Broadband terahertz absorber using superimposed graphene quantum dots

H. Deljoo\(^1\) · A. Rostami\(^{1,2}\)

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Abstract
In this study, we propose and investigate numerically a broadband THz metamaterial-based absorber, which is composed of superimposed graphene quantum dots. Based on this idea, a new way to engineering the absorption band is introduced. We will show that using the proposed idea, it is possible to design a THz absorber with a given bandwidth. To show the capability of the idea, we consider a three-layer structure, and the top layer is superimposed graphene disks. The middle layer is a lossless dielectric thin layer and eventually gold is placed in the bottom layer. Simulation results reveal a broadband absorption in the range of \(5.86-7.57\text{THz}\), \(5.89-7.56\text{THz}\), and \(5.89-7.58\text{THz}\) while absorption values respectively are above 89\%, 88.49\%, and 88.32\%. The dielectric material is Si\(_3\)N\(_4\) in the proposed structure. Also, the broadband absorption range is 7.47–9.87THz with an absorption value above 80\% while the dielectric material is SiO\(_2\).

Keywords Broadband absorber · Graphene · Metamaterial · Quantum dot

1 Introduction

Metamaterials are artificial materials that are designed in periodic arrays. They have interesting electromagnetic properties, like negative refractive index (Pendry 2004), asymmetric transmission (Xiao et al. 2015), and cross-polarization conversion (Tang et al. 2016). Due to the above-mentioned properties metamaterials can become perfect choices for the electromagnetic absorber. Metamaterial absorber has been demonstrated for the first time by Landy et al. in 2008 (Landy et al. 2008). After that, different designs for metamaterial absorbers have been proposed in the electromagnetic spectral range including microwave (Wu et al. 2014), terahertz (Liu et al. 2017), infrared (Guo et al. 2016; Zhong et al. 2017), and optical frequency (Lin et al. 2011).
Terahertz technology is developing increasingly. Terahertz has interesting applications in information and communication technology, biomedical imaging, security, astronomy, and spectroscopy (Chen et al. 2009; Jansen et al. 2010; Jepsen et al. 2011; Saeedkia et al. 2005; Tonouchi 2007; Williams 2005). A little number of materials in nature can interact with Terahertz waves. Due to the lack of efficient Terahertz sources and detectors, working with Terahertz waves is still an enormous challenge (Ma et al. 2011). By changing the size of the metamaterial structure they can easily respond to Terahertz waves. These structures have the limitation that when they are designed they can act only in a single frequency.

Most of the absorbers have the limitation that they only can work at a single band to multi-band. Also, they have limitations in the frequency range. Broadband absorption has been the approach of different attempts in the last decade. Some works are fabricated or designed to reach broadband absorption in the visible (Dorche et al. 2016; Ghobadi et al. 2017; Hubarevich et al. 2015), near-infrared (Chen et al. 2011; Ding et al. 2016), mid-infrared (Arik et al. 2016; Cui et al. 2012; Feng et al. 2012; Guo et al. 2016), and Terahertz (Arik et al. 2017; Chen et al. 2017; Khavasi 2015; Zang et al. 2015; Liu et al. 2020) ranges. The tendency is towards designing structures with the ability of tunability so this requires new materials.

Graphene is a 2D nanomaterial, which consists of a single layer of carbon atoms that are arranged in a hexagonal lattice (Wang et al. 2018). It has been applied in different optoelectronic applications due to its excellent properties such as optical transparency, flexibility (Andryieuski and Lavrinenko 2013), and ultrahigh carrier mobility (Bolotin et al. 2008). Its carrier mobility and conductivity can be tuned by applying an external electric field (Zhao et al. 2017; Wang et al. 2020; Zhou et al. 2021; You et al. 2021) or chemical doping (Vakil and Engheta 2011) in the range of infrared to terahertz. This property caused graphene to be the most important candidate in perfect absorbers.

In this study, we propose a broadband metamaterial terahertz absorber in the range of (5.86 THz to 7.57 THz), (5.89 THz to 7.56 THz), (5.89 THz to 7.58 THz), and (7.47 THz to 9.87 THz). This structure consists of 7 sets of disks with different radii located on a lossless dielectric thin layer and a metal film at the bottom.

2 Structure and design

The proposed structure is demonstrated in Fig. 1. The absorber has three layers. The first layer consists of a single layer of graphene disks (superimposed Graphene Q Ds) in 7 sets. The middle layer is Silicon Dioxide with a permittivity of 3.9. The thickness of the middle layer is 3.9 µm. The length of this layer is 29.4 µm and the width of this layer is 4.2 µm. We considered gold at the bottom layer which its electric conductivity \( \sigma_{\text{gold}} = 4.56 \times 10^{7} \text{s/m} \). The thickness of this layer is 0.2 µm. The length of the gold layer is equal to 29.4 µm and the width is 4.2 µm. Each set of graphene disks has a specified radius. It means that in the first set of disks, the radius is equal to 400 nm, in the second set, the radius is equal to 430 nm, in the third 461 nm, in the fourth 493 nm, in the fifth 525 nm, in the sixth 556 nm, and in the seventh set, the radius of disks is equal to 586 nm. Our proposed structure consists of 7 unit cells with a length of 4.2 µm and a width of 4.2 µm. These unit cells are beside each other. In every set of graphene disks, one disk is in the middle of the unit cell, and the other four disks are on the diagonals.
Regarding the Kubo formula, the surface conductivity of graphene consists of interband and intraband contributions (Hanson 2008a; Morozov et al. 2008),

$$\sigma_S = \sigma_S^{\text{intra}} + \sigma_S^{\text{inter}}$$

(1)

$$\sigma_S^{\text{intra}} = \frac{2k_BT e^2}{\pi \hbar^2} \ln \left( 2 \cosh \frac{E_F}{2k_BT} \right) \frac{i}{\omega + i\tau^{-1}}$$

(2)

$$\sigma_S^{\text{inter}} = \frac{e^2}{4\hbar} \left[ H\left(\frac{\omega}{2}\right) + i\frac{4\omega}{\pi} \int_0^\infty \frac{H(\Omega) - H\left(\frac{\omega}{2}\right)}{\omega^2 - 4\Omega^2} d\Omega \right]$$

(3)

where $H(\Omega) = \sinh \left( \frac{\hbar \Omega}{k_BT} \right) \left[ \cosh \left( \frac{\hbar \Omega}{k_BT} \right) + \cosh \left( \frac{E_F}{k_BT} \right) \right]$, $T$ is the temperature, $E_F$ is electrochemical potential (Fermi energy), $\omega$ is the frequency of the electromagnetic wave and $\tau$ is relaxation time and $e$ is the charge of an electron. In the THz range, because of photon energy $\hbar \omega \ll E_F$, so we can neglect the interband part in comparison with the intraband part. As a result, the surface conductivity of graphene in the THz range can be described by the Drude model (Hanson 2008b):

$$\sigma_g(\omega) = \frac{e^2E_f}{\pi \hbar^2} \frac{i}{\omega + i\tau^{-1}}$$

(4)

At a specified $E_f$, graphene conductivity changes by changing frequency. Whereas the imaginary part of the graphene conductivity determines resonance spectral shift and the real part of graphene conductivity determines resonance amplitude modulation, by applying an external electric field or using an optical pump we can tune the absorption by controlling the Fermi level.

The proposed structure is illuminated by the TE wave in which propagation direction is along the z-direction. CST Microwave Studio commercial software was used in this study to carry out numerical simulations. Unit cell boundary conditions were applied in x and y directions. The open space boundary conditions were used in the z-direction. Absorption can be calculated using $A(\omega) = 1 - |S_{11}|^2 - |S_{21}|^2$, where $S_{11}$ and $S_{21}$ are reflection and
transmission coefficients respectively. These parameters can be acquired from CST simulation results. Since the thickness of the bottom metallic layer is thicker than the skin depth at frequencies that we carry out our study, approximately no electromagnetic wave penetrates the structure. So we can suppose $S_{21} = 0$, then $A(\omega) = 1 - |S_{11}|^2$.

3 Results and discussion

The goal of this research is to design a broadband THz detector. To this end, first of all, we must find a unit cell structure with maximum absorption, then placing these unit cells beside each other in the horizontal direction we expect to design a structure with broadband detection. We have used the TE wave to study the proposed absorber. We have supposed Fermi energy of graphene as $E_f = 0.6\text{eV}$ and relaxation time as $\tau = 0.5\text{ps}$. To approach the best result, we should find the unit cell structure with maximum absorption. Then, placing these unit cells beside each other, we want to discover the structure with broadband absorption. According to (Wang et al. 2018), we have considered a unit cell with three layers. The bottom layer consists of gold with a height of 200 nm, the middle layer is SiO$_2$ with a height of 3900 nm, and the top layer is composed of 5 disks of single-layer graphene, as shown in Fig. 2.

The results of graphene disk radius sweep from 300 to 700 nm are demonstrated in Fig. 3.

In Fig. 3 maximum absorption is occurred with radius = 350 nm, at the frequency of 11.25 THz with an absorption value of 99.96%. The results for gold layer height sweep from 40 to 320 nm with a step of 40 nm are shown in Fig. 4.

Figure 4 shows that sweeping gold layer height, absorption values are near to each other. In 40 nm, 80 nm, 120 nm, 160 nm, 200 nm, 240 nm, 280 nm, and 320 nm max absorption are 0.999912, 0.999518, 0.999715, 0.999834, 0.999881, 0.999949, 0.999798, 0.999728 respectively. So we choose 240 nm as the height of the gold layer because it has a max
absorption value. Figure 5 demonstrates the results of the height sweep of the SiO₂ layer from 300 to 4500 nm with a step of 300 nm.

According to the above figure, when the height of SiO₂ layer = 3900 nm, maximum absorption occurs with the value of 99.99% when the frequency is 11.25 THz. The following figure depicts the sweeping result of the dimension of the unit cell from 600 to 5400 nm.
In Fig. 6 the maximum absorption value is 99.94% in the frequency of 8.34THz with the dimension of unit cell = 3600 nm. Figure 7 shows the results of sweeping the dimension of the unit cell from 700 to 5600 nm.

In the above figure, the maximum absorption value is 99.96% in the frequency of 10.96THz with the dimension of unit cell = 2100 nm. The following figure demonstrates the results for the unit cell dimension sweep from 800 to 5600 nm (Fig. 8).

The maximum absorption value is 99.95% in the frequency of 7.89THz with the dimension of unit cell = 4000 nm. We have located one of five graphene disks in (0,0) and placed the other four disks in (x,y), (x,-y), (-x,y), (-x,-y). We considered x = y. Figure 9 denotes the results for the sweep of x and y from 500 to 1750 nm.

Maximum absorption value is 99.99% when (x,y) = (1050,1050). Due to above sweeps, maximum absorption with the value of 99.99% occurs when the dimension...
of unit cell = 2100 nm, gold layer height = 240 nm, SiO₂ layer height = 3900 nm, location of five graphene disks are (−1050,−1050), (-1050,1050), (0,0), (1050, −1050), (1050,1050).

As previously mentioned, we have designed a structure with maximum absorption. Then we should place these structures beside each other, and find a structure with broadband absorption, so we place three unit cells beside each other to find the structure with broadband THz detection, as shown in Fig. 10.

We have assumed the radii of disks in the first unit cell as 350, in the second unit cell as 370, and the third unit cell as 390. We have allocated different materials for the middle layer in Fig. 10. We have considered dielectric constant = 3.1, 3.3, 3.5, 3.7, 3.9, 7.5 respectively for Rubber, Zircon, Polyimide, Quartz, SiO₂, and Si₃N₄. The result is depicted in Fig. 11.

We have assumed the radii of disks in the first unit cell as 350, in the second unit cell as 375, and the third unit cell as 400. We have allocated different materials for the middle layer in Fig. 10. We have considered dielectric constant = 3.1, 3.3, 3.5, 3.7, 3.9, 7.5

![Fig. 10](image1.png)  Placing 3 unit cells beside each other

![Fig. 11](image2.png)  Radii of graphene disks in first unit cell = 350 nm, second = 370 nm, and third = 390 nm with middle layer dielectric constant = 3.1 (Rubber), 3.3 (Zircon), 3.5 (Polyimide), 3.7 (Quartz), 3.9 (SiO₂), and 7.5 (Si₃N₄)

![Fig. 12](image3.png)  Radii of graphene disks in first unit cell = 350 nm, second = 375 nm, and third = 400 nm with middle layer dielectric constant = 3.1 (Rubber), 3.3 (Zircon), 3.5 (Polyimide), 3.7 (Quartz), 3.9 (SiO₂), and 7.5 (Si₃N₄)
respectively for Rubber, Zircon, Polyimide, Quartz, SiO\textsubscript{2}, and Si\textsubscript{3}N\textsubscript{4}. The result is demonstrated in Fig. 12.

We have assumed the radii of disks in the first unit cell as 350, in the second unit cell as 380, and the third unit cell as 410. We have allocated different materials for the middle layer in Fig. 10. We have considered dielectric constant = 3.1, 3.3, 3.5, 3.7, 3.9, 7.5 respectively for Rubber, Zircon, Polyimide, Quartz, SiO\textsubscript{2}, and Si\textsubscript{3}N\textsubscript{4}. The result is demonstrated in Fig. 13.

According to Figs. 11, 12, 13, we can see that placing 3 unit cells beside each other has not satisfied us in approaching a broadband THz detector. So we decide to place 5 unit cells beside each other and improve the results, see Fig. 14.

In Fig. 14 we assumed radii of disks in the first unit cell as 350, in the second unit cell as 370 and the third unit cell as 390, in the fourth unit cell as 410, and finally in the fifth unit cell as 430. Also, we have considered different materials for the middle layer. The dedicated dielectric constants are as following: 3.1, 3.3, 3.5, 3.7, 3.9, 7.5 respectively, for Rubber, Zircon, Polyimide, Quartz, SiO\textsubscript{2}, and Si\textsubscript{3}N\textsubscript{4}. The results are visualized in Fig. 15.

We assumed the radii of disks in the first unit cell as 350, in the second unit cell as 375 and the third unit cell as 400, in the fourth unit cell as 425, and finally in the fifth
unit cell as 450. Also, we have considered different materials for the middle layer in Fig. 14. The results are depicted in Fig. 16.

We assumed the radii of disks in the first unit cell as 350, in the second unit cell as 380 and the third unit cell as 410, the fourth unit cell as 440, and finally in the fifth unit cell as 470. Also, we have considered different materials for the middle layer in Fig. 14. The results are depicted in Fig. 17.

Referring to Fig. 17 we can conclude that continuing the process of placing unit cells beside each other will improve the output waveform to achieve broadband detection, so we put 7 unit cells beside each other and continue the simulation process, as shown in Fig. 18.

In Fig. 18 we assumed radii of disks in the first unit cell as 350, in the second unit cell as 370 and the third unit cell as 390, in the fourth unit cell as 410, in the fifth unit cell as 430, in the sixth unit cell 450, and finally in the seventh unit cell as 470. Also, we have considered different materials for the middle layer. The results are demonstrated in Fig. 19.

We assumed radii of disks in the first unit cell as 350, in the second unit cell as 375, and the third unit cell as 400, in the fourth unit cell as 425, in the fifth unit cell as 450, in the sixth unit cell 475, and finally in the seventh unit cell as 500. Also, we have considered different materials for the middle layer in Fig. 18. The results are demonstrated in Fig. 20.
We assumed the radii of disks in the first unit cell as 350, in the second unit cell as 380, in the third unit cell as 410, in the fourth unit cell as 440, in the fifth unit cell as 470, in the sixth unit cell 500, and finally in the seventh unit cell as 530. Also, we have considered different materials for the middle layer in Fig. 18. The results are demonstrated in Fig. 21.

According to Figs. 19, 20, 21, and 22, we can see that using SiO$_2$ or Si$_3$N$_4$ as dielectric material can result in broadband absorption. So, to improve the results, we assign the dielectric material as SiO$_2$ or Si$_3$N$_4$, and we sweep the radius of each set of disks (Quantum Dots). The mathematical relations between radii of 5 graphene disks in 7 unit cells are
Table 1  The mathematical relation between radii of 5 graphene disks in 7 unit cells that are placed beside each other in Fig. 23

| Unit cell   | Radius (nm) | Added amount to the previous unit cell radius |
|-------------|-------------|---------------------------------------------|
| 1st unit cell | 350         | 0                                           |
| 2nd unit cell | 380         | 30                                          |
| 3rd unit cell | 411         | 31                                          |
| 4th unit cell | 443         | 32                                          |
| 5th unit cell | 475         | 32                                          |
| 6th unit cell | 506         | 31                                          |
| 7th unit cell | 536         | 30                                          |

Figure 23  Radii of graphene disks in first unit cell = 350 nm, second = 380 nm, third = 411 nm, fourth = 443 nm, fifth = 475 nm, sixth = 506 nm and seventh = 536 nm with middle layer dielectric constant = 7.5 (Si₃N₄)

given in Table 1 to Table 7. The simulation results corresponding to each table are depicted in Figs. 23, 24, 25, 26, 27, 28, 29 and 30, respectively.

Figure 23 illustrates the simulation results corresponding to Table 1.
Figure 24 illustrates the simulation results corresponding to Table 2.
Figure 25 illustrates the simulation results corresponding to Table 3.
Figure 26 illustrates the simulation results corresponding to Table 4.
Figure 27 illustrates the simulation results corresponding to Table 5.
Figure 28 illustrates the simulation results corresponding to Table 6.
Figure 29 illustrates the simulation results corresponding to Table 7.
Figure 30 illustrates the simulation results corresponding to Table 8.

Comparing Figs. 23, 24, 25, 26, 27, 28, 29 and 30, broadband absorption occurs in 4 figures. Figure 27 reveals broadband absorption in the range of (5.86THz to 7.57THz). In this condition, the maximum absorption value is 97.1% in the frequency of 6.91THz, and
**Fig. 24** Radii of graphene disks in first unit cell = 350 nm, second = 380 nm, third = 412 nm, fourth = 446 nm, fifth = 480 nm, sixth = 512 and seventh = 542 with middle layer dielectric constant = 7.5 (Si$_3$N$_4$)

**Fig. 25** Radii of graphene disks in first unit cell = 350 nm, second = 381 nm, third = 412 nm, fourth = 443 nm, fifth = 474 nm, sixth = 505 and seventh = 536 with middle layer dielectric constant = 7.5 (Si$_3$N$_4$)

**Fig. 26** Radii of graphene disks in first unit cell = 400 nm, second = 430 nm, third = 461 nm, fourth = 493 nm, fifth = 525 nm, sixth = 556 and seventh = 586 with middle layer dielectric constant = 7.5 (Si$_3$N$_4$)

**Fig. 27** Radii of graphene disks in first unit cell = 400 nm, second = 431 nm, third = 463 nm, fourth = 496 nm, fifth = 529 nm, sixth = 561 and seventh = 592 with middle layer dielectric constant = 7.5 (Si$_3$N$_4$)
Fig. 28 Radii of graphene disks in first unit cell = 400 nm, second = 431 nm, third = 463 nm, fourth = 495 nm, fifth = 527 nm, sixth = 559 and seventh = 590 with middle layer dielectric constant = 7.5 (Si₃N₄)

![Absorption vs Frequency (THz)](image)

Fig. 29 Radii of graphene disks in first unit cell = 400 nm, second = 431 nm, third = 463 nm, fourth = 495 nm, fifth = 526 nm, sixth = 558 and seventh = 590 with middle layer dielectric constant = 7.5 (Si₃N₄)

![Absorption vs Frequency (THz)](image)

Fig. 30 Radii of graphene disks in first unit cell = 400 nm, second = 430 nm, third = 461 nm, fourth = 493 nm, fifth = 525 nm, sixth = 556 and seventh = 586 with middle layer dielectric constant = 3.9 (SiO₂)

![Absorption vs Frequency (THz)](image)

Table 2 The mathematical relation between radii of 5 graphene disks in 7 unit cells that are placed beside each other in Fig. 24

| Unit cell   | Radius (nm) | Added amount to the previous unit cell radius |
|-------------|-------------|----------------------------------------------|
| 1st unit cell | 350         | 0                                            |
| 2nd unit cell | 380         | 30                                           |
| 3rd unit cell | 412         | 32                                           |
| 4th unit cell | 446         | 34                                           |
| 5th unit cell | 480         | 34                                           |
| 6th unit cell | 512         | 32                                           |
| 7th unit cell | 542         | 30                                           |
Table 3  The mathematical relation between radii of 5 graphene disks in 7 unit cells that are placed beside each other in Fig. 25

| Unit cell    | Radius (nm) | Added amount to the previous unit cell radius |
|--------------|-------------|---------------------------------------------|
| 1st unit cell| 350         | 0                                           |
| 2nd unit cell| 381         | 31                                          |
| 3rd unit cell| 412         | 31                                          |
| 4th unit cell| 443         | 31                                          |
| 5th unit cell| 474         | 31                                          |
| 6th unit cell| 505         | 31                                          |
| 7th unit cell| 536         | 31                                          |

Table 4  The mathematical relation between radii of 5 graphene disks in 7 unit cells that are placed beside each other in Fig. 26

| Unit cell    | Radius (nm) | Added amount to the previous unit cell radius |
|--------------|-------------|---------------------------------------------|
| 1st unit cell| 400         | 0                                           |
| 2nd unit cell| 430         | 30                                          |
| 3rd unit cell| 461         | 31                                          |
| 4th unit cell| 493         | 32                                          |
| 5th unit cell| 525         | 32                                          |
| 6th unit cell| 556         | 31                                          |
| 7th unit cell| 586         | 30                                          |

Table 5  The mathematical relation between radii of 5 graphene disks in 7 unit cells that are placed beside each other in Fig. 27

| Unit cell    | Radius (nm) | Added amount to the previous unit cell radius |
|--------------|-------------|---------------------------------------------|
| 1st unit cell| 400         | 0                                           |
| 2nd unit cell| 431         | 31                                          |
| 3rd unit cell| 463         | 32                                          |
| 4th unit cell| 496         | 33                                          |
| 5th unit cell| 529         | 33                                          |
| 6th unit cell| 561         | 32                                          |
| 7th unit cell| 592         | 31                                          |

Table 6  The mathematical relation between radii of 5 graphene disks in 7 unit cells that are placed beside each other in Fig. 28

| Unit cell    | Radius (nm) | Added amount to the previous unit cell radius |
|--------------|-------------|---------------------------------------------|
| 1st unit cell| 400         | 0                                           |
| 2nd unit cell| 431         | 31                                          |
| 3rd unit cell| 463         | 32                                          |
| 4th unit cell| 495         | 32                                          |
| 5th unit cell| 527         | 32                                          |
| 6th unit cell| 559         | 32                                          |
| 7th unit cell| 590         | 31                                          |
absorption values are above 89% in this range. In Fig. 28, broadband absorption occurs in the range of (5.89THz to 7.56THz). In this range, the max absorption value is 97.3% in the frequency of 7.24THz, and absorption values are above 88.49%. Figure 29 denotes broadband absorption (5.89THz to 7.58THz) while the max absorption value is 96.91% in the frequency of 6.96THz. In this range, absorption values are above 88.32%. In Figs. 27, 28, and 29, the dielectric material is Si$_3$N$_4$. Finally, Fig. 30 demonstrates broadband absorption in the range of (7.47THz to 9.87THz) with an absorption value above 80%, while the dielectric material is SiO$_2$. Max absorption value is 94.46% in the frequency of 6.52THz in this range.

### 4 Conclusion

In summary, a broadband graphene-based metamaterial absorber was designed and investigated. The structure consists of graphene disks at the top layer, the dielectric material in the middle layer, and a gold layer at the bottom. Simulation results reveal broadband absorption in the range of (5.86THz to 7.57THz) while max absorption value is 97.1% in the frequency of 6.91THz, in the range of (5.89THz to 7.56THz) while max absorption value is 97.3% in the frequency of 7.24THz and the range of (5.89THz to 7.58THz) while max absorption value is 96.91% in the frequency of 6.96THz. Absorption values respectively are above 89%, 88.49%, and 88.32% in the above-mentioned ranges and the middle dielectric material is Si$_3$N$_4$. The broadband absorption range is 7.47THz to 9.87THz with an absorption value above 80% while the dielectric material is SiO$_2$. Max absorption value is 94.46% in the frequency of 6.52THz in this range.
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