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Brief Note

Optimizing the bowtie nano-rectenna topology for solar energy harvesting applications

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ABSTRACT

This work illustrates the effect of nano-antenna shape on the efficiency of a complete nano-rectenna system for one specific geometry: the bowtie. The bowtie geometry is very well known for its wider band characteristics compared to the straight dipole. Based on full wave electromagnetic field solvers, the radiation efficiency and maximum matching efficiency for nano-bowties with different lengths and base angles are calculated. The results demonstrate that by adopting the bowtie topology, the radiation efficiency for an aluminum dipole can be improved from 51% to 61%, while the relative total efficiency can be improved from 46% to 57%, compared to the common straight nano-dipole mainly used in literature.

1. Introduction

The fundamental question whether optical waves can be efficiently converted into electricity using nanometer scale antennas and rectifiers is a highly important research field. The idea was originally proposed by Robert L. Bailey in 1972 (Bailey, 1972). However, it was not until 2005 that real research had started due to the lack of technical ability to manufacture structures at the nanoscale (Sarehraz et al., 2005). Nowadays, by some researchers it is claimed that so-called nano-rectennas could harvest more energy from a wider spectrum of sunlight, in this way offering a more efficient and cheaper alternative to traditional silicon solar cells (Kempa et al., 2007; Gadalla et al., 2014). Once realized, this concept could revolutionize the energy market and partially solve the energy problem of human kind in a completely clean and renewable way.

In recent years, the concept of using nano-rectennas in solar energy harvesting has been intensively investigated. A thorough numerical investigation was published in Kotter et al. (2010), Vandenbosch and Ma (2012). It was shown there that at a single frequency in the solar spectrum, up to 90% of the energy can be made available at the output of a silver dipole nanoantenna. Further, S.S.A. Obayya used a tapered dipole to tune the impedance and thus improve the matching efficiency (El-Toukhy et al., 2017a, 2017b). E. Briones numerically evaluated the conversion efficiency of thermally isolated Seebeck nanoantennas (Briones et al., 2016). Some more topologies were studied in Briones et al. (2013), including log-periodic antennas and spiral antennas. However, all these works essentially deal with efficiencies at single frequencies or as a function of frequency. No effort was performed to derive an "integrated" overall efficiency over the wide frequency range over which solar radiation is spread out, mainly in the visible and near-infrared bands. Such a parameter is necessary to evaluate the performance of the whole rectenna system. Therefore, the concept of total harvesting efficiency was defined in Kotter et al. (2010), taking this issue into account, yielding levels of about 60–70%. The upper bounds for the receiving efficiency for 5 different metals in terms of the dimensions of a dipole nanoantenna were reported in Vandenbosch and Ma (2012). The receiving efficiency also takes into account the matching with the rectifier circuits. For aluminum dipoles, a maximum receiving efficiency of about 46% was obtained. For a more complete overview on the state-of-the-art in this research field, we refer to Modell et al. (2013).

The main objective of this manuscript is to investigate to which level the receiving efficiency (including a matched rectifier) can be increased by optimizing the shape and material of a bowtie dipole nanoantenna. By tuning the antenna's geometry, e.g. length, width, and base angle (as shown in Fig. 2), we gradually depart from the traditional nanodipole topology to a bowtie shaped nanoantenna. The change in the receiving efficiency with these variations is thoroughly investigated using the commercial computational tool Lumerical (www.lumerical.com). As a result, we find that the bowtie topology (disregarding the composing material) in general offers around a 10% increase in the receiving efficiency. This is an important finding on top of

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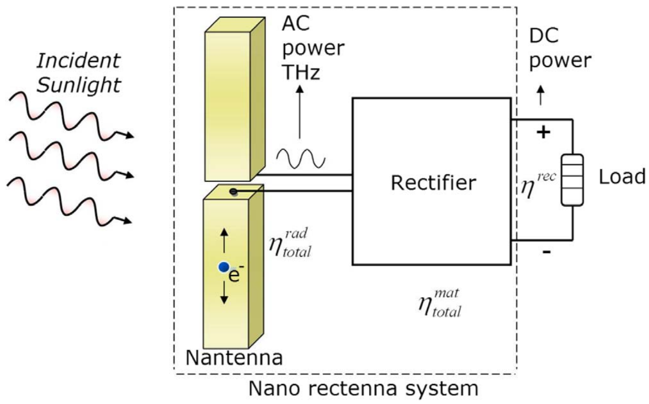

Fig. 1. Schematic representation of a solar energy harvesting system. The incoming optical radiation induces currents flowing in the nanoantenna. Then, the generated AC power is fed through a matched rectifier to produce DC power. η_{total}^{rad}, η_{total}^{mat} and η^{rec} denote the total radiation efficiency, the total matching efficiency, and the nano-rectenna system efficiency, respectively.

the levels already found in the basic paper (Ma and Vandenbosch, 2013a).

2. The solar energy harvesting system

A solar energy harvesting system, i.e. a nano-rectenna system, consists of two parts, see Fig. 1. The incident light induces an electric current in a nanoantenna. In this conversion, the total radiation efficiency (Kotter et al., 2010) may be defined as,

$$\eta_{total}^{rad} = \frac{\int_{\lambda_{start}}^{\lambda_{stop}} P_{inc}(\lambda)\eta^{rad}(\lambda)d\lambda}{\int_{\lambda_{start}}^{\lambda_{stop}} P_{inc}(\lambda)d\lambda}. \tag{1}$$

In Eq. (1), λ is the wavelength of the incident light and the upper and lower integration limits λ_{start} and λ_{stop} should cover the optical range for the solar energy harvesting. $\eta^{rad}(\lambda)$, the radiation efficiency of the antenna as a function of the wavelength, is the ratio of the radiated power P^{rad} in the transmit mode to the injected power P^{inject} available at the antenna's input port,

$$\eta^{rad} = \frac{P^{rad}}{P^{inject}} = \frac{P^{rad}}{P^{rad} + P^{loss}}, \tag{2}$$

where P^{loss} is the power dissipated by the material of the antenna.

Moreover, P_{inc} in Eq. (1) follows Planck's law for black body radiation

$$P_{inc}(\lambda) = \frac{2\pi hc^2}{\lambda^5} \times \frac{1}{e^{hc/\lambda kT} - 1}, \tag{3}$$

where T is the absolute temperature of the surface of the sun (in K), h is Planck's constant ($6.626 \cdot 10^{-34}$ J s), c is the speed of light in vacuum

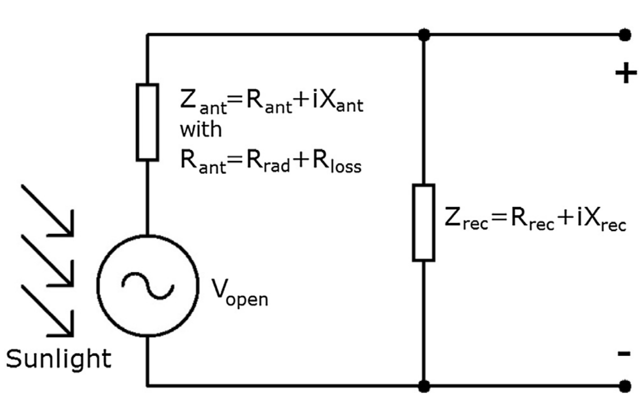

Fig. 2. Equivalent circuit for rectenna system.

($3 \cdot 10^8$ m/s), and k is the Boltzmann constant ($1.38 \cdot 10^{-23}$ J/K).

Since the current flowing in the antenna's body oscillates around hundreds of THz, a rectifier is connected to the input port, in order to generate DC power in the load. Similar to the total radiation efficiency defined in Eq. (1), we may also define the total matching efficiency,

$$\eta_{total}^{mat} = \frac{\int_{\lambda_{start}}^{\lambda_{stop}} P_{inc}(\lambda)\eta^{rad}(\lambda)\eta^{mat}(\lambda)d\lambda}{\int_{\lambda_{start}}^{\lambda_{stop}} P_{inc}(\lambda)\eta^{rad}(\lambda)d\lambda}. \tag{4}$$

where η^{mat} is the matching efficiency of the nanoantenna rectifier system. This parameter is calculated as

$$\eta^{mat} = \frac{4R_{rec}R_{ant}}{|Z_{rec} + Z_{ant}|^2} \tag{5}$$

where Z_{rec} is the impedance of the rectifier, Z_{ant} is the input impedance of the nanoantenna, R_{rec} is the real part of the rectifier impedance, and R_{ant} is the real part of the nanoantenna input impedance. All these quantities are marked in the equivalent circuit of the total rectenna system depicted in Fig. 2.

Here, we must point out that, at present, the realization of rectifiers at optical frequencies is still a huge challenge in the design of nano-rectenna systems. In a conventional rectification, i.e. at RF and microwave frequencies, a diode is used. Such rectennas have been proven to successfully convert microwave radiation into DC power, achieving conversion efficiencies as high as 91% (Brown, 1996). MIM (metal-insulator-metal) point contact diodes based on Nb_2O_5 and Nb-TiO_2 have been fabricated and successfully tested at somewhat lower frequencies (Periasamy et al., 2010). However, present-day diodes are still unable to efficiently rectify at visible and near-infrared frequencies. Since thermodynamic calculations suggest that rectennas can convert any electromagnetic radiation to DC power with a conversion efficiency of at least 85% (Corkish et al., 2002), the search for the proper diode technology is currently fully in progress.

Last but not least, we may combine Eq. (1) with Eq. (4) to define the rectenna efficiency η^{rec}, which assesses the global performance of the nanoantenna – rectifier system.

$$\eta^{rec} = \eta_{total}^{rad} \times \eta_{total}^{mat}. \tag{6}$$

3. Simulation and numerical results

In this section, the efficiency parameters defined in the previous section are numerically evaluated for the bowtie topology. The topology, the dimensions and the depth profile of the bowtie antenna are illustrated in Fig. 3(a). In the simulations, while G, H, and W are kept constant, the dipole length L varies between 100 nm and 400 nm, with a step of 20 nm. The base angle Φ has a range between 0° and 50° with a step of 5°. Having energy harvesting in mind, the efficiencies of the final structures are of crucial importance. In (Vandenbosch and Ma, 2012; Ma and Vandenbosch, 2013a, 2013b) it is clearly proven that Au (the material most used in plasmonics) is considerably inferior compared to Ag and Al. On top, in Ma and Vandenbosch (2013b) it is also proven that Ag may show serious reductions of the efficiencies due to its oxidation when it is exposed to air, while aluminum has a natural oxide which is transparent, i.e. loss-free at the frequencies considered. This is the major argument to choose aluminum in this study. The incident electric field is polarized along the Y-axis. The efficiency calculation is performed in the wavelength range between 500 nm and 1500 nm where about 80 percent of the energy radiated by the sun is present. The permittivity of Aluminum is taken from Palik (1985) and the permittivity of the SiO_2 substrate is 2.15.

The power captured by the bowtie is fed to the rectifier circuit via a port defined near the middle of the gap (see Fig. 3(b)). The input impedance of the nanoantenna may be defined as,