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# Metamaterial-based Nano-Antenna Design of Enhanced Plasmonic Electromagnetic Properties

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***Keywords:***
*Directivity; EBG; Fractal; Hilbert; Metamaterial; Minkowski; Nano-antenna; Plasmonic.*

***Highlights:***

- *Design of Nano antenna for optical band application.*
- *Combining metamaterial with fractal geometry.*
- *Improving the characteristics of Nano antennas by incorporating a band gap (EBG) layer.*

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**Abstract**: This work, presents a design of a nano-antenna based plasmonic materials at the frequency range from 192THz to 195THz for modern applications, including THz communication systems. The proposed antenna is constructed from the $3^{rd}$ iteration of the Hilbert curve patch fed with a modified coplanar 50Ω port. The back layer of the antenna was covered with a partial ground plane defective with a metamaterial-based electromagnetic band gap (EBG) layer. The antenna shows high directivity up to 68dBi at 193.4THz with an excellent matching over the entire frequency band of interest. The proposed antenna is considered of gold conductive layer mounted on a silicon dioxide ($SiO_2$) layer. The proposed EBG was designed as the second order of the Minkowski fractal geometry. The obtained results in terms of S11 were below -10dB for the frequency band of 3THz. These results were validated using numerical techniques based on CST MWS by invoking the time domain (TD) and frequency domain (FD) solvers. The results achieved from the considered techniques agreed very well with each other.

# تصميم هوائي نانو قائم على المواد ما بعد المادية لخصائص الكهرو-بصرية المحسنة

**أحمد عماد سليم، جواد عبد الكاظم حسن**
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**الخلاصة**
في هذا العمل، تم تصميم مواد بلازمية تعتمد على هوائي متناهي الصغر نانوي في نطاق تردد من ١٩٢ تيرا هيرتز – ١٩٥ تيرا هيرتز. تم بناء الهوائي المقترح من اشكال التجزئة للمستوى الثالث ضمن منحنى هيلبرت التي يتم تغذيتها من خلال منفذ ذو مقاومة ٥٠ اوم. الطبقة الخلفية للهوائي مغطاة بموصل بشكل جزئي والمكسوة بطبقة الفجوة الكهرومغناطيسي (EBG) القائمة على المواد الخارقة. يُظهر الهوائي اتجاهية عالية تصل إلى ٦٨ ديسيبل مع مطابقة ممتازة عبر نطاق التردد بأكمله. يعتبر الهوائي المقترح والمكون من طبقة موصلة من الذهب مركب على طبقة من أوكسيد السيليكون. تم تصميم EBG المقترح باعتباره الترتيب الثاني لهندسة كسورية نوع مينكوفسكي. تم العثور على النتائج التي تم الحصول عليها من حيث S11 أدناه ١٠ ديسيبل - لنطاق التردد ٣ تيرا هيرتز. تم التحقق من صحة النتائج التي تم الحصول عليها باستخدام تقنيات عددية تعتمد على CST MWS من خلال استدعاء المجال الزمني (TD) والمجال التردد (FD). تم استحصال توافق جيد جدا بين النتائج المحققة من التقنيات المدروسة مع بعضها البعض.

**الكلمات الدالة:** الهوائيات النانوية، البلازمونيك، THz، الاتجاهية، EBG، المواد الخارقة، التجزئة، مينكوفسكي، هيلبرت.

## 1.INTRODUCTION

Nano-antennas, referred to as antennas or plasmonic antennas, are structures created to handle and govern light on a nano-scale [1]. They work similarly to antennas used in radio communication and within the optical or infrared range of the electromagnetic spectrum [2]. Nano-antennas usually consist of particles, like gold or silver displaying special characteristics because of localized surface Plasmon resonance (LSPR) [3]. LSPR happens when the incoming light interacts with the combined movement of free electrons in the metal, causing electromagnetic fields around the nanoparticle [4]. Nano-antennas can be customized in terms of their size and shape to tune how they interact with light [5]. Adjusting the nanoparticles' size influences how light interacts with nano- antennas affects light absorption, scattering, and transmission across frequencies [6]. Nano-antennas have many applications in nano photonics, i.e., optoelectronics and sensing. One important use involves improving the interaction between light and matter through nano-antennas to focus light in areas. This feature benefits tasks like improving sensor sensitivity, boosting panel efficiency, or enabling detection [5]. Nanoscale imaging and microscopy-based nano-antennas [7] are new techniques to improve the clarity of images beyond what diffraction allows. Concentrating light into a spot at the nanoscale, these methods make it possible to observe valuable details for biological imaging and examine Nano-sized structures [8]. Utilizing plasmonic waveguides to direct and control light on a scale using Nano-antennas [9]. Nano-antennas can be strategically positioned to create patterns that form plasmonic waveguides, allowing manipulation and guidance of light on a scale. This capability plays a role in developing circuits and signal processing at the nanoscale. Additionally, Nano-antennas have applications in detection and analysis serving as sensors to distinguish substances and molecules accurately [10]. The electromagnetic fields near the nanoparticles allow for analysis of the surroundings, making them ideal for use in chemical and biological sensing and surface-enhanced Raman spectroscopy (SERS) [11]. The primary gap in the research nano-antennas field is not considering the material dispersion effects at THz frequency ranges [12]. In this work, the authors used material dispersion effects in their calculation to realize its impact, including the material losses on the antenna performance. Nano-antennas represent a rapidly evolving field of research with ongoing efforts to explore new materials, geometries, and functionalities. Nano-antennas offer exciting prospects for developing advanced nanophotonic devices and technologies, opening up possibilities for miniaturization and integrating optical components at the nanoscale. In this work, a design on nano-antenna is developed for THz communication systems. The work is devoted to designing a methodology described in Section 2. The antenna design details and specifications are discussed in Section 3. The results validation and discussions are considered in Section 4. Finally, the paper is concluded in Section 5.

## 2.DESIGN METHODOLOGY

Nano-antenna plasmonic fractal metamaterials combine the concepts of nano-antennas, plasmonic, fractals, and metamaterials to create structures with unique optical properties, discussed below:

### *2.1.Nano-Antenna*

As mentioned earlier, a nano-antenna is a subwavelength metallic structure designed to manipulate and control light at the nanoscale [13]. Nano-antennas can enhance light-matter interactions and enable efficient manipulation of light [14]. It studies the interaction between light and free electrons in metallic structures. Plasmonic materials exhibit unique optical properties due to exciting surface plasmons, i.e., collective oscillations of electrons [15]. These surface plasmons can be harnessed to control light at the nanoscale; described with the Drude model [16], as given in Eq. (1):

$$\varepsilon r(\omega) = 1 - \frac{\omega_p^2}{\omega^2 + i\Gamma\omega} \quad (1)$$

where; $\Gamma$ (=1/ $\tau$D) is the electron relaxation rate, $\omega_p$ (=$(Ne^2/\varepsilon_o m^*)^{0.5}$) is the plasma frequency, N is the number of electrons per unit volume, e is the electron charge, $\varepsilon_o$ is the permittivity of free space, and $m^*$ is the electron's effective mass. In another matter, fractals are complex geometric patterns that exhibit self-similarity across different scales. They are characterized by repetitive patterns, where each part of the structure resembles the whole. Fractals have unique properties, such as infinite complexity and non-integer dimensions. In the present case, using 3rd iteration of the Hilbert curve and the 2nd order of the Minkowski fractal geometry were applied. Fractal geometry, an idea utilized in creating fractal antennas, showcases self-replicating patterns and intricate designs across sizes. This unique feature can enhance antenna performance in terms of size minimization and multi-band functionality. Crafting fractal antennas entails defining the proportions and repetitions through a formula. One commonly used is Eq. (2) for designing fractal antennas [17].

$$L_n = a_n \times L_{n-1} \quad (2)$$

Where: $L_n$ is the length of the $n^{th}$ iteration of the fractal antenna, $a_n$ is a scaling factor that determines the size of each iteration, and $L_{n-1}$ is the length of the $(n-1)^{th}$ iteration of the fractal antenna. The value of $a_n$ is determined by the fractal geometry used, typically falling within the range of 0 to 1. Various values of $a_n$ can lead to designs for fractal antennas. It is worth noting that the equation mentioned above offers a general method for creating fractal antennas. The specific implementation and equations may vary based on the desired fractal shape, such as Minkowski or Hilbert, as illustrated in Fig. 1. Factors like feed point placement, substrate properties, and resonant frequency must also be considered in the design process. Developing a fractal antenna may necessitate equations, algorithms, or software tools beyond the initial iterative equation mentioned earlier. Seeking advice from antenna design experts or referring to literature in this field can offer comprehensive insights and guidance on crafting unique fractal antenna designs.

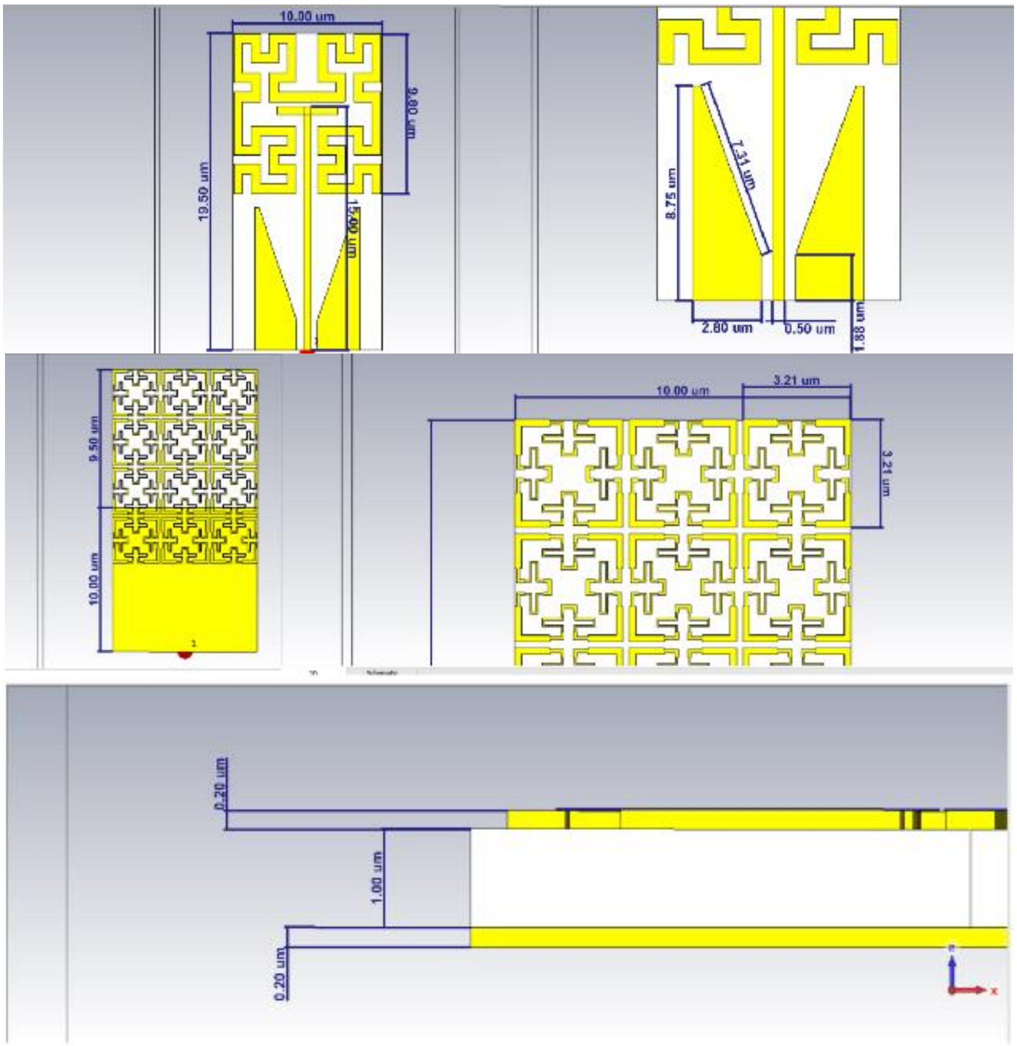


**Fig. 1** The Proposed Antenna Design.

### 2.2. Metamaterials

Artificial materials, called metamaterials, are created to showcase characteristics that are not typically seen in substances. These materials consist of unit cells smaller than the wavelength of light and are crafted to control how electromagnetic waves behave. By arranging these unit cells, metamaterials can demonstrate features like refractive index, unique dispersion properties, and improved interactions between light and matter. The proposed Minkowski design is introduced as EBG defects in the antenna ground plane. Therefore, evaluating the effective band gap range of interest is a good idea. The effective medium theory (EMT) is a useful approach for calculating the effective permittivity of materials or structures that exhibit plasmonic behavior in certain frequency bands invoked in this research. Plasmonic materials are characterized by the collective oscillations of free electrons, known as surface plasmons, which can strongly interact with incident electromagnetic waves. In the context of EMT, the effective permittivity of a plasmonic material is calculated by viewing it as an " effective medium" that responds, on average, to the electromagnetic field. This approach simplifies the computations and modeling of plasmonic structures. The effective permittivity ($\varepsilon_{eff}$) [13] can be calculated using Eq. (3).

$$\frac{1}{\varepsilon_{eff}} = \frac{V_m}{\varepsilon_m} + \frac{(1 - V_m)}{\varepsilon_d} \quad (3)$$

Where: $V_m$ is the volume fraction or filling factor of the plasmonic material in the composite structure, $\varepsilon_m$ is the permittivity of the plasmonic material, and $\varepsilon_d$ is the permittivity of the surrounding medium or host material. The above equation assumes a two-component composite structure, where the plasmonic material is dispersed within a host material. In the realm of plasmonic bands, the conduct of substances influences the reaction, leading to an effective permittivity $\varepsilon_{eff}$ that typically exhibits negativity or features a minimal real part accompanied by a pronounced imaginary part. $\varepsilon_{eff}$ tends to be negative or have a very low real part with a strong imaginary part. This negative or low real part is associated with surface plasmons and their resonance in the material. It is important to note that the effective medium theory provides a simplified approximation and may not accurately capture all the plasmonic materials' detailed properties. It is particularly effective when the plasmonic material is in the form of nanoparticles, thin films, or periodic structures, where the plasmonic elements' size or arrangement the can be considered an effective medium. However, for more complex or non-periodic structures, the effective medium theory may have limitations; therefore, more advanced computational techniques, such as finite element methods or rigorous coupled wave analysis, may be necessary. Additionally, the effective permittivity calculated using EMT is often frequency-dependent, as plasmonic resonances strongly depend on the incident wavelength or frequency. Therefore, it is common to consider the effective permittivity as a function of frequency or wavelength to accurately model the plasmonic behavior over a broad spectral range. In this regard, the effective permittivity ($\varepsilon_{eff}$) was calculated as shown in Fig. 2.

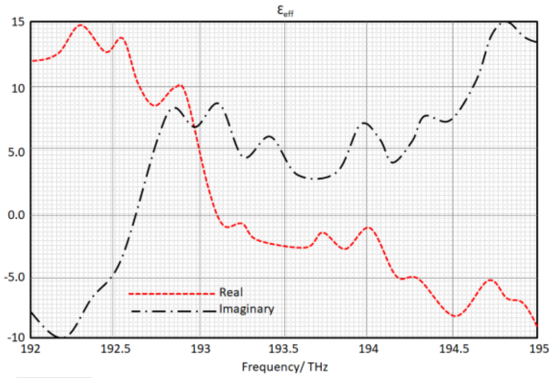


**Fig. 2** Effective Permittivity of the Proposed EBG Defects.

By combining these concepts, nano-antenna plasmonic fractal metamaterials incorporate fractal patterns into nano-antennas design, thereby creating structures with enhanced functionalities and unique optical responses. The self-similar nature of fractals allows for multiple resonances and increases complexity in the interaction with light.

### 3. DESIGN DETAILS AND SPECIFICATIONS

Designing nano-antenna plasmonic fractal metamaterials involves modeling simulation techniques and experimental characterization. Below is an outline of the steps:

1) Characteristics of optical properties: Determine the required properties that must be treated in the fractal metamaterial that must appear in the plasmonic nano-antenna. For example, several factors can be considered including resonant frequencies, absorption efficiency, scattering properties, or specific applications like sensing or imaging.
2) Choosing the fractal pattern: select the desired optical properties by applying suitable fractal geometry. Fractal geometry can be chosen based on fractal shapes, including Sierpinski triangles, Koch curves, or Menger sponges.
3) Configuring plasmonic nano-antennas: it must be combined with the fractal structure to prepare a plasmonic nano-antenna. The resonant frequencies, and plasmonic properties required

depend on selecting nano-antennas, such as, dipole, bowtie, or nanorod.

4) Theoretical Simulation: Bring the design into the phase of modeling and simulating the optical response of the nanoplasmonic fractal metamaterial using finite element analysis (FEA), finite-difference time-domain (FDTD) simulations, and rigorous coupled-wave analysis (RCWA). This approach predicts and enhances its characteristics and performance. Since these results that appear through simulation show the performance and properties that must be improved, techniques such as optical spectroscopy, near-field scanning optical microscopy (NSOM), and dark-field microscopy can also be used to ensure the quality and effectiveness of the designed nanoplasmic fractal metamaterial.

5) Continuous improvement: Monitor the results and determine the difference between the input data and the simulation modeling process, then repeat the simulation production and evaluation times to improve the efficiency of the nano-antenna plasmonic fractal metamaterial. After that, the effective parameters change on the proposed antenna parameters X and Y was calculated. Those parameters were changed as: (0.5mm and 1mm for X), and (1mm and 2mm for Y) to be given in terms of S11 spectra, as shown in Fig. 3. It was found that increasing the distance Y directly affected the antenna matching impedance in terms of S11 magnitude, attributed to the fact of capacitive effect between the antenna patch and the ground plane of the antenna [15].

Next, the same variations on the antenna parameters were applied to monitor their effects on the antenna gain, as shown in Fig. 4. The variation is attempted to realize the effects of changing the coplanar feed distance and the PG length on the antenna performances. The effects of the distance X were significant on the antenna gain due to the surface wave suppressions at the end of the antenna substrate edges. The proposed antenna showed excellent enhancements in performance, with a bandwidth from 192THz to 195THz and a maximum gain of 62dBi at 192.8THz. Later, to emphasize the effects of the antenna parameters on the performance, the authors changed the patch iteration number from 1 to 3 with respect to the S11 and gain spectra. It was found that the proposed antenna realized the optimal performance at the 3$^{rd}$ iteration, as shown in Fig. 5. The effects of changing the fractal order impacted the generated frequency modes and bandwidth. Increasing fractal order increased the antenna bandwidth due to increased in the current patches within a limited area. After achieving the optimal design, a complete analysis was applied to check the effects of introducing the EBG and ground plane structure. As shown in Fig. 6, it was found that the proposed antenna realized significant enhancements after introducing the proposed EBG structure. Introduction the EBG structure impacted antenna gain and bandwidth. Therefore, using the EBG structure increased the antenna gain and bandwidth due to the surface wave suppression increasing the surface current density. Next, the effects of varying the number of the proposed EBG rows on the antenna performance were studied, as seen in Fig. 7. It was found that increasing the number of EBG rows rapidly increased the antenna bandwidth and gain due to the effect of increasing the electromagnetic impedance in a series manner with increasing the rows number.

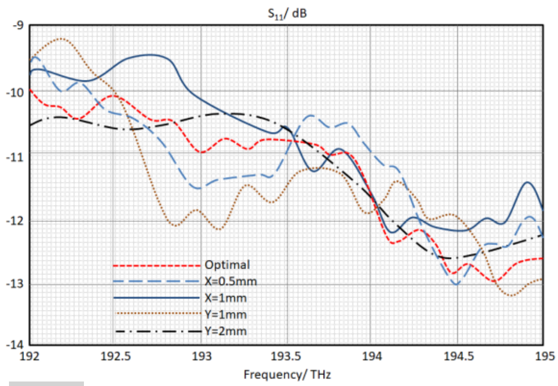


**Fig. 3** The Evaluated $s_{11}$ Spectra with Varying the Antenna Parameters with Respect to the Optimal Design.

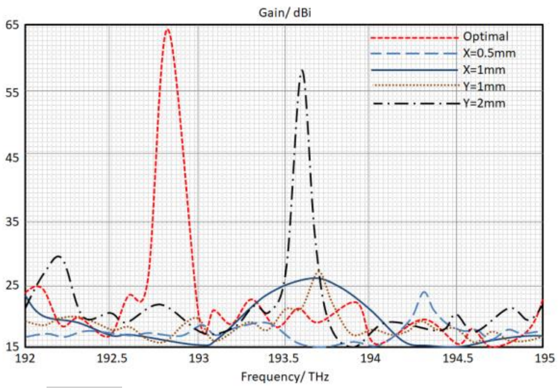


**Fig. 4** The Evaluated Gain Spectra with Varying the Antenna Parameters with Respect to the Optimal Design.

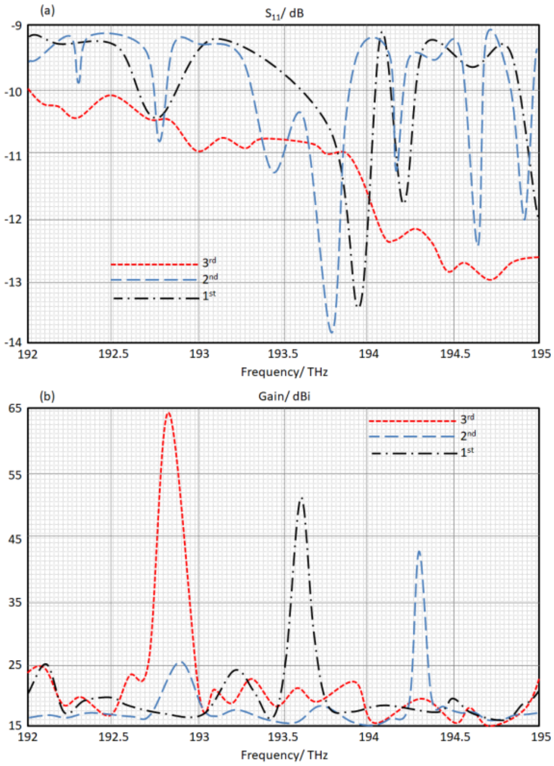


**Fig. 5** The Evaluated Antenna Performance with Varying the Patch Iteration with Respect to the Optimal Design: (a) S11 and (b) Gain Spectra.

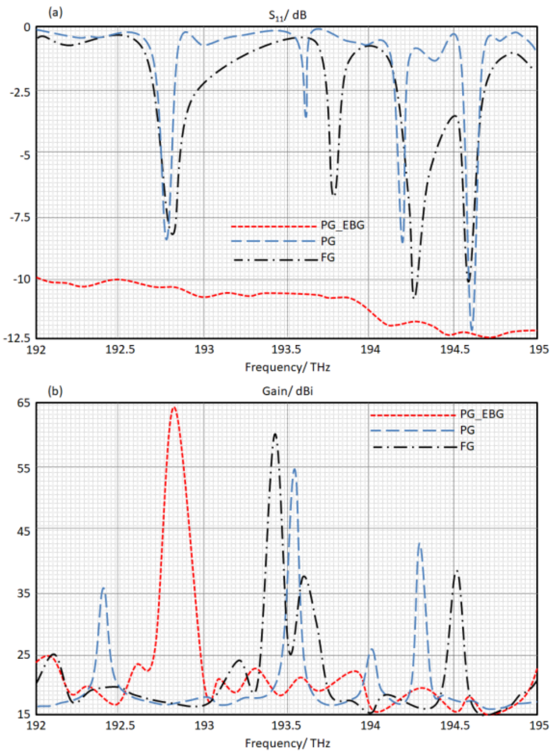


**Fig. 6** The Evaluated Antenna Performance with Varying EBG with Respect to the Optimal Design: (a) $s_{11}$ and (b) Gain Spectra.

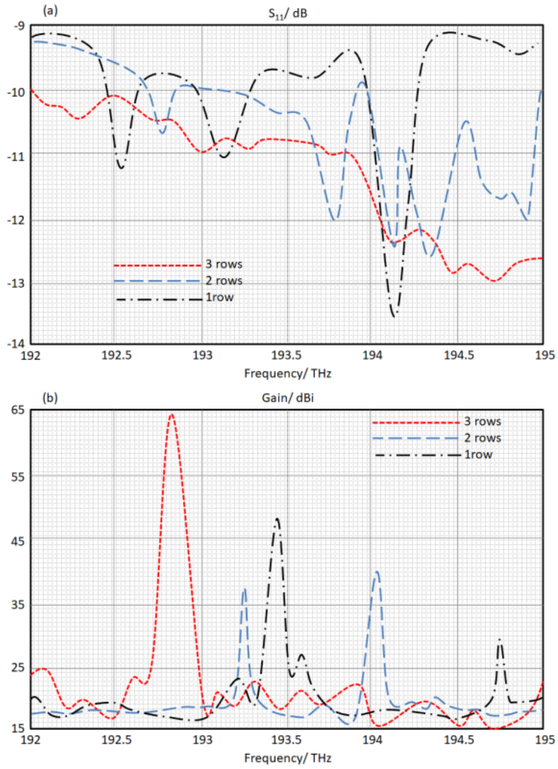


**Fig. 7** The Evaluated Antenna Performance with Varying EBG with Respect to the Optimal Design: (a) $s_{11}$ and (b) Gain Spectra.

## 4. RESULTS VALIDATION AND DISCUSSIONS

After achieving the optimal design, the authors validated the results by invoking TD and FD solvers based on CST MWS algorithms. It was found that the proposed antenna, see Fig. 8, realized a wide band from 192THz to 195THz with maximum gain at 192.8THz about 62dBi. The main effective radiation was directed to the main lobe, as shown in Fig. 8 (c) and Fig. 7 (d). Finally, a general overview of some key performance parameters and characteristics of plasmonic nano-antennas are presented in Table 1. It is observed that the future directions of such research include but are not limited to:

1) Enhanced Sensing and Imaging: Nano-antennas can be further developed to enhance sensing capabilities in various fields, such as medicine (biosensors for detecting biomolecules), environmental monitoring (detection of pollutants), and security (identification of hazardous materials). Additionally, advancements in nano-antenna-based imaging techniques could lead to higher resolution and sensitivity in microscopy and medical imaging.
2) Tunable and reconfigurable nano-antennas: Developing nano-antennas with tunable resonant frequencies and reconfigurable properties would enable dynamic control over their electromagnetic response, achieved through various means, such as applying

external stimuli, e.g., voltage and temperature, using phase-change materials, or employing MEMS (Micro-Electro-Mechanical Systems) techniques.

3) Metamaterials and metasurfaces: Integrating nano-antennas into metamaterials and metasurfaces can lead to novel optical properties, such as negative refractive index, perfect absorption, and cloaking. These structures could find applications in super-resolution imaging, flat optics, and controlling light propagation at the nanoscale.
4) Plasmonic circuitry and nanophotonics: Nano-antennas can be integrated into on-chip plasmonic circuitry for signal processing, modulation, and routing at the nanoscale, which could enable the development of compact and efficient photonic devices for information processing, communication, and sensing.
5) Nonlinear optical effects: Exploring nonlinear optical effects in nano-antennas, such as harmonic generation, four-wave mixing, and optical parametric amplification, could open up new possibilities for ultrafast optical signal processing, frequency conversion, and generating coherent light sources.
6) Energy harvesting and conversion: Nano-antennas have the potential to effectively capture and transform energy into electricity using plasmonic or quantum mechanisms. Future studies may focus on improving nano-antenna-driven power systems' effectiveness, scalability, and durability for energy solutions.
7) Biomedical applications: Nano-antennas are promising for biomedical applications, including targeted drug delivery, photothermal therapy, and bioimaging. Future research could focus on developing biocompatible and targeted nano-antennas for precise manipulation and sensing of biological systems.
8) Quantum nano-antennas: Delving into the quantum characteristics of nano-antennas and their interaction with individual quantum emitters like "quantum dots and NV centers" could potentially drive advancements in quantum information processing, quantum communication, and quantum sensing.
9) Integration with emerging technologies: Nano-antennas can be combined with cutting-edge technologies such as 2D materials like transition metal dichalcogenides and topological insulators, to form hybrid nanostructures with distinctive optical and electronic properties.
10) Standardization and scalability: Ensuring uniformity in fabrication methods and enhancing scalability are key to in using of nano-antennas in real-world applications. Future studies may concentrate on developing cost solutions.
11) Fabrication methods and scalable manufacturing processes for nano-antenna-based devices.

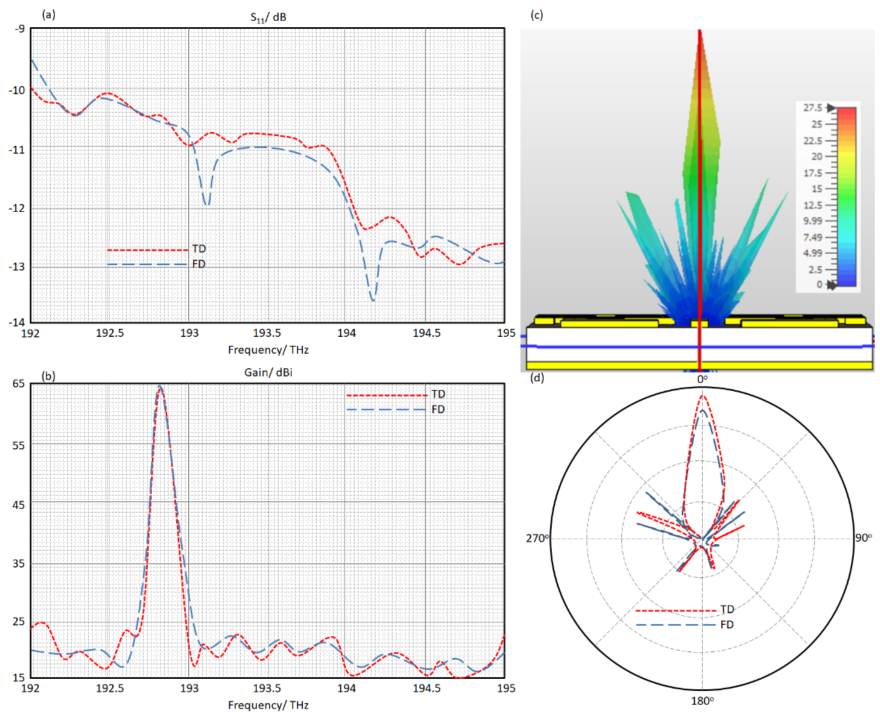


**Fig. 8** The Proposed Antenna Performance: (a) $s_{11}$ , (b) Gain Spectra, (c) 3D Radiation Pattern, and (d) 2D Radiation Pattern.

**Table 1** Overview of performance and characteristics of plasmonic nano-antennas.

| Nano-antenna Type | Operating Wavelength | Efficiency | Directivity | Polarization | Bandwidth | References |
|---|---|---|---|---|---|---|
| Plasmonic Bowtie | 0.8 µm | 60-80% | 5-10 dBi | Broadband | 50-100nm | [1-3] |
| Plasmonic Disk | 1.55 µm | 70-90% | 8-12 dBi | Polarized | 100-200nm | [4-6] |
| Plasmonic Nanorod | 2.4 µm | 50-70% | 6-8 dBi | Linear | 200-400nm | [7-9] |
| Plasmonic Patch | 10 µm | 80-95% | 10-15 dBi | Polarized | 500-900nm | [10-12] |
| The Proposed Antenna | 1.55 µm | 84-97% | 62dBi | Polarized | 1537.397-1561.42nm | This work |

## 5.CONCLUSION

In summary, the developing and applying of nano-antennas based on metamaterials have displayed the potential to enhance electromagnetic characteristics. By leveraging the features of metamaterials, like refractive index, subwavelength focusing, and adjustability; these nano-antennas offer improved functionality compared to traditional metallic antennas. Nano-antennas represent a field of study within nanotechnology and photonics. These minuscule structures a few nanometers in size, are engineered to interact with light and facilitate manipulating electromagnetic waves at the nano level. The proposed research holds promise for communication systems operating in the terahertz spectrum. The antenna demonstrated a range from 192THz to 195THz with a gain of 62dBi at 192.8THz. The antenna showed a plasmonic effect due to the self-resonance at a particular frequency indifferent to anther frequency band of interest. A notable advantage of metamaterial-based nano-antennas lies in their capability to achieve subwavelength confinement and focus waves, achieved by customizing the parameters of the metamaterial to demonstrate refractive index behavior, allowing the antenna to effectively manage and direct light flow on a nanoscale level. The proposed antenna showcased S11 levels below 10dB with 68dBi gain, VSWR of 1.2, and impedance consisting of a part with 51Ω and an imaginary part with 0.23Ω.

As a result, these nano-antennas can concentrate and direct electromagnetic energy with unprecedented precision, enhancing signal sensitivity and localization.

## ABBREVIATIONS

| | |
|---|---|
| THz | Terahertz |
| EBG | Electromagnetic Band Gap |
| $SiO_2$ | Silicon Dioxide |
| LSPR | Localized Surface Plasmon Resonance |
| SERS | Surface-Enhanced Raman Spectroscopy |
| CST | Computer Simulation Technology |
| MWS | Microwave Studio |
| FD | Frequency Domain |
| TD | Time Domain |
| nM | Nanometer |
| GHz | Gigahertz |
| dB | Decibel |

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