



High Efficiency Tunable Graphene-Based Plasmonic Filter in the THz Frequency Range

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Abstract

A tunable plasmonic filter waveguide with indium antimonide activated by graphene layer configuration is proposed and numerically investigated. We demonstrate that the proposed tunable single-stub plasmonic filter using a thin layer of graphene can operate in the terahertz (THz) region as a notch filter. To investigate the transmission response of the structure, finite element method (FEM) calculations are utilized. The designed filter has precise minimum of zero at the notch frequency and also it improves the maximum transmitting light. Moreover, by applying the gate voltage between the graphene sheet and the InSb substrate, it can be seen that the central frequency of the filter is shifted by 32 GHz, and also the maximum of the transmission has been improved by 64% from 0.56 to 0.92 which shows less power loss. Furthermore, a band-stop plasmonic filter is proposed by increasing the number of stubs, which improves the bandwidth of the filter by 33% in compare to a single-stub structure. With such advantages, this structure is promising for future integrated plasmonic devices for applications such as communications, signal filtering, and switching.

Keywords Tunable notch filter · Tunable bandpass filter · Graphene · Therahertz · Plasmonic

Introduction

Optical field manipulation and flow control of the electromagnetic wave is very important in photon based-communication and information transportation. In recent years, development of photonic components is growing and find its way in replacing electrical devices with their subwavelength dimensions [1, 2, 4]. By discovering two dimensional materials such as graphene, a huge revolution has happened in the size of optical and electro-optical elements and also their functions [5]. Graphene, a 2D sheet consisting of carbon atoms in a hexagonal configuration which are connected to each other with the SP² hybrid, had created for the first time in 2004. In graphene, each atom

is connected to three other atoms that the carbon-carbon bond length is about 0.142 nm [6]. The unique electrical and optical properties of graphene such as tunability of permittivity by applying the gate voltage or impurity injection in the wide range of electromagnetic spectrum from microwave to visible region, high conductivity, and also its high thermal resistance, make it an ideal candidate to be used in optical and electro-optical devices [7–9]. Due to the fact that the real part of permittivity of graphene is negative in the terahertz (THz) range and its ability to support surface plasmons, make it really popular in this frequency region [10–12].

In this paper, we used indium antimonide (InSb) as a semiconductor which supports surface plasmons in the THz frequency range to design a stub waveguide for notch filter application. To make this filter tunable, we added thin layers of graphene with ability of permittivity control under applying the desired gate voltage. Not only the central frequency of the proposed filter is shifted by changing the applied voltage, but also the maximum of the transmission power is increasing significantly which leads to enhanced efficiency of the designed filter. Furthermore, by increasing the number of stubs, we can have a tunable band-stop filter with a wider bandwidth and also reasonable maximum and minimum of transmission.

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Single-Stub InSb Notch Filter

Indium antimonide (InSb), a semiconductor from group III-V with negative real part of its permittivity in the THz frequency range, is a suitable candidate for designing the plasmon-based devices [3]. To design a notch filter in this frequency range, we proposed an InSb-based waveguide with one stub in it to trap the incident wave in the desired frequency (Fig. 1a) and set the dielectric core to be air. In this design, subwavelength dimensions of the structure are set as $W = 50 \mu\text{m}$, the core width; $L = 300 \mu\text{m}$ and $W_s = 50 \mu\text{m}$, the length and width of the stub, respectively. In our simulations, the waveguide is terminated by Perfect Matched Layer (PML) boundaries all around the structure. The incident light passes through the core with its magnetic field perpendicular to the plane of incidence (H_z , TM polarization). InSb, permittivity can be described by the Drude model approximation [13]:

$$\epsilon(\omega, T) = \epsilon_\infty - \frac{\omega_p^2(T)}{\omega[\omega + i\Gamma(T)]} \quad (1)$$

where ω and ϵ_∞ are the incident light-frequency and high-frequency permittivity, respectively. ω_p is the plasma frequency as a function of temperature and Γ is the collision frequency. At $T = 300^\circ\text{K}$ and in the THz region, the real part of InSb's permittivity has negative value which is similar to the plasmonic metals in the visible range [14]. We use air for the dielectric core and inside the stub with $n = 1$.

Figure 1a shows the transmission spectrum of the designed single-stub filter of the inset of Fig. 1a between

1.4 – 2 THz. It is clear that the structure guides the incident light as a notch filter with a decline at frequency of 1.66 THz. Figure 1b and c show the normal magnetic field distribution (H_z) at two different frequencies, corresponding to the notch frequency (1.66 THz) and the frequency with maximum light transmission (1.95 THz). Resonant light trapping inside the subwavelength stub in the form of standing Fabry-Pérot (FP) mode can be seen in Fig. 1b [17, 18].

Tunable Notch Filter Based on Graphene

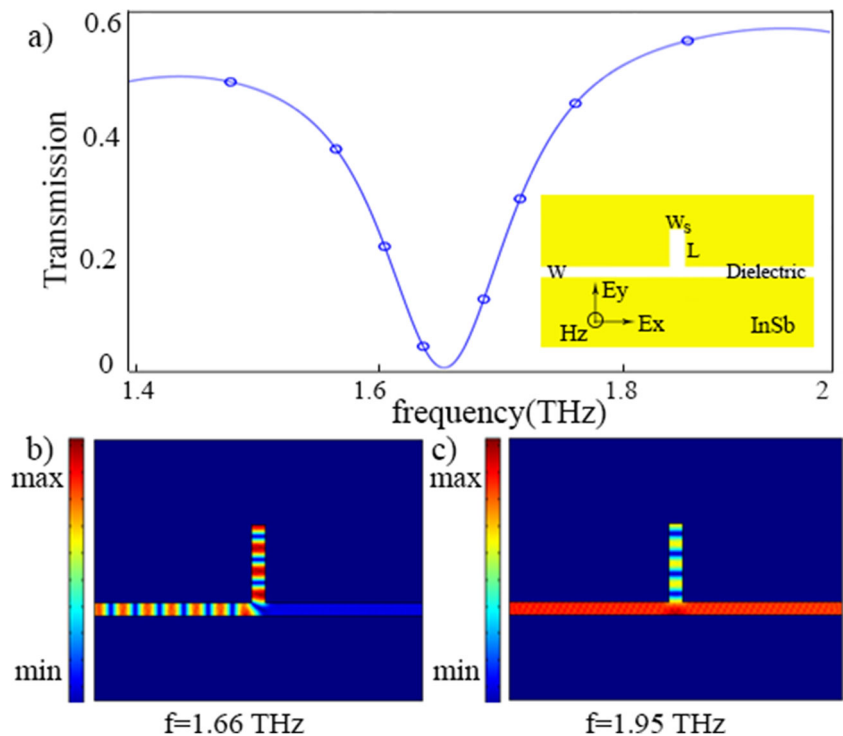
In order to make the filter tunable, we add thin layers of graphene in the structure. Graphene with its ability to support surface plasmons in the THz frequency range not only makes the filter tunable, but also increases its efficiency significantly. The complex surface conductivity of graphene as a key parameter can be described with two different parts using Kubo's formula [15]:

$$\sigma = \sigma_{inter} + \sigma_{intra} \quad (2)$$

where σ_{inter} and σ_{intra} show the interband electron transition and intraband electron photon scattering, respectively, and we have:

$$\sigma = \frac{ie^2}{4\pi\hbar} \ln \left[\frac{2\mu_c - (\omega - 2i\Gamma)}{2\mu_c - (\omega + 2i\Gamma)} \right] + \frac{ie^2k_B T}{\pi(\omega + 2i\Gamma)\hbar^2} \left[\frac{\mu_c}{k_B T} + 2 \ln(e^{\frac{-\mu_c}{k_B T}} + 1) \right]. \quad (3)$$

Fig. 1 a Transmission spectrum of the filter structure with single stub and its H_z field distribution at frequencies of b 1.66 and c 1.95 THz with minimum and maximum light transmission



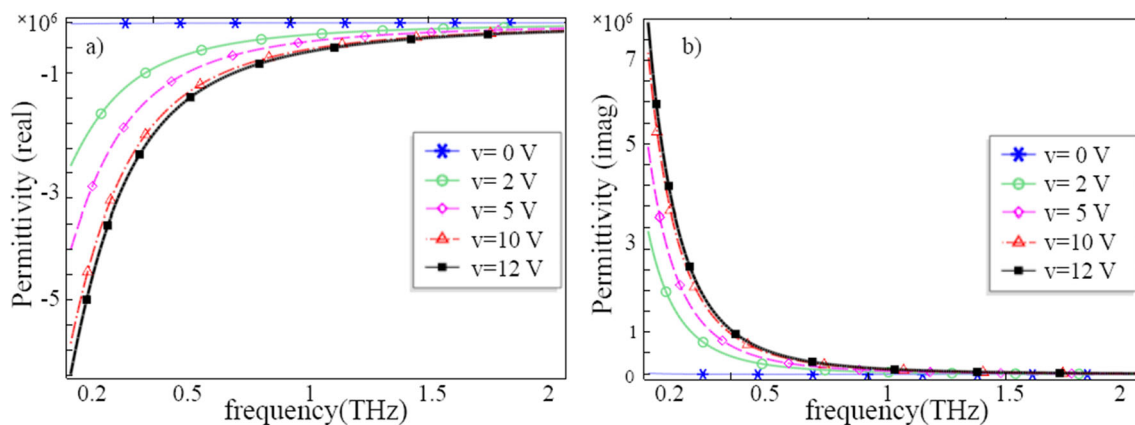


Fig. 2 a Real and b imaginary parts of the graphene permittivity

In Eq. 3, μ_c is the chemical potential of the doped graphene material which is a function of the applied gate voltage according to $\mu_c = \hbar v_f \sqrt{\frac{\pi \epsilon_r \epsilon_0 V}{q e T}}$. $\Gamma = 0.1 eV$ is the damping constant and $T = 300^\circ K$ is the temperature. The relative permittivity of graphene is defined by

$$\epsilon = 1 + i \frac{\sigma}{\epsilon_0 \omega t_g} \tag{4}$$

where ϵ_0 and ω are free space permittivity and angular frequency, respectively, and t_g is the graphene thickness. In Fig. 2a and b, real and the imaginary parts of the graphene permittivity as a function of frequency for different applied voltage values are plotted, respectively. As it is shown in Fig. 2a, by applying the gate voltage to graphene, real part of its permittivity changes to negative values, which leads to the ability of graphene to support surface plasmons [16].

To make the designed filter tunable, we add two thin layer of graphene between the dielectric core and the two InSb layers, as it is illustrated in Fig. 3a. Figure 3b shows

the transmission spectra of the single-stub filter structure in the presence (red starred curve) and absence (blue circled line) of the graphene layer. It can be seen in Fig. 3b that adding the graphene layer itself with null voltage (crossed green line) neither changes the transmission maxima, nor the working frequency of the filter. While, by applying the 2-V gate voltage between the graphene sheet and the InSb substrate not only the maximum transmission is improved from 0.56 to 0.8, but also the notch frequency of the filter is tuned from $f = 1.66$ to $f = 1.675$ THz. Searching the physics behind this behaviour leads us to Fig. 3a where the real part of permittivity of graphene is plotted under different gate voltages. The key point is the graphene permittivity alteration from positive to the negative values with applying voltage which leads the graphene to support surface plasmons. Coupling the InSb plasmons to that of the graphene will strengthen and confines guided plasmons to the 1-nm thick graphene which increases maximum light transmission significantly which is a determinative

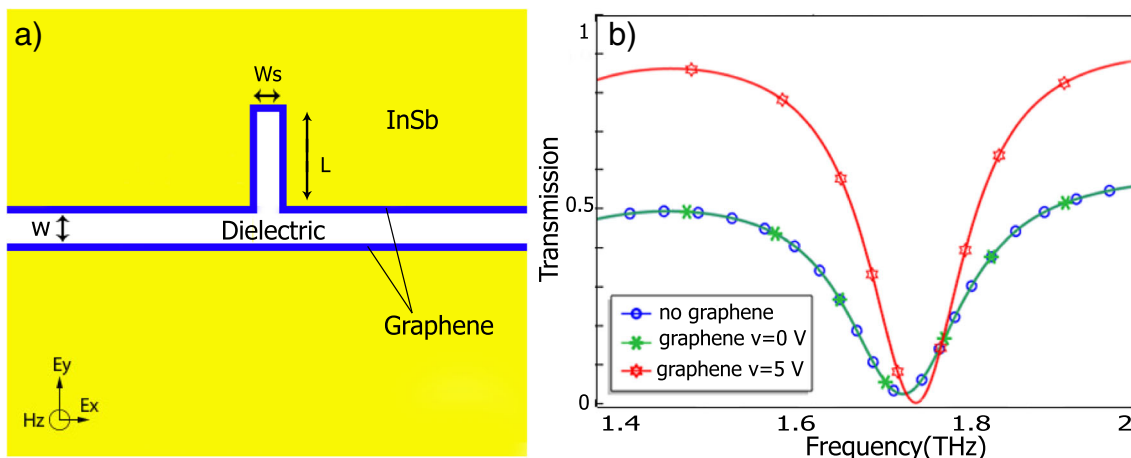


Fig. 3 a Single-stub plasmonic filter structure with two thin layers of graphene with thickness of 1 nm, covering the InSb and b transmission spectra of the structure with graphene under 2 V (red starred curve), with no applied voltage (green crossed line) and without graphene (blue circled line)

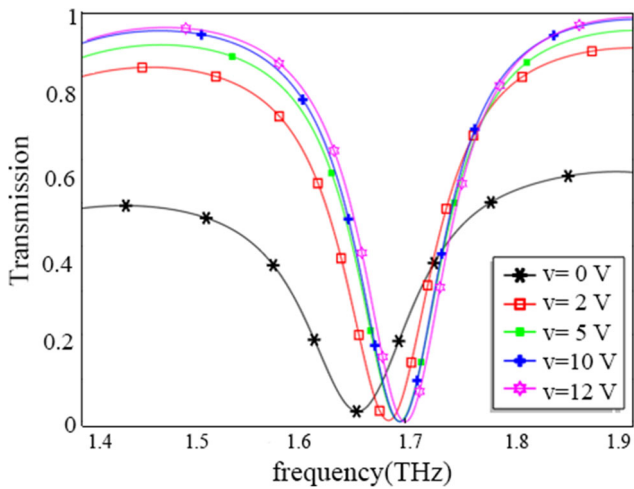
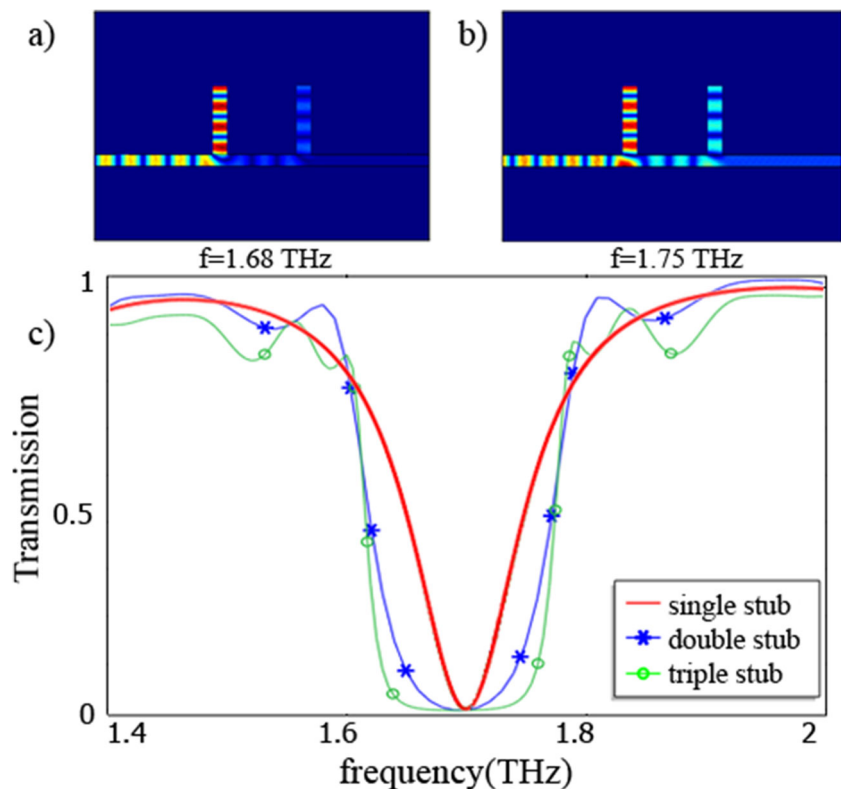


Fig. 4 Transmission spectra of the single-stub plasmonic filter based on graphene for different applied voltages

parameter in filtering operation efficiency. Figure 4 shows that increasing the gate voltage from 2 to 10 V will shift the notch frequency of the designed filter from $f = 1.66$ to $f = 1.69$ THz, which would be equivalent to 32 GHz frequency shift ($\Delta\lambda = 9.3\text{mm}$). With $v = 10$ V, the structure guides maximum 92% of the incident power to the output port, which is 64% more than the designed filter without graphene. This notch shift to the higher energies with higher transmission efficiency is due to the excitation of strongest plasmons with increased negative permittivity of

Fig. 5 H_z field distribution at frequencies of **a** 1.68 and **b** 1.75 THz for a double stub structure. **c** Transmission spectra of the single (blue-circled curve), double (green-crossed curve), and triple (red-starred curve) stub filters. 10-V voltage is applied to the graphene layers



graphene with higher applied voltages (Fig. 2a). Increasing the applied voltage to the values higher than 10 V not changing the notch frequency and maximum transmission of the filter anymore. Looking at Fig. 2a illustrates the fact that graphene permittivity will be saturated and not changing significantly for voltages higher than $v = 10$ V.

Band width (BW) of 0.15 THz is attained by the structure when the gate voltage of $v = 10$ V is applied. The BW is calculated by obtaining the cutoff frequencies (which the output is -3 dB of the nominal pass band value) for the filter.

Band-Stop Plasmonic Filter

To develop the designed filter to a band-stop one, we replace the single stub by multi-stub structures, as what is shown in Fig. 5. W and W_s , width of the waveguide and each stub are set to be $50\ \mu\text{m}$ and the height of each stub is $300\ \mu\text{m}$. The distance between two consecutive stubs is selected to be $300\ \mu\text{m}$. Similar to the previous structure, the dielectric core is chosen to be air and the applied voltage to the graphene is 10 V. In addition to the trapped modes in each stub, in the multi-stub structures the incident light can be coupled to the FP-like modes that creating standing waves between two consecutive stubs which makes the filtering frequency-band widen. Figure 5c shows that compared to the single stub, double-stub filter has wider band-stop with bandwidth

of 0.2 THz and the triple-stub structure filters frequencies between 1.6–1.8 THz (0.2 of bandwidth). While keeping the maximum value of the power transmission more than 90%, minimum value of the filtered frequencies are kept almost zero in the band-stop frequency range. Figure 5a and b shows the H_z field distributions at stopped frequencies of 1.68 and 1.75 THz for the double-stub filter structure. In 1.68 THz, light trapping mostly in the first stub as a FP resonance is evident while in 1.75 THz, the standing wave is created between the two stubs which make the filtering working frequency widen.

Conclusion

In this paper, a tunable plasmonic notch filter based on graphene in the THz frequency range is proposed. Study on the transmission spectra of the structure by taking the advantage of FEM calculations shows that increasing the applied voltage to the graphene layer, not only the central frequency is shifted, but also level of the pass band is improved. Increasing the voltage to 10 V will shift the notch frequency by 32 GHz with 64% improvement of the transmission maximum. More over, at the notch frequency the power transmission is zero. In addition, a band-stop plasmonic filter with BW of 0.2 THz is designed with double-stub and triple-stub structures which has improved the BW by 33% compare to the single-stub plasmonic filter. Our results pave a new and promising way to enhance the efficiency of the plasmonic filters, which is potentially applicable in tunable graphene-based devices at the THz frequency range.

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