Terahertz Photoconductive Antennas based on Arrays of Metal Nanoparticle Structures

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Research Article

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Terahertz photoconductive antennas based on arrays of metal nanoparticle structures

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Abstract

In this study, in order to amplify the radiation at Terahertz (THz) 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 strike 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 to 10 THz) is called the Terahertz (THz) region [1-5]. THz waves cause vibrations in molecules. Therefore, the effects of the chemical bonding within drugs can be determined using these waves [3-8]. Cancerous tissues contain more water than healthy ones. Since THz waves are absorbed by water, THz waves can be used to detect cancerous tissues [8-11].

The best source for the generation of THz waves is a THz photoconductive antenna, introduced in the 1980s [12-13]. This antenna has grown 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 [14] using trapezoidal interlocking finger-print in the gap area of the antenna [15].

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 [16]. 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 [17]. 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 light current on the surface of the antenna. For this purpose, silver nanostructures have been recommended [18-21].

This study contributes to the literature by proposing spherical metal nanoparticles arrays in THz photoconductive antennas. It increases the intensity of light 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 Figure 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 strikes 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 [13, 19].

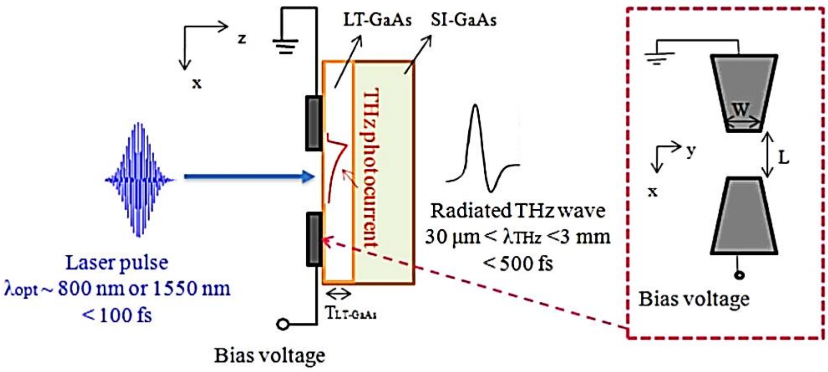

Figure 1. The structure of a THz photoconductive antenna: the location of the electrodes and the occurrence of a femtosecond laser pulse in the area between the electrodes (i.e., the antenna gap) [20-19]

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 current density is created in a specific way. First, it is assumed that the antenna gap is uniform and E_{DC} is the voltage applied by the electrodes in the antenna gap [13, 20].

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

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 light current generated in the antenna gap is calculated as follows [13,20].

$$I = \frac{eV_b\mu_e\tau\eta_L P_L}{hf_L l^2} \quad (2)$$

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 light 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 light 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 light current density [13,20].

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

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 [*20*].

$$\eta_{LE} = \frac{eV_b^2\mu_e\tau^2\eta_L P_L}{hf_L l^2} \quad (4)$$

3. THz photoconductive antenna design

A THz photoconductive antenna consists of two metal electrodes with the thickness of 0.1 um (micrometer) on a GaAs semiconductor. As shown in Figure 2, the length and the width of the antenna are 140µm and 90µm respectively. The gap between the two electrodes, which forms the active area of the antenna, is 10 and 5 um in length and width respectively [21]. This antenna, which is based on metal nanoparticles, exactly has the dimensional specifications of a simple antenna.

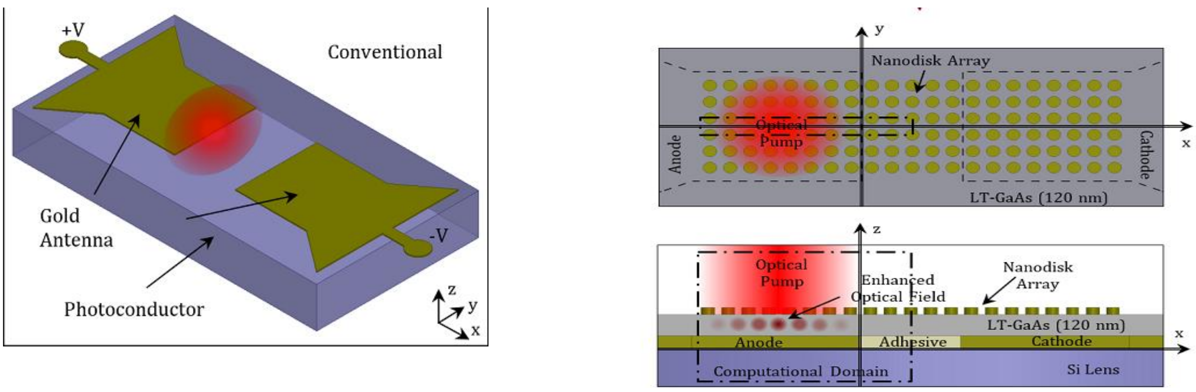

Figure 2. THz photoconductive antenna (Bottom Located Thin Film, BLTF) with and without metal nanoparticles on the semiconductor layer and gap of antenna [21]

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 μm. 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 um.

4. Simulation results

In the first step, according to Figure 2A and following the procedure in reference [21], two electrodes are placed on the top of a semiconductor. When a laser light struck 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 light struck 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 Equations 1 to 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 Figures 3A and 3B, were simulated with different laser powers.

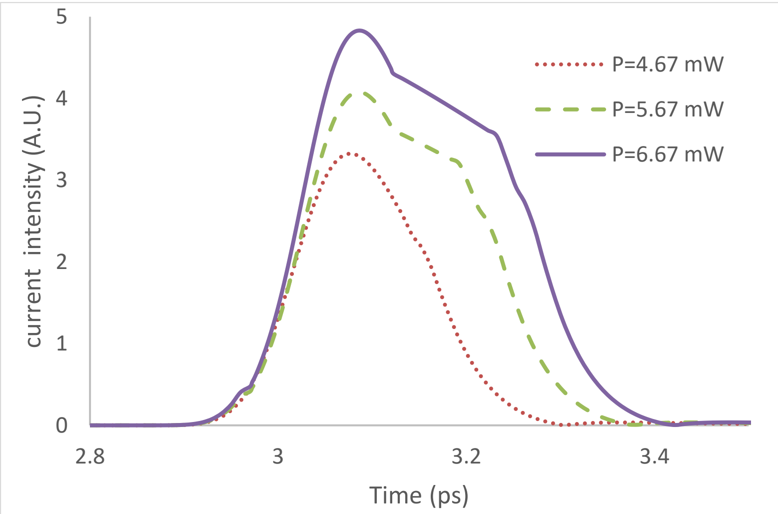

Figure 3A. Changes in the electrical current at the surface of the photoconductive antenna for different laser powers

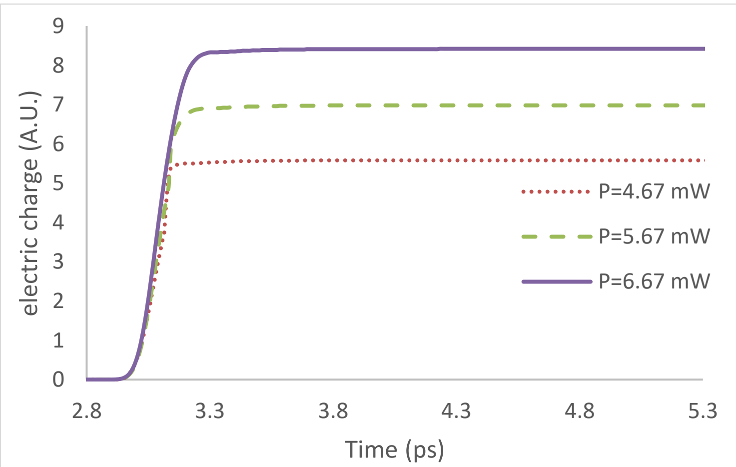

Figure 3B. Changes in the electrical charge at the surface of the photoconductive antenna for different laser powers

According to Equation 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 [21], 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 4 shows the changes of the electric field in a THz photoconductive antenna. They occurredat 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.

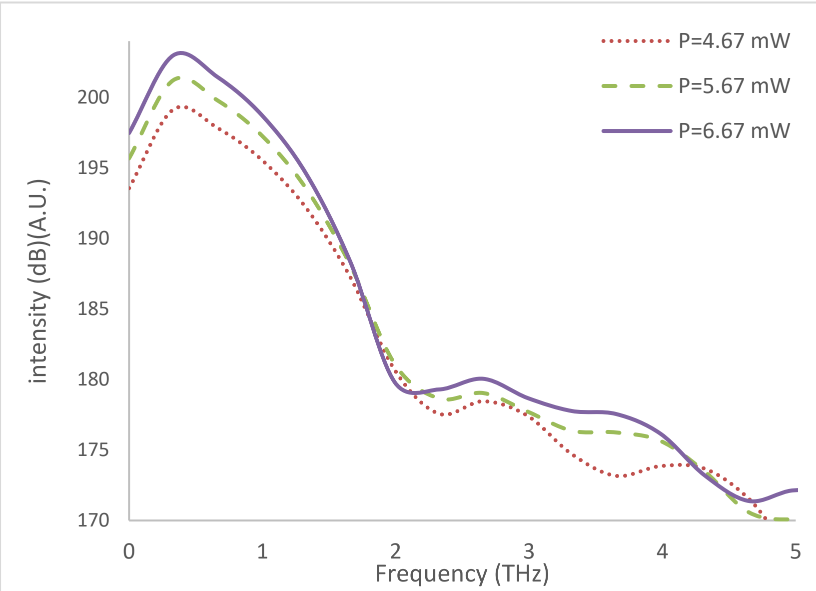

Figure 4. Changes of the electric field in the frequency range of 0.1-5 THz with different laser powers

Finally, to amplify the electric current in the antenna structure, as shown in Figure 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 [21]. The changes of the electric current in the BLTF antenna took place in two states with and without nanoparticles, as shown in Figure 5. The changes of the radiation field in the semiconductor are also shown in Figure 6.

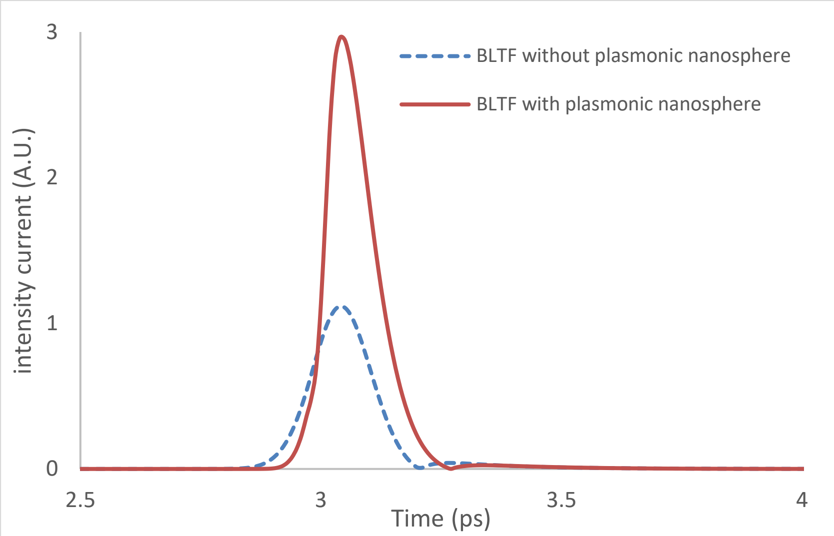

Figure 5. The performance of the BLTF photoconductive antenna improved with plasmonic spherical nanoparticles

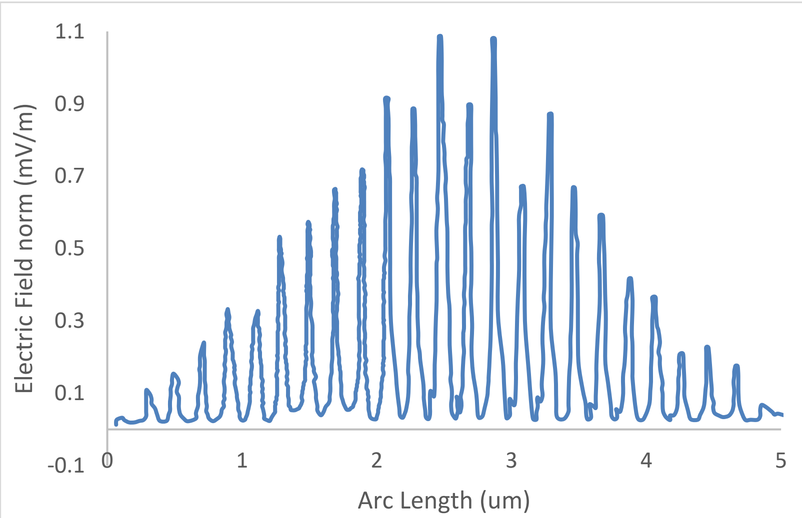

Figure 6. Changes in the radiation field along the antenna semiconductor

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. The changes of the current in the antenna electrode and the semiconductive environment 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 (Figure 7).

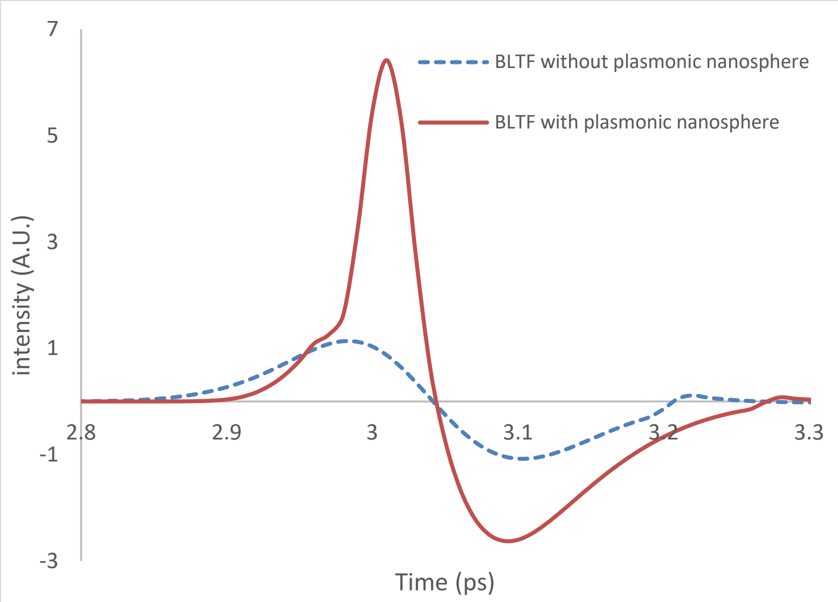

Figure 7. Effect of the spherical nanoparticles on the BLTF antenna

The Fourier transform of the THz radiation is shown in Figure 8. As it can be seen, the radiation has changed in the range of 0.1 to 5 THz.

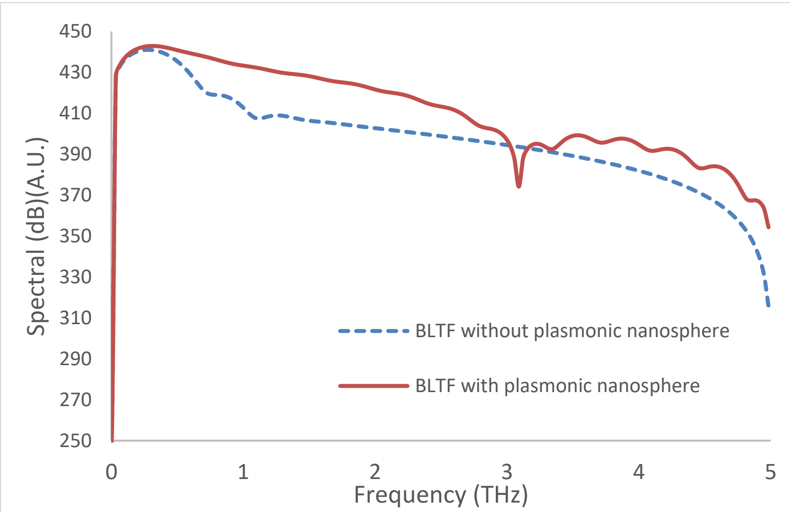

Figure 8. Effects of the nanoparticles on the THz radiation in the frequency range of 0.1 to 5 THz

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.

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Figures

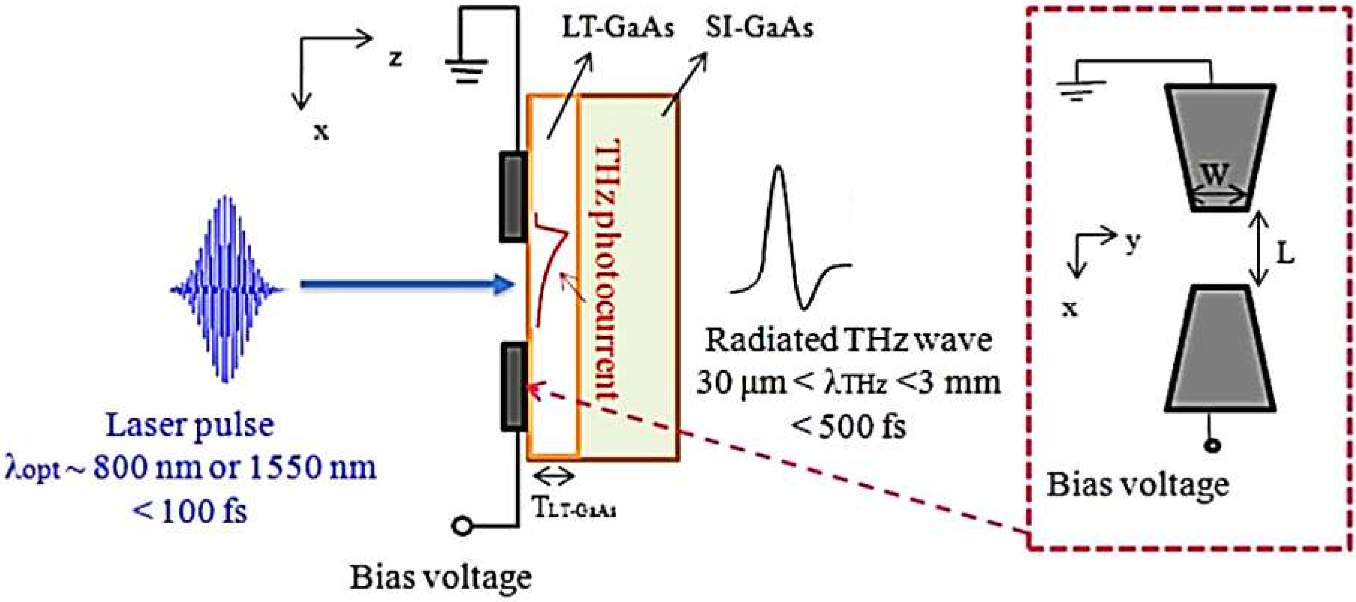


Figure 1

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) [20-19]

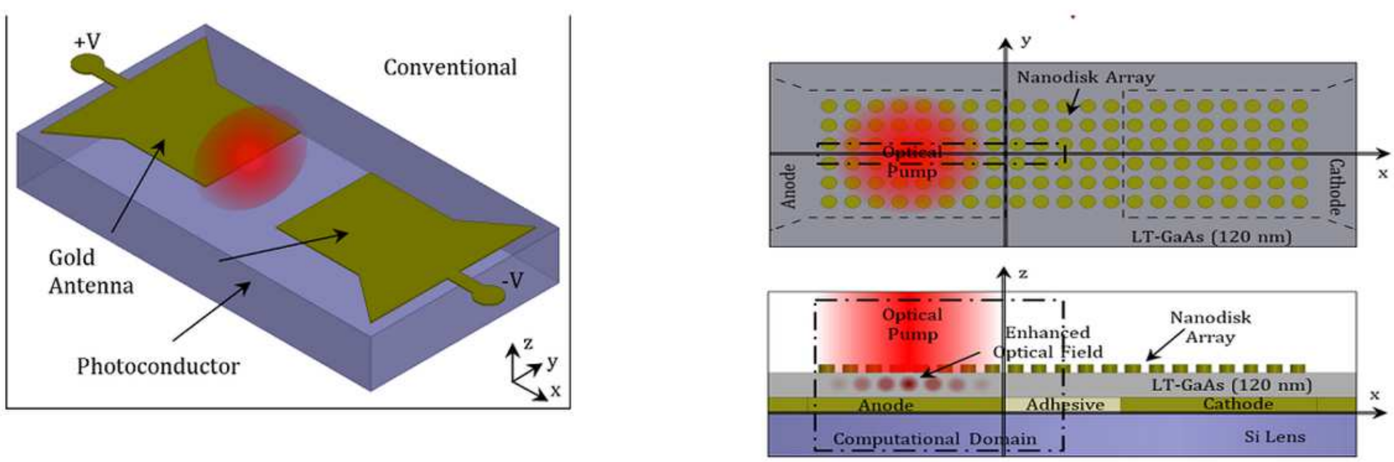
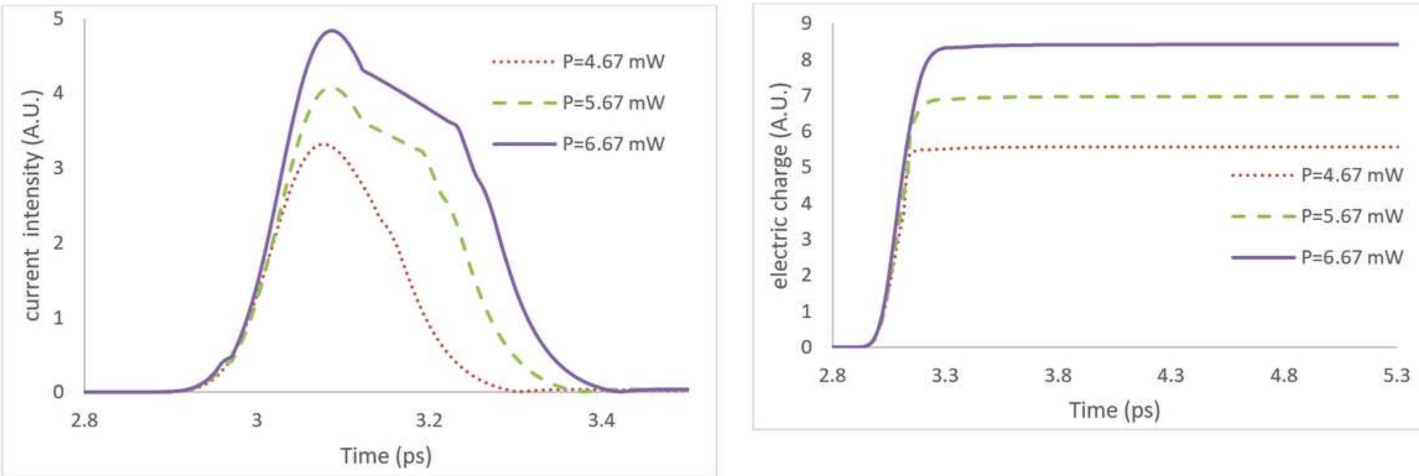


Figure 2

THz photoconductive antenna (Bottom Located Thin Film, BLTF) with and without metal nanoparticles on the semiconductor layer and gap of antenna [21]



A B

Figure 3

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

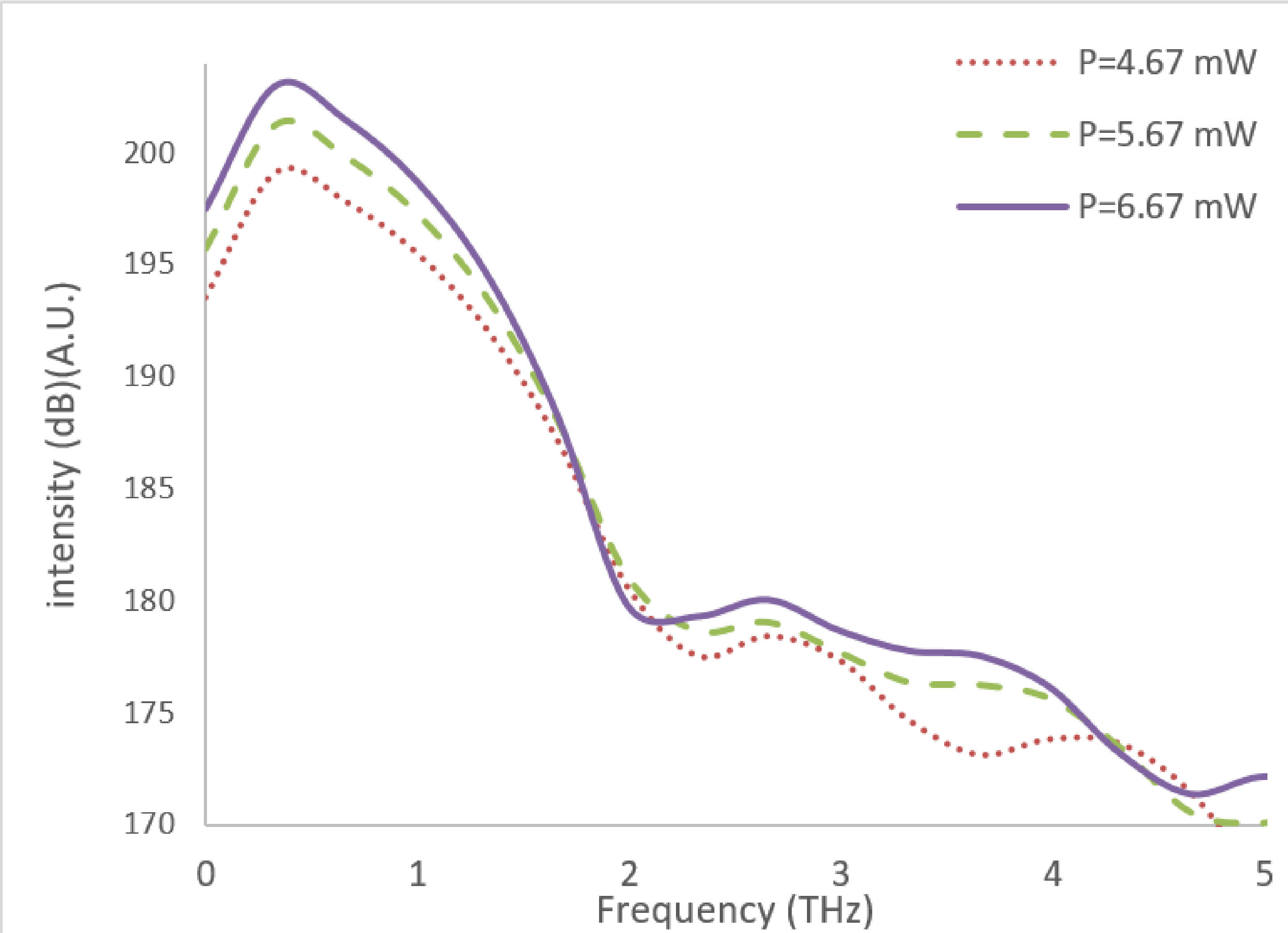


Figure 4

Changes of the electric field in the frequency range of 0.1-5 THz with different laser powers

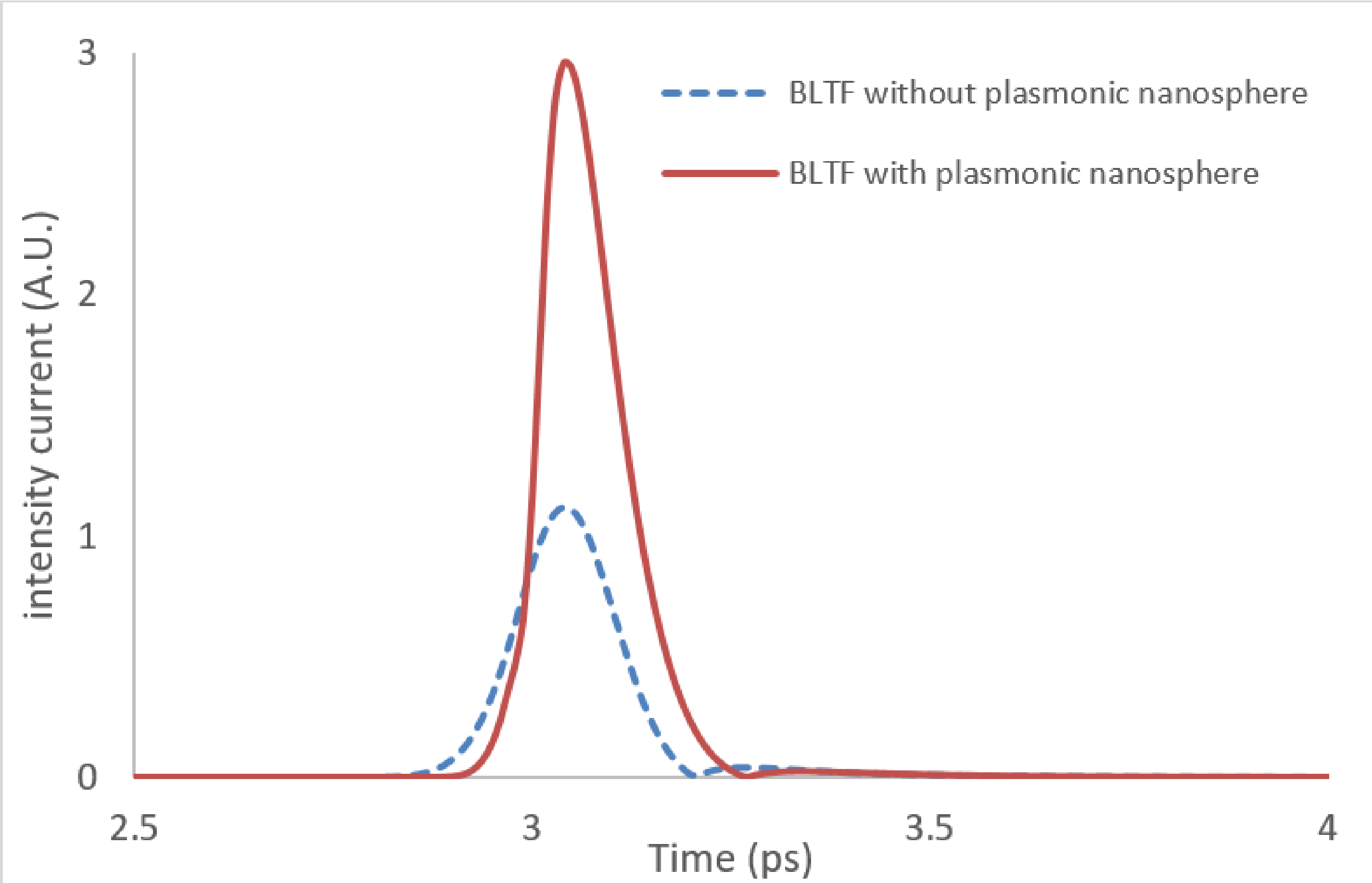


Figure 5

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

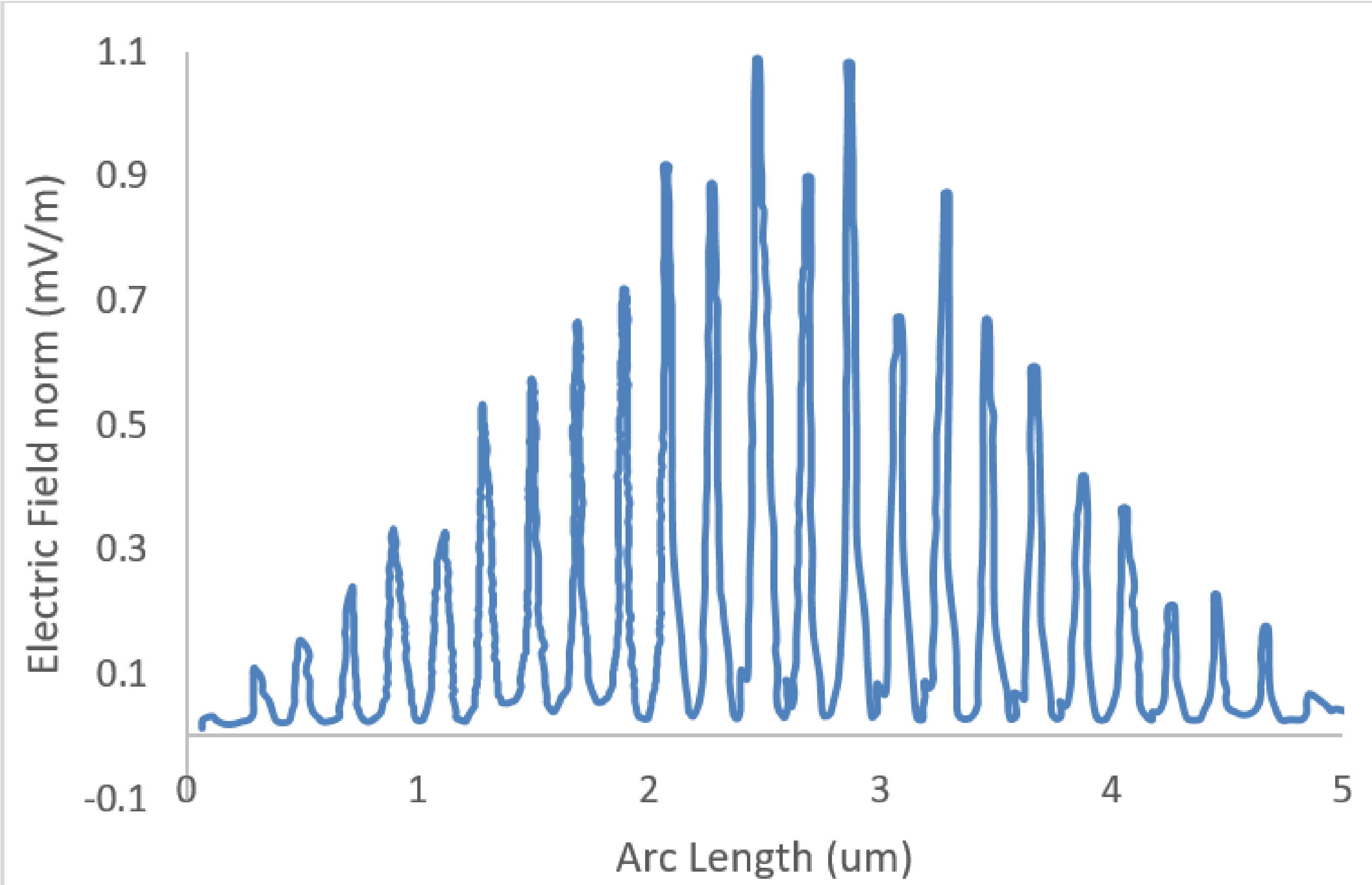


Figure 6

Changes in the radiation field along the antenna semiconductor

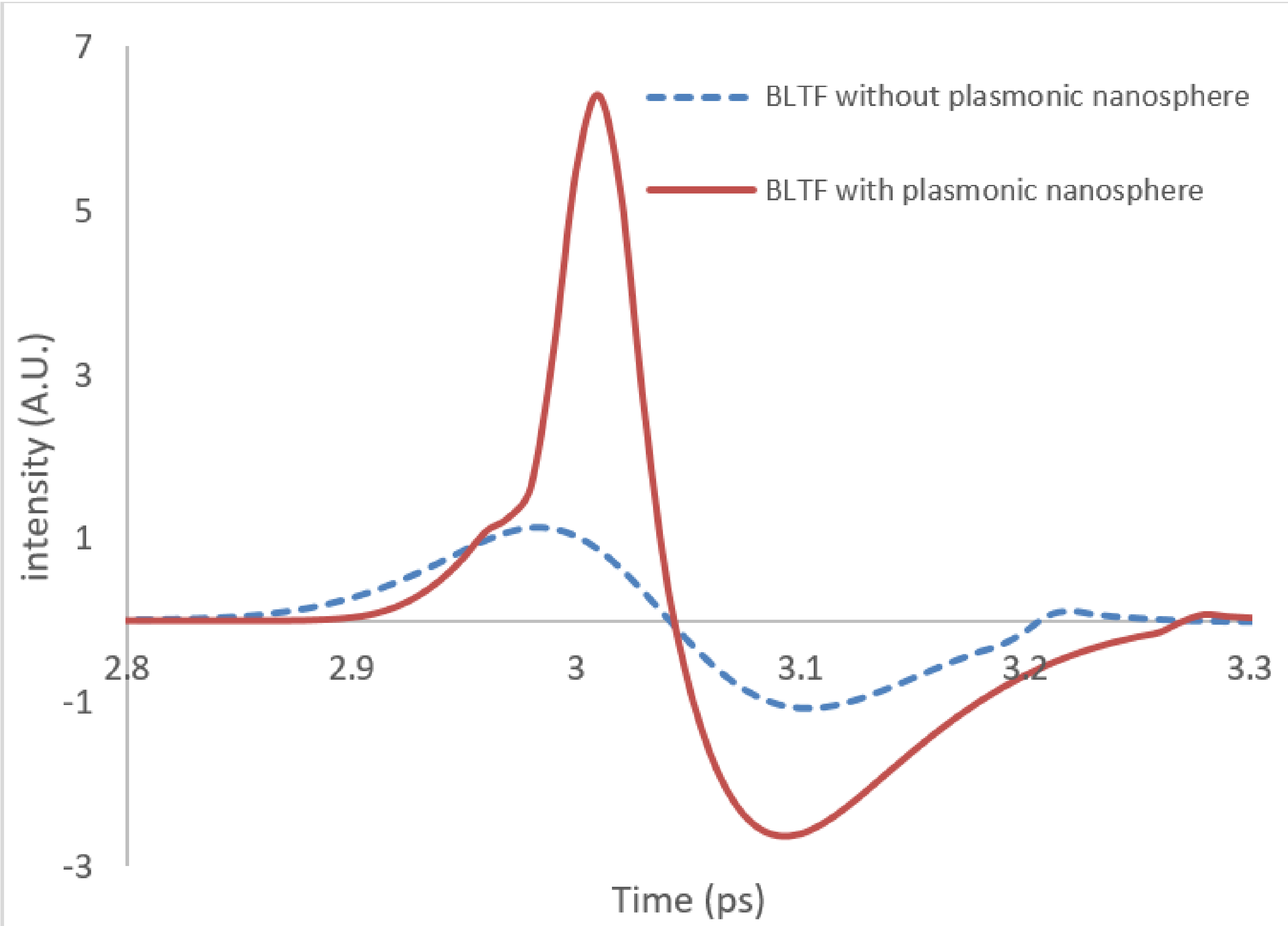


Figure 7

Effect of the spherical nanoparticles on the BLTF antenna

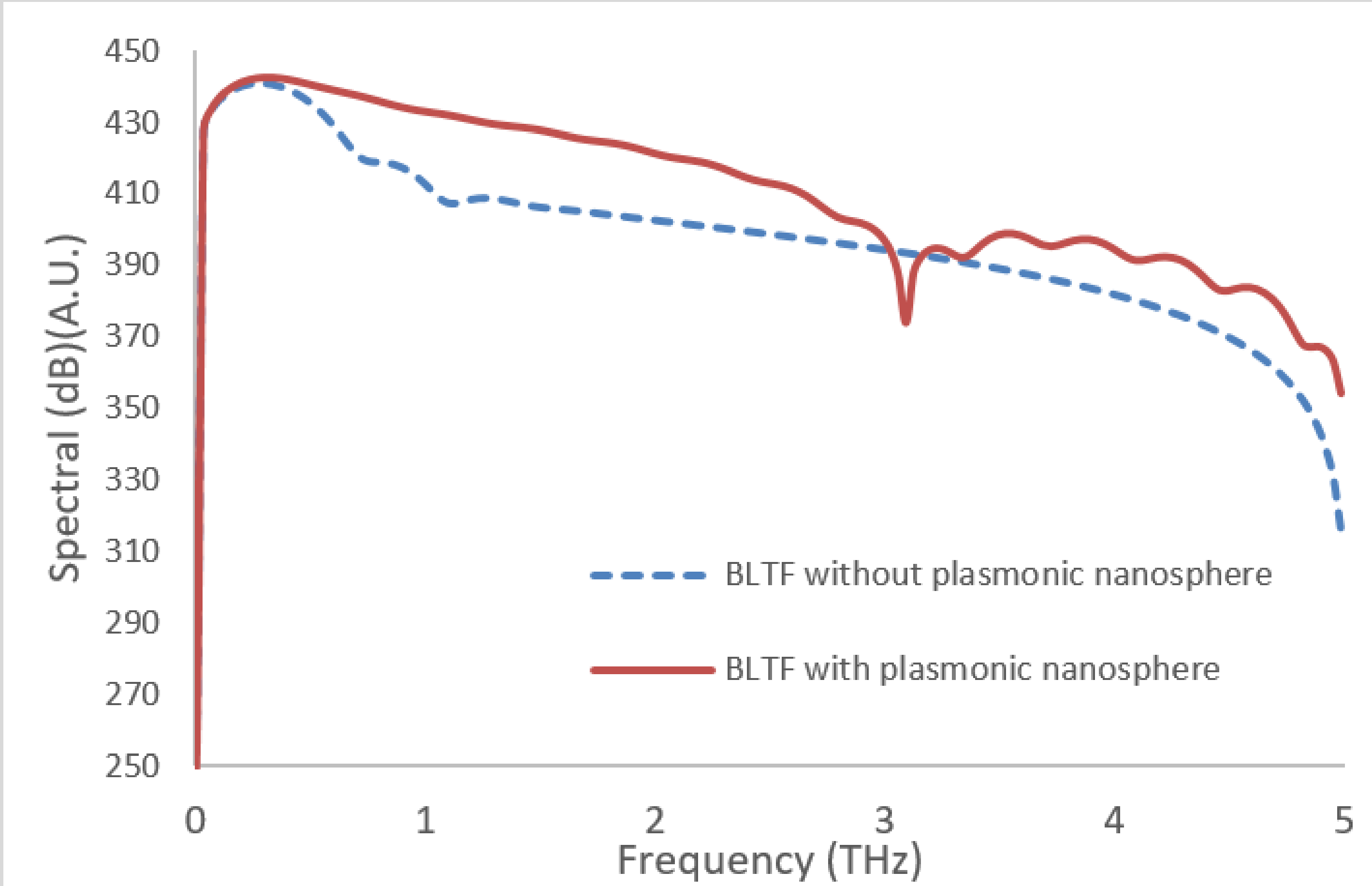


Figure 8

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