



Terahertz photoconductive antennas based on arrays of metal nanoparticle structures

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Received: 8 May 2021 / Accepted: 18 December 2021 / Published online: 9 February 2022
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Abstract

In this study, in order to amplify the radiation at Terahertz photoconductive antennas, metal nanoparticles are used in semiconductor layers based on plasmonic principles. The use of nanoparticles between antenna electrodes and semiconductor layers not only enhances the THz radiation intensity but also changes the radiation frequency peak. The changes of electric charge carriers versus the incidence of laser pulses and the production of an electric current on the antenna surface are simulated with the COMSOL Multiphysics software through the FEM method. The changes of the electric current at the semiconductive surface generate electric field radiation. This has been simulated using the CST STUDIO software through the FDTD method.

Keywords Finite element method (FEM) · Finite different time domain (FDTD) · THz photoconductive antenna · Metal nanoparticles · Surface plasmonic

1 Introduction

In recent years, THz technology has been expanded and applied in various fields such as communication, spectroscopy, medicine, security, imaging and remote control. Research on this issue has also experienced a great growth. The frequency range between the far infrared and the microwave frequency of the electromagnetic spectrum (0.1–10THz) is called the Terahertz (THz) region (Carelli et al. 1995; Pine et al. 1996; Hu and Nuss 1995; Woodward et al. 2003; Gregory et al. 2005). THz waves cause vibrations in molecules. Therefore, the effects of the chemical bonding within drugs can be determined using these waves (Hu and Nuss 1995; Woodward et al. 2003; Gregory et al. 2005; Saeedkia and Safavi-Naeini 2006; Khiabani et al. 2013; Mittleman et al. 1998). Cancerous tissues contain more water than healthy ones. Since THz waves are absorbed by water, THz waves can be used to detect cancerous tissues (Mittleman et al. 1998; Fitch and Osiander 2004; Taday 2003; Wallace et al. 2004).

The best source for the generation of THz waves is a THz photoconductive antenna, introduced in the 1980s (Moreno et al. 2018; Auston et al. 1984). This antenna has grown

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significantly due to its superior characteristics over other THz sources, such as simple layout structure, low cost, better signal-to-noise ratio, continuous wide bandwidth, and room temperature performance. However, the main disadvantage of a THz antenna is its low efficiency. Generally, the efficiency of such antennas is less than 0.1%. To increase it and to amplify the output THz power, many efforts have been made such as examining the parameters affecting the performance of THz photoconductive antennas using numerical methods and of large aperture antenna (Nazeri and Massudi 2010) using trapezoidal interlocking finger-print in the gap area of the antenna (Khiabani et al. 2014).

In recent years, the application of metamaterials has greatly expanded in various types of antennas, sensors and filters. In this regard, certain plans have been proposed to use metamaterials in the substrate of THz photoconductive antennas to increase their output power and improve their orientation. For example, a new design of such antennas has been presented based on metamaterial structures (Alizadeh et al. 2020). It has been found that, in a THz photoconductive antenna with a metamaterial structure and a frequency peak of 0.8THz, the frequency peak increases to 1.3THz. Another method of increasing THz field radiation is the use of helical electrodes in conventional bipolar antennas (Saeid and Bahari 2021). The present study benefits from the inductive property of electric current movement in helical lines to increase the intensity of electrical current and electrical radiation.

A method to improve the performance of THz photoconductive antennas is the use of a material that can increase the amount of optical current on the surface of the antenna. For this purpose, silver nanostructures have been recommended (Lepeshov et al. 2017; Preu et al. 2011; Chuang 2012; Burford and El-Shenawee 2016).

This study contributes to the literature by proposing spherical metal nanoparticles arrays in THz photoconductive antennas. It increases the intensity of optical current in the antenna gap and ultimately enhances the output power and efficiency of the antenna. In addition, with a different modeling of the antenna behavior, the dimensions and distance of nanoparticles are optimized and a higher THz output power is achieved.

2 Antenna structure

A THz photoconductive antenna, as in Fig. 1, consists of two metal electrodes located on a semiconductive substrate. Semiconductors have a very short lifetime (about 300 femtoseconds). An antenna of this type operates when a laser pulse whose energy is higher than the gap energy of the semiconductor stimulates the active area of the antenna to produce electron-hole pairs. As a constant electric field is applied between two metal electrodes, charge carriers (electrons and holes) are accelerated and optical current is generated at the antenna surface (Auston et al. 1984; Preu et al. 2011).

The current density created in the antenna gap depends on the characteristics of the semiconductor and the laser pulses. According to the Drude model, the electric current density is created in a specific way. First, it is assumed that the antenna gap is uniform and E_{DC} is the electric voltage applied by the electrodes in the antenna gap (Auston et al. 1984; Chuang 2012).

$$J(t) = \int_0^{+\infty} \frac{P_{em}}{\tau_{las}} \exp\left(\frac{-4\ln(t-t')^2}{\tau_{las}^2}\right) \times \exp\left(-\frac{t'}{\tau_{em}}\right) \times \frac{\delta\tau_{em}}{m_{em}} \left(1 - \exp\left(\frac{-t'}{\delta t_{em}}\right)\right) E_{DC} dt' \quad (1)$$

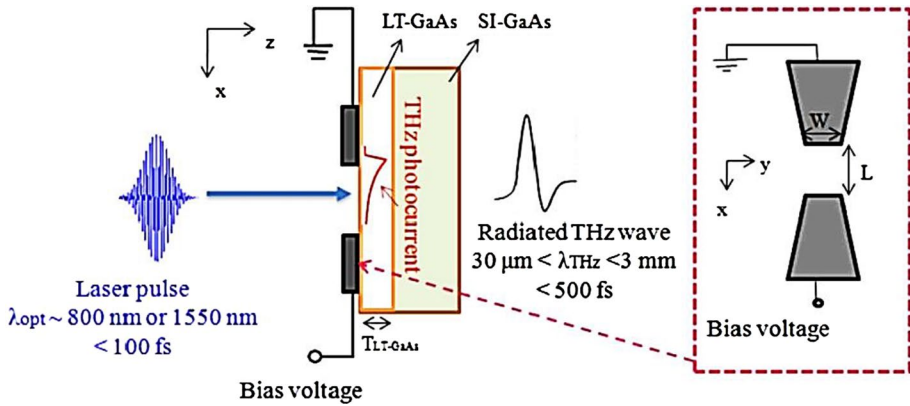


Fig. 1 The structure of a THz photoconductive antenna: the location of the electrodes and the occurrence of a femtosecond laser pulse in the area between the electrodes (i.e., the antenna gap) (Preu et al. 2011; Chuang 2012)

where τ_{em} is the lifetime of the carriers, τ_{las} laser pulse period, P_{em} is the laser average power input, and E_{DC} is the bias electrical field between the electrodes.

Because the lifetime of electron-holes is very short, an electromagnetic pulse at the THz frequency is generated from the temporal changes in the velocity of the carriers. The density of the current created in the antenna gap depends on the characteristics of the laser pulse and the semiconductor. According to the Drude model, the optical current generated in the antenna gap is calculated as follows (Auston et al. 1984; Chuang 2012).

$$I = \frac{eV_b\mu_e\tau\eta_L P_L}{hf_L L^2} \tag{2}$$

where e is the electron charge, V_b is the applied bias voltage, μ_e is the mobility of the charge carriers, τ is the time duration of the optical current, η_L is the optical efficiency, P_L is the input laser power, h is the Planck constant, f_L is the laser frequency and L represents the length of the antenna gap. Because the density of the optical current directly depends on the electric field, the use of metal nanoparticles in the gap area and the semiconductor environment of the antenna intensify the conduction of electrons and generate a local electric field around each of the metal nanoparticles. Thus, in contrast to a simple antenna, a THz photoconductive antenna achieves amplified optical current as the laser pulse is radiated on a gallium arsenide (GaAs) semiconductor, a constant electric field is applied between the two electrodes and local electric fields are formed around each metal particles. THz radiation directly depends on the first-order time derivative of the antenna optical current density (Auston et al. 1984; Chuang 2012).

$$E_{THz} \propto \frac{dI(t)}{dt} \tag{3}$$

According to the following equation, the efficiency of a THz antenna increases with an increase in the current density at the antenna surface. This increased efficiency leads to the amplification of the antenna output pulse (Chuang 2012).

$$\eta_{LE} = \frac{eV_b^2 \mu_e \tau^2 \eta_L P_L}{hf_L L^2} \tag{4}$$

3 THz photoconductive antenna design

A THz photoconductive antenna consists of two metal electrodes with the thickness of 0.1 μm (micrometer) on a GaAs semiconductor. As shown in Fig. 2, the length and the width of the antenna are 140 μm and 90 μm respectively. The gap between the two electrodes, which forms the active area of the antenna, is 10 and 5 μm in length and width respectively (Burford and El-Shenawee 2016). This antenna, which is based on metal nanoparticles, exactly has the dimensional specifications of a simple antenna.

Figure 1(c) shows an *x*-*z* cross section of the device taken at the *y* coordinate corresponding to the device center. The THz-PCA anode and cathode are located on the bottom of the LT-GaAs thin-film layer, while an array of plasmonic nanoparticle is located on the top surface. The incident optical pump excites plasmon resonances in the nanoparticle array, leading to the enhanced optical field in the LT-GaAs layer. In addition to the plasmonic enhancement, the proposed thin film PCA will have improved performance due to complete usage of the available optical pump area. The boundary conditions for the optical response are periodic on the *x*-*z* boundaries and absorbing impedance-matched boundaries are assumed on all other faces. The excitation was incident in the *z* direction, with polarization and center location varying depending on the configuration of the electrodes under consideration.

Various parameters such as dimension, distance and arrangement of nanoparticles can affect the output and performance of an antenna in a desired frequency range. In this study, nanoparticles were simulated with a diameter of 50 to 250 nm, a thickness of 5 to 20 nm and a distance of 0.6 to 2 mμ. Based on this design, the most optimal mode was implemented to achieve the maximum output power. Accordingly, the optimal diameter of each nanoparticle emerged to be 100 nm, its thickness was 10 nm and the distance between the particles was 1.4 mμ.

Comparison of the results from Burford et al. (Burford and El-Shenawee 2016) and Moreno et al. (Moreno, et al. 2014) to calculations utilizing the model proposed in this

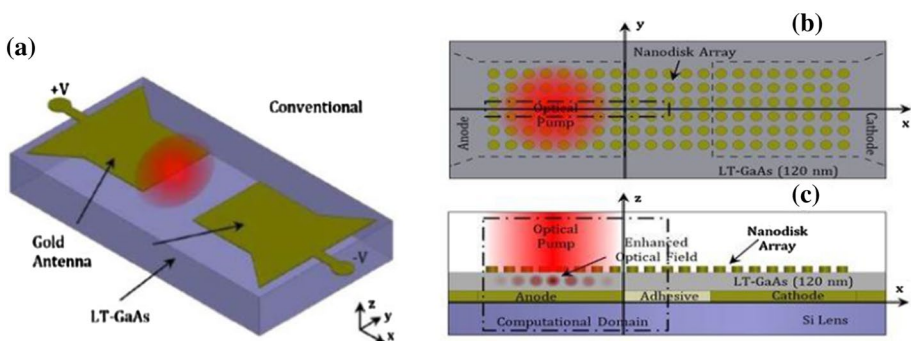


Fig. 2 THz photoconductive antenna (Bottom Located Thin Film, BLTF) with and without metal nanoparticles on the semiconductor layer and gap of antenna (Burford and El-Shenawee 2016)

work is illustrated in Fig. 3. The optical excitation is temporally centered at $t_0 = 3ps$ in all cases. Both results are normalized to the peak value of $0.02 A/\mu m^2$.

4 Simulation results

In the first step, according to Fig. 2(a) and following the procedure in reference (Burford and El-Shenawee 2016), two electrodes are placed on the top of a semiconductor. When a laser optical incident the gap between the electrodes, the electric current created on the surface was modeled in two stages using the COMSOL Multiphysics software and the FEM method. In the first stage, the laser optical is incident the antenna gap, and electric charge carriers were created inside the gap. In the second stage, with the help of bias voltage connected to the electrodes, the electric charge carriers generated an electric current at the surface of the semiconductor and the electrodes. Due to the importance of the laser radiative power and according to Eqs. 1, 2, 3 and 4 an increase in the power caused an increase in the electric current and the charge carriers generated at the surface of semiconductors. The changes in the electric current and the charge, as reported in Fig. 4(a) and (b), were simulated with different laser powers.

According to Eq. 3, the changes in the electric charge and the field caused radiation at the antenna surface. In the next step, following the procedure in reference (Burford and El-Shenawee 2016), these changes were achieved with the CST STUDIO software, Maxwell equations and the FDTD method. Once these electrical current changes were entered in the software space, the radiation changes in the THz frequency were calculated. Figure 5 shows the changes of the electric field in a THz photoconductive antenna. They occurred at the frequency of 0.1 to 5 THz and with different laser powers. The frequency peak of this type of antenna was 0.5 THz.

Finally, to amplify the electric current in the antenna structure, as shown in Fig. 2, metal Plasmon nanoparticles were used inside the antenna gap and the semiconductor. The plasmonic nanoparticles were spherical, which could achieve more amplification than other forms

Fig. 3 Comparison of the calculated photocurrent at the center of the gap

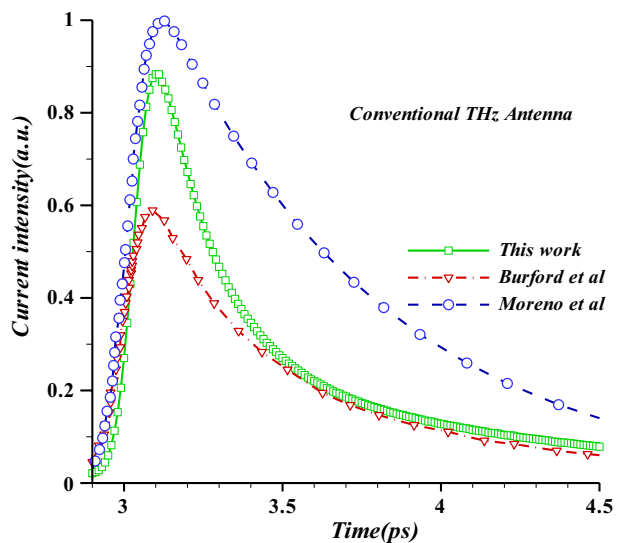
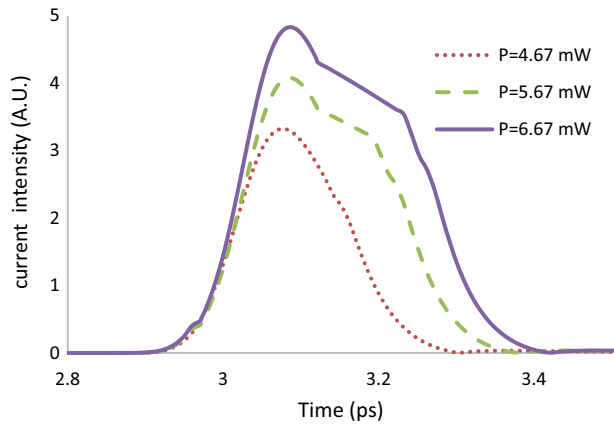
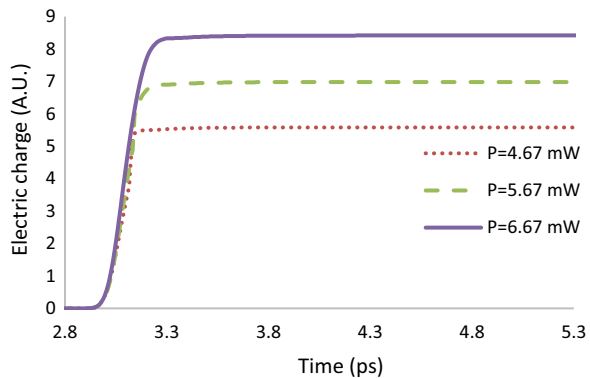


Fig. 4 **a** Changes in the electrical current at the surface of the photoconductive antenna for different laser powers **b** Changes in the electrical charge at the surface of the photoconductive antenna for different laser powers



(a) Changes in the electrical current at the surface of the photoconductive antenna for different laser powers



(b) Changes in the electrical charge at the surface of the photoconductive antenna for different laser powers

(Burford and El-Shenawee 2016). The changes of the electric current in the BLTF antenna took place in two states with and without nanoparticles, as shown in Fig. 6. The changes of the radiation field in the semiconductor are also shown in Fig. 7.

Using the calculation of electric current with the help of COMSOL software, this electric current enters the antenna electrodes in CST software to calculate the radiation field. (Table 1) The changes of the current in the antenna electrode and the semiconductor media led to the formation of a THz electric field. In addition, the presence of the spherical nanoparticles made of gold enhanced the output radiation of the antenna Fig. 8.

The Fourier transform of the THz radiation is shown in Fig. 9 As it can be seen, the radiation has changed in the range of 0.1–5THz.

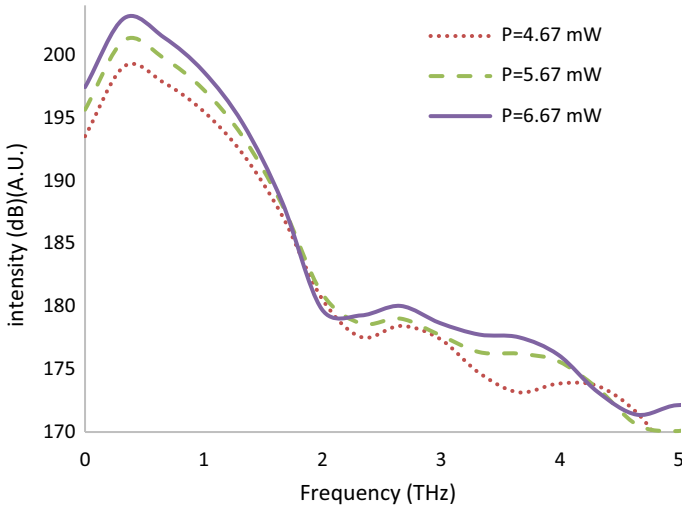


Fig. 5 Changes of the electric field in the frequency range of 0.1–5 THz with different laser powers

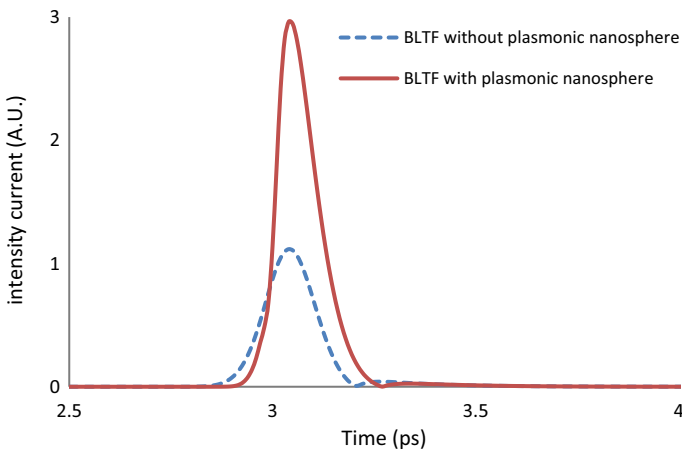


Fig. 6 The performance of the BLTF photoconductive antenna improved with plasmonic spherical nanoparticles

5 Conclusion

The radiation power in the THz area has been studied for photoconductive antennas. Since typical photoconductive antennas have low radiation power (the efficiency less), designing an appropriate structure for photoconductive antennas is of high importance. To increase the radiation output power of antennas, spherical nanoparticles of gold have been used. These nanoparticles cause an increase in the variable electric current over time.

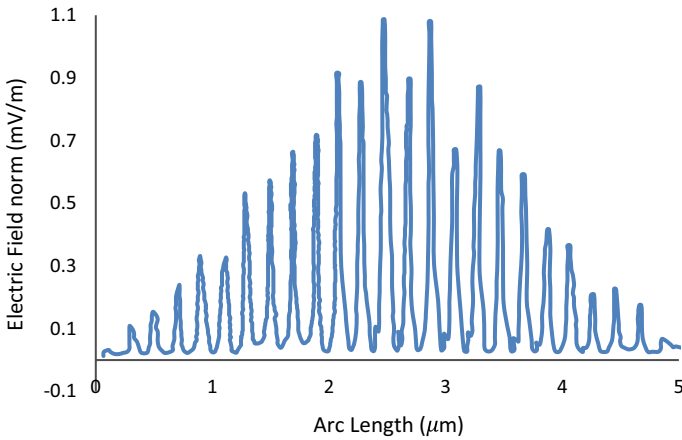


Fig. 7 Changes in the radiation field along the antenna semiconductor

Table 1 summarizes the model parameters use in this study (Burford and El-Shenawee 2016)

Symbol	Description	Value
λ	Free-space wavelength	780nm
P_{ave}	Average laser power	3.57mW
ϵ_r	Au	-22.5
σ	Au	2.4×10^3
ϵ_r	LT-GaAs	13.7
σ	LT-GaAs	1.1×10^3

This accounts for the LT-GaAs and electrodes in our model

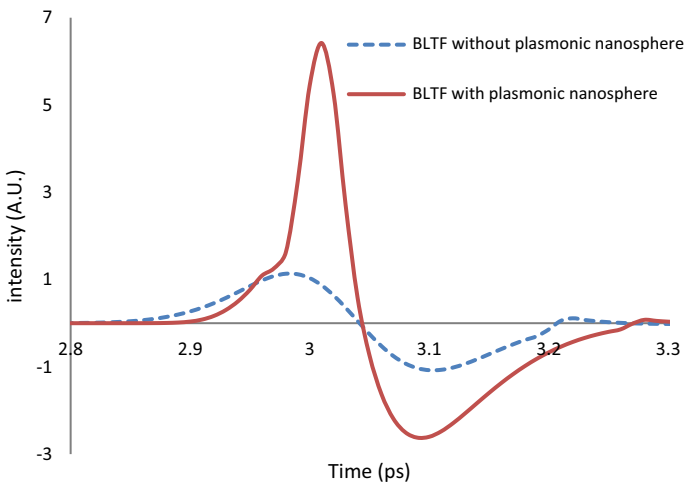


Fig. 8 Effect of the spherical nanoparticles on the BLTF antenna

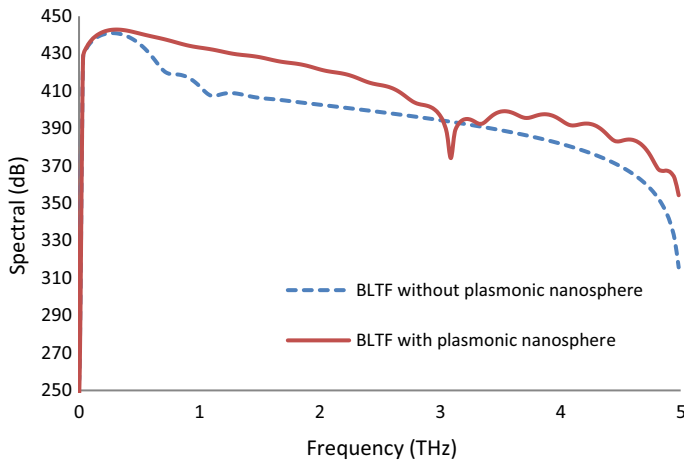


Fig. 9 Effects of the nanoparticles on the THz radiation in the frequency range of 0.1 to 5 THz

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