Transmittance characteristics of the plasmonic graphene ribbon with a wing

Lin Yuan1,2), Xin Yan1,2), Yueke Wang1,2)*, Tian Sang1,2) and Guofeng Yang1,2)

1Optical Information Science and Technology Department, Jiangnan University, Wuxi, Jiangsu 214122, China

2Optoelectronic Engineering and Technology Research Center, Jiangnan University, Wuxi, Jiangsu 214122, China

ykwang@jiangnan.edu.cn

Abstract. We investigate the transmittance characteristics of graphene ribbons with a wing numerically by Finite Element Method. By conducting the dispersion relation of edge graphene plasmons (EGPs) modes and analyzing the mode distributions, it is believed that the transmission dips originate from the resonances of three kinds of EGPs modes respectively, including the symmetrical EGPs, anti-symmetrical EGPs, and EGPs of a semi-infinite sheet. By changing the width and length of the wing, the conclusion that transmission dips originate from EGPs modes is further approved. Thanks to the tunable permittivity of graphene by gate voltages, the transmittance dips can be easily tuned.

Recently, the research of graphene attracts more and more attention due to mechanical, electrical, optical, and thermal properties1). Especially, graphene is the most suitable candidate for establishing the platform of surface plasmons (SPs) at infrared frequencies2). Compared with the counterpart in the visible frequencies, which propagates along the noble metal surface, graphene SPs(GPs) show attractive properties, including high effective refractive index, strong confinement and tunable optical properties by gate voltage3). Many novel GPs phenomena have been studied such as cloaking4, 5), Talbot effect6), superlens7), negative refraction8) and so on. Also, tunable plasmonic devices in infrared frequencies are designed, including polarization converters9), absorbers10), filters11), and switches12).

With the development of the graphene manufacturing technique, many researchers pay more attention to the research on GPs propagating along the graphene nanoribbons, which are called as Edge GPs (EGPs) modes13, 14). EGPs modes are firstly observed experimentally by a scattering type SNOM in a patterned graphene nano-ribbon on the Al2O3 substrates15). The EGPs modes, which can possess deep-wavelength confinement, pave a new way to build compact plasmonic waveguide devices, including splitters16, resonators17, 18), demultiplexers19) and so on. Optical circuit model20) and plasmon wave function21) are also proposed to explain the physical meaning. Besides, other interesting optical phenomena of graphene nanoribbons structures are reported, such as plasmonic bistability22), plasmon induced transparency23), and sensors24).
In this paper, we propose a graphene ribbons structure, which is composed of an input graphene ribbon with a wing. Based on simulation results, we obtain the transmittance spectra in the infrared region ranging from 7\(\mu\)m-8.5\(\mu\)m, which include three transmission dips. By analyzing the mode distribution and dispersion, we believe the transmission dips come from the resonances of symmetrical EGPs (SEGPs), anti-symmetrical EGPs (AEGPs), and EGPs of a semi-infinite sheet (SIEGPs). By changing geometry parameters of the wing, the transmission dips are further proved to originate from the resonances of three kinds of EGPs mode. Besides, we also discuss the tuning of transmittance dips by the gate voltage.

![Fig. 1 Basic configuration of the graphene ribbons structure with a wing](image)

The proposed structure consists of a graphene ribbon waveguide on the SiO\(_2\) substrate with a wing shown as Fig. 1. The thickness of the graphene structures is 1nm. The refractive index of SiO\(_2\) substrate and medium above the graphene are 1.5 and 1, respectively. The length and width of the wing are \(l\) and \(w\). And the width of the input ribbon waveguide are \(w_0\) (Here, we choose \(w_0\) as 20nm, and incident ribbon waveguide only supports SEGPs mode ranging from 7\(\mu\)m to 8.5\(\mu\)m).

Commercial software COMSOL Multiphysics based on Finite Element Method(FEM) is adopted to solve the Maxwell equations.

The surface conductivity of graphene is \(\sigma_g\), which is obtained by the Kubo formula:

\[
\sigma_s = \frac{ie^2E_f}{\pi\hbar^2(\omega+i\tau)^{-1}} + \frac{ie^2}{4\pi\hbar} \ln\left[\frac{2E_f - (\omega+i\tau)^{-1}h}{2E_f + (\omega+i\tau)^{-1}h}\right] + \frac{ie^2k_BT}{\pi\hbar^2(\omega+i\tau)^{-1}} \ln[\exp(-\frac{E_f}{k_BT})+1]
\]

Here, temperature \(T\) is 300 K. It is obvious that \(\sigma_g\) depends on chemical potential \(E_f\), momentum relaxation time \(\tau\), and photon frequency \(\omega\). \(E_f\) can be tuned by the gate voltage which is applied on graphene. Besides, \(e, \hbar, k_B\) represent the electron charge, reduced Plank’s constant and Boltzman’s constant, respectively. The permittivity of graphene is governed by:

\[
e_s = 1 + \frac{\sigma_g\eta_0}{k_0\Delta}
\]

\(\eta_0\ (\approx 377\Omega)\) is the impedance of air, \(\tau\) is chosen as 0.5 ps. \(\Delta(=1nm)\) is the thickness of graphene. The permittivity of graphene can be electrically tuned by gate voltage, and therefore leads to a voltage-tuned value based on Eqs. (1) and (2).

Before investigating the transmittance characteristics, we first calculate dispersion relations and modes distributions of EGPs supported by graphene shown in Fig. 2. Figs. 2(a) and (b) show the real part of effective refractive index Re(neff) of EGPs with wavelength, when \(E_f=0.2eV\). As discussed in Refs. 13 and 14, the graphene ribbon with finite width can support two EGPs modes, including SEGPs and AEGPs mode. EGPs propagation directional component of the electric field is symmetrical for SEGPs, and anti-symmetrical for AEGPs. The semi-infinite graphene sheet can support only one EGPs (SIEGPs) mode. It is found that Re(neff) decreases with wavelength for the three EGPs modes. For SEGPs mode and AEGPs mode, Re(neff) decreases and increases with the width of the ribbon increasing, respectively. For 20 nm width graphene ribbon, the ribbon only supports SEGPs mode for the wavelength region (7\(\mu\)m-8.5\(\mu\)m) and AEGPs mode is cut off. And under the same wavelength, the...
Re(\text{n}_{\text{eff}}) of SEGPs is always larger than that of SIEGPs; that of SIEGPs is always larger than the Re(\text{n}_{\text{eff}}) of AEGPs. Besides, Fig. 2(c) shows that Re(\text{n}_{\text{eff}}) decreases with \text{E}_f increasing for all of the edge modes. Figs. 2(d)-(f) plot EGP propagation directional component of the electric field of SESPs, AESPs and SIESPs respectively, which can depict the mode distributions.

![Fig. 2](image)

**Fig.2.** (a) and (b) Real part of effective refractive index Re(\text{n}_{\text{eff}}) of three ESPs modes vs wavelengths under different width \( w \) of ribbons. (c) Re(\text{n}_{\text{eff}}) of three ESPs modes vs wavelengths under different Femi levels. The color plots for the EGP propagation directional component of the electric field of (d) SESPs mode, (e) AESPs mode, and (f) SIESPs mode.

When SEGPs mode propagates along the input ribbon along y-direction, EGPs can be excited in the wing. The wing can be assumed to be an F-P resonator for the EGPs, when the length \( L \) of the resonator is satisfied as:

\[
\text{Re}(\text{n}_{\text{eff}}) \frac{2\pi}{\lambda} L + \theta = m\pi
\]

the resonator is in F-P resonance, most energy of electromagnetic field is coupled into the wing, and the transmission reaches the minimum. Here, Re(\text{n}_{\text{eff}}) is the real part of the EGPs mode, \( m \) is the resonance order, \( L \) is the circumference length of EGPs resonator, and \( \theta \) is the additional phase (here, we ignore \( \theta \) for simplicity). The circumference length \( L \) of resonator is \( l \) for SESPs and AESPs mode; and \( w+2l \) for SIEGPs mode. The calculated transmission spectrum of the ribbon structure for different \( l \) (changing from 100nm to 104 nm) is shown in Fig. 3(a). Other parameters here are assumed to be \( w = 40nm \), and \( \text{E}_f = 0.2eV \). There are three groups of transmission dips (I, II and III) in the infrared region (ranging from 7\( \mu \)m to 8.5\( \mu \)m), the resonance wavelengths of which red-shift with the length \( l \) of the wing increasing. Figs. 3 (b), (d), and (f) plot the y component of the electric field of group I, II, and III, respectively, which shows the edge modes hardly propagate...
the wing. Concentration of electric field along the edges of wing proves that EGPs modes are excited in the wing and in resonance. Thus, we deduce transmission dips I, II, and III originate from the ring resonance of SIEGPs, third order resonance of SESPs, and second order resonance of AESPs respectively, based on Figs. 3(b)-(d). Symmetrical distribution of Ey in Fig. 3(c) illustrates dips II come from resonance of SESPs and anti-symmetrical distribution of Ey in Fig. 3(d) illustrates dips III come from resonance of AESPs, which are in accordance with Figs. 2(d) and (e), respectively. When increasing l, L of the resonator for all of three modes is lengthened. So, increasing l will produce the red-shift of the resonance wavelengths for the three transmission dips based on Eq. (3), shown in Fig. 3(a). The reason we draw the conclusion transmission dips I come from the resonance of SIEGPs will be further discussed below.

To further investigate the transmittance characteristics, we calculate transmission spectrum of ribbon structure under different width w of wing (ranging from 20nm to 60nm) in Fig. 4. Other parameters here are assumed to be l = 100nm, and Ef = 0.2eV. It is found the transmission dips II blue-shift, changing from 8.39 μm to 7.61 μm with increasing w. It is because the Re(neff) of SEGPs decreases with increasing w (shown in Fig. 2(a)), thus transmission dips II blue-shift with w based on Eq. (3), if we ignore θ. So we further confirm that the transmission dips II originate from the third resonance of the SEGPs. To the contrary, the transmission dips I change from 7.28 μm to 7.45 μm when w ranging from 40 nm to 60nm. It is because that though the Re(neff) of SIEGPs mode is independent on w, the circumference length L(=w+2l) for SIEGPs mode increases a little with w, so the transmission dips I red-shifts a little (about 170 nm), based on Eq. (3). Besides when w is 20 nm and 30 nm, there is no dip for the resonance of SIEGPs mode. It is because the width of the wing is so narrow that it can not support the SIEGPs mode in the region from 7μm to 8.5μm. The transmission dips III also red-shift changing from 7.43 μm to 8.45 μm when w is ranging from 30 nm to 50nm. We believe this group of transmission dips originates from the second order resonance of AEGPs mode. It is because Re(neff) of SEGPs increases with w (shown in Fig. 2(b)), and the resonance wavelength red-shifts based on Eq. (3). When w = 20 nm, the wing can not support AEGPs; and w = 60 nm, transmission dip of second order AEGPs moves to the wavelength larger than 8.5μm. Thus, there is no transmission dip III when w = 20 nm and 60 nm, in Fig. 4.
To further verify the transmittance dips I come from the ring resonance of SIEGPs mode, we calculate the evolution of transmission spectrum when fixing the circumference \((w+2l)\) of the wing to be 240 nm, shown in Fig. 5. It is found the wavelengths of the dips I are unchanged \((7.28 \mu m)\), when width \(w\) and length \(l\) of the wing varying from \((40 \text{ nm and } 100 \text{nm})\) to \((48 \text{ nm and } 96 \text{nm})\). It is because \(\text{Re}(\text{neff})\) and \(L(w+2l)\) are unchanged for SIEGPs mode, so does the resonance wavelength of dips I based on Eq. (3). Thus, the conclusion, that transmittance dips I originate from the ring resonance of SIEGPs mode, is approved. But wavelengths of the dips II blue-shift and III red-shift as \((w\) and \(l\)) changing from \((40 \text{ nm and } 100 \text{nm})\) to \((48 \text{ nm and } 96 \text{nm})\). It is because that \(\text{Re}(\text{neff})\) of SEGPs and \(L\) decreases with \(w\), so the resonance wavelength of dips II blue-shifts based on Eq. (3). Besides, \(\text{Re}(\text{neff})\) of AEGPs increases with \(w\), and the decrease of \(L\) is less, so the resonance wavelength of dips III red-shifts based on Eq. (3).

The transmission spectra under different Fermi level of graphene \(E_f\) (ranging from 0.2eV to 0.208eV) are shown in Fig. 6. Other parameters here are assumed to be \(l = 100 \text{nm}\), and \(w = 40 \text{nm}\). It is found that the three groups of transmission dips I, II, and III all blue-shift with \(E_f\). It is because \(\text{Re}(\text{neff})\) of all the three EGPs modes decrease with increasing \(E_f\) shown in Fig. 2(c). So the blue-shift happens when increasing \(E_f\) based on Eq. (3). It is believed that the simulation results pave a way to design tunable multiple windows of plasmonic filter in infrared region.

We have proposed a plasmonic graphene ribbon with a wing, and investigate the transmittance characteristics by FEM. We believe the transmission dips originate from the resonances of SEGPs mode, AEGPs mode and SIEGPs mode, by studying the dispersion relations and mode distributions of the three kinds of EGPs modes. The change regulations of the three transmission dips with the
geometry of the wing further confirm our findings. Besides, the transmission dips can be easily tuned by gate voltage, which provides a smart method to design tunable infrared plasmonic filters.

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