Superlensing with twisted bilayer graphene

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Introduction
Planar superlenses reconstitute the near-field of the source by virtue of resonant surface waves.


N. Fang et al., Science 308, 534 (2005)
Plasmons in double layer systems, e.g., Topological Insulators

Optical Mode

\[ \omega_+^2 = \frac{\alpha v_F^2 (k^T_F + k^B_F)}{(\varepsilon_T + \varepsilon_B)} q \]

Acoustic Mode

\[ \omega_-^2 = \frac{\alpha v_F^2 k^T_F k^B_F}{\varepsilon_{TI} (k^T_F + k^B_F)} q^2 \]

Exponential amplification of evanescent modes

Exponential amplification of evanescent modes for $R=0$.

\[ T \propto e^{2qd} \]

Analogy to Pendry's perfect lens

WANTED:

Plasmonic mode with constant energy dispersion


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Exponential amplification of evanescent modes

Exponential amplification for all modes at constant energy
Continuity equation and linear response yields:

\[ \omega^2 = \chi(\omega, q) \frac{e^2 q}{2\varepsilon_0 \kappa} \]

Approximate current response by Drude weight \( D \):

\[ D = e^2 \chi(\omega \rightarrow 0, q = 0) \]

Plasmon dispersion in local approximation for 2D systems:

\[ \omega_p = \sqrt{\frac{D}{2\varepsilon_0 \kappa}} q \]

Do plasmons exist in a neutral system (D=0)

EELS of Graphene on Ir

In pure Dirac systems, there are no interband plasmons because the charge response is always negative.

\[ \chi_\rho(q, \omega) = -\frac{1}{4\hbar} \frac{q^2}{\sqrt{(v_F q)^2 - \omega^2}} < 0 \]

But there can be an enhanced charge response as seen in the maximum of the loss function.

\[ S(q, \omega) = -\text{Im} \frac{1}{1 - v_q \chi_\rho(q, \omega)} \]

\[ \omega^2 \neq \chi(q, \omega) \frac{e^2 q}{2 \varepsilon_0 \kappa} \]

Are interband plasmons possible?

BHZ-model for fermions in Hg(Cd)Te:

\[ H = \mathbf{d}_k \cdot \mathbf{\sigma} \]

\[ \mathbf{d}_k = (v_F k_x, v_F k_y, M - B k^2) \]

**Mixture between Dirac and Schrödinger electrons yields plasmons at zero doping**

Twisted bilayer graphene
Twisted bilayer graphene
Brillouin zone for twisted bilayer graphene

Two Dirac cones

Twist angle parameterized by $i$

$$E_n(k)/t = \begin{cases} 0 & \text{if } n \text{ is even} \\ \cos \theta_i = 1 - \frac{1}{2A_i} & \text{if } n \text{ is odd} \end{cases}$$

$$A_i = 3i^2 + 3i + 1$$
Renormalization of the Fermi velocity:

\[
v = v_F \left( 1 - 9 \frac{t_\perp}{v_F \Delta K} \right)
\]


Appearance of magic angles for i>31

Merging of the pseudo-spin texture

Crossover from large angle regime to low angle regime

M. Zhu et al., 2D Mater. 4, 011013 (2017)
Localized states around AA-stacked islands

Crossover from extended to localized states

Local density of first six conduction bands:

Plasmons in twisted bilayer graphene
Local optical response of twisted bilayer graphene

Plasmons in local approximation

Incoming momentum couples to reciprocal lattice vectors

\[ V_{\text{ext}}(r) = v_q e^{iqr} \]

\[ \delta \rho(r) = \sum_G \delta \rho(q, G)e^{i(q+G)r} \]
**Introduction**

Twisted bilayer graphene

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**Charge response with local field effects**

**Incoming momentum couples to reciprocal lattice vectors**

\[
V_{\text{ext}}(r) = v_q e^{i q \cdot r}
\]

\[
\delta \rho(r) = \sum_G \delta \rho(q,G) e^{i(q+G) \cdot r}
\]

**Charge susceptibility**

\[
\chi_{G,G'}(q,\omega) = \frac{g_s}{(2\pi)^2} \int_{1.BZ} d^2 k \sum_{n,m;\kappa=\pm} f_{G,G'}^{n,m;\kappa}(k,q) \left[ \frac{n_F(E_k^s) - n_F(E_{k+q}^s')}{E_k^s - E_{k+q}^s' + \hbar \omega + i\delta} \right]
\]

**Band overlap including local field effects**

\[
f_{G,G'}^{n,m;\kappa}(k,q) = \langle k,n;\kappa | e^{-i(q+G) \cdot \hat{r}} | k + q,m;\kappa \rangle \langle k + q,m;\kappa | e^{i(q+G') \cdot \hat{r}} | k,n;\kappa \rangle
\]
Crossover from linear to quadratic behavior

\[ a t_0 \text{Re} \chi(q, \omega=0) \]

T. Stauber and H. Kohler, Nano Lett. 16, 6844 (2016)
Dynamical response of twisted bilayer graphene

Crossover at $i=15-20$:

$q_a=0.02$

T. Stauber and H. Kohler, Nano Lett. 16, 6844 (2016)
Dynamical response of twisted bilayer graphene

Crossover at $i=15-20$:

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T. Stauber and H. Kohler, Nano Lett. 16, 6844 (2016)
Loss function for $i=25$

**Quasi-flat plasmonic bands for $\theta \approx 1.6^\circ$:**

$\tilde{\eta} \omega / t_0$

$qa$

TWISTED BILAYER GRAPHENE:

Plasmonic mode with constant energy dispersion

T. Stauber and H. Kohler, Nano Lett. 16, 6844 (2016)
1. For small enough twist angle, we find a novel plasmonic resonance of almost constant energy at zero doping. This mode can be tuned and quenched/enhanced by changing the twist angle and chemical potential, respectively.

2. The novel mode can be characterised as collective excitonic in-phase oscillations in a periodic, but quasi-confining potential surrounding the AA-stacked regions.

3. Twisted bilayer graphene resembles a new metamaterial with extraordinary properties in the THz to mid-infrared region leading to enhanced absorption and exponential amplification at constant energy reminiscent to Pendry's perfect lens, but without the need of left-handed materials.

Thank you for your attention!