GRAPHENE FOR US

International Conference
ONLINE
★ April 06-07, 2022 ★

Fizeau Drag in Grpahene Plasmonics

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Background

Dragging of light by moving media was predicted by Fresnel and verified by Fizeau's celebrated experiments with flowing water. This momentous discovery is among the experimental cornerstones of Einstein's special relativity theory and is well understood in the context of relativistic kinematics. By contrast, experiments on dragging photons by an electron flow in solids are riddled with inconsistencies and have so far eluded agreement with the theory.

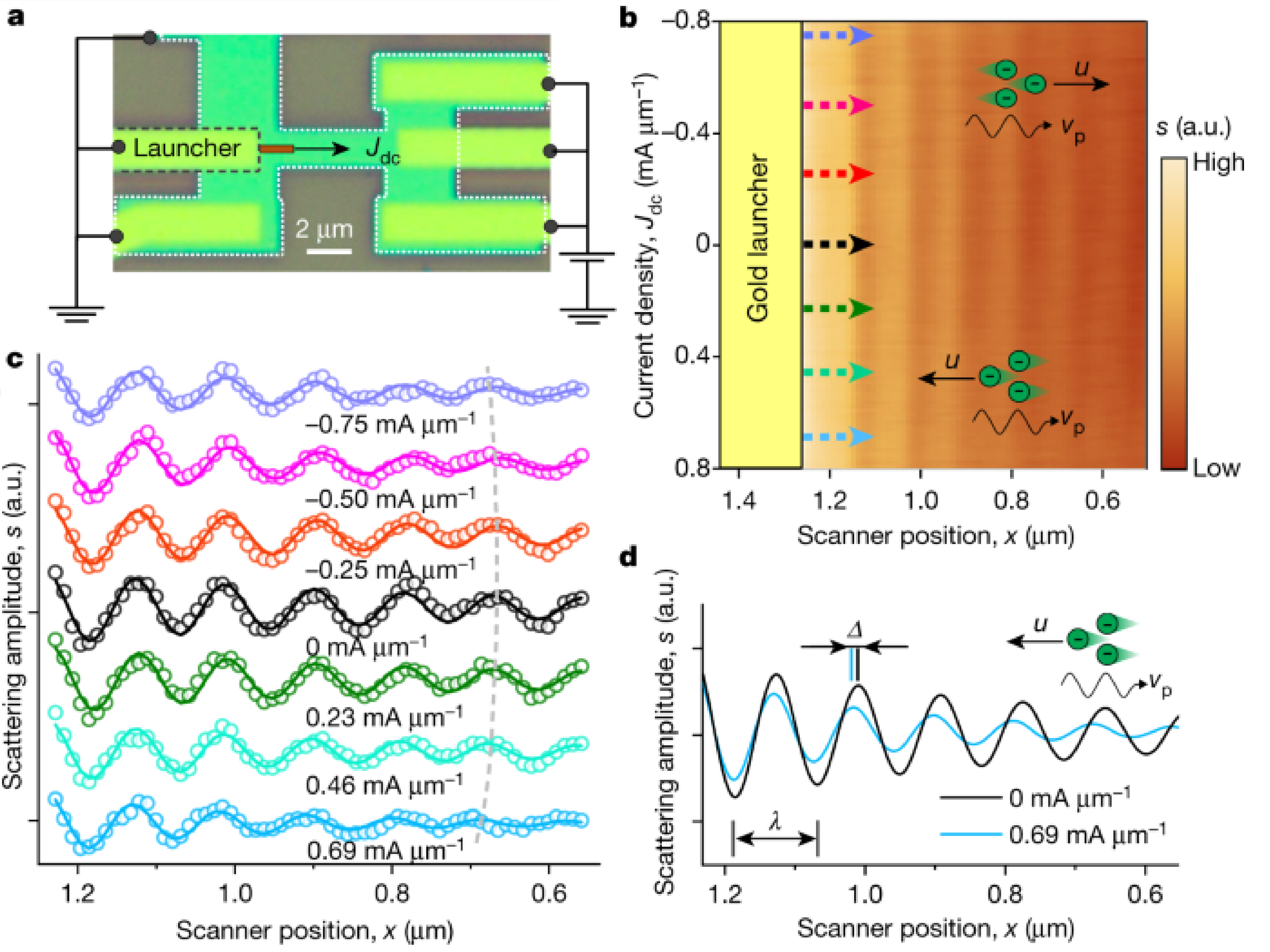
Methods

To explore the plasmonic Fizeau drag, we fabricated multi-terminal graphene devices as shown in Fig. 1a. Monolayer graphene encapsulated in hexagonal boron nitride (hBN) was integrated into back-gated structures assembled on a Si/SiO2 substrate. Gold SPP launchers were deposited directly on the graphene among drain electrodes such that the current-gating effect from spatial inhomogeneity of electron density was minimized. The gold launcher also served as an Ohmic contact to the graphene and as a heat sink for electrons in our high-current experiments. The width of the current-carrying graphene channel was narrowed down to 2 μm to boost the local current density and enhance the Fizeau drag effect. Real-space SPP images (Fig. 1b) were acquired using low-temperature near-field optical nanoscopy techniques. An infrared laser of frequency ω illuminated the gold launcher which excited propagating SPPs. The SPP electric field was out-coupled by a metallized tip of an atomic force microscope into free-space photons and subsequently registered by a detector. Using the demodulated detector signal, the real-space profiles of SPPs were reconstructed.

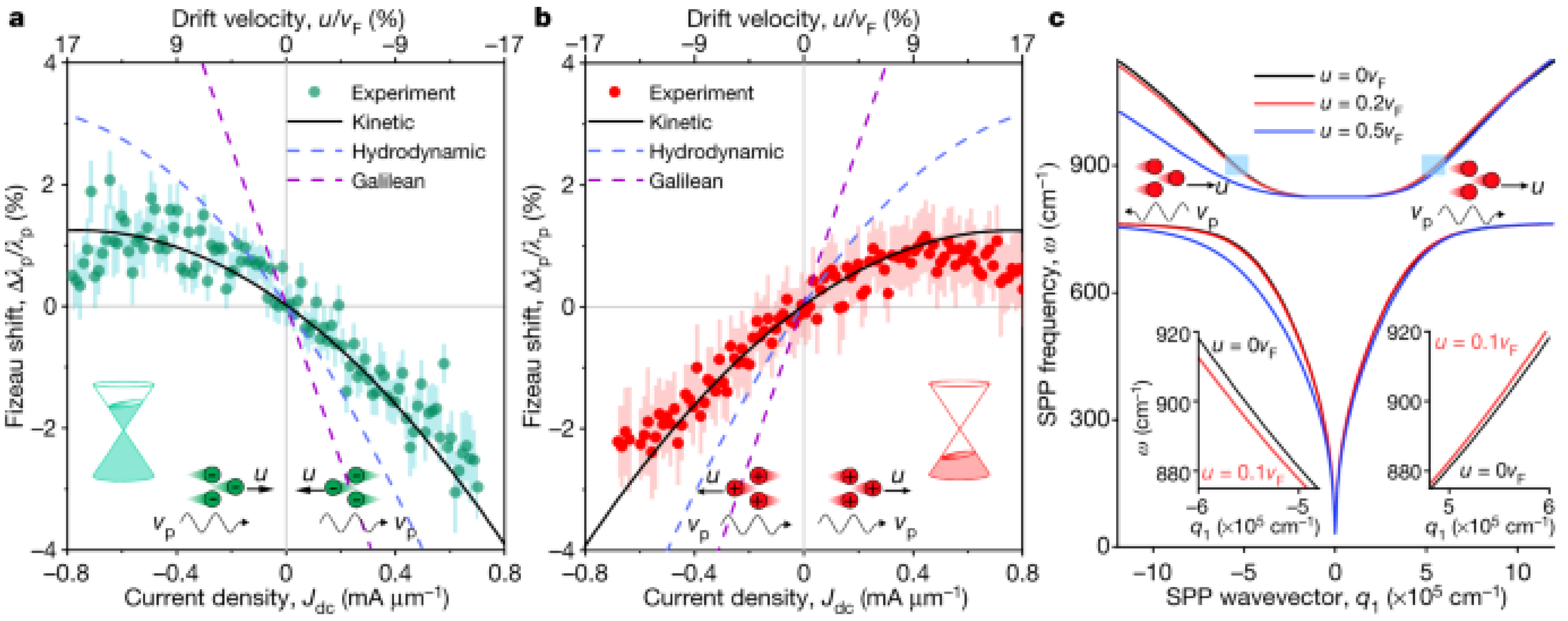
Summary

Here we report on the electron flow dragging surface plasmon polaritons (SPPs): hybrid quasiparticles of infrared photons and electrons in graphene. The drag is visualized directly through infrared nano-imaging of propagating plasmonic waves in the presence of a high-density current. The polaritons in graphene shorten their wavelength when propagating against the drifting carriers. Unlike the Fizeau effect for light, the SPP drag by electrical currents defies explanation by simple kinematics and is linked to the nonlinear electrodynamics of Dirac electrons in graphene. The observed plasmonic Fizeau drag enables breaking of time-reversal symmetry and reciprocity at infrared frequencies without resorting to magnetic fields or chiral optical pumping. The Fizeau drag also provides a tool with which to study interactions and nonequilibrium effects in electron liquids.

Results



Experimental line profiles at different current densities show a smooth evolution of the SPP wavelength with current density (Fig. c). For positive current densities, electrons flow towards the launcher and SPPs propagate away from the launcher. The counter-propagation of electrons and plasmons results in a clear reduction of the SPP wavelength, as evident from the comparison of the fitting results in Fig. 1d. Changing the sign of the backgate results in a similar current-density dependence of the Fizeau shift (Fig.2a, b). The experiment data conforms to the calculated results of kinetic regime (solid lines in Fig. 2a and b) in contrast to Galilean and hydrodynamic regimes.



The Fizeau shift in graphene can be expressed by the formula below, where the drag coefficient η encodes properties of the electrons. Here, ¼ ≤ η ≤ ½ depending on the quasiparticle collision rate. Worth to mention, the quadratic term of the Fizeau drag is directly related to the third order nonlinear conductivity of graphene Dirac electrons.

$$\frac{\Delta\lambda_p}{\lambda_p} = \eta\frac{u}{v_g} - \left(\eta + \frac{1}{4}\right)\frac{v_p}{2v_g}\frac{u^2}{v_F^2},\ v_p = \frac{\omega\lambda_p}{2\pi}$$

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