Design and analysis of triple-bands microstrip patch nanoantenna for terahertz applications

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ABSTRACT

Terahertz (THz) technology is the utilization of electromagnetic waves with frequencies in the range of 0.1 to 10 terahertz. This frequency range is also known as the submillimeter range, lying between the microwave and infrared regions of the electromagnetic spectrum. Terahertz technology has numerous applications in various fields, such as communications, spectroscopy, imaging, and sensing. In communications, terahertz waves can transmit large amounts of data over short distances and potentially revolutionize wireless communication networks. Recently, scientists and researchers have been concentrating on terahertz technology as it continues to evolve. In this paper, we design and simulate a rectangular-shaped patch nanoantenna with a line-feeding technique; the proposed antenna is based on three layers: a perfect electric conductor (PEC) patch, a silicon substrate layer, and a fully PEC ground plane layer. The main aim is to study the impact of altering the nanoantenna's parameters, including shape, size, ground plane, feed line, and patch nanostructures, on its behavior. The simulated antenna operates in triple-bands of frequrncywhich are 571.85, 715.66, and 905.05 THz. As a result, the applications of this terahertz frequency band are within the visible range.

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1. INTRODUCTION

Terahertz (THz) regime falls in the range between microwaves and infrared radiation on the electromagnetic spectrum and is often referred to as the submillimeter range. The unique characteristic of terahertz waves lies in their ability to penetrate various materials, such as clothing, plastics, and paper, while also being non-ionizing, making them safe for biological tissues. This has led to exciting possibilities for terahertz technology in fields such as communications, spectroscopy, imaging, and sensing. Researchers are actively exploring the potential of terahertz waves in developing advanced communication networks, high-resolution imaging systems, and non-invasive medical diagnostics. With its promising applications and intriguing properties, the terahertz regime continues to garner significant interest and investment in scientific research and development [1], [2].

Nano-optics is the study of optical phenomena and related methods at the nanometer (nm) scale. The term optical antenna is often used interchangeably with nanoantenna. While optical antennas function in a manner similar to conventional antennas, nanoantennas specifically operate within the optical frequency range of the electromagnetic spectrum. To achieve resonance at optical frequencies, antennas need to be scaled down to the nanoscale, aligning with the working wavelength. A nanoantenna can be described as a metallic structure at the nanoscale that enhances the interaction of optical radiation with matter [3], [4].

Antennas are commonly characterized using specific performance metrics, including input impedance, polarization, gain, beamwidth, directivity, bandwidth, and radiation pattern. Feynman's concept has materialized due to advancements in nanofabrication techniques and studies in nanotechnology, leading to the creation of numerous nanoantennas for various applications. The optical antenna exhibits similar general characteristics to its radio frequency and microwave counterparts. However, when comparing conventional antennas to nanoantennas, limitations arise due to the divergence of material properties and responses at optical frequencies from those at RF/microwave frequencies. As a result, classic antenna theory cannot be directly applied and scaled down for nanoantennas, necessitating the development of a new theory specifically tailored to nano-scaled-down antennas that accounts for the unique processes occurring at optical frequencies [5], [6] or at terahertz frequencies [7]–[10], and the surface plasmon polariton phenomena appeared at this frequency range [11], [12].

The K. B. Crozier Group at Stanford University coined the term "nano-optical" to describe the structure of the nanophotonic device that efficiently connects optical-frequency electromagnetic waves to the sub-wavelength scale through surface plasmon phenomena. As a result, nanoantennas can find applications in polarimetric imaging systems, optical sensors, and other fields. They are specifically designed to detect light in the visible and infrared spectra [13].

The optical properties of plasmonic nanoantennas (PNAs) are primarily sought after in the medical industry for their nano-structures of metals, which are crucial components in designing optimal parameters. These requirements can be fulfilled by microstrip patch antennas (MPAs). In addition to their low profile and simple structure, the MPAs offer advantages such as a small and lightweight footprint, low fabrication costs, and the ability to be adapted to planar or non-planar surfaces using printed circuit boards [14]–[16].

The contribution of this work can be summarized as the utilization of various approaches, including different sizes of the ground plane, patch, and feed line, to enhance the performance characteristics of the patch antenna. These enhancements encompass factors such as bandwidth, reflection coefficient, gain, directivity, and efficiency. Specifically, the designed microstrip antenna is constructed with a regular rectangular patch, a silicon dielectric substrate, and a full ground plane. The materials chosen for the ground plane and patch are perfect electric conductors (PEC) due to their high conductivity and the preservation of characteristics within the THz range. Through this design, we achieve strong bands within the THz region, which are well-suited for visual applications, resulting in excellent directivity and gain.

Generally, this paper is made up of 6 fundamental sections, section 2 presents the theory and principle of microstrip nanoantenna. Section 3 presents the proposed configuration of the proposed nanoantenna. Section 4 presents the parametric study that describes the obtained results. Section 5 presents a discussion of the obtained results. Finally, section 6 exhibits the conclusion after making this work.

2. MICROSTRIP NANOANTENNA THEORY

The structure of a microstrip nanoantenna consists of several key components. At its core, there is a patch antenna, typically made of a PEC material. This patch serves as the radiating element of the antenna. The patch is placed on a silicon dielectric substrate, which provides mechanical support and insulation. Below the substrate lies the ground plane, also made of PEC material, which acts as a reflector and helps in achieving the desired radiation characteristics. The microstrip feed line, used to supply power to the antenna, is usually inset-fed and connected to the patch, as shown in Figure 1. This structure allows for compact dimensions, low profile, and ease of integration into planar or non-planar surfaces using printed circuit board technology. The design and optimization of the microstrip nanoantenna's structure play a crucial role in determining its performance and functionality in various applications. The following subsections interpret the elements of the microstrip nanoantenna [17], [18].

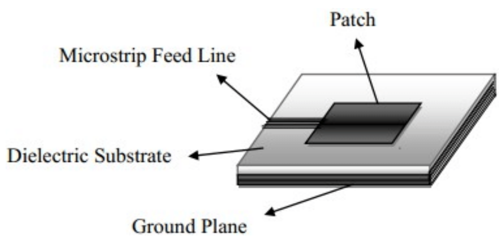


Figure 1. General structure for microstrip nanoantenna

2.1. Radiating patch

A patch serves as the foundational layer in a planar antenna, and MPAs represent one of the fundamental and significant types of these devices. Many concepts and techniques employed in MPAs can be directly applied to other planar antennas. The MPAs are the simplest form of microstrip antennas, comprising three layers, as illustrated in Figure 1. This layer governs the radiation characteristics. It is fabricated by printing or etching a thin conducting material, such as gold or copper, onto the dielectric substrate, which constitutes the second layer positioned in the center of the antenna structure. Various geometrical shapes, including square, rectangular, triangular, elliptical, and circular are commonly employed to create the patches [19].

2.2. Dielectric substrate

An antenna substrate is a material that provides the physical structure for an antenna and facilitates the transmission of electromagnetic waves. The substrate is often made of a dielectric material, such as fiberglass, ceramic, or plastic, chosen based on the required electrical and mechanical properties of the antenna. The substrate performs several crucial functions in antenna construction. Firstly, it offers mechanical support for the conducting elements of the antenna, which are typically printed onto the surface of the substrate [20].

2.3. Ground plane

The ground plane can be considered the bottom layer of the microstrip patch antenna and is typically made of copper material. This layer serves as the conductive surface that interfaces with the substrate, ensuring proper matching. It acts as the third layer in the antenna structure and the lowest one [21].

3. DESIGN AND CONFIGURATION OF NANOANTENNA

In this section, we present the layers, sizes, materials used, figures, and relationships of microstrip nanoantennas. The microstrip design of nanoantennas employs various approaches, including different sizes of the ground plane. As depicted in Figures 2(a) and (b), the simulated microstrip nanoantenna is composed of three layers: patch, substrate, and ground. The patch, made of PEC metal, serves as the nanoantenna's radiating element. The substrate is made of silicon, a dielectric material with a thickness of 20 nm and a dielectric constant of 11.9. The ground layer is also made of PEC metal. Additionally, to achieve satisfactory results for both the reflection coefficient S_{11} and the farfield, a waveguide excitation port with line feeding structureis utilized. All the parameters of the microstrip nanoantenna are listed in Table 1.

In order to formulate the dimensions of the designed microstrip nanoantenna, the straightforward equations of the transmission line analysis model are used [22], [23], as listed:

$$W_p = \frac{\upsilon_o}{2f_o\sqrt{\frac{\varepsilon_r+1}{2}}} \tag{1}$$

$$\varepsilon_{r_{eff}} = \frac{\{(\varepsilon_r+1)+(\varepsilon_r-1)\}}{2}\left[1+12\frac{h}{W_p}\right]^{-\frac{1}{2}} \tag{2}$$

$$L_p = \frac{\upsilon_o}{2f_o\sqrt{\varepsilon_{r_{eff}}}} - 2\left\{0.412h\frac{\left(\varepsilon_{r_{eff}}+0.3\right)\left[\frac{W_p}{h}+0.264\right]}{\left(\varepsilon_{r_{eff}}-0.258\right)\left[\frac{W_p}{h}+0.8\right]}\right\} \tag{3}$$

Where υ_o is stands for the speed of light in the air, $f_o$is stands for the resonant frequency of the designed microstrip nanoantenna, ε_r is stands for the relative permittivity of the dielectric material, $\varepsilon_{r_{eff}}$ is stands for the effective relativepermittivity, and h stands for the thickness of the dielectric material.

To achieve optimal electric coupling, the inset line feeding method is utilized. With this method, the input impedance of the radiating patch of the antenna reaches its maximum value at the edge and gradually decreases towards the center, ultimately becoming zero at the patch center. In this study, the inset feeding technique is analyzed based on the following equations [24], [25]:

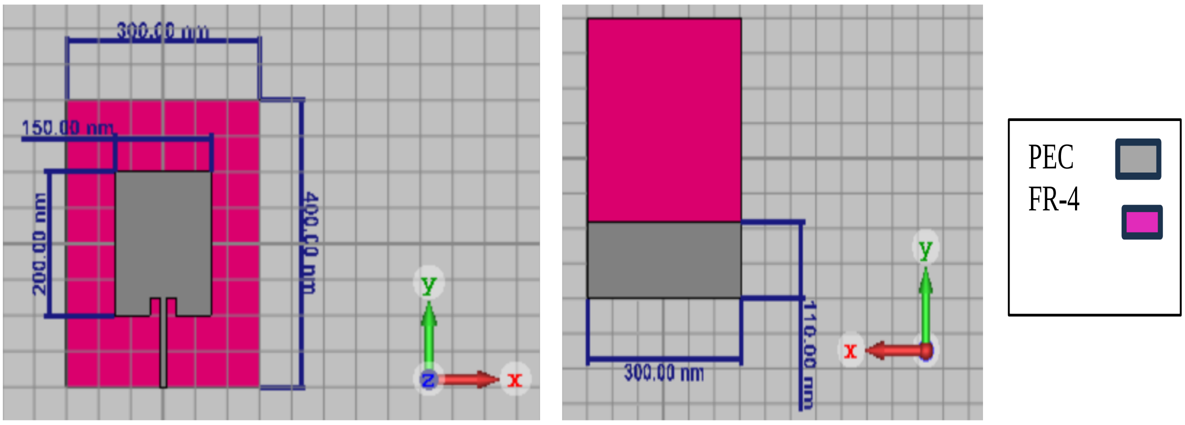
$$W_{feed} = \frac{2h}{\pi}\left\{\frac{377\pi}{2Z_0\sqrt{\varepsilon_r}} - 1 - \ln\left(2\times\frac{377\pi}{2Z_{feed}\sqrt{\varepsilon_r}} - 1\right) + \frac{\varepsilon_r-1}{2\varepsilon_r}\left[\ln\left(\frac{377\pi}{2Z_0\sqrt{\varepsilon_r}} - 1\right) + 0.39 - \left(\frac{0.61}{\varepsilon_r}\right)\right]\right\} \tag{4}$$

$$f_{inset} = \frac{\cos^{-1}\left(\sqrt{\frac{Z_{feed}}{R_{in}}}\right)}{\frac{\pi}{L}} \tag{5}$$

$$L_{feed} = 3.96 \times W_{feed} \quad (6)$$

$$G_{ap} = \frac{\upsilon_o \times 4.65 \times 10^{-9}}{f_o\sqrt{2\varepsilon_{reff}}} \quad (7)$$

Where W_{feed} is stands for the width of the transmission feeding line, Z_{feed} is stands for the equivalent feed line impedance, f_{inset} is stands for the distance that how much the feed line inserted within the patch, L_{feed} is stands for the length of the feeding line, and G_{ap} is stands for the gap between the feed line and the patch of the simulated nanoantenna.



(a) (b)

Figure 2. Simulated nanoantenna inside CST software: (a) front view and (b) back view

Table 1. Dimensions of a nanoantenna

Parameters	Value (nm)
Patch width (W_p)	150
Patch length (L_p)	200
Ground width (W_g)	300
Ground length, (L_g)	110
Substrate width (Ws)	300
Length of the substrate (Ls)	400.50
Thickness of the substratum (h)	20
Feed linewidth (W_f)	10
Feed line length (L_f)	140
Metal thickness (M_T)	1

4. PARAMETRIC STUDY

This section of the paper presents the results obtained for the proposed nanoantenna using computer simulation technology (CST) software. In addition, a parametric study will be conducted to examine the impact of the feeding line length and ground plane length on the overall antenna performance. Subsequently, the results obtained from this study will be presented.

4.1. Effects of changin ground plane length

The parameter investigated in this subsection is the length of the ground plane, aiming to minimize the usage of metal and keep the size as compact as possible. It is worth mentioning that reducing the size of the ground plane is crucial for generating a semi-omnidirectional nanoantenna, which is necessary for THz-based nanoantennas utilized in short-range communications. Table 2 displays the selected values for the ground plane length and the corresponding changes in antenna $f_o$and reflection coefficient S_{11}. Furthermore, Figure 3 illustrates the S_{11} of the antenna for several chosen ground plane lengths.

Table 2. Return loss for the proposed nanoantenna with a different ground plane length

Size (nm)	Resonance frequency (THz)	Return loss (dB)
112	722.8	-28.5
111.5	720.1	-29.6
111	719.2	-31.6
110.5	717	-36.0
110	715.6	-43.9

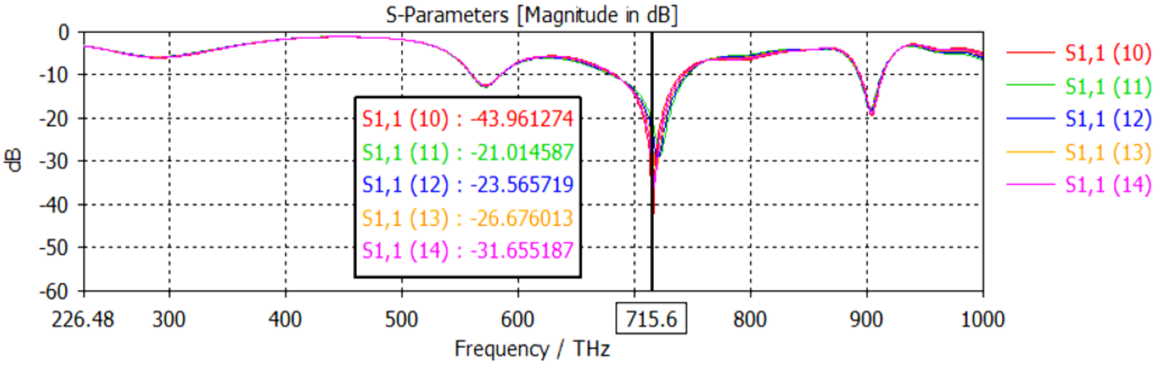


Figure 3. Return loss results for the simulated nanoantenna with different ground plane lengths

4.2. The effect of patch size

The results demonstrate that the proposed model achieves good radiation and impedance matching at the operation region, with a higher decrease in width compared to a typical nanoantenna, as shown in Figure 4. After many studied trials, the proposed design has a patch size that is half the size of a standard nanoantenna. The final size for the simulated nanoantenna is summarized and presented in Table 3. It can be noticed that the width has been calculated as 150 nm, resulting in an antenna configuration with the optimal patch size of 150×200 nm.

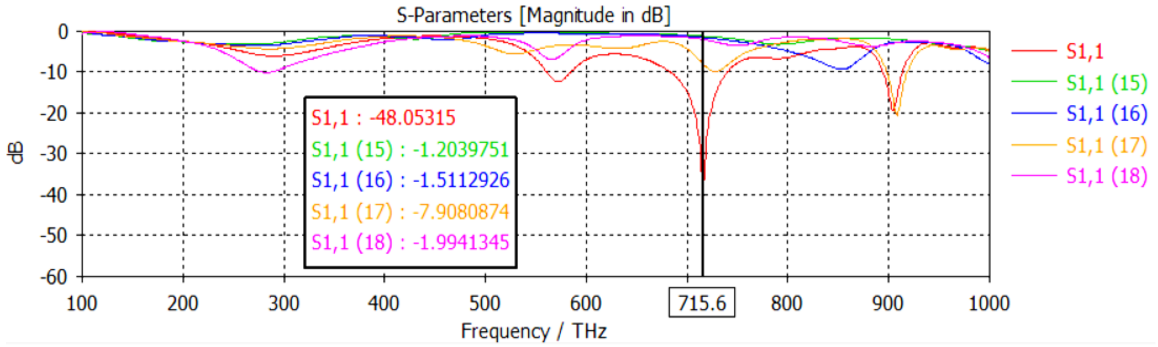


Figure 4. Return loss results for the simulatednanoantenna with different patch width

Table 3. Results of optical microstrip nanoantenna with a different patch width

Size (nm)	Resonance frequency (THz)	Return loss (dB)
300	1000	-4
250	853.3	-9
200	908.2	-20
150	715.6	-48
100	282.7	-10

4.3. The effect of different materials

In the higher frequencies, most of the pure and highly conductive materials act as semiconductors or insulators as reported in [26]. In this work, the performance of the simulated nanoantenna is studied at different highly conductive materials and the obtained results are illustrated in Figure 5. Based on the

Figure 5, the best impedance matching has been achieved at 715.6 THz for the PEC material. The reason for this difference between the PEC material and the other materials used is due to the nature of conductive materials, which tend to lose most of their conductivity at higher frequencies. However, it is important to note that PEC is an idealized material introduced for theoretical purposes, and comparison, is not readily available in reality. Many studies have reported that graphene material exhibits superconductivity, making it ideal for higher frequencies, comparable to and even surpassing PEC.

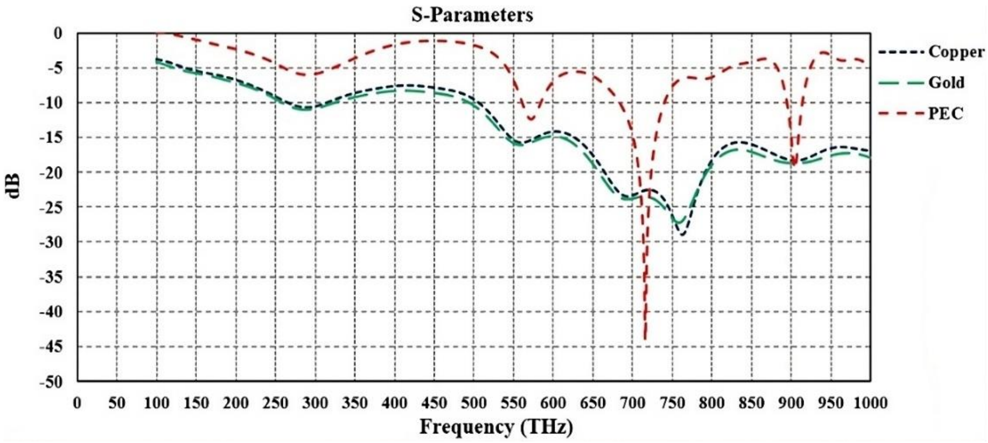


Figure 5. Return loss for the simulated nanoantenna with deifferent materials

5. PERFORMANCE EVALUATION AND RESULT DISCUSSION

After optimizing the dimensions of the simulated nanoantenna. The results demonstrate its good performance across three frequency bands: 571.85 THz with -12.39 dB S_{11}, 715.66 THz with -43.77 dB S_{11}, and 905.05 THz with -19.25 dB S_{11}, as illustrated in Figure 6. Antenna bandwidth refers to the range of frequencies over which an antenna can effectively operate without significant loss in performance. It is a measure of the antenna's ability to receive or transmit signals across a wide frequency spectrum. Generally, the antenna bandwidth is determined from the S_{11} plot at S_{11}=-9.5 dB which signifies that the antenna received 90% of the supplied power and reflects the rest to the source. Figure 7 shows the obtained bandwidth results for the simulated nanoantenna and Table 4 shows the upper and lower frequency for each f_o.

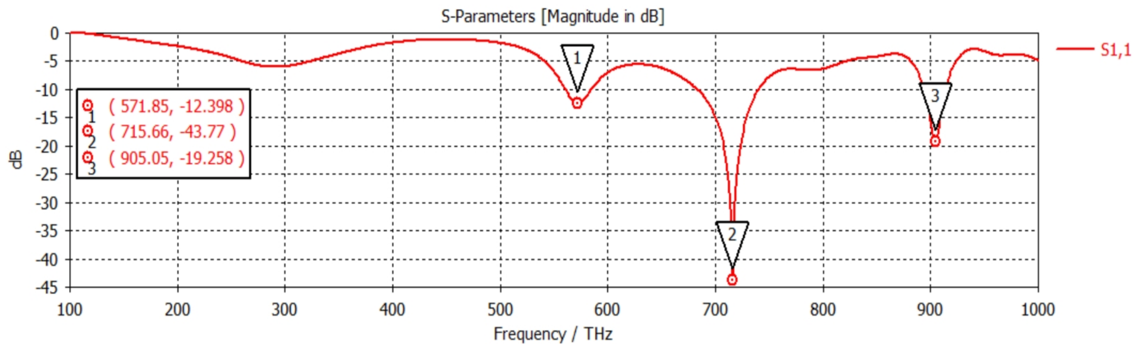


Figure 6. The simulated input return loss of the nanoantenna

Microstrip antennas often face the issue of poor gain, where the gain decreases as the relative permittivity of the substrate; and increases and increases as the height of the substrate increases. Figures 8(a) to (c) displays the gain of the simulated nanoantenna across the triple operating bands at PEC material. To demonstrate the deterioration of antenna, gain at optical frequencies, a gain monitor is created in CST to measure the antenna gain at a frequency of 715.66 THz for both copper and gold materials. This frequency was selected as a reference point among all the materials used, as depicted in Figures 9(a) and (b).

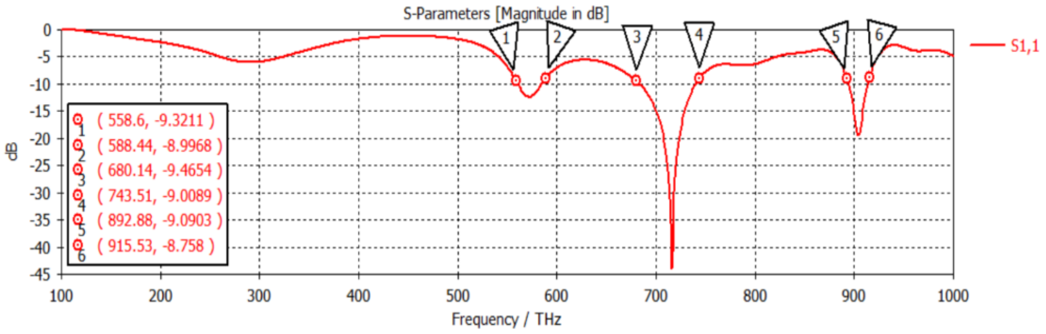
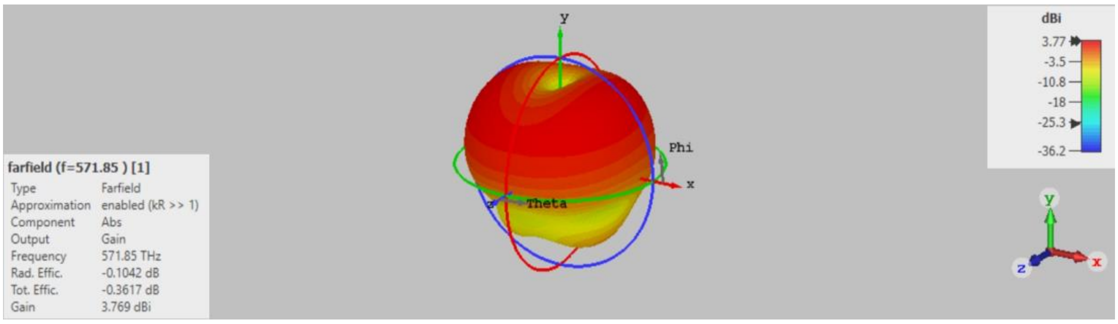


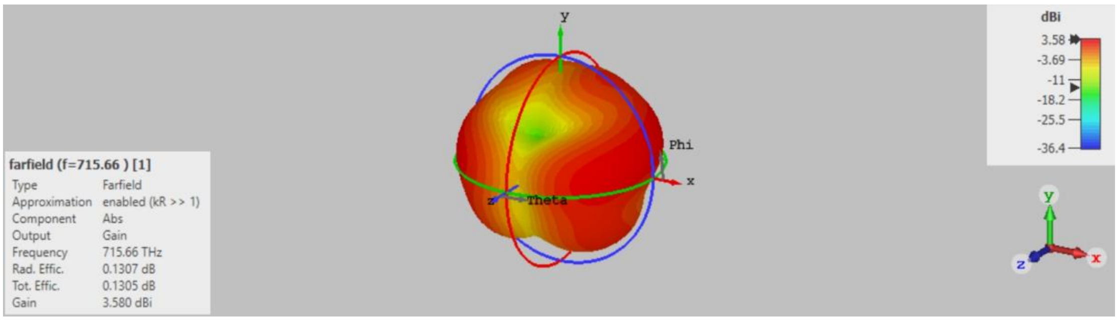
Figure 7. Bandwidth result for the simulated nanoantenna

Table 4. Calculated bandwidth results

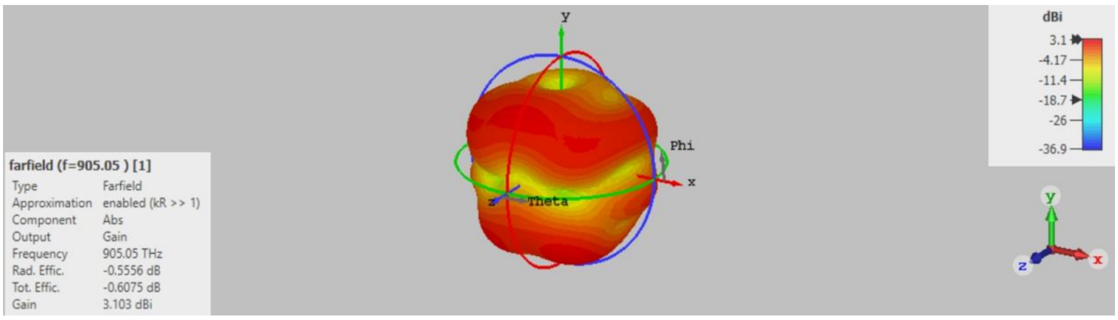
Resonant frequency (THz)	Upper frequency (THz)	Lower frequency (THz)	Bandwidth (THz)
571.85	588.44	558.6	29.84
715.66	743.51	680.14	63.37
905.05	915.53	892.88	22.65



(a)

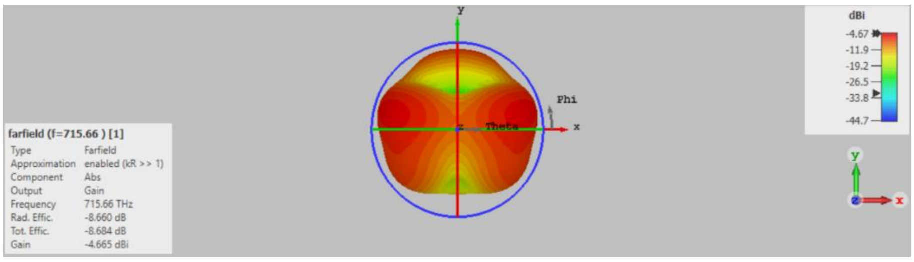


(b)

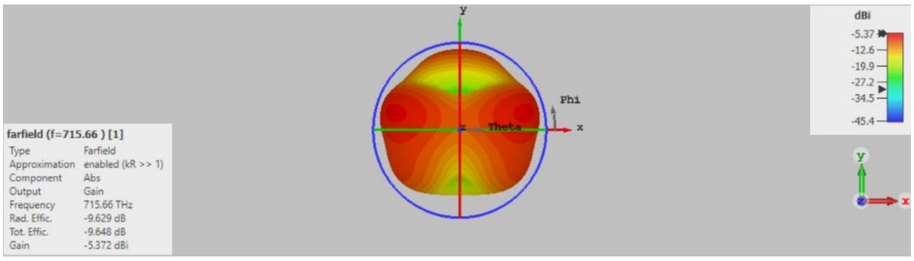


(c)

Figure 8. Nanoantenna gain at PEC material: (a) $f_o = 571.85\ THz$, (b) $f_o = 715.66$ THz, and (c) $f_o = 905.05\ THz$



(a)

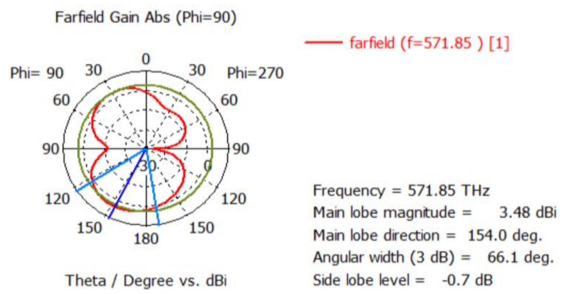


(b)

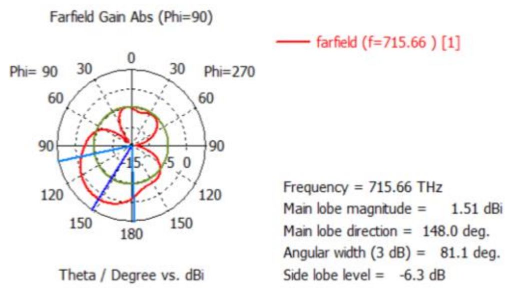
Figure 9. Obtained gain at different conductive materials: (a) $f_o = 715.66$ THz at copper material and (b) $f_o = 715.66$ THz at gold material

According to the results obtained for the antenna gain from CST software, as shown in the previous Figure 8, the gain is significantly degraded and becomes negative due to the behavior of copper and gold materials in optical frequencies, acting like semiconductors. In order to achieve a positive gain, the PEC material has been used as reported previously. However, in practical work, graphene material could serve as a good alternative.

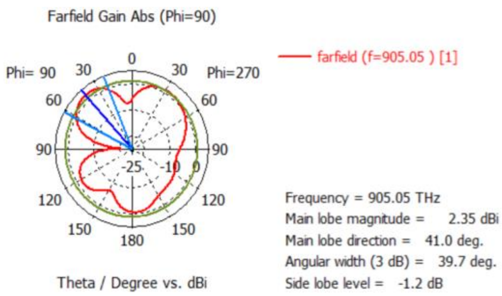
The antenna radiation pattern describes the directional distribution of radiated or received electromagnetic waves by an antenna. In the case of the simulated nanoantenna with a partial ground plane, it exhibits a close resemblance to a semi-omnidirectional pattern, which is crucial for achieving effective performance in higher-frequency antennas. Figures 10(a)–(c) shows the simulated nanoantenna radiation pattern.



(a)



(b)



(c)

Figure 10. Radiation pattern for the simulated nanoantenna: (a) $f_o = 571.85$ THz, (b) $f_o = 715.66$ THz, and (c) $f_o = 905.05$ THz

6. CONCLUSION

The main tool for controlling the far-field area and manipulating light at the nanoscale is an optical antenna. Advances in nanofabrication technology and RF antenna analogs have significantly impacted the current state of optical antenna development. This study focused on investigating the performance of a nanoantenna under various conditions. The simulated nanoantenna's performance was examined with different ground plane and patch dimensions. Additionally, its performance was studied using different conductive materials, including copper, gold, and PEC. The behavior of the used conductive materials resembled that of a semiconductor, resulting in a negative gain, except for PEC, which exhibited exceptional performance. Practically, PEC is expected to be replaced by graphene which will be used in various optical applications. The simulated antenna was operated within a triple band of optical frequencies at 571.85, 715.66, and 905.05 THz, demonstrating a positive and substantial gain.

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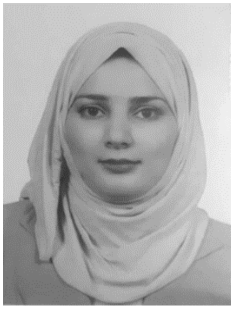

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