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Confined transverse-electric graphene plasmons in negative refractive-index systems

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Transverse electric graphene plasmons are generally weakly confined in the direction perpendicular to the graphene plane. They are featured by a skin depth δ , namely the penetration depth of their evanescent fields into the surrounding environment, much larger than the wavelength λ in free space (e.g., $\delta > 10\lambda$). The weak spatial confinement of transverse electric graphene plasmons is now the key drawback that limits their practical applications. Here we report the skin depth of TE graphene plasmons can be largely decreased down to the subwavelength scale (e.g., $\delta < \lambda/10$) in negative refractive-index environments. The underlying mechanism originates from the different existence conditions for TE graphene plasmons in negative and positive refractive-index environments. To be specific, their existence in negative (positive) refractive-index environments requires $\text{Im}(\sigma_s) > 0$ ($\text{Im}(\sigma_s) < 0$) and lies in the frequency range of $\hbar\omega/\mu_c < 1.667$ ($\hbar\omega/\mu_c > 1.667$), where σ_s and μ_c are the surface conductivity and chemical potential of monolayer graphene, respectively.

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INTRODUCTION

In their seminal work in 2007, Mikhailov S. A. and Ziegler K.¹ proposed an exotic electromagnetic mode in the monolayer graphene, namely the transverse electric (TE, or *s*-polarized) graphene plasmons. The TE graphene plasmons lie in the frequency range of $\hbar\omega/\mu_c > 1.667$, since their existence requires $\text{Im}(\sigma_s) < 0$ ¹, where σ_s and μ_c are the surface conductivity and chemical potential of graphene, respectively. Another key feature for TE graphene plasmons is the spatial confinement. Note that highly confined surface plasmons^{2,3}, such as the transverse magnetic (TM, or *p*-polarized) graphene plasmons^{4–7}, can enable the flexible control of light flow in the subwavelength scale and even the extreme nanoscale; as such, they can enable many promising applications, including the on-chip terahertz to X-ray radiation sources^{8,9}, miniaturized modulators¹⁰, subwavelength guidance^{11–13}, deep-subwavelength imaging^{14–17}, and light energy harvesting and scattering^{18–20}. The spatial confinement of graphene plasmons in the direction perpendicular to the graphene plane can be quantitatively characterized by the skin depth δ . Here the skin depth²¹ is defined as the penetration depth of the evanescent fields carried by graphene plasmons into the surrounding environment. For TE graphene plasmons, their skin depth is inversely proportional to $|\text{Im}(\sigma_s)|$ ¹. Due to the small achievable negative-value of $\text{Im}(\sigma_s)$ (i.e., $\max(|\text{Im}(\sigma_s)|) \sim G_0$ (Fig. 1)), TE graphene plasmons are featured by a skin depth at least in the wavelength scale, where $G_0 = e^2/4\hbar$ is the universal optical conductivity. To be specific, we generally have $\delta > 10\lambda$ (Supplementary Fig. 1) for TE plasmons in monolayer graphene, where λ is the wavelength in free space. As severely limited by the weak spatial confinement, only several potential applications of TE graphene plasmons have been reported, such as Brewster effects²², polarizers²³, optical sensors²⁴, waveguide phase, and

amplitude modulators²⁵. On the other hand, rapid progress in nano-photonics has fuelled a quest for highly confined TE graphene plasmons, in addition to the highly confined TM graphene plasmons. This way, highly confined graphene plasmons can be achieved without stringent requirement on the polarization of light and can benefit more practical applications based on TE waves. Such a quest still remains elusive, although many researches of TE polaritons in graphene^{26–29} and other 2D materials^{30–34} have been ignited by the pioneering work in 2007.

Here we theoretically reveal a viable way to largely enhance the spatial confinement of TE graphene plasmons by using the environment with the negative permeability or refractive index. As firstly proposed by Veselago in 1968³⁵, the negative refractive-index materials simultaneously have negative permittivity and negative permeability; they have triggered tremendous researches both on fundamental science and practical applications^{36–40}, exemplified by the well-known negative refraction⁴¹, the perfect lens/superlens^{37,42}, the inverse Doppler effect^{43–46} and the backward Cherenkov radiation^{47–50}. In principle, the environment with the negative permeability or refractive index can be effectively constructed, for example, by metamaterials^{36,41,51} and photonic crystals^{52–55}. We find the existence condition of TE graphene plasmons in negative refractive-index environments is drastically different from that in positive refractive-index environments. In negative refractive-index environments, the existence of TE graphene plasmons become to require $\text{Im}(\sigma_s) > 0$; as a result, TE graphene plasmons now lie in the frequency range of $\hbar\omega/\mu_c < 1.667$ at room temperature. Moreover, due to the availability of the large positive value of $\text{Im}(\sigma_s)$ ($\max(|\text{Im}(\sigma_s)|) \sim 10^2 G_0$), the skin depth of TE graphene plasmons can be largely decreased down to the subwavelength scale (e.g., $\delta < \lambda/10$).

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Fig. 1 Existence condition of TE graphene plasmons in the negative and positive refractive-index environments. **a** Structural schematic. The monolayer graphene is located in a symmetric environment with the relative permittivity $\epsilon_{r1} = \epsilon_{r2} = \epsilon_r$ and the relative permeability $\mu_{r1} = \mu_{r2} = \mu_r$. **b** Existence condition of TE graphene plasmons in environments with various values of ϵ_r and μ_r . **c** Surface conductivity of monolayer graphene as a function of frequency at 300 K. The emergence of TE graphene plasmons in environments with $\mu_r > 0$ requires $\text{Im}(\sigma_s) < 0$, which exists in the frequency range of $\hbar\omega/\mu_c > 1.667$. In contrast, their emergence in environments with $\mu_r < 0$ requires $\text{Im}(\sigma_s) > 0$, existing in the range of $\hbar\omega/\mu_c < 1.667$. Here we set the chemical potential $\mu_c = 0.2$ eV and the relaxation time $\tau = 0.2$ ps. $G_0 = e^2/4\hbar$ is the universal optical conductivity.

RESULTS AND DISCUSSION

General existence condition for TE graphene plasmons

We focus on the discussion of TE surface plasmons supported by the monolayer graphene. For TE graphene plasmons, their in-plane wavevector q (parallel to the graphene plane) is generally comparable to the wavevector $k_0 = \omega/c$ of light in free space, where c is the speed of light in free space. As such, the nonlocal response of graphene is negligible, and it is reasonable to use the local Kubo formula to describe the surface conductivity σ_s of graphene. That is $\sigma_s = \sigma_{s,\text{intra}} + \sigma_{s,\text{inter}}$, where

$$\sigma_{s,\text{intra}} = \frac{ie^2 k_B T}{\pi \hbar^2 (\omega + \frac{i}{\tau})} \left(\frac{\mu_c}{k_B T} + 2 \ln \left(e^{-\frac{\mu_c}{k_B T}} + 1 \right) \right) \quad (1)$$

and $\sigma_{s,\text{inter}} = \frac{ie^2 (\omega + \frac{i}{\tau})}{\pi \hbar^2} \int_0^\infty \frac{f_d(-x) - f_d(x)}{(\omega + \frac{i}{\tau})^2 - 4(\frac{\hbar}{2})^2} dx$. Here $\sigma_{s,\text{intra}}$ and $\sigma_{s,\text{inter}}$ are the parts of the conductivity related to the intra-band and inter-band transitions, respectively; $f_d(x) = (e^{\frac{x - \mu_c}{k_B T}} + 1)^{-1}$ is the Fermi-Dirac distribution function; e is the electron charge, T is the temperature, τ is the relaxation time, and μ_c is the chemical potential.

Figure 1 shows the general existence condition for TE graphene plasmons. The monolayer graphene is located at the interface between region 1 and region 2 (Fig. 1a). Region 1 with $z < 0$ (region 2 with $z > 0$) has the relative permittivity ϵ_{r1} (ϵ_{r2}) and the relative permeability μ_{r1} (μ_{r2}). For conceptual demonstration, we let $\epsilon_{r1} = \epsilon_{r2} = \epsilon_r$ and $\mu_{r1} = \mu_{r2} = \mu_r$. From the classical electromagnetic wave theory (see Supplementary Notes 1 and 2), the dispersion for TE graphene plasmons is governed by

$$2k_z + \omega \sigma_s \mu_0 \mu_r = 0 \quad (2)$$

where $k_z = \sqrt{\frac{\omega^2}{c^2} \epsilon_r \mu_r - q^2}$ is the out-of-plane (perpendicular to the graphene plane) component of wavevector; μ_0 is the permeability in free space.

Equation (2) explicitly indicates the existence condition for TE graphene plasmons, as briefly summarized in Fig. 1b, c. To be specific, for the environment with $\mu_r > 0$ (e.g., positive refractive-index environments), Eq. (2) has solutions only if $\text{Im}(\sigma_s) < 0$, where the negative $\text{Im}(\sigma_s)$ lies in the frequency range of $\hbar\omega/\mu_c > 1.667$ (Fig. 1c). In contrast, for the environment with $\mu_r < 0$ (e.g., negative refractive-index environments), the existence of TE graphene plasmons becomes to require $\text{Im}(\sigma_s) > 0$ from Eq. (2) (Fig. 1b) and lies in the range of $\hbar\omega/\mu_c < 1.667$ at room temperature (Fig. 1c).

On the other hand, Eq. (2) also indicates that the skin depth of TE graphene plasmons is proportional to $1/|\text{Im}(\sigma_s)|$ for arbitrary μ_r , since the skin depth is mathematically defined as $\delta = 1/\text{Im}(k_z)$. In other words, in the frequency range where TE graphene plasmons could exist, a larger value of $|\text{Im}(\sigma_s)|$ would lead to a smaller skin depth and thus a larger spatial confinement. Note that the value of $\text{Im}(\sigma_s)$ for the monolayer graphene is dominantly determined by $\sigma_{s,\text{intra}}$ especially in the frequency range of $\hbar\omega/\mu_c \ll 1.667$, while it is mainly determined by $\sigma_{s,\text{inter}}$ if $\hbar\omega/\mu_c > 1.667$. As a result, the maximum value of $|\text{Im}(\sigma_s)|$ can reach $\sim 40G_0$ at $\hbar\omega/\mu_c < 1.667$ due to the contribution of $\sigma_{s,\text{intra}}$ (Fig. 1c); in contrast, it is only $\sim 0.3G_0$ at $\hbar\omega/\mu_c > 1.667$ with the negligible contribution from $\sigma_{s,\text{intra}}$ (Fig. 1c). This way, the minimum skin depth of TE graphene plasmons in negative permeability environments would be much smaller than that in positive permeability environments.

Moreover, if $\hbar\omega/\mu_c \ll 1.667$, $\sigma_{s,\text{intra}}$ in Eq. (1) is dependent on the temperature T , the relaxation time τ , and the chemical potential μ_c besides the angular frequency ω . These parameters (T , τ and μ_c) provide us extra degrees of freedom to achieve the large value of $|\text{Im}(\sigma_s)|$; see for example in Fig. 2. Then in negative permeability environments, these parameters could enable us the capability to flexibly modulate the basic features of TE graphene plasmons (Figs. 2 and 3), including their spatial confinement. Below the influence of these parameters on TE graphene plasmons in negative refractive-index environments is analyzed in detail, where the negative refractive-index environment ($\mu_r < 0$ and $\epsilon_r < 0$) is a typical negative permeability environment ($\mu_r < 0$). In addition, the loss in the surrounding environment is artificially neglected, since the reasonable amount of loss will not have a drastic influence on the confined TE graphene plasmons.

Influence of the relaxation time on TE graphene plasmons

Figure 2 shows the influence of relaxation time on TE graphene plasmons in negative refractive-index environments, from the perspective of the in-plane wavevector. According to Eq. (2), it is straightforward to derive the expression for the in-plane wavevector q , that is

$$q = \sqrt{k_0^2 \epsilon_r \mu_r - \frac{1}{4} \omega^2 \mu_0^2 \mu_r^2 \sigma_s^2} \quad (3)$$

To facilitate the discussion, the effective refractive index of TE graphene plasmons is denoted as $n_{\text{eff},0} = \text{Re}(q)/k_0$ and plotted in Fig. 2; see the information of $\text{Im}(q)/k_0$ in Supplementary Fig. 2 in Supplementary Note 3. In addition, since the quality factor $\text{Re}(q)/\text{Im}(q)$ is oftentimes regarded as a key parameter to characterize the basic feature of surface plasmons, the quality factor of TE graphene plasmons is also briefly discussed in Supplementary Figs. 3 and 4 in Supplementary Note 4. For the monolayer graphene, the maximum positive value of $\text{Im}(\sigma_s)$ appears in the frequency range of $\hbar\omega/\mu_c < 0.1$ (Fig. 2a). If the relaxation time increases (i.e., the loss in graphene decreases), $\max(|\text{Im}(\sigma_s)|)$ in the interested frequency range increases and can be up to $\sim 100G_0$ (Fig. 2a). Due to the availability of large positive $\text{Im}(\sigma_s)$, the

Fig. 2 TE graphene plasmons in negative refractive-index environments. For conceptual demonstration, the negative refractive-index environment has the relative permittivity $\epsilon_r = -1$ and the relative permeability $\mu_r = -1$. **a** Surface conductivity of monolayer graphene for different values of relaxation time τ . **b** Dispersion of TE graphene plasmons. For each dispersion curve, its peak (highlighted by the solid dot) corresponds to the maximum in-plane wavevector $\text{Re}(q)_{\text{peak}}$ of TE graphene plasmons at the frequency of ω_{peak} . **c** Influence of the relaxation time on $\text{Re}(q)_{\text{peak}}$ and ω_{peak} . Here $\mu_c = 0.2$ eV and $T = 300$ K. In **c** the colored dots are extracted from **(b)**; the black solid line (i.e., relation between ω_{peak} and τ) is the analytical solution of $d[\frac{\text{Re}(q)}{k_0}]/d\omega = 0$; the gray solid line (relation between $\text{Re}(q)_{\text{peak}}$ and τ) is obtained by substituting the analytical solution of ω_{peak} into Eq. (3).

Fig. 3 Influence of the temperature and the chemical potential on TE graphene plasmons in negative refractive-index systems. **a** In-plane wavevector $\text{Re}(q)$ of TE graphene plasmons (normalized by the wavevector of light in free space k_0) as a function of the temperature T . **b**, **c** Skin depth δ and quality factor $\text{Re}(q)/\text{Im}(q)$ of TE graphene plasmons at different temperatures and chemical potentials (their values are denoted in the figure). λ is the wavelength of light in free space. Here $\epsilon_r = -1$, $\mu_r = -1$, and the electron mobility is $\mu = 10000 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$. The corresponding relaxation time can be obtained from $\tau = \mu_c \mu / (e v_F^2)$, where $v_F = 1 \times 10^6 \text{ m s}^{-1}$ is the Fermi velocity.

maximum $n_{\text{eff},0}$ in negative refractive-index environment is much larger than 1 (e.g., up to $n_{\text{eff},0} \approx 1.4$ in Fig. 2b, c; also see Supplementary Note 5), and the maximum value of $n_{\text{eff},0}$ would increase if the relaxation time increases. Such a large value of $n_{\text{eff},0}$ is favored for the practical application of TE graphene plasmons. We emphasize that in positive refractive-index environment, $n_{\text{eff},0}$

is generally very close to 1, such as $n_{\text{eff},0} \approx 1.00006$ in Supplementary Fig. 5 in Supplementary Note 6.

Influence of T and μ_c on TE graphene plasmons

Figure 3 shows the influence of the temperature T and the chemical potential μ_c on TE graphene plasmons in negative

refractive-index environments. In short, if the temperature or the chemical potential increases, the achievable maximum value of $n_{\text{eff},0}$ for TE graphene plasmons would increase, e.g., up to $n_{\text{eff},0} = 1.65$ in Fig. 3a. We note that in Fig. 3a, the achievable maximum value of $n_{\text{eff},0}$ at high temperatures is more sensitive to the temperature variation than that at low temperatures. This phenomenon is caused by the fact that in Eq. (1), the temperature-insensitive term of $\frac{ie^2 k_B T}{\pi \hbar^2 (\omega + \frac{i}{\tau})} \cdot \frac{\mu_c}{k_B T} = \frac{ie^2 \mu_c}{\pi \hbar^2 (\omega + \frac{i}{\tau})}$ plays a dominant role at low temperatures for $\sigma_{s,\text{intra}}$, while the temperature-sensitive term of $\frac{ie^2 k_B T}{\pi \hbar^2 (\omega + \frac{i}{\tau})} \cdot 2 \ln(e^{\frac{\mu_c}{k_B T}} + 1)$ becomes important to $\sigma_{s,\text{intra}}$ at high temperatures.

Correspondingly, if the temperature or the chemical potential increases, the minimum skin depth of TE graphene plasmons would decrease (Fig. 3b). To be specific, the minimum skin depth of TE graphene plasmons in negative refractive-index environments can readily become subwavelength, such as $\delta/\lambda < 1$ for the case with $\mu_c = 0.2$ eV at $T = 300$ K in Fig. 3b. Furthermore, the skin depth can even be decreased down to the deep-subwavelength scale, such as $\delta/\lambda < 0.1$ for the case with $\mu_c = 0.5$ eV at $T = 300$ K in Fig. 3b. As such, the usage of negative refractive-index environments can largely decrease the minimum skin depth of TE graphene plasmons by at least two orders of magnitude, compared to positive refractive-index environments in which $\delta/\lambda > 10$ (Supplementary Fig. 1). We emphasize that the enticing subwavelength skin depth of TE graphene plasmons can already be achieved at room temperature, although the temperature's influence in Fig. 3 is studied in a relatively wide range of temperature and the high temperature such as 3000 K in practical scenarios might lead to the instability of negative refractive-index materials. Moreover, it is worthy to highlight that the phenomenon of the temperature-induced large enhancement of the spatial confinement for TE graphene plasmons is only exists in negative refractive-index environments (Fig. 3) and will not happen for positive refractive-index environments (Supplementary Fig. 5). In addition, TE graphene plasmons in negative refractive-index environments generally have a relatively small quality factor $\text{Re}(q)/\text{Im}(q)$ (Fig. 3c), due to their high spatial confinement and the large material loss of graphene at the studied frequency range.

Influence of μ_r and ϵ_r on TE graphene plasmons

Figure 4 shows the drastic difference of TE graphene plasmons in positive and negative refractive-index environments from another perspective of view, that is, the influence of $|\mu_r|$ and $|\epsilon_r|$ on $\text{Re}(q)/|k|$, where $k = k_0 \sqrt{\epsilon_r \mu_r}$ is the wavevector of light in the surrounding environment. Physically, $\text{Re}(q)/|k|$ is equivalent to the ratio between the wavelength of light in the surrounding environment λ_{environ} and the wavelength of TE graphene plasmons λ_{plasmon} , namely $\text{Re}(q)/|k| = \lambda_{\text{environ}}/\lambda_{\text{plasmon}}$. That is, a large $\text{Re}(q)/|k|$ indicates a larger contrast between λ_{environ} and λ_{plasmon} . Note that $k \neq k_0$ where k_0 is the wavevector of light in free space, and thus $\text{Re}(q)/|k|$ is not the effective refractive index of TE graphene plasmons $n_{\text{eff},0} = \text{Re}(q)/k_0$ discussed in Figs. 2 and 3.

From Fig. 4, the variation of both $|\mu_r|$ and $|\epsilon_r|$ for negative refractive-index environments would have a large impact on $\text{Re}(q)/|k|$ than that for positive refractive-index environments. To be specific, in negative refractive-index environments, $\text{Re}(q)/|k| > 10$ is achievable if we increase $|\mu_r|$ and decrease $|\epsilon_r|$. As such, a larger contrast between λ_{environ} and λ_{plasmon} exists in negative refractive-index environments. In contrast, in positive refractive-index environments, $\text{Re}(q)/|k|$ is insensitive to the variation of $|\mu_r|$ and $|\epsilon_r|$, and it is always very close to 1. Therefore, there is the negligible contrast between λ_{environ} and λ_{plasmon} in positive refractive-index environments. Note that the large value of $\text{Re}(q)/|k|$ is favored in practical applications, which can be used, for

Fig. 4 Influence of $|\mu_r|$ and $|\epsilon_r|$ on TE graphene plasmons in negative refractive-index environments. Here the in-plane wavevector $\text{Re}(q)$ of TE graphene plasmons is normalized by the wavevector $k = k_0 \sqrt{\epsilon_r \mu_r}$ of light in the surrounding environment. The setup of monolayer graphene is the same as that in Fig. 2a with the relaxation time $\tau = 0.2$ ps. For comparison, the influence of $|\mu_r|$ and $|\epsilon_r|$ on TE graphene plasmons in positive refractive-index environments is also shown. For the negative refractive-index environments, $\epsilon_r < 0$ and $\mu_r < 0$ and $T = 300$ K; for the positive refractive-index systems, $\mu_r > 0$, $\epsilon_r > 0$ and $T = 100$ K. The environments with ϵ_r near zero or μ_r near zero can be effectively constructed for example via metamaterials^{36,41,51}, photonic crystals^{52–55}, and waveguides^{57–59}.

example, to achieve the extraordinarily large scattering cross section from tiny objects in low-index environments⁵⁶. More discussion on the influence of $|\mu_r|$ and $|\epsilon_r|$ can be obtained in Supplementary Figs. 6 and 7 in Supplementary Note 7.

In conclusion, we have theoretically revealed some emerging features of TE graphene plasmons in negative refractive-index environments, including their existence condition of $\text{Im}(\sigma_s) > 0$ and their existing frequency range of $\hbar\omega/\mu_c < 1.667$. Importantly, these TE graphene plasmons can become highly confined in the direction perpendicular to the graphene plane. To be specific, their skin depth can decrease down to the deep-subwavelength scale (e.g., $\delta < \lambda/10$). Then the existence of these highly confined TE graphene plasmons should be robust to various surrounding environments (i.e., the permittivity and/or permeability of the substrate and superstrate can be largely different). Such a feature is drastically different from the weakly confined TE graphene plasmons in the positive refractive-index environment, which exist mainly in the almost symmetric environments (the substrate and superstrate should have the negligible difference in their permittivity or permeability)^{1,28}. Our findings in this work further indicate that the negative refractive-index materials might serve as a versatile platform to enable more practical applications of TE graphene plasmons, such as subwavelength guidance, some exotic scattering phenomena of light, and the exploration of TE plasmons in controlling the free electron radiation (e.g., Cherenkov radiation).

METHODS

Dispersion of TE graphene plasmons

Without loss of generality, the monolayer graphene is located at the interface between region 1 and region 2 (Fig. 1a), where region 1 with $z < 0$ (region 2 with $z > 0$) has the relative permittivity ϵ_{r1} (ϵ_{r2}) and the relative permeability μ_{r1} (μ_{r2}). For TE graphene plasmons, their electric fields are along the y direction. According to the electromagnetic theory¹⁹, one can

set the electric fields in each region as

$$\mathbf{E}_1 = \hat{y}E_1 e^{iqx - ik_{z1}z} \quad (4)$$

$$\mathbf{E}_2 = \hat{y}E_2 e^{iqx + ik_{z2}z} \quad (5)$$

Accordingly, the relationship between $k_{z1,2}$ and q is

$$k_{z1,2} = \sqrt{\frac{\omega^2}{c^2} \epsilon_{r1,2} \mu_{r1,2} - q^2} \quad (6)$$

In the above equations, q is the component of the wavevector parallel to the interface, k_{z1} and k_{z2} are the component of the wavevector perpendicular to the interface in region 1 and region 2, respectively, and ω is the angular frequency. The magnetic field in each region can be obtained according to $\nabla \times \mathbf{E} = i\omega\mu\mathbf{H}$. By enforcing the boundary conditions:

$$\hat{n} \times (\mathbf{E}_1 - \mathbf{E}_2) = 0 \quad (7)$$

$$\hat{n} \times (\mathbf{H}_1 - \mathbf{H}_2) = \sigma_s \mathbf{E}|_{\text{boundary}} \quad (8)$$

we can obtain the dispersion of TE graphene plasmons as

$$\frac{k_{z1}}{\mu_{r1}} + \frac{k_{z2}}{u_{r2}} + \omega\sigma_s\mu_0 = 0 \quad (9)$$

where μ_0 is the permeability in free space.

DATA AVAILABILITY

The data that support the plots within this paper and other findings of this study are available from the corresponding author upon reasonable request.

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REFERENCES

- Mikhailov, S. A. & Ziegler, K. New electromagnetic mode in graphene. *Phys. Rev. Lett.* **99**, 016803 (2007).
- Basov, D. N., Fogler, M. M. & García de Abajo, F. J. Polaritons in van der Waals materials. *Science* **354**, 195–204 (2016).
- Low, T. et al. Polaritons in layered two-dimensional materials. *Nat. Mater.* **16**, 182–194 (2017).
- Grigorenko, A. N., Polini, M. & Novoslov, K. S. Graphene plasmonics. *Nat. Photon* **6**, 749–758 (2012).
- Koppens, F. H. L., Chang, D. E. & García de Abajo, F. J. Graphene plasmonics: A platform for strong light–matter interactions. *Nano Lett.* **11**, 3370–3377 (2011).
- Xu, Q. et al. Effects of edge on graphene plasmons as revealed by infrared nanoimaging. *Light Sci. Appl.* **6**, e16204 (2017).
- Lu, Y. et al. Highly efficient plasmon excitation in graphene-Bi₂Te₃ heterostructure. *J. Opt. Soc. Am. B* **33**, 1842–1846 (2016).
- Wong, J. L., Kaminer, I., Ilic, O., Joannopoulos, J. D. & Soljačić, M. Towards graphene plasmon-based free-electron infrared to X-ray sources. *Nat. Photonics* **10**, 46–52 (2016).
- Rosolen, G. et al. Metasurface-based multi-harmonic free-electron light source. *Light Sci. Appl.* **7**, 64 (2018).
- Liu, M. et al. A graphene-based broadband optical modulator. *Nature* **474**, 64–67 (2011).
- Liu, L., Han, Z. & He, S. Novel surface plasmon waveguide for high integration. *Opt. Express* **13**, 6645–6650 (2005).
- Vakil, A. & Engheta, N. Transformation optics using graphene. *Science* **332**, 1291–1294 (2011).
- Iranzo, D. A. et al. Probing the ultimate plasmon confinement limits with a van der Waals heterostructure. *Science* **360**, 291–295 (2018).
- Zhu, J. et al. A holey-structured metamaterial for acoustic deep-subwavelength imaging. *Nat. Phys.* **7**, 52–55 (2011).
- Sapienza, R. et al. Deep-subwavelength imaging of the modal dispersion of light. *Nat. Mater.* **11**, 781–787 (2012).
- Lin, X. et al. All-angle negative refraction of highly squeezed plasmon and phonon polaritons in graphene-boron nitride heterostructures. *Proc. Natl. Acad. Sci. U.S.A.* **114**, 6717–6721 (2017).

- Jiang, J., Lin, X. & Zhang, B. Broadband negative refraction of highly squeezed hyperbolic polaritons in 2D materials. *Research* **2018**, 2532819 (2018).
- Aubry, A. et al. Plasmonic light-harvesting devices over the whole visible spectrum. *Nano Lett.* **10**, 2574–2579 (2010).
- Qian, C. et al. Experimental observation of superscattering. *Phys. Rev. Lett.* **122**, 063901 (2019).
- Qian, C. et al. Multifrequency superscattering from subwavelength hyperbolic structures. *ACS Photonics* **5**, 1506–1511 (2018).
- Kong, J. A. *Electromagnetic Wave Theory* (EMW Publishing, Cambridge, 2008).
- Lin, X., Shen, Y., Kaminer, I., Chen, H. S. & Soljačić, M. Transverse-electric Brewster effect enabled by nonmagnetic two-dimensional materials. *Phys. Rev. A* **94**, 023836 (2016).
- Bao, Q. et al. Broadband graphene polarizer. *Nat. photonics* **5**, 411–415 (2011).
- Sun, L. et al. Refractive index mapping of single cells with a graphene-based optical sensor. *Sens. Actuators B Chem.* **242**, 41–46 (2017).
- Shkerdin, G., Alkorre, H., Guoqiang, H. & Stiens, J. H. Modified TE modes of metal waveguide with integrated graphene structure in the sub-terahertz frequency rang. *IEE Microw. Antenna P* **10**, 692–699 (2016).
- Ye, Q. et al. Polarization-dependent optical absorption of graphene under total internal reflection. *Appl. Phys. Lett.* **102**, 021912 (2013).
- Bludov, Y. V., Smirnova, D. A., Kivshar, Y. S., Peres, N. M. R. & Vasilevskiy, M. I. Nonlinear TE-polarized surface polaritons on graphene. *Phys. Rev. B* **89**, 035406 (2014).
- Bordag, M. & Pirozhenko, I. G. Transverse-electric surface plasmon for graphene in the Dirac equation model. *Phys. Rev. B* **89**, 035421 (2014).
- Chamanara, N. & Caloz, C. Graphene transverse electric surface plasmon detection using nonreciprocity modal discrimination. *Phys. Rev. B* **94**, 75413 (2016).
- Musa, M. Y. et al. Confined transverse electric phonon polaritons in hexagonal boron nitrides. *2D Mater.* **5**, 015018 (2018).
- Lin, X. et al. Tailoring the energy distribution and loss of 2D plasmon. *N. J. Phys.* **18**, 105007 (2016).
- Merano, M. Transverse electric surface mode in atomically thin boron-nitride. *Opt. Lett.* **41**, 2668–2671 (2016).
- Ukhtary, M. S., Nugraha, A. R. T. E., Hasdeo, H. & Saito, R. Broadband transverse electric surface wave in silicene. *Appl. Phys. Lett.* **109**, 063103 (2016).
- Lin, X. et al. Chiral plasmons with twisted atomic bilayers. Preprint at <https://arxiv.org/abs/2006.10474> (2020).
- Veselago, V. G. The electrodynamics of substances with simultaneously negative values of permittivity and permeability. *Sov. Phys. Usp.* **10**, 509–514 (1968).
- Cui, T. J., Smith, D. R. & Liu, R. P. *Metamaterials: Theory, Design, and Applications* (Springer, New York, 2010).
- Pendry, J. B. Negative refraction makes a perfect lens. *Phys. Rev. Lett.* **85**, 3966–3969 (2000).
- Smith, D. R. et al. Composite medium with simultaneously negative permeability and permittivity. *Phys. Rev. Lett.* **84**, 4184–4187 (2000).
- Shen, L. et al. Broadband enhancement of on-chip single-photon extraction via tilted hyperbolic metamaterials. *Appl. Phys. Rev.* **7**, 021403 (2020).
- Hu, H. et al. Controlling Cherenkov threshold with nonlocality. Preprint at <https://arxiv.org/abs/2002.04252> (2020).
- Shelby, R. A., Smith, D. R. & Schultz, S. Experimental verification of a negative index of refraction. *Science* **292**, 77–79 (2001).
- Zhang, X. & Liu, Z. Superlenses to overcome the diffraction limit. *Nat. Mater.* **7**, 435–441 (2008).
- Shi, X. et al. Superlight inverse Doppler effect. *Nat. Phys.* **14**, 1001–1005 (2018).
- Lin, X. & Zhang, B. Normal Doppler frequency shift in negative refractive-index systems. *Laser Photonics Rev.* **13**, 1900081 (2019).
- Bearpark, T. & Seddon, N. Observation of the inverse Doppler effect. *Science* **302**, 1537–1540 (2003).
- Chen, J. et al. Observation of the inverse Doppler effect in negative-index materials at optical frequencies. *Nat. Photonics* **5**, 239–242 (2011).
- Xi, S. et al. Experimental verification of reversed Cherenkov radiation in left-handed metamaterial. *Phys. Rev. Lett.* **103**, 194801 (2009).
- Chen, H. & Chen, M. Flipping photons backward: reversed Cherenkov radiation. *Mater. Today* **14**, 34–41 (2011).
- Lin, X. et al. Controlling Cherenkov angles with resonance transition radiation. *Nat. Phys.* **14**, 816–821 (2018).
- Luo, C., Ibanescu, M., Johnson, S. G. & Joannopoulos, J. D. Cherenkov radiation in photonic crystals. *Science* **229**, 368–371 (2003).
- Valentine, J. et al. Three-dimensional optical metamaterial with a negative refractive index. *Nature* **455**, 376–379 (2008).
- Cubukcu, E., Aydin, K., Ozbay, E., Foteinopoulou, S. & Soukoulis, C. M. Negative refraction by photonic crystals. *Nature* **423**, 604–605 (2003).

53. Huang, X., Lai, Y., Hang, Z. H., Zheng, H. & Chan, C. T. Dirac cones induced by accidental degeneracy in photonic crystals and zero-refractive-index materials. *Nat. Mater.* **10**, 582–586 (2011).
54. Joannopoulos, J. D., Johnson, S. G., Winn, J. N. & Meade, R. D. *Photonic Crystals: Molding the Flow of Light* (Princeton University Press, Princeton, 2008).
55. Song, J. et al. Efficient excitation of multiple plasmonic modes on three-dimensional graphene: an unexplored dimension. *ACS Photonics* **3**, 1986–1992 (2016).
56. Zhou, M., Shi, L., Zi, J. & Yu, Z. Extraordinarily large optical cross section for localized single nanoresonator. *Phys. Rev. Lett.* **115**, 023903 (2015).
57. Silveirinha, M. & Engheta, N. Tunneling of electromagnetic energy through subwavelength channels and bends using ϵ -near-zero materials. *Phys. Rev. Lett.* **97**, 157403 (2006).
58. Edwards, B., Alu, A., Young, M. E., Silveirinha, M. & Engheta, N. Experimental verification of epsilon-near-zero metamaterial coupling and energy squeezing using a microwave waveguide. *Phys. Rev. Lett.* **100**, 033903 (2008).
59. Liberal, I., Mahmoud, A. M., Li, Y., Edwards, B. & Engheta, N. Photonic doping of epsilon-near-zero media. *Science* **355**, 1058–1062 (2017).

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AUTHOR CONTRIBUTIONS

X.L. conceived the idea. X.Z. performed the calculations. H. H., X.L., L.S., B.Z., and H.C. contributed insight and discussion on the results. X.Z. and X.L. wrote the paper. X.L., B.Z. and H.C., supervised the project.

COMPETING INTERESTS

The authors declare no competing interests.

ADDITIONAL INFORMATION

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