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Energy Harvesting Enhancement of Nanoantenna Coupled to Gemometric Diode Using Terhertz Transmitarray

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Abstract

This paper introduces the use of rhombus shaped dipole nanoantenna coupled to geometric diode in energy harvesting at 19.4 THz. An arc-shaped geometric diode is placed in the gap between the dipole arms. The diode I–V characteristics are investigated using the Monte Carlo simulation. Two approaches for enhancing the received voltage of nanoantenna energy harvesting at 19.4 THz are investigated. In the first approach, a terahertz transparent transmitarray is used to focus the electromagnetic waves on the surface of the nanoantenna coupled to the geometric diode. The received voltage is increased from 16.5 μV for single nanoantenna to 97.6 μV for the transmitarray coupled to the nanoantenna. In the second approach, Yagi nanoantenna arrangements are used to enhance the directivity of the single element and is coupled to the transmitarray.

Keywords Graphene · Rectenna · Geometric diode · Nanoantenna · Transmitarray · Energy harvesting

1 Introduction

The demands in renewable energy sources have been increased recently. The solar energy is the greatest source of renewable energy which provides a continuous stream of power [1]. Various technologies and methods are applied to directly or indirectly achieve renewable energy. The traditional photovoltaic (PV) cells are depending on daylight, and sensitivity to the weather conditions [2]. New technologies based on thermal energy harvesting from the Sun, and the reemitted radiation from the Earth have been introduced. The energy harvesting based on collecting the electromagnetic wave (EMW) radiation at the terahertz

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band from suitable antennas called nanoantennas has been investigated [3]. Nanoantennas introduce potential advantages such nanoscale size, polarization, tunability and rapid time response [4]. Different nanoantenna shapes are introduced for energy harvesting, such as dipole, bowtie, and spiral configurations [5].

The captured EMW by nanoantennas induces an AC current with the same frequency of the wave onto the antenna surface and is applied to an external load to be rectified [5].

Different types of rectifiers, such as, Schottky diode, Metal-Insulator-Metal diode, and graphene geometric diode have been investigated in [6, 7]. The geometrical diode is an electronic device in which the current flow is controlled by its geometry. This diode is capable to meet the dual necessities of a low resistance and a low capacitance required to operate at infrared frequencies. The planar configuration of the diode makes it an extremely low capacitance, making it more suited for high frequency performance than the MIM diode [8]. The received voltage using nanoantenna coupled to geometric diode is in the range of few microvolt which is limited to the nanoantenna size. To overcome this problem, antenna array has been employed to enhance the received voltage across the diode [1]. The terahertz lens is used to concentrate the EMW energy in a focused beam using different shapes. Transmitarrays are planar antennas consists of a number of antenna elements arranged to convert the spherical EMW into a plane wave concentrated in a focused beam [9, 10]. Different transmitarray configurations have been investigated in the terahertz band.

In this paper, The received voltage using nanoantenna coupled to the geometric diode is enhanced using two approaches. The first approach introduces the using of terahertz transparent transmitarray to focus the EMW toward to the rhombus shaped nanoantenna coupled to the geometric diode. In the second approach, the received voltage is enhanced by using a Yagi nanoanenna arrangement with a focused transmitarray. The paper is organized as follows: Sect. 2 introduces the design of the proposed nanoantenna and geometric diode for energy harvesting at 19.4 THz. Section 3 presents the design of transmitarray for receiving voltage enhancement. The using of Yagi arrangement of nanoantenna coupled to the geometric diode and transmitarray for receiving voltage enhancement is investigated at Sect. 4. Finally, Sect. 5 concludes these results. The proposed nanoantennas are designed and simulated using the finite integration technique (FIT) [11].

2 Nanoantenna Coupled to Geometric Diode

The IR energy harvesting is achieved by using rhombus shaped dipole nanoantenna with geometric diode placed in its gap. The detailed structure designed to receive IR radiation at a frequency 19.4 THz is shown in Fig. 1a. Each arm of the dipole nanoantenna

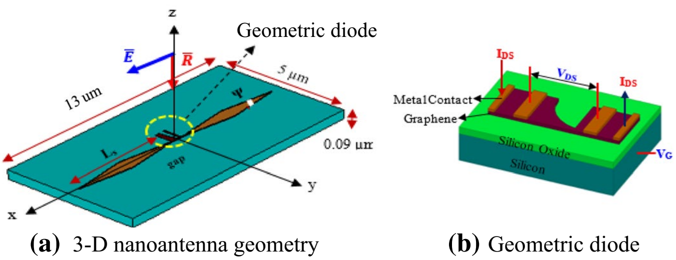
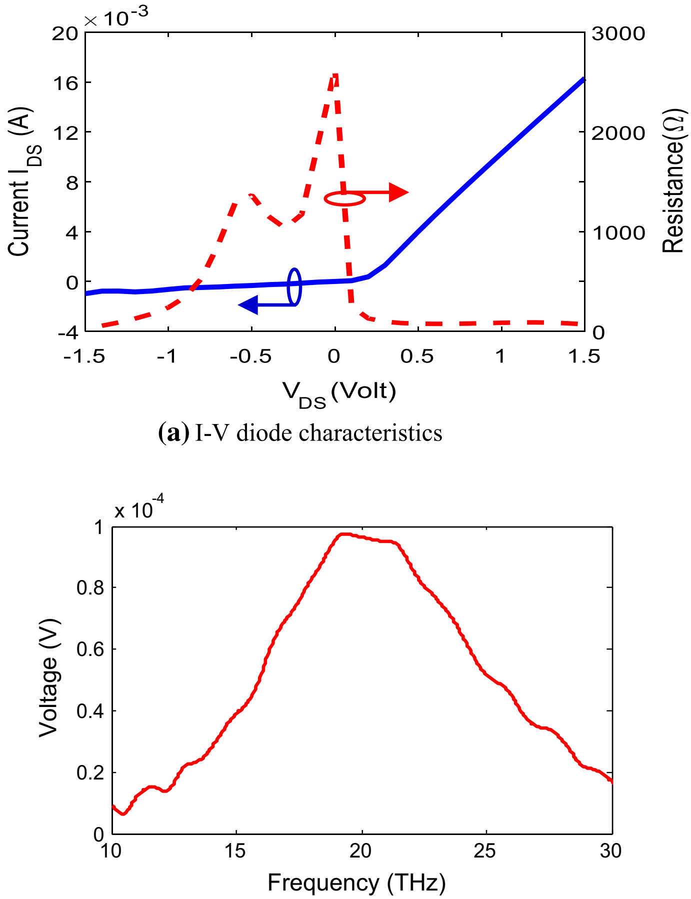


Fig. 1 The configuration of the IR nanoantenna coupled to arc-shaped geometric diode

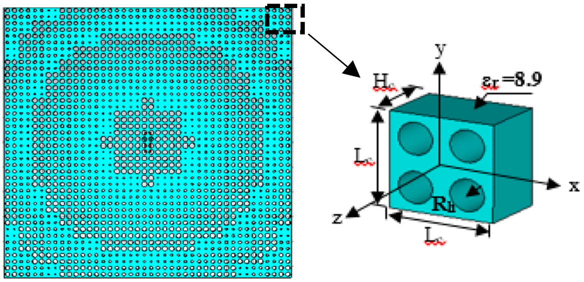
has a rhombus shape with arm length $L_s = 1.79$ µm, gap 0.6 µm, and tip angle $\Psi = 15°$ made from gold. The dipole is printed on a SiO_2 dielectric substrate with $\varepsilon_r = 3.9$ and dimensions of $13 \times 5 \times 0.09$ µm^3. An arc-shaped geometric diode is placed in the gap between the dipole arms. The geometric diode consists of rectangular section from graphene with constant shoulder length, 1 µm, neck width of 50 nm, and width of 500 nm. The upper-right part of the graphene layer is a quarter ellipse with minor radius, 50 nm, and major radius, 950 nm, optimized for high forward current as shown in Fig. 1b. The diode is designed and simulated using the Mont Carlo's simulation [12]. The geometric diode I-V characteristics and its equivalent resistance are shown in Fig. 2a. The diode introduces a peak forward current of 16.3 mA at 1.5 V with high asymmetry ratio. The high impedance of the geometric diode allows good impedance matching with the nanoantenna at the designed frequency. An x-polarized plane wave incident on the rectenna structure is used to calculate the received voltage across the geometric diode. The received voltage variations versus frequency are shown in Fig. 2b. The geometric



(a) I-V diode characteristics

(b) The received voltage

Fig. 2 **a** The I–V geometric diode characteristics and its equivalent resistance. **b** The received voltage across the geometric diode coupled to nanoantenna



(a) 4-D transmitarray structure **(b)** unit-cell configuration

Fig. 3 The transmitarray with the IR nanoantenna placed at the feeding point

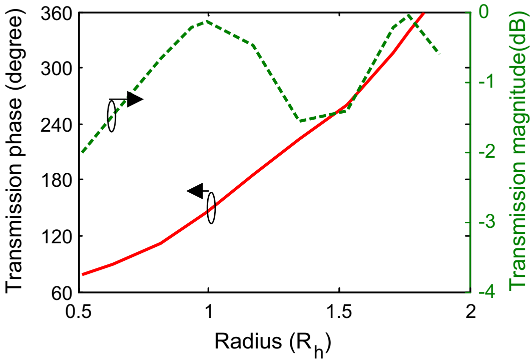


Fig. 4 The variation of transmission coefficient phase and magnitude versus the hole radius of the unit-cell element

diode has a negligible effect on the received voltage with maximum value of 16.5 μV at 20.5 THz.

3 Focused Transmitarray Fed by Nanoantenna Coupled to Geometric Diode

In order to enhance the recived voltage by the IR nanoantenna, a dielectric transmitarray is employed. The transmitarray acts as a lens which focuses the IR energy on the nanoantena and hence increase the received voltage. The proposed transparent transmitarray consists of 21 × 21 unit-cell elements using a single dielectric sheet from indium-tin-oxide (ITO) material of $\varepsilon_r = 4.76$ and total dimensions $214.2 \times 214.3\ mm^2$ is shown in Fig. 3. The transmitarray transforms the spherical wave into a plane wave by adding an additional phase shift to the transmitarray unit-cell elements [10]. Each unit-cell element has four holes with radius R_h which is changed according to the required phase compensation for the transmitarray. The variations of the transmission coefficient phase and magnitude versus the hole radius are shown in Fig. 4. The unit-cell element introduces 360° phase variation with magnitude varies from 0 to −2 dB. The nanoantenna coupled to the geometric diode is placed at a distance of 214.2 um from the array aperture.

In the transmitting mode, the nanoantenna feeds the transmitarray to produce a focused beam at boresight direction. The E- and H-plane radiation patterns at 19.5 THz compared to the nanoantenna alone are shown in Fig. 5. The transmitarray introduces a focused beam with half-power beamwidth (HPBW) of 3.8° and side-lobe level (SLL) of 14.5 dB. The maximum gain variations versus frequency of the transmitarray and the feeding nanoantenna are shown in Fig. 6. The transmitarray introduces a high gain of 20.5 dB and 1-dB bandwidth of 2.14 THz compared to maximum gain of 2.76 dB for the nanoantenna. In the receiving mode, the nanoantenna receives the focused electromagnetic energy collected by the transmitarray at its focus. The received voltage response of the nanoantenna in the presence of the focused transmitarray is shown in Fig. 7. The maximum received voltage is 97.6 μV with half -field bandwidth (HFBW) of 10.92 THz. The transmitarray increase the incident electromagnetic energy on the nanoantenna which improve the charge accumulation between the nanoantenna arms across the geometric diode.

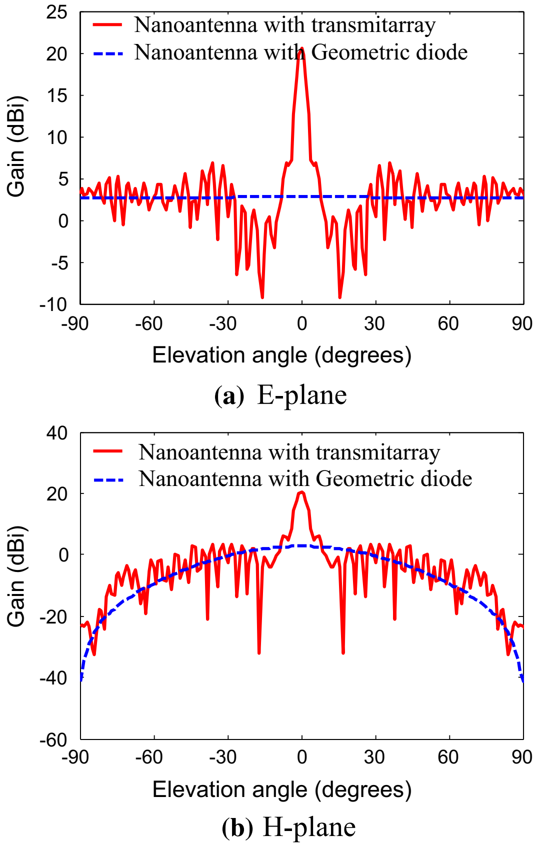


Fig. 5 The E- and H-plane Gain patterns of 21 × 21 unit-cells transmitarray nanoantenna

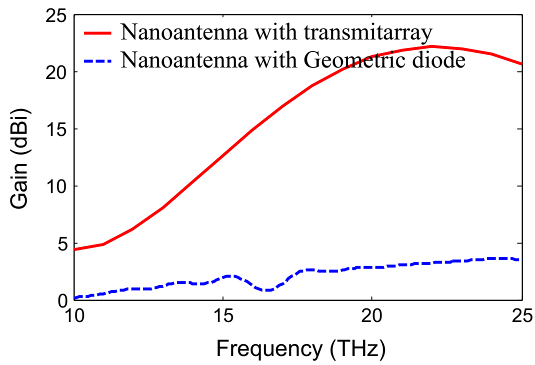


Fig. 6 The variation of gain versus frequency of 21 × 21 unit-cells transmitarray nanoantenna

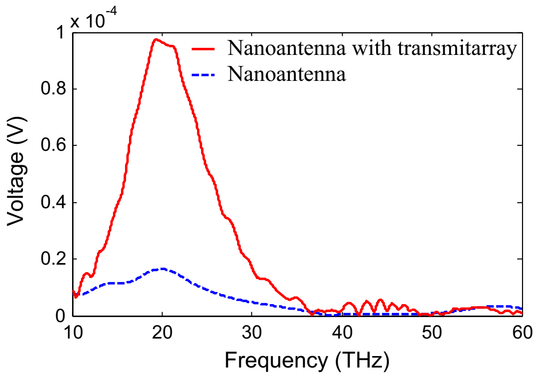


Fig. 7 The received voltage of the IR nanoantenna coupled to Geometric diode with transmitarray 21 × 21 cell element

4 Ygai Nanoantenna Coupled to the Geometric Diode

The received voltage can be improved by increasing the directivity of the nanoantenna coupled to the geometric diode by using Yagi arrangement as shown in Fig. 8. Two rhombic shaped dipoles are used as reflectors with length of 15.3 µm and distance 1.85 µm from the nanoantenna element. Three directors, each of length 13.3 µm are placed at distance 0.96 µm from the nanoantenna element. The received voltage responses of the Yagi nanoantenna arrangement for one, two, and three directors are presented in Fig. 9. The maximum recived voltage is increased by increasing the number of directors to be 27.7 µV, 34.1 µV, and 39.15 µV with HFBW of 4.05 THz. for the 1st, 2nd, and the 3rd director respectively due to the increase in antenna directivity.

The Yagi nanoantenna arrangement is used to feed the transmitarray in the transmitting mode. The E- and H-plane radiation patterns of the transmitarray compared to the Yagi nanoantenna arrangement at 19.4 THz are shown in Fig. 10. The HPBW is 4.2°/45.1° and SLL of 13.2/5.6 dB for the transmitarray/Yagi nanoantenna in E-plane. The gain response for the transmitarray and the Yagi nanoantenna are shown in Fig. 11. The transmitarray gain is increased by increasing the number of directors to 20.7 dB with 1-dB bandwidth of 0.705 THz compared to 7.3 dB gain for the Yagi nanoantenna alone. A focused directed beam is achieved. In the receiving mode, the received voltage by the Yagi nanoantenna arrangement is increased by applying the focused transmitarray to the enhance the

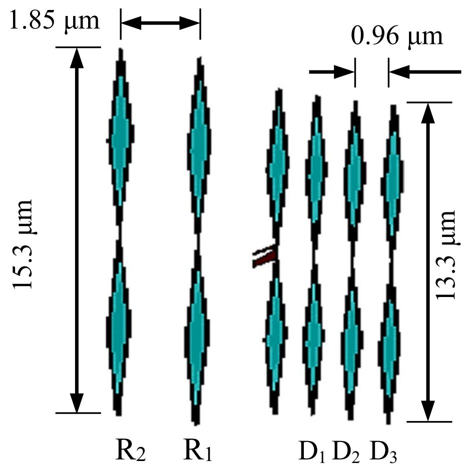


Fig. 8 The Yagi-arrangement of nanoantenna coupled to geometric diode

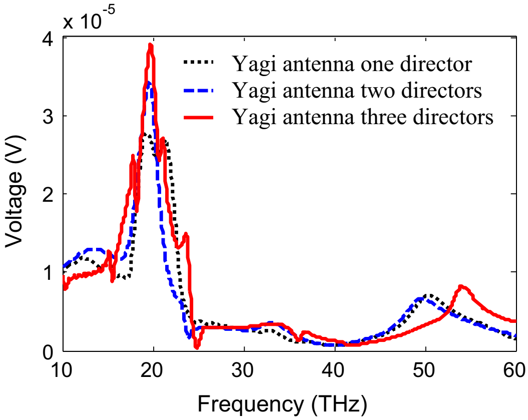


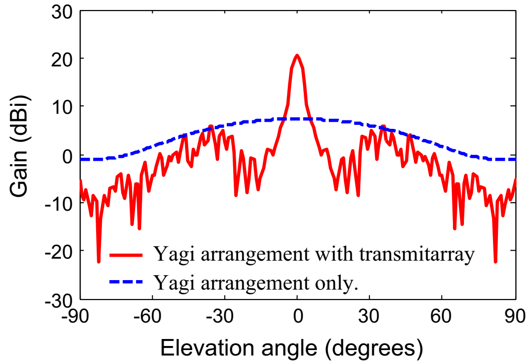
Fig. 9 The received voltage verses frequency of the Yagi nanoantennas arrangement

received electromagnetic energy. The received voltage response of the transmitarray with the Yagi nanoantenna arrangement is shown in Fig. 12. The maximum received voltage across the geometric diode is 0.202 mV with HFBW of 5.719 THz.

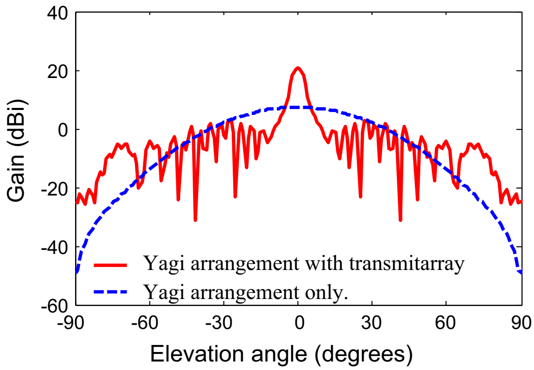
5 Conclusion

This paper introduces a dipole nanoantenna coupled to an arc-shaped geometric diode for terahertz energy harvesting at 19.5 THz. The single nanoantenna receives voltage of 16.5 µV with high conversion efficiency. A novel technique for increasing the receiving voltage of the nanoantennas has been introduced. A transparent transmitarray consists of a single dielectric sheet shaped with holes to focus the EMW into the nanoantenna surface placed at 214.2 µm from the array aperture is proposed. In the transmitting mode, transmitarray introduces a high gain of 20.5 dB with a 1-dB bandwidth of 2.14 THz compared to 2.76 dB for the nanoantenna alone. In the receiving mode, the maximum received voltage is 97.6 µV with HFBW of 10.92 THz. In the second technique the Yagi nanoantenna

Fig. 10 The E- and H-plane radiation patterns of the 21×21 transmitarray with the Yagi nanoantennas arrangement

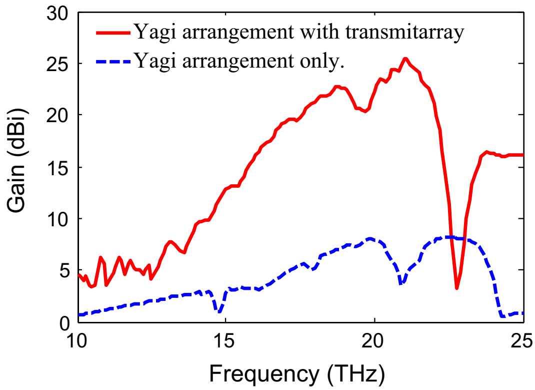


(a) E-plane



(b) H-plane

Fig. 11 The variation of gain versus frequency for the 21×21 transmitarray with the Yagi nanoantennas arrangement



arrangement is used to improve the nanoantenna directivity. Parametric studies on the number of reflectors, and directors are introduced for maximum received voltages. The maximum received voltage is increased by increasing the number of directors to be 27.7 μV, 34.1 μV, and 39.15 μV. for the 1st, 2nd, and the 3rd director respectively. The transmitarray coupled to the Yagi nanoantenna arrangement increases the received voltage to 0.202 mV with high conversion efficiency.

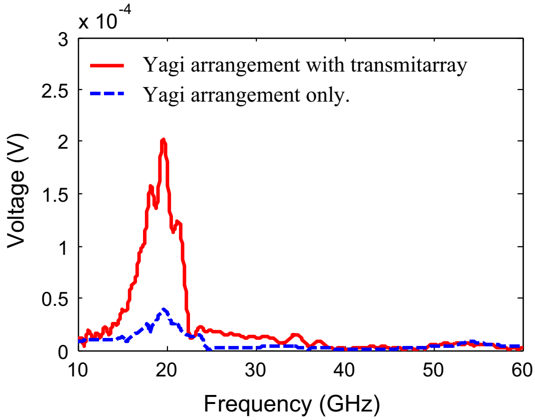


Fig. 12 The received voltages of the 21 × 21 transmitarray with the Yagi nanoantennas arrangement three directors

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