Analysis of Infrared Nano-antennas Material Properties for Solar Energy Collection

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Abstract ─ This work presents the effect of material properties on three infrared nano antennas that are rectangular, bowtie, and elliptical-shaped designed to collect a maximum field in the gap between the two dipole arms over a frequency band of 28-29THz. The dipole shapes are comprised of conducting dipoles printed on a dielectric substrate. The bowtie is designed to be curved with an exponential shape, and itis found to collect a higher value of the electric field in the gap than do the other two shapes. The above antennas are investigated with different materials for the dipoles and the substrate to study the effect of material variation on the electric field collected in the dipole gap. Three different types of conducting materials, namely, gold, chromium, and titanium are used. It is found that the collected gap field intensity is directly proportional to the conductivity of the dipole material. The effect of three different types of substrates; quartz (GaAs), silicon, and SiO2 on the collected gap field is also investigated.

Index Terms ─ Electric field, energy harvesting, infrared, nano-antenna.

I. INTRODUCTION

Solar energy has recently been viewed as one of the most accessible sources of renewable energy [1], and it can be harvested by using antennas that operate at infrared or visible frequency bands [2]. Several infrared antennas with different geometrical shapes have been investigated in the literature including rectangular [3, 4]; circular [4] spiral; bowtie [5, 6, 7, and 8]; dipole [9, 10, and 11]; elliptical [12]; and Vivaldi [13].

Optical antennas are currently being used for various medical applications such as breast cancer treatment [14]. To treat cancer, optical antennas are placed in contact with the malignant breast. The antenna is excited by a near infrared plane wave. The intense field in the antenna gap resulting from the excitation causes arises in the distribution of local temperature, which helps destroy the cancerous cells. Additionally, these antennas are also used as biological sensors [15].

The infrared rectenna (antenna+rectifier) is comprised of a receiving antenna, designed for infrared frequencies, together with a rectifying diode, which converts the infrared waves into electric power. Optical and infrared rectennas are superior to the photovoltaic cells, whose conversion efficiencies are limited [7]. The rectennas use the natural energy of the sun (lights), and in contrast to the photovoltaic cells, their conversion efficiency can reach up to 100% [7]. Generally, the rectenna needs to be designed such that it harvests the maximum amount of energy from the impinging electromagnetic wave. In addition, good impedance match between the rectifier and the antenna is required [7] to achieve a maximum power transfer. Nano-antennas should be optimized to realize the maximum field intensity for the specific operating frequency. Finally, the electromagnetic study and numerical simulations of the nano-antennas designed with real and special materials, dimensions, and substrate thickness is actually a challenge. The simulation of nano-antennas with thin substrate layers such as nanometers and without substrate is already have been performed to obtain the maximum field intensity at an operating frequency. The objective of this paper is twofold; the first one is to study the effect of the conducting material of the nano-antennas based on the structures presented in [21], in order to collect maximum energy at the resonance frequency of 28.3 THz. The second is to study the effect of the substrate material on maximizing the electric field intensity across the antenna gap. Analysis of the obtained simulated results shows that the using of

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the high conductor material, Gold, leads as to have the highest gap electric field intensity for any structure. The choice of the Quartz as a substrate for these nano-antennas allow a better collection for the electric field in comparison with the most used substrate material; Silicon (Si) and Silicon oxide (SiO2).

This paper is organized as follows: Section II describes the geometries of three proposed antennas in detail, using the Drude model to describe the conductors' properties in terahertz frequency band. Following this, Section III presents the simulation results and discussions.

II. ANTENNAS DESIGN

The proposed IR nano-antennas were designed for harvesting of solar energy over the frequency range of 28-29 THz. The three different antenna shapes presented in [21] are optimized to realize a maximum level of the electric field intensity at 28.3 THz. The antennas are printed on a dielectric substrate and placed on a conducting ground plane. The ground plane has a thickness of 0.2µm which may improve the antenna coupling of the substrate.

Each of the three shapes are investigated to determine the effect of choosing the dipole shape as well as its material properties on the level of energy that is possible to collect in the gap.

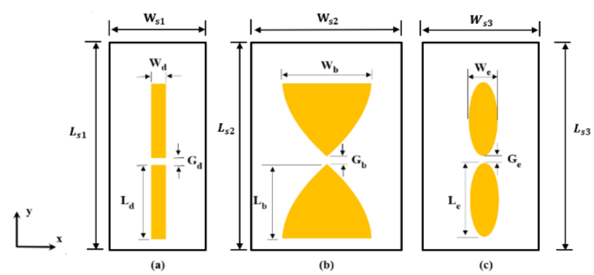


Fig. 1. The structure of the proposed dipole optical antenna: (a) rectangular, (b) bowtie, and (c) elliptical.

First, we start to study a simple rectangular dipole di to its advantages related to its small dimension, low cost, light weight and its manufacturing feasibility. The proposed rectangular dipole antenna is shown in Fig. 1 (a). We note that each rectangular arm has a length L_d=1.8µm, width of W_d=0.15µm, separation gap of Gd= Wmin=0.05µm and conductor thickness of 0.08µm. The dimension of the substrate is Ls1=3.8µm and Ws1=1.2 µm.

Next, we studied a modified bowtie antenna. Usually the bowtie antenna consists of two triangularly shaped arms. However, here the two arms of the bowtie are designed to have a curved exponential shape, represented by (1), where V is the curvature coefficient, W_{max} and W_{min} are the maximum and the minimum widths of the tapered arm respectively, and B is given by (2). Figure 1 (b) shows the proposed curved bowtie nano-antenna. The conductor thickness is 0.1µm and its gap size is 0.05 µm. The geometrical parameters of this structure are W_{s2}=4 µm, L_{s2}=7µm, W_b=2.52µm, L_b=2.5µm, Wmin=G_b=0.05µm, W_{max}=5.05µm, and V=0.8µm:

$$g(x) = B(e^{V_x} - e^{-V_x}) + \frac{W_{min}}{2}, \quad (1)$$

$$B = \frac{W_{max} - W_{min}}{2(e^{V\frac{W_b}{2}} - e^{-V})}. \quad (2)$$

The third proposed shape is an elliptical dipole, whose conductor thickness is 0.1µm. As shown in Fig. 1 (c) the dimensions of the structure for the elliptical dipole are L_{s3}=17µm, W_{s3}=4 µm, W_e=1.6µm, L_e=8µm and the gap width is G_e=0.05 µm.

All three dipoles were printed on a substrate that has an area of 3.8×0.2µm^2 and thickness of 100µm.

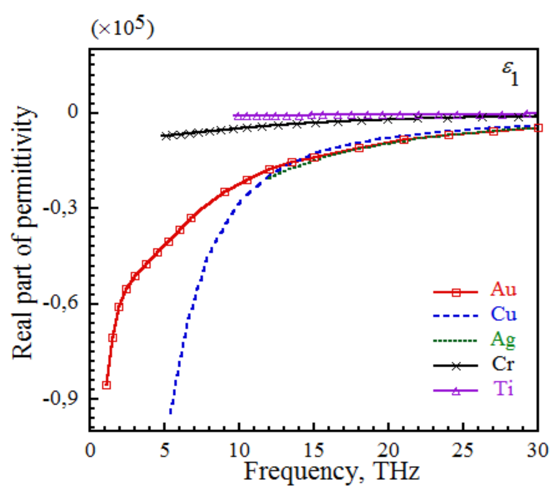
While the metal is considered as a perfect electric conductor at lower frequencies, e.g., RF. This is not the case at infrared frequencies in which it is plasmonic in nature [16] and is typically represented by the Drude model to describe the transport properties of electrons in materials [17]. The complex permittivity ε_c is given by:

$$\varepsilon_c = \varepsilon_1 + i\varepsilon_2. \quad (3)$$

The Drude model of ε_c is represented via the expression:

$$\varepsilon_c = \varepsilon_\infty - \frac{\omega_{p1}{}^2}{\omega^2 - i\Gamma\omega} + \frac{\omega_{p2}{}^2}{\omega_0{}^2 - \omega^2 + i\gamma\omega}. \quad (4)$$

In (4), where $\omega_0 = \frac{2\pi c}{\lambda_0}$, and ε_∞ is the contribution of the bound electron to the permittivity, γ denotes the damping frequency, ω_p is the plasma frequency, ω represents the angular frequency and ω_0 corresponds to the angular frequency. It is shown in [17] that expression in (4) agrees well with the experimentally measured dielectric properties of metal. Figures 2 (a) and (b) show that the variation of real and imaginary parts of permittivity for different metals, such as gold, copper, silver, chromium and titanium, still have good conductivity and low losses at the frequency range of 1 to 30 THz. It can be seen that the electrical permittivity varies from one metal to another and it decreases as the frequency is increased.



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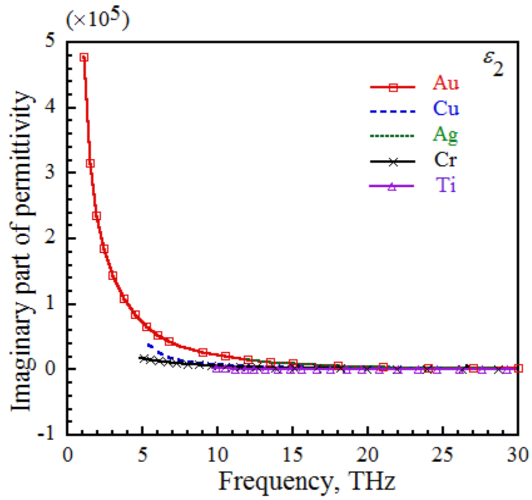


(b)

Fig. 2. The variation of the real and imaginary parts of relative permittivity for various metals.

Table 1: Real and imaginary part of relative permittivity at 28.3 THz

Conductor	ε_1	ε_2
Gold (Au)	–5605.6	2243.2
Copper (Cu)	–4261.8	1186.2
Silver (Ag)	–5061.3	1566.1
Chromium (Cr)	–1132.5	563.18
Titanium (Ti)	–306.94	301.73

The three antennas mentioned above, are simulated by using the Computer Simulation Technology (CST) [18] program package, where the metal properties of the gold are calculated by using the Drude model and are inserted in the CST Microwave Studio. The imaginary part of the permittivity is associated with the ohmic losses, which should be as low as possible. Alternatively, we can maintain the ohmic losses to be low by choosing a metal that has a significant real negative part. Table 1 lists the real and imaginary parts of the relative complex permittivity for five conductors of gold, copper, silver, chromium, and titanium.

III. RESULTS AND DISCUSSIONS

A. Effect of the conductor

Gold, silver, aluminum and copper are the three widely used materials in optical applications [19]. Gold and copper have almost the same dielectric and conduction properties with similar responses to Drude at less than 2.1 eV, and the beginning of inter-band transitions occurring around 2.3 eV (530-550 nm). These two types of materials generally have a good conductivity in the infrared region, whereas Titanium has a low conductivity compared to other metals previously studied.

In the terahertz frequency band, the conductivity of the metal is complex, given by:

$$\sigma = \sigma_1 + i\sigma_2, \tag{5}$$

where σ_1 and σ_2 can be calculated by using the following equations:

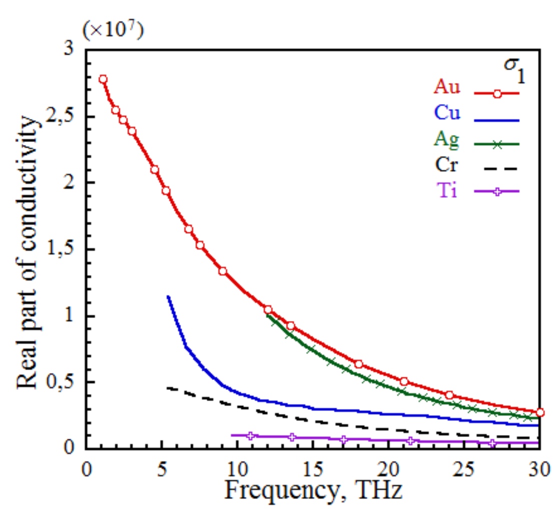
$$\sigma_1 = \varepsilon_0 \varepsilon_2 \omega, \tag{6}$$

$$\sigma_2 = \varepsilon_0 (\varepsilon_1 - 1)\omega. \tag{7}$$

The conductivity of different metals is calculated at different frequencies by using the above expressions. Figures 3 (a) and (b) show the variations of the conductivities of different metals vs frequency. It is obvious that the conductivity of the metals reduces as we increase the frequency. Also, the real and imaginary values of the conductivity for gold are higher than those of other metals because gold is characterized by its high absorption of radiation at terahertz frequencies [7]. Silver and copper have conductivity values that are near – but less than – that of gold. This can be noticed in Table 2.

Since the conductivity of titanium is the least among the selected metals, we can anticipate that the titanium antennas will collect less electric field than would the others. This can be seen from Figs. 4 (a), (b) and (c), which present the results for the three different dipole shapes.

The gold is chosen for the rectangular, curved bowtie and elliptical dipole shaped antennas which realize field strengths of 350.75, 429.858, and 330.01 V/m, respectively, at 28.35 THz. This choice is based on the results obtained from the simulation of these antennas and are shown in Fig. 3. A set of conductors are used for each dipole, instead of a single conductor for each arm. By combining gold with chromium, gold with titanium, and chromium with titanium. Figures 4 (d), (e), and (f) show the effect of the conductors on the collected electric field in the gap for the three different dipole shapes. It can be seen that the structures with the gold collect the higher electric field than the other structures.



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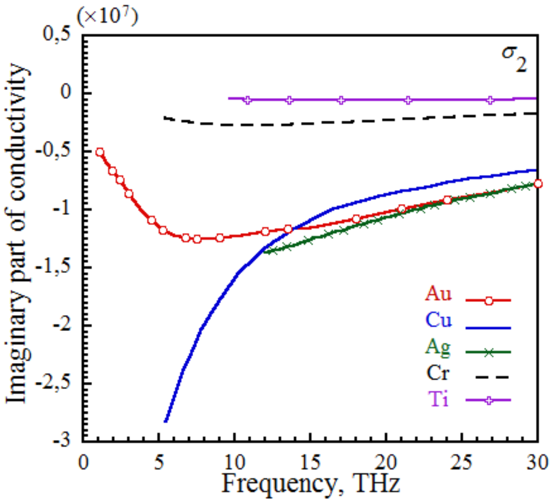
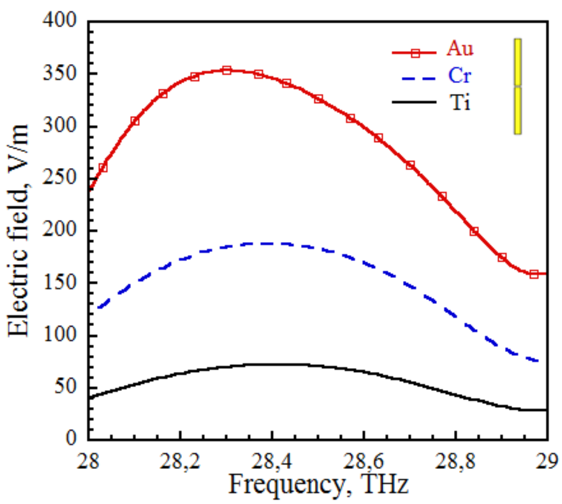


(b)

Fig. 3. Variation of metal conductivity versus frequency band [0...50THz].

Table 2: Real and imaginary part of conductivity at 28.3 THz [20]

Conductor Type	σ_1 (S/m)	σ_2 (S/m)
Gold(Au)	0.33728×10^7	-0.84305×10^7
Copper (Cu)	0.18855×10^7	-0.67762×10^7
Silver (Ag)	0.25012×10^7	-0.80856×10^7
Chromium (Cr)	0.08889×10^7	-0.17893×10^7
Titanium (Ti)	0.047507×10^7	-0.04848×10^7



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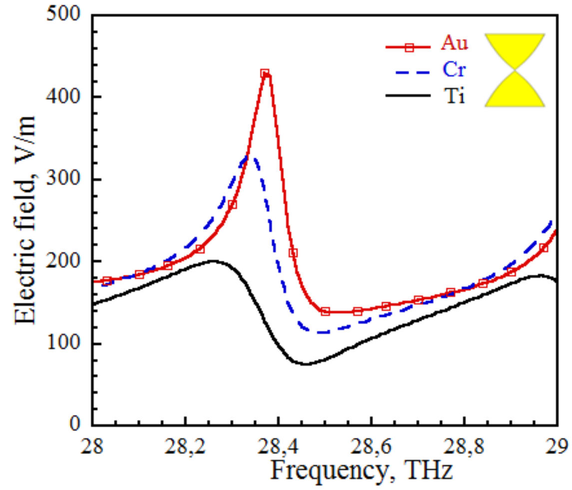

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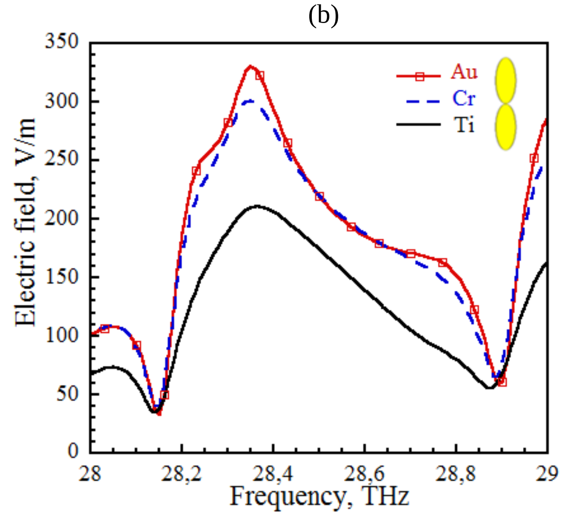

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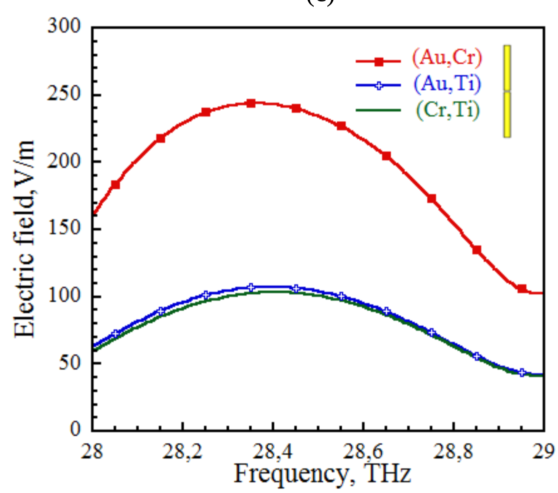

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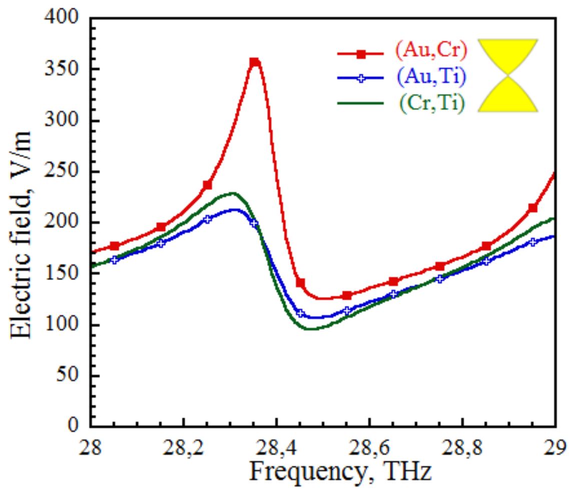

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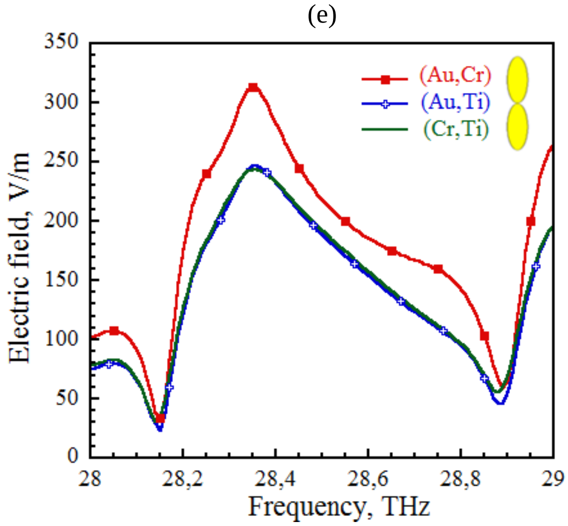
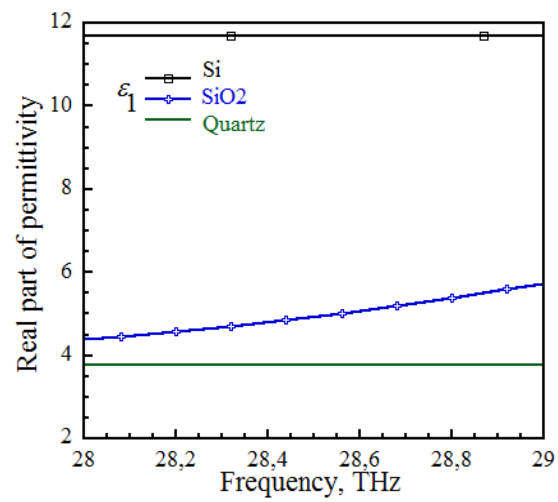


(f)

Fig. 4. The effect of metal type on electric field variation versus frequency for (a,d): rectangular, (b,e): curvature bowtie, and (c,f): elliptical antenna.

B. Effect of the substrate

The choice of the dielectric material plays an important role in the design of antennas. The best strategy is obviously to choose a substrate that has a low loss. At infrared, the type of the substrate plays a very important role where we attempt to improve the electric field amplitude in the gap of the antenna structure. We have investigated three different substrates to see which one has the best performance. The three substrates are: Quartz (GaAs, $\varepsilon_r = 3.75$, silicon (Si, $\varepsilon_r = 11.68$, and silicon oxide (SiO2, $\varepsilon_r = 4.71$ at 28.3 THz). Figures 5 (a) and (b) show variations of the real and imaginary parts of relative permittivity for the three different substrate materials versus frequency range of 28-29 THz. These three different substrates are used to evaluate their effect on the electric field captured in the gaps of the dipoles. The results are presented in Fig. 6, where we observe that the nano-antenna with quartz substrate achieved the highest gap electric field. The maximum field value obtained for the rectangular dipole antenna with the quartz substrate is at 353.743 V/m at 28.3 THz; for the bowtie dipole antenna, the maximum value is 429.858 V/m at 28.37 THz; and for the elliptical dipole antenna, the maximum value of electric field reaches 327.202 V/m at 28.35 THz. It should be noted that the substrate permittivity affects both the maximum value of the captured gap field and the resonance frequency. Additionally, we note, from Figs. 6 (a, b, c), that the quartz substrate allows for capturing a higher level of the field in the entire band.



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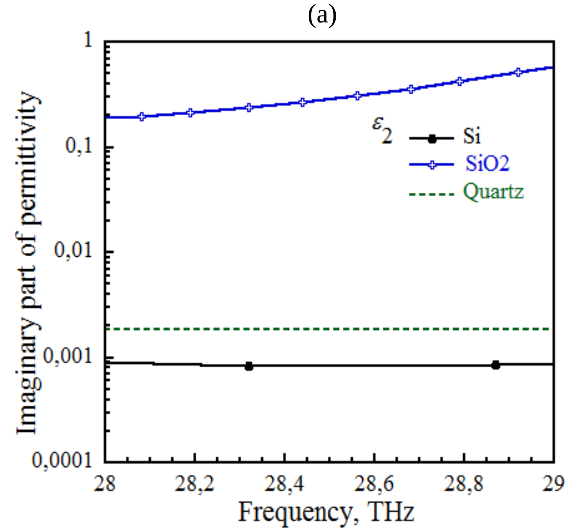

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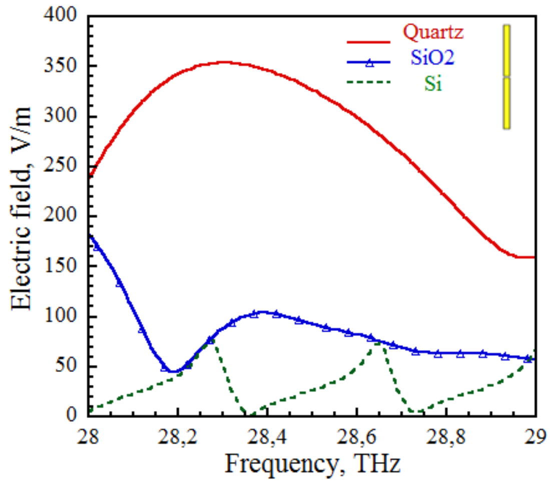
Fig. 5. Real and imaginary part of relative permittivity of studied substrates [20].



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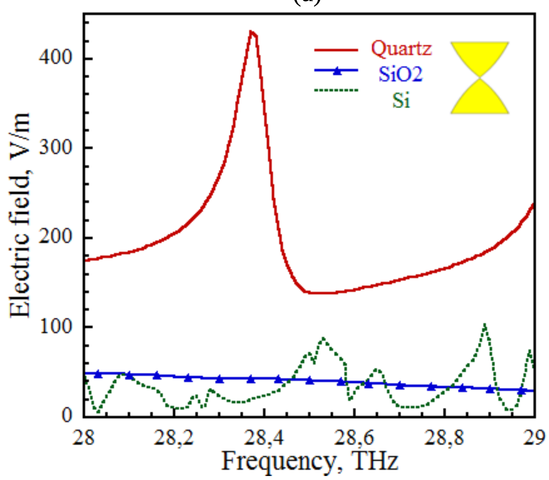

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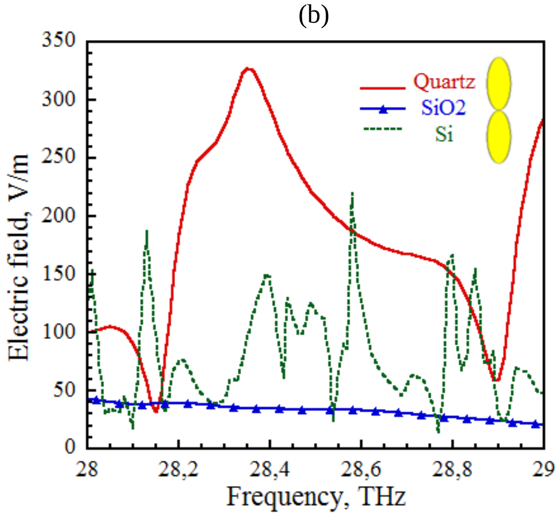

(c)

Fig. 6. Effect of substrate type and thickness on electric field distribution for the different structures.

We now compare the three different shapes of the studied dipole antennas. It is evident that the curved bowtie antenna has the highest value of the captured field at 28.3 THz, as compared to the dipole designs with elliptical and the rectangular shapes (See Fig. 7). Moreover, Table 3 summarizes the maximum field values realized by antennas with different metal types. It is evident that gold-based antennas provide the maximum electric field for rectangular, elliptical, and bowtie dipole shapes at 28.30, 28.32 and 28.33 THz, respectively.

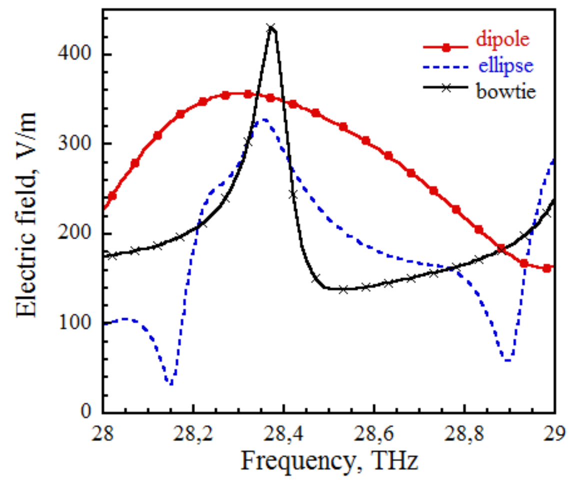

Fig. 7. Variation of electric field versus frequency for the optimum case of different dipole antenna shapes.

Table 3: E_{Max} at resonance frequencies for different conductor type

Dipole Shape	Type of Metal	Resonant Frequency (THz)	E_{Max} (V/m)
Rectangular	Au	28.30	353.75
	Cr	28.37	188.00
	Ti	28.42	72.67
	(Au,Cr)	28.36	244.032
Bowtie	Au	28.33	429.85
	Cr	28.34	331.52
	Ti	28.26	200.67
	(Au,Cr)	28.35	357.63
Elliptical	Au	28.32	327.20
	Cr	28.35	301.39
	Ti	28.32	200.03
	(Au,Cr)	28.35	313.22

IV. CONCLUSION

In this paper, a set of Ultra-Wideband optical nano-antennas operating in the infrared region were proposed and optimized to collect the maximum energy. A combination of three different dipole shapes, three different metals and three types of substrates were investigated. It was shown that using goldas a conductor achieved the highest gap electric field intensity for any dipole/substrate combination, and so did quartz for any dipole/conductor combination.This is due to gold having the highest conductivity and quartz having the lowest loss. We propose a future similar investigative study where a metal-insulator-metal (MIM) diode with a thin insulator layer of Al_2O_3 inserted in the antenna gap.

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Her research mainly focuses on the development of a modal analysis methods for printed structures based on the Method of Moments and singular decomposition to identify a chipless Radio Frequency Identification (RFID) and to localize a reader. Her research interests include Ultra-Wideband (UWB) optical rectennas for Solar Energy Harvesting, investigation of irregular fractal antennas, as well as on low profile antenna array and array optimization for 5G applications.

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