Nanoantenna arrays as diode-less rectifiers for energy harvesting in mid-infrared band

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Abstract
Unlike the solar energy, infrared radiation from black bodies around us is always available. In this paper, a novel energy harvesting device is proposed for absorption of the infrared radiation from hot objects around us at temperatures beyond 300 K, in the vicinity of 10 μm wavelength, or from the Earth itself. Electron field emission from sharp edges in vacuum, based on Fowler-Nordheim (FN) theory, is proposed as a means of rectification. A large number of nanoantennas are placed in an array to achieve high electric field, required for FN electron emission. The issue of wave spatial coherence is discussed in the paper, and it is shown that the device can operate with small affliction. Using the proposed device, the MIM/MIIM diode, which is usually used for rectification and has a very low efficiency, is avoided and therefore efficiency is highly improved. A planar spiral series nanoantenna array (SSNA) is designed, as an example, to demonstrate the concept. Bowtie and cross bowtie antenna geometries are considered and their performances are compared.

KEYWORDS
diode-less rectifier, energy harvesting, field electron emission, mid-infrared band, nanoantenna array

1 | INTRODUCTION
Solar radiation is categorized among green energy sources, since it is renewable and its employment would have little adverse effects on the environment. High amount of energy is accessible, if a device is designed for solar energy harvesting. However, solar radiation has large variations, round the clock in a day. After sunset, energy absorption of the solar panels is highly diminished. Similar situation happens in cloudy days, or in countries with low amount of annually sun radiation, due to the climate and also geographical latitude of the place on the Earth. On the other hand, infrared radiation from hot black bodies around us, and also from the Earth itself, is always available. Nonetheless, such radiations are much weaker than the sun radiation.

Infrared energy harvesting using nanoantennas has been proposed before. However, they require a rectification device to produce DC output current. The solution proposed in the literature is to use a Metal/Insulator/Metal (MIM) or Metal/Insulator/Insulator/Metal (MIIM) diode for rectification.1 Yet, they demonstrate low efficiencies, such as 3.6%.2

In this paper, we propose using the Fowler-Nordheim (FN) electron field emission from sharp edges in vacuum, as a means of rectification. Therefore, the diode is eliminated, and the energy conversion efficiency is highly improved. FN emission requires electric field amplitude in the range of 10^9 to 10^10 V/m. In this paper, we propose using a large array of nanoantennas, in the order of several ten thousand elements, to achieve such a strong electric field. To the best of our knowledge, this is the first report of nanoantenna arrays for energy harvesting, without the use of diodes. Also, due to the planar architecture and also avoiding lenses for field enhancement, a low cost design is achieved. It should be added here that if FN electron emission occurs in nanoantenna arrays with MIM/MIIM diode, higher efficiency can be achieved. However, due to the hot carriers that tunnel through the oxide, the device lifetime is reduced. In the proposed device, the FN field emission happens in the vacuum, and therefore, the device is not damaged.

2 | PROPOSED STRUCTURE
The proposed structure for energy harvesting is shown in Figure 1. It consists of a number of spiral series nanoantenna arrays (SSNAs) that operate in parallel in a vacuum
chamber. Each SSNA, as shown in Figure 2, is loaded with a large number of bowtie nanoantennas to produce enough field enhancement, so that in the array gap of the SSNA, electron field emission occurs. In the gap of each SSNA, there is a central collector, which absorbs the electrons from either the left or right feed line, based on the electric field direction. The collected current is rectified through the electron emission process, as explained next. The rectified currents of all SSNAs are summed up, by the backplane of the device, to which the collectors of all SSNAs are connected. The required number of SSNAs in parallel depends on the current required to supply the load.

Fabrication of the structure is performed on a silicon substrate, on top of which, a silicon dioxide layer is grown. After silver metal deposition on the oxide, the planar antenna arrays including the nanoantennas and the feeding lines are etched and the final device is achieved. A thin layer of chromium may also be placed between the metal and the dioxide layers for better adhesion. On the backside of the substrate, a metal backplane is placed, which is used to collect the current from all SSNAs. Optical permittivity of metals in the midinfrared range is considered for metal selection for nanoantennas, and based on that, silver is selected.

### 3 | PRINCIPLES OF RECTIFICATION

Figure 2 demonstrates a close view of the feed gap of a nanoantenna array, where field emission occurs. The two tips of the feeding lines ended at the array gap should be made sharp, as shown in the figure, to make the rectification possible. This also helps to increase the field enhancement. According to this figure, when the overall amplified electric field by the nanoantennas in the array is from left to right in the gap, which happens in a half cycle of the incident wave, the electrons are emitted from the right sharp tip toward the collector. In the second half cycle, the amplified electric field changes direction and the electron emission takes place from the left sharp tip toward the collector. As a result, the current is always toward the collector, and therefore, is rectified. The gap distance is adjusted such that the emitted electrons reach the collector in part of a half cycle of the incident wave. The electron emissions in the reverse direction, that is, from collector to the sharp tips, is negligible, in both half cycles.

### 4 | POWER ABSORPTION

According to the Stefan-Boltzmann law, the incident power density coming from a black body radiator is calculated by $H_{BB} = \varepsilon_{BB} \cdot \sigma \cdot T_{BB}^4$, where $\sigma$ is the Stefan-Boltzmann constant, and $\varepsilon_{BB}$ and $T_{BB}$ are respectively the emissivity (a value between 0 and 1) and Kelvin temperature of the black body. If all objects surrounding the device reside at $T_{BB}$, the power absorbed by the device is specified by the above equation. However, if those objects reside at different temperatures, the absorbed power would be $H_{abs} = \sum P_{BBi} \cdot \varepsilon_{BB} \cdot \sigma \cdot T_{BBi}^4$, in which, the summation is performed on all black bodies surrounding the device, and $P_{BBi}$ is the relative space viewing angle of the black body (means the percentage of space viewing angle of the black body to the total viewing angle of $4\pi$ steradians for the device). The device itself does some radiation, and therefore, loses some power, according to the same law, equal to $H_{loss} = \varepsilon_{dev} \cdot \sigma \cdot T_{dev}^4$. This amount of power is distributed in a spread range of wavelengths. However, the device is designed for absorption and conversion of only part of the received spectrum, and therefore, $H_{conv} = P_{conv} \cdot H_{net}$, in which, $H_{conv}$ is the absorbed power for conversion into electricity and $P_{conv}$ is the percentage of wavelengths absorbed, with respect to the received spectrum.
4.1 | Scenario 1: power absorption from hot black bodies

Assume the device and all objects surrounding it reside at 288 K (15°C). Therefore, $H_{\text{net}}$ and $H_{\text{conv}}$ would be zero. Now, assume there is a surrounding object with 45°C higher temperature (ie, at 333 K or 60°C) with viewing angle of $\pi$ sr ($P_{\text{BB}} = 25\%$), which means that the object is almost close to the device. Also, assume that the device and black bodies have typical emissivity of 0.5. Thus, $H_{\text{BB},288} = 195.1$ W/m$^2$, $H_{\text{BB},333} = 348.6$ W/m$^2$, $H_{\text{abs}} = 0.75 \times H_{\text{BB},288} + 0.25 \times H_{\text{BB},333}$, and $H_{\text{loss}} = H_{\text{BB},288}$. Therefore, $H_{\text{net}} = 0.25 \times (H_{\text{BB},333} - H_{\text{BB},288}) = 38.4$ W/m$^2$. If the device is designed to absorb wavelengths around 10 μm with 4 μm bandwidth (ie, from 8 to 12 μm), based on the band radiance at 333 K, around 28.3% of the power is converted, and therefore, $H_{\text{conv}} = 10.8$ W/m$^2$.

4.2 | Scenario 2: power absorption from the earth

If the harvesting device is resided at room temperature, the net power absorption from the Earth is zero. Keeping the device at lower temperatures requires power consumption for cooling the device. However, placing the device on airplanes or space satellites, where temperature falls to −50°C or lower, provides sufficient temperature difference for power absorption to generate electricity. As an example, if we assume: (1) The Earth average temperature is 285 K (12°C) with emissivity of 0.64; (2) The device resides at 223 K (−50°C) with a typical emissivity of 0.5; (3) The Earth fills around 2π sr or 50% of the total space viewing angle of the device, since the device is only few kilometers away from the Earth surface; (4) The other 50% of the space viewing angle of the device is the infinite space with temperature of 223 K (−50°C) with a typical emissivity of 0.5; and (5) The device is designed for absorption of 8-12 μm wavelengths; thus, $H_{\text{Earth},285} = 2.3 \times 9.4$ W/m$^2$, $H_{\text{space},223} = 70.1$ W/m$^2$, $H_{\text{abs}} = 0.5 \times H_{\text{Earth},285} + 0.5 \times H_{\text{space},223}$, and $H_{\text{loss}} = H_{\text{space},223}$. Therefore, $H_{\text{net}} = 0.5 \times (H_{\text{Earth},285} - H_{\text{space},223}) = 84.6$ W/m$^2$. Based on the band radiance at 285 K, around 25% of the power is converted, which results in $H_{\text{conv}} = 21.1$ W/m$^2$.

Assuming the worse scenario between the two, a power of around 10 W/m$^2$ is received and converted into electricity. Such amount of power is equivalent to an electric field of 86 V/m. Plane wave model is used for the simulations, which are performed in the Computer Simulation Tool (CST) environment. The simulations are based on finite element method (FEM).

5 | BUILDING THE NANOANTENNA ARRAY

To increase field enhancement by antennas, arrays are utilized. Two main geometries are available to form an array, that is, series and parallel, as shown in Figure 3. In the parallel form, electric field of different antennas is added constructively, since the distance between each nanoantenna and the gap is equal. In the series form, the field of different antennas is added in phase with the others’ field, if the distance between the elements is a multiple of the wavelength. Therefore, parallel arrays are wideband, while series arrays are narrowband. On the other hand, parallel arrays consume more implementation area, due to the increased total length of feeding lines, and therefore, demonstrate somewhat lower field enhancement, due to field attenuation across long wires. Here, to save some fabrication space, we select series arrays. However, to have a wideband device, parallel arrays can also be chosen.

Emission and receiving pattern of the antenna array is highly dependent on the geometry of a single nanoantenna. Dipole antenna has the simplest geometry with a very narrow bandwidth. Bowtie antenna, as shown in Figure 4, is a modified version with a wider bandwidth, and therefore, more suitable for energy absorption. However, bowtie is sensitive to polarity of the incident wave. Cross bowtie antenna shown in Figure 4, on the other hand, consists of two perpendicular antennas, which can be assumed as an unpolarized version of the bowtie antenna. Other geometries are also available and discussed in the literature. Typical sizes to achieve high field enhancements at 10 μm wavelength are achieved by simulations as: L = 4.5 μm, W = 1.2 μm.
thickness = 300 nm, and G = 4 nm, where G is size of the antenna feed gap.

However, as the radiations from Sun or other thermal sources have random polarity, both bowtie and cross bowtie geometries can be used for energy harvesting. In fact, if bowtie is used instead of cross bowtie, on average, almost half of the incident energy is absorbed. This is achieved at the advantage of lower area consumption. Also, due to the geometrical shape of bowtie, they could be placed closer in an array, and therefore, more antennas can be placed in the array. In both antenna types, by changing flare angle of the bowtie nanoantenna, absorption bandwidth can be adjusted. Higher flare angle results in larger bandwidth, and at the same time, lower field amplification. Field enhancement for single and eight element arrays of typical bowtie nanoantennas for different flare angles are shown in Figure 5.

A large number of array elements is required to achieve electric field intensity of $10^9$ to $10^{10}$ V/m in the array gap. FEM simulation is not practical for large number of array elements. However, the theory of antenna arrays proves that the field increases linearly with number of elements in the array, $N$. Simulations with 1, 2, 4, and 8 series and parallel nanoantennas, however, shows a sublinear relation. For example, for cross bowtie array, as shown in Figure 6, the slope of field enhancement vs $N$ on the logarithmic scale is achieved as 0.96 and 0.83, instead of 1, for series and parallel arrays, respectively. This can be attributed to the electric field attenuation in the long feeding wires. By extrapolating the simulation results, the required number of array elements can be estimated. As an example, to achieve electric field of $10^9$ V/m, around 20 000 and 115 000 cross bowtie nanoantennas are required, for series and parallel arrays, respectively.

The current collected by the central collector of an SSNA is a DC current and therefore can be added to the current from other SSNAs in the device. Current of single SSNAs is rectified, however, it could have some fluctuations, due to the AC (i.e., oscillating) field intensity of the incident wave. After current summation from a large number of SSNAs, the total current tends to be a DC value, and the random fluctuations would ideally cancel each other. Placing a capacitor at the device output helps in more output regulation.

### 6 | SPATIAL COHERENCE AND FABRICATION ISSUES

Spatial coherence is a prohibitive issue, when using lenses or arrays in concentrating the waves from different points, on a single point, as it results in cancellation. According to literature, five two points with 20 μm (50 μm) distance have 90% (60%) coherence for sunlight. At 300 K, that is, 20 times colder than the sun surface, 6000 K, the distance for 90% (60%) coherence increases to 400 μm (1 mm). A circle with 400 μm (1 mm) radius, or ~500 000 μm$^2$ (~3.14 mm$^2$) can store ~20 000 (~125 000) cross bowtie nanoantennas. This number almost doubled when bowtie is
used. This number of nanoantennas could be enough for the proposed rectifier, based on FN electron field emission.

If different bands or wider bandwidths are required for energy harvesting, the design of bowtie or cross bowtie nanoantenna geometries can be adjusted, as discussed before. Also, parallel arrays, instead of series, can be used for wider bandwidths. In addition, multiband energy absorption can be achieved using different nanoantenna lengths in different SSNA cells.6

Some low cost fabrication processes for large number of elements have been proposed before,7,8 which may suffer from fabrication tolerances. Simulations show that, for example, changing the array gap size by ±30%, changes the electric field across the array gap by +13% and −7%, respectively.

7 | CONCLUSION

In conclusion, a novel device for energy harvesting in infrared band is proposed in this paper. A large number of nanoantennas are placed in series arrays to amplify electric field resulted from an infrared incident wave. Rectification is performed with sharp edges in vacuum and without using diodes. By such a device, radiated electromagnetic energy from hot black bodies around us or from the Earth can be absorbed and converted into electrical energy.

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