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Original Research Article

Graphene based THz array (dipole elements) for high speed wireless applications

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ABSTRACT
In this paper, we elaborate the comparisons among different physical parameters of substrate materials that are used to design THz antennas with some specific properties. After the simulation of a graphene based miniaturized dipole antenna array (4*1) design fed by discrete port with 50 ohm input impedance. This antenna array design has two dissimilar substrates (Silicon and Quartz) layers and annealed copper as a ground conductor. This dipole antenna array resonates between 1.9915 THz to 2.508 THz frequency range with 8.0977 dBi to 9.1273 dBi gain and above 93% efficiency. Extensive simulation and optimization have been performed by electromagnetic field simulation software 2019 in the time domain.

1. Introduction

Terahertz (THz) antennas are designed to work in 0.1 to 10 THz frequency. THz range has high penetration power, so it is accurate for scanning opaque object, safety check applications and quality control in industries. Due to less attenuation loss it is used for detection and diagnostics of tumour and cancer tissues. Due to less photon energy of THz wave, ionization reaction will be negligible, it is not harmful for human body, so it is suitable for medical diagnosis like liver, skin, breast, any cancer detection by spectroscopy, vital sign monitoring and biological samples. It provides better spatial resolution (image) with high directivity. THz antennas are used as sensor in defence, industrial accuracy and agriculture field etc. 5G cellular network, terabit WLAN, civil security (quality and process control), design photoconductive switch, wireless identification, sensors, communication sensors, WPAN and RFID tag etc. Due to miniaturization of size these can used as micro and nano electronics devices such as Si FET plasma channel, quantum cascade lasers, meso-crystal microspheres, internet of nano things, on chip communication, THz local area network remote sensing and biological detection. But there are drawbacks e.g. path losses are high for high gain antennas, which is required for effective communication. This band has some transmission windows where path losses are relatively low. Wavelength of THz is very short so high cost effective fabrication and connectors will be highly expensive. THz devices like THz emitters based on MMIC modulator detectors. If dielectric constant increases then the surface wave losses will be increasing, so radiation efficiency will decreases. Microstrip patch antenna at sub THz frequencies designed by simple fabrication methods and such types of aerials have been tested (up to 0 .1 THz) by VNA [1].

Selections of substrate materials for graphene based antenna designing has an important role of controlling the transport property of graphene as well as manipulate the resonance property of graphene. If we use two different substrate materials for designing microstrip antenna, it will resonate at two different frequencies. If these resonating frequencies are close to each then bandwidth of antenna will increase. Surface conductivity of graphene is very high and is controlled by environmental temperature, applied gate voltages, operation frequency, electron mobility, chemical doping, relaxation time and Fermi energy (chemical potential). All above parameters are related to each other. Graphene conductivity controlled by Kubo formula

$$\left(\sigma(\omega,\mu_C,\Gamma,T)\right)=\frac{Je^2(\omega-j2\Gamma)}{\pi h^2}\left[\frac{1}{((\omega-2j\Gamma)^2)}\int_0^\infty \varepsilon\left(\frac{\partial f_{d(\varepsilon)}}{\partial\varepsilon}-\frac{\partial f_{d(-\varepsilon)}}{\partial\varepsilon}\right)d\varepsilon-\int_0^\infty\frac{f_d(-\varepsilon)-f_d(\varepsilon)}{(\omega-2j\Gamma)^2}d\varepsilon\right]$$

Graphene surface conductivity related to scattering rate Γ (electron relaxation time in graphene), chemical potential μ_C (vary 0.0001 to 1), temperature T, and frequency ω , where $f_d(\varepsilon)$ is the Fermi Dirac distribution function, k_B is the Boltzmann constant and e is charge of electron [2, 3].

RT/Duriod 5880 substrate available in the market has 127 micrometer thickness and it works up to 300 GHz due to some material property restrictions [4]. Some substrate materials are used in THz frequency like liquid crystalline polymers has good electrical performance in THz frequency band. It is available in the market with very small substrate thickness of 25 micrometer. Lot of substrate materials are used for designing THz antenna like LCP (Polymers such as polyamide and polystyrene are popular substrate materials for THz applications due to their low price, flexibility, and simplicity of processing); BCB (benzo cyclo butene), InP (Indium Phosphide), FR4, Si (Silicon has low loss tangent, high thermal conductivity and compatibility with standard micro fabrication techniques), high-resistivity silicon is a substrate material that has been gaining popularity in THz applications due to its high resistivity, low loss tangent, GaAs, polyamide, teflon, quartz (it has high transparency, low dielectric loss, and high mechanical strength), silicon dioxide and silica, sapphire (it has high thermal conductivity, high transparency and high mechanical strength) etc. The choice of substrate material depends on the specific requirements of the THz application, such as frequency range, bandwidth and device size. The comparison table 1 shows the physical properties of different materials, which are used for THz antenna designing [5-14]. We want to improve directivity and gain up to required level by enlarging the length of aerial, decreasing side lobe level, decreasing power loss and improving cross polarization level. Then we decrease above radiation parameters by idea of array concept. An array provides improve directional pattern, additional gain, little side lobe level and small level of cross polarization. An array system of aerial, individual elements are of identical dimensions. If number of radiators will be added to in a planar style by definite gap between elements, e.g. λ/4, λ/2, 3λ/4… etc. According to gap between elements radiation properties will vary in free space. We can use different discrete ports for feeding purpose. THz antennas have unique properties that make them attractive for a variety of applications such as high-speed wireless communication, imaging, spectroscopy, and sensing. The objective of THz antenna research is to develop high-performance antennas that can efficiently transmit and receive signals in the THz range. This requires designing antennas with specific characteristics, such as, high gain, wide bandwidth and low loss, while also considering the manufacturing and integration challenges associated with operating at such high frequencies. [15-21].

Table 1: A comparisons of different substrate material properties in THz range.

Substrate material	ε_r	Density (gm/cc^3)	Thermal conductivity (W/m^0K)	Dissipation factor	Radiation efficiency	Specific heat (j/kg.k)	Ref.
Quartz	3.78	2.5	1.4	.0004	87.6%	750	5
Si_3N_4	9.5	3.29	30	00	100%	691	
Al_2O_3	9.1	3.69	18	.0007	98.4%	880	
BN (boron nitride)	4.6	1.9	30	.0017	87.9%	1610	
Silica	4.0	2.2	1.5	NA	80-92.3%	745	
Glass	3.8	2.2	.8	1e-012	60%	840	
Indium Phosphide	12.4	4.81	68	NA	in combination 87%	310	6
BCB (benzo cyclo butene)	2.5	.957	.293	.0005		180	
Polymide	3.5	1.14	different	.008	60-80%	1500 (Nylon)	7
Liquid Crystalline Polymer	2.91	1.76	10	.0025	58.4%	970	8
Sapphire (alumina 99.9%)	10.06	3.98	34.6	$8.4*10^{-6}$	NA	648	9
Cyclo Olefin Copolymer	2.2	1.02	37.9 to 49.6	.0007	50% Gold, 85% graphene	NA	10
Duroid 6010	6.15,6.4 5,10.5	3.1	0.86	.0023	NA	1000	11
Rogers RT 6006	6.15	2.7	1.44	.0027	NA	NA	12
Duoid 6010	10.2	3.1	.86	.0023	NA	1000	13
SiO_2	3.9	2.2	1.5	.001	92.3-96.6 %	745	14
Quartz	3.75	2.65	7.7–8.4	NA	in combination 93 to 97 %	741	3

2. Design steps of antenna array

2.1 Design of graphene based dipole (single unit) antenna

Figure 1 shows the complete structure of the dipole antenna. Below structure is designed on two substrates namely Silicon ($\mathcal{E}r$ = 11.9) and Quartz ($\mathcal{E}r$ =3.75). Silicon and quartz are very popular substrate material for THz applications. Advantages of two substrates are mentioned in introduction of this paper. If two substrates with different dielectric constant, then antenna will resonate at two different frequencies. Two nearly resonating frequencies will improved the bandwidth of antenna. By using a low-permittivity substrate on the top layer, the antenna can have a wider bandwidth than, if it is constructed using a single substrate. This is because the low-permittivity substrate reduces the substrate resonance effects, which can limit the bandwidth of the antenna. Initially, we define graphene conductor material properties like chemical potential, thickness, temperature, relaxation time, maximum and minimum frequency etc. in computer simulated technology microwave studio suite, then a optimized dipole antenna is designed. We design two thin rectangular patches of length λ/4 using graphene as radiating material and according to input impedance of port spacing between two patches is 1 mm or 2 mm. Table 2 show the physical dimension of dipole antenna.

Table 2: Proposed antenna dimensions (in micrometers)

Parameter	Patch length	Patch width	Patch thickness	Substrate length and width
Value	λ/4= 17.5	4	0.6	200×200
Parameter	Ground length and width	Substrate thickness (Silicon)	Ground thickness	Substrate thickness (Quartz)
Value	200x200	40	0.6	20

2.2 *Optimized graphene based dipole antenna (single unit) design*

Figure 2 shows the complete optimized dimension of antenna like length, width and height of substrates. Graphene based dipole size is same as above. It will resonate with in complete frequency range. Optimized values provide good gain and directivity also. Antenna is fed by discrete port with 50 ohms input impedance.

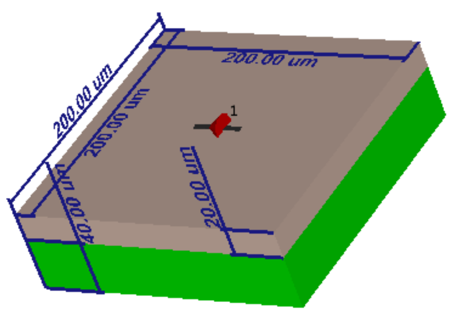

Figure 1: Structure of the created antenna.

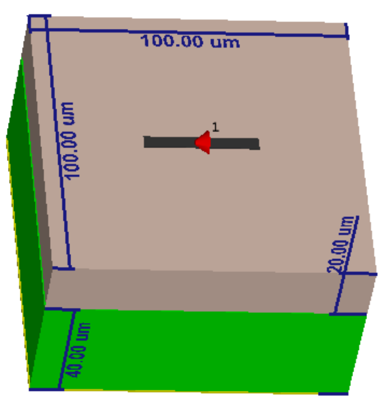

Figure 2: Structure of the optimize antenna.

2.3 *Designing of 4*1 elements antenna array*

Four similar optimized antennas are arranged in a parallel manner. The distances between two elements are 26 micrometer. Radiation characteristics can BE changed by distance between two individual elements of array. Four discrete ports are used for feeding at the same time with 50 ohm input impedance. Figure 3 demonstrates the complete dimension of array (4*1).

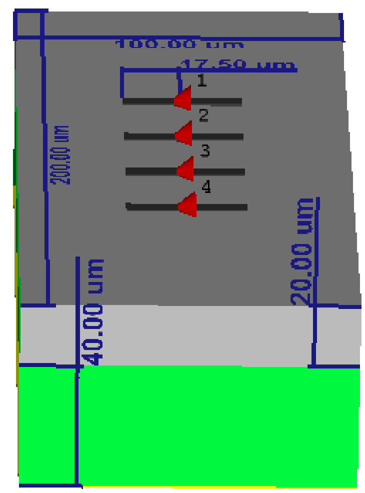

Figure 3: Structure of the antenna array (1*4).

3. Results and discussion

3.1 *Results of dipole (single element) antenna*

The use of two substrates in antenna design is often done to achieve specific performance goals such as improving the antenna's radiation pattern, bandwidth and gain. One common approach is to use a high-permittivity substrate on the bottom layer and a low-permittivity substrate on the top layer. This creates a dielectric contrast that can improve the antenna's radiation pattern by reducing the surface wave and edge diffraction effects. The high-permittivity substrate increases the fringing fields of the antenna, while the low-permittivity substrate reduces the parasitic coupling between the antenna and the ground plane. Figure 4 shows S_{11}(S parameters) parameters and peak of S_{11} shows the good impedance matching. S_{11} shows antenna resonates between 1.8924 to 2.4834 THz frequency below -10 dB and two other resonating peaks at 2.5778 and 2.6763 THz with very small bandwidth. The amount of power which reflect back from aerial it shown by S_{11}. The bandwidth is associated to quality factor of aerial and voltage standing wave ratio. Figure 5 shows the gain of aerial is 3.47 to 5.67 dB at 2.5778 and 2.6763 THz. Two substrates are used to improve the antenna's gain. By placing a high-permittivity substrate on the bottom layer, the antenna's gain can be increased due to the increase in the surface wave's velocity. This can be further enhanced by placing a low-permittivity substrate on the top layer to decrease the parasitic coupling between the ground plane and the antenna.

$$BW = (VSWR - 1)/ Q \times \sqrt{VSWR}$$

where, VSWR = (1 + |Γ|)/(1 − |Γ|) here Γ is reflection coefficient and it is equal to $\Gamma = (Z_{in} - Z_o)/(Z_{in} + Z_o)$, here Z_{in} the input impedance of the aerial and Z_o the characteristic impedance of the feed line.

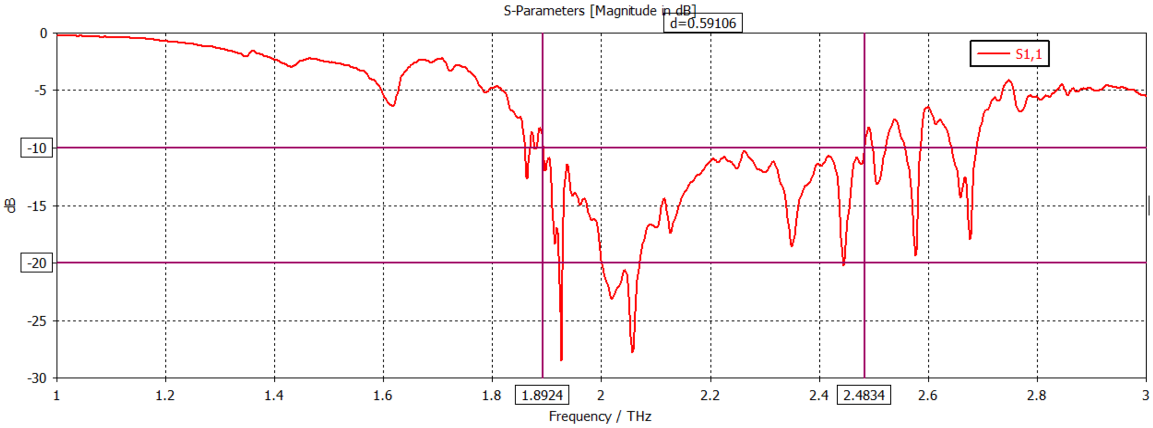

Figure 4: S_{11} parameters of the antenna.

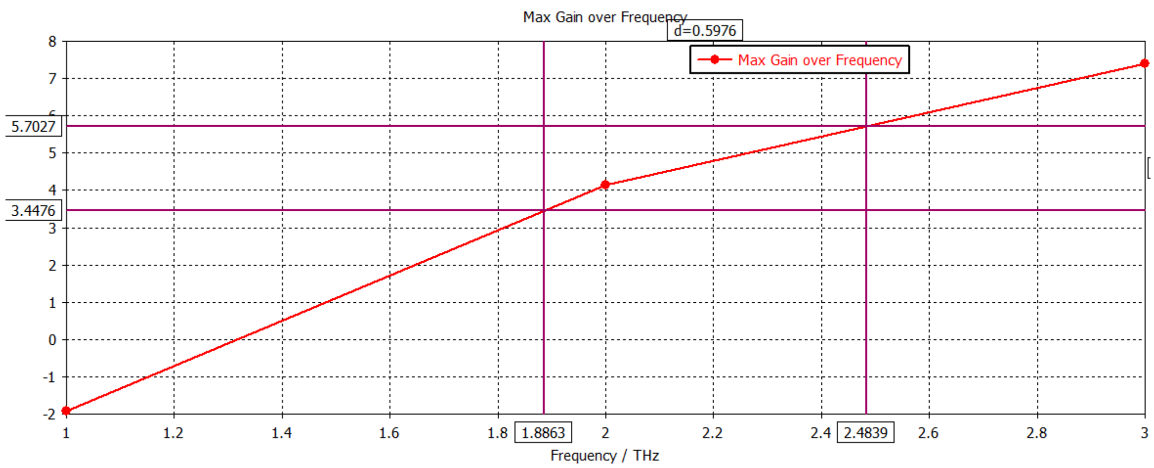

Figure 5: Gain v/s frequency.

3.2 Results of single unit optimize graphene based dipole antenna

Figure 6 shows three different S_{11} parameters when chemical potentials are 0.2, 0.6 and 1.0 eV. Here best results is achieved at 1.0 e volt corresponding to 2.09 to 2.54 THz, good impedance archived at 0.6 eV but it will be resonating at 2.08 to 2.51. Figure 7 shows the gain of optimized antenna 6.93 to 8.67 dBi at 0.6 and 1.0 eV.

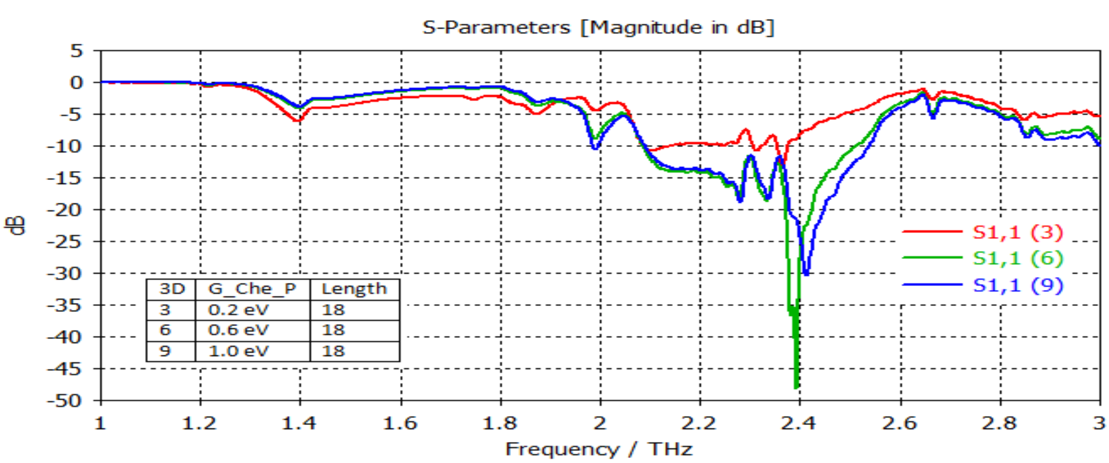

Figure 6: S_{11} parameters of the optimize antenna for different CP.

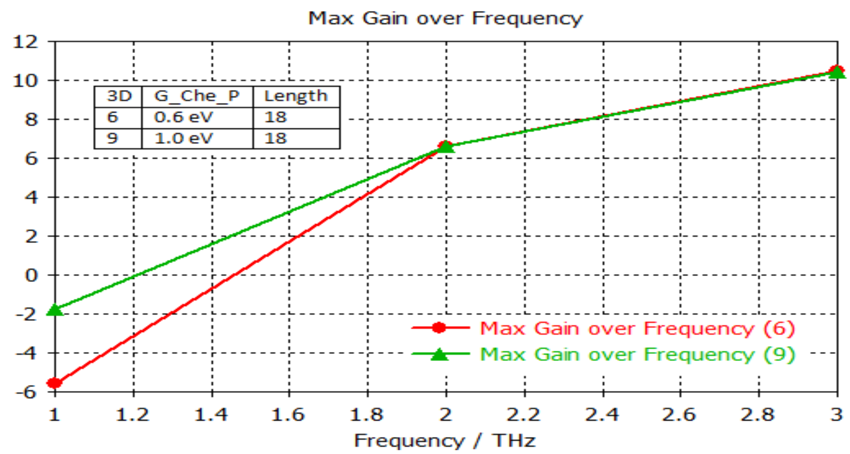

Figure 7: Gain for different cp frequency.

*3.3 Results of 4*1 element array antenna*

S_{11} scattering parameter of four elements (4×1) array antenna designed by graphene radiating patch is shown in Figure 8. It will be resonating at 1.9877 to 2.5065 THz frequency range. Resonance frequency became shifted into lower side because another three elements behave as parasitic elements for individual element, so physical size of antenna will be increased. Then antenna resonance will be shifted into lower frequency range. Figure 9 shows that the gain of antenna array is 8.0977 to 9.12 dBi. High gain provided by graphene radiating material, due to high electron mobility, high velocity of fermions (e) and high electric conductivity of graphene as compared to other conductors. The gain is very high despite less thickness of patch. High gain is used for many wireless applications in THz range.

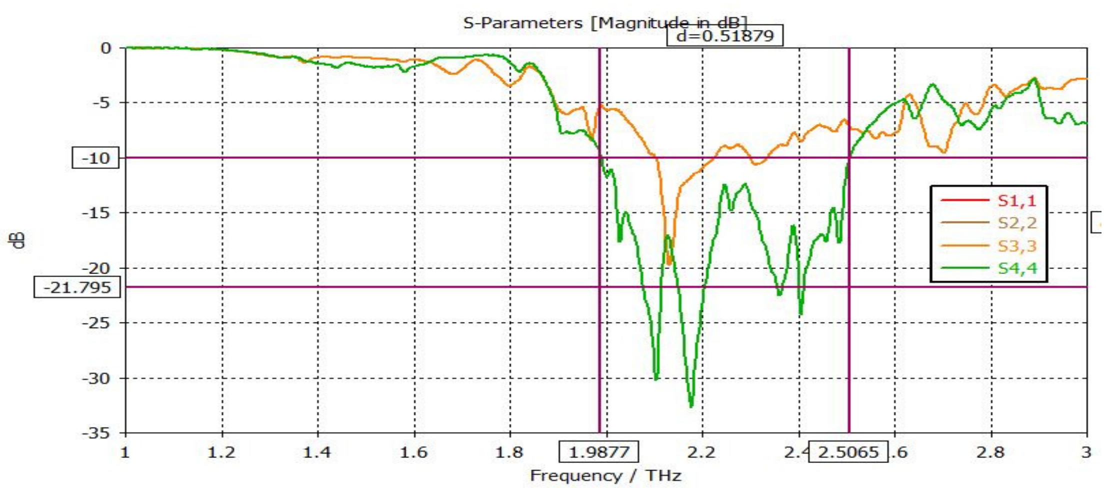

Figure 8: Scattering parameters.

Figure 9: Gain of antenna w.r.t. frequency.

Table 3: Comparison among previously work with presented work.

Ref.	Substrate used	Chemical potential	Resonance frequency in THz	Gain (dBi)	Directivity (dBi)	Efficiency in %
20	Quartz	0.19 eV	1.03	NA	1.8	NA
21	Glass	0.25 eV	1.534	NA	NA	4.5
2	SiO_2+Si	1 eV	2.50	NA	5.23	57.46
3	Quartz + Silicon	1 eV	2.09 to 2.54	6.7 to 8.6	7.2 to 8.8	≥ 93
Present Work	Quartz + Silicon	1 eV	1.9877 to 2.5065	8.0977 to 9.12	8.66 for 1,4 element and 10.17 for 2,3 element	≥ 93

Figure 10 shows the directivity of 2 or 3 elements. Figure 11 shows the directivity of 1 or 4 elements. Elements (1 and 4) and elements (2 and 3) have same directivity and gain. So efficiency ($G = \eta D$) of antenna array will be above 93 %. It is very good for wireless communication.

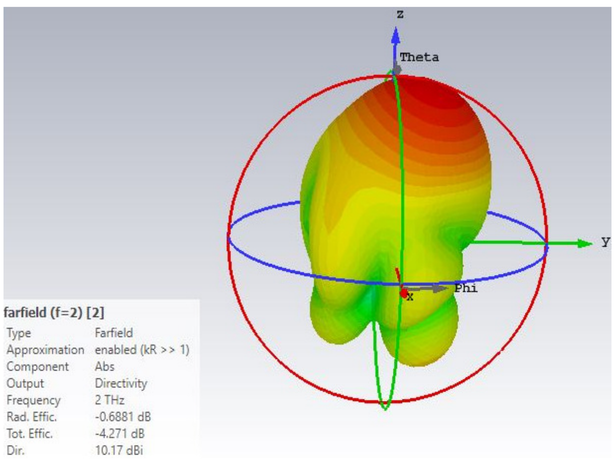

Figure 10: Directivity of 2 or 4 elements (radiation pattern).

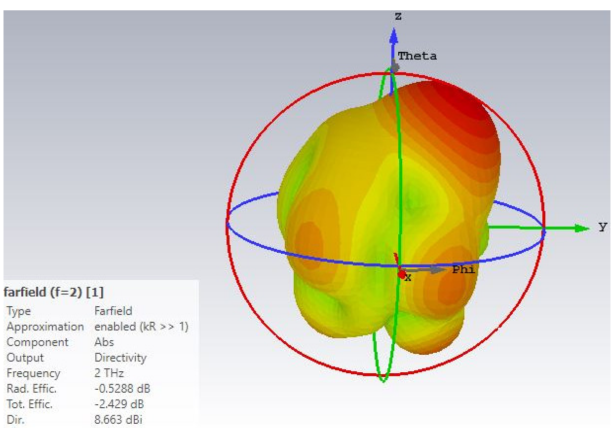

Figure 11: Directivity of 1 or 4 elements (radiation pattern).

Figure 12 (a) and (b) show the surface current at 2 THz frequency for (1 and 4) and (2 and 3) feeding ports. It will be same for (1 and 4) and (2 and 3). Surface current in an antenna refers to the flow of electrical current along the surface of the antenna, which is induced by the incident electromagnetic wave. When an electromagnetic wave interacts with an antenna, it induces an alternating voltage across the antenna's surface, which in turn drives a surface current.

This THz antenna (array) has the potential to enable new applications in high-speed wireless communication, imaging, spectroscopy, and sensing. They can also improve the performance of existing applications by providing better signal quality and more accurate measurements.

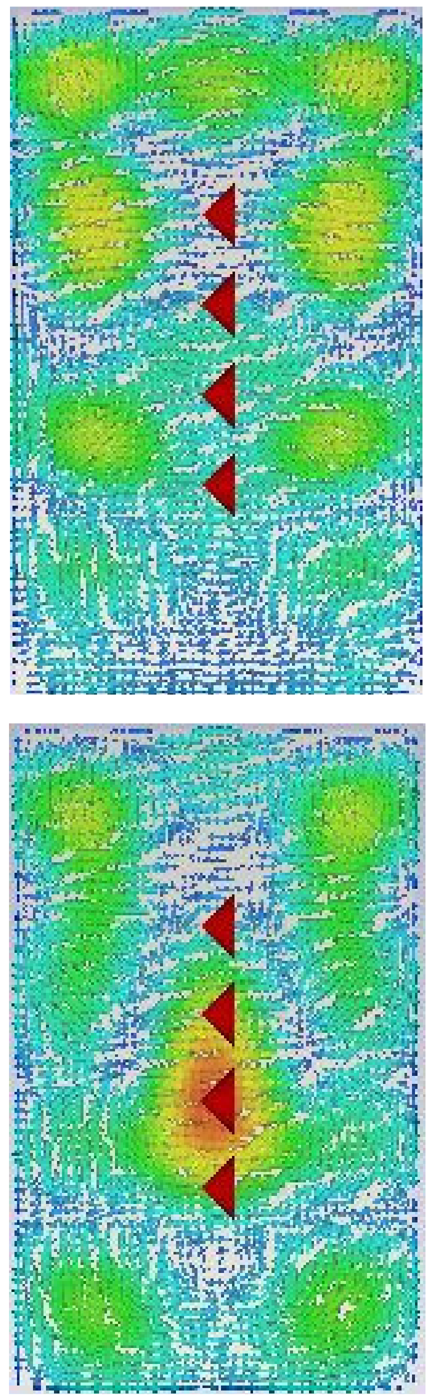

Figure 12: (a) and (b) Surface current at 2 THz.

4. Conclusions

The entire occupied volume of the dipole antenna array, including feeding network is 160×100×61.2 micrometer. Optimized results for four individual elements where length of dipole L = 35 micrometer ($\lambda/8$) and chemical potential 1.0 eV. Graphene provides better result with respect to gain (8.0977 to 9.12 dBi), bandwidth (518.8 GHz), and directivity (8.66 and 10.17dBi) for THz antennas. The use of two substrates in antenna design can provide significant performance benefits and is a common technique in THz and microwave antenna design. Here we have deployed linear polarization; however circular polarization can be tested by future researchers as challenge because thickness of antenna is very low. It will be the challenging task for researchers in field of THz range testing, fabrication and measurement.

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