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Review Article

Modeling and Characterizing of an Enhanced Practical Terahertz Photoconductive Antenna

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Abstract. Optical generation can be divided into photoconductive generation and optical rectification. Moreover, the generation of photoconductive is more efficient than optical rectification when standard laser oscillator systems are used. At photoconductive antenna (PCA), the efficiency and terahertz (THz) power generated are affected by different parameters (e.g. incident power of laser pump, dielectric properties and the applied DC bias voltage difference). In this research, four proposed designs of PCAs are presented and compared. Furthermore, microfabrication aspects and concerns have been considered in this study, which are rarely presented in the literature. Therefore, effects of different parameters are shown in this work such as adding adhesion layer in between electrodes and the substrate, varying of gap properties and dipole length. Output frequency, photocurrent and the total effective energy of different antenna models at different values of laser power have been studied and compared.

Keywords. Photoconductive antenna, Photocurrent, THz radiation, Laser pulse

Mathematics Subject Classification (2020). 62P10

1. Introduction

Terahertz technology can be used in different industries including medical industry, aerospace industry, wood products industry and semiconductor industry [19], which is lying in between the microwave and optical regions (0.1-10 THz) [1]. Those applications allow to explore how matter interacts with THz radiation. For example, water is classified as a highly absorptive [5]. Wood, plastics and paper (nonpolar and nonmetallic materials) are transparent. On the other hand, metals are classified as a reflective at this range of frequencies [2, 11]. Terahertz technology is considered as the future for wireless communication systems, which will support the operation of transmitters and receivers in microwave and high frequency ranges. Also, the speed of the data transfer will be enhanced. Terahertz sources and detectors went through many enhancement stages. This continuous enhancement will facilitate discovering new applications of terahertz spectrum. Optical and solid-state methods are used to generate THz radiation. However, using solid state method is limited because the generation should be done at cryogenic temperatures. Optical generation can be subdivided into two methods: Optical rectification and photoconductive generation. However, the photoconductive based method is considered more efficient than the first method when standard laser oscillator systems are utilized [6, 8, 14, 16]. Therefore, PCA is considered as one of the most useful tools for generating and detecting terahertz radiation [18, 20]. The efficiency and generated power of THz radiation are affected by different parameters (e.g. incident power of laser pump, DC voltage difference and dielectric properties) [22].

Different PCA designs and development have been done to serve different industries and applications However, many of these designs have been numerically studied without taking the manufacturing cost in their account [3, 7, 10]. Furthermore, most of these simulated designs have not considered the manufacturing viability. In these type of microfabrication, electrode of gold, aluminum, copper, or other materials cannot be deposited directly to the substrate without having a barrier layer in between the electrode and the substrate, which it results to materials diffusion to the substrate if a barrier layer is not utilized [9]. Consequently, this will result in diffusing current effects on the desired results [13, 17].

In this paper, four proposed designs of PCAs are developed and simulated using COMSOL Multiphysics, which include micro gold electrodes and titanium thin layer with specific dimensions that can be manufactured effectively and fill the gap of the conventional designs, which were commonly characterized and developed. However, fabricating titanium thin layer between electrodes and the substrate utilizes as an adhesion layer in between the metal and substrate (such as glass) and prevents creating metal diffusion in some other substrate cases such as silicon and germanium substrates. Moreover, one of the main disadvantages of some of the conventional designs are the difficulty and high-cost of fabricating thick gold electrodes thickness such as 1 μm. Furthermore, the proposed designs will study the effects of changing different parameters (e.g. dipole length, gap size, the value of laser power) and effects of adding different layers and their properties (e.g. adding a nano thin layer of titanium in between electrodes and the substrate). The developed designs are shown in materials and methods section.The simulated proposed designs are compared and discussed in the results and discussion section.

2. Materials and Methods

Figure 1 shows the schematic diagram of conventional PCA designs. However, Gallium Arsenide (GaAs) was used as a substrate material. GaAs is a semiconductor that has a carrier lifetime of few picoseconds [21]. Conventional designs were modeled as a cube that each length of its edges equals to 100 μm. While gold was deposited as electrode at the substrate and modeled with 1 μm thickness of gold. Figure 1(a) shows that the gap is air while Figure 1(b) shows that the gap is filled by the same material of substrate (GaAs).

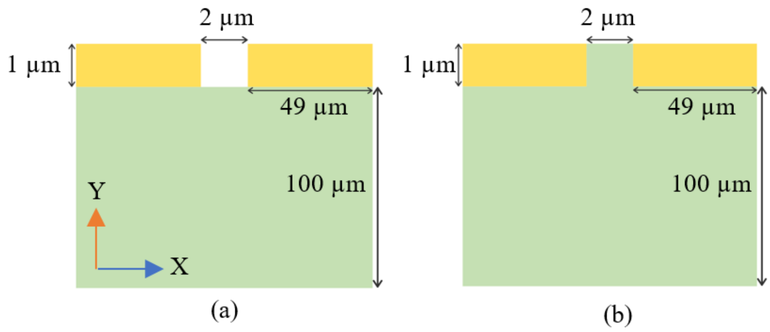

Figure 1. The schematic diagram of the conventional design with (a) air gap, (b) GaAs gap

Figure 2 shows the sequential steps, which were followed to get the four proposed designs of PCAs. Figure 3 shows the typical design of the proposed PCA that consists of two electrodes, however, a thin layer of titanium is modeled in between the gold electrodes and the substrate to prevent the gold diffusion to GaAs. Also, GaAs is designed to fill the gap in between the two electrodes.

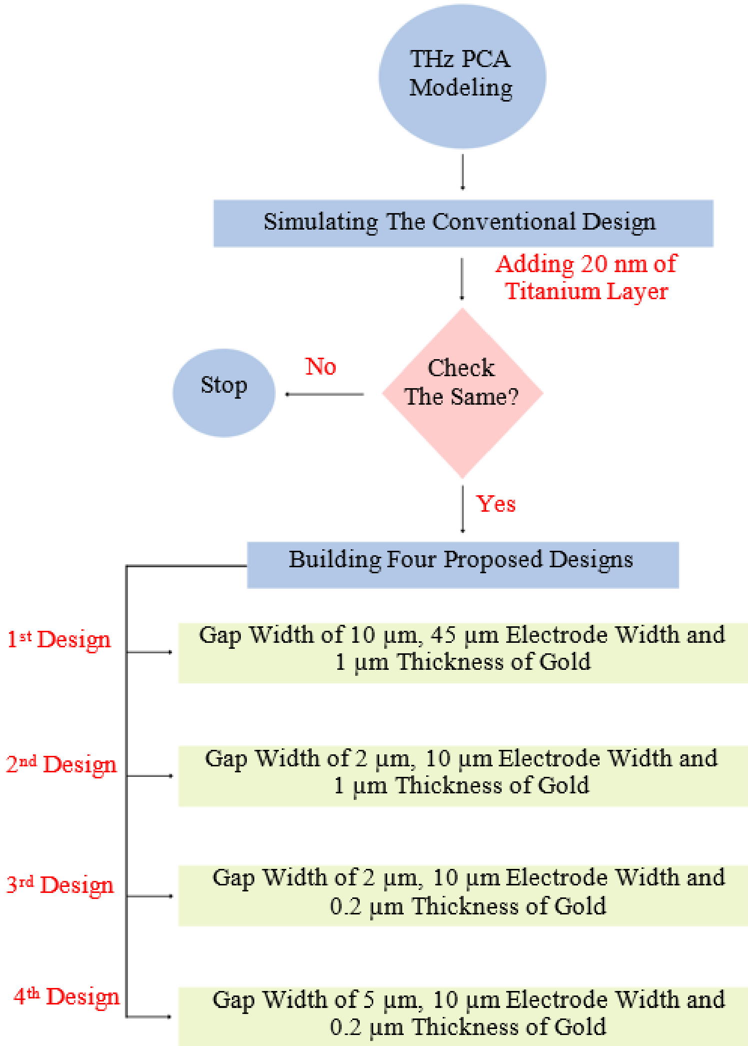

Figure 2. The sequential steps of building the proposed designs of PCAs

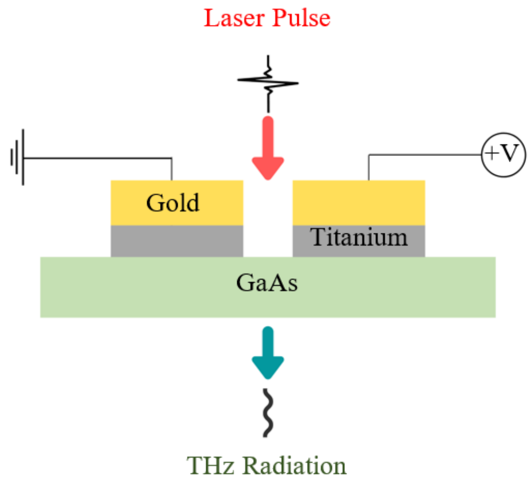

Figure 3. A typical design of PCA that works as a source of THz radiation

In Figure 4, ultrafast laser pulse in hundred femtosecond or less is illuminated the gap region. Also, a DC voltage is biased the electrodes as it is shown in the typical design of PCA in Figure 3. The biased field will actuate the photo excited carriers inside the semiconductor and the transient current will be generated. With help of electrodes, the transient current will be radiated into free space [4, 12, 15, 21].

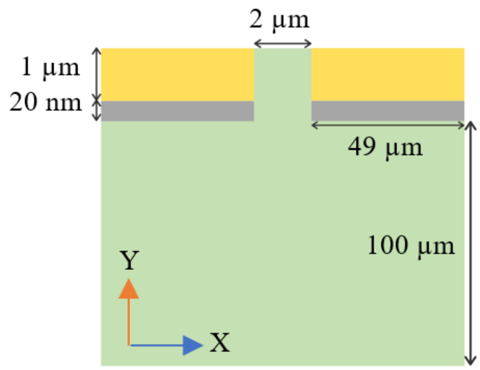

Figure 4. Thin titanium layer is added to the conventional design to show the validity of the proposed design

To show the validity of the typical design of the proposed PCA, thin titanium layer was added to the conventional design to check whether it has same simulation results of the conventional design or not as mentioned before. This design is shown in Figure 4. A10 V DC bias voltage was utilized to PCA. Also, 10 mW of incident optical pump was illuminated the gap of PCA as shown in Figure 5.

Four different proposed designs of PCAs were designed, simulated and compared. For all designs, titanium layer was added and GaAs was filled in all gaps as shown in Figure 6. The first proposed design has a gap width of 10 μm and 45 μm electrode width (Figure 6(a)). Then, for the gap and electrode width were reduced to 2 μm and 10 μm, respectively as shown in Figure 6(b). Furthermore, other parameters have been compared such as the electrode's thickness and the gap width as shown in Figure 6(c) and (d).

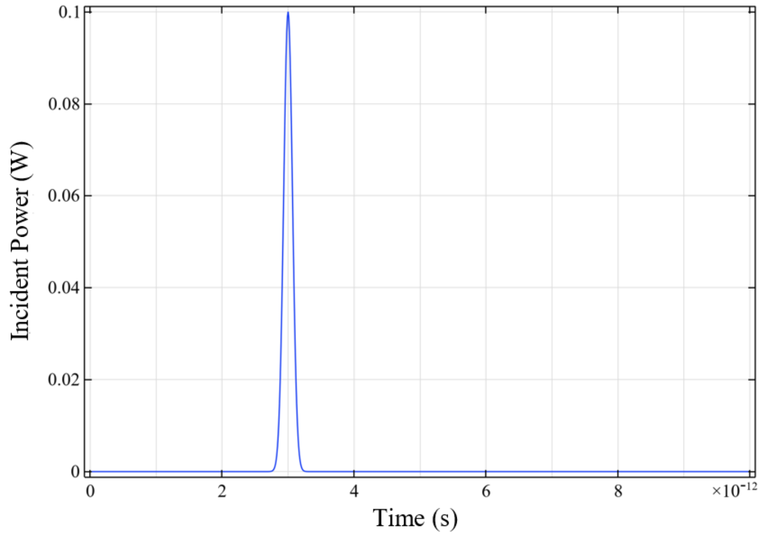

Figure 5. The peak value of the incident laser power is 0.1 W. This peak value exists at $t = 3$ ps

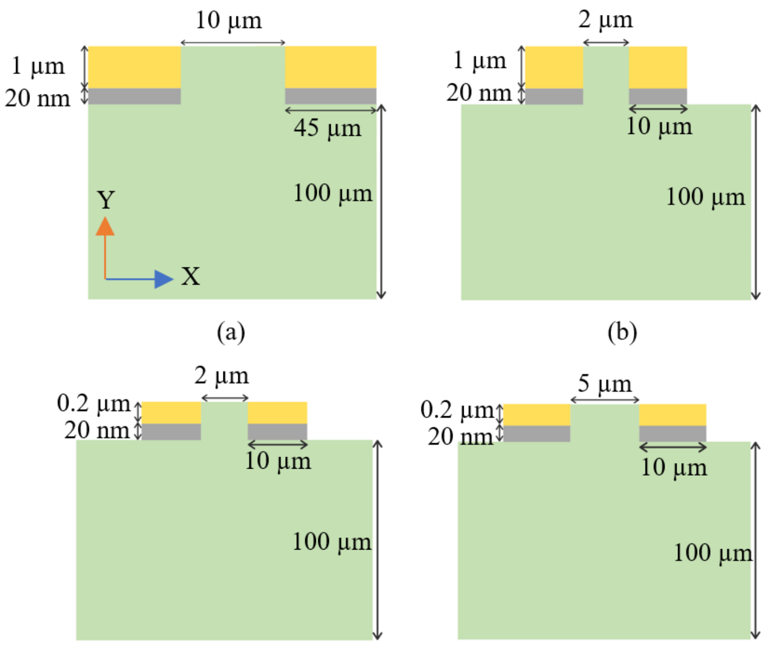

Figure 6. The (a) 1st, (b) 2nd, (c) 3rd and (d) 4th proposed design of PCA. Proposed designs include a 20 nm thin layer of titanium

COMSOL Multiphysics 5.6 version was used to simulate the conventional and proposed designs of PCAs. Results of that simulation are shown in the following section.

3. Results and Discussions

Initially, a photocurrent simulation that compare the effect of a thin layer of titanium in between the electrode and substrate is shown in Figure 7. Photocurrent values of PCA are equal for both cases (with/without titanium layer). Therefore, adding the isolation layer does not affect the results but the manufacturing process will be more practical.

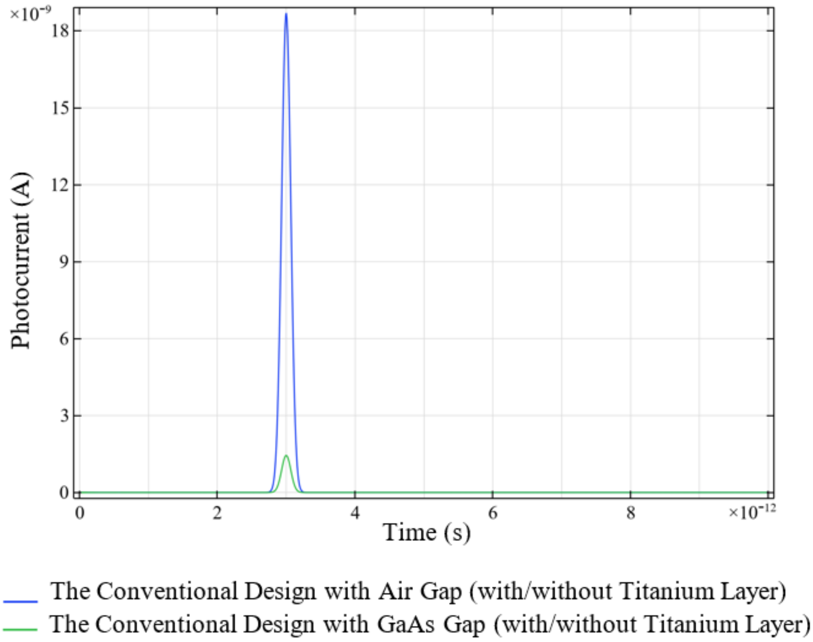

Figure 7. Photocurrent values of the conventional designs of PCAs with or without titanium layer are the same

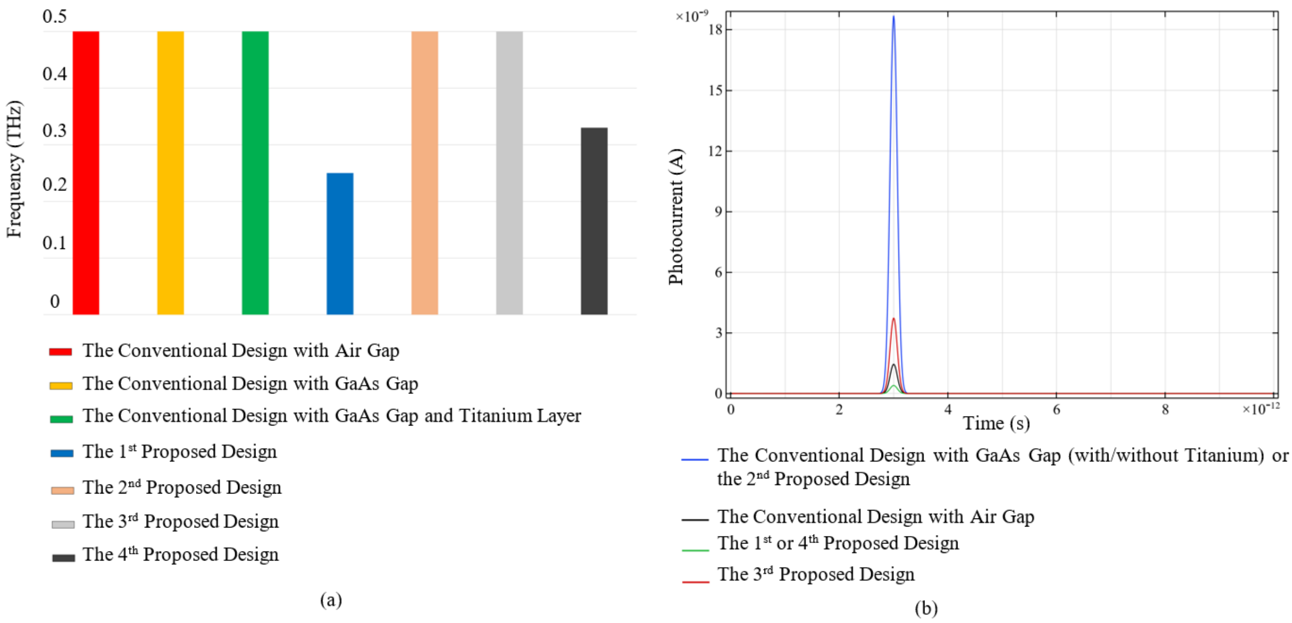

Figure 8. The (a) output frequency and (b) photocurrent values comparisons of the conventional and proposed designs of PCAs

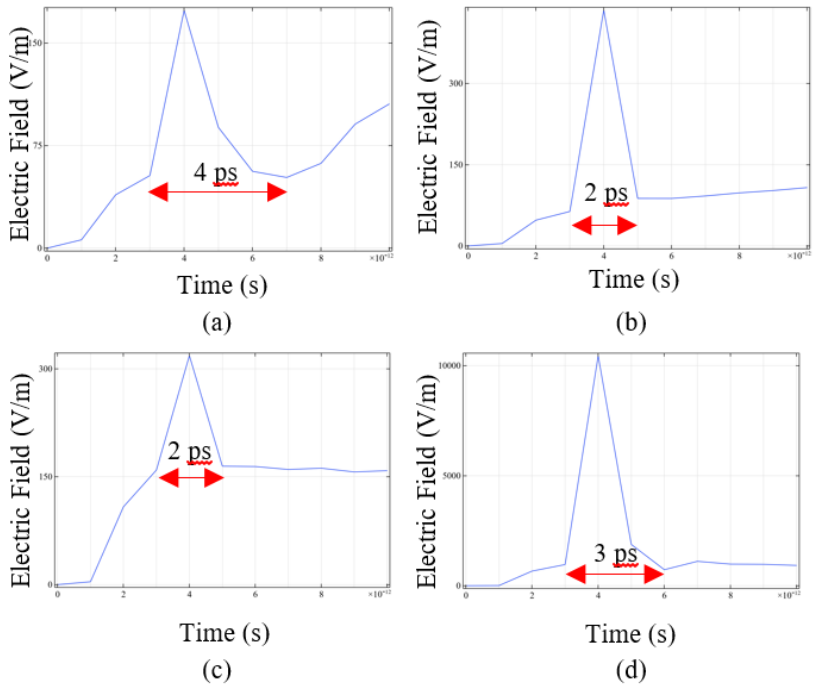

Figure 9. Output electric field of the (a) 1st, (b) 2nd, (c) 3rd and (d) 4th proposed design of PCA at the bottom of the substrate

As shown in Figure 8(a), the output frequency was not affected by varying the width and thickness of the electrodes. However, gap size is the main factor that affects the output frequency (with or without the titanium layer). So, all the conventional and proposed designs of PCAs could successfully work in the range of THz radiation. Also, as shown in Figure 8(b), the photocurrent values were not affected by varying the width of electrodes. However, the decreasing in the electrodes' gap result in higher photocurrent.

Figure 9 presents the electric field strength at the bottom of the substrate of the proposed designs of PCAs. The pulse of electric field approximately started at 3 ps, which is the time that incident laser power reached to its peak value as it is shown in Figure 5. In Figure 10, the electric field distributions of proposed designs of PCAs at $t = 3$ ps are presented. The electric field distributions depth and concentrations are different due to the electrodes' width and gap.

Figure 11 shows the electric field strength at $t = 3$ ps across the gap of the proposed PCAs at the surface of electrode. The electric field strength close to the electrode edge is approximately the largest; therefore, the largest THz power is expected if the incident laser is focused near the edge of each electrode. It is clear from Figure 11(c) and (d) that the electric field strength is effected by the thickness of electrodes and fluctuations have been shown.

The total effective energy of the second proposed design is the highest among other proposed designs as shown in Figure 12. The energy is converted into THz radiation power when PCA is excited with laser pump. However, choosing the best design among the proposed designs depends on the application of use. Because of that the second proposed design could be chosen as the best design in terms of total effective energy. However, the third design could be considered in terms of manufacturing cost as the best since the operating frequency range still in THz and the resulting photocurrent is considerable.

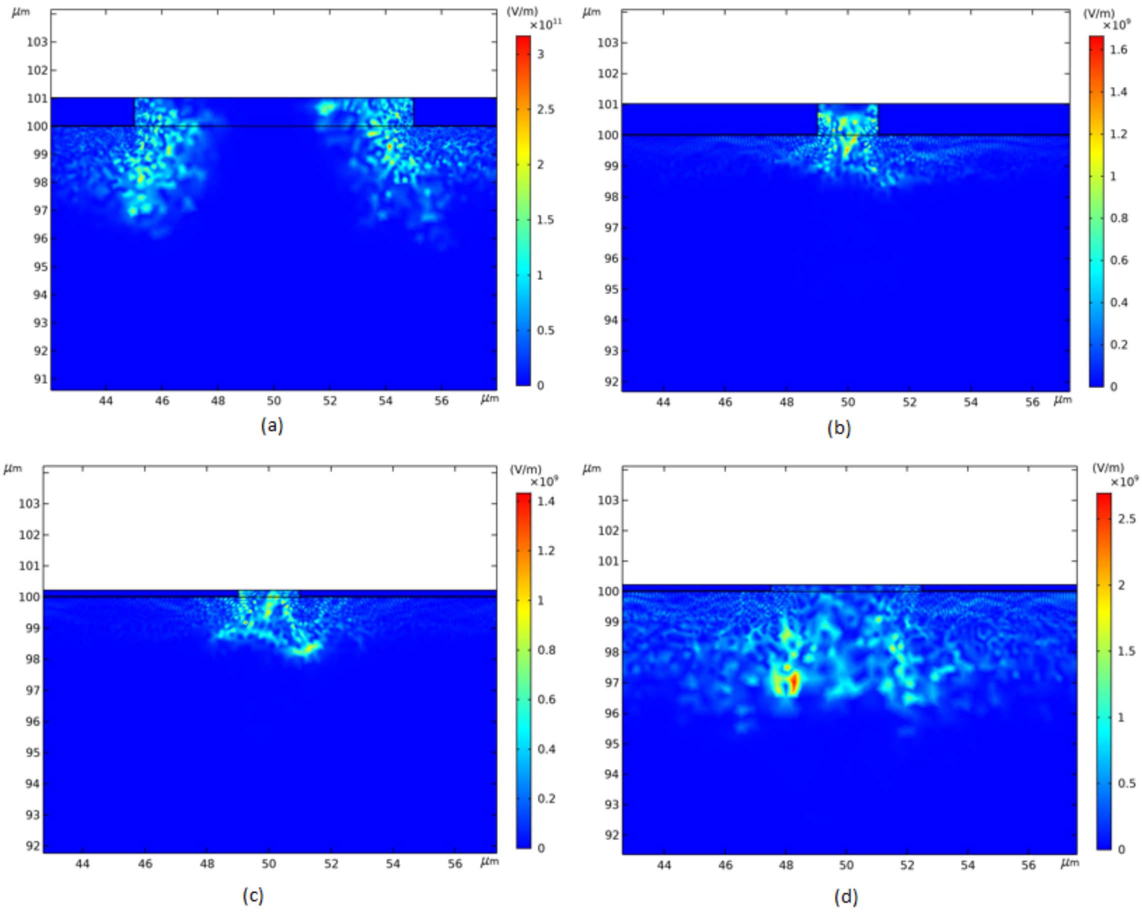

Figure 10. The electric field of the (a) 1st, (b) 2nd, (c) 3rd and (d) 4th proposed design of PCA at $t = 3$ ps

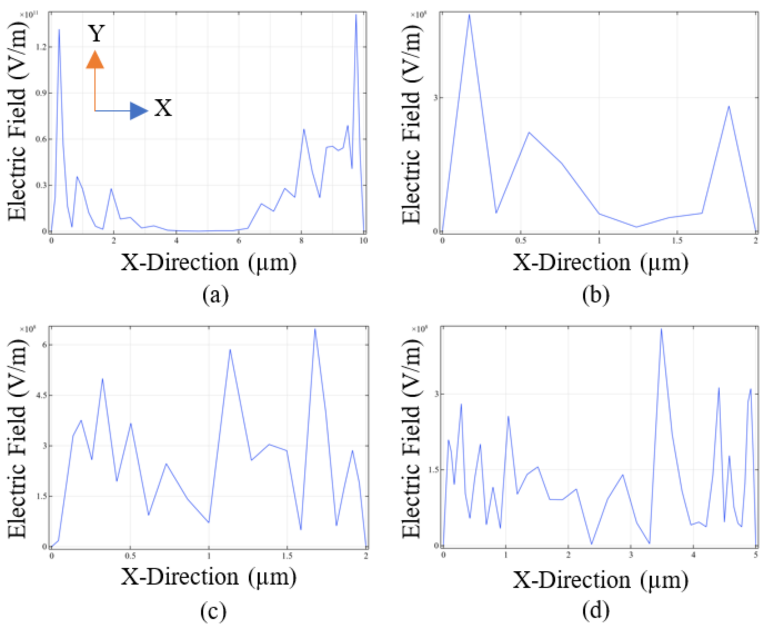

Figure 11. Electric field across the gap for the (a) 1st, (b) 2nd, (c) 3rd and (d) 4th proposed design at $t = 3$ ps

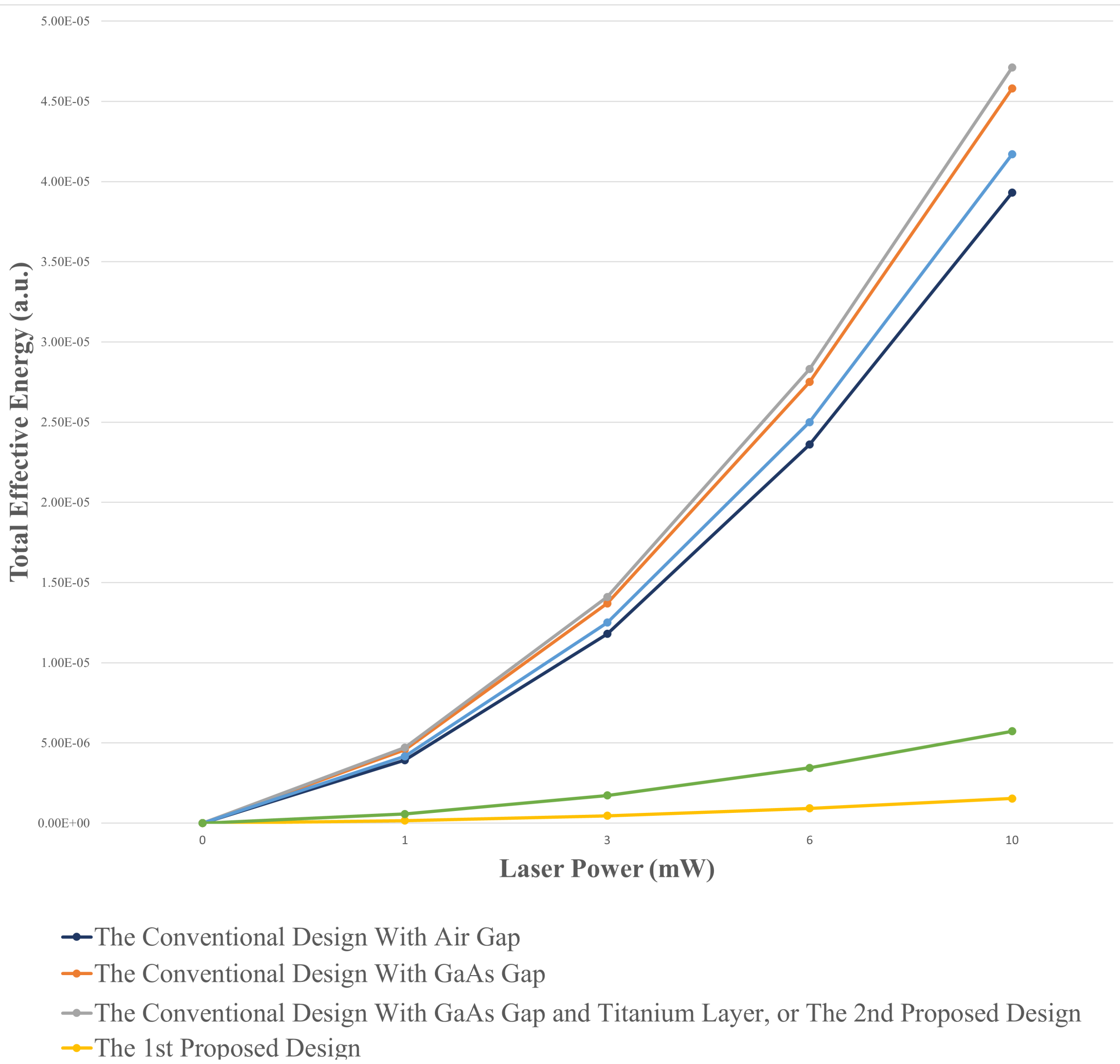

Figure 12. Total effective energy of conventional and proposed designs with variation of laser power value

4. Conclusion

Different proposed designs of PCAs are successfully simulated and compared using COMSOL Multiphysics as shown in this work. The structure of each design includes micro gold electrodes and a nano thin titanium layer in between the electrodes and the substrate. Therefore, manufacturing of the proposed designs can be realized effectively using the proposed gap properties and designs. Moreover, as shown,introducing a thin titanium layer between gold and GaAs layers does not affect the results efficiency of the proposed models as well as will prevents creating current diffusion as a consequence of metal diffusion. In addition, the proposed designs of PCAs are more cost efficient than the conventional designs due to smaller electrodes size comparing to the conventional designs. The total effective energy stored in PCAs with different values of laser power are presented. For example, the 3rd proposed design has a stored energy that is the highest among other proposed designs and closes to the conventional designs. However, it is possible to reduce dimensions of gold electrodes and get the same value of the total effective energy that allow to use PCA in different applications. For example, it is possible to use PCA to measure sugar blood level of a blood sample as a medical application.

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Competing Interests

The authors declare that they have no competing interests.

Authors' Contributions

All the authors contributed significantly in writing this article. The authors read and approved the final manuscript.

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