Control-Ability of Refractive Index Sensor Based on Plasmonic Induced Transparency in Graphene Meta-Material

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Abstract

In the current study, the refractive index sensor based on Plasmonic Induced Transparency which is composed of graphene meta-material has been investigated. In this sensor one graphene flat layer has been employed it is worth mentioning that two rods have come out of it Plasmonic Induced Transparency was examined by means of symmetry failure. In addition, through using an important feature of graphene in controlled electrical conductivity by changing the voltage range of the frequency range, the Plasmonic Induced Transparency is controlled, besides light slowing was increased to 690. Its sensitivity is $14.88\,{}^{\mu m}/_{RIU}$ *.The structural shape value is calculated as 48. This nanostructure, in addition to its bio-sensing capabilities, can be used for light slowing, optical switches, modulators.*

Keywords: Biosensor, graphene, light slowing, controllability, Plasmon induced transparency.

1. Introduction

Electromagnetic Inductance Transparency occurs in Atomic Three-Tier Systems wherein in quantum systems destructive, interactions of two laser beams are employed for making a bright hole. Several methods have been proposed to re-generate electromagnetic induction transparency such as mass and spring system and plasmonic Induced Transparency in meta-materials of which single cell size is smaller than descent-light's wavelength and are periodically put together thus it shows unique magnetic responses it has many applications in Biological sensors, Antennas, light slowing, modulators, optical switches and invisibilities. Using meta-materials it is possible to reproduce electromagnetic Inductance Transparency which is called Plasmon induced transparency. The optical properties of Plasmonic Nano-particles underlie the design of many optical devices such as biological and chemical sensors. The How of interaction of Nano-particles, depends heavily on size, shape and refractive index of the surrounding environment. In fact, for designing a refractive index sensor the type of shape geometry is of great role in identifying the different materials. In two ways, one can create the phenomenon of Plasmon induced transparency in meta-materials: one is through pairing of bright-bright mode and another is through pairing of dark-dark mode [11]. The overlapping of dark and bright mode or bright-bright mode and the destructive interactions that they are doing results in reduced absorption in optical responses as well as reduction in speed of light. In recent years' various meta-material structures have been made to create plasmon induced transparency and the most common one was through using Noble metals. It should be mentioned that the use of semiconductors in the Terahertz intervals, which depend heavily on temperature, provides opportunity to have temperature control in optical response.

Graphene is a 2D honeycomb material of which displays unique properties in the terahertz range such as high electrical conductivity, high thermal conductivity [13]. Because of these superb properties, graphene is a good alternative to noble metals in the meta-materials. The electrical conductivity of graphene changes with the voltage change which is a unique feature for making the optical device more controllable [14].In the present study a flat graphene layer of which two rods have been gotten out of graphene is introduced wherein with symmetry breaking in the structure, induced transparency can be created, also benefiting meta-material sensitivity to reflective index of surrounding environment the sensor property of the Nano structure can be investigated. In the following parts the controllability of the sensor with voltages changes will be mentioned and at the end the application of light slowing will be discussed.

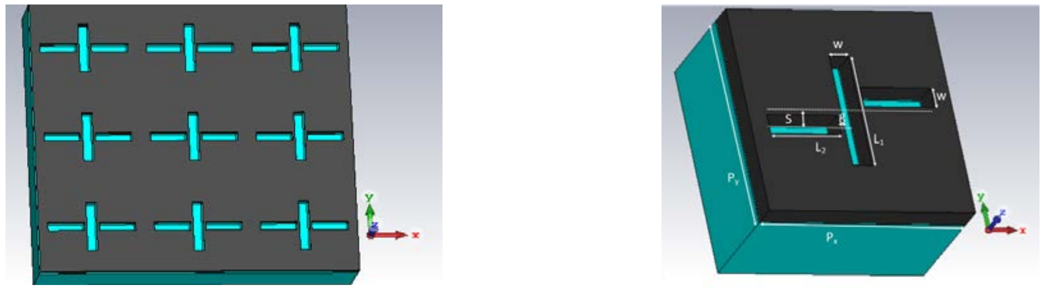
2. Structure and numerical methods (analytical)

In the present study a flat graphene meta-material of which supports two plasmony modes was utilized. In fact, a graphene layer of 1 nm thickness has been used. Two horizontal and vertical rods are cut from inside this graphene and was put on a substrate of SiO2 with a refractive index of nSiO2 = 1.97. As shown in Fig. 1, the structure is periodic one, the boundary condition for x and y is periodic, and in line z Light is sent while the electric field is in line y. To simulate this structure, CST MW software has been used wherein FIT is a numerical solution method. It is noteworthy that the gained results are calculated repeatedly. Other physical parameters used in this article are as follows: Px=Py=2.5 um ، w=240 nm ، L1=1.4 um and L2=870 nm and g=20 nm. As indicated in fig. 1 part b the structure of the symmetry breaking parameter is shown with S whose value varies. The electrical conductivity of graphene is expressed in the absence of a magnetic field by the Kubo formula which includes two inter-band and intra-band shares [15]. The graphene electrical conductivity in the terahertz range is carried out by conduction in the intra band. Because within this range, the dominant intra band interactions are dominant and it's possible to ignore the inter band conduction. Drude model is used for graphene modeling : $\varepsilon = 1 + \frac{i\sigma}{\omega\varepsilon_0 d}$

$$\sigma = \sigma_{intra} + \sigma_{inter}$$

$$\sigma = \frac{2ie^2Tk_B}{\pi\hbar^2\left(\omega + i\tau^{-1}\right)}\ln\left[2\cosh\left(\frac{\mu_c}{2k_BT}\right)\right] \qquad (1)$$

Where e, kB are, respectively electrical charge and Boltzmann's constant. For graphene modeling, the temperature is T = 300 at k it is worth to mention that the chemical potential value varies. The relaxation time equals $\tau = 1ps$ Graphene thickness is d = 1 nm.



a b

Fig.1 Schematic structure (a) in general (b) single cell

3. Results and Discussion

This graphene nanostructure contains two bright and dark modes, as shown in Fig. 2. Each of the modes has been investigated separately and the optical responses have been compared with each other. Afterwards through combining of these two bright and dark modes, the optical response is considered in a completely symmetric mode. Finally, with symmetry breaking, there is an attempt to create the Plasmon induced transparency in optical responses. As indicated in Fig. 1 with changing S from 0 to 150 nm we create a symmetry breaking in the structure and with the symmetry breaking, we control the transmission rate. As indicated in figure 2 part a the vertical rod is dark mode because it did not directly interfere with the incident light. The study of the distribution of the Electrical Field of the dark mode also indicates it. Now, by examining the field distribution of the bright mode it is indicated that one electric dipole in this horizontal rod is formed and is indicator of the bright mode of this element. Optical responses for two bright and dark modes are shown in Fig. 3.

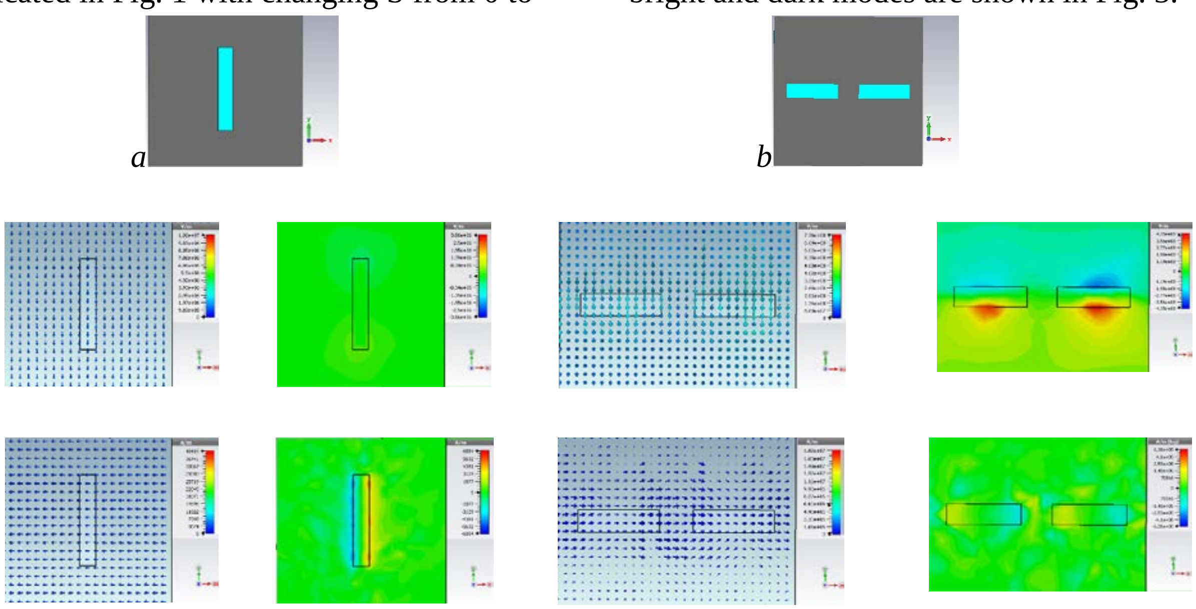


Fig. 2. Distribution of Electrical and magnetic field of bright and dark modes

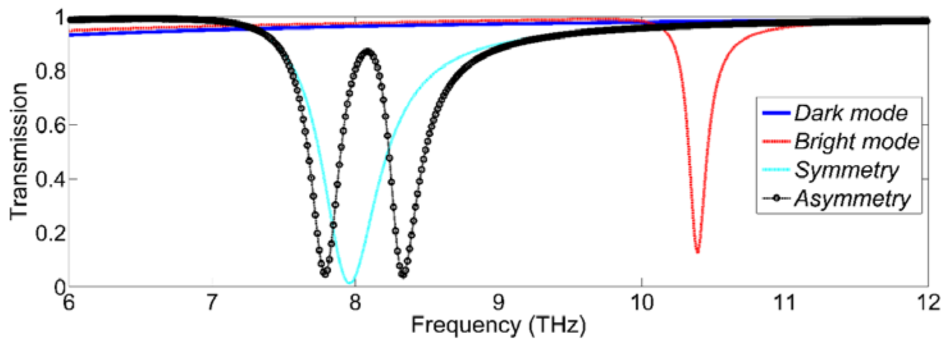


Fig. 3. Transit diagrams for bright, dark modes fully symmetrical and symmetry breaking

Now, putting these two bright and dark modes in a perfectly symmetrical manner the optical response and distribution of electric field will be investigated. When the structure is in a completely symmetric manner only one single resonance is observed at a frequency of 8 THz, which implies that the only bright mode has the ability to interact with the incident light so in this resonance, the pass rate is equal to 1% and the absorbance is 20%, as shown in Fig. 4. By examining the electrical field distribution for perfectly symmetrical mode can be seen in the Fig. 5 only Horizontal rod is stimulated and one electric dipole has been created inside this horizontal rod and the single resonance is due to this. Now through symmetry breaking the S value is increased from 0 to 150 nm and the optical responses have been investigated. As shown in the transmission diagram by disrupting symmetry in the structure of a incremental transmission peak, with increasing the symmetry breaking rate the transmission rate will be also increased and it increases transmission to 96.15% and it indicates that the dark mode is also evoked by the symmetry breaking as shown in the Fig. 6 . It is indicator of the fact that with evoking dark mode a pairing occurs between bright and dark modes which is increased with increase in symmetry breaking and results in increasing the transmission rate and sharp decreasing in absorption of the optical responses. Fig. 4 shows the comparison between optically responsive states of a completely symmetric state and the symmetry breaking. By examining the distribution of the electric field for symmetry breaking state, it is indicated that; with symmetry breaking in the structure, the dark mode has created a strong evoking with incident light and a strong electric dipole has been created in the vertical rod as shown in the Fig. 5.

Now, to give explanation for this phenomenon, the distribution of the magnetic and Electrical Field of this nanostructure will be discussed. As indicated in the figure 5 when the structure is in complete symmetry an electric dipole is created within two horizontal rods the vertical rod does not have interaction with the incident light. But with the symmetry breaking in the vertical rod structure there is severe interaction with incident light and the destructive interaction resulting from these elements display the Plasmon induced transparency in optical response.

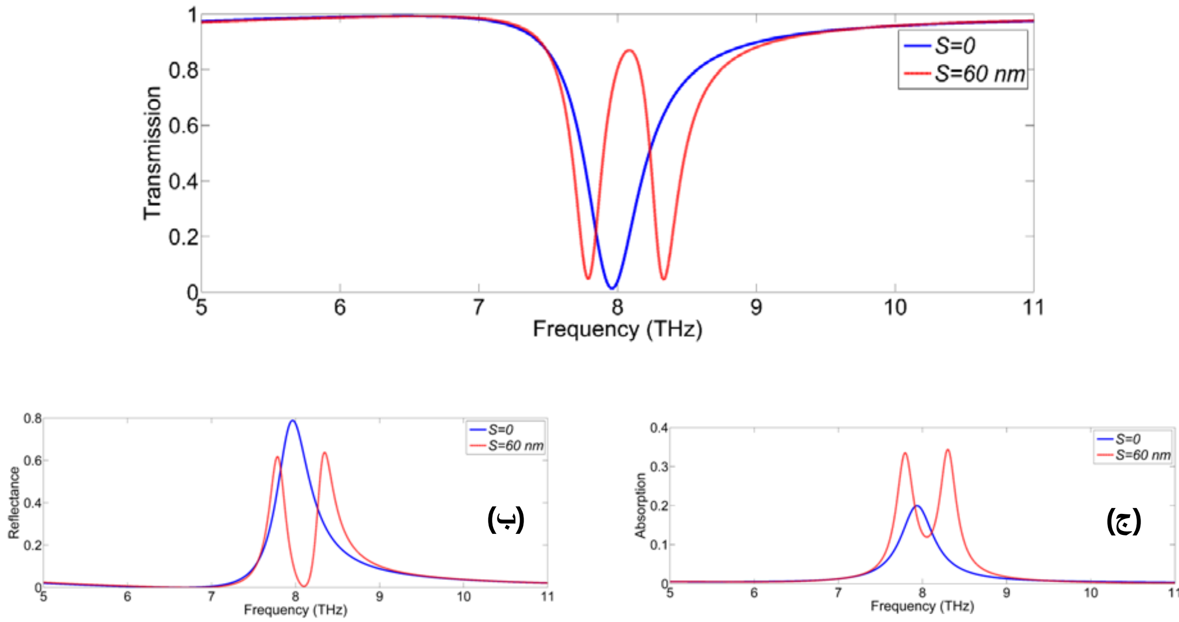


Fig.4. Transmission, reflection and absorption diagrams for both modes of S=0 & S= 60nm

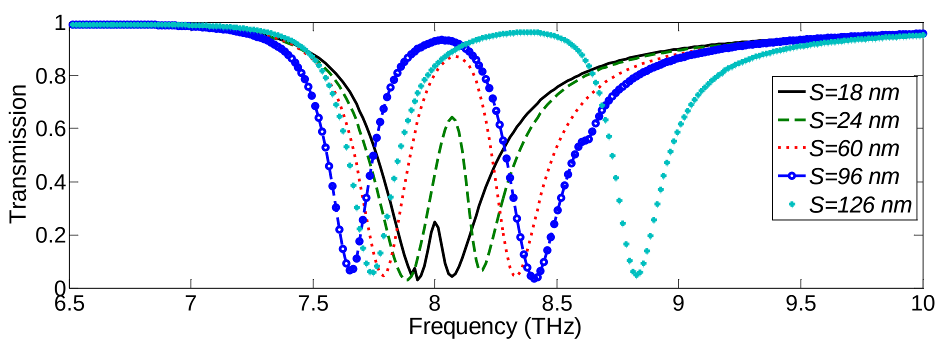


Fig. 6 the transmission chart with increasing symmetry track

3.1 Controllability with voltage change

One of the most important features of graphene is the controllability of its electrical conductivity which is possible with change voltage [16] .This feature is very important in the current study, since it provides opportunity to design a controllable sensor (Tunable). Since after designing an optical device, resonant frequency change is very difficult therefore making use of graphene has the ability to control the resonant frequency of the optical device with voltage(after designing). As indicated in the figure 7 by changing the chemical potential the frequency ranges of THz 6 to THz12 have been controlled from eV 0.3 to eV 0.9. In the figure four chemical potential changes have been displayed. The reason for this controllability is that with voltage changes the density of graphene load carriers also varies [14].

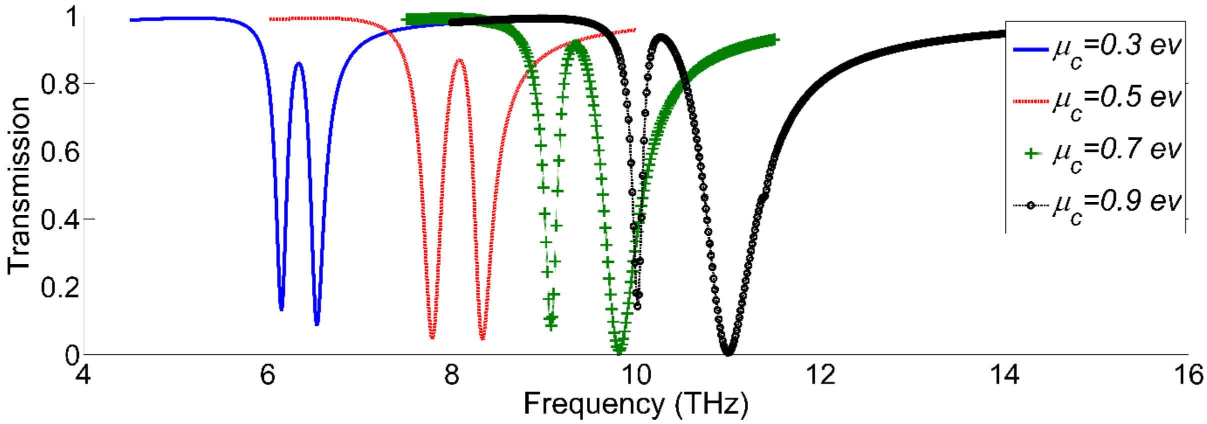


Fig. 7 Transmissions with Changing Chemical Potential

3.2 Sensory study

Fore sensory application the particular feature of the Meta-materials- that frequency intensity is strongly dependent on the refractive index of the environment- have been utilized [17-19] and the Nanostructure were put into materials with different refractive index and the refractive index sensor effect was investigated. For this state the Graphene Nano- structure are put in the materials with refractive indexes of n=1, 1.312, 1.322, 1.42, 1.54 which are respectively Vacuum, water, glucose, sugar and sodium chloride, then hoe of each optical response are investigated. As indicated in the figure 8 as the refractive index increases, it shifts toward lower frequencies wherein for the refractive index n = 1the resonant frequency in 8.08 THz and in water n=1.312 resonant frequency is 7.28 THz and in Glucose n=1.322 the resonant frequency is 7.16 THz and in sugar n = 1.420 the resonant frequency is 6.95 THz and in the sodium chloride n = 1.54 at 6.72 THz, the resonance occurred. Figure 9 part a indicated the relationship between the refractive index differences to the wavelength difference toward vacuum. Furthermore, according to the definition given for sensor sensitivity of the refractive index wherein the relative amount between the wavelength differences to the refractive index difference has been defined $Sensitivity = \frac{\Delta\lambda}{\Delta n}$ which is based on $\left({}^{\mu m}/_{RIU}\right)$.

The sensitivity diagram for the refractive index difference versus vacuum can be seen in Fig. 9 (b) and the maximum amount is for glucose and is equal to $14.88\,{}^{\mu m}/_{RIU}$.

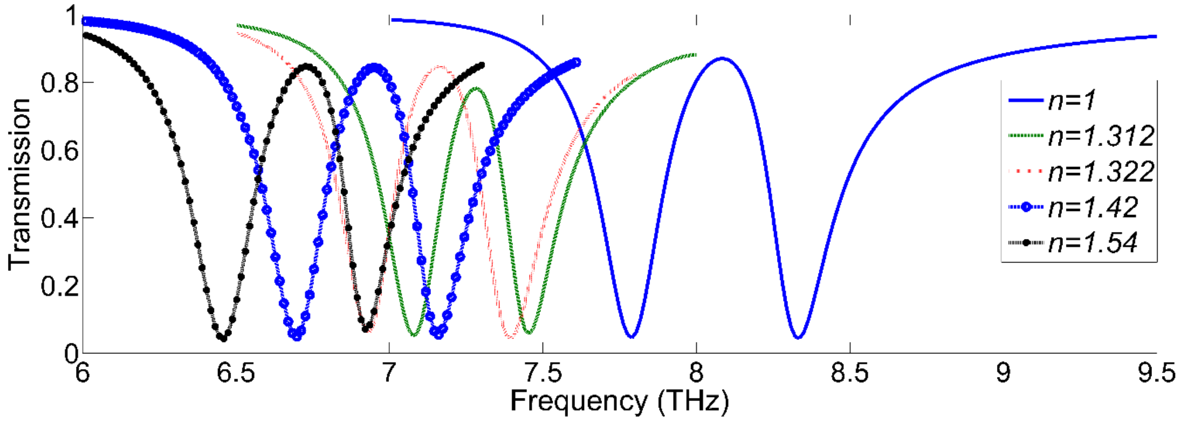


Fig.8 Transmission by changing the refractive index of the surrounding environment

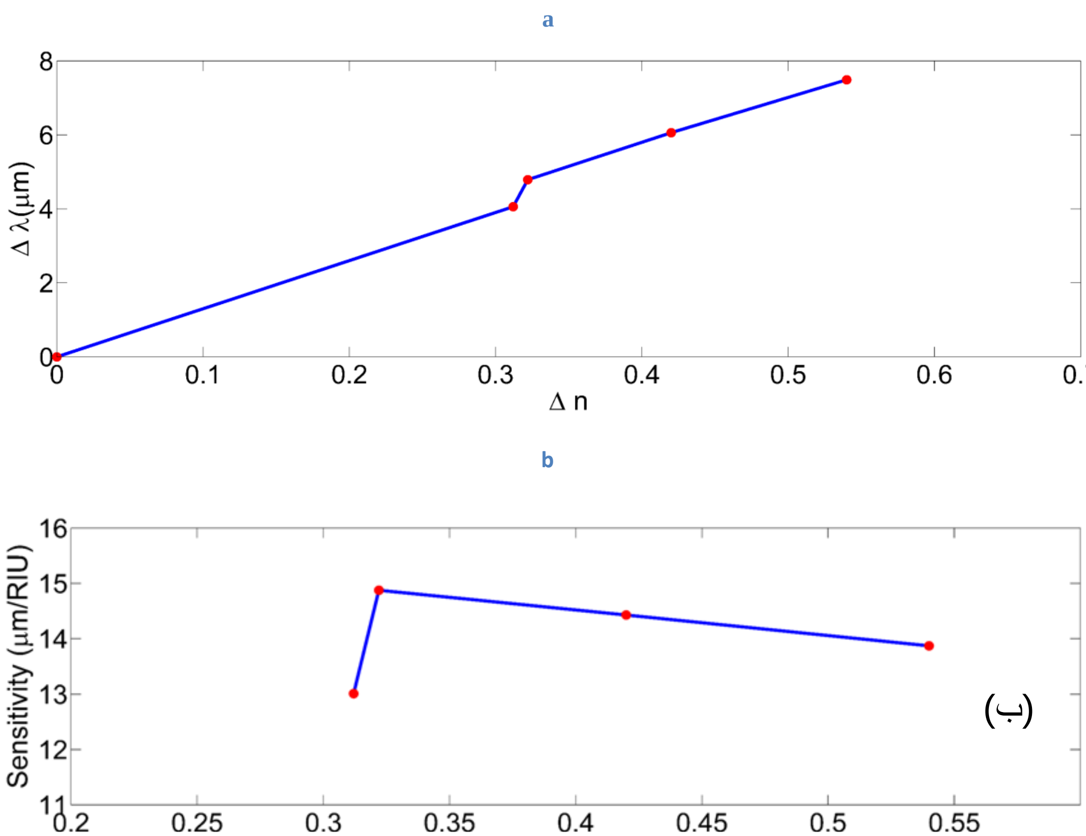


Fig. 9 (a)Changes in wavelength to refractive index of surrounding environment (b) Sensitivity to refractive index difference

Given that optical responses depend heavily on the symmetry breaking, shape value of Nanostructure FoM for different symmetry breaking have been investigated as indicated in the figure 10. The definition for the shape value is equal to $FoM = \frac{Sensitivity}{FWHM}$.

The ration of the sensitivity to Full-width half maximum is for Optical responses to different symmetry breakings. As inferred from the definition of FoM with increasing the S parameter in the structure, which means to increase the pairing between the bright and dark mode, the transparency bandwidth also increases, which reduces the FoM.

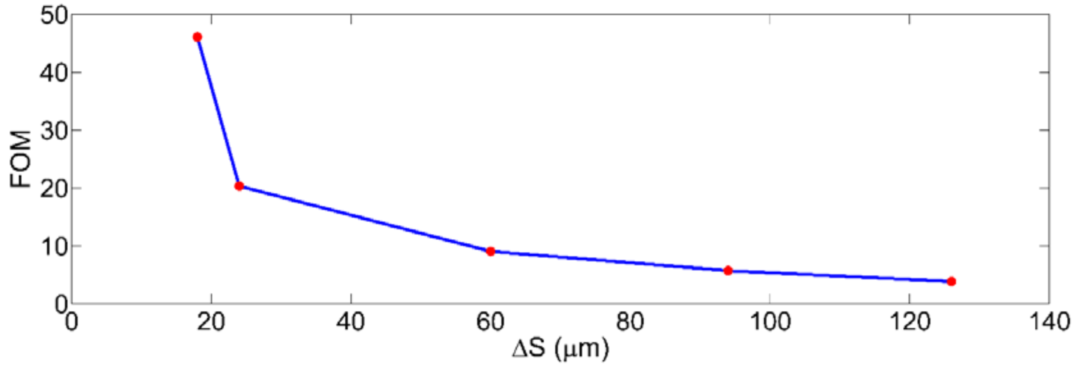


Fig. 10 changes of FoM versus the difference in the size of the parity of the symmetry breaking

3.3 Decreasing the group speed

One of the consequences of the Plasmonic Induced Transparency phenomenon is the decreasing the group speed which are used in optical memory and telecommunication systems (Optical storage of information) [11], [19-20]. The effect of reducing the speed of light is determined by the definition of the coefficient of the group which is obtained through the dispersion relationship calculated in Part A. In the figure 11 Group coefficient graph for two modes with complete symmetry and symmetry breaking can found. In fact, the positive and negative of the coefficient of the group means slowing and fastening of light. As can be inferred in the resonant frequency for a completely symmetrical mode, there is no light slowing. But with a symmetry breaking in the state S = 60 nm the value of the group coefficient is 690.6 namely the speed of light is reduced from the range of 690.6 whose relation is specified in equation 2. Given the graphene characteristics, the speed limit of light can be controlled by changing the chemical potential (as indicated in the figure 12.

$$V_g = \frac{c}{n_g} \tag{2}$$

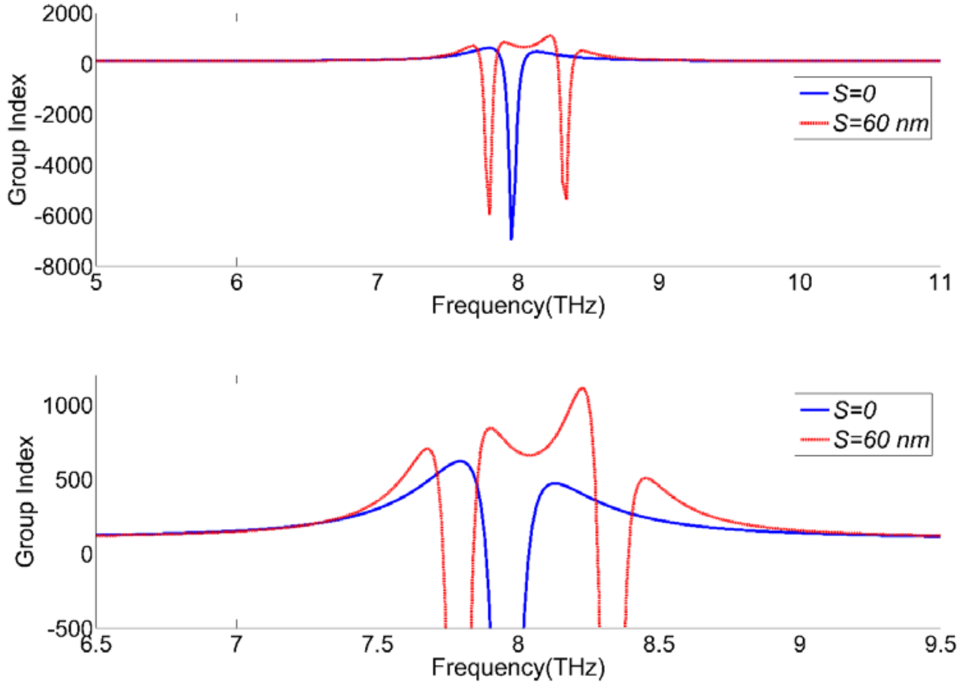


Fig. 11 the group coefficient for a perfectly symmetric mode and the symmetry breaking

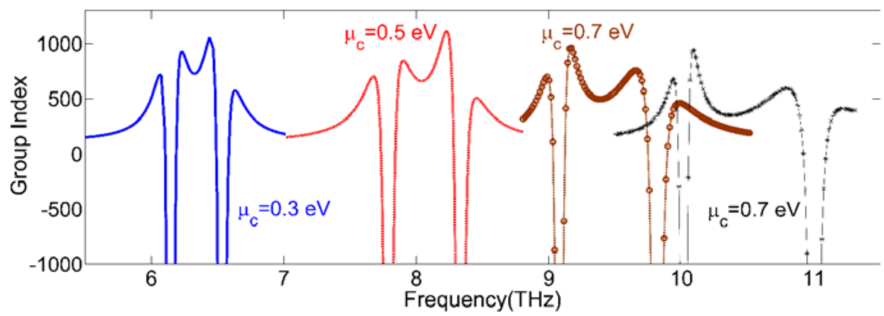


Fig. 12 Graph of control of the coefficient of the group with the change of chemical potential

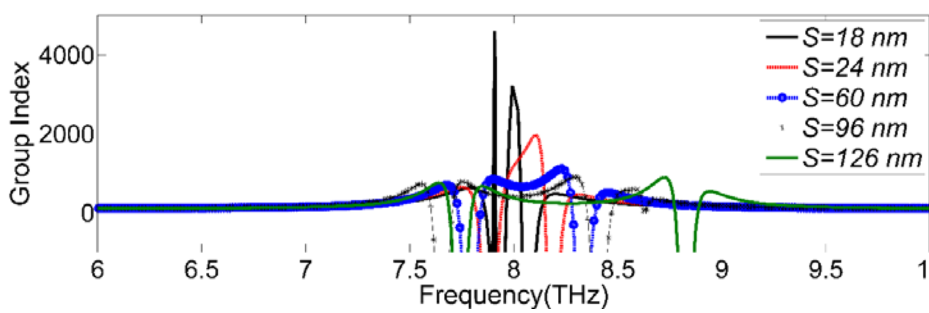


Fig. 13 Coefficient Chart of the Group by changing the symmetry breaking parameter

As indicated in the table 1 by increasing the parity of the symmetry breaking of the structure, the amount of pairing between the two bright and dark modes would also increase the amount of transmission will increase as well, the bandwidth will increase too; all of these result in reduction in the quality factor.

Table1

	Quality factor	*Full-width Halfmaximum FWHM(THz)*	*Group Coefficient*	*Transmission (%)*	*S(nm)*	*Row*
	142.86	*0.056*	*3210*	*24.7*	*18*	***1***
	56.04	*0.144*	*1976*	*64.16*	*24*	***2***
	23.08	*0.35*	*690.6*	*87.06*	*60*	***3***
	14.69	*0.546*	*404.5*	*93.16*	*96*	***4***
	9.44	*0.882*	*245.9*	*96.27*	*126*	***5***

4. Conclusion

In sum in the current study a flat meta-material this has two perpendicular rods have been utilized which includes two bright and dark modes and the destructive interaction of these two dark and bright modes by disrupting the symmetry in the structure of the induction of plasmonic transparency have been investigated. The transmission rate can be controlled by S symmetry breaking parameter, maximum transmission is 96.15%. By changing the chemical potential, PIT frequency range can be controlled which covers the frequency range of 6 to 12 terahertz. One of the consequences of the Plasmon induced transparency is reducing the light speed which all has been investigated in the present study. The light speed changes with the change of the symmetry breaking parameter. Light speed at the resonant frequency decreases from the range of the 690.9. Also, using the chemical potential change it is possible to control the Light slowing Frequency Range. Finally, the most important part of the article was the sensory issue and these refractive index sensors were put into Biomaterials with different refractive index and the sensitivity of this biologic N has been studied. The sensitivity of this sensor has been measured at range of $14.88\,{}^{\mu m}\!/_{RIU}$ .given that the structure is strongly dependent on the parity of the symmetry breaking the shape value for this nano-scale was also measured and calculated as 48.

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