Mode analysis and research on graphene nanoribbons parallel-plate waveguide

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A graphene nanoribbon parallel-plate waveguide (GNPPW) in the infrared band is reported. Owing to the large loss, difficulty of control and shortages of traditional metals, graphene has been considered as a novel plasmonic material as the substitute for metals. In this reported work, the relationship between the dispersion characteristics, the propagation loss of the GNPPW's surface plasmon and the filled dielectric into the GNPPW are analysed. The results show that filling dielectric with a large permittivity can improve the confinement of the symmetric mode supported by the GNPPW. Moreover, the transmission distance and dispersion characteristics of the GNPPW under different chemical potentials are analysed. The performance of the waveguide can be effectively controlled by the filling dielectric and external means such as static voltage, achieving easy regulation and control of graphene. This research has some reference values for the production of novel graphene waveguide devices.

1. Introduction: Graphene has wide applications as a new material [1], owing to its unique optical properties, which have potential applications in the optical communication, sensors, integrated circuits and biomedical fields. Single-layer graphene's special structure give it properties that other substances do not possess, such as low loss and tunable carrier density that have been thoroughly studied in recent papers [2]. Surface plasmons (Sps) have a hybrid photonic and electronic excited state, which has maximum value in the surface of metals and attenuates in the metal and dielectric exponentially [3]. Traditional metals, for example Au, Ag, etc., have poor confinement and great loss in the process of propagating Sps [2]. Recently, graphene, as a new 2D plasmon material, has been shown to not only have low ohmic loss, but also its dispersion characteristics can be tuned by the static voltage or chemical doping [4]. Finite-width graphene nanoribbons can support two fundamental modes – a localised edge mode and a waveguide mode [5, 6]. Based on the graphene nanoribbon waveguide, the graphene parallel-plate waveguide filled with different mediums is proposed in this Letter, for which it is easy to conduct the experiment thanks to its simple structure.

2. Calculation method: The surface conductivity of graphene with random-phase approximation can be expressed as [7]

$$\sigma_g(\omega, \mu_c, \Gamma, T) = -\frac{ie^2(\omega + i2\Gamma)}{\pi\hbar^2}\left[\frac{1}{(\omega + i2\Gamma)^2} \times \int_0^\infty x\left(\frac{\partial f_d(x)}{\partial x} - \frac{\partial f_d(-x)}{\partial x}\right) \times \mathrm{d}x - \int_0^\infty x\left(\frac{\partial f_d(-x)}{(\omega + i2\Gamma)^2} - \frac{\partial f_d(x)}{4(x/\hbar)^2}\right)\mathrm{d}x\right] \quad (1)$$

Here, μ_c is the chemical potential, ω is the angular frequency, and Γ is the scattering rate ($\Gamma = 1/2\tau$). T is set as 300 K, the frequency f is equal to 30 THz. If the condition $K_BT \ll \mu_c$ is satisfied, (1) can be simplied as [8]

$$\sigma_{\text{inter}} \simeq \frac{ie^2}{4\pi\hbar}\ln\left[\frac{2|\mu_c| - (\omega + i/\tau)\hbar}{2|\mu_c| + (\omega + i/\tau)\hbar}\right] \quad (2)$$

$$\sigma_{\text{intra}} = \frac{ie^2K_BT}{\pi\hbar^2(\omega + i/\tau)}\left[\frac{\mu_c}{K_BT} + 2\ln\left(e^{-\mu_c/K_BT} + 1\right)\right] \quad (3)$$

According to the Maxwell equation, the permittivity [9, 10] of the graphene is derived by

$$\varepsilon(\omega) = 1 + i\sigma_g/(\varepsilon_0\omega h) \quad (4)$$

where h is the thickness of graphene and ε_0 is permittivity of air. If we want to make graphene exhibit metallic properties, where the real part of the relative permittivity must be negative [11], we can tune the static voltage to change the chemical potential to get the target value. In our simulation, the thickness of the graphene is set as 0.4 nm, which is close to the theoretical value [12]. The finite element method solver is also employed to solve the Maxwell equations in order to get eigensolutions of the wave vector. The transmission mode of the electromagnetic field can be written as

$$\mathrm{E}(x, y, z) = \mathrm{E}(y, z)\exp(i\beta k_0x - i\omega t) \quad (5)$$

The effective mode index and the propagation loss can be derived from the real and imaginary parts of the wave vector β [13].

3. Results and discussion: The graphene nanoribbon parallel-plate waveguide (GNPPW) structure is shown in Fig. 1, where the upper and lower layers are graphene and the middle layer is the dielectric. The width of the graphene nanoribbons is 15 nm, because it can achieve single-mode transmission when the width of the graphene nanoribbon is <55 nm [5] as shown in Fig. 2*a*. There exists a coupling effect between the single-layer graphene nanoribbons, resulting in two types of electromagnetic modes – a symmetric modes and an antisymmetric modes. First, we analyse the effects of the gap of graphene parallel-plate waveguides filled with air on the dispersion characteristics. As shown in Fig. 2*b*, the effective mode index of the waveguide is affected by the gap of the GNPPW. When the gap of the GNPPW increases, it leads to the effective mode index of the symmetric mode rising and the antisymmetric falling. Finally, the two modes approximately tend to intersect to each other. Furthermore, according to the simulation analysis, when the gap is <2 nm, there appears a higher mode. If the gap is >2 nm, the higher-order mode will suddenly cutoff. To get strong confinement and avoid the high-order mode, in the following analysis we select the width of the graphene parallel-plate waveguide as 2 nm.

The width of the graphene nanoribbon we used was 15 nm and the gap of the waveguide was 2 nm, which can be achieved in

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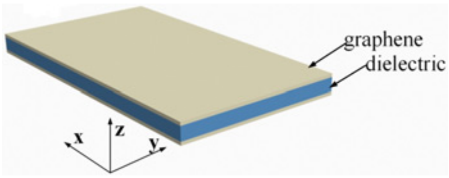

Figure 1 *Schematic of GNPPW structure*

modern optical technology because of the simple structure. We define the two different electromagnetic modes, the symmetric and the antisymmetric mode, based on the coupling between two graphene nanoribbons. The transmission performance is shown in the Fig. 3. The effective mode index of the two modes rises with the increase of permittivity, indicating the better and better confinement, but the antisymmetric mode fails to change significantly. The propagation loss of the two modes also rises as the permittivity increases; however, the propagation loss of the antisymmetric mode has a small change. This is reasonable because the propagation distance increases at the cost of confinement. In Figs. 4*c* and *d* we can visually distinguish the symmetric mode and the antisymmetric mode according to the direction *y* of the electric field distribution. From Figs. 4*a* and *b*, we can conclude that the electromagnetic energy of the symmetric mode is well confined in the region of the dielectric. As the permittivity increases, confinement is greatly improved. A possible reason is that light spreads along in the medium at the cost of the shortest time according to the format's principle. High permittivity always leads the light into the dielectric, hence the higher the permittivity the better the confinement. However, when the permittivity increases, the antisymmetric mode's confinement has a little change. The reason is that the energy of antisymmetric mode is mainly distributed in the sides of the waveguide as shown in Fig. 4*b*, leading to much energy diffusion outwards. On the contrary, the antisymmetric mode of the parallel-plate waveguide has lower transmission loss. Graphene is a lossy material, and the electromagnetic energy distribution on the side of the waveguide will avoid most of the electromagnetic energy loss, resulting in a long distance. However, the electromagnetic energy of the symmetric mode distributes in the area of the dielectric, which leads to strong confinement. As the permittivity increases, the parallel-plate waveguide also produces two kinds of high order modes, as shown in Figs. 4*e* and *f*. The increase of permittivity causes the electromagnetic energy to concentrate in the middle of the waveguide. More and more energy will concentrate in the middle of the waveguide, resulting in the electromagnetic wave number increasing sharply. Hence, two types of high-order mode will occur.

Sps in graphene can be tuned by static voltage besides the geometry structure, which is superior to noble metal. To comprehensively

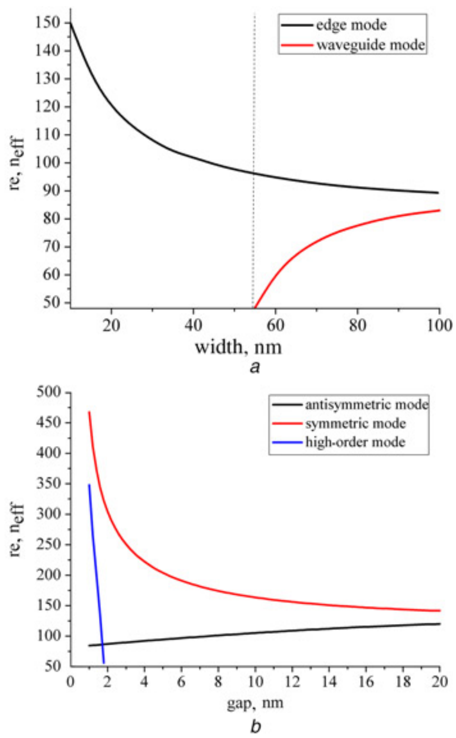

Figure 2 *Dependence of effective mode index on the width of the nanoribbon (Fig. 2a), and the parallel-plate waveguide gap (Fig. 2b)*

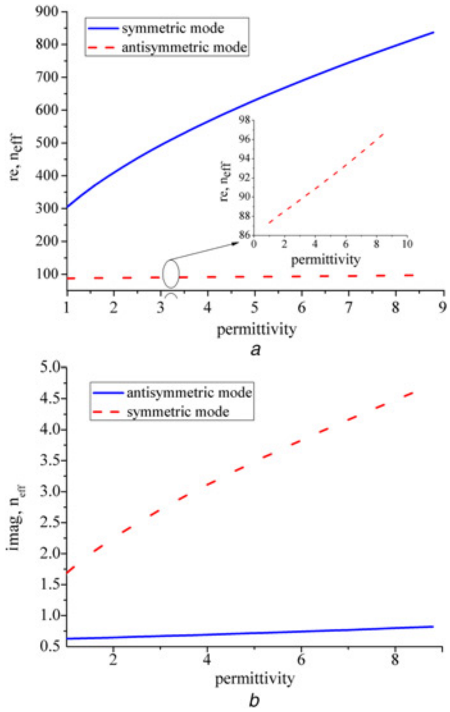

Figure 3 *Effective mode index (Fig. 3a), and propagation loss against permittivity (Fig. 3b)*

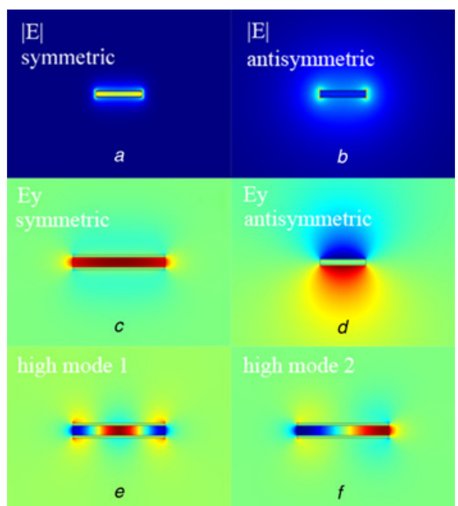

Figure 4 *|E| distribution of GNPPW's symmetric mode (Fig. 4a) and of GNPPW's antisymmetric mode (Fig. 4b); Ey distribution of GNPPW's symmetric mode (Fig. 4c) and of GNPPW's antisymmetric mode (Fig. 4d); Ey distribution of high-order mode1 (Fig. 4e) and of high-order mode2 (Fig. 4f)*

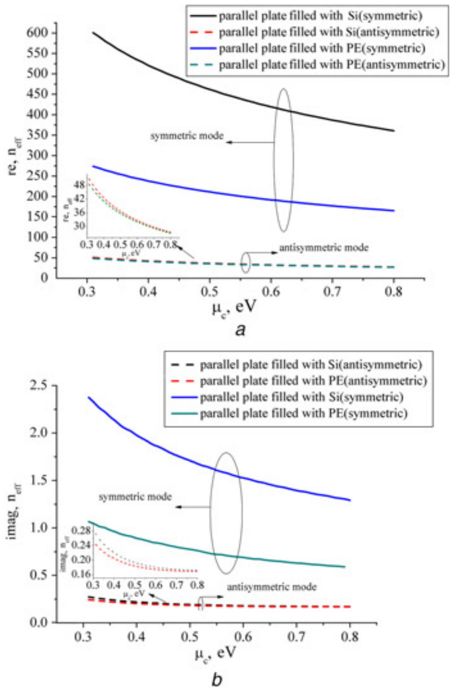

Figure 5 *Parallel waveguide's effective mode index (Fig. 5a), and propagation loss when filled with silicon and polyethylene against chemical potential μ_c (Fig. 5b)*

analyse the performance of the waveguide, we also calculated the performance of the GPPNW filled with different dielectric (PE and silicon) as function of the chemical potential μ_c. As shown in Fig. 4, when the chemical potential increases, both the effective mode index and the propagation loss of the two modes falls no matter which material is filled. The symmetric mode's confinement is strong but has a relative large transmission loss. The antisymmetric mode's confinement is poor but has a long propagation distance. Not only permittivity but also the chemical potential has little effect on the performance of the antisymmetric mode because of the edge effect of graphene (Fig. 5).

4. Conslusion: We have studied the performance of a GNPPW filled with different dielectric. According to the FEM simulation results, it has been shown that with the increase of the permittivity of the filling dielectric, the symmetric mode supported by the GNPPW has strong confinement and the antisymmetric mode has a long propagation distance. There are more high-order modes supported by the waveguide, which is helpful in the designing of THz devices such as multimode interferometers. We further analyse the performance of a parallel-plate waveguide filled with Si and PE under different chemical potentials, and we can obtain different transmission characteristics. Our study offers some reference values for future graphene plasmonic devices.

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6 References

[1] Luo X., Qiu T., Lu W., Ni Z.: 'Plasmons in graphene: recent progress and applications', *Mater. Sci. Eng. R Reports*, 2013, **74**, (11), pp. 351–376
[2] Jablan M., Soljacic M., Buljan H.: 'Plasmons in graphene: fundamental properties and potential applications', *Proc. IEEE*, 2013, **101**, (7), pp. 1689–1704
[3] Jiang T., Shen L., Wu J.-J., Yang T.-J., Ruan Z., Ran L.: 'Realization of tightly confined channel plasmon polaritons at low frequencies', *Appl. Phys. Lett.*, 2011, **99**, (26), p. 261103
[4] Vakil A., Engheta N.: 'Transformation optics using graphene', *Science*, 2011, **332**, (6035), pp. 1291–1293
[5] He S., Zhang X., He Y.: 'Graphene nano-ribbon waveguides of record-small mode area and ultra-high effective refractive indices for future VLSI', *Opt. Express*, 2013, **21**, (25), pp. 30664–30673
[6] Nikitin A.Y., Guinea F., Garcia-Vidal F.J., ET AL.: 'Edge and waveguide terahertz surface plasmon modes in graphene microribbons', *Phys. Rev. B*, 2011, **84**, (16), p. 161407
[7] Hanson G.W.: 'Dyadic Green's functions and guided surface waves for a surface conductivity model of graphene', *J. Appl. Phys.*, 2007, **103**, (6), pp. 1–18
[8] Low T., Avouris P.: 'Graphene plasmonics for terahertz to mid-infrared applications', *ACS Nano*, 2014, **8**, (2), pp. 1086–1101
[9] Zhu B., Ren G., Zheng S., Lin Z., Jian S.: 'Nanoscale dielectric-graphene-dielectric tunable infrared waveguide with ultra-high refractive indices', *Opt. Express*, 2013, **21**, (14), pp. 17089–17096
[10] Ooi K.J.A., Chu H.S., Ang L.K., Bai P.: 'Mid-infrared active graphene nanoribbon plasmonic waveguide devices', *J. Opt. Soc. Am. B*, 2013, **30**, (12), p. 3111
[11] Gómez-Díaz J.S., Perruisseau-Carrier J.: 'Graphen e–based plasmonic switches at near infrared frequencies', *Opt. Express*, 2013, **21**, (13), pp. 15490–15504
[12] Koppens F.H.L., Chang D.E., Garcia de Abajo F.J.: 'Graphene plasmonics: a platform for strong light–matter interactions', *Nano Lett.*, 2011, **11**, (8), pp. 3370–3377
[13] Liu P., Zhang X., Ma Z., Cai W., Wang L., Xu J.: 'Surface plasmon modes in graphene wedge and groove waveguides', *Opt. Express*, 2013, **21**, (26), pp. 32432–32440

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