Enhancing Tunability of EIT in Plasmonic Split Disk Resonator Using Graphene and Fused Silica

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Abstract

Terahertz (THz) wave technology has attracted a significant number of researchers; however, it requires fundamental research and development compared with near-infrared and microwaves. The big challenge in terahertz technology is to find the material that provides a powerful response. The terahertz wave absorption has inspired researchers for the further research in this area, due to its many applications in various sciences such as material identification, medicine, and security. The present discussion is mainly about the general overview of electromagnetically induced transparency (EIT), metamaterial, tunable band-pass filter, graphene, nano, fused silica, and alumina oxide.

In fact, we designed and simulated a graphene-based band-pass filter with a tunable cut-off wavelength in which an intermediate layer is first filled with fused silica and then with alumina oxide along with graphene disks. The results were obtained to improve filter function and response at the terahertz frequency as well as short wavelengths at a numerical range of 1.55 μm in a highly sensitive and accurate range for both modes. And optimal results were obtained to improve filter performance as well as filter response at the mentioned range. Then, in the first case, for the innovation in the use of graphene disks and fused silica, the precision is 1.54 to 1.58 μm. In the second innovation with graphene disks and alumina oxide, the numerical range is for a wavelength of 1.52 to 1.72 μm. Therefore, in the present study, by changing the chemical potential of graphene even after the completion of the desired design, the cut-off wavelength, and eventually, the tunable EIT were obtained in the band-pass filter.

Keywords Metamaterial · Filter · Graphene · Electromagnetically induced transparency · High-frequency wave length · Nano

Introduction

In recent years, terahertz technology has been highly regarded for its unique capabilities and applications in science and technology. Today, due to the remarkable advances in optics and quantum mechanics, optical properties of matter can be modified using laser light. One of these is the phenomenon of EIT, which is a quantum phenomenon that occurs due to the interference of two different coherent laser lights while passing through an atomic environment, resulting in the suppression of absorption and thus, the creation of transparency in the opaque environment, as well as the reduction of group velocity. In this paper, the metamaterial structure has been investigated due to the destructive interference between the slit ring resonator and the graphene ribbon resonator of the EIT. The

ability to perform EIT in semiconductors in today's world will be nothing but very beneficial. In addition, coherence will cause significant changes in the optical properties of the environment. Graphene is a carbon sheet with a honeycomb structure. It has very interesting electronic and mechanical properties, including the high speed of electrons. Hence, in the electronics industry, graphene can be used as a substitute for silicon. Graphene has nonlinear optical properties, which means that the output rays are more intense than the input rays in this material, which can be manipulated to build telecommunication devices and lasers and create transparency.

The terahertz wave lies between the microwave and infrared in the electromagnetic spectrum. In recent years, terahertz technology has attracted considerable attention, due to various applications in the field of biotechnology, spectroscopy, imaging, etc. Terahertz waves offer wider bandwidth compared with microwave waves. The resonance is the tendency of the system to fluctuate with the maximum amplitude at specific frequencies, which is referred to as resonance frequency. At such frequencies, vibrational energy is stored in the object, and as a result, the small and alternative force can cause

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oscillation with larger amplitude. When the valence electrons oscillate with each other, carrying same frequency of the light used to excite them, resonance occurs [16]. Graphene is one of the carbon derivatives referred to as an extraordinary element, due to its simple structure, which consists of regular array of carbon atoms in the form of a honeycomb, with unique and significant properties whose single feature can create a massive revolution in various fields of science and industry. Graphene is one of the carbon allotropes.

The graphene electrical conductivity for the terahertz range encompasses inter-band as well as intra-band interactions; however, the intra-band interactions have a dominant contribution. With these in mind, the first part of the Kubo formula will prevail for graphene conductivity within the terahertz range, which is related to intrinsic intra-band interactions. The electrical conductivity of graphene is estimated using the Kubo formula, which is written in the absence of an electric field. Today, the EIT is more commonly used in metamaterials because by changing the geometry of the system and the polarization of light, one can simply control the electrical conductivity of graphene and there is no need to use two different lasers and the classical mode of the system is still valid.

The mechanism of this phenomenon is based on the destructive interference between atomic coherence created by laser fields, which makes the atomic environment transparent for the poor field of view. One of the important effects of EIT is the reduction of group velocity, leading to the creation of light in the environment. EIT is a quantum mechanic phenomenon that occurs due to the coherent interaction of two different laser lights while passing through the environment, resulting in the suppression of adsorption and eventually creating transparency in the environment that was opaque before.

The main purpose of this study is to design and simulate tunable band-pass filters with high and low cut-off wavelengths based on graphene disks using fused silica materials and graphene disks. In the second design, we use graphene disks and alumina oxide to study tunability at the significant wavelength of 1.55 μm. In conjunction with the use of two resonators in the metamaterial structure, a destructive interference between the two resonators has led to the creation of a phenomenon known as EIT. One of the significant advantages of both proposed designs is the possibility of changing and adjusting the high and low cut-off wavelengths even after the construction of the metamaterial by changing the numerical value of the chemical potential in the graphene disks [1, 2]

The present article contains several sections which are discussed below. In the "Introduction" section, we described a method used to tackle the problem discussed and compared them with the articles published in this field.

In the next section, the review and verification of the reference article have been discussed. Further, the proposed approach and various aspects of this approach are presented.

Finally, the results of the proposed method, discussion, and analysis are presented in the "Result and Discussions" section.

Verification

In the proposed method, the design and simulation of EIT in hybrid systems with a graphene-based metamaterial structure have been investigated. In this method, we study and simulate a hybrid system with a coherent quantum metamaterial structure consisting of graphene strip as a bright resonator tunable with a change in the chemical potential along with the dielectric ring resonator as the quasi-dark element TiO_2 and substrates of Si and SiO_2 in the frequency range of 18 to 23 THz, which overlaps the spectrum of these two resonators and leads to the formation of an EIT by causing a destructive interference between these two resonators [3–5, 13–17].

This structure consists of a bright element that interacts directly with the incident light, which is called bright mode, and also includes a quasi-dark element that indirectly interacts with the incident light [10, 11, 18 and 19]. The combination of these two dark and bright modes is a destructive interference creating a transparent hole similar to that of EIT in atomic systems. In fact, in the proposed design in this paper, the resonance frequency consists of two bright and quasi-dark unequal modes that are somewhat overlapping within their spectrum. Therefore, EIT's effect is obtained by using a coupling between bright and quasi-dark resonance, which provides a new method for the construction of the EIT metamaterials [20–23].

Maxwell's defined equations are available in CST microwave studio software for single-cell analysis in the frequency domain under defined boundary conditions.

The geometric parameters of the unit cell shown in Fig. 1 are designed as $L = 5$ μm, $W = 1.4$ μm, $W1 = 0.5$, $A = 8$, $S = 0.8$ μm. In the simulation of the graphene strip, a thin film has been used (Figs. 2, 3).

The electric field on the graphene strip and DSRR [20–23] has a very strong coupling. Typically, after the completion of metamaterial construction, the change in the EIT window is not possible, but, in this structure, using the graphene strip and changing the numerical value of the chemical potential of induced transparency, can be tuned which is one of the most important advantages of using graphene strip in the construction of a dielectric metamaterial.

There is a graphene strip with a length of 8 μm and a width of 1.4 μm ranging from − 0.7 to + 0.7 μm, and for a titanium dioxide slit ring resonator, a square with a length of 0.5 μm and a thickness of 0.2 μm with a slit of 0.8 μm created on the right side. A slit is used to adjust the frequency, which has an inherent loss of 0.01. The thickness of graphene can be considered 0.2 due to the graphene two-dimensional structure, since the surface area-to-volume ratio in graphene is very

Fig. 1 (a) Unit cell of EIT hybrid structure (front side). (b) Periodical array of EIT hybrid structure (back side). (c) Three-dimensional sketch of EIT hybrid structure [3]
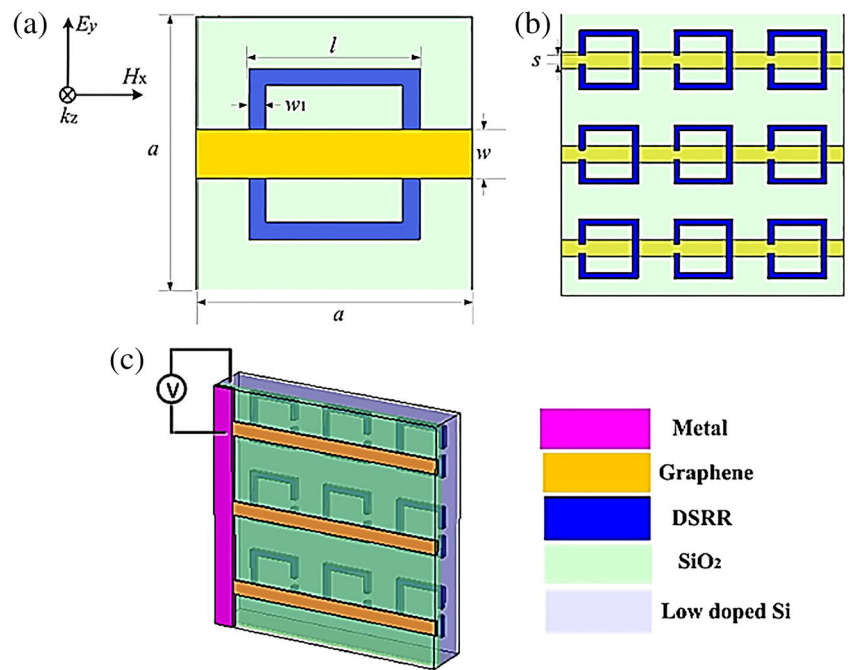
large, and in fact, it is possible to neglect specifying a numerical value for graphene, but the thickness is usually considered to be 1 nm. In the SiO_2 layer, on both sides of the silicon substrate, the length is 8 nm and the thickness is 0.8 μm. For the intermediate layer Si, the length is 8 μm, the width is considered to be 8 μm, and the thickness is 0.3 μm.

In this simulation, there are two upper and lower bounds shown as Z_{max} and Z_{min} and represented by the input and output ports in which the upper port (Z_{max}) apply the radiation and the bottom port (Z_{min}) measures the output value [3]. The unit cell configuration and simulation results for the article are as follows:

In the verification, two states have been considered. At first, only the graphene strip resonator is active while the TiO_2 dielectric resonator is inactive; in the latter case, it is totally reversed and the graphene strip resonator is inactive while the TiO_2 resonator is activated, the output resulted from these two modes are as follows:

When both resonators are active in the unit cell, an EIT phenomenon is created due to the destructive interference created between this graphene ribbon and the split ring resonator, which results in the curves given in Figs. 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16 [3].

Proposed Method

In the proposed design, the purpose is to design and simulate a tunable band-pass filter with the low and the high cut-off wavelengths through changing the chemical potential of the graphene disks. Graphene is the thinnest transparent material

in the world, which absorbs white light independently of its wavelength. Graphene is a two-dimensional, metallic sheet with a large surface area-to-volume ratio in the hexagonal configuration of its carbon atoms. Each carbon atom has a covalent bond with three other carbon atoms, a strong bond with the angles equal to 120° between these bonds, creating a regular hexagonal lattice with a bond length of 0.142 nm. The graphene layers are held together by a van der Waals bond, which is a weaker bond compared with that of a covalent one, which causes layers of the graphene slip on each other. The distance between planes is 0.35 nm. Graphene's stability is due to its tightly packed carbon atoms and a sp2 orbital hybridization, a combination of orbitals s, Px, and Py that constitute the σ-bond. Graphene is composed of a hexagonal carbon-atom pattern juxtaposed and densely packed on a plane. Each carbon is in a bond with three other carbon atoms and the angles between these bonds are equal to 120°, arranged in a hexagonal lattice. The carbon–carbon bond length in graphene is about 0.142 nm.

The EIT, which is a quantum phenomenon as well as an optical process, results from the interference of the two different coherent laser light interactions while passing through an atomic environment, resulting in the suppression of absorption as well as creating transparency in an environment which was opaque before. Moreover, one of its crucial effects is the reduction of the group velocity.

Today, the EIT is more commonly used in metamaterials, as well as in some environments that do not normally pass through the specific wavelengths of the light. The EIT phenomenon is used to slow down optical pulses and store them in environments such as ultra-cold atomic clouds. Our
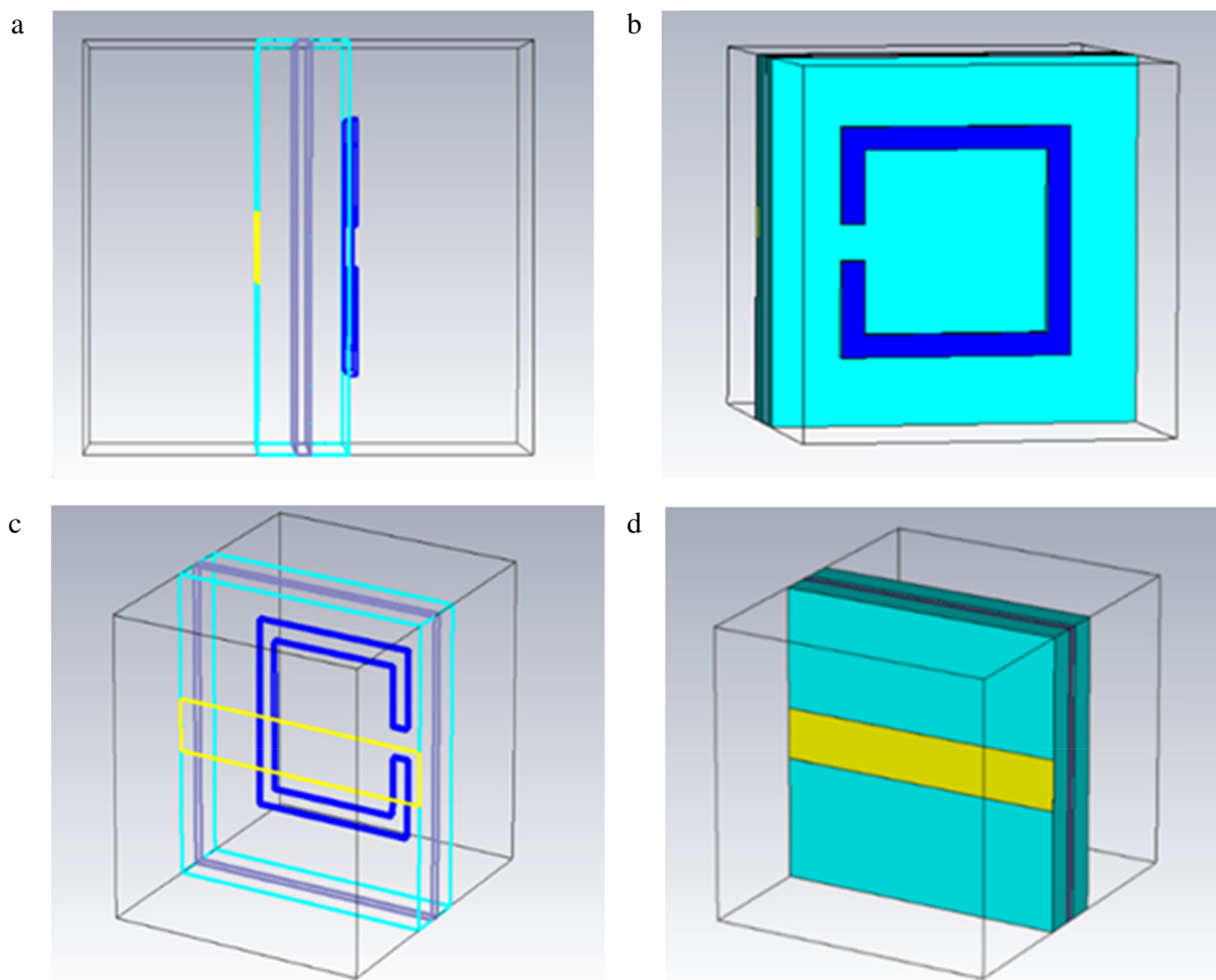
Fig. 2 (a) Structural view from Z_{min} point of view (DSRR layer). (b) Tilted view of the structure. (c) View of structure from Z_{max} point of view (graphene strip layer). (d) View of all layers of the layout [3]

designed band-pass filter in this paper just passes a specific group of wavelengths and blocks the rest.

In this paper, we first studied the metamaterials, terahertz waves, EIT, types of interferences, graphene, and all kinds of filters. The purpose of the reference conveyor design was to study the EIT in the hybrid structure of the metamaterial using a bright resonator of graphene strip and circular dielectric slit ring resonator called DSRR made of TiO$_2$, which is resulted from a destructive interference between these two resonators, leading to the phenomenon of EIT. This phenomenon gives transparency to this structure by changing the amount of Fermi energy of graphene strip even after its construction, and this is the main advantage of using the resonators in the metamaterial structures.

In novel designs, an intermediate layer of fused silica, a silicon derivative, and a ceramic dielectric layer, along with graphene disks on both sides of the structure were studied and simulated in the CST microwave studio. By changing and

adjusting the value of the Fermi energy variables in the graphene disks, the band-pass filter with high and low cut-off wavelengths at 1.55 μm ranging from 1.54 to 1.57 μm was obtained.

In the second innovative design, using an intermediate layer of alumina oxide, along with graphene disks embedded on both sides of the middle layer, the tunable band-pass filter has been achieved based on graphene disks with high and low cut-off wavelengths which can be adjusted to the significant tele-communication wavelength of 1.55 μm ranging from 1.25 to 1.75 μm.

Structure and Simulations

To simulate the unit cell designed in the periodic boundary conditions, a solution in the frequency domain is used. This article is presented investigating a short wavelength of
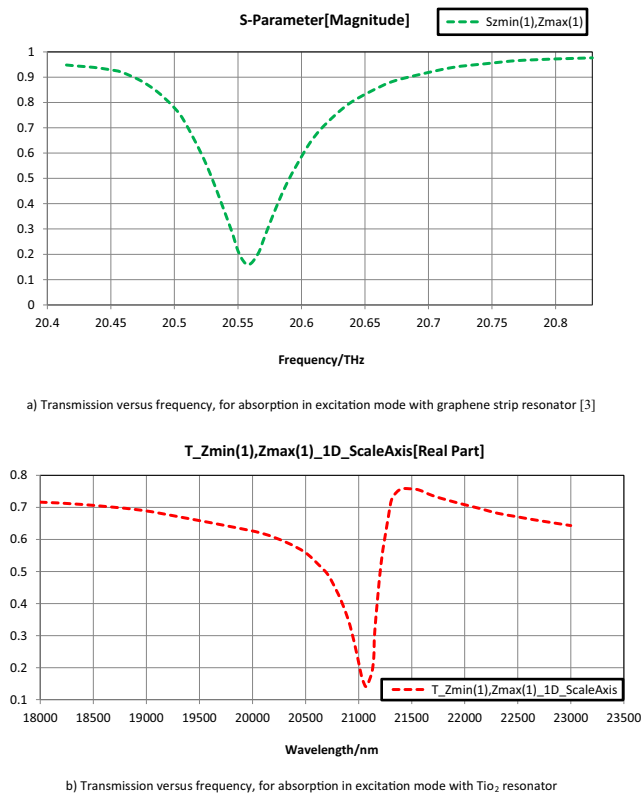
a) Transmission versus frequency, for absorption in excitation mode with graphene strip resonator [3]

b) Transmission versus frequency, for absorption in excitation mode with Tio₂ resonator

Fig. 3 (a) Transmission versus frequency, for absorption in excitation mode with the graphene strip resonator [3]. (b) Transmission versus frequency, for absorption in excitation mode with the TiO₂ resonato

1.55 μm and a high terahertz frequency with 193 THz for designing an adjustable band-pass filter. In the simulation software, the incident light beam used to excite the input port is upward (i.e., from the Z_{max} side). The proposed structure consists of three layers in which geometric parameters for the middle layer are made of fused silica with a thickness of 20 nm, length and width of 10 nm, and a refractive index of $n^2 = 1.458 \times 1.458 = 2.1276$. On both sides of this layer, two graphene disks with a radius of 3 nm were used to create resonance.
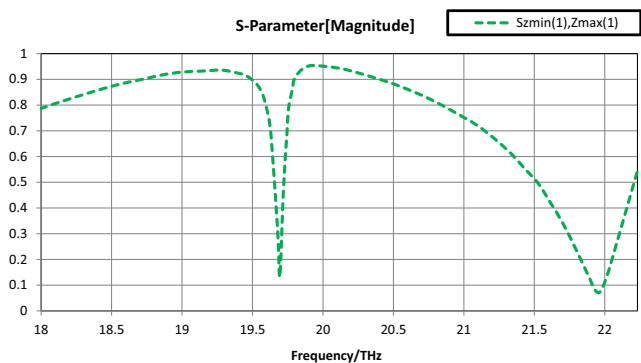

Fig. 4 Transmission versus frequency, excited with two resonators simultaneously [3]

$$\sigma_g = \sigma_{intra} + \sigma_{inter} \qquad \text{here } \sigma_{intra} \text{ and } \sigma_{inter} \tag{1}$$

For the top graphene disk, the ambient temperature, the chemical potential, and the thickness of the layer are 293 K, 1.27 eV, and 1 nm, respectively, with the relaxation time of 0.4 ps. Likewise, for the bottom graphene disk, the ambient temperature, the chemical potential, and the thickness of the layer are 293 K, 1.3 eV, and 1 nm, respectively, with the relaxation time of 0.4 ps. The conductivity level can be obtained from the following formula:

$$\sigma_S^{total} = \sigma_S^{intra} + \sigma_S^{inter} = \frac{2K_B}{\pi\hbar^2} \ln\left(2\cosh\frac{E_F}{2K_BT}\right) \frac{i}{\omega + i\tau^{-1}}$$
$$+ \frac{ie^2}{4\pi\hbar} \ln\left[\frac{|E_F| - (\omega + i2\tau^{-1})\hbar}{|E_F| - (\omega + i2\tau^{-1})\hbar}\right] \tag{2}$$

The graphene conductivity can be adjusted in several ways, including the voltage applied by the Kubo formula, and its thickness is usually considered to be 1 nm.

$$\sigma_g = \frac{e^2 E_F}{\pi\hbar} \frac{i}{\omega + i\tau^{-1}} \tag{3}$$

Here, the σ_{intra} is dominant and we will have graphene conductivity:

$$\mathcal{E} = 1 + \frac{j\sigma_g}{\mathcal{E}_0 \omega t} \tag{4}$$

where $\hbar$ is the Planck constant, e is the electron charge, τ is the relaxation time of the carrier, and E_F represents the level of Fermi energy of the graphene strip. The graphene permittivity is obtained as follow:.

$$\nabla \times H = J + \frac{\partial}{\partial t} D \tag{5}$$

In various materials, especially in metals, free electrons of conductive layer form the major part of conductivity, and this is why, only electrons of this layer are usually considered in the calculations of conductivity in the equations.

$$V(t) = V_0 \cdot e^{j\omega t} \tag{6}$$

If electromagnetic wave oscillations are considered in the positive direction of trigonometry, this means that each electromagnetic parameter can be written as follows:

$$\nabla \times H = j\omega\varepsilon_0 \left(\frac{\sigma}{j\omega\varepsilon_0} + 1\right) E = j\omega\varepsilon_0\varepsilon_{eff}E \tag{7}$$

In this case, with the single-frequency excitation, we can write the relation (1-1) in the frequency domain and replace
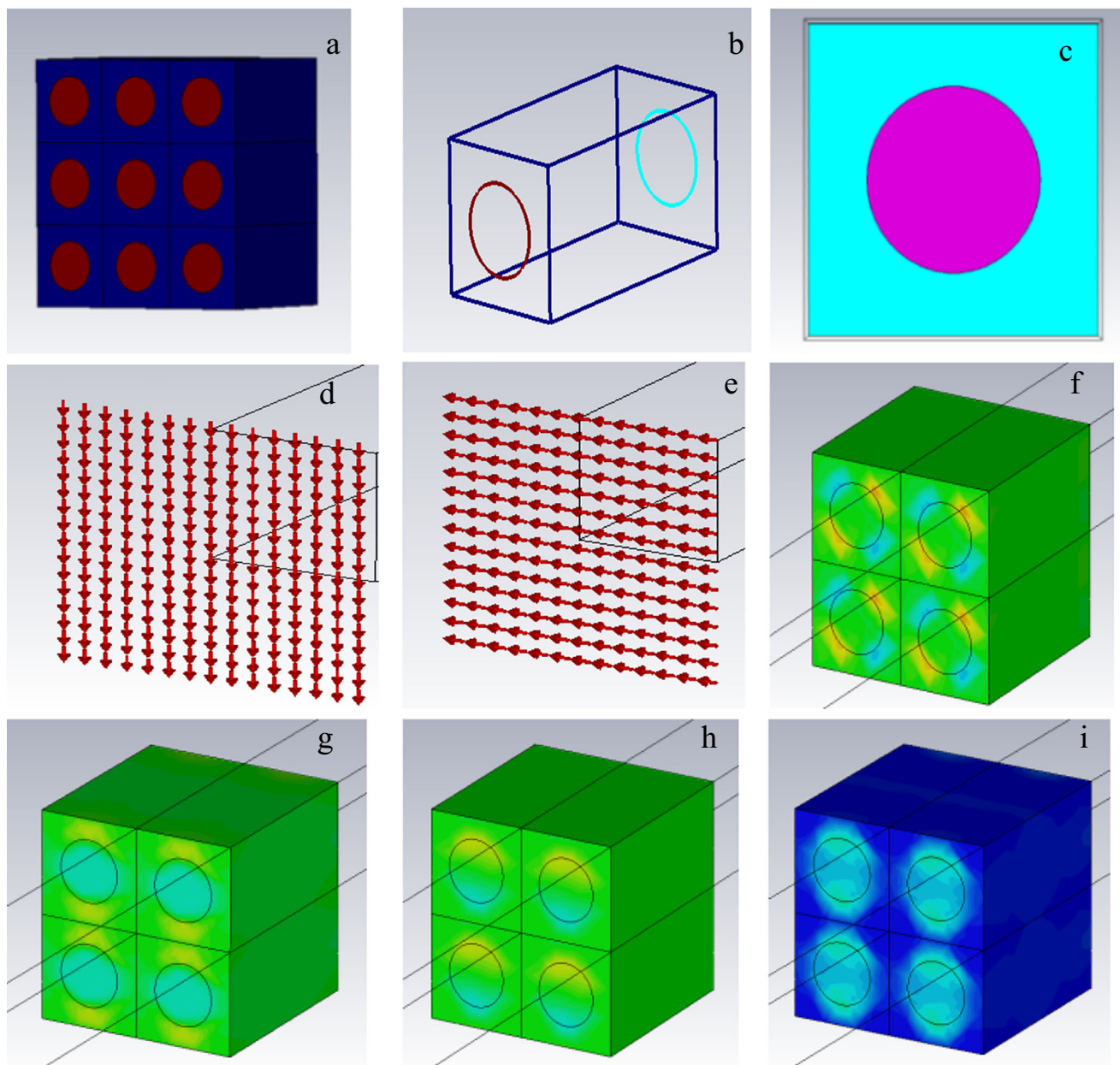
Fig. 5 (a) Top view of the structure under study. (b) 3D design structure created. (c) Unit cell structure. (d) H1 magnetic field on Z_{max} side. (e) E1 Electrical field on Z_{max} side. (f) Electrical field in X-direction. (g) Electrical field in Y-direction. (h) Absorption in Z_{max}. (i) Electrical field in Z-direction
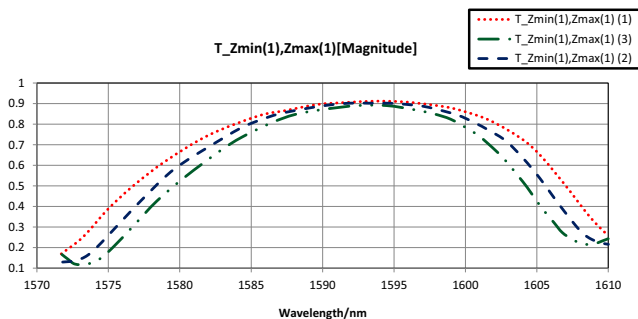

Fig. 6 Transmission versus wavelength with tunable lower and upper cut-off wavelengths

the time derivatives with its equivalent term in frequency domain (jω). On the other hand, according to the relation ($\sigma = J/E$), the conductivity is the ratio of the current density created to the electric field applied to the load carrier. Therefore, the relationship between the magnetic and electric fields will be as follows:

$$\sigma = j\omega \frac{|P|}{|E|} \qquad (8)$$

On the other hand, the relative permittivity coefficient is calculated from the polarization vector as follow:.

T...Graphene_ChemPotential=1.251
T...Graphene_ChemPotential=1.253
T...Graphene_ChemPotential=1.255
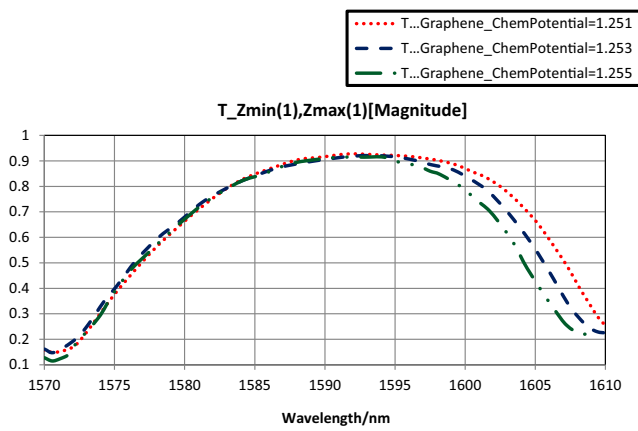
T_Zmin(1),Zmax(1)[Magnitude]

Fig. 7 Transmission versus wavelength with a tunable upper cut-off wavelength

Drude Model

This model is so similar to that of Lorentz Harmonic-Oscillator model. In this section, the free electron mobility equation is presented:

$$m_\varepsilon \frac{\partial^2 \mathrm{r}}{\partial \mathrm{t}^2} + \frac{m_\varepsilon}{\tau} \bullet \frac{\partial \mathrm{r}}{\partial \mathrm{t}} = -eE_0 \mathrm{e}^{\mathrm{j}\omega \mathrm{t}} \tag{9}$$

where $m_{(\varepsilon)}$ is the effective mass of electron, r is the displacement vector from the variance, τ depicts the electron inertia time, e is the charge of the electron, and $E_0 e^{\mathrm{j}\omega \mathrm{t}}$ is the external electric field. By solving the equation above in the frequency domain, electron displacement vector is obtained as the following

$$r = \frac{-eE_0}{\mathrm{j}\omega \frac{m_\varepsilon}{\tau} - m_\varepsilon \omega^2} e^{\mathrm{j}\omega \mathrm{t}} \tag{10}$$

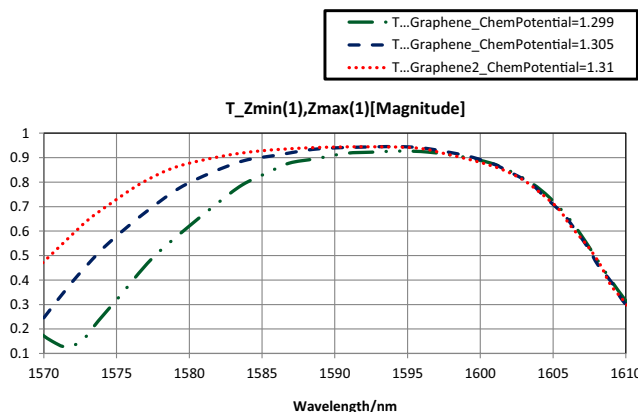At this stage, we can obtain the final polarization vector according to the following equation.

T...Graphene_ChemPotential=1.299
T...Graphene_ChemPotential=1.305
T...Graphene2_ChemPotential=1.31

T_Zmin(1),Zmax(1)[Magnitude]

Fig. 8 Transmission versus wavelength with a tunable lower cut-off wavelength

T_Zmin(1),Zmax(1) (5)
T_Zmin(1),Zmax(1) (3)
T_Zmin(1),Zmax(1) (4)
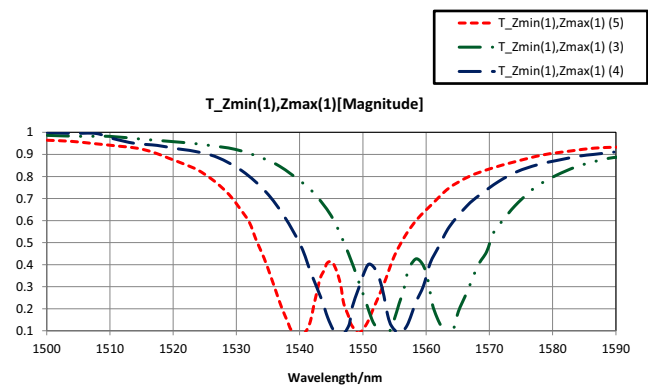
T_Zmin(1),Zmax(1)[Magnitude]

Fig. 9 The numerical values for the chemical potential of graphene

$$P = n_s \mathrm{er} = \frac{n_s e^2 E_0}{\omega m_\varepsilon \left(\frac{j}{\tau} - \omega\right)} e^{\mathrm{j}\omega \mathrm{t}} \tag{11}$$

In n_s, the density of electrons in metal is per volume unit. Finally, the conductivity in metals can be calculated according to the parameters of the metal and frequency using Eq. (12).

$$\sigma = \frac{\omega_p^2}{1 + \mathrm{j}\omega\tau} \tag{12}$$

where $\omega_p = \sqrt{n_s e^2 / m_\varepsilon \varepsilon_0}$ is the plasma frequency.

Graphene Electrical Conductivity

The electrical conductivity of graphene consists of two portions, inter-band and intra-band interactions. For the terahertz range, inter-band interactions are dominant band. Hence, the first part of the Kubo formula will prevail for graphene conductivity within the terahertz range, which is related to inter-band interactions.

$$\sigma_S^{\mathrm{total}} = \sigma_S^{\mathrm{intra}} + \sigma_S^{\mathrm{inter}} = \frac{2k_B}{\pi\hbar^2} \ln\left(2\cosh\frac{E_\mathrm{F}}{2k_B T}\right) \frac{i}{\omega + i\tau^{-1}}$$
$$+ \frac{ie^2}{4\pi\hbar} \ln\left[\frac{|E_\mathrm{F}| - (\omega + i2\tau^{-1})\hbar}{|E_\mathrm{F}| + (\omega + i2\tau^{-1})\hbar}\right] \tag{13}$$

The electrical conductivity of graphene is estimated using the Kubo formula, which is written in the absence of an electric field and consists of four main parameters of the angular frequency ω, time, temperature τ, temperature T, and chemical potential in which chemical potential E_F is identical to the Fermi energy level. Using these four main parameters, one can control the electrical conductivity of graphene.
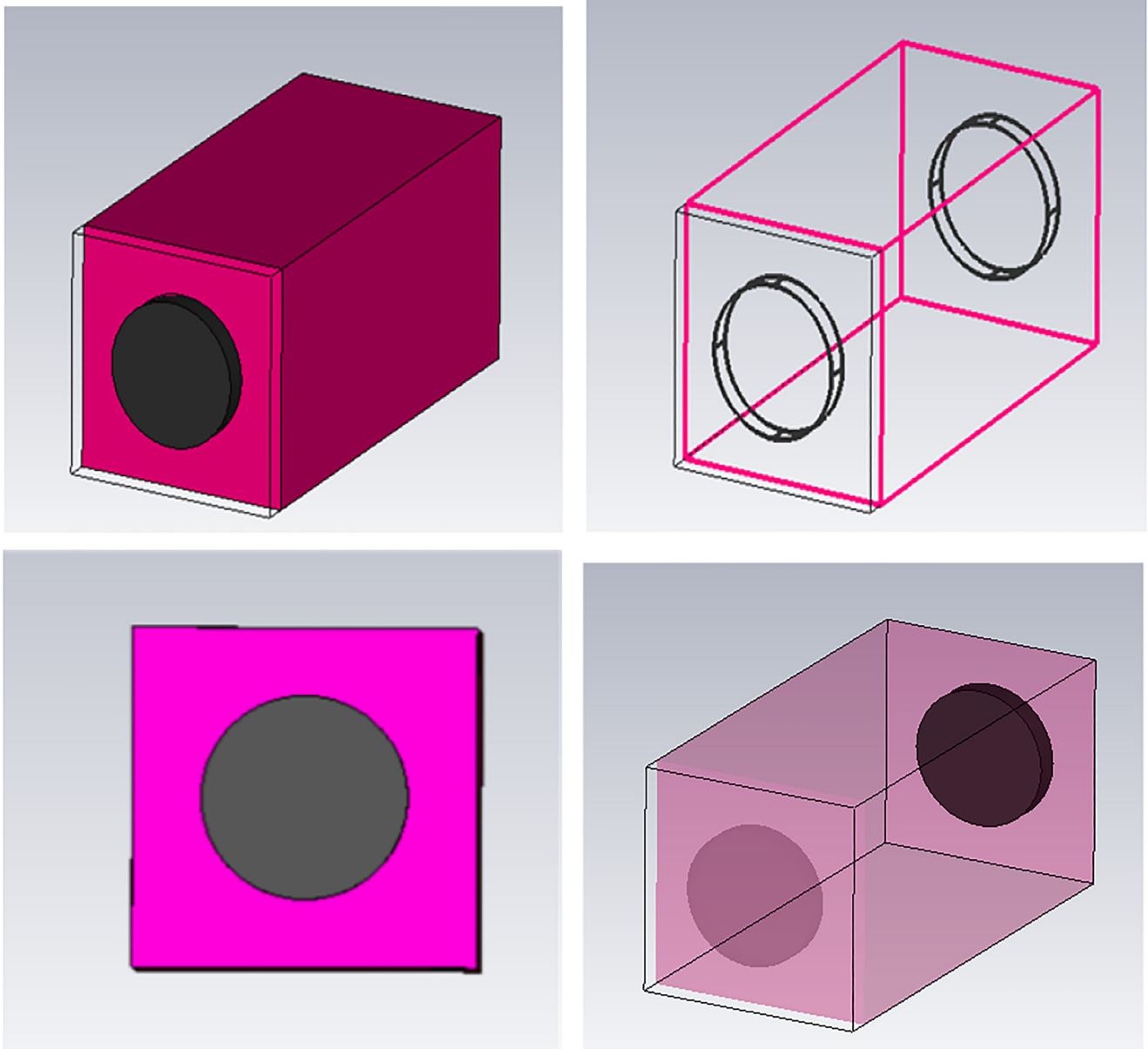
Fig. 10 3D view of the structure using the middle layer of AL_2O_3 and graphene disks on both sides up and down
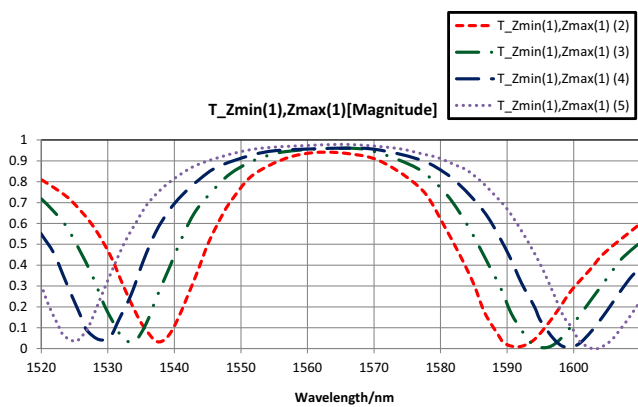

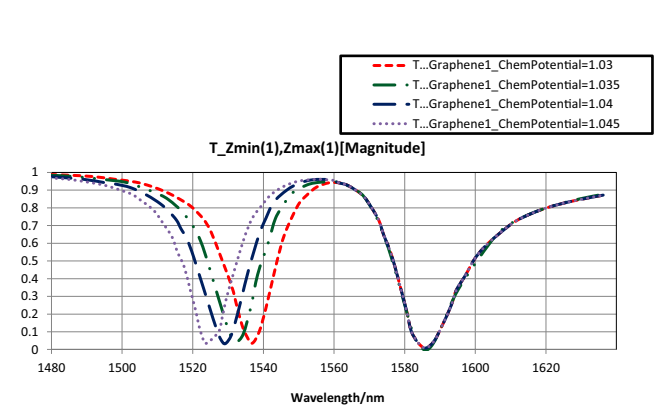**Fig. 11** Output of band-pass filter with an adjustable cut-off wavelength

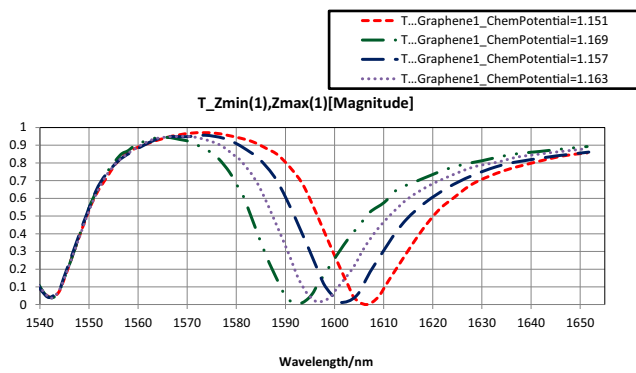**Fig. 12** The band-pass filter with a tunable low cut-off wavelength

Fig. 13 The band-pass filter with a tunable high cut-off wavelength

Fig. 15 The sweep mode for a top graphene disk

Principles of absorption using the dispersion matrix are expressed with S parameters as follows:

$$A = 1-R-T \qquad (14)$$

In the equation above, A is absorption and R and T represent reflection and transmission respectively. It can also be written as below.

$$A = 1-|S_{11}|^2-|S_{21}|^2 \qquad (15)$$

n_{eff} shows the effective refractive index.

$$n_{eff} = \frac{1}{kd} \cos^{-1} \left[\frac{1}{2S_{21}} \left(1-S_{11}^2 + S_{21}^2 \right) \right] \qquad (16)$$

K is the wave number in vacuum, d is the width of the metamaterial with propagation direction S_{22}, and S_{11} is the reflection and the transmission coefficient. The structure has been shown in the following figures.

Result and Discussion

In presenting the effect of applying change on the chemical potential of graphene, simulation results in CST software in
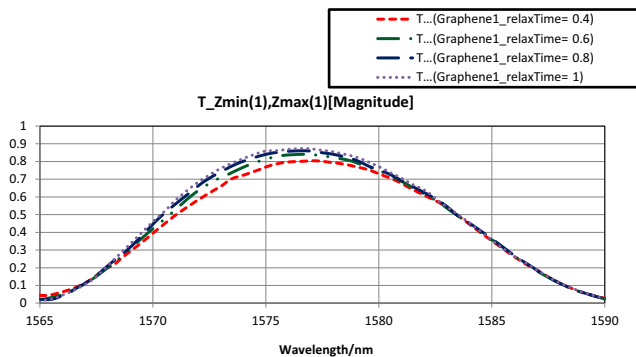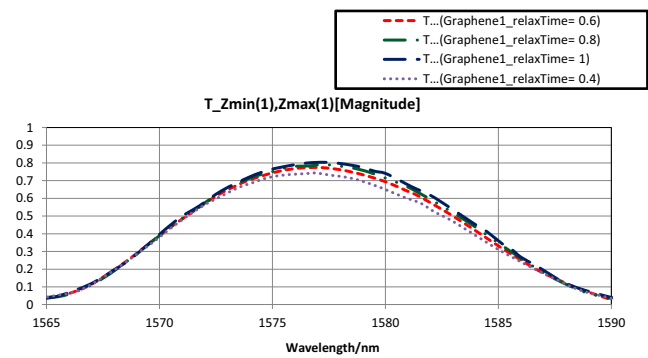
step 1; chemical potential for top and bottom disks are 1.27 and 1.3 eV respectively. In stage 2, chemical potential is 1.27075 eV for the top disk and 1.2995 eV for the bottom disk and in stage 3, 1.271 eV for the top disk and 1.299 eV for the bottom disk Tables 1, 2.

For the tunability of the high cut-off wavelength, the chemical potential of the top graphene disk should be exactly 1.3 eV and the chemical potential of the bottom graphene disk swept from the initial value of 1.251 eV with step 0.02 and the answer is as follows:

For the tunability of the low cut-off wavelength, the chemical potential of the bottom graphene disk should be exactly 1.27 eV and the chemical potential of the top graphene disk swept from 1.3 eV with step 0.05, which has the following results.

In the case of equal quantities of chemical potentials for both disks, the values such as 1.29, 1.3, 1.31 eV result in alternative state and the amplitude is constant, while the location changes as follows:

In the second case, graphene and AL_2O_3 were used where graphene disks embedded with a radius of 3 nm and thickness of 1 nm on both sides of the middle layer of Al_2O_3 with an epsilon value of 3.69, the width of 10 nm, and the thickness of 20 nm. For the top and bottom graphene disks, the relaxation time, the graphene thickness, and the ambient temperature are 0.4 ps, 1 nm, and 293 K, respectively. The graphene chemical
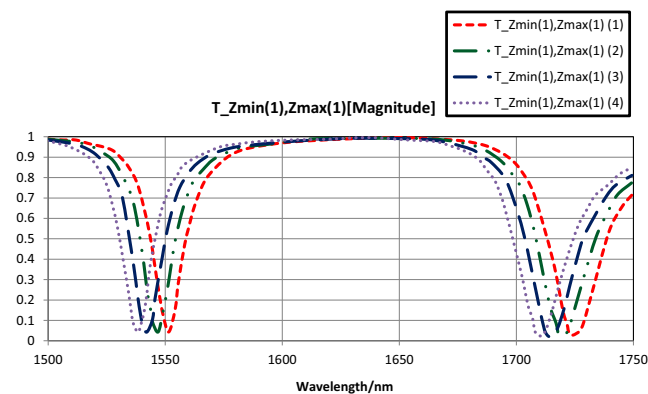

Fig. 14 The sweep mode for the bottom graphene disk

Fig. 16 The shift mode for both graphene disks with equal values

Table 1 Variable values for the chemical potential of graphene disks (in terms of electron volts)

Lower graphene disk	Upper graphene disk
1.3	1.27
1.2995	1.27075
1.299	1.271

potential for the top and bottom disk is described in the table below:

Aluminum oxide or alumina is one of the ceramic materials with mechanical properties such as high compressive strength and high hardness.

For the initial state, the output of the band-pass filter with the tunable cut-off wavelength around 1.55 μm is as follows:

After sweeping chemical potential for the top graphene disk with the initial value of 1.03 to 1.045 eV and step of 0.05, the tunable low cut-off wavelength is.

After sweeping chemical potential for the top graphene disk with the initial value of 1.151 to 1.169 eV and step of 0.04, the tunable high cut-off wavelength is

After sweeping the relaxation time, the bottom graphene disk is equal to the constant value of 0.4 ps and the top graphene disk from 0.4 to 1 ps with step of 0.2. The tunable low cut-off wavelength is as follows:

In the sweep mode, for the top graphene disk, the fixed value is 0.4 ps and the bottom graphene disk starts from 0.4 to 1 ps with step of 0.2. The tunable high cut-off wavelength is as follows:

In the case where the chemical potential of both graphene disks is the same, we will have a shift with constant amplitude and a change in position in the values 1.015, 1.02, 1.025, and 1.03.

Conclusions

The present study mainly focuses on electromagnetically induced transparency, the metamaterial, tunable band-pass filter, graphene, nano, fused silica, and alumina oxide. In fact, we design and simulate a graphene-based band-pass filter with a tunable cut-off frequency and the middle layer of fused silica. As a second alternative, we used alumina

Table 2 Bottom graphene disk and top graphene disk

Up graphene disk	Down graphene disk
1.155	1.045
1.16	1.04
1.165	1.035
1.17	1.03

oxide in the middle layer along with graphene disks and obtained the optimal results for improving the filter function and response at a high terahertz frequency as well as short wavelengths in the 1.55 μm, a very sensitive and precise range for both modes. Hence, in the first case of innovation in the use of graphene disks with fused silica, the range of precision is 1.54 to 1.58 μm, and in the second innovation with graphene disks and alumina oxide, a numerical range of 1.55 to 1.72 μm is required. Therefore, we could achieve a cut-off wavelength and eventually adjust the band-pass filter by changing the chemical potential of the desired design.

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