Efficient Nanoantenna Simulation for IR Energy Harvesting and Detection Devices

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Abstract

A novel nanoatenna is designed for enhancing an IR energy harvesting device and realization of a focal plane array polarimetric IR detector. Instead of using a bulk semiconductor material for photovoltaic detection, the semiconductor p-n junction is scaled down and loaded at the antenna's terminal where the antenna field enhancement can be utilized. For infrared (IR) devices, a low-band gap material, Indium Gallium Arsenide Antimonide (InGaAsSb) is used and its electrical properties are analyzed in order to optimize it as the antenna load. For maximum power transfer between the antenna and the load, the impedance matching is established by optimizing the antenna geometrical and material parameters as well as utilizing a reactive shunt transmission line stub. In numerical simulations, the Drude model for metal is incorporated in the FEM code to account for plasmonic effects. Also to match the antenna to high load impedance, the antenna is operated at its anti-resonance mode. It is shown that the antenna loaded with InGaAsSb can present a field enhancement as high as 23.5 in a near-IR band. The performance of the IR harvesting device in terms of absorption efficiency is enhanced by 50%. Also the detectivity of the uncooled-IR detecting device made by such antenna and load is improved by a factor equal to the field enhancement factor (~23).

1. Introduction

Recently, an ordinary nanoantenna was introduced as a promising device for photovoltaic and photodetector applications [1]. The basic concepts of nano-dipole antennas including the plasmonic effects have been studied extensively [2]. In [3], field enhancement is achieved by tuning the dimensions of a dipole antenna in addition to placing the antenna over a ground plane. In [4] an optical circuit composed of a transmitting antenna, a receiving antenna and a co-planar strip transmission line is considered. Through simulations, it is demonstrated that the input impedance of the nanoantennas can be matched to the transmission line impedance by varying the dipole's geometric parameters. In [5] a two wire transmission line of particular length attached to a dipole nanoantenna is connected to a thermocouple to achieve an improved impedance match. Those numerical simulation and experimental demonstration have paved a way to realize the maximum power transfer between the antenna and the load. In this paper, the antenna structure for enhancing the performance of TPV (one kind of IR energy harvesting devices) based on the InGaAsSb semiconductor and the IR detecting device is introduced and the performance enhancement also is presented.

2. Nanoantenna Design

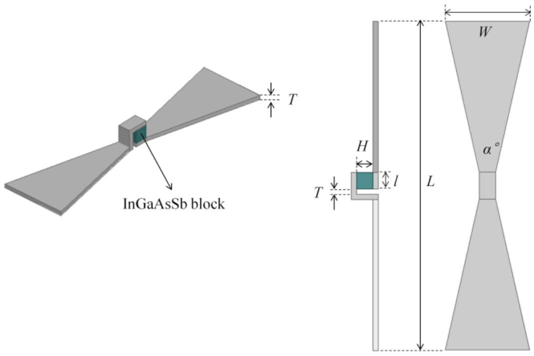

Fig. 1. Bowtie antenna structure in one plane.

The proposed bowtie antenna structure is shown in Fig. 1. An antenna load is chosen with a low band gap semiconductor, InGaAsSb which has been used for TPV. TPV p-n junction semiconductor devices which convert

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thermal energy to electricity can be considered as an counterpart of PV system in IR regime. The high resistance and capacitance of the InGaAsSb in near-IR should be accounted for the antenna design. For impedance matching, the parallel resonance(high impedance mode) of the antenna must be used. It is shown that antenna length of 605 nm must be chosen at the desired frequency of 180 THz in order to operate at the antenna's parallel resonance frequency. The other dimensions are set as follows: W = 160 nm, T=10nm, and α = 30°. The integrated antenna load, InGaAsSb block is placed in the middle between two small metallic electrodes. The dimension of InGaAsSb load can be represented as A, the area of the electrode and as H, the separation between the two electrodes. The dimension of the InGaAsSb load is fixed to 30 nm × 30 nm × 30 nm ($H \times l \times l$). From the antenna geometry and load optimization, the resistance of the antenna is matched with the load resistance. Also to compensate for the high capacitance of the InGaAsSb load at 180 THz, an open-ended transmission line is connected to the antenna terminal. The optimization of the transmission line realizes the impedance matching which guarantee the maximum power transfer between the load and the antenna.

3. TPV and IR detector performance improvement

The antenna optimization provides the field enhancement of ~23.5 at the InGaAsSb load near 180 THz where the InGaAsSb material shows the maximum quantum efficiency. By utilizing the field enhancement, an array of the antennas can be used for the efficient TPV system. The absorption rate which is a ratio between the incident power and the absorbed power shows that most of the power is captured at the desired resonance frequency. This absorption improvement compared to the conventional TPV can increase the efficiency about 50 %. Also the field enhancement which is related to the effective area of the antenna also improves the InGaASSb IR detector. The detectivity of the detector when the noise is dominated by the Johnson noise can be improved by ~23 which is the ratio between the InGaAsSb load size and the effective area of the antenna.

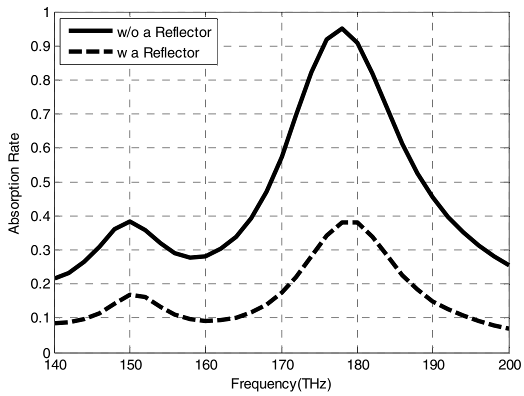

Fig. 2: Absorption rate of bowtie nanoantenna loaded InGaAsSb block with and without a back metallic reflector.

4. Conclusion

Novel nanoantenna design procedure for enhancing the IR harvesting and detecting devise is introduced. The field enhancement of 23.5 at the InGaAsSb load is shown through the optimized bowtie-shaped antenna. An IR energy harvesting device, Thermophotovoltaics (TPV) mounted with the bowtie antenna design demonstrates that almost 95% of the incident power is absorbed through the array of the antennas. Also the uncooled-IR detector using the antenna structure shows the enhancement of its sensitivity as high as the field enhancement ratio (~23).

5. References

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