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DIMES

# Wide-Angle and Polarization-Insensitive Fractal Metasurface for Energy Harvesting


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# Outline

- Introduction to Radio Frequency (RF) energy harvesting
- Metamaterial harvesters: a promising alternative to conventional rectennas
- A novel polarization independent metamaterial energy harvester :
  - *Geometry and layout*
  - *Advantages*
  - *Principle of operation*
  - *Design and analysis*
  - *Numerical validation*
- Conclusions

# Introduction to Radio Frequency Energy Harvesting

In the last decade, **energy harvesting technology** has attracted huge attention due to its **ability to produce electricity** from various **environmentally friendly energy sources** such as solar, wind, motion, vibration, and radio frequency (RF)

Due to the increasing availability of free RF energy **RF energy harvesting is very attractive** for wireless sensor networks (WSNs) applications and low-power devices for consumer electronics

**Ambient RF energy** could be provided by several RF broadcasting infrastructures such as **analog/digital TV**, **AM/FM radio**, **GSM and Wi-Fi networks**

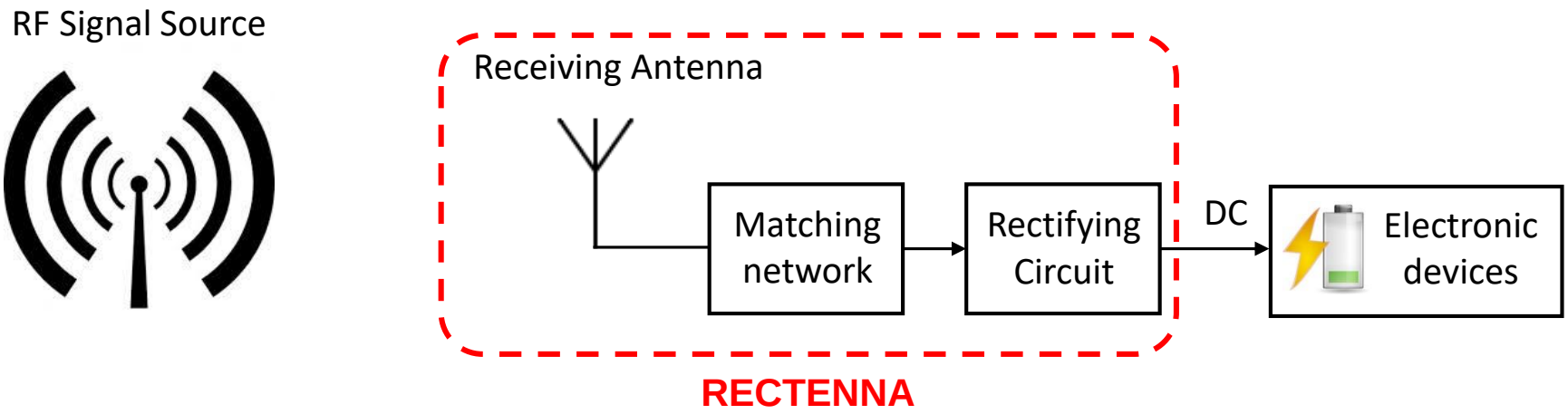
# Introduction to Radio Frequency Energy Harvesting

Usually, an RF harvesting system includes

a rectifying antenna (namely a **RECTENNA**)

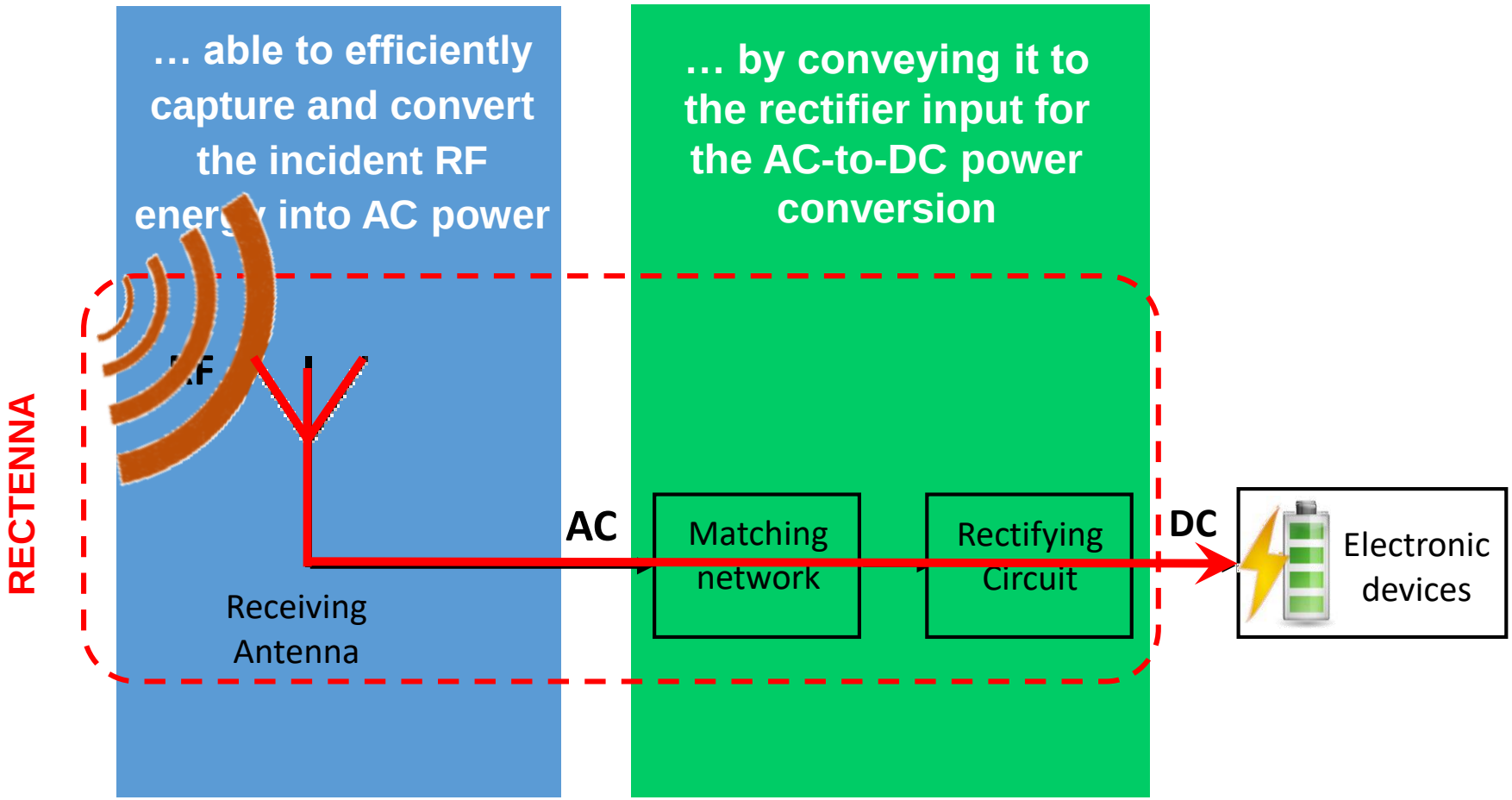
which **is able to harvest high-frequency energy** in free space

and **convert it to DC power**



# Introduction to Radio Frequency Energy Harvesting

The **antenna** is the key element of an RF-energy harvesting system…



# Introduction to Radio Frequency Energy Harvesting

Antennas adopted in conventional rectenna-based harvesters offer a very simple integration with the most rectifier circuits in the literature, also producing high harvesting efficiencies in the overall conversion path from RF-to-DC power

**However…**

… the amount of energy collected by a single antenna is relatively small and useful only for very-low-power applications

In order to achieve greater amounts of harvested power

**the use of rectennas in array form is recommended**

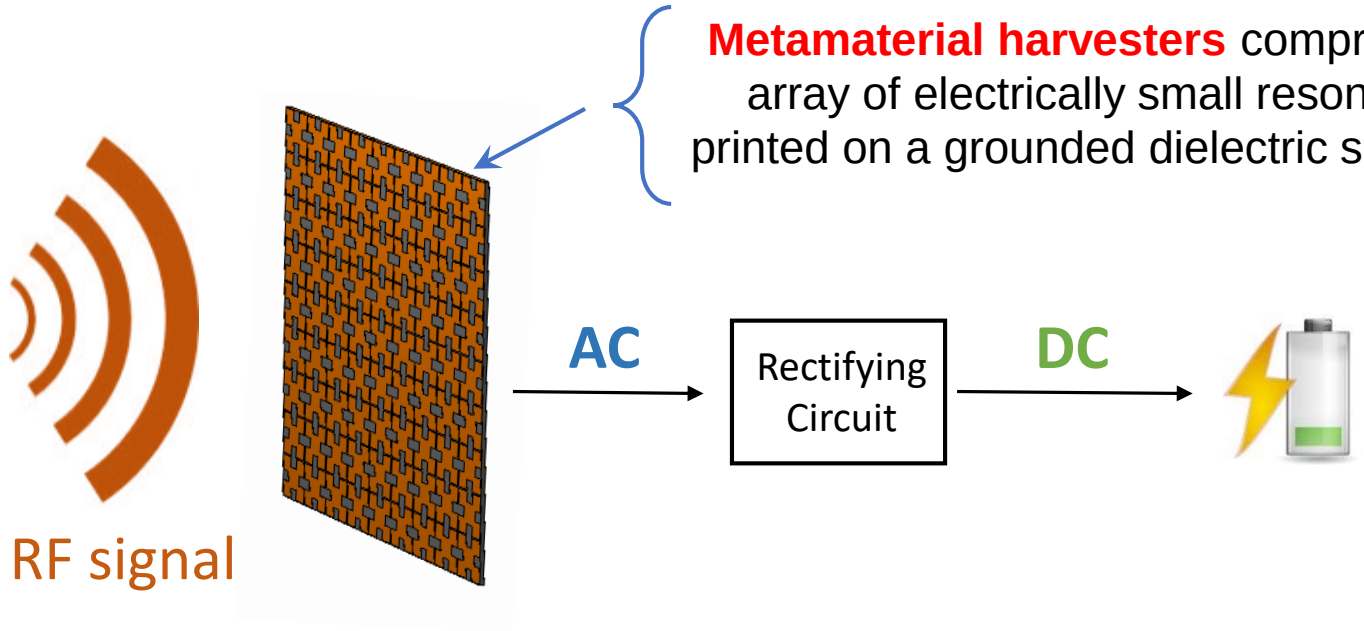
as the contribution of each individual cell is constructively added

# Metamaterial harvester: a promising alternative to conventional rectennas

**Metasurface (or metamaterial) structures**

have been investigated as **a promising alternative to conventional rectennas**

with the key advantage of greater amounts of harvested power and higher efficiencies in the preliminary conversion stage from RF-to-AC power [1, 2]





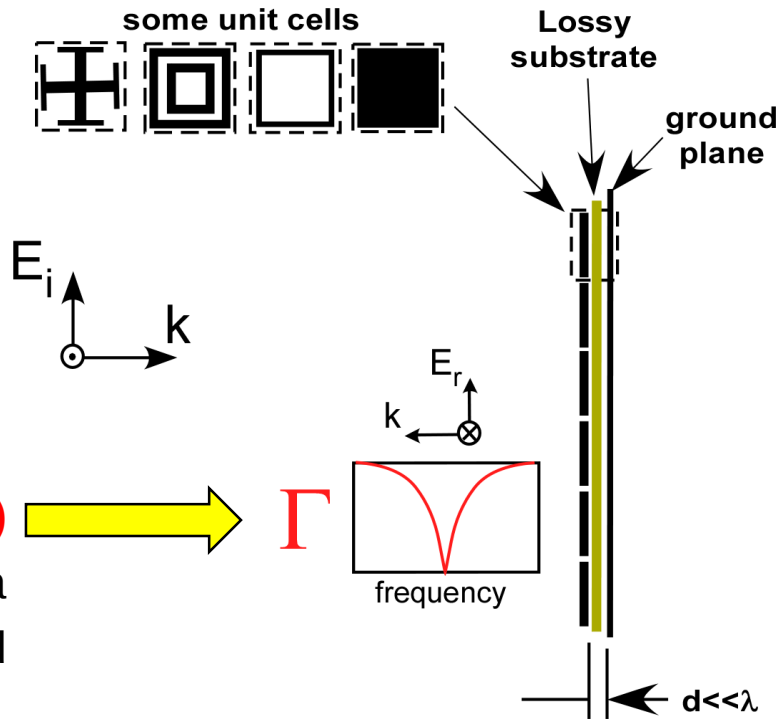
1. Ramahi, O.M.; Almoneef, T.S.; AlShareef, M.; Boybay, M.S. Metamaterial particles for electromagnetic energy harvesting, *Applied Physics Letters*, **2012**, *101*, 173903.
2. Alavikia, B.; Almoneef, T.S.; Ramahi, O.M. Electromagnetic energy harvesting using complementary split-ring resonators, *Applied Physics Letters,* **2014**, *104*, 163903.

# Metamaterial harvester: a promising alternative to conventional rectennas

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**

… achieving **perfect absorption (i.e. $\Gamma \cong 0$)** around a given frequency and/or a frequency band

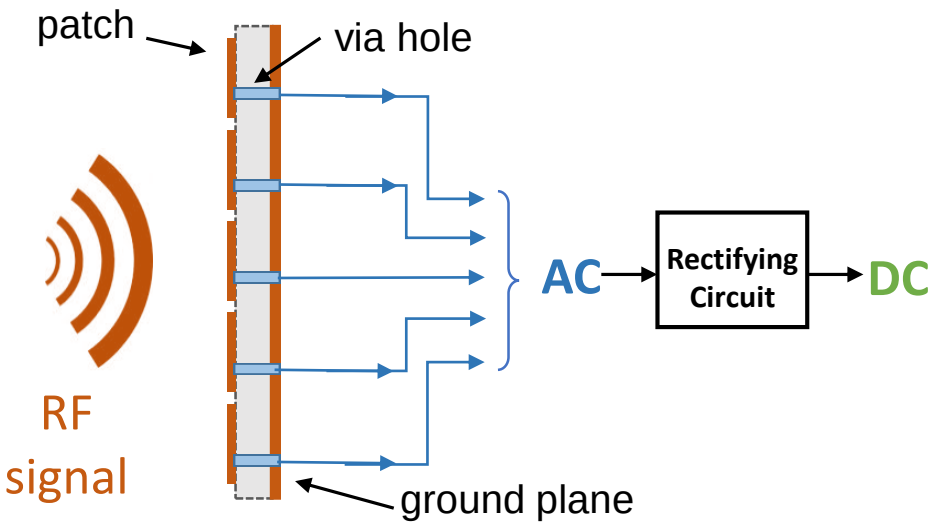


# Metamaterial harvester: a promising alternative to conventional rectennas

**However…**

while **metamaterial absorbers** dissipate the collected EM power within their structure (either as ohmic or dielectric losses)…

… **the energy captured** by each element of **metamaterial harvesters** **is channeled through one or more vias to a feeding network** that collects the AC power and feeds it to a rectification circuitry [3-5]





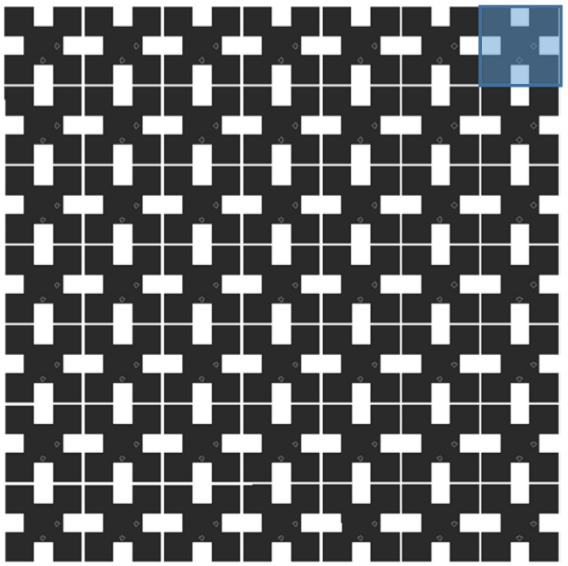
3. El Badawe, M.; Almoneef, T.S.; Ramahi, O.M. A metasurface for conversion of electromagnetic radiation to DC, *AIP Advances*, **2017**, 7, 035112.
4. Ghaderi, B.; Nayyeri, V.; Soleimani M.; Ramahi O.M. Pixelated Metasurface for Dual-Band and Multi-Polarization Electromagnetic Energy Harvesting, *Scientific Reports,* **2018**, *8*, Article number: 13227.
5. Almoneef, T.S.; Erkmen, F.; Ramahi, O.M. Harvesting the energy of multi-polarized electromagnetic waves, *Scientific Reports*, **2017**, *7*, p. 14656

# A novel polarization independent metamaterial energy harvester

## *Geometry and layout*

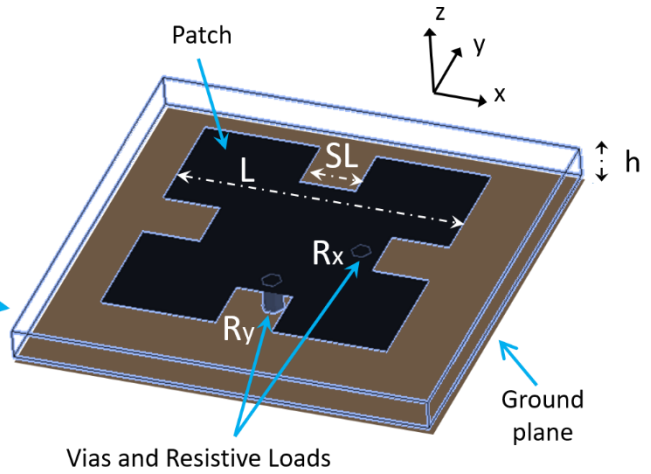
A novel wide-angle and polarization independent metamaterial energy harvester is proposed

It consists of a **periodic pattern** of identical unit cells printed on a very thin grounded dielectric slab



Metamaterial Pattern – front view

Unit cell




Each cell comprises a **Minkowski fractal patch loaded by two resistive loads** which model the downstream rectification circuitry

# A novel polarization independent metamaterial energy harvester

## *Advantages*

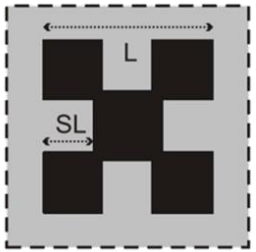
**a)** The adopted fractal shape allows to fit an electrically longer resonator into a smaller unit cell thus offering **very exciting miniaturization skills** practical for **reducing size and mass of the harvester** [6, 7]

***Infact…***

*the effective side length of the patch, approximately equal to* $L_{eff} = (1+2S)L$,

*is inversely proportional to the patch resonance frequency (i.e.* $f_0 \sim 1/L_{eff}$)

→ ***the combined use of a smaller patch length L and a greater S-value allows to move down the resonant frequency*** $f_0$, *keeping a reduced footprint*




***Furthermore…***

**b)** The adopted fractal patches can be fruitfully exploited to obtain **multiband operation skills** [7, 8]

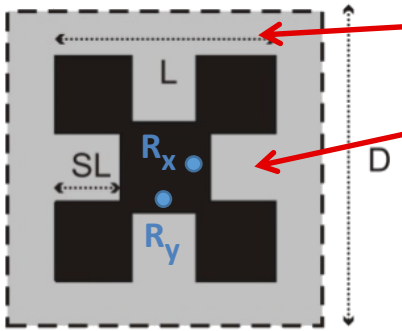

6. Venneri, F.; Costanzo, S.; Di Massa, G. Fractal-shaped metamaterial absorbers for multireflections mitigation in the UHF band, *IEEE Antennas and Wireless Propag. Letters*, **2018**, 17, 255-258.
7. Venneri, F.; Costanzo, S.; Borgia A. A dual-band compact metamaterial absorber with fractal geometry, *Electronics*, **2019**, 8(8), 879.
8. Costanzo, S.; Venneri, F.; Borgia A.; D. Massa, G. Dual-band dual linear polarization reflectarray for mmWaves/5G applications, *IEEE Access*, **2020**, *8*, pp. 78183-78192.

# A novel polarization independent metamaterial energy harvester

## *Principle of operation*

In order to achieve the **perfect absorption condition (i.e. $\Gamma \cong 0$)** the **Minkowski patch**

is properly synthesized to match the unit cell input impedance $Z_{cell}$ with that of the **free space** $\zeta_{0.}$




unit cell

**Both degrees of freedom** inherent to the adopted FSS shape, namely:

- **the patch length L**
- **the inset size SL**

are properly exploited to satisfy the **matching condition** [9]:

$$\mathrm{Re}\{Z_{cell}\} = \zeta_{0.}$$

***Furthermore…***

both **vias positions** as well as the **resistive value of the two loads** are properly chosen to satisfy the following goals:

- maximize the percentage rate of the absorbed RF energy
- assure a polarization insensitive behavior with respect to the incident electromagnetic signal


9. Costanzo, S.; Venneri, F. Miniaturized fractal reflectarray element using fixed-size patch, *IEEE Antennas and Wireless Propagation Letters*, **2014**, *13*, 1437-1440.

# A novel polarization independent metamaterial energy harvester

## *Design and Analysis*

A miniaturized **0.123λ×0.123λ cell** is designed to operate at the LTE/Wi-Fi frequency $f_0$**=2.45 GHz**

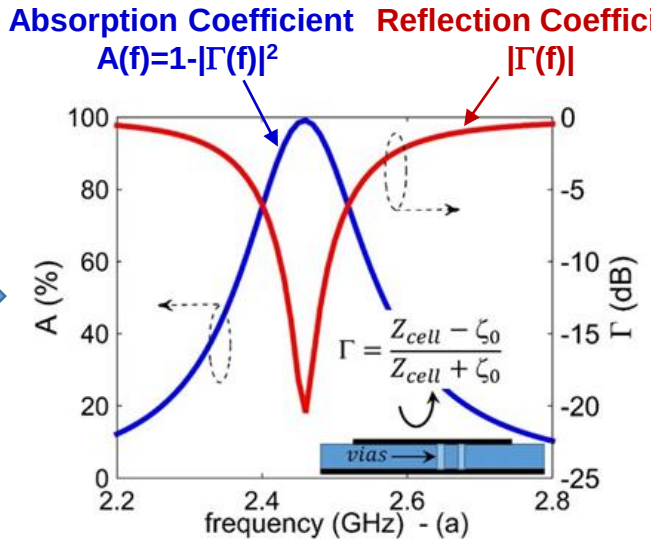
*A commercial full-wave code, based on the infinite array approach, is adopted (Ansys Designer)*

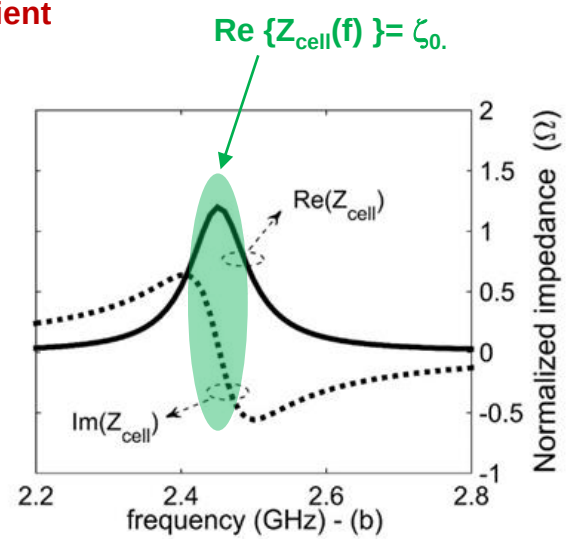
**Unit cell parameters**

| | |
|---|---|
| Dielectric substrate: | **Rogers TMM10i** ($\varepsilon_r$=9.8, tan$\delta$=0.002, h= 1.524mm) |
| Minkowski patch sizes: | **L=14.5mm and S=0.245** |
| Resistive loads: | **Rx=Ry=R= 50 Ω** |

An **absorption peak** equal to about **99%** is obtained at **2.45 GHz** …

… due to the **perfect matching** between unit cell and free space

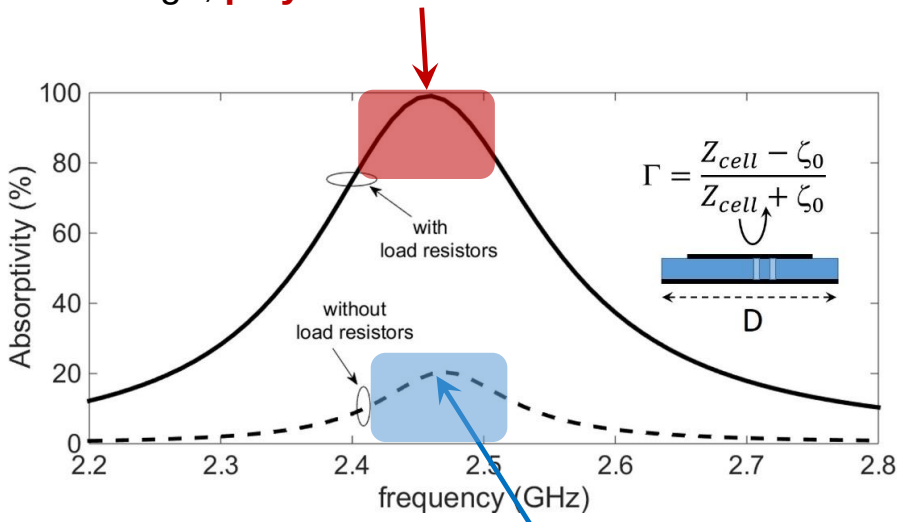


# A novel polarization independent metamaterial energy harvester

## *Design and Analysis*

The resistor loads, **Rx and Ry**, namely the input impedance of the rectification circuitry necessary for the AC-to-DC conversion stage, **play a crucial role…**




***Infact…***

the same metallic resonator (L=14.5mm and S=0.245), **without any vias and resistor loads**, does **not satisfy the perfect absorption condition…**

**offering an absorption rate of just 20%**, due to the high mismatching obtained between free space and unit cell impedances ($Z_{cell} \cong 2.9\ k\Omega$ @2.45 GHz)

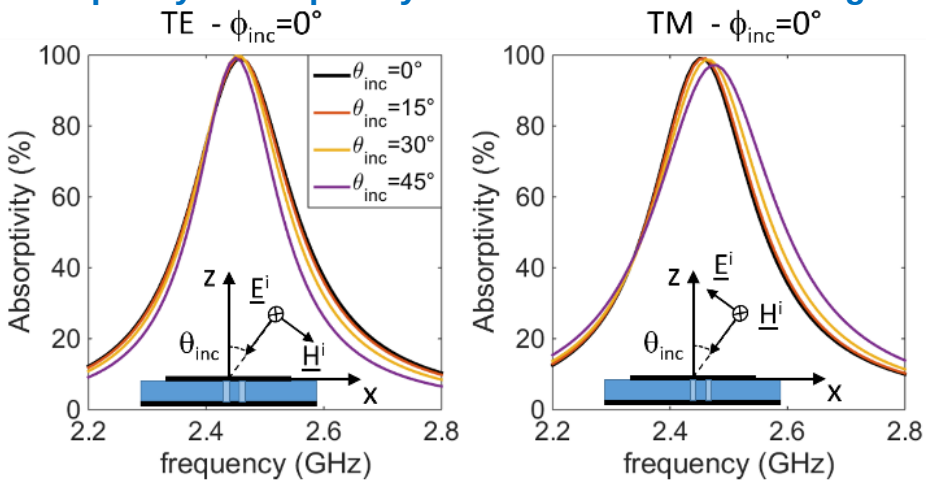
# A novel polarization independent metamaterial energy harvester

## *Design and Analysis*

A good angular stability is demonstrated for both TE and TM polarizations

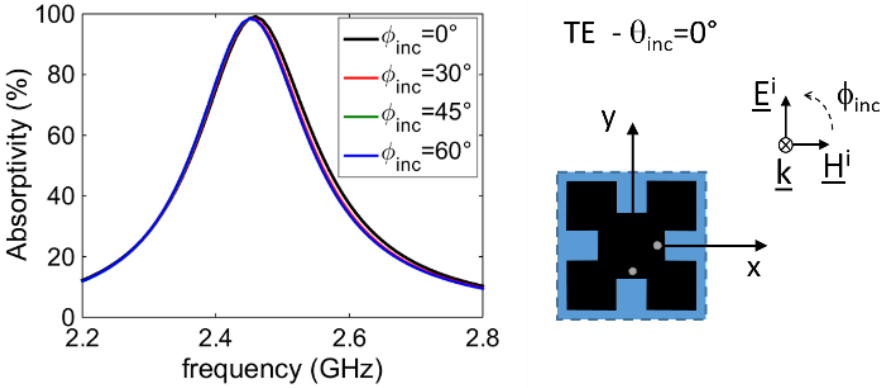
Very high peak values are achieved **( ≥ 96% )**

**Absorptivity *vs* frequency for different incidence angles $\theta_{inc}$**




**Furthermore…**

a quite good and stable absorption rate is achieved for different $\phi$ angles, demonstrating the polarization-insensitive behavior of the proposed MA cell




**Absorptivity vs frequency for different polarization angles**

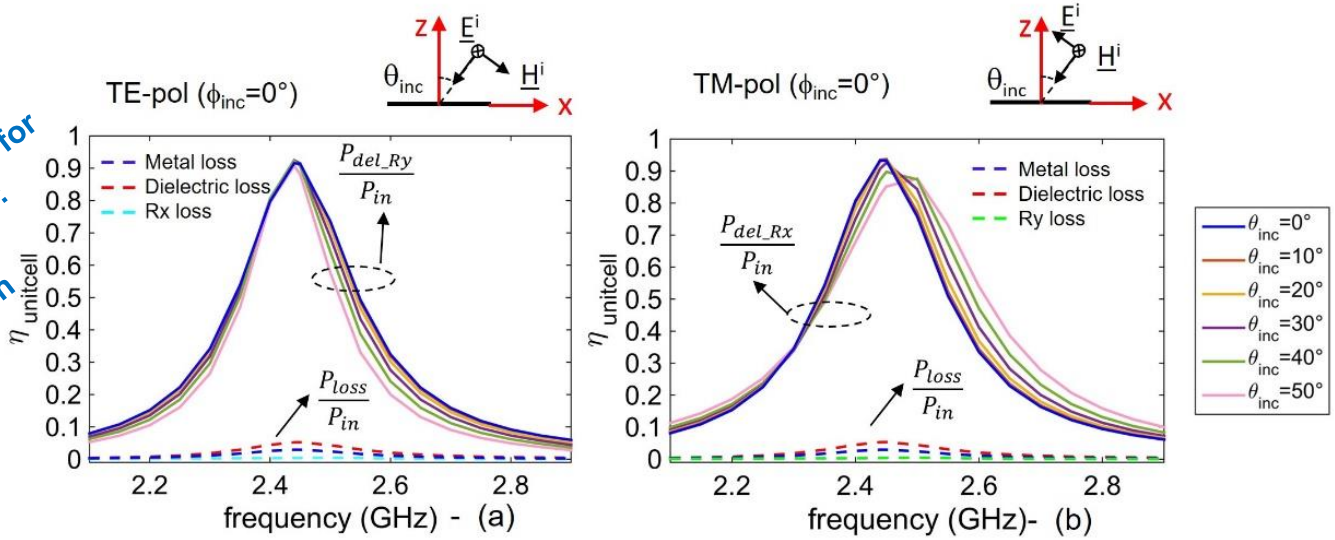
# A novel polarization independent metamaterial energy harvester

## *Unit Cell Efficiency Analysis*

The power losses within the proposed unit cell are evaluated by the full-wave frequency domain solver CST Microwave Studio

The structure is excited by a Floquet port giving a plane wave; the incident power is set to a value equal to $P_{inc}$=0.5 W

Unit cell efficiency vs frequency for different incidence angles:
(a) TE-polarization
(b) TM- polarization




**Most of the power is delivered to the load located in the corresponding polarization direction**

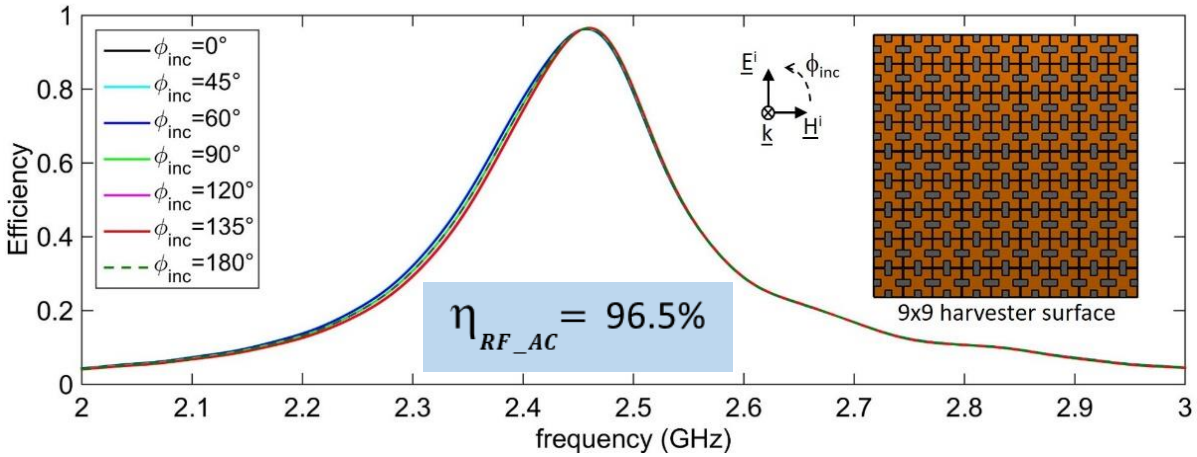
… only a small amount is dissipated within the copper (≅ 0.028 $P_{in}$), the dielectric (≅ 0.05 $P_{in}$) and the load located outside the polarization direction (≅ 0.0036 $P_{in}$).

# A novel polarization independent metamaterial energy harvester

## *Numerical validation of a 9x9 harvesting panel*

In order to give a preliminary numerical validation of the proposed fractal unit cell, a 9×9 metamaterial harvester is designed and simulated with CST Microwave Studio

The metamaterial surface ($A_{harvester} \cong 1.1\lambda \times 1.1\lambda$) is illuminated by a normal incident plane wave having an electric field strength $|\underline{E}_{inc}| = 1$ V/m




The RF-to-AC efficiency ($\eta_{RF\_AC}$) of the metamaterial harvester is evaluated as the ability of the absorber to capture the energy per footprint area

$$\eta_{RF\_AC} = \frac{\sum P_{del\_load}}{P_{in}}$$

total power delivered to the loads inside the 9x9 cells

power incident onto the array surface

$$P_{inc} = S_{inc} A_{harvester} = \frac{1}{2\zeta_0} |E_{inc}|^2 A_{harvester}$$

# Conclusions

- A **miniaturized metamaterial unit cell** has been introduced **for ambient energy harvesting applications**, within the 2.45 GHz Wi-Fi frequency band
- An extensive numerical analysis of the unit cell has been performed, demonstrating:
  - *very high absorption percentages*
  - *good angular stability*
  - *very high polarization independence*
- A **9×9 metamaterial harvester panel** is designed and simulated, demonstrating a very high **RF-to-AC efficiency equal to 96.5%**
- The finite size harvester shows a polarization-insensitive behaviour, making the proposed configuration **very appealing for the implementation of environmentally friendly energy harvesting solutions**

# Thanks for the attention