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Research Article

Equilateral Triangular Dielectric Resonator Nantenna at Optical Frequencies for Energy Harvesting

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The last decade has witnessed a remarkable growth in the telecommunication industry. With the introduction of smart gadgets, the demand for high data rate and bandwidth for wireless applications have increased exponentially at the cost of exponential consumption of energy. The latter is pushing the research and industry communities to devise green communication solutions that require the design of energy saving devices and techniques in one part and ambient energy harvesting techniques in the other part. With the advent of nanocomponents fabrication technology, researchers are now able to tap into the THz frequency regime and fabricate optical low profile antennas at a nanoscale. Optical antennas have proved their potential and are revolutionizing a class of novel optical detectors, interconnectors, sensors, and energy harvesting related fields. Authors in this paper propose an equilateral triangular dielectric resonator nantenna (ETDRNA) working at 193.5 THz standard optical frequency. The simulated antenna achieves an impedance bandwidth from 192.3 THz to 197.3 THz with an end-fire directivity of 8.6 dBi, covering the entire standard optical window of C-band. Numerical demonstrations prove the efficiency of the nantenna at the frequencies of interest, making it a viable candidate for future green energy harvesting and high speed optical applications.

1. Introduction

Antennas are found around us in abundance when we are in the midst of communicating either locally or globally via radio frequencies or microwave technologies. Since the inception of classical electromagnetics to the wonders of modern electromagnetism [1], antennas in any size or form have and are still working diligently to uphold their purpose, that is, to convert the electromagnetic energy available in free space into confined electric signals and vice versa. As the telecommunication industry is reaching new technological heights, the demand for energy consumption is also surging, resulting in an increase in environmental problems in the form of carbon emissions [2]. One proposed solution is the concept of "green communication," which primarily aims at improving the energy efficiency while reducing the CO_2 emissions and energy consumption of communication networks [3]. In order to realize this concept, researchers are now persuaded on designing antennas by utilizing the electromagnetic spectrum in the high frequency bands (THz), which fulfills the bandwidth hunger requirements of smart devices, provides low cost designs with high connectivity, and satisfies the consumer needs while keeping the environment clean and energy consumption to a minimum. The antennas designed in the THz regime are given the name of optical antennas.

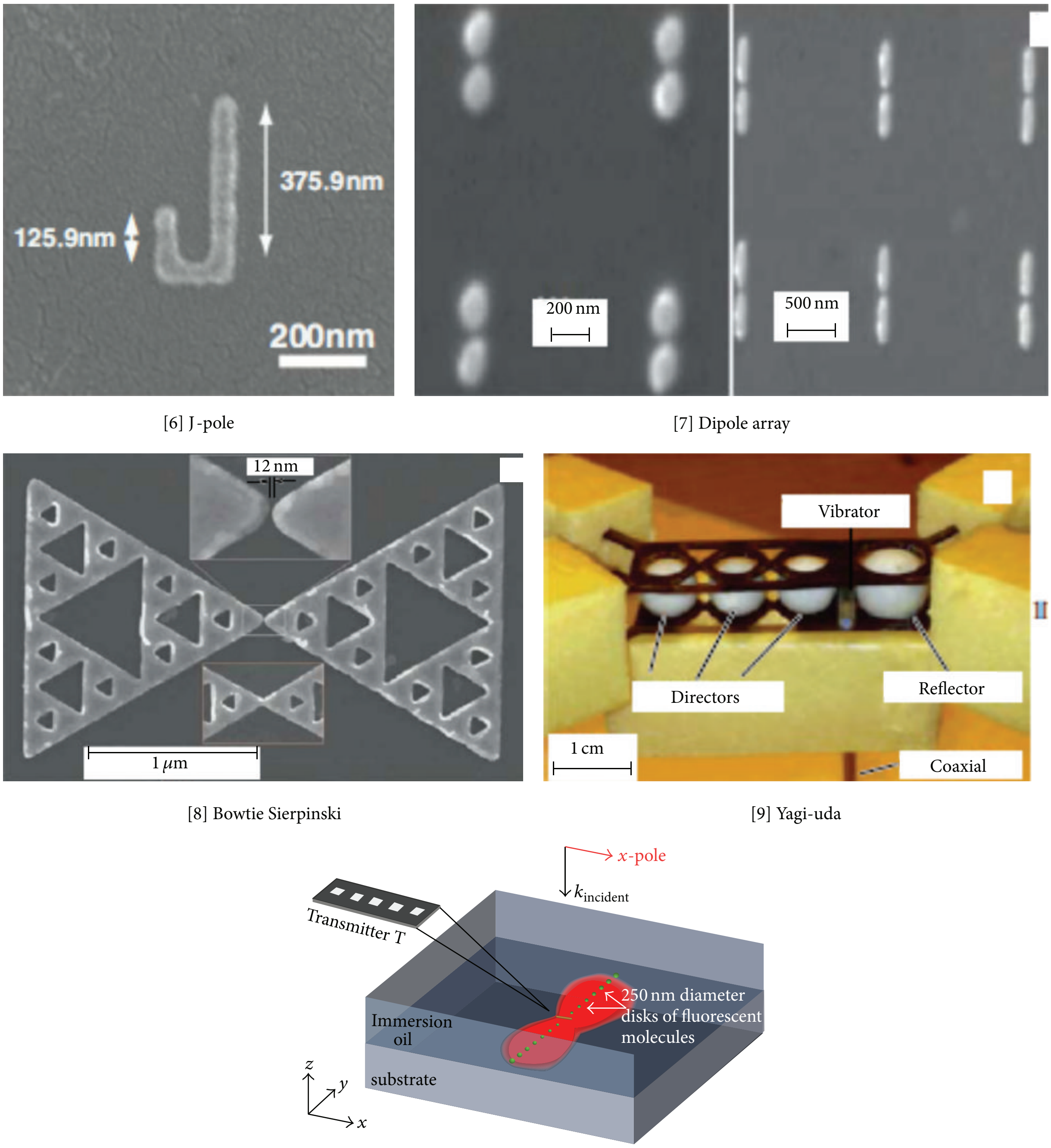
Optical antennas are a quite new concept in physical optics. They were initially developed for optical microscopic applications. Their basic principle of operation lies in their ability to confine light to subwavelength volumes, plasmonic nanoparticles, and nanoantennas, providing a fundamental link between electronic and photonic circuits by associating the large size mismatch between the electronic and photonic wave functions [4]. Optical antennas have some similarities to their radio frequency (RF) and microwave counterparts, but major differences arise with their physical properties and scalable behaviors. The major difference among the two counterparts is in terms of interaction of electromagnetic waves with metals. This term is known as Plasmon's at optical frequencies, where the EM waves interact with noble metals, that is, silver, gold, and aluminum, which are not perfect conductors. These noble metals are defined and solved via Drude model equations [5]. Optical antennas have now started to gain popularity among the researchers and scientists. Few years back, optical antennas were not so popular because of limited fabrication techniques and equipment. With the advent of nanoscience and nanotechnology machine fabrication, optical antennas can now be realized to solve the problem of high data rates, wide bandwidth, and environmental problems, that is, CO_2 emissions. Also working with antennas at higher frequency bands (THz), the researchers are introduced to an insight to the natural and analytical properties of nanofabrication and nanoantenna designs. Figure 1 shows various fabrication techniques. Interested readers, about these techniques, are referred to the list of pioneering research publications [6–10]. Apart from fabrication, some of the excitation techniques for optical nantennas can be performed (1) through a coupling of light using the so called nanotapers [11, 12]. Since nanoantennas cannot handle much power because of their small footprints, this makes them ideal candidates for being excited by micro lasers such as micro disks and photonic crystal lasers. Another method of excitation, which outperforms the former micro laser based technique by reducing the reflection induced power loss, exploits (2) slot dielectric waveguides [13]. It is evident that the fabrication of optical antenna structures provides an emerging opportunity for realizing new optoelectronic devices with importance in applications such as photo detection, light emission, sensing, energy harvesting, and spectroscopy.

Analysis of traditional antenna design provides great opportunity for the research industry to design and analyze nanoantennas at optical frequencies. Apart from many designs, keeping in view of wide band characteristics at THz regime, one such design is making use of dielectric resonator antennas (DRAs), firstly proposed and realized in 1939 by Richtmyer, and their modes were first analyzed by Okaya and Barash in the 1960s [14, 15]. DRAs' physical and electrical properties allow them to be flexible and diversely suited to any communication application. In microwaves, DRAs are nonmetallized dielectric objects normally made of ceramics with high permittivity (relative dielectric constants of the order of 10–300) which are used as resonant cavities for storage of electromagnetic (EM) energy. Compared to metallic antennas, which produce high radiation losses at higher frequencies, DRAs with low loss dielectric materials have some advantages such as high radiation efficiency due to lack of surface waves, small size proportion to wavelength, wide impedance bandwidth, many feeding arrangements, numerous geometries, and different excitation methods with several modes producing broadside or end-fire radiation patterns [16–24].

In this paper, drawing inspiration from traditional radio and microwave design [24] and benefiting from DR characteristics, we propose and explore simulated design of an equilateral triangular dielectric resonating nantenna (ETDRNA), for the first time to the best of our knowledge, at optical frequencies. Apart from many applications [9, 10], in this paper, we address the nantenna design for solar energy harvesting application. Since the introduction of the preliminary concept four decades ago, very limited work has been done because of the unavailability of nanomaterial fabrication techniques [25–27]. Nowadays, whether nanofabrication progressively became less challenging, the testing, measurement, and characterization of nantennas are still experimentally hard and very expensive. However, these limitations did not stop research community from continuing their work with high frequencies designs using theoretical and numerical modelling and performance investigation [28–31]. Keeping with the state of the art, we propose, numerically simulate, and investigate a nantenna consisting of "Ag-SiO_2-Ag" structure. The dielectric resonator is made of "Si" having an equilateral triangular shape. The nantenna is excited via a nanostrip transmission line made of a noble metal silver "Ag." The theory of Drude model is used to analyze and examine the conductive properties of the noble metal "Ag." It is worthy to note that the proposed nantenna can be operated as a receiving antenna for future green communication systems. The antenna exhibits a wide impedance bandwidth of 2.58% (192.3 THz–197.3 THz) at a center frequency of 193.5 THz, covering the entire standard optical C-band transmission widow. The achieved directivity of the nantenna is 8.6 dBi with end-fire radiation pattern. The obtained results make it a viable candidate for a green-field approach that takes into account the reduction of carbon footprints generated by human activity in the last decade.

2. Proposed Antenna Configuration

The proposed configuration (side view and top view) of the equilateral triangular dielectric resonator nantenna (ETDRNA), designed to operate as a receiving antenna for capturing energy in free space, in the standard optical communication band at a wavelength of 1.55 μm, is shown in Figures 2(a) and 2(b). The corresponding central frequency is 193.5 THz. The dimensions of the simulated antenna consist of a "SiO_2" substrate with a thickness of $h_1 = 0.150\,\mu$m, $\varepsilon_r = 2.09$, and loss tangent $\tan\delta = 0$ [32]. The ground plane is on the bottom side with a partial rectangular geometry with optimized dimensions of $W_g \times L_g$ having a thickness of $t = 0.010\,\mu$m and nanostrip on the top side with a thickness, $h_2 = 0.025\,\mu$m. The ground and the nanostrip are made up of silver (Ag). The dimensions of the substrate are taken as $W \times L = 5 \times 5\,\mu\text{m}^2$. The equilateral triangular dielectric is made of silicon "Si," with $\varepsilon_r = 11.9$ and estimated loss tangent $\tan\delta = 0.003$ at 100 THz [33, 34]. The antenna is excited via the 50 Ω silver nanostrip feed that has a width of W_f and optimized length of L_f. In order to control the matching at the central frequency of 193.5 THz and to achieve a wide bandwidth with acceptable radiation patterns the same "SiO_2" substrate material with thickness $h_3 = 0.015\,\mu$m



[6] J-pole

[7] Dipole array

[8] Bowtie Sierpinski

[9] Yagi-uda

[10] Multilayer disk

Figure 1: Various nanoantennas fabricated with different techniques. Source [6–10].

has been introduced between the equilateral triangle and the nanostrip. The dimensions of the equilateral triangular dielectric are calculated from the following [23, 24]:

$$f_{mnl} = \frac{c}{2\sqrt{\varepsilon_r}} \left[\sqrt{\left(\frac{4}{3a}\right)^2 + \left(\frac{p}{h}\right)^2} \right]^{1/2}, \tag{1}$$

where "a" is the side length of the equilateral triangular DRA, ε_r is the dielectric constant of the DRA, "h" is two times the height of the triangular DRA to account for the image effect of the ground plane, and $p = 1$ for the fundamental mode [24]. The three integers l, m, and n have a relation of $(l + mn + n = 0)$ but are not zero simultaneously. For a low-profile triangular DRA, we have $a \gg h$, and therefore the following demonstrates that the frequency is predominantly determined by the height of the DRA:

$$\text{fr} = \frac{c}{4h\sqrt{\varepsilon_r}}, \tag{2}$$

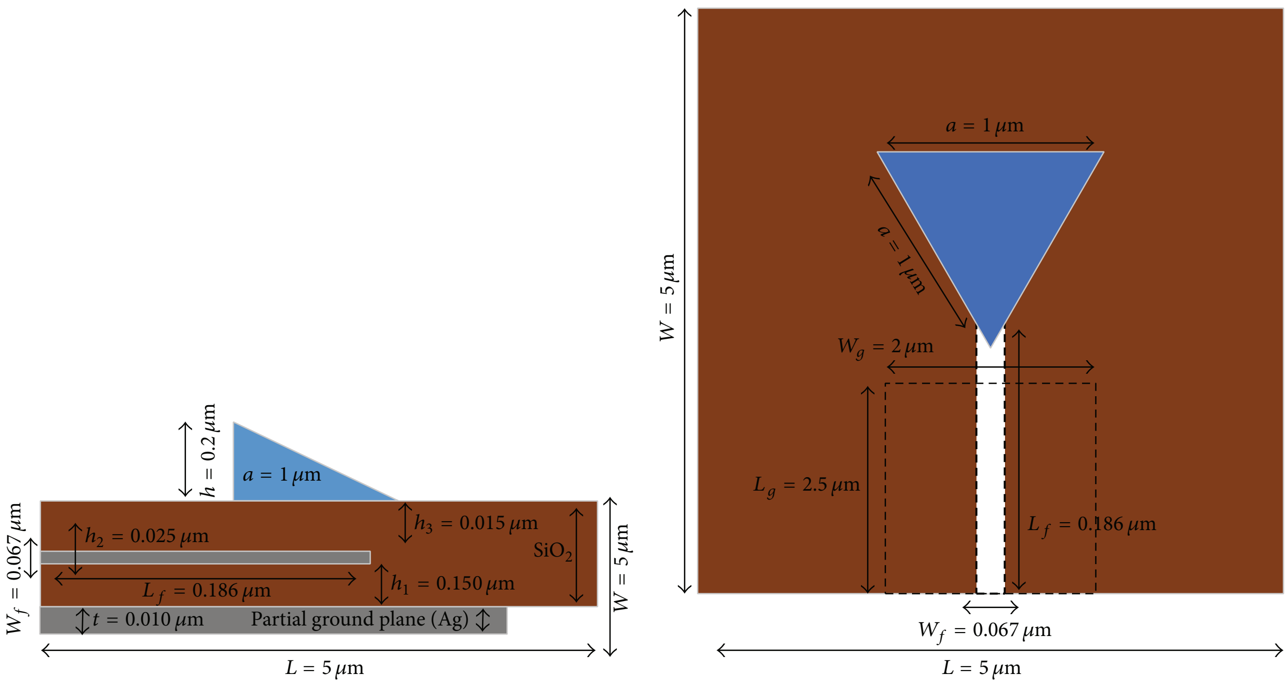


FIGURE 2: (a) Side view of ETDRNA. (b) Top view of ETDRNA with equal side lengths "a."

where h and ε_r are the height and dielectric constant of triangular DRA.

Since, at optical frequencies, metals appear with a negative permittivity therefore complex permittivity $\varepsilon_{\mathrm{Ag}}$ of silver (Ag) was calculated from (3) explained by the Drude model [32]:

$$\varepsilon_{\mathrm{Ag}} = \varepsilon_o \left\{ \varepsilon_{\infty} - \frac{f_{p^2}}{[f(f + i\gamma)]} \right\} = -129.17 + j3.28, \quad (3)$$

where $\varepsilon_o = 8.85 \times 10^{-12}$ [F/m], $\varepsilon_{\infty} = 5$, plasmonic frequency $f_p = 1.41e^{16}$ rad/s, f = central frequency, and collision frequency $\gamma = 2.98e^{13}$. The proposed model has taken into account the conductive and dielectric losses and has been simulated in commercially available EM simulator CST MWS 2014 based on FIT numerical technique using optical template.

3. Parametric Studies

For understanding the role of each geometric design of the proposed dielectric triangular nantenna structure, various parameters were extensively optimized. In order to study the effects on the antenna performance in terms of bandwidth and directivity, the following parameters were studied and analyzed.

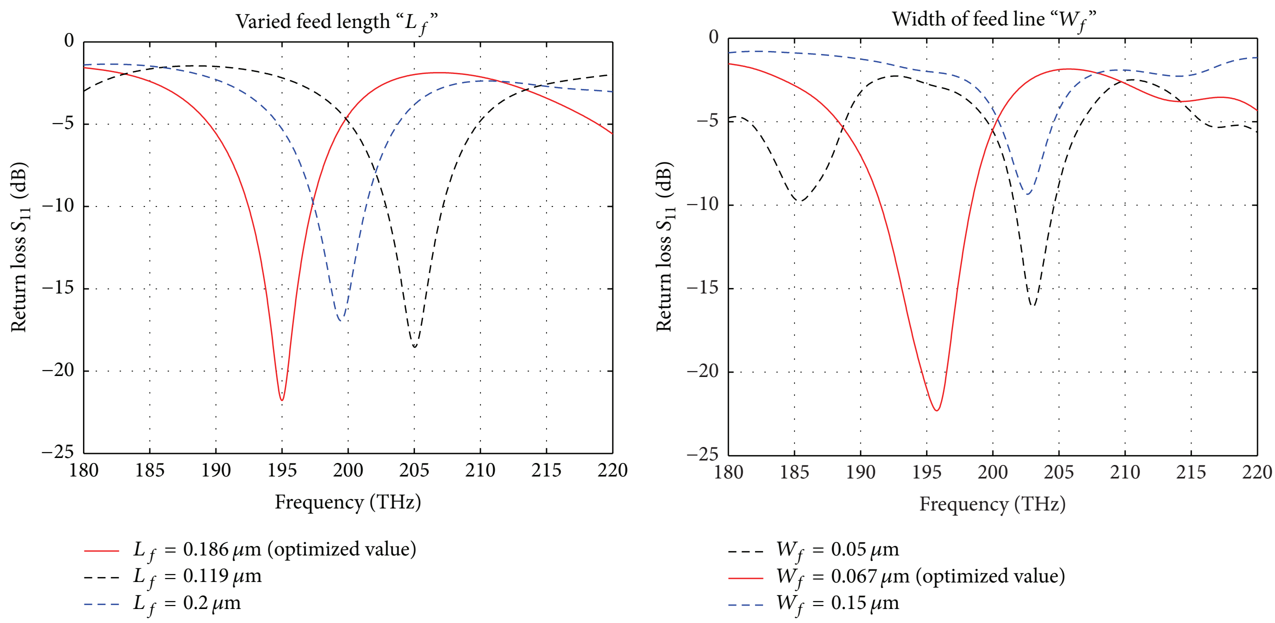
3.1. Nanostrip Feed. The silver nanostrip characterized by Drude model was optimized in terms of its length and width. The traditional empirical formulas [1] were used as a starting point for the nanostrip design. The nanostrip acts like a coupling resonator that excites the triangular dielectric place on an upper SiO_2 substrate with height h_3. Traditionally at RF frequencies the length of the transmission lines is characterized to the wavelengths (λ) of incoming and outgoing radiations. However working at the optical frequencies, the traditional RF wavelength characteristics scenario no longer applies as the incident waves are not perfectly reflected back from the metal's surface. Instead, radiation penetrates into the metal giving rise to the excitation of the free electron gas. Hence, at optical frequencies, instead of using the traditional wavelength (λ) we make use of shorter effective wavelength (λ_{eff}) which depends on the material properties [35, 36] given by the following equation for length of a transmission line [37]:

$$\frac{m\lambda_{\mathrm{eff}}}{2} = L(\lambda_0), \quad (4)$$

where (4) shows the relationship between the free space wavelength (λ_0) and the effective wavelength (λ_{eff}) and the order of resonance (m). Here effective wavelength is given by

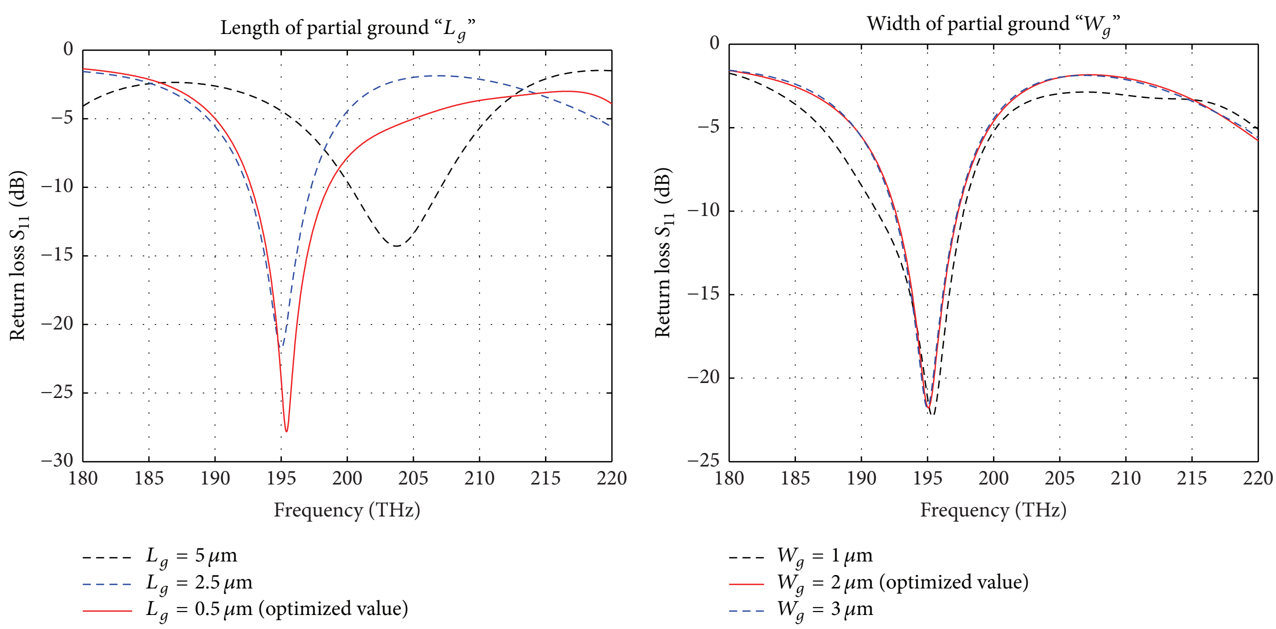
$$\lambda_{\mathrm{eff}} = \frac{\lambda_0}{n_{\mathrm{eff}}}. \quad (5)$$

Typical values of n_{eff} have been measured to be in the range of 1.5–3 [38]. In our simulation, for the silver nanostrip design, the selected $n_{\mathrm{eff}} = 2.8$ [39] resulted in the minimum resonating length of the nanostrip being 0.27 μm. The length L_f of the nanostrip was optimized from 0.1 μm to 0.27 μm with the best optimized value producing required resonance at 193.5 THz which was at $L_f = 0.186\,\mu$m as shown in



(a) (b)

Figure 3: Optimized parameters. (a) Length of nanostrip. (b) Width of nanostrip.



(a) (b)

Figure 4: Optimized parameters. (a) Length of partial ground. (b) Width of partial ground.

Figure 3(a). The effect of the width "W_f" of the nanostrip was also examined by extensive parametric studies. Initial values were taken from the empirical formulas [1] and optimization was done from 0.02 μm to 0.28 μm. Figure 3(b) shows the best optimized value achieved at resonance of −22 dB with W_f = 0.067 μm.

3.2. Partial Ground Plane. Effects of the ground plane were studied on the nanoantenna design. Initially a finite ground plane was used to achieve a good radiation pattern with an acceptable bandwidth. The ground plane was then optimized and a partial ground plane was selected with dimensions $L_g \times W_g$ = 0.5 μm × 2 μm. Figures 4(a) and 4(b) show the effects of varying the ground plane in terms of its length and width. The optimized results produce a wide impedance bandwidth of 2.5% (192.3 THz–197.3 THz) at a center frequency of 193.5 THz, covering all of the standard optical transmission widow (C-band), with a directivity of 8.6 dB.

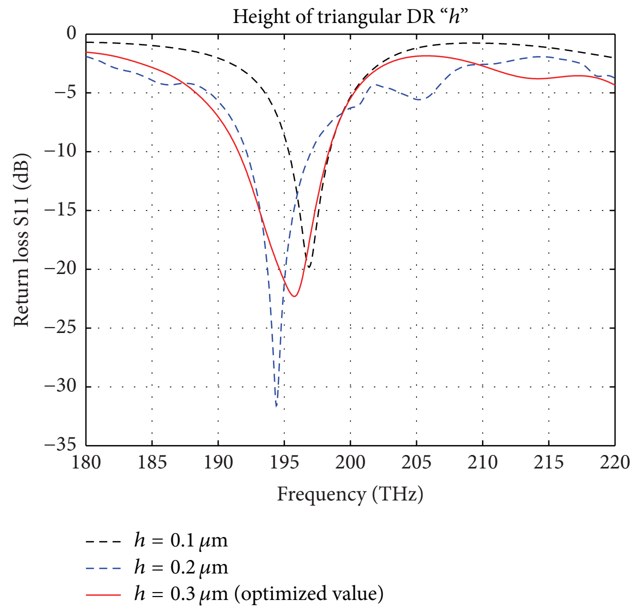


Figure 5: Varied height of triangular DR.

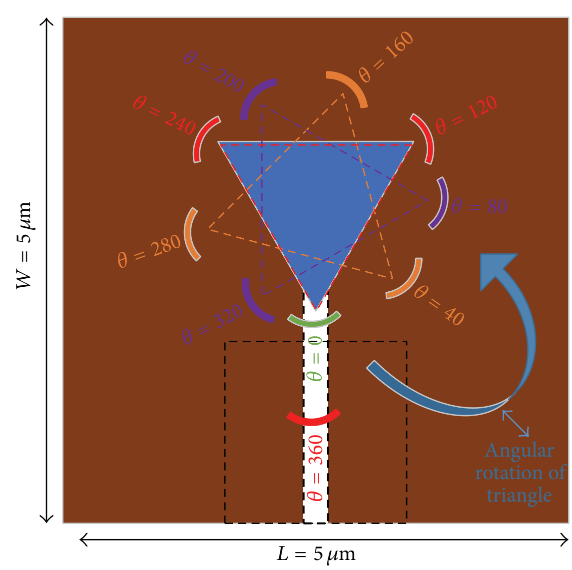
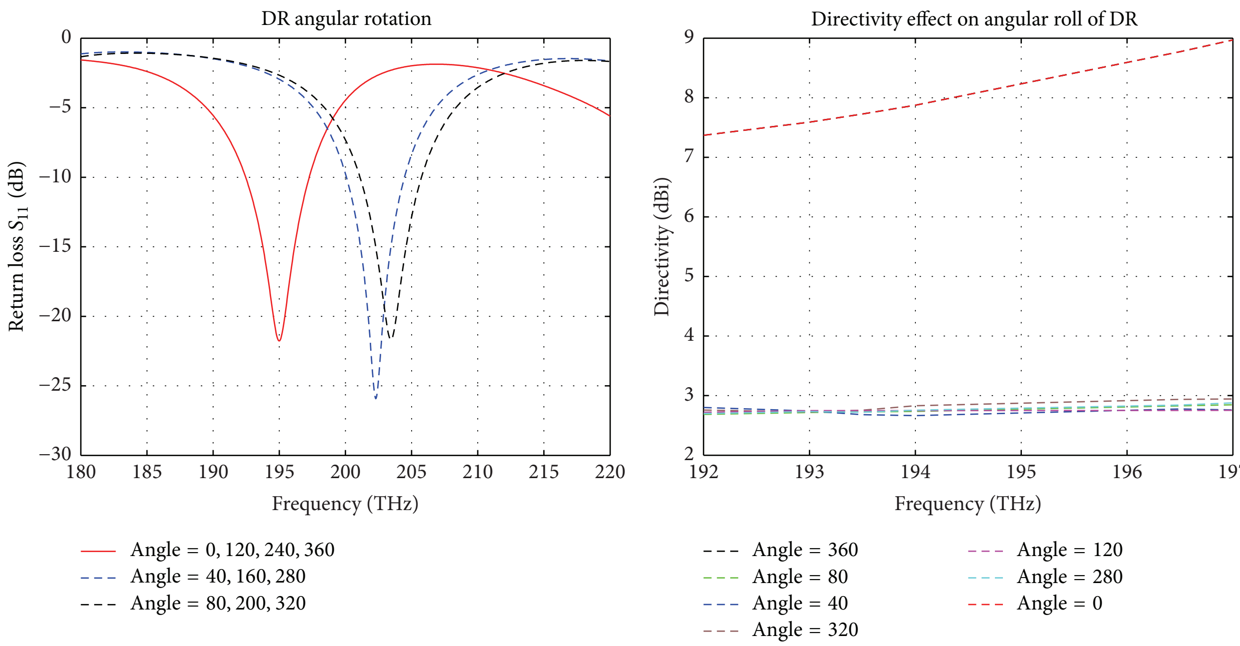


Figure 6: Angular rotation of triangular DR.

3.3. Height of Triangular DR. Since the height of the triangular DR predominately determines the resonance frequency according to (2), the height h of the DR was optimized from $0.1\,\mu$m to $0.5\,\mu$m. Figure 5 shows the best optimized value of $h = 0.3\,\mu$m having a resonance at −23 dB.

3.4. Rotation of Triangular DR. In order to study the effects of bandwidth, frequency shift, and directivity of the nanoantenna design, the triangular DR was rotated on its axis. The rotation was from 0° to 360° with an angular spacing of 40°. Figure 6 shows the angular rotation of the triangular DR. The tip of the triangle was initially aligned at 0° shown in green color. The DR was then rotated along the counterclockwise direction with varying angles. It was observed that, with the rotation of the DR, the bandwidth remained the same at 2.5% but the resonant frequency shifted to other bands (200 THz–205 THz) in the frequency range from 180 THz to 220 THz as shown in Figure 7(a). Since the triangle is an equilateral one, the angular rotation produces the same shifts at other angles; that is, the shift will be the same at 0 = 120 = 240 = 360 degrees as shown in Figure 7(b). The directivity was also affected with the rotation of the triangle as shown in Figure 7(b). It is clear that the effect of the rotation of the triangular DR lowers the directivity to nearly 3 dBi.

After performing the above parametric studies, optimized geometric parameters of the proposed ETDRNA, resulting in



(a) (b)

Figure 7: (a) Angular rotation effect on resonant frequency. (b) DR's angular rotation effect on directivity.

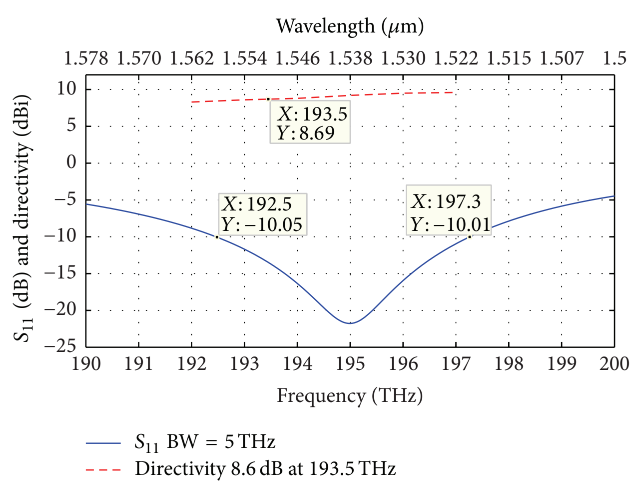


Figure 8: Return loss S_{11} and directivity of ETDRNA.

a wide impedance bandwidth of 2.5% (192.3 THz–197.3 THz) and a directivity of 8.6 dB, are displayed in Table 1. It was also observed that while keeping the antenna with optimized parameters as listed in Table 1, the simple triangular nantenna structure can act as a tunable resonator when rotated around its axis resulting in usage of applications that work in the wavelengths in the range of 1463 nm–1500 nm. The proposed design, if facility exists, can be fabricated via the techniques mentioned in [6–10]. In our case, the fabrication will follow a bottom-up approach where the quartz or SiO_2 substrate will have silver deposited on its surface.

4. Results

The simulated return loss (S_{11}) and directivity of the nanoantenna are shown in Figure 8. The 3D radiation patterns of the nanoantenna at 192 THz, 193.5 THz, and 197 THz are shown in Figures 9(a)–9(c). The ETDRNA exhibits resonance frequency at 193.5 THz ($\lambda_0 = 1.55\,\mu$m) with maximum dip around −22 dB. The antenna covers most part of the S-band and all the portion of the C-band in optical domain and can be used for relevant optical applications in nanonetworks, high speed optical data transfer, and harvesting energy.

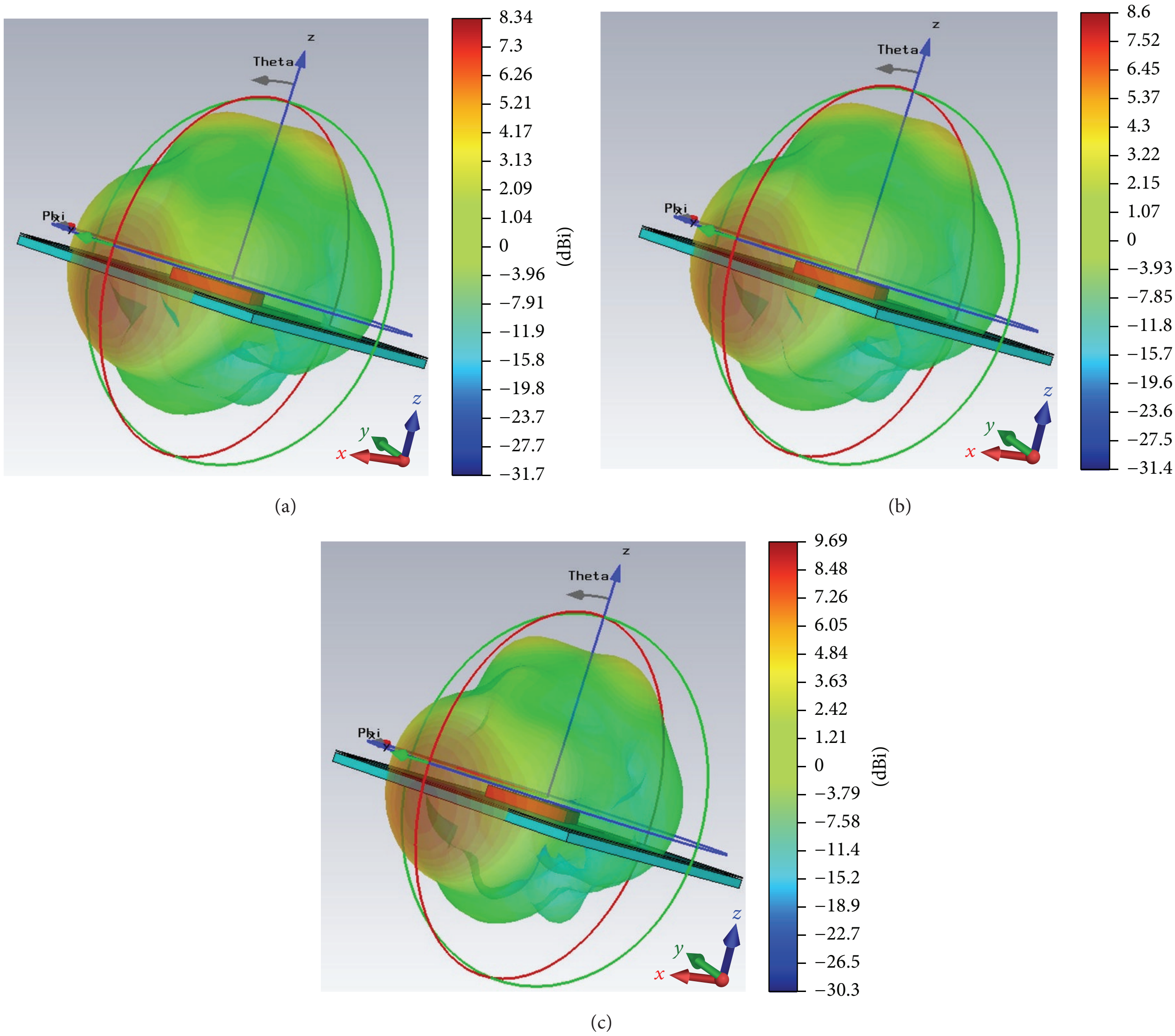


FIGURE 9: (a) 3D end-fire pattern at 192.5 THz. (b) 3D end-fire pattern at 193.5 THz. (c) 3D end-fire pattern at 197 THz.

The directivity of the antenna is 8.6 dBi. Examining the 3D radiation patterns in Figure 9 provides the proof of the ETDRNA radiating in end-fire pattern.

5. Conclusion

In this paper, we have proposed an equilateral triangular dielectric resonator nantenna for next-generation green communication that could be in the form of solar energy harvesting at the infra-red range and optical wireless charging and for high speed optical communication applications. The nantenna is composed of a “Ag-SiO_2-Ag” structure with a nanosilver “Ag” transmission line that excites a triangular dielectric made of “Si” material. The antenna yields a wide impedance bandwidth of 2.58% (192.3 THz–197.3 THz) with a high directive radiation pattern of 8.6 dBi at 193.5 THz (1.55 μm) with an end-fire radiation pattern. At present, the nanofabrication technology is limited and the proposed design is a theoretical one, yet we believe that our contribution in the fast growing field of nantennas, with the proposed ETDRNA design, will prove itself to be a promising candidate for next-generation energy harvesting and green sustainable solution applications based on nanotechnology designs.

TABLE 1: Optimized parameters of ETDRNA.

Parameters	Value (μm)
Feed length L_f	0.186
Feed width W_f	0.067
Ground length L_g	2.5
Ground width W_g	2
Height of triangular DR h	0.2
Area of triangular side a	1
Rotation angle θ	0°

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgment

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