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Nanofocusing in a tapered graphene plasmonic waveguide

Yunyun Dai[1,2], Xiaolong Zhu[2,3], N Asger Mortensen[2,3], Jian Zi[1,4] and Sanshui Xiao[2,3]

[1] Department of Physics, Key Laboratory of Micro- and Nano-Photonic Structures (Ministry of Education) and State Key Laboratory of Surface Physics, Fudan University, Shanghai 200433, People's Republic of China
[2] DTU Fotonik—Department of Photonics Engineering, Technical University of Denmark, DK-2800 Kongens Lyngby, Denmark
[3] Center for Nanostructured Graphene (CNG), Technical University of Denmark, DK-2800 Kgs. Lyngby, Denmark
[4] Collaborative Innovation Center of Advanced Microstructures, Nanjing University, Nanjing 210093, People's Republic of China

E-mail: saxi@fotonik.dtu.dk

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Abstract

Gated or doped graphene can support plasmons making it a promising plasmonic material in the terahertz regime. Here, we show numerically that in a tapered graphene plasmonic waveguide mid- and far-infrared light can be focused in nanometer scales, far beyond the diffraction limit. The underlying physics lies in that when propagating along the direction towards the tip both the group and phase velocities of the plasmons supported by the tapered graphene waveguide are reduced accordingly, eventually leading to nanofocusing at the tip with a huge enhancement of optical fields. The nanofocusing of optical fields in tapered graphene plasmonic waveguides could be potentially exploited in the enhancement of light–matter interactions.

Keywords: graphene plasmonics, nanofocusing, waveguiding

1. Introduction

Nanofocusing of light far beyond the diffraction limit has attracted intensive attention due to many potential applications [1]. Surface-plasmon polaritons bounded at metal surfaces have been exploited to achieve nanofocusing of light due to the strong ability to concentrate light at subwavelength scales. Indeed, various plasmonic structures have been proposed for nanofocusing including metal cones [2, 3], tapered gap waveguides between metal films [4–7], metal wedges [8], tapered sections of a metal film on a dielectric substrate [9, 10], and tapered metal V-grooves [11]. In addition to the strong localization of optical fields, nanofocusing is typically associated with a significant reduction of both the phase and group velocities of the plasmonic modes [2, 12]. Although the nanofocusing of mid-infrared light is important for a variety of applications such as sensing [13, 14] and chemical analysis [15, 16], metals such as gold and silver commonly used in the aforementioned plasmonic structures are not ideal in the mid- and far-infrared regimes.

Graphene is a monolayer of carbon atoms closely packed in a two-dimensional honeycomb lattice [17–20] with interesting electronic and optical properties. Doped or gated graphene can support plasmons in the mid- and far-infrared ranges with interesting optical features such as the tunability by changing the Fermi level, the deep subwavelength confinement, and the huge enhancement of optical fields [21–27]. As a result, a number of photonic devices such as waveguides, splitters, and superlenses could be envisioned [19, 28, 29]. Nanofocusing of light has been theoretically proposed in a monolayer graphene with spatially varied chemical potential [30]. However it is a big challenge to realize the spatial control of graphene potential. A tapered silicon waveguide has been used to achieve the field concentration for near-infrared light in graphene [31]. In this paper, we study theoretically the propagation of plasmons in a freestanding tapered graphene waveguide structure and show

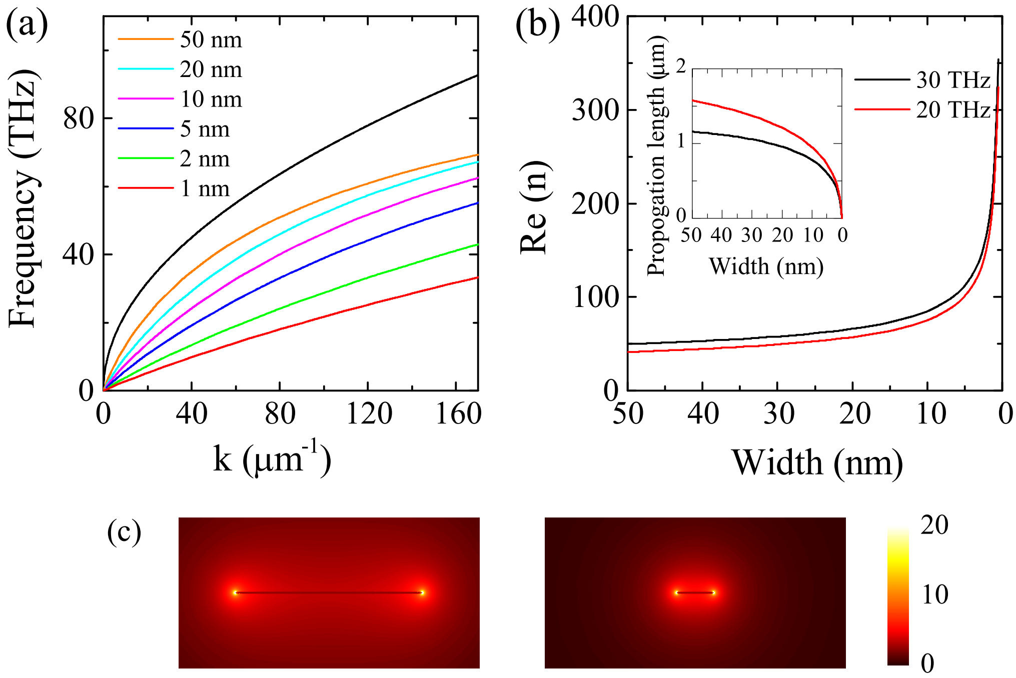

Figure 1. (a) Dispersion of plasmons in a graphene nanoribbon with different widths. The black line stands for that in a continuous graphene sheet. (b) Real part of the effective refractive index for two plasmon modes with a frequency of 20 and 30 THz as a function of the width. The inset illustrates the propagation length of the two plasmon modes. (c) Transverse cross-sectional view of the distributions of the electric-field amplitude of a plasmon mode with a frequency of 30 THz in a graphene nanoribbon with a width of 50 (left) and 10 nm (right).

numerically that mid- and far-infrared light can be sharply localized at the taper tip with a huge enhancement of optical near-fields.

2. Dispersion of plasmons in a graphene nanoribbon

Let us first investigate the dispersion of plasmons in a free-standing graphene nanoribbon with a constant width, obtained from COMSOL eigenvalue solver. In the simulations, graphene is modeled as an ultrathin film with a thickness $t = 0.5$ nm and a dielectric function $1 + \mathrm{i}\sigma(\omega)/\omega t\epsilon_0$, where ω is the angular frequency and ϵ_0 is the vacuum permittivity. The optical conductivity $\sigma(\omega)$ of graphene, obtained from the standard random-phase approximation [32, 33], is given by

$$\sigma(\omega) = \frac{\mathrm{e}^2 E_\mathrm{F}}{\pi\hbar^2}\frac{\mathrm{i}}{\omega + \mathrm{i}\tau^{-1}} + \frac{\mathrm{e}^2}{4\hbar}\left[\theta\left(\hbar\omega - 2E_\mathrm{F}\right) + \frac{\mathrm{i}}{\pi}\left|\frac{\hbar\omega - 2E_\mathrm{F}}{\hbar\omega + 2E_\mathrm{F}}\right|\right], \qquad (1)$$

where E_F is the Fermi energy, τ is the relaxation time, and θ is the Heaviside step function. The first and second terms on the right side are the intra- and inter-band contributions, respectively. In this work, we consider the case where the photon energy $\hbar\omega$ is always less than $2E_\mathrm{F}$ such that the intra-band contribution to the conductivity dominates. In all calculations, we take $E_\mathrm{F} = 0.3$ eV and $\tau = 0.3$ ps [22].

Figure 1(a) shows the dispersion of plasmons in a graphene nanoribbon with different widths. That of a continuous freestanding graphene sheet, approximately given by $\omega = \sqrt{4\alpha c E_\mathrm{F} k/\hbar}$ [34] with α being the fine structure constant and k the wavevector of plasmons, is also shown for comparison. Obviously, at a fixed frequency the corresponding wavevector of a plasmon mode in a graphene nanoribbon increases with a decrease in its width. This feature influences considerably both the phase and group velocities of plasmon modes in graphene nanoribbons with different widths. In figure 1(b) the real part of the effective refractive index of plasmon modes for a graphene nanoribbon as a function of its width together with their propagation length is shown. At a fixed frequency, the real effective index increases with decreasing width. In contrast, the propagation length shrinks with decreasing ribbon width. It can be understood by the fact that the electric field of the plasmon mode is more tightly confined at the narrow graphene ribbon compared to a wide one, as shown in figure 1(c). This leads to a higher loss and a shorter propagation length when the graphene nanoribbon has a narrow width [35, 36]. Clearly, these plasmon modes are the fundamental ones [28] with optical fields extremely confined to the graphene nanoribbon. Note that besides fundamental modes, graphene nanoribbons may support higher-order plasmonic modes and edge or 'bulk' modes [28, 37]. With the decrease in the nanoribbon width, however, there exists cut-offs for these high-order modes. For sufficiently small widths, graphene nanoribbons only support fundamental modes, e.g., for a free-standing graphene ribbon of width 100 nm and Fermi energy 0.5 eV, the cut-off for the high-order mode is around 0.16 eV [37].

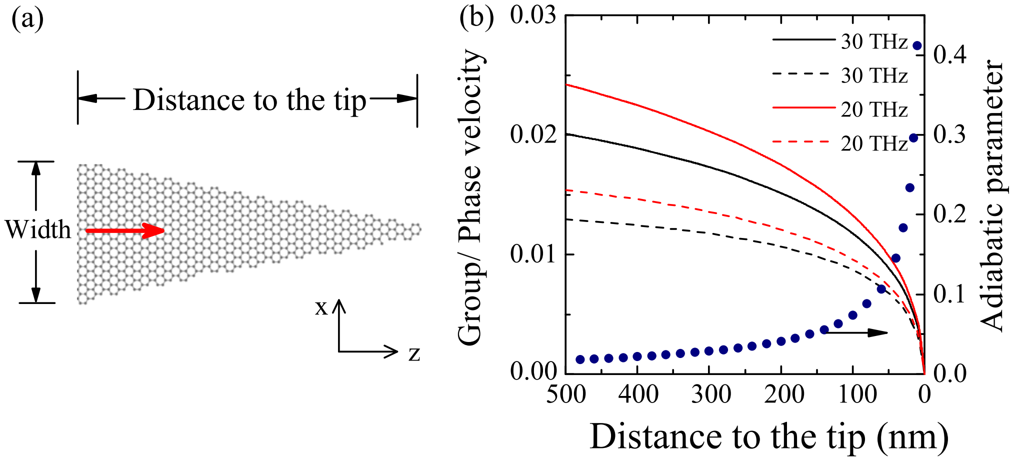

Figure 2. (a) Schematics of a tapered graphene waveguide. (b) Phase (solid lines) and group (dashed lines) velocities of two plasmon modes in a tapered graphene waveguide as a function of the distance to the tip. Circles represent the adiabatic parameter for a plasmon mode with a frequency of 30 THz.

3. Plasmons in a tapered graphene waveguide

The graphene waveguide structure under study is a tapered graphene nanoribbon with a gradually reduced width along the z direction, as schematically shown in figure 2(a). For the sake of simplicity, the tapered graphene waveguide is assumed to stands freely in air. The propagation of plasmons along a tapered graphene waveguide is strongly influenced by how rapidly the width varies with distance along the waveguide, mainly determined by the taper angle. For sufficiently small taper angles, the so-called adiabatic approximation is applicable. The tapered waveguide can now be viewed approximately as a series of short nanoribbons. In each short nanoribbon, the dispersion of plasmons is determined by its own width, discussed in the previous section.

We now consider a tapered graphene waveguide: the width of the wide side is 50 nm and the length from the wide side to the tip is 500 nm, corresponding to a taper angle $\theta = 5.72°$. Under the adiabatic approximation, the local phase and the group velocities of plasmons in the tapered graphene waveguide can be evaluated, shown in figure 2(b). Both the phase and group velocities of plasmons decrease when propagating along the direction towards the tip, and at the tip they tend to zero. Consequently, when propagating along the direction towards the tip plasmons will be slowed down asymptotically and eventually stopped at the tip.

To access the adiabatic approximation, an adiabatic parameter $\delta(z)$ is usually introduced [2, 12]

$$\delta(z) = \left| \mathrm{d}(k(z))^{-1}/\mathrm{d}z \right|, \tag{2}$$

where $k(z)$ is the wavevector of plasmons as a function of the position along the propagating direction z. To satisfy the adiabatic condition, the condition $\delta(z) \ll 1$ should be satisfied. The calculated adiabatic parameter is also shown in figure 2(b). For a plasmon mode with a frequency of 30 THz, $\delta(z)$ is small in the location away from the tip. It increases towards the tip which is a singularity. Note that the adiabatic condition implies a suppression of the back reflection and radiation scattering into free space during the propagation of plasmons. Therefore, in a tapered graphene waveguide with a gradually varying width plasmons can adiabatically propagate along the waveguide.

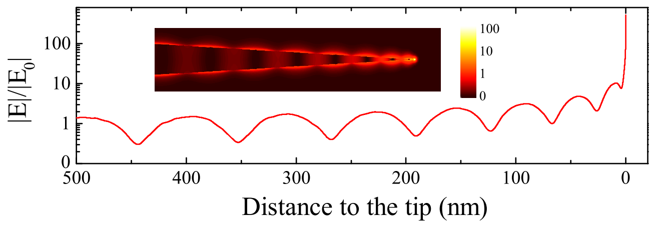

Figure 3. Amplitude of the local electric fields at one edge of a tapered graphene waveguide as a function of distance to the tip, normalized to that of a 50 nm wide graphene ribbon waveguide. The distributions of the amplitudes of the electric field at the tapered graphene waveguide is shown in the inset.

For plasmons propagating in a tapered graphene waveguide, there is a strong competition between the field localization and propagation loss including the intrinsic loss, back reflection due to the change in the effective refractive index, and radiation scattering into free space. In the region where the adiabatic condition is satisfied, plasmons can propagate adiabatically almost without back reflection and radiation scattering. However, the adiabatic condition does not hold in the vicinity of the tip, inevitably leading to back reflection and radiation scattering. As a result, the localization of optical fields should be influenced when approaching the tip.

To evaluate the nanofocusing in a tapered graphene waveguide with a taper angle of 5.72°, full-wave simulations (CST Microwave Studio) are performed for a plasmon mode with a frequency of 30 THz.Again, graphene is modeled as an ultrathin film with a thickness $t = 0.5$ nm, same to the COMSOL model used above, and the mesh size inside graphene is 0.1 nm and gradually increases outside graphene layer. The distributions of the amplitudes of the local electric fields are shown in figure 3. As propagating in the direction towards the tip, the effective wavelength of the plasmon mode

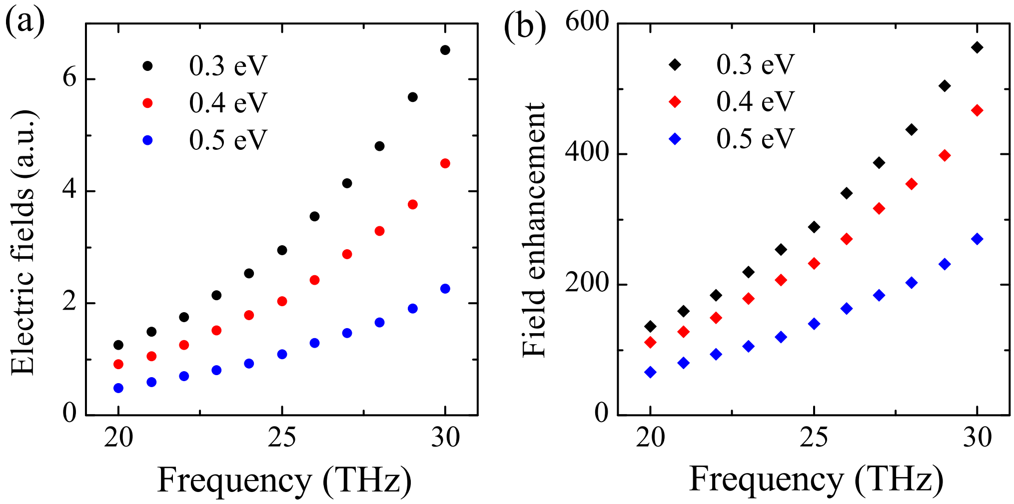

Figure 4. (a) Amplitudes of electric fields from 20 to 30 THz for different Fermi energies of graphene. (b) Field enhancement at the tip of the tapered graphene waveguide. Here, the field enhancement is defined as the electric files at the tip of a tapered graphene waveguide divided by that at the edge of a 50 nm wide graphene ribbon waveguide under the same condition.

is reduced progressively and the confinement of optical fields increases due to the slowing down of the mode. At the tip, the local electric field is strongest even in the presence of the intrinsic loss, back reflection, and radiation scattering. With respect to a 50 nm wide graphene ribbon waveguide, the electric field at the tip is enhanced by a factor about 560. This demonstrates clearly the nanofocusing and a huge enhancement of optical fields at the tip.

4. Nanofocusing and field enhancement

The nanofocusing in our proposed tapered graphene waveguide is wideband in nature. In principle, nanofocusing in the mid- and far-infrared regimes can be achieved at the tip provided that the taper angle is properly chosen. Figure 4 illustrates amplitudes of electric fields and the field enhancement achieved at the tip of tapered graphene waveguide from 20 to 30 THz for different Fermi energies with a taper angle of 5.72°. The field enhancement becomes stronger with the increase of the frequency. This is due to the fact that the propagation loss of the graphene plasmon mode decreases when increasing the frequency, leading to the higher field enhancement [29]. On the other hand, for the increased Fermi energy, the field enhancement turns weaker, which is attributed to the increased propagation loss of the graphene plasmon mode. It should be mentioned that our analysis relies on a classical electromagnetic description where graphene is described by a local conductivity, and the microscopic details of the edges of graphene nanoribbons [28] are not considered. For graphene nanoribbons with a very small width, non-local and even quantum effects may appear [38, 39]. With the aid of tight-binding model and random-phase approximation, the graphene plasmon energy shows a small blue shift at small ribbon widths when comparing the value from the classical model. The non-local effect normally serves to smear out field singularities [40]. These effects may have influences to our results, while the nanofocusing of graphene plasmon in general exists in the system we study here.

Conclusion

In conclusion, we have proposed and numerically analyzed the propagations of plasmons in a tapered graphene waveguide. When propagating towards the tip, both the phase and group velocities of plasmons are reduced progressively, eventually leading to the standstill of plasmons at the tip. As a result, the optical fields are hugely enhanced in the vicinity of the tip even in the presence of the intrinsic loss, back reflection, and radiation scattering, leading to nanofocusing. Our proposed tapered graphene waveguide for nanofocusing can work in a wide range of frequencies and may be potentially interesting for many applications.

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