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Innovative Fractal-Based Metasurface for Energy Harvesting Technology

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Abstract

A novel metasurface unit cell, based on the use of the Minkowski fractal geometry, is proposed for ambient power harvesting applications within the Wi-Fi band. The simulated fractal-based cell offers very high absorption coefficients, a wide-angle and polarization insensitive behavior, and very small cell sizes. Thanks to its appealing features, the proposed metamaterial configuration could be very attractive for the implementation of high efficiencies and compact harvesting systems.

1 Introduction

In the last decade, energy harvesting technology has attracted huge attention due to its ability to produce electricity from various environmentally friendly energy sources. Particularly, radio frequency (RF) energy harvesting is very attractive in wireless sensor networks (WSNs) applications, for low-power wireless devices and consumer electronics [1], in order to reduce dependency on batteries. Ambient RF energy could be provided by several RF broadcasting infrastructures, such as analog/digital TV, AM/FM radio, GSM and Wi-Fi networks.

Usually, a RF harvesting system includes a rectifying antenna, namely a rectenna, which is able to harvest high-frequency energy in free space and convert it to DC power [1]. Recently, metasurface (or metamaterial) structures have been investigated as a promising alternative to conventional rectennas, with the key advantage of higher efficiencies [2, 3].
A metamaterial harvester is composed by an array of electrically small resonators, printed on a grounded dielectric substrate. Similarly to metamaterial absorbers, each resonator effectively couples to the incident electromagnetic (EM) wave, at the resonance, thus capturing the EM power from the ambient.
However, while metamaterial absorbers dissipate the collected EM power within their structure, either as ohmic or dielectric losses, in the case of metamaterial harvesters, the energy captured by each resonator is channeled through one or more vias to a feeding network that collects the AC power and feeds it to a rectification circuitry [2 - 4]. Without loss of generality, a metamaterial harvester can be designed to achieve outstanding performance in terms of absorption efficiency, by modeling the input impedance of each branch of the feeding network with a grounded resistive load.

In this work, a wide-angle and polarization-independent metamaterial energy harvester is proposed. The unit cell consists of a miniaturized Minkowski fractal element printed on a thin grounded dielectric substrate. The fractal geometry, already proposed by the authors for reflectarrays design [5, 6], as well as in the framework of metamaterial absorbers for multipath reduction [7, 8], allows to achieve very small unit cells with respect to standard geometries.
Furthermore, as demonstrated in [8], the adopted fractal patches can be fruitfully exploited to obtain multiband operation skills.

A preliminary analysis of the proposed fractal-based harvester is presented and discussed in the following sections. Good miniaturization capabilities, very high absorption percentages, good angular stability and very high polarization independence are demonstrated in correspondence of the LTE/Wi-Fi frequency (i.e. 2.45 GHz). A thorough analysis of the proposed unit cell performances in terms of harvesting energy efficiency will be illustrated during the conference.

2 Unit Cell Layout

The proposed metamaterial unit cell for ambient power harvesting is depicted in Fig. 1. It consists of a Minkowski fractal metallic patch printed on a very thin grounded dielectric slab. Two vias are used to channel the collected EM energy to the resistor loads, modeling the downstream rectification circuitry.

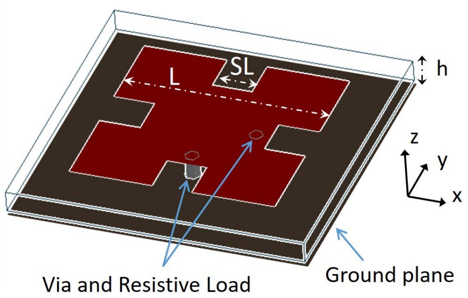

Figure 1. Metamaterial unit cell for ambient power harvesting.

The proposed fractal shape is synthesized for perfect absorption, namely to perform the matching between the unit cell and the free space impedance at a given resonant frequency f_0. As thoroughly discussed in [7], both degrees of freedom inherent to the adopted Minkowski shape, i.e. the patch length L and the inset size SL (Fig. 1), are properly exploited to satisfy the above condition. Furthermore, both the vias position as well as the resistance of the two loads play a key role for maximizing the percentage absorption rate of the synthesized structure.

Following the design rules outlined in [7], a miniaturized 0.12λ×0.12λ cell is designed to operate at the central frequency f_0 = 2.45 GHz. To minimize dielectric losses, a Rogers TMM10i dielectric substrate is considered, having a loss tangent equal to 0.002, a dielectric constant ε_r=9.8, and a thickness h= 1.524mm. A commercial full-wave code (Ansys Designer), based on the infinite array approach, is adopted. As demonstrated by the computed absorption coefficient of the cell (i.e. $A(f)=1-|\Gamma(f)|^2$) in Fig. 2, an absorption peak equal to about 99% is achieved at the design frequency f_0 = 2.45 GHz. The resistive load is assumed to be equal to 50Ω, while the dimensions of the Minkowski patch are fixed to the following values: L=14.5 mm and S=0.245 mm.

In the same Fig. 2, it can be observed how the resistor load, namely the input impedance of the rectification circuitry necessary for the AC-to-DC conversion stage, plays a crucial role. As a matter of the fact, the same metallic resonator without any vias and resistor loads does not satisfy the perfect absorption condition (see Fig. 2).

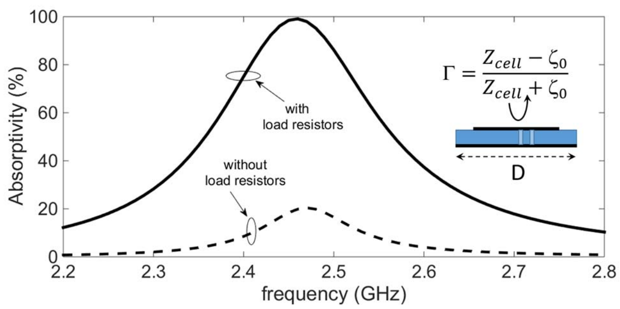

Figure 2. Unit cell absorptivity *vs.* frequency.

As a further analysis, a good angular stability is demonstrated for both TE (Fig. 3(a)) and TM (Fig. 3(b)) polarizations. To this end, the absorption coefficients *vs.* frequency are computed for different incidence angles θ_{inc}, showing very high peak values (≥ 96%), for both TE and TM polarizations. Finally, Fig. 4 shows the polarization-insensitive behavior of the proposed MA cell, for the normal incidence at different ϕ angles.

The above results make the proposed structure very appealing for energy harvesting application within the 2.45GHz Wi-Fi frequency band.

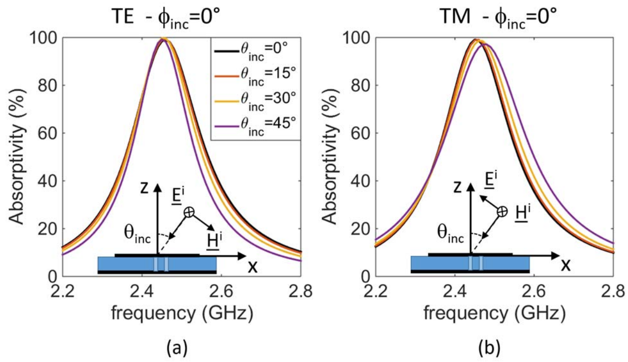

Figure 3. Absorptivity *vs.* frequency of the synthesized metamaterial harvester for different incidence angles: (a) TE-polarization (b) TM- polarization.

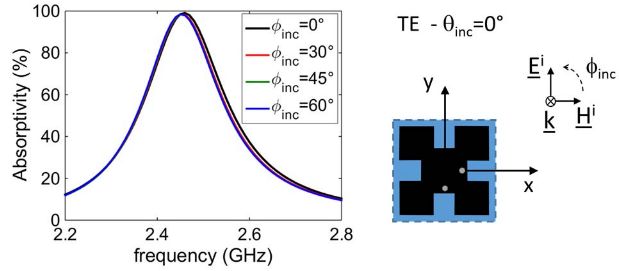

Figure 4. Absorptivity *vs.* frequency of the synthesized metamaterial harvester for different polarization angles at normal incidence.

3 Conclusions

A miniaturized metamaterial unit cell has been introduced for ambient energy harvesting applications. An extensive numerical analysis of the unit cell has been performed, demonstrating very high absorption percentages, good angular stability and very high polarization independence within the 2.45 GHz Wi-Fi frequency band. This makes the proposed configuration appealing for the implementation of environmentally friendly energy harvesting solutions.

As future developments, the proposed configuration will be further investigated and optimized in terms of harvesting energy efficiency.

7 References

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