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Electromagnetic Radiation Energy Harvesting – The Rectenna Based Approach

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Additional information is available at the end of the chapter

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1. Introduction

The energy available in the electromagnetic spectrum

How much energy is available around us? Which use can we give to this energy? These are two questions to which answers had been changing over time. What would be our particular answer if a forefather or an ancestor would ask them to us? Some sources of energy like sun, wind or sea waves have been present unaltered since the prehistoric times and before to nowadays. Some others like oil and natural gas have been progressively reduced by the action of man. But it is interesting to notice that there are some other sources, which we can name as artificial sources, and that have emerged by man's action, as a consequence of industrial and technological development. Such modern or artificial energy sources are directly connected to the energy harvesting technology since, for instance, most of the vibrations or temperature gradients are produced by machines and engines. Also in the electromagnetic spectrum, we can harvest energy not only from natural sun radiation, but also from all the artificial radio-frequency sources that are permanently increasing in number and which are a consequence of one of the last technological revolutions: the Information and Communications Technology (ICT) revolution.

Although when we think about electromagnetic (EM) waves at present time, we probably tend to think about examples like radio, TV or cell phones, where the information part of the electromagnetic signal is the protagonist, we should bear in mind that those signals are in fact a combination of information and energy. In this chapter, we are not interested in describing how information can be transmitted through electromagnetic waves but how the energy of these waves is transmitted and collected to be harvested and used to supply ICT devices. In order to calculate how much energy can be associated to an electromagnetic wave, we have to consider the physical nature of these particular waves.

1.1. Basic concepts

Electromagnetic waves in the electromagnetic spectrum (figure 1) are characterized by their wavelength λ or, alternatively, by their frequency ν. Both magnitudes are related with the propagation speed of such waves, the speed of light c, through:

$$c = \lambda \cdot \nu \qquad (1)$$

On the other hand, the frequency of EM radiation is directly related to the energy E of a photon associated to this radiation, i.e. the quantum of EM radiation or the most fundamental constitutive part of this radiation as defined by quantum mechanics, by

$$E = h \cdot \nu \qquad (2)$$
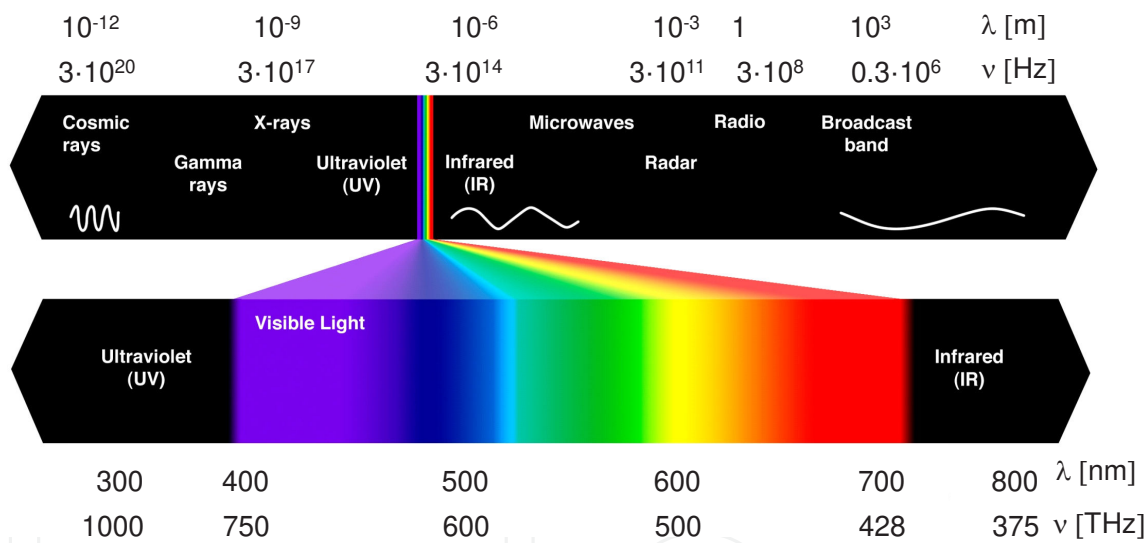
where h=6.626 10^{-34} J s is the Planck constant.

Figure 1. Diagram of the electromagnetic spectrum with indications of the wavelength, λ, and frequency, ν, of the most representative radiations from shorter and most energetic, cosmic rays, to the longer and less energetic radiofrequencies. A zoom detail of the optical part of the spectrum shows that light radiations is in the hundred nm and THz range of wavelengths and frequencies respectively.

Unlike what occurs in photovoltaics technology, where optical radiation energy is better accounted in terms of photon energy since there the conversion mechanism is based in photon-electron interactions, in rectenna technology it is more convenient to express the input EM radiation in terms of the power or the power density of the EM wave.

An EM wave can be defined as a form of energy radiated by a source which results in a combination of oscillating electric and magnetic fields. In most of materials, the direction of the EM wave propagation is perpendicular to the electric and magnetic fields, which are also oscillating in phase perpendicular to each other.

The set of equations which describe how electric and magnetic fields propagate, interact and how they are influenced by material properties are Maxwell's equations. An EM wave can be described with these equations, which must be met for a set of particular boundary conditions. Maxwell's equations are summarized in Table 1.

Law	Integral form	Differential form
Faraday's law of induction	$\oint_c \vec{E} \cdot d\vec{l} = -\dfrac{\partial}{\partial t} \iint_s \vec{B} \cdot d\vec{s}$	$\nabla \times \vec{E} = -\dfrac{\partial}{\partial t}\vec{B}$
Ampère's circuital law	$\oint_c \vec{H} \cdot d\vec{l} = \iint_s \vec{J} \cdot d\vec{s} + \dfrac{\partial}{\partial t}\iint_s \vec{D} \cdot d\vec{s}$	$\nabla \times \vec{H} = \vec{J} + \dfrac{\partial}{\partial t}\vec{D}$
Gauss's law	$\oiint_s \vec{D} \cdot d\vec{s} = \iiint_v \rho \cdot dV$	$\nabla \times \vec{D} = \rho$
Gauss's law for magnetism	$\oiint_s \vec{B} \cdot d\vec{s} = 0$	$\nabla \times \vec{B} = 0$

Table 1. Maxwell's equations.

where $\vec{E}$ is the electric field intensity, $\vec{B}$ and $\vec{H}$ are the magnetic fields, $\vec{J}$ is the total current density, $\vec{D}$ is the electric displacement field and ρ is the total charge density.

The propagation of a plane EM wave can be described by the EM wave equation, which can be derived from Maxwell's equations. The homogeneous form of this second-order differential equation can be written in terms of either the electric field or the magnetic field as

$$\left(\nabla^2 - \mu\varepsilon\frac{\partial^2}{\partial t^2}\right)\left\{\begin{matrix}E_y(x,t)\\B_z(x,t)\end{matrix}\right\} = 0 \qquad (3)$$

where μ and ε are the permeability and the permittivity of the propagation medium, respectively.

Knowing that EM waves carry energy with them in the form of electric and magnetic fields, we can compute their energy flow per unit area using the so called Poynting vector

$$\vec{S} = \vec{E} \times \vec{H} \qquad (4)$$

From the Poynting vector and considering a uniform plane wave the time-average power density of the EM wave can be computed as [1]

$$P_{av} = \frac{1}{2} \cdot \frac{|E_0|^2}{\mathrm{Re}\{\eta\}} \qquad (5)$$

where E_0 is the peak value of the electric field and η is the impedance of the propagating medium. If the wave propagates in a loss-less dielectric medium η is a real number. Being this medium the free space, the impedance can be computed as follows:

$$\eta_0 = \sqrt{\frac{\varepsilon_0}{\mu_0}} = \frac{1}{\varepsilon_0 \cdot c_0} \tag{6}$$

where μ_0 is the vacuum permeability, ε_0 is the vacuum permittivity and c_0 is the speed of light in free space. The value for the impedance of the vacuum is about 377Ω.

A good approximation to the radiated power at a certain distance d from an emitter can be computed considering that the emitter is an isotropic radiator (EM point source which radiates the same power in all directions)

$$\mathrm{P}_{\mathrm{r}d} = \frac{P_{rT}}{4 \cdot \pi \cdot d^2} \tag{7}$$

where P_{rT} is the total radiated power and d the distance from the emitter. Notice that real antennas do not radiate isotropically, they have a certain radiation pattern which depends mainly on the geometry of the antenna and the surrounding media.

In 1999 the Council of the European Union made some recommendations on the limitation of exposure to electromagnetic fields [2]. Table 2 summarizes the maximum recommended values for the electric field.

Frequency range	E-field strength (V/m)
0-1 Hz	–
1-8 Hz	10000
8-25 Hz	10000
0.025-0.8 kHz	250 / f
0.8-3 kHz	250 / f
3-150 kHz	87
0.15-1 MHz	87
1-10 MHz	$87 / f^{0,5}$
10-400 MHz	28
400-2000 MHz	$1,375 \cdot f^{0,5}$
2-300 GHz	61

Table 2. Reference levels for electric fields from 0 Hz to 300 GHz.

On the other hand, the IEEE International Committee on Electromagnetic Safety has made some additional recommendations in order to protect human beings from harmful effects caused by the exposure to electromagnetic fields [3]. Table 3 summarizes the maximum recommended values for the RMS electric field, magnetic field and power density.

Frequency range (MHz)	RMS electric field strength (V/m)	RMS magnetic field strength (A/m)	RMS power density (E-field, H-field) (W/m²)
0.1-1	1842	16,3 / f	(9000 , 100000 / f^2)
1-30	1842 / f	16,3 / f	(9000 / f^2 , 100000 / f^2)
30-100	61,4	16,3 / f	(10 , 100000 / f^2)
100-300	61,4	0,163	10
300-3000	–	–	f / 30
3000-30000	–	–	100
30000-300000	–	–	100

Table 3. Reference levels for electric, magnetic fields from 0 Hz to 300 GHz.

Finally, although tables 2 and 3 give a good idea of the maximum energy available from RF emissions in terms of electric field and power density, in table 4 power density values and ranges corresponding to different applications are also summarized and compared to sunlight in the visible range.

Application	Power density (mW/cm²)
Old UHF TV band	10^{-9}
FM radio @ 50 km from 100kW base station	10^{-7}
ISM bands: Zigbee/Bluetooth/WIFI	$10^{-8}/10^{-7}/10^{-6}$
Standard ambient level with no high power equipment	$10^{-6} - 10^{-5}$
GSM, UMTS (3G telecom) @ 10 m from base station	$10^{-6} - 10^{-4}$
Cellular phone @ 50 m from base station	$10^{-4} - 10^{-2}$
Solar Power Satellite (SPS) Wireless Power Transmission (WPT)	$10^{-1} - 10$
Solar radiation in the visible range	10^2

Table 4. Comparison of power densities for different applications with solar radiation in the visible range.

1.2. Photovoltaics versus rectenna technologies

When electromagnetic waves were experimentally observed, they were generated using antennas and radiating elements. Along the development of radio emission, antenna design

became a separate area of expertise where the geometry of those elements configured the characteristics and capabilities of emission and reception of the EM waves. The shape and orientation of those antennas determine the polarization and direction of the emission, and reception. Electromagnetic spectrum was mastered and used in science and technology. Fortunately, the wavelengths associated with the radioelectric and microwave spectra allowed the manufacturing of radiating elements with the available fabrication tools. When increasing the frequency of the electromagnetic radiation, the geometries were shrunk accordingly and new fabrication strategies were used. Actually, an important leap in antenna design and fabrication appeared when using planar antennas written on flat substrates by microlithography techniques. Millimeter waves and Terahertz still benefit from those fabrication techniques. However, when the optical domain was placed as a feasible goal for antenna design, the use of electron beam lithography, focused ion beam, and related nanometric precision manufacturing tools were necessary. Even more, those metals traditionally used as materials for antenna fabrication appeared to behave as non-perfect conductors, showing spectral dispersion and a non-negligible penetration depth.

At the same time that antennas were clearly devoted to the emission and detection of EM wave in the radioelectric, and microwave regimes, light and optical spectrum was covered with other reliable technologies for emission (incandescence lamps, spectral lamps, lasers, etc.) and detection (Golay cells, thermoconductors, photovoltaics, etc.) mainly based for detection in the quantified energy levels of semiconductors. Then, photodetectors improved their performance in responsivity, signal-to-noise ratio, cut-off frequency, size, and biasing requirements.

Then, it is easy to understand that antennas did not find a suitable place to develop as optical detectors. Semiconductor detectors were here to stay, fabrication of optical antennas is difficult and requires high-tech machinery, and metals are non-perfect conductors anymore in the optical regime.

However, some advances were made in using antenna-coupled detectors in the detection of light at higher and higher frequencies, and in its use as frequency mixer or coupled to bolometric devices. Besides, nanoscience has found optical antennas as promising elements to explore materials and media with high spatial resolution. Plasmonic optics has become an emerging field, where the collective oscillation of charges produces exotic phenomenologies that are used for sensing and probing sub-wavelength structures.

Several reports and papers [4,5,6,7] have been published in the past years presenting optical antennas and rectennas as harvesters of electromagnetic radiation in the infrared and visible spectrum. They are based on the principle of rectification of the currents generated in an antenna structure that resonates at the visible frequency. The idea, although appealing, has been somehow over-estimated when promising efficiencies above 80%. However, as we will see in this chapter, some important problems need to be addressed before fabricating an operative device. Unfortunately, the task of rectifying electric fields oscillating at 10^{14}-10^{15}Hz frequencies is formidable, and the efficiency figures obtained so far are well below the announced limit. The bottleneck of the technology remains in the rectification process. At the same time, some important advances have been made to tailor the impedance of optical antennas to properly couple the electromagnetic field and also to transfer the power to the

load, i.e., to the rectifier. Then, optical rectennas can be considered as a promising technology with high potential. Based on the current results, more effort needs to be allocated to leap over the rectifying mechanism with novel technologies.

Although it is limited to the solar region of the electromagnetic spectrum, the most mature and standard technology (developed since the mid 70's) to harvest energy from EM radiation is photovoltaics (PV). According to the *National Renewable Energy Laboratory (NREL)*, conversion efficiency of PV technologies has been increasingly evolved during the last 40 years (figure 2). From the most simple variant of the 1st generation represented by the silicon based cells, to the 2nd and 3rd generations corresponding to thin-film and the most sophisticated multijunction cells respectively, a trade-off between efficiency and production cost is defining the market of each variant (table 5).

PV technology	Efficiency (%)	Market Share (%)
1st generation	20	90
2nd generation	5-12	10
3rd generation	40-50	--

Table 5. Efficiency versus market of the 3 different PV technology generations.

The basic element in PV technology is the photovoltaic/solar panel/module which is composed of photovoltaic cells connected in parallel, when photogenerated current must be enhanced, or placed in series, when the output voltage is the parameter that needs to be maximized (see chapter 10: "Electronics for Power and Energy Management").

The working principle of a photovoltaic cell is based on the photovoltaic effect, which was firstly described by Alexander-Edmond Becquerel in 1839. As it is reviewed in chapter 3 about Solar Energy Harvesting, the photovoltaic effect has the same quantum nature as the photoelectric effect, so both can only be described by considering that the energy of the electromagnetic radiation is quantized in quanta called photons, with an energy hν, as it has been explained before (equation 2). As it is shown in figure 3.a, photovoltaic effect takes place at the core of the cell, which is found at the junction of the two semiconductors that integrates a typical PV cell. When an individual photon interact with an individual electron at the valence band of the semiconductor, the energy of the photon (and the photon itself) can be absorbed by the electron to get promoted to the conduction band, leaving a hole in the valence band. This process called, photo-generation of an electron-hole pair, is only possible if the photon energy is at least equal to the energy of the band-gap (energy distance between the conduction and valence band). The population of photogenerated electrons and holes is then driven by the electrical field in the depletion zone of the PN junction and can eventually contribute to a photovoltage and the corresponding photocurrent, when an electric load is connected to the PV cell. In this case, both the photovoltage and the photocurrent are *dc* magnitudes and their product gives directly the electrical power converted by the PV cell.
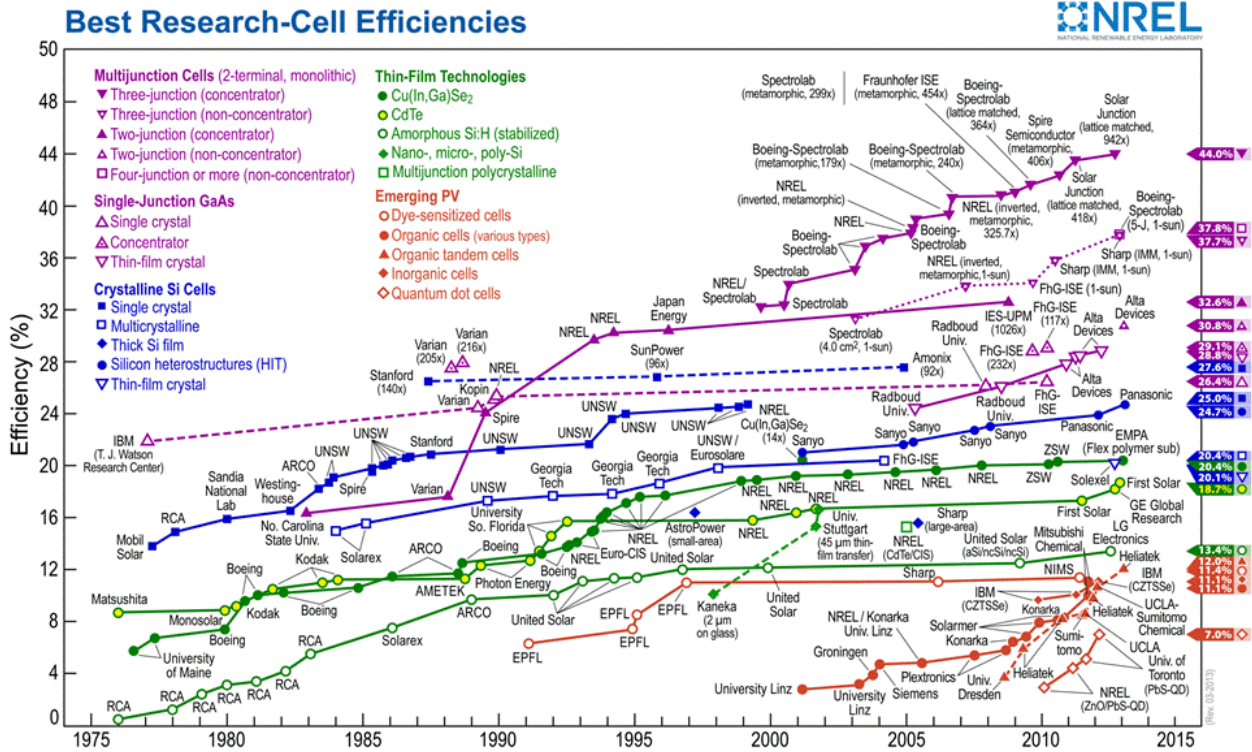
Figure 2. Efficiency evolution of the main photovoltaic technologies (from *National Renewable Energy Laboratory*).

Instead, the radiofrequency rectenna (RFR) technology is based on the combined operation of two basic elements: an electrical rectifier that follows an electromagnetic antenna (rectenna). The operation principle (figure 3.b) does not require quantum mechanics to be explained since, in this case, electrons in the metallic antenna are already in the conduction band, and do not need to be promoted in energy by absorbing photons from the electromagnetic radiation. In this case, the phenomenology is better explained by the interaction between the electrons in the antenna and the electric field of an electromagnetic incident wave. Similarly to PV technology, in rectenna technology matching conditions must be also satisfied. Now, the wavelength of the EM incident wave has to be a multiple of the antenna characteristic length in order to induce a resonant electrical current in the antenna. As opposite to a PV cell, an antenna will generate at its output both an *ac* voltage and an *ac* current. For this reason, a rectifier is needed as the first basic electrical component to transform *ac* values into *dc* values.

Optical rectenna (OR) technology can be considered as a particular case of rectenna technology where the frequency of the electromagnetic radiation involved is in the optical range. So, from this point of view, RFR technology covers the radiofrequency part of the electromagnetic spectrum and OR the optical part (figure 4). However, as it will be described in a next section of this chapter, OR technology cannot be considered just as an extrapolation of the RF rectenna concept to the optical range, since neither the antenna element, in this case a nanoantenna, nor the rectifier, typically a metal-insulator-metal (MIM) diode, have exactly the same properties of the RF counterparts. New physics such as plasmon resonances have to be taken into account

in the optical antenna (OA), an antenna with characteristic lengths in the nanometer range (nanoantenna) to match the wavelengths of light radiation. Also special structures and materials are needed to achieve response times short enough to rectify signals in the THz range, which are induced in the nanoantenna element by the incident optical radiation.
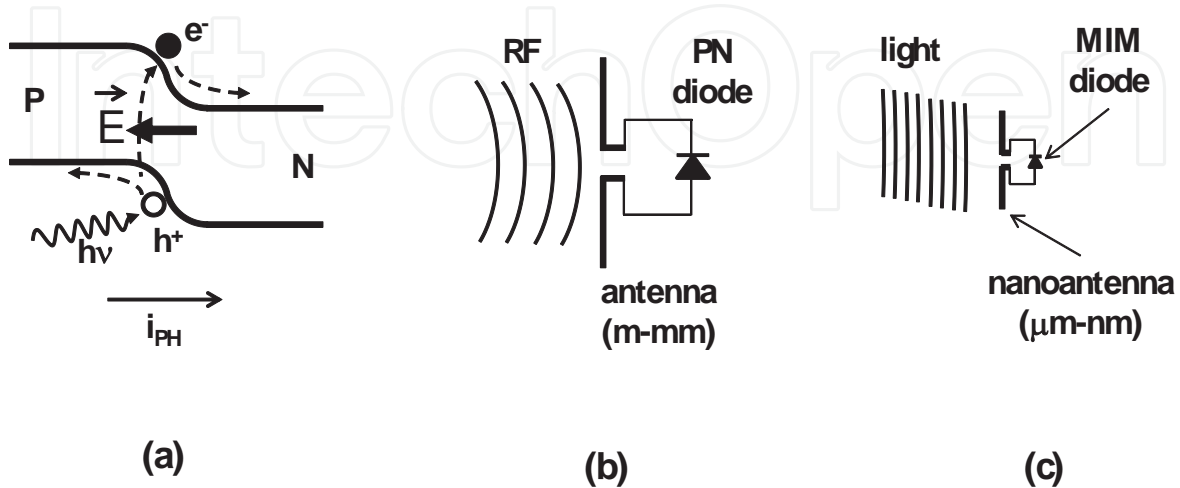

Figure 3. Scheme of the operation principle of three different technologies used to harvest energy from the electromagnetic spectrum. (a) Photovoltaic technology (PV), (b) radiofrequency rectenna technology (RFR) and (c) optical rectenna technology (OR).
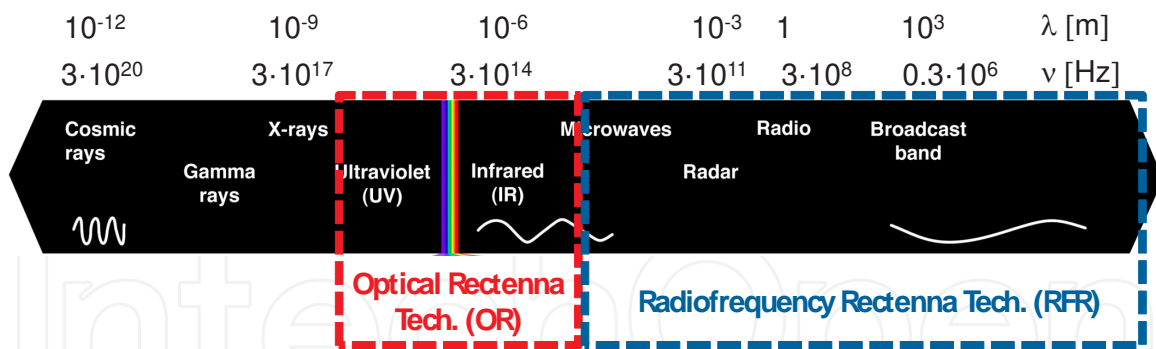

Figure 4. Spectral range coverage of the RF and optical rectenna technologies.

When used as light detectors, optical antennas involving rectifiers perform quite well in several specifications, especially in those related with their intrinsic electromagnetic nature. Table 6 shows these figures for a few technologies working in the visible and the infrared. We may already see in this table that the responsivity of optical antennas is lower than the rest of technologies. This figure is in accordance with the low efficiency of rectennas that has been observed in actual experiments involving MIM, or Metal-Insulator-Insulator-Metal (MIIM), junctions as transducers. Summarizing this table we may say that optical antennas are point detectors, very fast, work at room temperature, can be integrated with some other elements

and devices (for example with focusing optics), and they present a broad tuneability, and a remarkable selectivity in direction and polarization.

	Visible CCD/ CMOS	MIM Junctions	Avalanche Photodetectors	Pyroelectric Detectors	Bolometric Detectors	Optical Antennas
Size	$10^2\lambda^2$	$10^2\lambda^2$	$10^2\lambda^2$	10^1-$10^2\lambda^2$	10^1-$10^2\lambda^2$	10^{-2}-$10^0\lambda^2$
Polarization selective, directivity, tuneability	No	No	No	No	No	Yes
Cooling	Better performance	No	Better performance	No	No	No
Responsivity	10^3-10^4 V/W	0,7-0,9 A/W	0.7 A/W	10^3-10^4 V/W	10^3-10^4 V/W	0.1 V/W
Time response	100 ns	10 ps	9 ps	400 µs	400 µs	1 ps

Table 6. Four different photodetection mechanisms are compared with optical antennas technology.

Nowadays, space in urban areas, including work and home environments is strongly packed with EM radioelectric waves at various bands and spectral regions: besides the ubiquitous presence of radio and TV bands, cell phones and personal communications devices, a myriad of wi-fi stations, Bluetooth gadgets, and remote emitters and detectors produce a non-negligible amount of EM energy flowing around us. Then, from a harvesting point of view this energy could be recycled and properly used by electronic systems with ultra-low power requirements. This strategy may work in those environments with strong RF signals, where signal-to-noise ratio of other operative elements is not compromised. This idea of RF and microwave recycling has been developed some time ago in the form of antenna arrays and half or full wave rectifiers. Optical rectennas can be seen as an evolution and transposition of those designs and devices already working in the microwave region. In this band some designs have demonstrated more than 75% of efficiency when used for power transmission [8]. These figures are reduced when considering broad-band antennas designed to recycle microwave energy from ambient background.

Unfortunately, so far the efficiency number obtained at those frequencies have not been replicated at infrared or visible frequencies. The reasons are mostly derived from the inherent behaviour of materials when frequency increases. Besides, the difficulties of designing THz electronics and oscillators, metals begin to behave as dispersive materials and the currents built on their surface penetrates within the structure.

In order to place the reader in a position to make an educated guess on the different technologies we present here a brief comparison among the photovoltaics, radiofrequency rectifiers, and optical rectennas (optical antennas coupled to rectifiers)

Photovoltaics: Direct conversion of light into electric power using the photovoltaic effect exhibited by semiconductor materials.

- Efficiency: The theoretical limit is around 41% for single junction solar cells, and reaches 87% for multiple junctions.

- Pros: Well established and mature technology. Fabrication issues have been solved due to the intrinsic relation with semiconductor technology.

- Cons: The performance is strongly dependent on temperature, especially for multiple junction cells.

Radiofrequency Rectifiers: Direct conversion of light into electricity using a rectifier working at radio or microwave frequencies.

- Efficiency: The limit is set around 85%. Practical devices have been demonstrated with an efficiency larger than 75%.

- Pros: Well known basic mechanism of rectification. Fabrication can be made using standard photolithography on dielectric substrates.

- Cons: Polarization and spectral selectivity.

Optical Rectennas: Direct conversion of light into electricity using rectifiers working at optical frequencies.

- Efficiency: The theoretical limit is around 85%.

- Pros: Antenna theory and its scaling to optical frequencies is known and antenna-coupled detectors have been demonstrated in the infrared and the visible. Minimum size of about λ^2, allowing very high packaging. No dependence with temperature. Metals are used for fabrication with some advances in the use of conducting graphene.

- Cons: The efficiency of working devices is well below 85%. Barrier rectifiers are not able to follow optical frequencies and behave as square law rectifiers. Further advances are needed to have feasible rectifying mechanisms. Nano-fabrication technologies are necessary (nano-imprint could solve large scale fabrication numbers).

1.3. Historical overview of wireless power transmission

The precedents of the rectenna technology are found in the first attempts to transmit power through radio waves. The early history of RF power transmission dates from the experiments of Heinrich Hertz (1857-1894). Hertz was the first to rigorously prove the existence of electro-magnetic waves. The experiments carried out for this purpose (figure 5) were based on transmitters and receivers of radio pulses that were combined with reflectors to create standing waves between the emitter and the receiver. In such experiments, *dc* power was converted to UHF radio waves by means of an LC oscillator connected to a device called *spark gap*. The emitted UHF EM wave from the dipole antenna was directed to the receiving antenna, an open loop ring with also a spark gap, by means of a parabolic reflector. When the emitted wave impinged on the receiving loop, a current was induced and a spark was produced. Hertz was

in this way able to verify experimentally the existence and propagation in free space of EM radiated waves and to measure that such propagation is produced at the velocity of light.
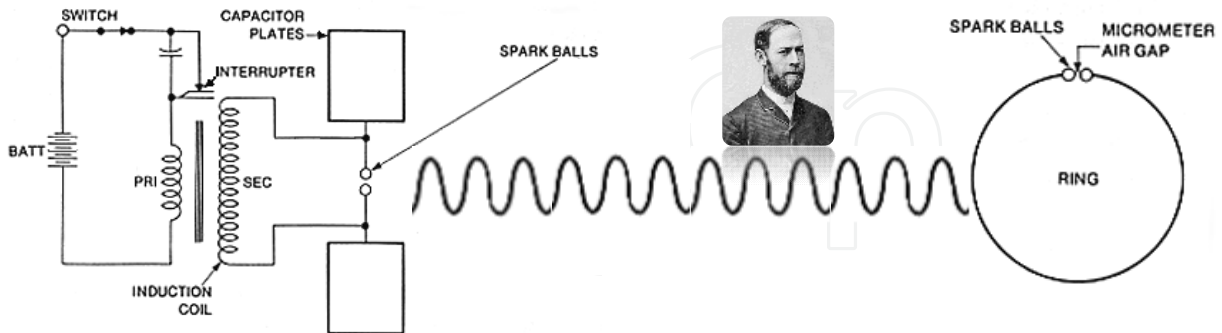

Figure 5. Scheme of the experiments carried out in 1887 by Heinrich Hertz to demonstrate the existence and propagation of electromagnetic waves in free space.

It was some years later, at the turn of the century, that Nikola Tesla (1856-1943) became interested in transmitting electrical power from one point to another wirelessly. Several famous attempts are described elsewhere. In the first one, which was carried out in 1899 at the Colorado Springs Laboratory, an approximately 60 m mast antenna with a 1 m diameter copper ball on top was built. An enormous coil that was fed with 300kW of electrical power got in resonance at a frequency of 150 kHz. When this coil was connected to the mast antenna, an RF potential of 100 MV with respect to the Earth was produced. The only record from this attempt were the discharges from the sphere to ground (figure 6 left), but no data about the power radiated and the power collected at a certain point were reported.
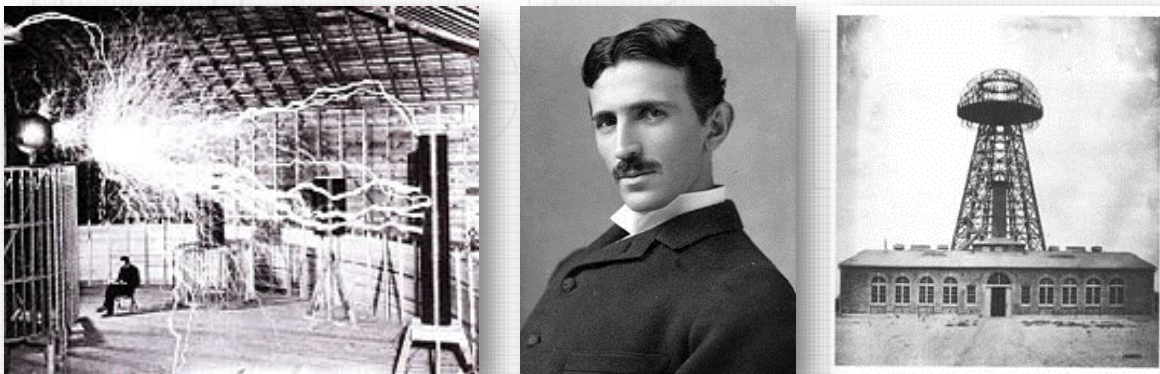

Figure 6. Pictures of the Colorado Spring Laboratory experiments (left), Nikola Tesla (center) and Wardenclyffe plant (right).

Starting in 1901, a similar frustrated attempt to transmit power wirelessly was performed by Tesla in the Wardenclyffe plant at Long Island (figure 6 right), New York. In this occasion, a wooden tower 46 m tall was built to place a 30 m in diameter doughnut-like copper electrode. With this giant installation, Tesla wanted to transmit electrical power across the Atlantic, from the USA east coast to Great Britain. In 1914 the tower was demolished after Tesla lost funding to continue this project.

During the 1930's decade, less ambitious and more controlled experiments performed in the Westinghouse Laboratory led H.V. Noble to successfully transfer hundred watts of power between two 100 MHz dipoles placed 1.5m apart.

A retrospective analysis shows that the initial Teslas's failures and the lack of a clear demonstration of wireless power transfer during the first half of the past century is because power transfer starts to be efficient at the microwave range and above in frequency. At that time the technology to generate power in this wavelength range was not developed enough. It was not until the development of the klystron and the magnetron, combined with the end of the World War II that power transfer technology could start to be notably unfolded. A detailed description of this ramp-up period of the modern history of wireless power transfer is done by one of the most prominent protagonists, William C. Brown [9]. Brown is famous by the invention of the crossed-field amplifier, also known as *Amplitron*, but he can be also considered as the pioneer of the microwave power transmission and the first in developing a rectenna. Most of Brown's achievements were carried out at the Raytheon Company and at the Jet Propulsion Laboratory (NASA), and were mainly driven by two applications respectively: the Raytheon Airborne Microwave Platform (RAMP), a microwave-powered helicopter and the solar-power satellite (SPS), with microwave power transfer to the Earth. The requirements demanded by both applications gave rise to the development of the Amplitron and the first rectenna, as solutions to the generation of high Continuous-Wave (CW) powers of microwaves to be transmitted and to the direct conversion of the received microwaves into *dc* power, in order to drive the motors of the helicopter rotor blades. Thus, in 1964, the first flight of a helicopter prototype was demonstrated. It was propelled by the 270W *dc* provided by a 1.4 kg array-like rectenna integrated by 4480 1N82G semiconductor diodes in a 0.4 m^2 area, which corresponded to a power to mass ratio of 5 kg/kW. Eight years later, in 1968, the improvements introduced by the use of Schottky diodes produced an enhancement of this ratio of one order of magnitude. Finally, in 1983, the introduction of the thin film etched-circuit rectenna technology made possible *dc* to *dc* efficiencies of 85% and power to mass ratios of 1kW/kg.

Further advances in the wireless power transfer technology have been made during the last part of the past century and the beginning of the present one. As a consequence of this last evolution, a company called WiTricity Corp. and a technology called passive Radio Frequency IDentification (RFID) have become the two most meaningful examples of successful application of wireless power transfer.

WiTricity Corp. was born in 2007 to commercialize the applications of a technology developed at Massachussetts Institute of Technology (MIT) by Professor Marin Soljačić and co-workers [10]. The operation principle of this technology is based in the non-radiative power transfer between two self-resonant coils operating in the strong coupling regime.
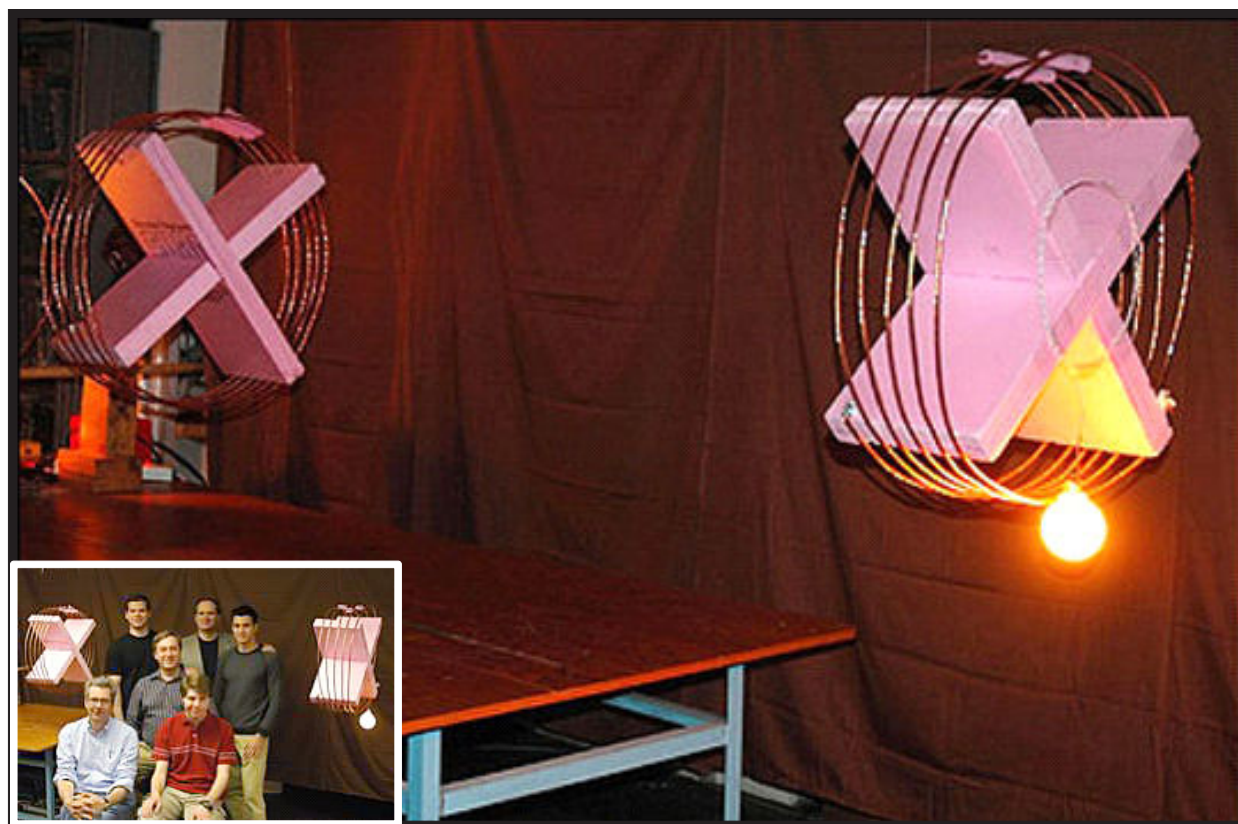
Figure 7. Picture (top) and scheme (bottom) of the WiTricity concept experimental setup. In the inset, the team of Prof. Soljačić at MIT is placed between both coils during operation, trying to demonstrate that the technology is harmless.

In figure 7, the setup used to demonstrate the WiTricity concept is shown. A single loop, A, connected to a sinusoidal signal generator is magnetically coupled to a secondary 5-turns emitter copper coil 60 cm in diameter. An identical receiver coil is coaxially placed at a 2m difference from the emitter, and also coupled capacitivelly to a secondary single loop connected to a 60W bulb load. The system, which is designed to resonate at 9.9 MHz, transfers the 60W of power needed to light the bulb with an efficiency of around 45%. At a shorter distance of 3 ft, the 60W are transferred with an efficiency of 90%.

Finally, RFID technology is also drawing on wireless power transfer technology [11]. In the active RFID variant, the RFID transponder, also called "tag", get the energy from a battery to supply its Application-Specific Integrated Circuit (ASIC). By contrast, in a passive RFID technology, the voltage generated in the tag antenna by the transmitted RF signal during the periods of unmodulated carrier is converted to a dc voltage. This voltage is used to power up the active ASIC chip circuitry which controls the input impedance of its front end. Communication between the base station (RFID reader) and the active tag is based on the modulation of the back-scattered signal produced by the toggle of the input front end impedance between two states (figure 8).
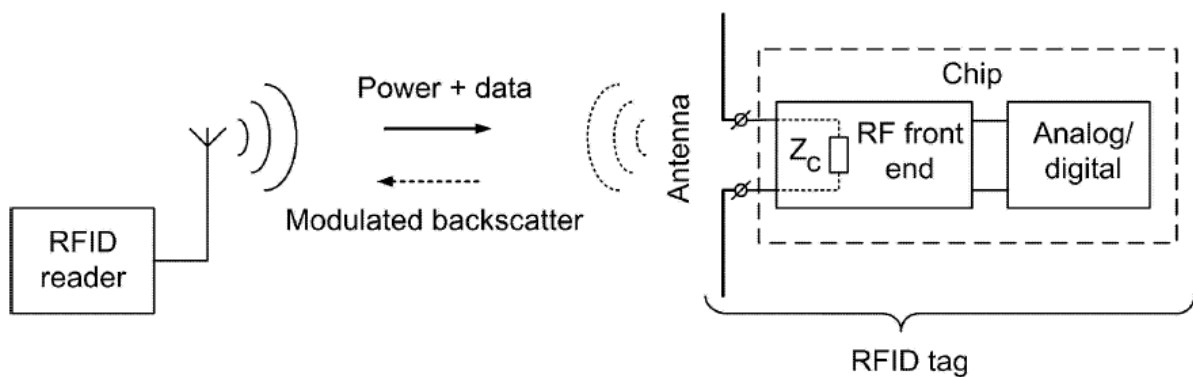

Figure 8. Scheme of an RFID system. When RFID is passive, the power transmitted by the reader during the unmodulated periods is converted in a dc power at the input of a passive circuitry of the tag to supply the rest of the active chip [11].

2. Electromagnetic radiation energy harvesting. The rectenna approach

As it has been pointed out above, a rectenna is the basic element of the RF and optical rectenna technologies. It basically consists (figure 9) of an antenna, in charge of efficiently collecting the energy emitted from a radiative source in the EM spectrum, and a diode, in charge of rectifying the *ac* voltage induced at the antenna terminals by the EM radiation. Eventually, a low pass filter follows the diode in order to obtain a *dc* voltage from the rectified signal. Usually, a *dc-dc* converter is also needed to adapt the voltage levels of the filter output with the level required by the application, represented in figure 9 by its equivalent load. As in most of the energy harvesters, control electronics will manage the flow of energy from the *dc-dc* converter to the application load or to a storage device, usually a battery, depending on whether the energy harvested by the rectenna can satisfy the application demand or, instead, it is better to store the harvested energy until the load demand could be satisfied.
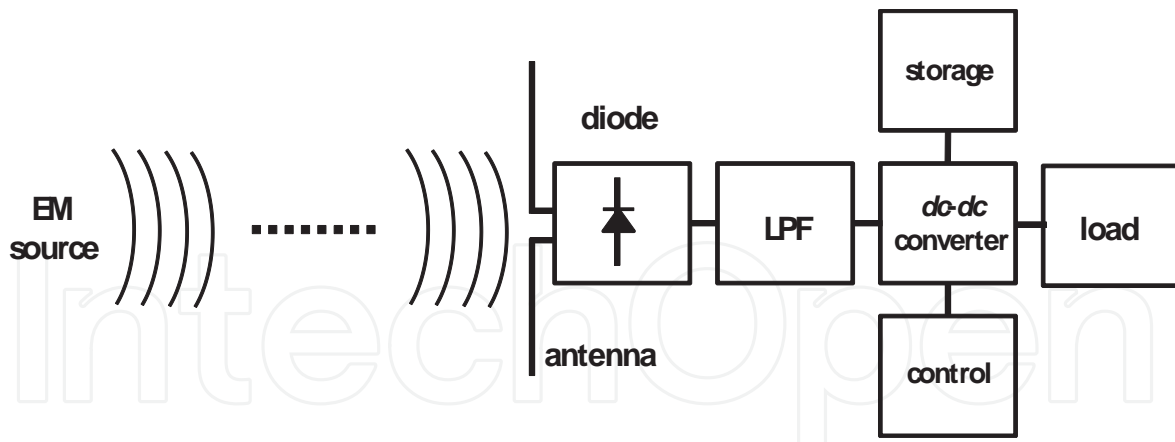
Figure 9. Block diagram of a rectenna.

The core of the rectenna, i.e. the antenna and the rectifier, can be replicated in an array configuration in order to improve the collection efficiency. Thus, a 2D array of identical rectenna elements can be connected in series or in parallel to increase the effective collection area and to increase the output voltage or the output current respectively [12]. Another 2D array configuration strategy is based on combining rectenna elements with different characteristics in order to match the different wavelengths of an EM sources set.

2.1. The antenna as transducer element

An antenna is a device made to transmit and/or receive EM waves. By converting an electric current into an electromagnetic field on one end and converting this EM field into a voltage on the other, a pair of antennas gives the capability of making a wireless link between two points.

The most important parameters of a transmitter antenna are described below:

• Impedance: given the fact that the antenna must be connected to a transmitter, through a transmission line, and radiate the maximum amount of power with the lowest losses, the impedance of the transmitter, the transmission line and the antenna must be the same. The antenna itself introduces losses in the system, normally ohmic. In almost all the EM antennas the input impedance can be computed as the sum of the losses (R_Ω) and the radiation (R_r) resistance

$$Z_{in} = R_r + R_\Omega \tag{8}$$

The total delivered power to the antenna should then be calculated as:

$$P_T = P_r + P_\Omega = I_{in} \cdot R_r + I_{in} \cdot R_\Omega \tag{9}$$

- Efficiency: given the losses and radiation resistances the efficiency of an antenna can be computed as

$$\eta_e = \frac{R_r}{R_r + R_\Omega} \tag{10}$$

- Directivity: the directivity of an antenna is defined as the relation between the radiated power density in one particular direction and the radiated power density which would radiate an isotropic antenna emitting the same power.

- Radiation pattern: the radiation pattern of an antenna describes the relative field strength of the radiated EM waves in all the directions from the antenna, at a fixed distance. For directional antennas the radiation pattern shows that there is a particular direction on which the antenna emits more efficiently. For omnidirectional antennas the radiation patter is almost equal for all directions.

- Gain: compared to an isotropic radiator, which will equally distribute the radiated power in all directions, real antennas with either a directional or omnidirectional radiation pattern will radiate less power in some directions and more in others. Therefore it can be considered that there is a gain between the different radiation directions. This gain can be defined as the ratio between the transmitted signal strength value at the more efficient direction and the value using a reference antenna. If the reference antenna is an isotopic source the used units will be dBi.

- Polarization: the polarization of an antenna is defined as the orientation plane in which the radiated or absorbed electric field vibrates with respect to a reference plane, for example the Earth's surface. It is determined by the physical construction of the antenna and its orientation, especially by its radiating element. The most common polarizations are linear and circular, which are particular cases of elliptical polarization. In the first one, the electric field vector stays in the same plane whereas for the second one it appears to be rotating with a circular motion around the direction of propagation.

- Bandwidth: most of the EM antennas operate efficiently over a relatively narrow frequency span due to their geometry. As a consequence, they must be tuned in order to have the same frequency band operation as the electronic system at which they are connected.

The most important parameter of a receiver antenna is

- The effective area: an antenna extracts power from the wavefront of an EM wave, thus it represents a certain capture area or effective area. This area is defined as the relation between the power delivered to the receiver circuitry and the power density of the incident wave.

Additionally, antennas comply with the law of reciprocity. This law states that given two identical antennas placed at some distance, each of them can be operated either as a transmitting antenna or as a receiving antenna. Suppose that the one working as a receiver is kept intact, while the performance is modified so that, for a fixed amount of radiated power, the signal

received by the other antenna changes by a factor. If the same modified antenna is used for receiving the transmitted signal by the unmodified one, its performance will also be changed by the same factor. This theorem can be formally derived from Maxwell's equations and its validity can be easily verified.

As a consequence of this law, all the previous described antenna characteristics (efficiency, radiation pattern, gain, polarization, bandwidth and effective area) are the same whether the antenna takes part in a transmitter or a receiver scheme. Besides, when designing optical antennas, this reciprocity law is used to simplify the calculation, for example, when calculating the radiation/receiving patterns and some other important parameters of the antenna.

The simplest designs of radiofrequency antennas are developed as wires or loops of conductors properly arranged and connected to an electronic element to produce and detect electromagnetic radiation with a wavelength scaled to the size of the antenna. An important step forward was made when planar structures used the resonant properties of metal patches and planar strips. These could be fabricated using photolithography in a very similar manner as it was done with printed circuits. When the frequency increases the resolution of manufacturing techniques also increases to produce thinner and finer structures. Then, when moving to terahertzs and infrared frequencies only nanofabrication techniques are suitable to realize those antennas. The reasons are twofold. On the one hand is the shrinking of the wavelength towards the nanometric scale, and on the other hand the quality of the finishing elements in terms of roughness and surface smoothness, which may interact with the currents and scatter the charge carriers around non useful directions. These nanophotonic devices are still considered as antennas because they can produce or detect electromagnetic radiation using wires or resonant patches. In a simple manner, optical antennas are defined as resonant structures able to produce an electric signal related with the incident optical radiation.

At the same time, taking into account the re-emission of electromagnetic radiation by resonant structures, it is possible to define a new kind of element that changes the properties of the light that interacts with it. We will name these elements as belonging to the "resonant optics" area. Conventional, reflective or refractive, and diffractive optics relies on the geometrical and wave models of light. Then, resonant optics uses the electromagnetic interaction of light waves with geometrical structures, typically fabricated with conductors, which work building currents up. They have been used as frequency selective surfaces, polarization elements, or phase shaping devices. Some of the designs are scaled versions of their microwave counterparts, where they were first demonstrated. In the recent past we have seen a growing number of scientific contributions where these elements are analyzed and exploited for a variety of applications. At the same time, they have been denoted with different names, mainly depending on the origin of the research teams that develop them: metamaterial surfaces, flat optics, 2.5D photonic crystals, etc.

Both optical antennas and resonant structures are determined by geometry and material parameters. Geometry mostly drives the polarization and spectral selectivity. Intrinsically, the size of the antenna is related with the wavelength. Therefore, when considering infrared and optical radiation, optical antennas become, by nature, nanophotonic devices. For example, a dipole antenna has a length of a few microns for far infrared radiation, and a few hundreds of

nanometers for visible light. At the same time, the width of the dipole is limited by fabrication constrains and can be as narrow as a few tens of nanometers. Consequently, the area of detection of the incoming radiation, which extends a little farther from the antenna itself, is about l^2, depending on the geometry of the antenna. The far-field pattern of optical antennas resembles that of their radiofrequency counterparts.

Also, as it happens with planar antennas written on dielectric substrates, the responsivity of optical antennas is larger when light is incident from the substrate side than when it is incident from the air, mostly because of the larger electric permittivity of the substrate. The ratio between the power radiated, or received, by an antenna located between two media of electric permitivities ε_1 and ε_2 is [13,14]

$$\Gamma = \frac{P_1}{P_2} = \left(\frac{\varepsilon_1}{\varepsilon_2}\right)^{3/2} \tag{11}$$

Besides, the effective wavelength at which the resonance takes place moves because of this situation. This effective wavelength is given classically as

$$\lambda_{eff} = \frac{\lambda_0}{\sqrt{\frac{\varepsilon_1 + \varepsilon_2}{2}}} \tag{12}$$

and when considering the plasmon resonances as

$$\lambda_{eff} = n_1 + n_2 \frac{\lambda_0}{\lambda_p} \tag{13}$$

where n_1 and n_2 depend on the geometry and material parameters, and λp is the wavelength of the plasmon resonance [15]. This equation already shows the influence of the material parameters in the performance of optical antennas. At the infrared and visible frequencies metals are no longer perfect conductors and behave as dispersive materials [16]. This means that the radiation losses increase and the surface currents penetrate deeper within the materials. However, metals also present interesting phenomena at optical frequencies. The optical radiation can excite the collective resonance of the charge carriers. They now, oscillate as a unique particle that is named as plasmon. The plasmonic resonances have been devoted increased attention along the past years, producing a myriad of papers and novel applications. In the area of optical antennas, plasmons play an important role because of their occurrence at optical frequencies.

Although in this chapter we focus our attention on optical antennas, we have to mention the important role that resonant structures may play in the improvement of photovoltaic solar cells. It is known that when populating a surface with metal nano-structures, the interaction of light with the structure changes. If the surface is that one of a solar cell, photons can be scattered by the resonant structures and the optical path within the material is enlarged. Also the enhancement of the electric field near the nano-structures may increase absorption, or

directly, those photoexcited electrons can be injected into the cell, contributing to the total current delivered by the cell [17]. Some advances have been made reporting 50% increase of the transmittance of the surface using plasmonic nanoparticles [18]. This path is quite promising for improving the performance of traditional photovoltaic cells.

2.2. Rectifying devices and technologies

Rectification is commonly performed by p-n junction diodes when RF radiation is in the kHz-MHz low frequency range. However, when operation frequencies are in the GHz-THz range, semiconductors and devices with shorter transit times and lower intrinsic capacitances like GaAs Schottky diodes are needed. Typical maximum operation frequency of Schottky diodes is 5 THz and although theoretical efficiencies approach 90%, only values of just around 50% have been demonstrated experimentally.

In most common rectifying situations, which correspond to low frequency and high power conditions (LFHP), diodes produce a half-wave rectification with an efficiency given by

$$\eta_{LFHP} = \frac{1}{1 + \frac{v_D}{2v_{dc}}} \tag{14}$$

where v_D and v_{dc} are respectively the voltage drop across the diode and the output rectified *dc* voltage.

However, in the opposite conditions of high frequency and low power (HFLP), which corresponds to those of RF signals to be harvested by a rectenna, rectification is much more complex Since: first the incident power is not only low but fluctuant in value and, second, because matching of the antenna and the diode is an issue. Consequently, the power at the output of the rectenna, P_{dc}, will be obtained from the incident RF power, P_{RF}, by

$$P_{dc} = P_{RF} \cdot \eta_{HFLP}(P_{RF}, \rho) \tag{15}$$

where the rectification efficiency, η_{HFLP}, depends explicitly on P_{RF} and on the antenna to diode matching ρ. This explicit dependence cannot be described analytically with a closed expression like in the LFHP case and the problem of P_{dc} prediction has to be solved by simulation. Time-domain analysis has been successfully applied to address this problem for single frequency or narrow-band rectenna applications [19]. However, a frequency-domain approach based on the harmonic balance (HB) method is more appropriated for wide-band applications [12], where some characteristics of the diode as the nonlinearity of its capacitance, the reflected harmonic energy at input/output or the self-biasing effects start to be relevant.

In the case of optical antennas, they work by combining the effect of two physical mechanisms. One of them is the coupling of the optical radiation to the device. This task is in charge of the metal structure. The other is the transduction mechanism used to provide the output signal. So far, two main types of transducers have been demonstrated. The bolometric response of the material is used to produce a change in the voltage measured from the device. However, this

mechanism is dissipative and it does not provide a positive balance of power, and therefore it is not useful for harvesting applications, at least directly. As an interesting outcome of the Joule dissipation we find that when incorporating resonant elements to thermoelectric pairs, the combination of localized heating and the Seebeck effect can be of use to produce electric power [20,21]. The other mechanism is the rectification of currents using a diode. This is the case implemented in rectennas. Metal-Insulator-Metal (MIM), and Metal-Insulator-Insulator-Metal (MIIM) have been demonstrated as effective diodes from the microwave to the visible wave ranges [22, 23, 24, 25]. Typical MIM materials are Cr/CrO$_x$/Au, Nb/NbO$_x$/Nb or Al/AlOx/Pt, and state of the art MIM diodes can operate at frequencies up to 150 THz. These junctions work as square-law rectifiers. The rectified current is given as

$$I_{DC} = \gamma \; \frac{|V_{diode}|^2}{4R_{diode}}$$

(16)

where γ represents the non-linearity of the current-voltage curve of the device. Non-linearity, γ, which is defined from the i-v diode characteristic as $\gamma \equiv (d^2i/dv^2)/(di/dv)$, should be at least 3 or larger to start getting reasonable values of conversion efficiency. Figure 10 shows the line transmission schematics of the antenna-diode element. When optimizing this structure for maximum efficiency the impedance of the antenna has to compensate the impedance of the load (the diode). This means that the antenna has to present an imaginary part of the impedance that is not typically included when maximizing the performance.
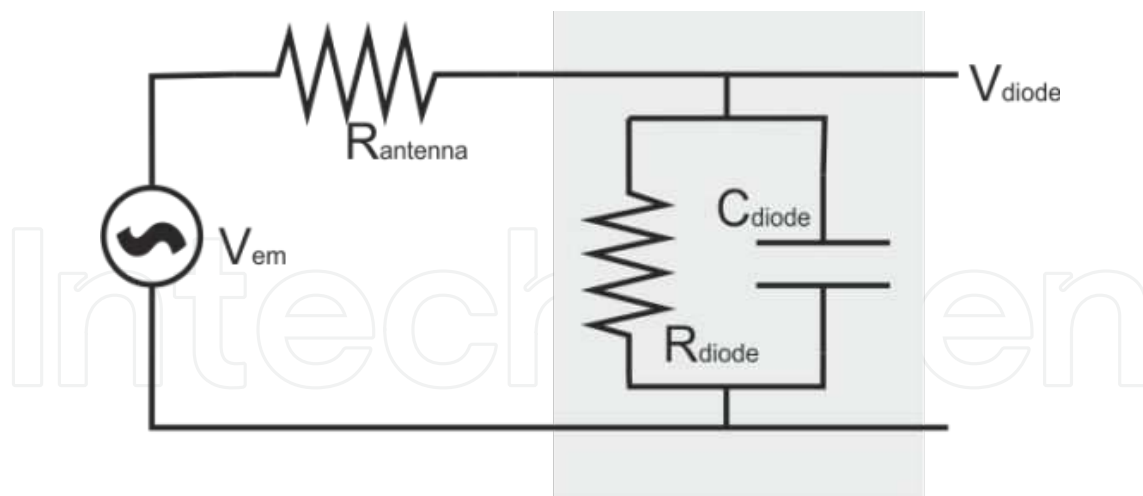

Figure 10. Transmission line schematics of a diode coupled to an antenna. The antenna is considered as having an impedance of R$_{antenna}$.

On the other hand, the cut-off frequency of the element is given as

$$f_{cutoff} = \frac{1}{2\pi RC}$$

(17)

where the RC constant should be smaller than 10^{-14} s^{-1} to reach the infrared and optical regions. The junction itself works as a capacitor. To reduce its capacitance we cannot increase the thickness of the junction because in that case tunnelling would be not possible. Because of that, it has a thickness of about 2-3 nm, depending on the insulator. Therefore, in order to have a low capacitance the junction area should be small. On the other hand, to efficiently transfer the power to the load, the impedance mismatch should be corrected. These issues are being addressed in several ways and some promising results have been already published [26,27]. However, when combining MIM diodes with antennas, the conversion efficiency given as the ratio between the power obtained after rectification and the incident power is quite low for these square law rectifiers [28]. The values for this efficiency is lower than 10^{-6}, showing that some better rectifying technologies need to be developed before practical devices based on direct rectification of light, become competitive against other solar energy harvesters. In Figure 11 we show the response of an optical antenna placed in front of a black body at 1000°K, demonstrating the existence of an output signal for this extreme condition.

Figure 11. Response of an optical antenna located on the image of a blackbody radiator at 1000°K. This image was obtained by a relay optical system fabricated in ZnSe and having an F/# equal to 1 [29].

A modification of the traditional MIM diode, the travelling-wave metal-insulator-metal diode (TW-MIM), allows obtaining a quantum efficiency of 3.6% in the IR region [30]. The TW-MIM is based on the rectification of the surface plasmon excited by the antenna on a plasmonic waveguide.

Some interesting advances in rectification at terahertz and quasi-optical frequencies have been proposed using a novel approach. The geometric rectifier (see Figure 12) has been demonstrated at GHz frequencies [31]. Here the rectification is given by deflecting the trajectories followed by the charge carriers through an asymmetric channel. The simplest case is an arrow shaped element that selectively directs charge carriers in a given direction, preventing the movement of those carriers towards the opposite direction [32]. These geometric rectifiers need materials and conditions where the carriers exhibit a free mean path longer, or much longer, than the size of the rectifying structure, i.e., a few hundreds of nanometers. Besides the electric properties of metals, exhibiting free mean paths in the range of a few tens of nanometers (for example for Au this parameter is around 20 nm), the conduction properties of graphene can be tailored to produce feasible devices having this effect [33].

Figure 12. Basic scheme of a geometric rectifier. The horizontal arms of a dipole antenna intersect at the feed point. This feed point is shaped as an asymmetric defect that deflects charge carriers towards the bottom of the geometric rectifier [34].

Also a device based on grapheme, the field effect transistor (G-FET) in common source configuration, can potentially be a promising candidate as rectifier component for optical rectennas. The extremely high mobility of graphene combined with the ambipolar transport properties would allow to implement full-wave rectification at THz in a single device [35].

Finally, two examples of RF rectenna (RFR) and optical rectenna (OR) from the literature are shown in figure 13 in order to compare dimensions and performances.
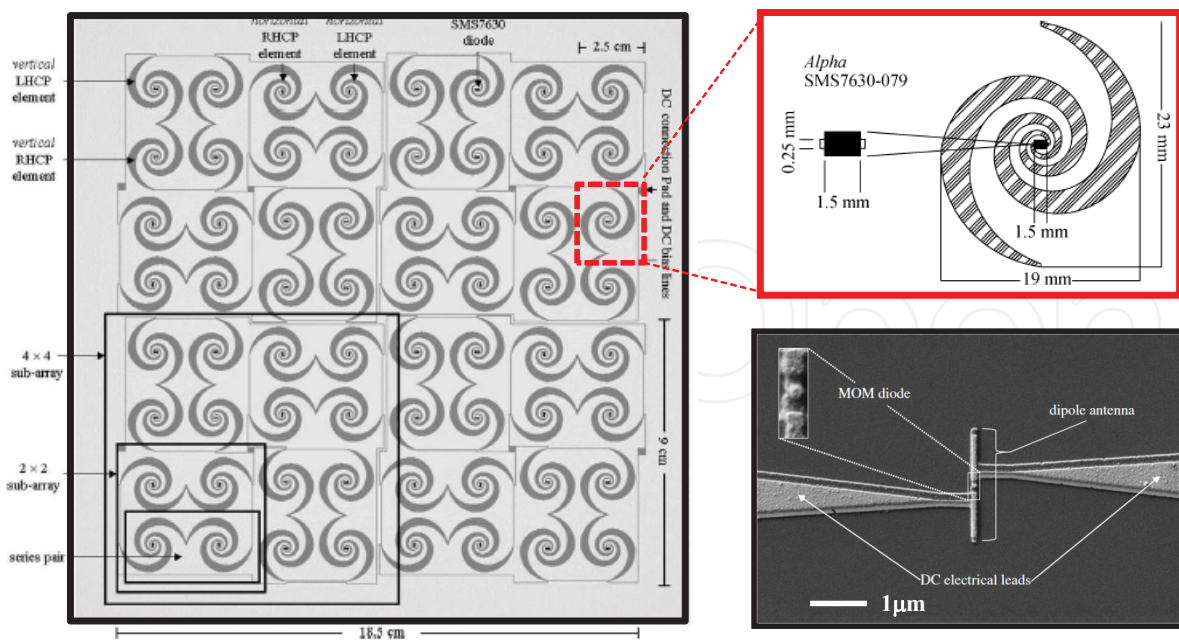
Figure 13. RF rectenna array (left) integrated by 64 single spiral rectennas (right top) [12]. Optical rectenna for the IR range consisting on a dipole coupled to a MOM diode (right bottom) [36].

The RF rectenna of figure 13 corresponds to a rectenna array configuration designed to operate in the 2-18 GHz region and for input power densities from 10 nW/cm^2 to 0.1 mW/cm^2. The spiral rectenna elements are distributed along the 324 cm^2 array area with different orientations in order to harvest energy from different polarized sources. So, considering an effective area of A_{eff}=25 cm^2, then input RF power will vary between P_{RF}=250 nW and P_{RF}=2.5 mW. If rectification efficiencies for such input powers results to be η(250nW)=1% and η(2.5mW)=20%, then the output *dc* power harvested by this array will theoretically vary between 2nW and 450 μW. Other examples of rectenna designs achieved efficiencies from 40-50% operating at 10^{-2} mW/cm^2 [37] to 80% at 10 mW/cm^2 [38].

By contrast, in the optical rectenna (figure 13 right bottom), designed to operate in the IR band, the 19x23 mm^2 area of the RF rectenna element is reduced to less than 1 μm^2. In this case, an Al/AlO$_x$/Pt MOM diode is chosen to implement the rectifier, which is coupled to a dipole 1 μm long nanoantenna. However, as it has pointed out above, the maximum conversion efficiency of 20% shown by the RF rectenna is reduced below 10^{-6} in optical rectennas like this one.

3. Conclusions

In this chapter, the most important concepts needed to understand how energy from the electromagnetic spectrum can be harvested by means of the rectenna technology have been introduced. Main differences with the well stablished photovoltaic approach have been analyzed and a comparative list of pros and cons has been provided. An historical overview

of the first works on wireless power transmission has been useful to understand the origin of the rectenna concept. The most relevant technical characteristics of both components of a rectenna, the antenna and the rectifier device, have been also decribed, and the specific features of each element have been explained for the readiofrequency and the optical range.

Acknowledgements

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