Electromagnetic energy harvesting using nonlinear metasurfaces

G. T. Oumbe Tekam,[1] V. Ginis,[1,2] J. Danckaert, [1] and P. Tassin[3]

[1] Applied Physics Research Group, Vrije Universiteit Brussel, Pleinlaan 2, B-1050 Brussels, Belgium
[2]Harvard John A. Paulson School of Engineering and Applied Sciences, Harvard University, Cambridge, Massachusetts 02138, USA
[3] Department of Applied Physics, Chalmers University, SE-412 96 Göteborg, Sweden

In this contribution, we present a cut-wire metasurface for an electromagnetic energy harvesting with a PN junction diode embedded in the metasurface to channel the DC output power. The structure is optimized to work for a broad range of angle of incident and by optimizing the characteristics of the diode, we obtain an efficiency of 50 %, which corresponds to the theoretical upper limit. A robust collection mechanism is also made to collect the harvested DC current from all cells, solving in this way a common problem in nonlinear metasurface.

Introduction

The world of technology is growing very fast, driving the volume reduction of computing systems. It is expected that in 2020, mm-scale sensors will largely be important with the expansion of IoT (Internet of Things) and the 5G technology for smart cities and intelligent systems. One of the big challenges at this moment will be the powering of sensors. A smart use of energy will be required and a method to do so is to harvest the surrounding ambient energies like radio frequency energy, which will spreed over the world. increase with the Wi-Fi networks and other sources alike.

Radio frequency electromagnetic energy is the lowest-power system among all energy sources [1], but it has the advantage to be the only one available everywhere, day and night. While most of the energy is normally lost, it could be used instead to power sensors. Recently metamaterials were proposed to harvest electromagnetic energy. These engineered materials can be designed to resonate at particular frequencies and they provide a powerful platform for electromagnetic wave manipulation [2-6]. The integration of AC-DC rectifiers in this kind of system is a challenging situation since it can destroy the harvested energy [7-9].

In this paper, we propose cut-wires metasurface with integrated PN junction diodes as rectifiers for electromagnetic energy harvesting. Proceeding with this purpose, the design of the structure will be presented in the next section following by a section on a collection mechanism to harvest DC current from all the cells.

Metasurface design for electromagnetic energy harvesting

The design of the metasurface energy harvester is done in 3 steps, shown in Fig.1.

The first step consists of the choice and the design of the unit cell, operating at a particular frequency. Typically, this is realized based on the shape, the geometry, the size and the orientation of the metamaterial unit cell. Here we consider a perfect electric conductor cut-wire metamaterial with a quasistatic electric dipole moment designed to resonate at around 3 GHz. The dimensions of the cell are given in the caption of Fig. 2. When the electric dipole moment of this cell is excited by an electromagnetic plane wave, an electric current is induced in the structure, whose dynamics is very similar to an RLC circuit with equivalent electric parameters. These parameters can be estimated by doing a fit between the electric conductivity of the structure and the equivalent electrical conductivity [10].

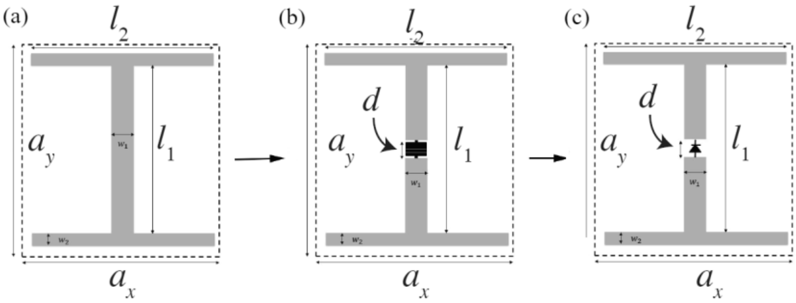

Fig. 1 Design steps: (a) Cut-wire particle with full length, (b) cut-wire particle with embedded resistance and (c) cut-wire particle with embedded diode.

The second step consists of the creation of a narrow gap in the length of the cut-wire particle as shown in Fig. 1(b), and the insertion of a lumped element. By sweeping over the impedance of the lumped element, we find the value for which an impedance matching of the structure with the free space impedance is achieved. This value is equal to 150 Ω and corresponds to be the impedance value of the structure where the maximum of electromagnetic radiation is transformed into AC current.

Finally in step 3, the lumped element is replaced by a PN junction diode with an intrinsic resistance equal to 150 Ω in the aim to maintain the impedance matching between the structure and the free space impedance, and also between the cut-wire and the diode.

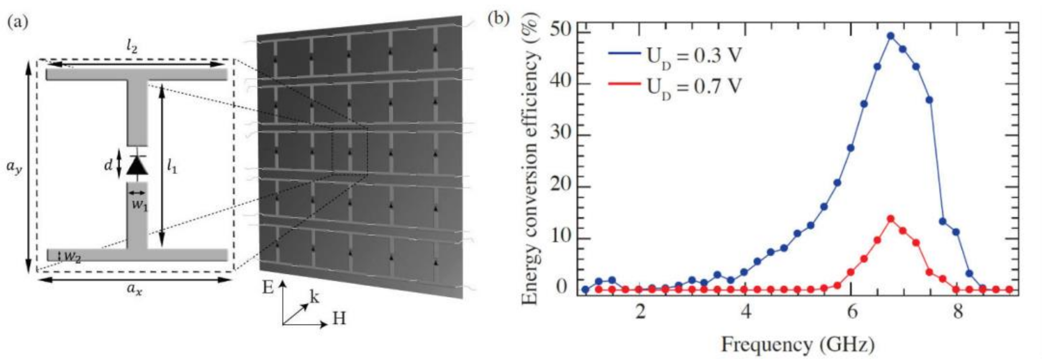

Fig. 2 (a) Design of the metasurface energy harvester composed of cut-wire cells with an integrated diode, (b) energy conversion efficiency for different values of the threshold voltage. $a_x = a_y = 30$ mm, $l_1 = 23.6$ mm, $l_2 = 22.8$ mm, $w_1 = 3$ mm, $w_2 = 1.6$ mm, $d = 2.95$ mm.

Fig. 2(a) presents the complete metasurface energy harvester. To study the efficiency of the structure, we make some assumptions:

- the electromagnetic incident plane wave is normal to the metasurface;
- the distance between the source and the metasurface is sufficiently small $\approx \lambda/2$;
- the conversion efficiency is the one considered here.

We consider as input signal, the microwave electric field of common wireless communication systems which equals 20.5 V/m, corresponding to an incident power density of 1.13 W/m^2 with a Gaussian time profile. The energy conversion efficiency is investigated for two different types of diodes: a Silicon diode with a threshold voltage of 0.7 V and a Germanium diode with a threshold voltage of 0.3 V. Fig. 2(b) shows that the Germanium diode obtains a fivefold energy conversion efficiency (from 12.5% to 50%) in comparison with the use of Silicon diode. Furthermore, the maximum of energy conversion occurs at 6.75 GHz due to extra capacitance introduced by diode. For waves incident under an angle θ, the effect of varying angles translates directly into a varying equivalent impedance of the surface, given by $150/\cos(\theta)\ \Omega$. Using the equivalent electrical circuit model, whose performances have already been verified [10], we calculated the efficiency of the metasurface energy harvester for varying incident angles. As illustrated in Fig. 3, the structure performs well for wide range of incidence angle and only a small range of incidence angle will lead to less efficient harvesting.

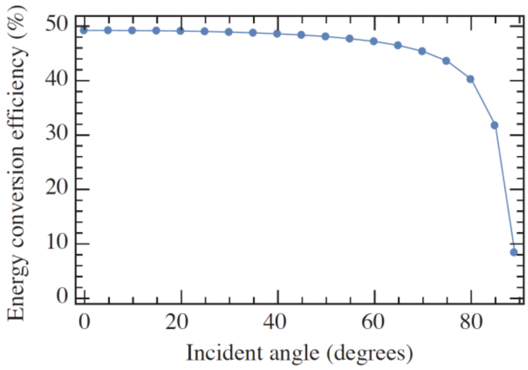

Fig. 3 The performance of the structure as a function of the incidence angle.

Collection mechanism of the harvested DC current

We investigate how the DC current can be collected from all the unit cells of the metasurface. This is a common problem in nonlinear metasurface. To address the issue, thin metallic wires with high inductance are added between the end caps of adjacent unit cells. The high inductance allows the flow of current between the unit cells with barely any degradation of the output energy.

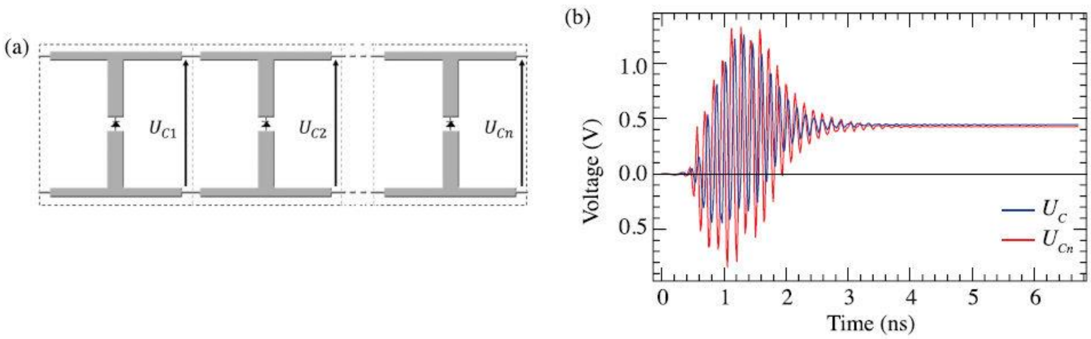

Fig. 4 (a) Connection of the cells to channel the energy harvested. (b) Time evolution of the voltage across an unconnected cell (U_C) and the one of a connected cell (U_{Cn}).

This is confirmed in Fig. 4 where the time evolution of the voltages across an unconnected cell (U_C) and the one across a connected cell (U_{Cn}) are the same. This demonstrates that DC electrical energy can be easily collected in a large array of the metasurface.

Conclusion

We designed a planar metasurface for electromagnetic energy harvesting integrating a PN junction diode as a rectifier. This diode does not require a bias voltage to trigger its operation. For a realistic incident power density of $1.13\,\text{W/m}^2$, using a Germanium diode is more interesting since it leads to increase of the power conversion efficient at 50% in comparison with a Silicon diode because of its lower threshold voltage. Our unit cell is electromagnetically subwavelength and thus can be used as power source for small-scale sensors.

References

[1] C. M. F. Carvalho and N. F. S. V. Paulino, "CMOS indoor light energy harvesting system for wireless sensing applications," New York: Springer International Publishing Switzerland, ch. 1-2, pp. 1-42, 2016.
[2] D. R. Smith, J. B. Pendry and M.C. K. Wiltshire, "Metamaterials and negative refractive index," Science, vol. 305, 788-792, 2004.
[3] V. Ginis, P. Tassin, C. M. Soukoulis and I. Veretennicoff, "Enhancing optical gradient forces with metamaterials," Phys. Rev. Lett., vol. 110, 057401, 2013.
[4] S. Viaene, V. Ginis, J. Danckaert and P. Tassin, "Transforming two-dimensional guided light using nonmagnetic metamaterial waveguides," Phys. Rev. B, vol. 93, 085429, 2016.
[5] L. Lambrechts, V. Ginis, J. Danckaert and P. Tassin, "Transformation optics for surface phenomena: Engineering the Goos-Hänchen effect," Phys. Rev. B, vol. 95, 035427, 2017.
[6] O. M. Ramahi, T. S. Almoneef, M. AlShareef and M. S. Boybay, "Metamaterial particles for electromagnetic energy harvesting," Appl. Phys. Lett., vol. 101, 173903, 2012.
[7] A. M. Hawkes, A. R. Katko, and S. A. Cummer, "A microwave metamaterial with integrated power harvesting functionality," Appl. Phys. Lett., vol. 103, 173903, 2012.
[8] X. Duan, X. Chen, and L. Zhou, "A metamaterial electromagnetic energy rectifying surface with high harvesting efficiency," AIP Advances, vol. 6, 125020, 2016.
[9] R. Wang, D. Ye, S. Dong, Z. Peng, Y. Salamin, F. Shen, J. Huangfu, C. Li and L. Ran, "Optimal matched rectifying surface for space solar power satellite applications," IEEE Transactions on Microwaves Theory and Techniques, vol. 62, No. 4, 2014.
[10] G. T. Oumbe Tekam, V. Ginis, J. Danckaert and P. Tassin, "Designing an efficient rectifying cut-wire metasurface for electromagnetic energy harvesting," Appl. Phys. Lett., vol. 110, 083901, 2017.