c).

Measurements of reflection coefficient at the four input ports were performed using the VNA WILTRON 37269A. During measurements, only one port at a time is excited, the other three being matched ( $50\ \Omega$ ). The simulated and measured return loss results are depicted in Fig. 4. As shown in this figure, the impedance matching of the antenna is good (i.e., the measured return loss is lower than  $-10$  dB) at the three operating frequencies  $f_1 = 1.3$  GHz,  $f_2 = 1.6$  GHz, and  $f_3 = 2.3$  GHz. Regarding the interelement coupling at the three operating frequencies, the simulated  $S_{12}$ -parameter takes values between  $-7.8$  dB and  $-9.6$  dB while the simulated  $S_{13}$ -parameter varies between  $-11.3$  dB, and  $-12.6$  dB.

The radiation patterns measurements at the three operating frequencies were performed using the Compact Antenna Test Range (CATR) at CNS (The French Space Agency). Fig. 5 displays the measured as well as the simulated Right Handed (RH-) and Left Handed (LH-) Circular Polarization (CP) directivity patterns of the antenna at the three operating frequencies.

As expected the radiation patterns of the antenna are quasi-hemispheric. Such radiation patterns are appropriate for satellite navigation reception antennas, thus allowing a maximum signal reception from the satellites in sight.

By adjusting the inclination of the four radiation elements, different shapes of the radiation patterns can be obtained. The cross-polarization level is lower than  $-10$  dB in the half space of interest, ensuring a good purity of polarization. Thanks to the cutoff circular waveguide, the maximum of rear radiation directivity is lower than  $-10$  dB at the three operating frequencies.

From these results we conclude that the multiband behavior and the circular polarization of the proposed antenna have been validated experimentally.

#### IV. CONCLUSION

A novel pyramidal antenna based on Sierpinski triangles loaded with a cutoff metallic waveguide was designed and tested experimentally. The measurement results confirm the good performance of the designed antenna. The original solution that consists of loading the ground plane of the pyramidal antenna by a cutoff and open-ended metallic waveguide proposed here has been developed for a triband application but, it can also be advantageously applied for applications with more frequency bands. Moreover, the exploitation of available volume offers various degrees of freedom for the pyramidal antenna design such as the angle of inclination of the pyramid and the radius of the circular hole bored in the ground plane as well as the length of the back-loaded cylinder. Due to its multiband property, the proposed pyramidal antenna can be used to replace heavier combinations of two or more single band antennas. For example this antenna can be used for both radio-navigation (GPS, Galileo, ...) and telemetry applications.

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