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Review of Infrared Nanoantennas for Energy Harvesting

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Abstract. The Sun is the greatest source of energy providing a continuous stream of power; its exploitation has stimulated several approaches and technologies to directly or indirectly achieve renewable energy. New devices, which exploit the thermal radiation created by the Sun, that is transferred in the form of electromagnetic waves into free space, and finally absorbed by the surface of the Earth, are under study. The aim of this contribution is to critically compare advantages and disadvantages of new types of suitable antennas operating at nanometers wavelengths, called nanoantennas, for infrared energy harvesting, focusing on the state of the art and its perspectives.

Key words
Nano-rectenna, Seebeck nanoantennas, infrared detection, energy harvesting.

1. Introduction

Nowadays, the worldwide demand for photovoltaic conversion (PV) is increasing every year and the industry's estimates suggest that, as much as 18 billion watts per year could ship by 2020. To meet this increasing demand, new technologies overcoming the drawbacks of the traditional PV conversion are expected. In truth, traditional PV sources suffer from the fact that photons charged with an energy equal to the band gap can only be efficiently harvested; moreover, they are strongly dependent on daylight, making them sensitive to the weather conditions [1-2]. The above-mentioned limits could be overcome by new devices, which exploit the thermal radiation created by the Sun transferred in the form of electromagnetic waves into free space, and finally absorbed by the surface of the Earth. Due to this radiation, the Earth's temperature rises and, as a consequence, electromagnetic radiations, classified as short-wave and long-wave infrared (LWIR), are reemitted. The reemitted LWIR radiation energy is an electromagnetic wave radiation at terahertz frequency that can be harvested by suitable antennas called nanoantennas, as they operate at nanometers wavelengths [3]. Nanoantennas, whose dimensions are in a range that goes from a few hundred nanometres to a few microns, have been only recently considered thanks to the development of electron beam lithography and similar techniques, which are able to assure the required level of miniaturization with the purposes of realization and demonstration. Actually, they exhibit potential advantages in terms of polarization, tunability, and rapid time response. Furthermore, the nanoscale dimensions, combined with the high electric field enhancement in the antenna gap, enable a small device footprint, making it compact enough to be monolithically integrated with electronics and auxiliary optics [4-5]. Similar to traditional RF antennas, nanoantennas capture the incident infrared electromagnetic wave causing an AC current onto the antenna surface, such that it oscillates at the same frequency of that wave. The movement of the electrons produces an alternating current in the antenna circuit. As the aim of these devices is to supply an external load, the AC current has to be rectified [6-7]. Two main types of rectifiers can be recognized: an ultrafast diode and a thermocouple that exploits Seebeck effect. The aim of this contribution is to critically compare advantages and disadvantages of new infrared nanoantennas for energy harvesting, focusing on the state of the art and its perspectives.

2. Infrared nano-rectennas

Since, as stated above, the nanoantenna output is an AC signal, a rectifying circuit is required. This circuit contains one or more diodes whose power loss and fast response can influence the whole device efficiency [8]. This nanoantenna, with its rectifier, is known as rectenna. The typical block diagram is shown in figure 1 [8-13].

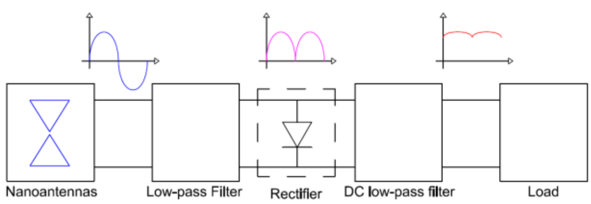

Fig.1: Block diagram of infrared nano-rectenna

Currently, several nanoantennas, e.g. the half wave dipole, bowtie antenna and spiral antenna, are under study. Once optimized, the conversion efficiency will be greater than PV devices.

A. Dipole Nano-antenna

A dipole nanoantenna consists of two rods, typically made of gold, placed together. They offer several advantages in terms of easy production, fine-tuning and high confinement of electric field in the gap [3, 5, 14]. Figure 2 shows a dipole nanoantenna.

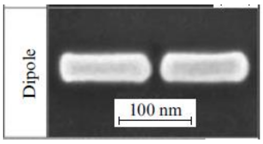

Fig.2: Dipole nanoantenna [5]

Different rectifiers coupled to dipole nanoantennas are used in order to obtain a DC signal [15-20]. The main ultra-high speed diode for rectification, which could operate at petahertz frequencies, is the Metal-Insulator-Metal diode (MIM diode). It is a thin film device that consists of a few-nanometers-thick insulator layer placed between two metal electrodes [8, 13]. This diode exploits the electron tunneling process through the insulator layer to rectify the AC signal. Furthermore, it has a carrier transit time on the order of femtosecond and can be easily integrated with the nanoantenna. It exhibits a large RC time constant and can work efficiently at low Terahertz frequencies. An example of a rectenna consisting of an IR dipole nanoantenna coupled to an MIM diode is in [17], where one end of both dipole's arms has been cut in order to build an MIM diode. The two arms of the dipole are then overlapped over an area of 50×50 nm^2, where an insulator layer of 8.5 nm-thick has been inserted within the gap region, figure 3.

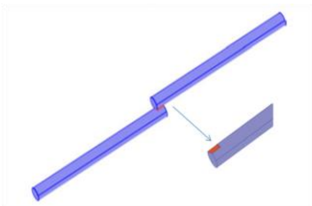

Fig.3: Dipole nanoantenna coupled MIM diode [17]

The MIM diode used in this system reveals a diode resistance R_D of about 100Ω and a cut-off frequency of 76.43 THz, so that this configuration is suitable to rectify the 10µm incident infrared wave [17]. To ensure that the rectification is based only on the tunneling effect, the insulator layer should be very thin, less than 4 nm. Therefore, it needs to have add another insulator layer otherwise it could be possible to employ a new type of rectifier, named travelling wave rectifier, consisting of an MIM plasmonic waveguides [18-20]. The antenna captures the electromagnetic wave that propagates through a transmission line rectifier and decays totally by the end of the transmission line. Two types of travelling wave MIM plasmonic waveguides are considered in [19]: vertical coupled strips (VCS) and lateral coupled strips (LCS) transmission lines. Figure 4 shows these types of infrared rectennas.

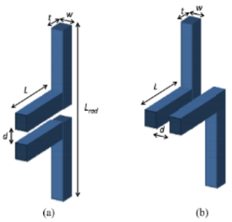

Fig.4: Dipole nanoantenna terminated by travelling wave MIM plasmonic waveguides: (a) vertical coupled strips, (b) lateral coupled strips [19]

These two metallic strips are placed on top of each other or beside each other. Their length is greater than the surface plasmon decay length at the minimum frequency of the band of interest. In this way, the travelling wave is attenuated along the line and there is not reflection at the open-circuit end of the line. Therefore, these transmission lines have the input impedence equal to their characteristic impedances. In order to obtain a dipole nanoantenna that resonates at 30 THz, its length should be optimized Moreover, the cross-section dimensions of the dipole's arms are fine-tuned to ensure best matching with the transmission lines. The antenna efficiency for nanodipole terminated by VCS and LCS is respectively 83.61% and 80.15%. The total efficiency, which is the product of antenna harvesting efficiency, matching efficiency and rectifier quantum efficiency, is nine order of magnitude higher for nanodipole terminated by VSC rectifier than that for nanodipole terminated by LSC rectifier [19-20].

B. Bowtie Nano-antenna

A bowtie nanoantenna consists of two triangles facing each other tip-to-tip with a gap in between. The electric field is typically concentrated in the gap [5]. The design of this configuration is very simple and allows broadband impedance. This type of nanoantenna offers several advantages due to the larger amount of metal used for its fabrication: broad bandwidth, lower confinement factor and greater dissipative losses. Moreover, this nanoantenna allows to build an array by coupling several bowtie elements in one configuration and to combine the electric field from each element at array feeding point, where a rectifier can be embedded [3, 8, 14]. Figure 5 shows a bowtie nanoantenna.

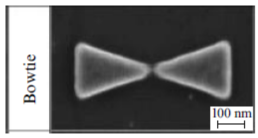

Fig.5: Bowtie nanoantenna [5]

To achieve an output DC signal, the bowtie nanoantenna is usually coupled with an ultra-fast rectifier [21-28]. The Metal-Oxide-Metal (MOM) tunnel diode is often used to rectify THz radiation. In particular the Ni-NiO-Ni MOM diode is usually employed because it is characterized by fast response time in mid-infrared measurements and it has a non-linear I-V characteristic. In order to obtain a conversion efficiency of harvesting system, a bowtie nanoantenna with misaligned arms made of different metals is realized [21]. The MOM diode is built between the misaligned arms. To increase the conversion efficiency other solutions are realized. They consist of bowtie coplanar slots with MOM diode building between hot and ground metallization of a coplanar waveguide. In this way, the DC power obtained is about 4.6 pW [22-23]. Figure 6 shows a bowtie nanoantenna coupled with MOM diode.

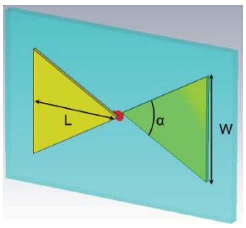

Fig.6: Bowtie nanoantenna coupled with MOM diode [21]

Another type of rectifier used in the rectenna system is a planar MIM diode formed by two crossed thin film metallic strips made of gold (Au) and copper (Cu) with a very thin copper oxide (CuO) in between them. This diode is integrated with bowtie nanoantennas whose arm is overlapped and the diode is realized in between this overlap. This configuration offers two main advantages: higher field enhancement due to the sharp bowtie tip and a path only available through the rectifier for the highly localized electromagnetic fields [24]. Best performances are obtained employing a sharp tip bowtie nanoantenna with $Au/Al_2O_3/Pt$ MIM diode due to the overlapping antenna arms and the utilization of different electrodes that produces a higher value of tunneling current [25]. It is possible to achieve some improvements increasing the work function difference between the two metal electrodes. So, the I-V characteristic becomes strongly non-linear and the contact area of the tunnelling junction is reduced; as a consequence, it is obtained a better impedance matching between antenna and diode. For this reason, sector bowtie nanoantenna coupled with $Au/TiO_x/Ti$ MIM diode is realized [26]. The choice of sector sharp instead of a traditional triangle is due to the fact that sector configuration can avoid the issue of sharp corners that exist in the traditional triangle configuration. The $Au/TiO_x/Ti$ MIM diode is chosen because gold and titanium are characterized by a large difference in the work function and so a strong rectifying effect is achieved [26]. A design of sector bowtie nanoantenna is showed in figure 7.

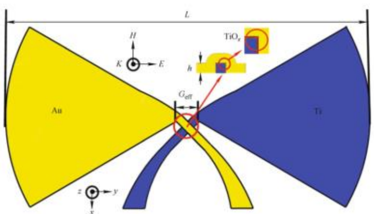

Fig.7: Design of sector bowtie nano-rectenna [26]

By increasing the refractive index of the substrate, the value of power conversion efficiency reached with this type of nano-rectenna is 11.1% [26]. Despite their widespread utilization, the MIM and MOM diodes are characterized by several limitations. In particular, the operating frequency is limited due to large RC response time and poor impedance matching to nanoantenna. Moreover, the MOM diode reveals low efficiency, even less 0.1%, in the far infrared region [13, 17, 21]. In order to overcome these shortcomings, a new type of diode made of graphene is realized. This device is a ballistic ultralow-voltage diode with geometrical asymmetry, low capacitance and low resistance to match the antenna impedance [27]. Its planar structure allows charge carriers to flow in one direction. The diode is a thin film device designed in order to obtain the asymmetric constriction in the neck region, on the order of the mean-free-path (MFPL) of the charge carriers or smaller than MFPL. Graphene is chosen because the MFPL of charge carriers is an order of magnitude greater than those in metals at room temperature [28]. The shape of such a geometric graphene diode is an inverse arrowhead so that the charge carriers flow through forward direction, from left to right. This device is usually built in the gap of misaligned planar bowtie nanoantenna and the value of power conversion is about 33pW. By employing an array topology, the value of power conversion increases up to 250pW [29-30].

C. Spiral Nano-antenna

A spiral nanoantenna has a planar structure and can be designed typically by using Archimedean spiral geometries or square spiral geometries. It can be polarized with linearly or circularly waves. The electric field is concentrated in the gap between two metallic arms. This type of nanoantenna is a good resonator and it is able to produce a large field at the feeding point. Increasing the number of arms can enhance its performance and, as a consequence, its aperture area is also increased [3, 8, 14]. A square Spiral nanoantennas is represented in figure 8.

Fig.8: Spiral nanoantenna [31]

The main drawback of this nanoantenna is the difficulty in constructing an array. However, it is possible to couple two or more spiral nanoantennas - thus to design an array – by using feeding lines. The MIM diode, usually employed for rectification, is embedded in the feeding gap. In the case of an array of spiral nanoantennas, it needs to embed only one rectifier reducing the rectifier related thermal losses and improving the efficiency of the rectenna system [31]. The spiral nanoantenna is also coupled to the Esaki diode, a device that consists of an insulating layer between two thin electrodes and it is based on the tunnel effect. The conversion efficiency obtained using the Esaki diode is on the order of 10^{-9}, whereas an MIM diode coupled to a spiral nanoantenna has a value of efficiency on the order of 10^{-12} [32].

3. Seebeck nanoantennas

Despite nanoantennas coupled to an ultra-high speed rectifier offer high theoretical efficiency, this rectenna system reveals low efficiencies due to the poor performance of the common rectifiers at optical frequencies. So in the last decade new devices based on the use of nanoantennas to confine optical energy and on the exploitation of the thermoelectric properties of their metallic interfaces to recover energy, are under study. This new device consists of a nanoantenna coupled to a metallic thermocouple. The rectification mechanism is based on the Seebeck effect, a thermoelectric voltage generation due to the infrared irradiation induced currents in the antenna [33]. A thermocouple is usually built from two wires of several materials; one end of each wire is connected to a junction (hot junction) while the other ends are unconnected (cold junction). If the temperature of the joined ends increases, an open-circuit voltage occurs across the cold junction of the thermocouple. The value of open-circuit voltage V_{OC} is proportional to the temperature difference between the two junctions and the two Seebeck coefficients of the metals:

$$Voc = (Sa - Sb) \bullet \Delta T \qquad (1)$$

This new device reduces the complexity of the fabrication process. Moreover, it is possible to increase the sensitivity of the detectors by varying the material combinations. Figure 9 shows the electric equivalent circuit of the antenna-coupled thermocouples. A high-frequency voltage source, an antenna resistance and a reactance represent the antenna. A current controlled voltage source and an internal resistance represent the thermocouple.

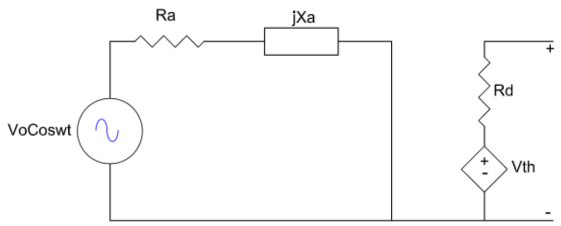

Fig.9: Electric equivalent circuit of the antenna-coupled thermocouples

Similarly to the rectenna, the main types of nanoantennas coupled to thermocouples are the dipole, bowtie antenna and spiral antenna.

A. Dipole Nano-antenna

An antenna-coupled thermocouple in [33] consists of hot junction of a nanowire thermocouple placed at the feed point of a dipole antenna. The hot junction is heated by the dissipation of induced currents due to incident radiation. Different combinations of materials are taken into account for the thermocouple. The best normalized detectivity is obtained with the Palladium-Chromium (Pr-Cr) thermocouple [33-34]. An array of dipole antenna coupled to thermocouples is in [35]. The authors compare this device with the dipole antenna coupled to an MIM rectifier. The conversion efficiency due to thermal effects is better than that due to tunnel effects [35]. Dipole antennas coupled to thermocouples made of the same metal are in [36]. The hot junction of a single metal thermocouple is located close to the center of the dipole. The nanowires of the thermocouples are made of the same metal and with different cross-sections. The time response of this nanostructured thermocouple is a Picosecond and so it actually is the fastest THz detector [36].

B. Bowtie Nano-antenna

A bowtie nanoantenna coupled to a thermocouple is in [37]. The thermocouple consists of two wires made respectively of gold and palladium. The hot junction is placed where the wires are joined to each other in the antenna. A transmission line, typically a coplanar strip transmission line, is used to connect the antenna to the thermocouple and to realize an impedance matching between them. The response of this device is obtained varying the length of the transmission line. The best response is recovered using a device with a transmission line of 1.3 μm of length. This value is 2.4 fold higher than that of the device without the transmission line. Further improvements can be achieved varying the dimensions of the transmission line, adjusting its characteristic impedance, and as a consequence, by optimizing the impedance match between the antenna and the thermocouple [37].

C. Spiral Nano-antenna

The Spiral nanoantenna is a convenient system for energy harvesting due to its ideal frequencies-independent electrical impedance. This device can be polarized linearly although better performances are obtained with the right-handed circularly polarized light; the electrical field is concentrated at the center of the nanoantenna [38]. A new device proposed in [38] consists of a metallic thermocouple shaped as a spiral nanoantenna whose size is suitable for the resonance at mid-infrared wavelengths. This device exploits the temperature gradient caused by the resonant currents in the structure in order to generate a dc voltage V_{OC} thanks to the Seebeck effect at its open ends. Two types of structures have been chosen for the spiral nanoantenna: square spiral and Archimedean spiral. Thin film thermocouples shaped as spiral nanoantenna are built with their arms made of different metals. To optimize the thermal energy harvesting, the chosen power generators have one Ti-Ni interface located at the center of the structures. The percent total efficiencies obtained with these two spiral thermocouples are around 10^{-6} and 10^{-7} [38-39]. An array of metallic thermocouples shaped as spiral nanoantennas are proposed as infrared detectors in [40]. The thermocouple is built employing Archimedean geometry with a left-handed and right-handed spiral connected by the ends and separated from the centers by a distance of 4 μm. The efficiency values obtained with these types of Seebeck nanoantennas are in a range from 10^{-9}% to 10^{-5}% [40].

4. Technological issues

Despite the big potential advantages, many issues have to be considered before these commercial devices are put on the market, i.e. the choice of suitable materials and the right technology for the design and fabrication of efficient THz rectifiers, the accurate design of the antenna, the matching optimization among antenna, rectifier and load. To ensure a better rectification with an ultra-high speed rectifier, several conditions need to be satisfied: 1) the insulator layer should be on the order of a few nanometers, by doing so, it is possible to allow sufficiently large electrical current and to ensure the tunneling effect; 2) the I-V characteristics of the rectifiers should be asymmetric, i.e. different metals should be used on both sides of the insulator layer with great work function difference between them; 3) in order to increase the cut-off frequency and to allow the THz rectification, the area must be very small. Moreover, the antenna resistance has to be close to the diode's resistance in order to provide a good impedance matching between them and, as a consequence, to increase the total efficiency [13, 17]. By taking into account the several conditions mentioned above, an ultra-high speed diode used to obtain a DC signal has to fulfill many requirements, such as high responsivity, small size, small turn on voltage and efficient performance at THz e IR frequencies. Furthermore, these types of rectifier should be coplanar and coupled to the nanoantenna. The equivalent circuit of a solar rectenna consists of the rectifier in parallel with the nanoantenna circuit. The equivalent scheme is shown in figure 10 [9].

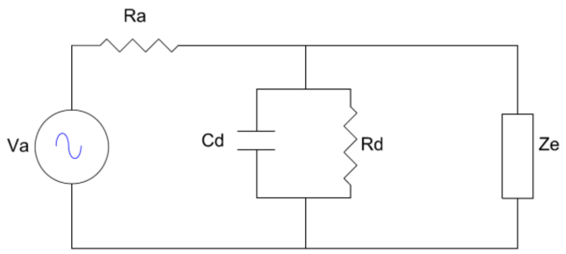

Fig.10: Equivalent circuit of a solar rectenna

The conversion efficiency of a rectenna is conditioned by the power loss in the diodes, by the impedence matching between the nanoantenna and the rectifier and between the rectifier and the load, and by the nanoantenna efficiency [3, 9]. Relatively to the rectifier, the main problems regard diode resistance, capacitance, and reverse-bias leakage. To obtain an efficient power transfer, the coupling between the impedance of the diode and the impedance of the nanoantenna is required. The latter is usually characterized by the resistance in a range from few hundreds to thousand ohms at visible light frequencies and lower at terahertz frequencies [6]. Thus, to improve the power transfer, the diode resistance has to be sufficiently low and close to the nanoantenna resistance. In this way a significant reduction of power loss is achieved. The diode capacitance gives a significant contribution to its switching time. In order to have a fast diode, the value of this capacitance has to be small. Another problem is the significant current for negative voltages in the diode. This current is required to be lower, on the order of 1μA or less. This represents the main challenge in achieving a diode for optical and infrared frequency rectification [6]. A low-pass filter is placed between the nanoantenna and the rectifier. The aim of this device is to avoid that the radiation of higher harmonics, generated from the rectification of the non-linear diode, comes back to the nanoantenna resulting in power losses. Furthermore, this filter makes possible the matching between the nanoantenna and the following circuitry [8]. To allow the maximum signal transfer to the load, the impedance matching between the rectenna system and the load is required. The maximum power transfer is reached when the load impedance is the conjugation of the rectenna impedance. In order to separate the high-frequency component from the DC signal, a DC low-pass filter is placed between the rectifier and the load [3]. Seebeck nanoantennas suffer from heat losses through the substrate, so the efficiencies remain low. It is possible to increase the response of Seebeck nanoantennas reducing the effective thermal conductivity of the substrate. This can be achieved by using freestanding architecture, i. e. by suspending the device on air above its substrate [38].

5. Conclusion

New devices for infrared energy harvesting, consisting of nanoantennas coupled to an ultra-high speed rectifier or to a thermocouple, are described in this paper. These devices exploit the thermal radiation created by the Sun transferred in the form of electromagnetic waves into free space, and finally absorbed by the surface of the Earth. The advantages and disadvantages of these devices have been critically compared. Despite some technological issues, mainly regarding the circuits between the antenna and the load to be overcome, they show a greater efficiency than traditional PV solar cells and could be an alternative to the latter in the energy harvesting process in the next future.

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