Seebeck Nanoantennas for Infrared Detection and Energy Harvesting Applications

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Abstract—In this letter we introduce a new type of infrared sensor, based on thermocouple nanoantennas, which enables the energy detection and gathering in the mid-infrared region. The proposed detector combines the Seebeck effect, as a transduction mechanism, with the functionalities of the optical antennas for optical sensing. By using finite-element numerical simulations we evaluate the performance and optical-to-electrical conversion efficiency of the proposed device, unveiling its potential for optical sensing and energy harvesting applications.

Index Terms—Seebeck nanoantennas, infrared detector, energy harvesting.

I. INTRODUCTION

Nanoantennas are metallic resonant structures at the core of new advances in photonics due to their capability to confine and manipulate light into a sub-wavelength scale [1,2]. These types of nanostructures take advantage of the wave-nature of radiation in order to induce a resonant current along their structure [3,4], which is subsequently used to sense or retrieve the optical energy[5,7].

Early works on infrared detection with optical antennas were performed by using niobium coupled-microbolometers in order to sense the antenna’s resonant current [8,9]. These devices were successfully incorporated into large phase-arrays of optical antennas, leading to the development of faster thermal imagining acquisition systems, with efficiencies around 0.01 % [10]. Meanwhile, the use of coupled nano-rectifiers has enabled the nanoantennas to retrieve optical energy [11]. These so-called rectifying antennas (rectennas) seems to have a great potential in the field of energy harvesting since they exhibit a high theoretical efficiency (claimed to be 100 % [6,7]) and the ability to resonate at any-wavelength. In this context, several devices based on nanoantennas coupled to metal-insulator-metal (MIM), metal-insulator-insulator-metal (MIIM) and Esaki tunnel barriers, have been experimentally realized and measured as a proof-of-concept [12-17]. However, in spite of their attractive functionalities, actual rectifying nanoantennas have presented up to now a low efficiency, which is around 10% [7,8,17]. In order to incorporate nanoantennas into harvesting applications different retrieving mechanisms must then be explored [18,19].

II. NUMERICAL SIMULATIONS

A. Devices

In this manuscript, we present a new type of infrared device based on the combination of nanoantennas for optical sensing with the Seebeck effect as a transduction mechanism [20-24]. These devices work by exploiting the temperature gradients, caused by the resonant current induced along their structure, when the nanoantennas are illuminated. The thermal gradients in turn generate a DC voltage \( V_{OC} \) (by Seebeck effect) that can be sensed at the open edges of the structures, defining the retrieving energy mechanism [25]. This signal can be evaluated by:

\[
V_{OC} = (S_A - S_B) \Delta T
\]

where \( S_A \) and \( S_B \) refers to the Seebeck coefficient of the metals that form the nano-thermocouple and \( \Delta T \) refers to the temperature difference between the center and the open edges of the structure.

The proposed devices present some advantages when compared to the rectifying nanoantennas counterpart. Rectifying antennas have drawbacks on their responsivity and efficiency, which is due to the very different impedance between their elements (i.e. the high-speed rectifier and the nanoantenna), causing the efficiency to drop by a huge amount of several orders of magnitude. On the other hand, the performance of the current high-speed rectifiers is still low due to their poor diode-like behavior [17]. The incorporation of Seebeck nanoantennas can surpass those difficulties since it permits to discard the mismatch impedance (energy transfer) between elements. Seebeck nanoantennas are reappearing quite recently as good candidates to exhibit a better performance than antennas based on other transduction mechanisms [21-24].
confined and enhancement of the incident optical field at
the gap of the structures [26]. The nanoantenna lies on the top
of a half-space SiO₂ substrate and its size was appropriately
adjusted to resonate to mid-infrared wavelengths (40µm long).

The arms of the nanoantenna are made of titanium and
nickel since those metals exhibit low-thermal conductivity (κ₉₅ =
90 W/mK and κ₇₇ = 21.9 W/mK), enhancing thus the thermal
gratings along the spiral and the harvesting/detection of
energy. These metals also show a considerable difference in
their Seebeck coefficients (S₉₅ = 19.5 μV/K and S₇₇ = 7.19
μV/K [25]). The modeling of the device was performed by
using COMSOL Multi-Physics ver3.5a (based on the finite-
element method) commercial package that provides a good
multi-physics platform where both the electromagnetic and the
thermal domains are fully integrated [27]. The numerical
model was built by using the reported optical and thermal
properties of the materials, as an input into the solver, in the
wavelength range of interest (from 3 µm to 50 µm) [25,28].

The response of the Seebeck device is obtained at each
single frequency by using a right-handed circularly polarized
(RHCP) monochromatic plane-wave for normal far-field
illumination. The irradiance $I$ of the wave was systematically
adjusted for each frequency to be 117 W/cm² (intensity value
currently used in antenna-based sensors measurements [9]).

### B. Thermal simulations and Seebeck voltage

The map of temperature the device exhibits at 10.6µm is
shown in Fig. 1(b). These numerical results were obtained by
considering the nanoantenna as the only heat of source (Joule
heating) and by solving the heat equation inside and outside
the nanostructure, whatever the distribution of the resonant
current inside the structure [29]. From this map, the Seebeck
voltage is easily derived from imaginary electrodes by using
(1). From the color map it can be seen that the temperature
increment $ΔT$ between the gap and the extremes of the spirals
is around 215 mK; this permits the antenna to act as a nano-
thermocouple, whose output is around 5.7 µV. The Seebeck
voltage for each single frequency is presented in Fig. 2. From
the figure it can be appreciated the wide band of the device,
which, as expected, is inherited from the optical properties of
the antenna.

![Fig. 1. (a) Schematic representation of the infrared Seebeck nanoantenna. The spiral nanoantenna is composed of two arms made-up of dissimilar metals joined at the center of the spiral. (b) Temperature map of the Seebeck nanoantenna 10.6 µm under circularly polarized illumination (taken from a plane 50nm below its surface).](image)

![Fig. 2. DC voltage generated by the Seebeck nanoantenna under an irradiance of 117 W/cm², as a function of the frequency of the excitation.](image)
The percent efficiency $\eta(\%) = \eta \times 100$ the Seebeck nanoantenna exhibits is shown in Fig. 3(b) as a function of the excitation frequency. The efficiency values range from $10^{-9}$ % to $10^{-3}$ %. These values are $10^3$ greater than the efficiencies reported for the rectifying antennas [17]. As we have previously mentioned, the performance of the rectifying antennas is drastically decreased by the unmatched impedance between the nano-rectifiers and the nano-antennas, as well as by the poor diode-like behavior of the tunnel barriers. By using Seebeck nanoantennas no impedance losses are seen, increasing this manner the nanoantennas overall performance. Moreover, the conversion efficiency could be increased by isolating the nanoantenna from the substrate in order to prevent the heat exchange between these two elements; by proceeding this way most of the optically induced heat will be exploited to induce the thermoelectric Seebeck voltage. From an experimentally point of view, this task could be achieved by suspending the device on air above its substrate (e.g., by using free-standing architecture).

IV. CONCLUSIONS

In summary, the optical-to-electrical conversion efficiency of a Seebeck nanoantenna infrared detector was evaluated by performing numerical simulations (in the electromagnetic and thermal domain). The performed analysis shows that Seebeck nanoantennas represent an alternative technology to recover the free-propagating optical energy; increasing the overall performance by a $10^3$ factor when compared to the rectifying nanoantennas counterpart. Its performance can be increased by implementing technological strategies that could prevent energy losses by heat dissipation. Moreover, engineering of large phase-arrays of nanoantennas acting as series thermocouples arrays can be implemented to increase the performance of devices.

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