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Enhancing The Efficiency of Terahertz Photoconductive Antenna for Terahertz Time-Domain Spectroscope System

Anthony Bawa[1*], Rob Donna [2]

Department of Computer of Science: Catholic Institute of Business And Technology (CIBT), Accra - Ghana

Abstract

The use of Terahertz wave spectrum across several fields like the identification of chemicals, medical diagnosis, biological image processing and sensing is of significant benefits. However the problem of the Terahertz (THz) wave is that we cannot achieve enough of it due to the low efficiency of the optical to THz convection using Photoconductive antenna. This study seeks to use a design technique of a Photoconductive (PC) antenna with nanoscale plasmonic electrodes that can enhance the performance of the photoconductive antenna significantly. In the design model a plasmonic photoconductive antenna with small gratings fabricated in a bow-tie shape as the semiconductor electrodes proves to enhance the performance of the optical to THz wave conversion and increase the power of the THz wave generated. The study compares two antennas in a simulation using comsol, the plasmonic photoconductive antenna with nanoscale gratings electrodes and a convectional photoconductive antenna without gratings. The plasmonic PC antenna with small size gratings is seen to have a much high performance and this design technique can increase the power of the THz wave generated.

Index Terms: Efficiency, photoconductive antenna, plasmonic, THz wave, optical

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1 INTRODUCTION

Terahertz radiation is used to describe the electromagnetic radiation which has its frequency in between the microwave and infrared spectrum region. Terahertz comes from the term electromagnetic radiation with the frequency of the 10^{12} Hz which is referred to as THz. Terahertz radiation in the electromagnetic frequency has the range from 0.3 to 3GHz [1]. The conversion of optical to terahertz radiation energy with Photoconductive emitter is essential for industrial use. They may be some other methods which can be applied in obtaining THz radiation wave for use by scientist. Some important uses of Terahertz radiation across fields that are of significant benefits to scientist and engineers are in areas such as medicine, biomaterial and electronics. The **figure 1** below describe the band of Terahertz radiation occupies in an electromagnetic wave band.

Figure 1[2], shows the THz band in an electromagnetic wave band

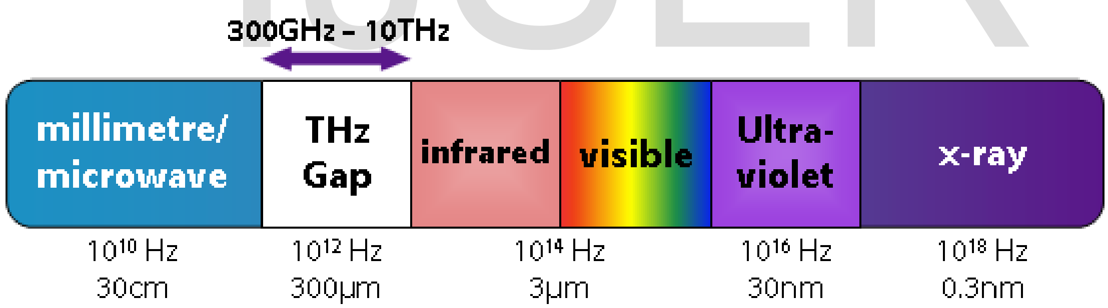

Fig 1 EM band

The uses of Terahertz (THz) radiation include the following;

Medical field: Terahertz radiation is used in the medical field for diagnosis to determine healthy tissue and non healthy tissue. The THz radiation when made to pass through a tissue is able to make concrete analysis of the tissue and diagnose where there is a problem.

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Chemical engineering: Terahertz radiation is used in chemical engineering systems where it is used to detect and recognize certain elements like organic molecules. It is also used to determine the stage of a chemical reaction status and image processing.

Security: Another important use of terahertz radiation is in a security systems, that is use to detect the presence of objects such as drugs, explosives and other harmful objects.

Microscope: Terahertz radiation is also widely used in microscope by scientist in order to see very minute objects like cells and insects. It is used in the microscope system to view very small objects and clearly identify each object.

Semiconductor industry: Scientist and engineers also make used of the terahertz frequency radiation to study the impurities, the electron concentration and as well as the movement of the electrons in a semi-conductor material.

Even though they are other important uses of Terahertz radiation in the industry, there is still a problem of obtaining enough Terahertz radiation (THz) source to be used in the THz technologies for the applications discussed earlier.

There are some devices which can be used to approximate the THz wave band, but there are drawbacks or problems with low quantum efficiency of the THz wave generated. This research paper therefore is seeking to carry out a study on photoconductive antenna and how its performance can be enhanced to maximize THz radiation generated. A proposed design technique on how the photoconductive antenna performance can be improved upon to enhance the efficiency of the THz wave. The photoconductive (PC) antenna is widely used as THz source in the generation of the THz radiation. In 1970s [3] the first PC antenna was designed. The frequency of this device is able to cover the Terahertz (THz) range. The PC antenna is quite familiar and mostly used in the application of spectroscopy, imaging processing and detection.

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1.1 Problem Formulation

The optical to terahertz conversion method with photoconductive antennas for Terahertz radiation is not very efficient and this gives a low quantum power of THz radiation generated. This is as a result of the fact that the optical to terahertz mismatch which reduces the efficiency of the field interaction in the photoconductive antenna. This does not achieve a higher gain of the THz radiation wave generated. Mismatch depends on the materials of the Photoconductive antenna and thus the photocurrent generated from the antenna is low. Also due to substrate material absorption the THz wave pulse generated is limited within a small range and falls on limited spot. This method of obtaining THz radiation with PC antenna has been extremely used and thus requires new techniques which can help improve upon the performance and to mitigate the low power efficiency of THz wave. The research paper therefore seeks to address the problem of low quantum performance of the PC antenna for THz radiation generation and increasing the power of the THz wave with the PC antenna.

1.2 Motivation

The main purpose of this study is to have a design technique that can enhance the performance of a photoconductive antenna and maximize the efficiency of Terahertz (THz) radiation. One main importance of this research will be how to improve or enhanced the performance of the Terahertz PC antenna. The reasons for this is because we want achieve high quantum of THz radiations generated and to mitigate the low efficiency. The design model for a photoconductive (PC) antenna should be fabricated in such a way that the THz PC antenna can incorporate the use of plasmonic electrodes that will give a high quantum efficiency of THz radiation. The configuration of plasmonic electrodes of nanoscale in a bow-tie shape on a PC antenna will aid the optical to terahertz conversion efficiency. The rest of the research paper is organized in four different phases which comprises of; **Phase 2**: In the second phase we look at some related works, a review on the of use of photoconductive antenna for the generation of THz radiation. The performance of PC antenna and its properties is looked at and as well as the different materials and parameters for its design. We will also discuss the low conversion efficiency of the optical to THz convention in a photoconductive antenna.

Phase 3: The third phase talks about the methodology we will be employing to achieve the goal of the research by maximize the efficiency and power of the photoconductive antenna. The design model strategy for the plasmonic PC antenna is explored and discussed.

Phase 4: In this phase a simulation experiment will be done using comsol to measure the power and efficiency of the THz wave radiations to be generated. The simulation results for plasmonic PC antenna and a convectional PC antenna will be compared and analyze. **Phase 5**: The conclusion of the research paper and the summary of the results obtained.

2 RELATED WORKS

In recent times, some significant work have been done to improve on the performance of THz PC emitter to obtain a high THz radiation efficiency and bandwidth and as well explore other techniques to achieve maximize power of THz radiation generated. New techniques are still sort after in order to maximize the efficiency of THz radiation generated and its sensitivity. The interest for the development of THz radiation sources is still on high demand today, with some research done in the use of miscrope mechanism and other techniques for generating of THz radiation wave with convectional semiconductors [4] and the search for new techniques in the THz generation and detection. Wu and Zhang [5] were able to demostrate that the sampling of free-space electro-optics can be used for generation of short THz radiation waves. In their work carried out, they used GaAs based photoconductive emitter in which they triggered upto 150-fs optical pulses in the range of 820nm. They were able to achieve enough radiation of THz waves using this technique. In order to improve upon the efficiency and the detection of the THz wave, they focused the THz radiation pulse into a crystal detector using a silicon lens with high resistivity. The shortcoming of this work is that the resolution for detecting the THz wave with a silicon lens is limited. This is due to the fact that there is high velocity mismatch between the THz frequencies and the lens. Another problem with this method is the way the geometric design of the THz PC antenna low power of the terahertz wave. The geometry design of the GaAs THz emitter should be modeled in a way to reduces velocity mismatch and maximize the THz radiation power. The feeding points are essential to reduce velocity mismatch.

C.D Wood *et al.* in 2009 [6] further gives understanding and clarity on the THz PC emitter. From the excitation of PC emitter at 800 to1550nm wavelength, it is possible to generate THz radiation wave. It is proven in their research work that InGaAs PC emitter with a doped Fe (iron) metal acting as the semiconductor can be used as an efficient source of THz radiation. In the variation on a time–domain, the THz radiation wave can be obtained by fabricating semiconductors with different wafers. This can be optimized in order to give a maximum efficiency of THz generated wave from infrared to terahertz down convection technique. It is possible to detect the THz radiation wave by using ZnTe crystals and that of GaP crystals with a pump wavelength being adjusted between 800 and 1550nm. Thus the efficiency and performance PC antenna for the terahertz radiation wave can increase with Fe-doped semiconductor electrode on an InGaAs THz emitter. However, the challenge with this technique is that, it is quite difficult to obtain communication wavelength in the range of (800 and 1550nm) to generate THz radiation using

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InGaAs based PC antenna. A work done by Y. Gao *et al.* 2012 [7], on enhancing the efficiency of THz using large aperture PC antenna shows another technique employed to maximize the THz radiation power and bandwidth by fabricating a strip line aperture on a PC antenna. The THz wave emitted is by exciting the patch with ultrafast pumped laser pulse beam. With the same input power of an ultrafast laser beam pump, it can be noted that the efficiency and bandwidth of the THz radiation generate is greater for the large aperture PC antenna than compare to PC alone without patch antenna. The strip line aperture on the PC antenna accounts for the in the overall high efficiency of the THz radiation. Although this experiment proves another breakthrough for improving THz radiation efficiency power and achieving a wider bandwidth it still had some minor issues.

2.1 The THz PC emitter

The photoconductive emitter is the most often and widely used antenna for THz emission source and can also serve as terahertz detectors in applications which may require sensing. However there are other devices which can be used for the emission of THz radiation. The use of PC antenna to act as a THz emission source is possible using Photoconductive semiconductor switch (PCSS). This largely depend on the material used in the PC antenna for THz generation and as well as the PCSS parameters. The method which makes the use of the THz PC antenna to serve as a THz source is based on two components. The two used key components here are; 1) photoconductive semiconductor switch [8] and the ultrafast laser pulse. A typical layout of a photoconductive antenna is shown below in **figure 2.1**

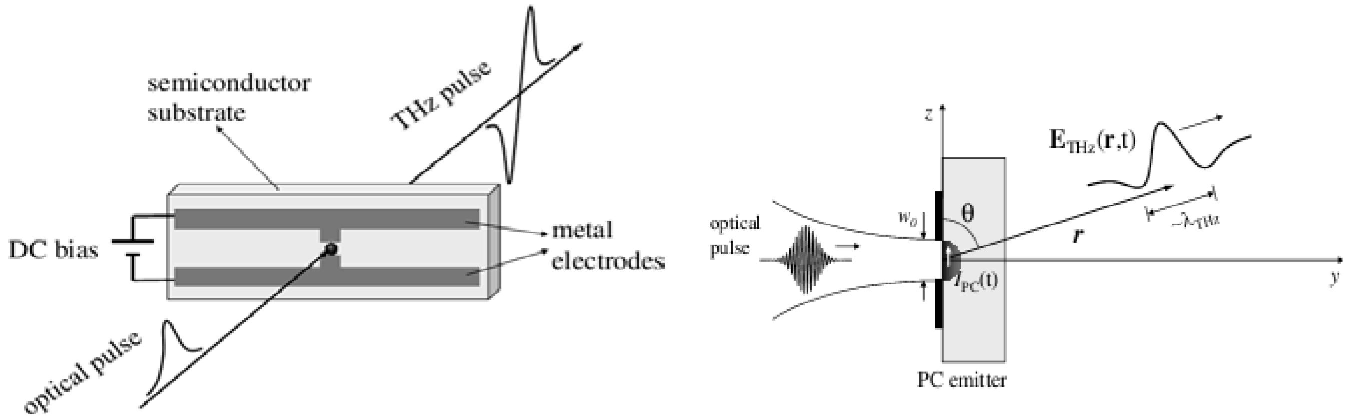

Figure **2.1** shows that THz pulse emission source of a photoconductive antenna excited by an optical pulse.

The photoconductive antenna structure in **Fig 2.1** can also be seen as a type of dipole antenna. A micro-stripeline antenna type is modeled on the substrate of the photoconductor with either Au or Ni material to make contact with GaAs substrate. The Au or Ni materials serve as the semiconductor cathodes. There is a biases gap from which the photoconductive semiconductor switch (PCSS) is illuminated by the optical pulse directed incident to it. The PCSS in the photoconductive emitter can conduct photocurrent through it when it is illuminated by the optical beam with the parameters set. In most cases, the PCSS serve as an electric switch but in the case of THz radiation generation, the PCSS electrodes act as transmitting antenna. The current which is produce by the PCSS is the photo generated current, which feeds the PC antenna to produce the terahertz wave. In order for the PCSS to conduct this current, the photon energy being excited by the optical beam pulse should be large than the material band gap. When an optical beam is released onto the band gab of the PC antenna there is the movement of charge photo-carriers in a biased electric field of the substrate. This then creates ultrafast pulse current in the substrate of the THz PC emitter. The ultrafast current which is created drifts for the generation of

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THz radiation wave. Thus it is this photo-current created which penetrates and passes through the substrate (GaAs) of the antenna which is seen as THz wave pulse. The THz radiation from the generated electric pulse will depend on the material used as substrate carrier lifetime of the THz PC emitter and the width of the laser pulse. These two factors can be used to estimate the bandwidth of the THz radiation generated. For the successful generation of electrical pulses that falls within the terahertz range, it requires ultrafast laser beam pulse (the pulse width in femtosecond should be approximately 1fs= 10^{-15}) and the substrate of the THz PC antenna should have a short carrier lifetime. Thus in choosing a material for THz PC emitter we should consider the band gab and the short carrier lifetime of the substrate material. The generation of this THz wave can be also be achieve by simply photo mixing a dipole antenna and laser pulse. A poorly geometric design THz PC antenna can affect the performance and efficiency of the THz radiation wave generated. Hence the geometric fabrication of a PC antenna employs an essential role in the performance of the antenna in the generation of THz radiation.

2.2 Comparing the PC antenna and RF/Microwave Antenna.

The photoconductive antenna is different from the other traditional microwave antennas. This is due to the fact that in traditional microwave antennas, the EM generated is always radiated or transmitted through a wave guide. The traditional type of antenna receives and propagates the signals through a guided wave but with the THz PC antenna, there is no transmission line or wave guide for the EM in front of the feeder. The antenna is feed directly by the photo current created. The THz radiated wave produce is able to penetrate out through the substrate of the PC antenna where it can be radiated into free space. A table below shows the comparison of the PC antenna and the Microwave antenna. **Table 2.1**

Parameters	PC antenna	RF/Microwave antenna
Direction of radiated wave	Penetrates through the substrate	Away from the substrate
Direct biased voltage	present	Not present
Substrate of material	Thickness of PC material can be compared to waveguide.	Dielectric with material thickness less wavelength
Feeder source	Laser beam pulse	Transmission line

2.3 The radiation of THz PC antenna

The radiation from a THz PC antenna occurs when the PCSS is being illuminated by ultrafast optical pulse beam with a bias voltage across it; this creates photo-excited carriers which is made electrons-holes pairs be accelerated in the bias field. This will generate ultrafast photocurrent if the optical beam pulse is larger than that of the band gap of the substrate material used in the THz PC antenna. The accelerated charge carriers in contact with the electrodes motion can then radiate EM waves when it passes through the material substrate under a bias voltage. This is responsible for the generation of the THz wave. The condition for photocurrent to be induced in the substrate area will depend on the free carriers' velocity and a well as time-variation of photocurrent. The transcient current emitting from the GaAs substrate is J(t) which radiates the EM pulse wave $E_{THz} \alpha \frac{\delta J(t)}{\delta t}$. Thus amplitude of THz radiation emitted is directly proportional to bias electric field and that of the movement of the photocurrent in the GaAs substrate.

2.4 Efficiency of the THz PC emitter.

From Balanis on antenna theory [9] the efficiency of an antenna can simply be described as the radiated power divided by the input power. $\eta_r = P_r / P_{in}$. Matching efficiency of an antenna is also given by the input power to the supplied power of the source by $\eta_m = P_{in} / P_s$. The THz PC

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antenna is excited by the illumination of optical beam pulse for creation of THz wave pulse. With this background, the efficiency of the PC antenna is given by $\boldsymbol{\eta} = \boldsymbol{P_{THz}/P_{optic}}$. For traditional microwave antennas the efficiency can be upto 50%, however THz PC antenna efficiency is normally very low. The low power efficiency of the THz PC emitter is due to the fact its feeding mechanism and the matching impedance of the PC antenna is difficult to achieve. This is because the matching impedance is usually low compared to traditional microwave antennas. Another reason for the low efficiency that, it is often difficult to get antennas that can efficiently radiate frequencies at that range. Optical to terahertz convention efficiency can be very high in some cases. The condition for this to occur is when there is a very high bias voltage and a high induce photocurrent. This often not possible because the charge carrier movement in the substrate is not easily enlarged. Also the bias voltage will not exceed certain value due to the breakdown of the substrate material. At a certain state the excitation by the laser pulse reaches a peak and gets saturate, therefore the power efficiency of the THz wave will not increase necessarily.

2.5 Substrate Material of the PC antenna

As discuss previously, the photoconductive process involves the illumination of an optical pulse beam for the purpose of exciting electrons at the electrodes. For this process to take place the photon energy should be bigger than that of the band gap of the substrate to precipitate the excitation of electrons. The first thing to consider in choosing a material to be used as the substrate material for a PC antenna is to consider the band gap of the material. The band gap should be smaller and its frequency must be within the range of ultrafast laser frequency. However, the most essential factors to also consider in choosing the substrate material is its carrier lifetime and as well as the mobility of charge carriers within the substrate. A shorter carrier lifetime of the material is usually required and a material with a high responsivity for the terahertz wave. The most suitable material for the fabrication of a THz PC antenna is the use of GaAs. This is because the GaAs material has small band gap, the materials falls within the range of the ultrafast laser frequency and has a good responsivity.

2.6 Approach adopted for the study

One new technique which been design by C.W. Berry *et al* [10], to reduce the low efficiency of the performance of THz PC emitter is by using plasmonic contact electrodes designed in nano-scale. This can maximize the power of THz radiation generated. In order to enhance the efficiency of LT-GaAs based THz PC emitter, we adopted a similar design technique in our study. The difference here has to do with the way the electrodes are fabricated on GaAs substrate. By incorporating contact electrodes design in smaller gratings made from Au material as the plasmonic electrodes, which will be fabricated onto the plasmonic PC antenna. The Au material will serve as the electrodes of the semiconductor that is fabricated in a bow-tie shape. The fabrication of a bow-tie shape nanoscale plasmonic electodes on the GaAs substrate will aid to mitigate the low efficiency and maximize the performance of the PC antenna. The modeling of the THz PC emitter will be done with comsol package.

3 METHODOLOGY

The comsol multiphysics package will be used for the simulation and analysis in this paper. The software package provides the geometry and other CAD interface with a fine mesh generation. It also has other numeric solvers and processing tools for the simulation of a photoconductive

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antenna. The package also allows for a complex mesh generation and the coupling of different number of physics solvers for the simulation process. In the methodology, we design a THz PC antenna to serve as a source of THz radiation. The measurements design of the PC antenna is also done in comsol multiphysics. For the purpose of this study we design two THz PC antennas to determine and compare the radiation power of the two antennas. One of the PC antennas is design and fabricated with a bow-tie antenna serving as the plasmonic semiconductor electrode. The fabrication of nano size plasmonic gratings as the contact electodes of the bow-tie antenna is incorporated on it. The other antenna is a normal conventional THz PC designed antenna which has no plasmonic gratings electrodes. It is called the conventional type of PC antenna designed for the purpose of the simulation. The measurements of the PC antennas design in comsol package are in micrometers (μm).

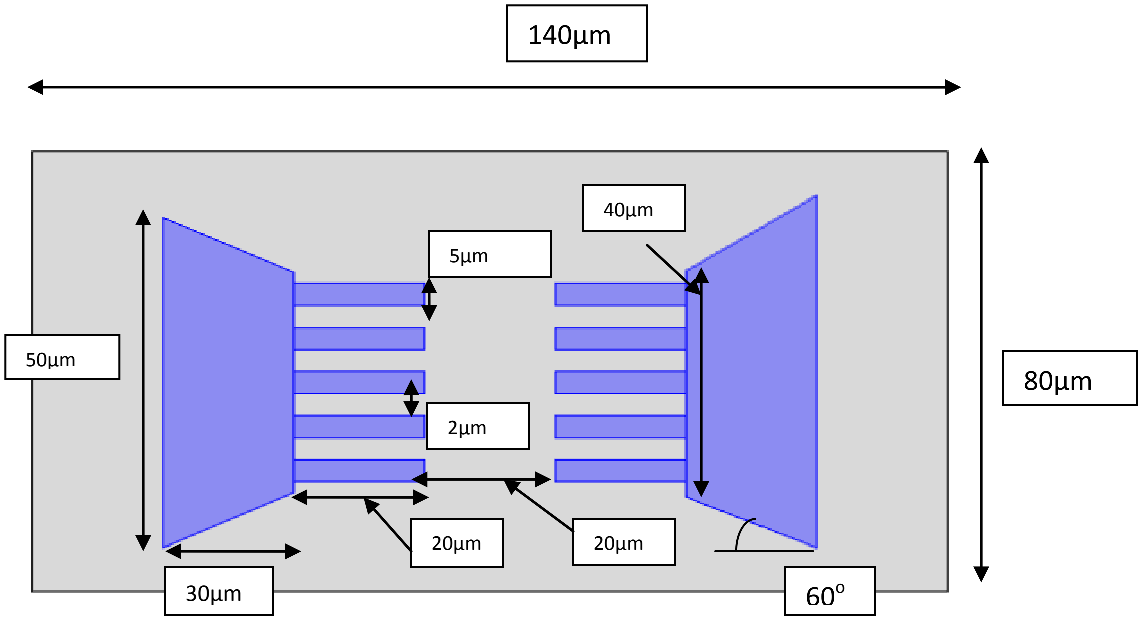

fig 3.1 Plasmonic Photoconductive antenna

The plasmonic PC antenna above is front view, designed with GaAs as the substrate of the antenna. The semiconductor electrodes fabricated in a bow-tie shape has Au (gold) as the material. The gratings of the plasmonic electrodes in contact with GaAs substrate are designed in nano scale. The plasmonic PC antenna designed measurements are in micrometers (µm) and shown above in **fig3.1** The length of the PC antenna is 140(µm) and the width is of it is 80(µm). The insulator material used for the designed is SiO2. The purpose of the insulator is to reduce the reflection of the optical laser pumped onto Au semiconductor and as well as improve upon the optical laser transmitted through the semiconductor [11]. The absorption of the semiconductor is due to the interaction by the pumped laser wave beam and whiles the transmission through the semiconductor is as a result of the excitation of the photocarriers. The importance of the plasmonic gratings designed is to increase significantly the amount of photocarriers generated beneath the semiconductor electodes so as to improve upon the transmission of the pumped laser pulse through the plasmonic electrodes onto the absorbing GaAs substrate material. Because each nanoscale gratings generate photocarriers, it minimizes the electrode space between each

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other and also reduce the photo-generated transportation path of the electrons species [12]. Minimizing the electron space transport path for the excited photocarriers generated will enhance the transmission of the pumped laser beam into the GaAs substrate to generate THz wave.

The conventional THz PC antenna.

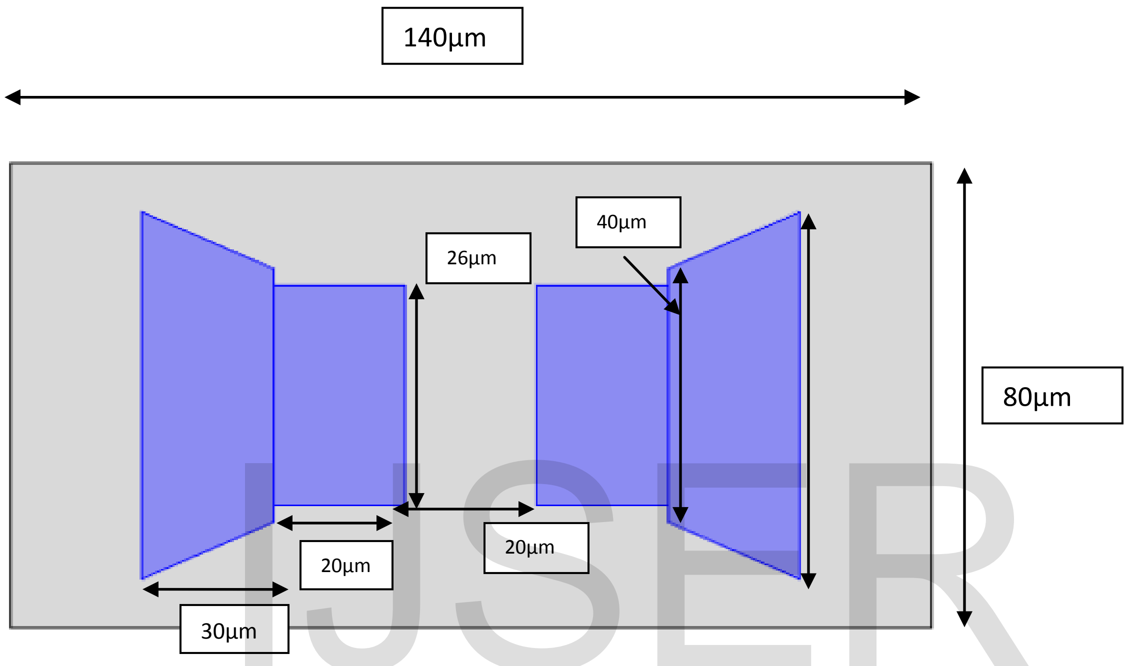

Fig 3.2 Conventional PC antenna

In **figure 3.2** the conventional PC antenna is designed with the same parameters as the plasmonic PC antenna but the absence of nanoscale plasmonic electrodes gratings. The length is 140(µm) and the width is 80(µm). The substrate material is also GaAs and the semiconductor electrodes fabricated in bow-tie antenna shape is made with gold (Au) material. The conventional PC antenna does not contain plasmonic gratings as the electrodes whiles the plasmonic PC antenna incorporates nanoscale gratings. The idea is that, the use of nano size gratings will aid in the larger transmission of the optical laser being pumped into the GaAs substrate-absorbing material by producing more photocarriers made up of electrons. Exciting the plasmonic electodes will allow for plenty photocarriers to be generated and hence the average photocarriers transport path

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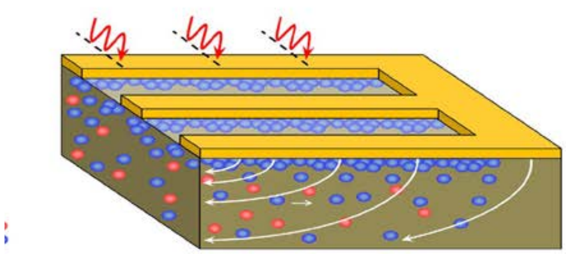
of electrons towards the anode will be shorter. More concentration of electrons than holes in plasmonic electrodes compared to the less electrons in convectional PC antenna.

3.1 Why the design strategy

In order to enhance a significant performance of the PC antenna depends on the photocarriers generated. The efficiency of the THz wave can be increase by a large amount of carriers generated. The plasmonic gratings electodes will maximize the generation of more photocarriers with electrons as the dominant carriers beneath the electodes which are very close to each other. An increase in the large number of photocarriers accumulated made up of more electrons than holes pairs will also increase the drift for high photocurrent induce at the electrodes in the bias field. In the case of the electrodes in the convectional antenna less charge photocarriers are generated. Thus there will be fewer electrons than holes generated, and these electrons are not close to each other in proximity due to presence of more holes at electrodes. The figure below shows the photocarriers generation by the Plasmonic PC antenna fig **3.3a** and that of the Convectional PC antenna in **3.3b** [10][12].



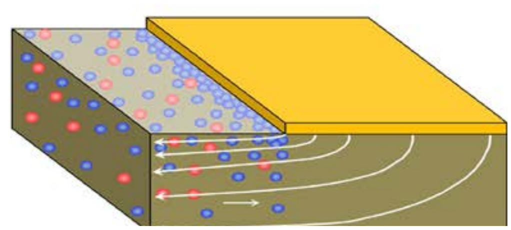


Fig 3.3

Electrons
Holes

fig 3.4

3.2 The PC antenna Configuration and Thickness

In the design of the PC antenna two main factors were considered for the designed. The thickness of the antenna and the configuration of the electrodes on the antenna. The main purpose of configuration of the electrodes is to increase the PC antenna radiation efficiency. The electrodes configuration plays an important role in generation of photocarriers to induce the photocurrent that passes through the absorbing GaAs material to generate the THz pulse. The electrodes provide the bias field from which the accelerate the photocarriers to the GaAs material. The most often use electrode configuration in THz PC antenna design are the dipole, stripline and the bow-tie antenna configurations. [13]. This design will make use of bow-tie antenna configuration by incorporating small plasmonic gratings as the semiconductor electrodes for the simulation.

3.3 Thickness of the PC antenna Substrate

After the materials have been choose and the electodes configuration decided for the THz PC antenna design, the next thing to consider is the thickness of the substrate. The thickness of the substrate can affect the performance of the THz PC antenna. This because a very tick substrate can increase the interaction between the laser pulse beam and the PC antenna whereby there will be more absorption. This may result in some of the THz waves being loss in the process. Thus it is important to have a less thick substrate which will to minimize the loses of the THz wave in the conversion process.

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3.4 The drift – diffusion Model of the semiconductor electrodes

A drift-diffusing model [14] is used to describe a simple model for the charged particles transport within the (Au) semiconductor electrodes of PC antennas under study. This can be express in Fermi Level as the current densities and shown in the formula below.

$$\overrightarrow{J_n} = -q\mu_n n \nabla \emptyset_n \text{..............................} 3.1$$

$$\overrightarrow{J_p} = -q\mu_p n \nabla \emptyset_p \text{……………….. ….} 3.2$$

Where μn represents the mobility of the electron, μp represents the mobility of the holes, $\emptyset_n$ represents the quasi Fermi level of the electron and $\emptyset_p$ is the holes quasi Fermi level. The occurrence of the quasi level is due to the fact that bias voltage is applied across the semiconductor electodes. This will depend on the concentration of the photocarriers and the Electric potential.

$$n = n_{ie} \exp\left[\frac{q(\psi - \emptyset n)}{kTL} \right] \text{………………………………….} 3.3$$

$$\emptyset n = \psi - \frac{kT_L}{q} \ln \left(\frac{n}{nie} \right) \text{…………………………………………….} 3.4$$

$$p = n_{ie} \exp\left[\frac{-q(\psi - \emptyset p)}{kTL} \right] \text{………………………………….} 3.5$$

$$\emptyset p = \psi - \frac{kT_L}{q} \ln \left(\frac{p}{nie} \right) \text{……………………………………. } 3.6$$

Where n_{ie} represents the effective intrinsic concentration and T_L represents the lattice temperature.

3.5 Feeding the PC antennas

The THz PC antenna is fed with generated photocurrent from an excited laser pulse. This photocurrent generated feeds the semiconductor electrodes for both the plasmonic PC antenna with the gold (Au) electrodes gratings and the convectional PC antenna. Since there is no transmission line between in the THz PC antenna, feeding for both antennas will be relate directly to the impedance matching between the feeder sources and the PC antennas. Correct impendence matching is essential to maximize the output from the antennas. Therefore the radiated power from the PC antenna depends on Photocurrent and the gap between the semiconductor electrodes of the antennas. From **figure 3.5**, the feeding port1 showing blue where the excitation of laser pulse is **ON** and the port 2 where the excitation of laser is **OFF**, for the PC antenna at two different ports. The boundaries conditions are periodic because of the repetition of the wave. For the simulation the pump optical field is placed along the x-axis and y-axis (blue) where there is excitation of electrodes by the laser pulse for both the plasmonic and convectional PC antennas.

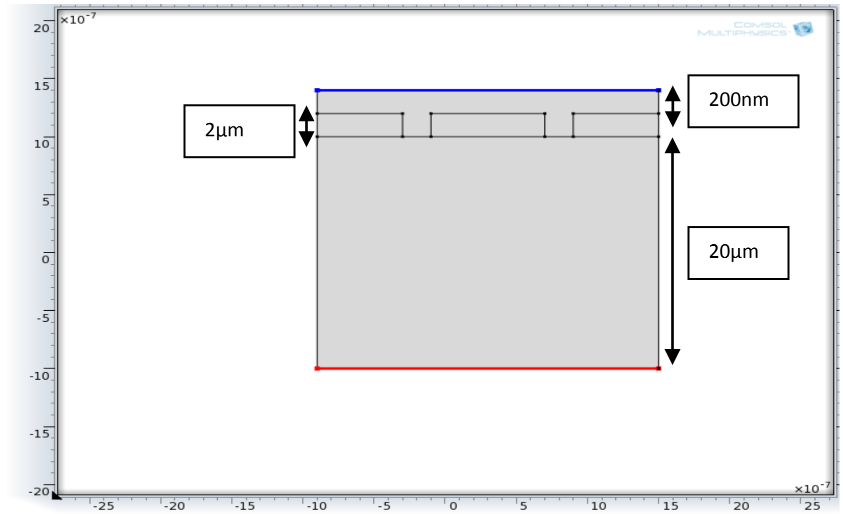

fig 3.5 Feeding the PC antenna

The graph in figure **3.6** shows the feeding S11 parameters at the two different feeding points of the antenna. The S11 parameters falls within the THz range in figure **3.6**

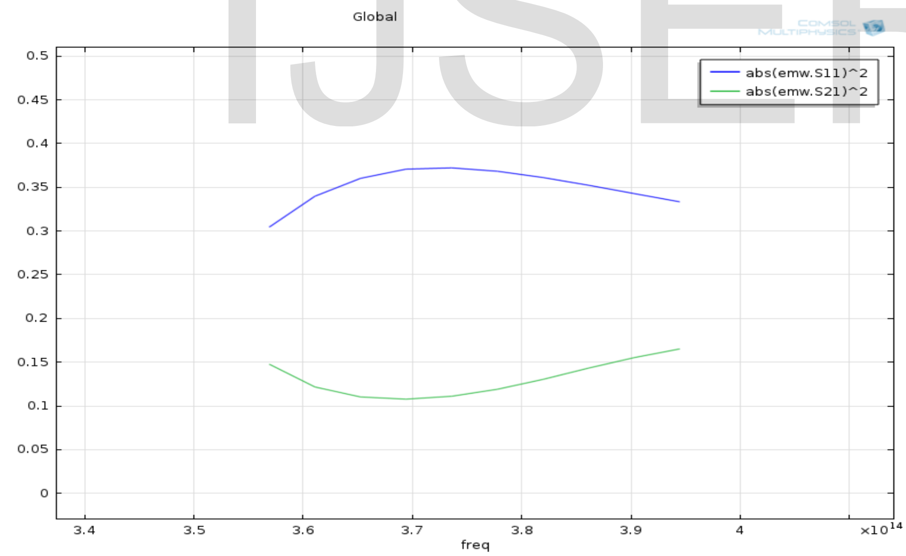

Fig 3.6 Graph of feeding ports of antenna.

3.6 The band gap of PC antenna

When the PC antennas are illuminated by the laser beam pulse, there is a resistance from the gap which is distributed across uniformly. The photocurrent generated and the radiated power is respectively represented by the formulae. [15]

$I \propto V_{bias}\,Gp$ ……………..(3.5) and the $P_{rad} \propto V_{bias}^{2}\,G_A\,\frac{GA}{GA+GP}$……………...(3.6) where Gp and GA the gap between the electrodes are approximately where $Gp=G_A$ are the same and V_{bias} is the bias voltage supplied by the electrodes. The graph in **fig 3.7** shows the gap of the electrodes ranging from 5 µm to 15 µm with a step of 5 µm. Thus a small band gap is required between the electrodes to give a higher magnitude of the THz power.

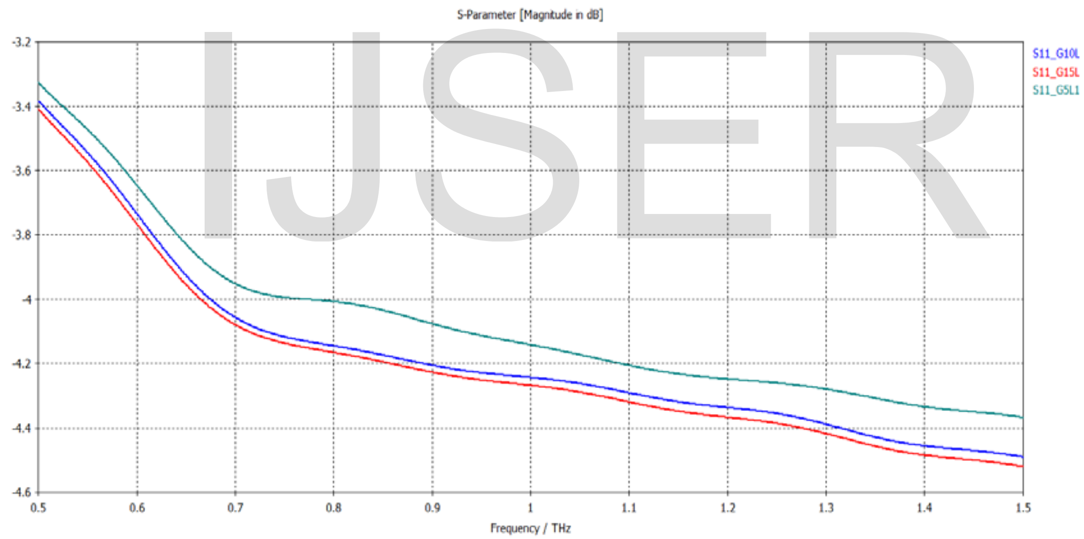

Fig 3.7 Graph of the electrodes gap

4 SIMULATION AND DISCUSSION OF RESULTS

The simulation for the two PC antennas, namely the Plasmonic PC antenna and that of the convectional antenna. For the purpose of this study the simulation is carried out in 2D, in the x and y components. By using a comsol multiphysics solver we are able to analyze the field interaction of the optical laser pumped of a lambda value λ =800nm for both plasmonic and convectional PC antennas. The first study deals with the absorption response of the laser impulse by the GaAs substrate. The responsivity of the substrate material used for the Antennas is done by approximating the response and then convolving it with optical absorption by the substrate. A flow Chart is used for the results obtained for clarity and systematic arrangement of data.

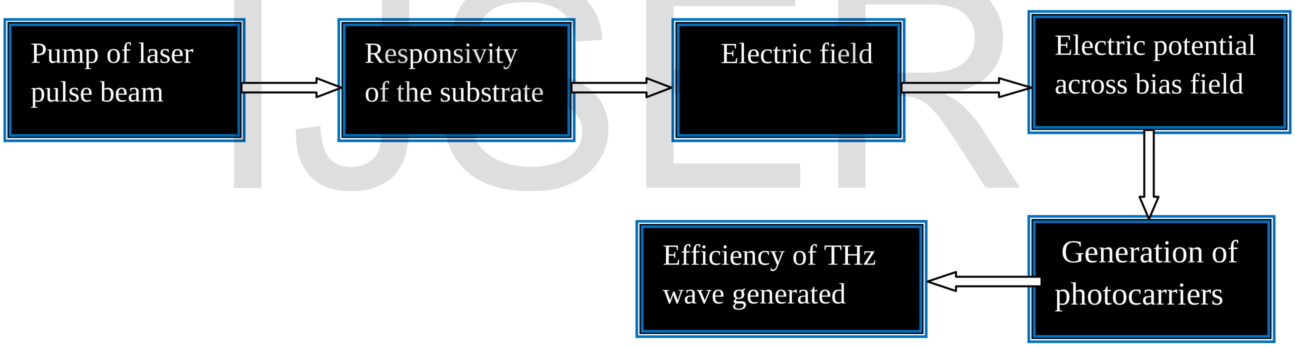

Fig 4.0 flow model of THz generation process

4.1 Interaction of pump laser beam with electrodes

When the laser beam pump is illuminated onto the band gap of the plasmonic electodes gratings, it produces photocarriers that increase the transmission of the laser beam pulse. From the simulation in figure **4.1a** the active surface area shows dominant green spots where most transmission of laser occurs with the electrodes. The maximum transmission of laser pulse through the electodes upto 4.5 x 10^6(μV/m). A few red spots on active surface area upto 5.2 x 10^6(μV/m). From simulation in figure **4.1b** there are less green spots indicating smaller photocarriers from the transmission of laser pulse in the active area. This is however not dominant across the active area for the convectional PC antenna from 2.6 x 10^6(μV/m) to 3.8 x 10^6(μV/m)

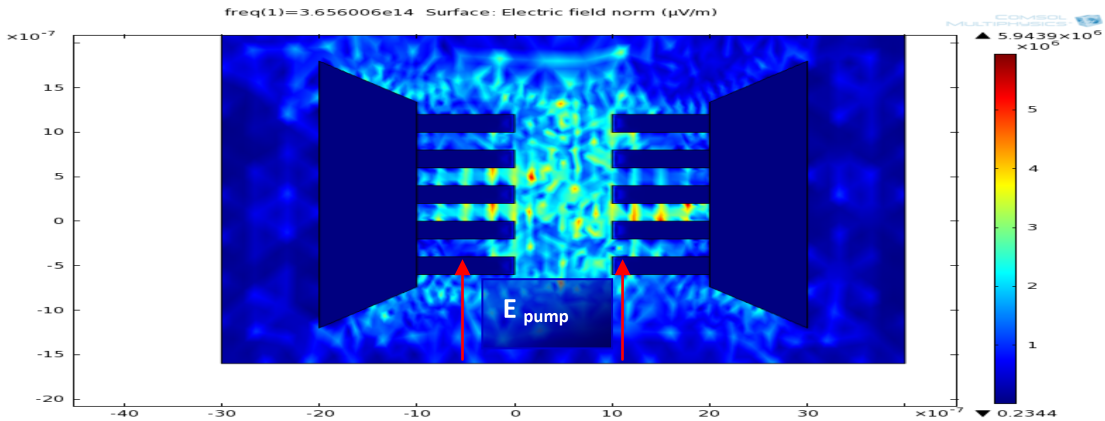

Fig 4.1a

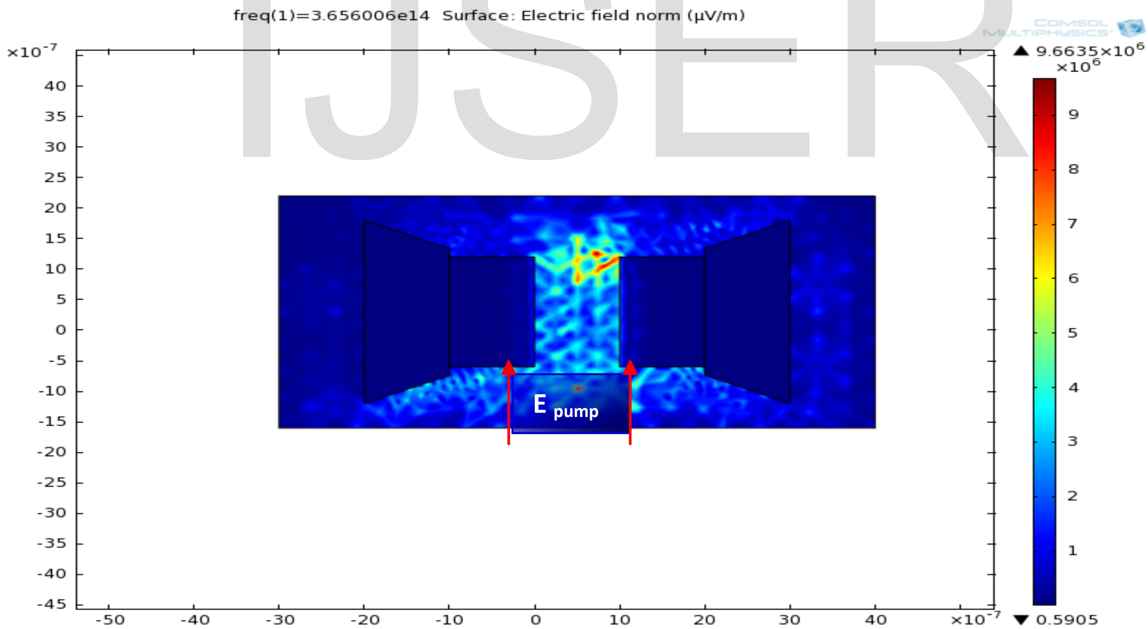

Fig4.1b

4.2 Responsiveness of GaAs substrates

The simulation below in shows the responsiveness of the GaAs substrate when laser beam transmitted through the electrodes indicated in the simulation.

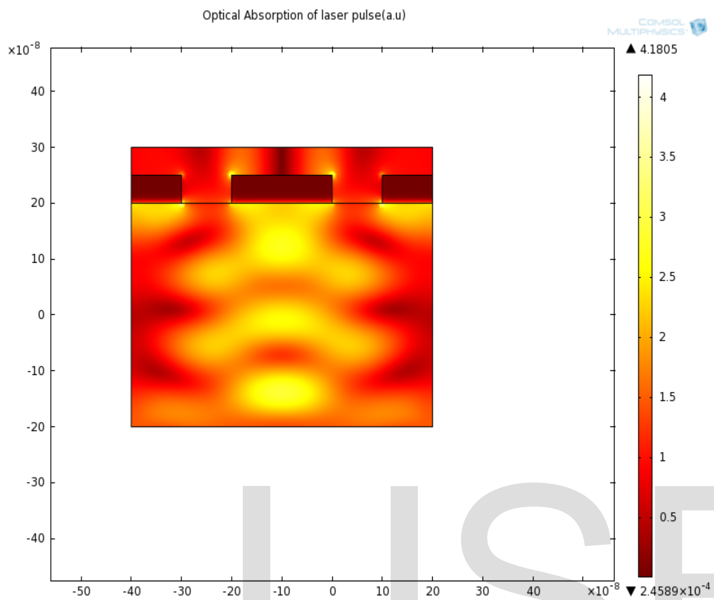

Fig 4.2a

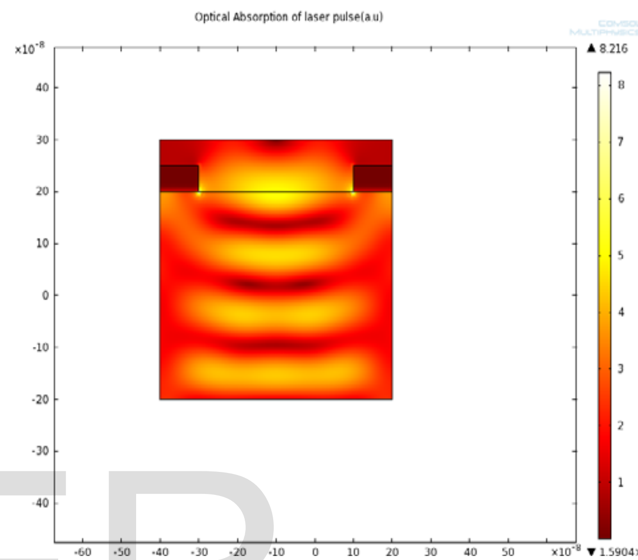

Fig 4.2b

From the simulation in **Fig 4.2a** represents the absorption and response of the GaAs from the transmitted laser pulse at the electrodes in plasmonic PC antenna where the boundary conditions for the antenna is set to periodic. In **fig 4.2b,** the boundary conditions of the convectional PC antenna are also set to periodic. Comparing the two simulations the absorption at the pump laser beam at the electodes in **fig4.2a** is the range of 2.5 ~3.5 (a.u) where as the absorption in **fig 4.2b** is in the range of 2.0 ~3.2 (a.u). This means there is a higher responsivity of the electrodes on the GaAs substrate at the plasmonic PC antenna compared to the convectional PC antenna electrodes

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4.3 Electric potential

A high electric potential across the bias field substrate will increase the accelerate photocarriers to travel through the absorbing GaAs substrate. Looking at the simulations below in fig **4.3a** the electric potential is greater for the Plasmonic PC antenna covering high potential up to 0.8V. This means the space charge density of the carriers in the depletion region of the plasmonic electrodes is high compared to the simulation in fig **4.3b** for the convectional PC antenna which has a low electric potential upto 0.05V. This means less effort is needed to accelerate the charge carriers in the Plasmonic PC antenna compared to the convectional PC antenna.

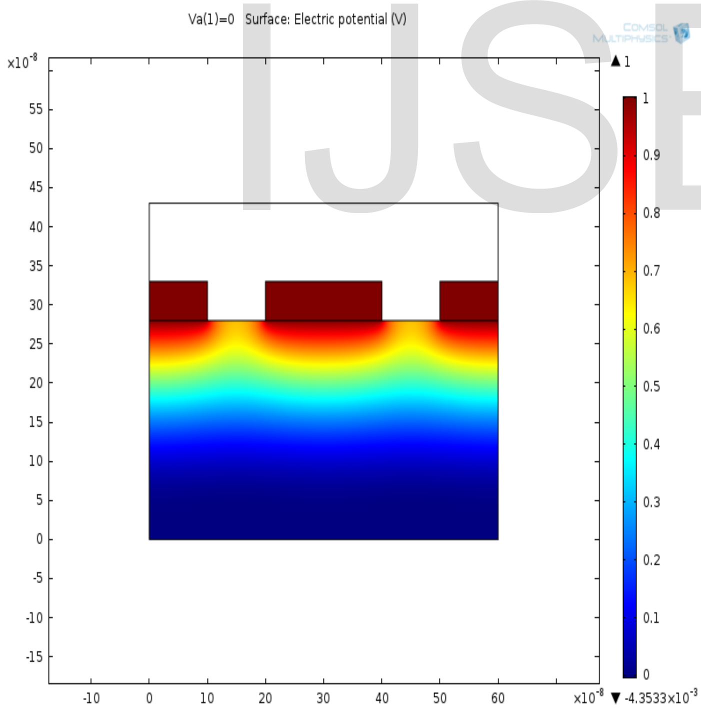

fig 4.3a

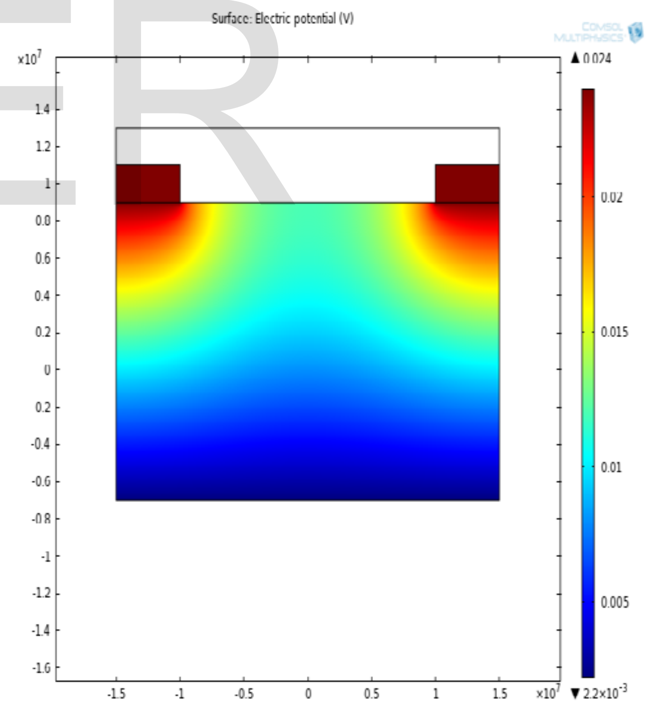

fig 4.3b

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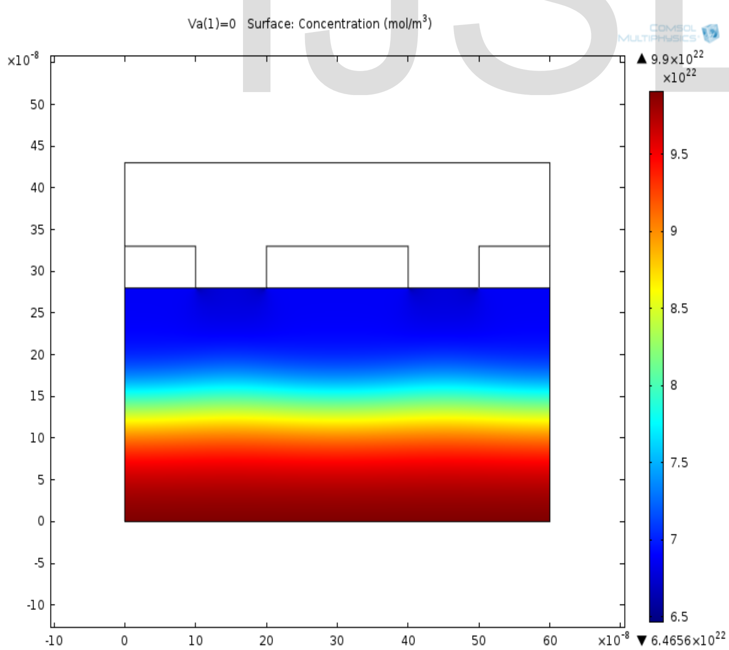
4.4 Generation of Photocarriers at electrodes

The charge photocarriers are generated after the excitation of the electrodes made of electrons and holes pairs. These photocarriers are transmitted through the GaAs substrate to generate the THz wave. The amount of photocarriers created to induce the photocurrent is directly proportional to the power of the THz radiation generated. The more photocarriers made of high concentration of electrons towards the anode will minimize the transport path and increase the photocurrent. From the simulation below in fig **4.4a** more concentration of charge photocarriers beneath the plasmonic electrode gratings with a high number of electrons (blue) than holes (green). The simulation in figure **4.4b** shows small concentration electrons (blue) and a high concentration of holes (green) creating spacing between charge particles. This also increases the transport path of the charge particles. A higher concentration of electrons will induce a high photocurrent to generate THz radiation.



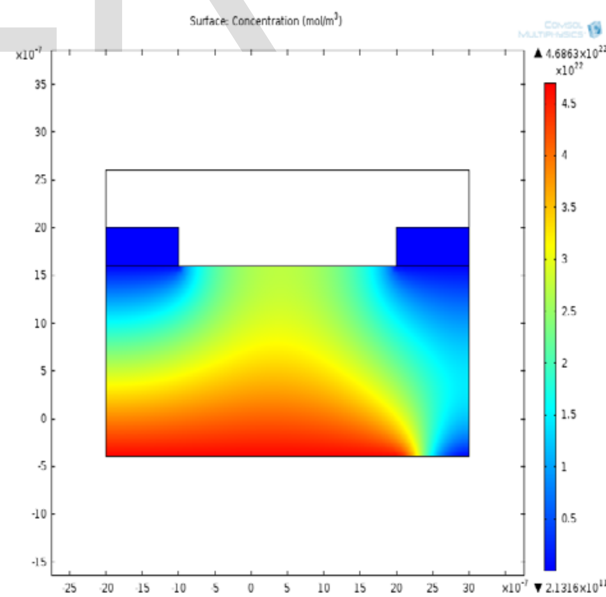


Fig 4.4a **Fig 4.4b**

The concentration of electrons as the major carriers with blue colour and the holes are the minority carriers' holes in green for the plasmonic PC antenna. In Fig **4.4a** each nanoscale gratings produces photocarriers with majority electrons that are in a very close proximity to each other. From figure **4.4b** shows a less concentration of photocarriers with majority holes and few electrons concentration. Therefore the induced photocurrent from the small electrons concentration for convectional PC antenna less compared to the plasmonic PC antenna.

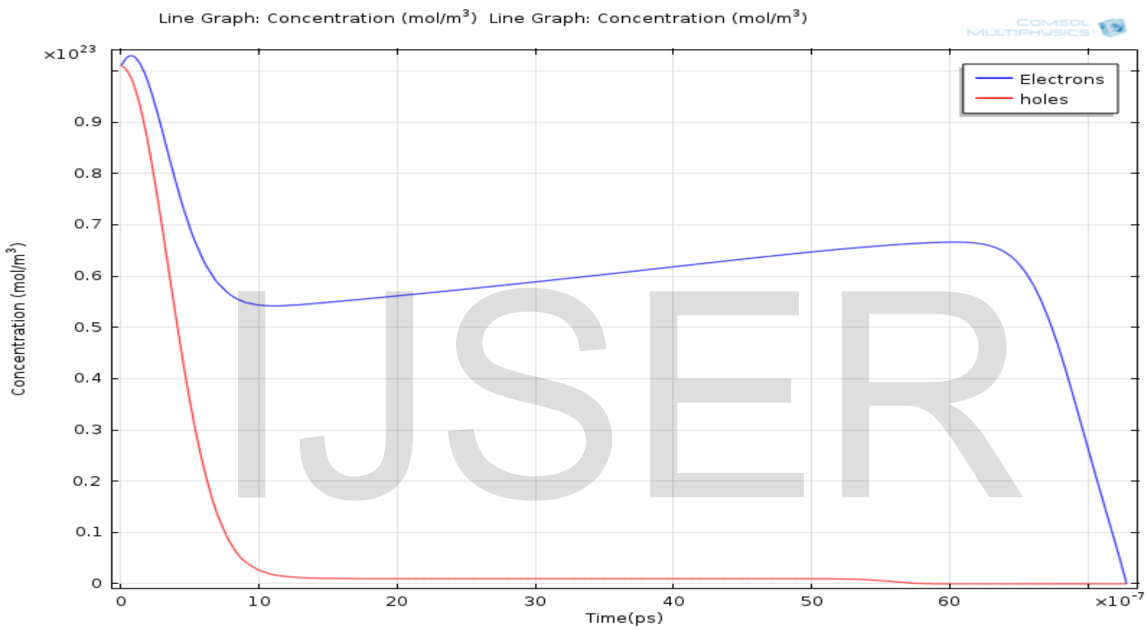


Fig4.5a A graph of electron to holes concentration for plasmonic PC antenna.

The graph in figure **4.5a** shows higher electrons concentration than holes for the plasmonic photoconductive antenna. The blue colour represents the electrons whiles the red colour represent the holes. Both have a peak value of $1x10^{23}$ mol/m^3. Then the holes concentration is seen to drop sharply to 0.02 x 10^{23} mol/m^3. However the electron concentration drops slowly to 0.56 $x10^{23}$mol/m^3 and then increases again at 0.68 $x10^{23}$ mol/m^3 and maintains a constant concentration till it finally drops to 0.02 x 10^{23} mol/m^3.

A graph of photocarriers concentration of convectional PC antenna without plasmonic gratings is shown below in **fig4.5b**. The graph indicates that the photocarriers generated have small electrons to holes concentration. The electrons have a peak value of $1x10^{23}$ mol/m^3 and drops to 0.12 x 10^{23}mol/m^3. The holes concentration rises upto 0.98 x10^{23}mol/m^3. This graph simply explains photocarriers made up of fewer electrons than holes and thus the photocurrent generated is smaller compared to the plasmonic electrodes.

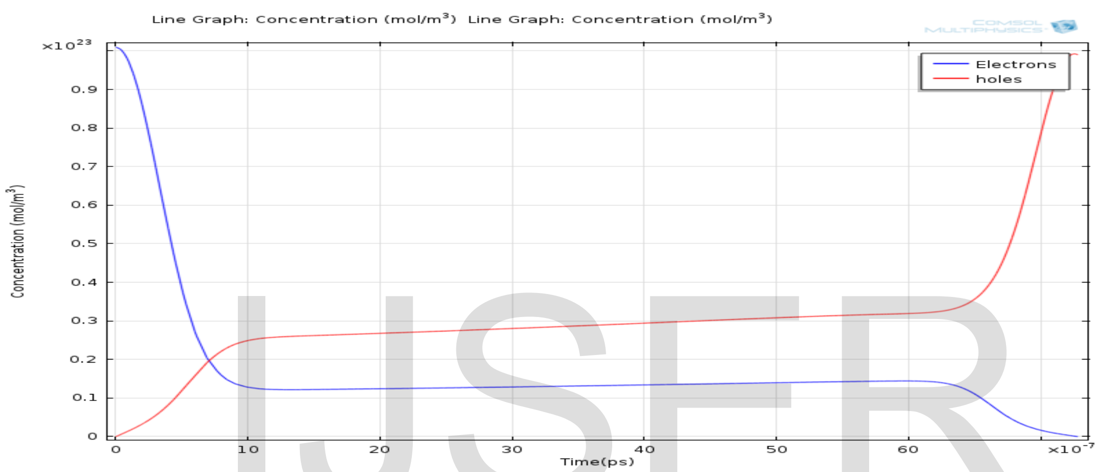


Fig 4.5b A graph of electron to holes concentration for convectional PC antenna.

4.5 Power Plot of the THz wave radiation

The graphs below are the plots of THz power flow with time for the plasmonic and convectional antenna in the simulation above.

Comparing the THz powers for the two graphs, the maximum power experience for the Plasmonic PC antenna is greater than that of the Convectional PC antenna. The use of nanoscale plasmonic gratings can significantly increase the power of THz wave radiation. The power flow for the two antennas are coupled together in figure **4.6**

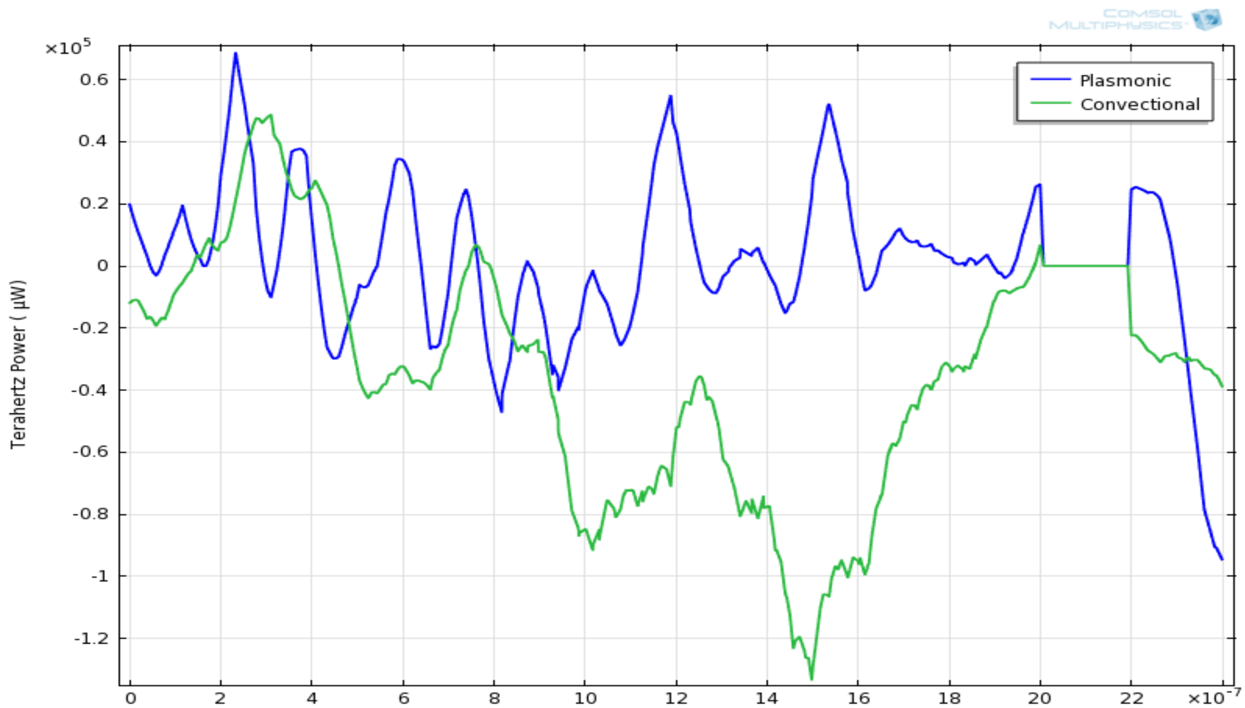


Fig 4.6 A graph of THz Power flow for plasmonic and convectional PC antennas.

4.6 The efficiency of the THz generated

The efficiency of the THz wave generated is given by the THz power output over the optical power input in the simulation formula; N_phtn=emw.Poavy/(plk*f0*c_const) where efficiency depends on the N_phtn = the magnitude of the photons, emw.Poavy = power of the THz wave and optical power input is plk = the plank constant representing the energy of each quantum (photon), c_const= constant for speed of light and frequency (f0).

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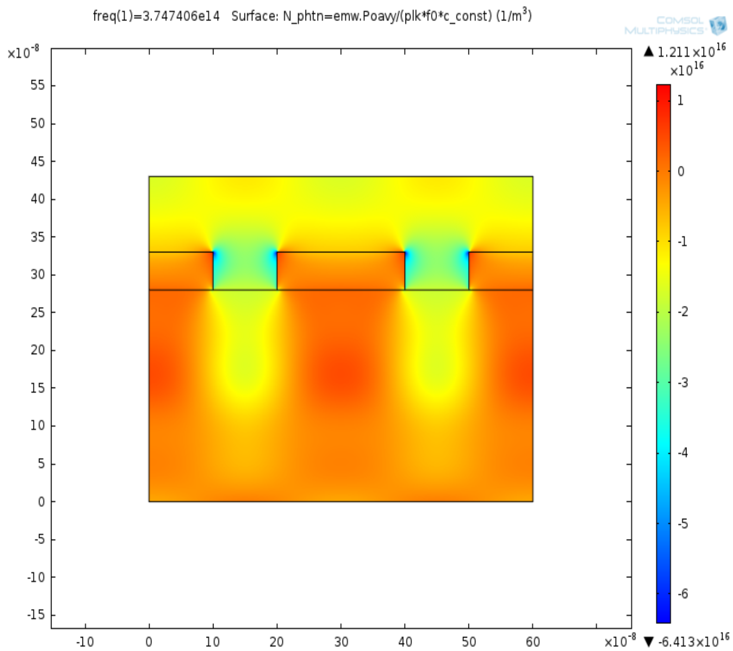

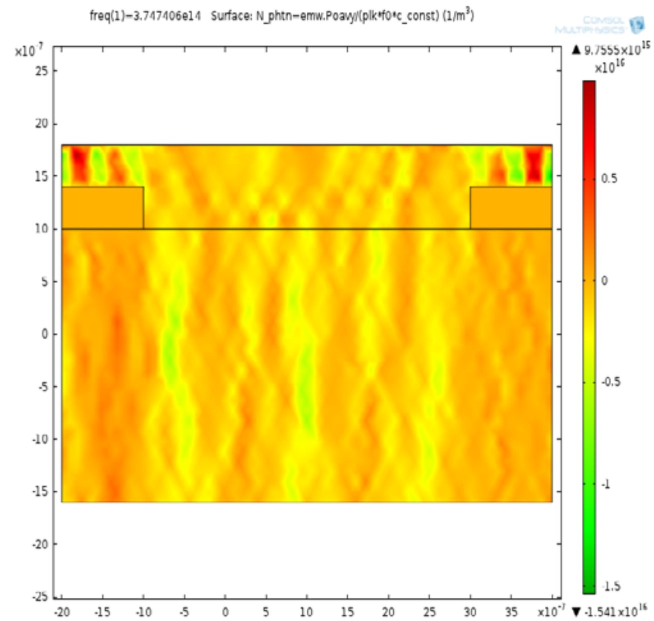

Fig 4.7a **fig 4.7 b**

The efficiency of the THz wave for the plasmonic PC antenna in figure **4.7a** is the range of $0.1\sim1.0\text{x}10^{16}$. The efficiency of the THz wave for the convectional PC antenna shown in fig **4.7b** $0.1\sim0.4\ \text{x}10^{16}$. Comparing the two simulations the efficiency of terahertz wave for the plasmonic antenna with nanoscale plasmonic electrodes is higher than the convectional antenna.

4.7 Performance of plasmonic PC antenna

Following the simulation experiment carried out, we are able to conclude that the power and efficiency of the THz radiation significantly higher in the Plasmonic PC antenna using nano scale plasmonic electrodes on the PC antenna. Thus we can evaluate the performance of the plasmonic THz PC antenna. As already discussed previously the detection efficiency of THz wave directly depends on the photocarriers generated that reach the plasmonic electrodes in a picoseconds (ps) time frame. The figure **4.8** shows the radiation of the Terahertz wave from the plasmonic PC antenna.

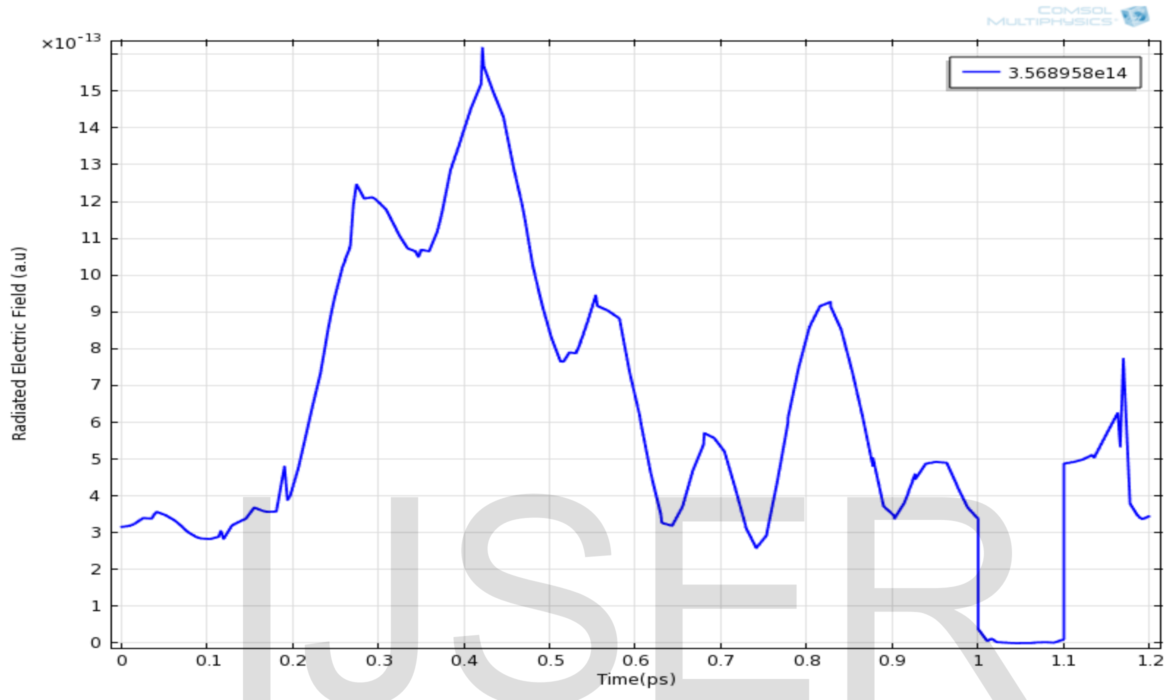

Fig 4.8 Radiated THz wave from the plasmonic PC antenna

4.8 Summary of Results Discussion

From the simulation experiment and graphs discussed earlier we have been able to demonstrate that the THz radiation efficiency can be enhance by the use of plasmonic antenna which incorporates the use of nanoscale plasmonic electrodes. The excitation of the plasmonic surface electodes provides a unique chance to maximize the efficiency of the THz wave power generated. Therefore in order to improve upon the performance of PC antenna we can incorporate the use plasmonic electrodes gratings fabricated in a bow-tie shape. This will significantly mitigate the low quantum efficiency of the photoconductive antenna for THz radiation wave generated. The plasmonic electodes design strategy increases the amount of photocarriers generated in order to increase the laser pulse transmission to the absorbing GaAs substrate and also to reduce the average transport path of the charged carriers in the active area of the substrate. Hence, from the simulation carried out we have ben able to experimentally demonstrate how the performance of a PC antenna can be improved in order to maximizing the efficiency of the THz wave generated.

5. CONCLUSION

In this paper we carried out a study on the mechanism of generation of THz wave radiation with photoconductive antenna. We discuss the features and material required for photoconductive antenna and a design technique for a photoconductive antenna that can enhance the efficiency and performance of THz radiation generated to achieve a higher gain of the terahertz wave. In the study, we demonstrate how the power of the generated THz is higher for plasmonic PC antenna by comparing it with a normal convection PC antenna. Even though fabricating the semiconductor electrodes in a bow-tie on a photoconductive antenna is known to maximize the efficiency of terahertz radiation, the radiation can further be enhanced significantly by designing the electrodes in nanoscale which increase the photocarriers generated and this induces a high photocurrent in a bias electric field that is essential for terahertz wave generated. The purpose of this design strategy is to further increase the photocarriers generated at the electrodes with high concentration of electrons and a small concentration of holes required to induce high photocurrent in order to penetrate through the absorbing GaAs for THz wave generation. A very high photocurrent produced will maximize terahertz wave generated. Ordinarily, we can also increase the generation of terahertz wave by simply increasing the intensity of the laser pulse beam which will increase the photocurrent in a bias electric field of the PC antenna but this has saturation limit and thus this design technique proves to be much more better and efficient for the performance of the PC antenna for THz radiation. Therefore we have been able to provide the design techniques for plasmonic PC antenna that will significantly enhance the efficiency of the THz radiation generated and provide a high power of THz wave.

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