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Single-mode and multimode Fabry-Pérot interference in suspended graphene

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We have achieved high-quality Fabry-Pérot interference in a suspended graphene device both in conductance and in shot noise. A Fourier analysis of these reveals two sets of overlapping, coexisting interference patterns, with the ratios of the resonance intervals being equal to the width to length ratio of the device. We show that these sets originate from the unique coexistence of longitudinal and transverse resonances, with the longitudinal resonances occurring due to bunching of modes with low transversal momentum. Finally, the high quality of our samples allows us to probe the interaction renormalization of the Fermi velocity as well as the coexistence of Fabry-Pérot oscillations with universal conductance fluctuations.

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Phase coherence of charge carriers leads to electron-wave interference in ballistic mesoscopic conductors [1]. In graphene, such Fabry-Pérot-like interference has been observed [2–6], but the two-dimensional nature of conductive transport together with substrate-induced disorder have prevented the full understanding of the complex interference patterns [7–9]. Experiments on suspended, exfoliated graphene have demonstrated mobilities exceeding 200 000 cm²/Vs [4,10], enabling experimental studies of ballistic transport in micrometer-sized graphene samples. The interference patterns in graphene are similar to those in SWCNTs but, principally, more involved due to the two-dimensional nature of graphene, which leads to increased complexity due to the presence of a large number of conduction channels. Nonuniform spatial conditions, like charge puddles [11] and flexural deformation [12], complicate the situation even further. As a consequence, there is no coherent picture of Fabry-Pérot interference in suspended graphene devices.

The theoretical conditions for Fabry-Pérot resonances have been analyzed in several recent works [7–9]. Guflycke and White [7] showed that with nonperfect contacts, evenly spaced Fabry-Pérot-like resonances should be observable in conductance measurements, with the periodicity being determined by the length of the sample and the velocity of the charge carriers. Such longitudinal resonances originate from simultaneous participation of modes in nonequivalent channels, facilitated by transversely quantized states with low transverse momentum and small energy separation. Müller et al. [9] emphasized that Fabry-Pérot resonances should be observable at suitable gate voltage in experimental setups with metallic contacts, due to the presence of p-n junctions. Additionally, they theorized that in low temperature and with high-quality edges, resonances that correspond to single transverse modes should also be observable. Previously, equivalent single-mode resonances have been observed in single-wall carbon nanotubes (SWCNTs) [13].

In this work, we employ conductance and shot noise measurements to analyze transport resonances with characteristic features of Fabry-Pérot interference. Our results show resonances that are attributable to both transverse (single-mode) and longitudinal (multimode) interference. Moreover, the suspended region of the sample yields a Fermi velocity  of the order of 2–2.8 × 10⁷ m/s at a charge density of n ∼ 1–2 × 10¹⁰ cm⁻². Although the exact value of  may be overestimated because of anomalies like nonuniform charge distribution [14], both theoretical predictions and experimental observations have suggested that in suspended graphene, many-body interactions may renormalize the Fermi velocity to a significantly higher value than found in graphene on a substrate [15,16].

Our experiments were performed at a temperature of 50 mK using a suspended graphene sample with length L = 1.1 μm and width W = 4.5 μm. The experimental setup is shown in Figs. 1(a) and 1(b). Before the measurements, the two-lead sample was annealed by passing a current of 1.1 mA through it (using a voltage of nearly 0.9 V over the sample). This resulted in an almost neutral, high-quality sample with the total shot noise being induced by a tunneling contact with a Fano factor  = 0.2 at n ∼ 3–4 × 10¹⁰ cm⁻², by assuming that the total shot noise is induced by a tunneling contact with  = 1.

We measured both the differential conductance and the differential Fano factor. Lines connected to the graphene device (source and drain) were connected to bias-Ts separating low-frequency signals (less than 1 kHz) and the high-frequency noise measurement signals above 600 MHz, dc biasing via a 0.5-MΩ resistor was employed. The high-frequency line on the source side was terminated by a 50-Ω shunt and the line on the drain side (shot noise measurement line) was connected to a low noise amplifier through a circulator [18]. Standard lock-in techniques were employed for measurements of the low-frequency conductance (around 35 Hz), the same...
excitation could also be employed to measure differential shot noise by directing the rectified output of the noise spectrometer to a lock-in amplifier.

As the Cr/Au contacts of the setup cause \( n \) doping of the underlying graphene, at negative gate voltage \( pn \) junctions are formed close to the contacts. This causes increased reflectivity [19,20], which assists in the formation of Fabry-Pérot resonances. The measured minimum conductivity falls under graphene, at negative gate voltage 

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FIG. 2. (Color online) (a) Simulated conductance curve showing the presence of fast and slow oscillations, corresponding to transverse and longitudinal Fabry-Pérot interference, respectively. The lines indicate resonances given by Eq. (1), with the solid lines corresponding to $q_L = 1$ and arbitrary $q_W$, and the dashed lines to $q_W = 0$ and arbitrary $q_L$. (b) Simulated map of the differential conductance $G_d$. (c) Fourier transform of $\partial G_d/\partial \mu$, highlighting the periodicities of the two sets of resonances.

Complete symmetry when $x = 0.5$. The obtained conductance map can be used to analyze the resonances quantitatively by first differentiating it with respect to $\mu$, and then performing a Fourier transform. The Fourier transformed map is shown in Fig. 2(c), with the periodicity of $E_L$ being clearly visible, while the periodicity of the fast resonances being slightly lower than $E_W$, due to resonances corresponding to relatively low $q_W$ [as the red bars in Fig. 2(a) show, with growing $q_W$ the spacing approaches $E_W$ from below].

In the experiments, scans over the bias voltage $V_{\text{bias}}$ and gate voltage $V_g$ show a Fabry-Pérot pattern both in conductance and in shot noise. The pattern is observable on both sides of the Dirac point, but it is more clear at negative gate voltage. To quantitatively study the experimental map of the differential conductance $G_d \equiv dI/dV_{\text{bias}}$, shown in Fig. 3(a), we convert the gate voltage into a low-bias chemical potential $\mu_0$. Using the density of states of graphene, the charge density can be converted into a zero-bias chemical potential through

FIG. 3. (Color online) (a) Measured differential conductivity map of the graphene device. (b) A zoom-in on the boxed region in (a), with the gate voltage converted into chemical potential. (c) The conductance map in (b) differentiated with respect to the chemical potential. The dashed lines are a fit of resonances with periodicity $E_W$, using $v_F = 2.4 \times 10^6$ m/s. (d) Fourier transform of (c). The solid lines are fit to the longitudinal interference and the dashed to the transverse interference, using the same $v_F$ as in (c). (e) Differential Fano factor differentiated with respect to the chemical potential. (f) Fourier transform of (e), with the solid and dashed lines being the same as those shown in (d).
\[ \mu_0 = \text{sgn}(n_0) v_F \sqrt{\pi |n_0|}. \] Figure 3(b) shows a zoom-in of the converted data at a charge density of \( n_0 = 1.1 \times 10^{10} \text{cm}^{-2} \), indicated by the box in Fig. 3(a). A diamond pattern appears if the conductance is differentiated with respect to the zero-bias chemical potential. The differentiated data, displayed in Fig. 3(c), indicates that there is a periodic modulation in \( \Delta_G \), especially visible well away from the Dirac point, which is located around \( V_g = -0.15 \text{V} \). A good fit with the experimental data can be obtained, if \( C_g \) is set to the value given by a plane capacitor model of the gate setup, i.e., \( 47 \text{ aF/\mu m}^2 \), and \( n_r \) to \( 9 \times 10^{10} \text{cm}^{-2} \), which is close to the value estimated using Fig. 1(d). The observed Fabry-Pérot resonances have relatively low amplitude. Weak reflection at the contact interfaces will lead to weak longitudinal interference [7], whereas edge disorder suppresses transverse resonances. In our simulation, the strength of the longitudinal resonances is determined by the amount of doping of the graphene leads.

The diamonds are not completely symmetric, which can be explained through slightly asymmetrical contacts. A best fit with the Landauer approach described earlier is achieved by setting \( x = 0.58 \). By setting \( W = 4.5 \mu \text{m} \) and \( v_F = 2.4 \times 10^6 \text{ m/s} \), we obtain the dashed lines shown in Fig. 3(c). However, if we assume that the average periodicity of the fast resonances is slightly less than \( E_W \), as in the simulation, we obtain the estimate \( v_F \geq 2.8 \times 10^6 \text{ m/s} \). Hence our measurements yield \( v_F = 2.4-2.8 \times 10^6 \text{ m/s} \) at \( n \sim 1-2 \times 10^{10} \text{cm}^{-2} \). The large Fermi velocity, well above values measured on a SiO\(_2\) substrate [23,24], is consistent with measurements of the cyclotron mass in freestanding graphene [15], which have indicated that \( v_F \) is between 2 and \( 3 \times 10^6 \text{ m/s} \) at similar charge density. This effect is thought to be caused by unscreened electron-electron interactions occurring in suspended graphene [16]. As in the simulation, Fourier analysis may be applied to reveal the presence of multimode resonances spaced as \( E_L \). In the Fourier-transformed plot, shown in Fig. 3(d), a strong resonance is indeed found at a periodicity that corresponds to a value close to \( L = 1.1 \mu \text{m} \).

The fast, transverse resonances, indicated by the dashed lines in Fig. 3(d), correspond to dashed diamond pattern in Fig. 3(e).

Shot noise yields complementary information on the distribution of transmission channels as well as interaction effects [25,26]. Shot noise can be quantified through the differential Fano factor, which is defined as \( F_d \equiv (1/2\nu_0) dS/dI \), where \( S \) is the correlation function of the current fluctuations \( \delta I(t) \), i.e., \( S = \int dt \delta I(t) \delta I(0) + \delta I(0) \delta I(t) \). Our measured results on shot noise are illustrated in Fig. 3(e), which depicts the derivative \( dF_d/d\mu \) as a function of \( \mu_0 \) and \( V_{\text{bias}} \) over the same area as in Fig. 3(b). Although the resonances in Fig. 3(e) are not straightforward to interpret, the Fourier transform shown in Fig. 3(f) reveals two clear sets of resonances with the same periodicities as the conductance data, with the solid and dashed lines corresponding to exactly the same values as in Fig. 3(d). The Fourier transforms of both the \( \delta G_d/\delta \mu \) and \( \delta F_d/\delta \mu \) maps contain additional spots between the innermost and outermost resonances, which indicate the presence of additional scattering.

A detailed analysis of \( G_d(V_{\text{bias}}, \mu) \) and \( F_d(V_{\text{bias}}, \mu) \) indicates the coexistence of periodic universal conductance fluctuations (UCF) and Fabry-Pérot oscillations at chemical potentials of 30–40 meV [26–39]. This conclusion is reached by making a careful comparison of the experimental results against tight binding simulations at a realistic density of resonant scatterers; the nature and distribution of the scatterers were selected to agree with the measured variance of zero-bias conductance fluctuations versus gate voltage near the Dirac point. The analysis indicates that the UCF oscillations can lead to periodic modulation on top of the Fabry-Pérot pattern and thereby produce additional peak structures in the Fourier spectra, both in conductance and noise analysis. This additional structure is identified with the intermediate peaks in the Fourier spectra of Fig. 3. The positions of these peaks were influenced by a small external field, which renders further support to the conclusion of the impurity-induced peak patterns in the Fourier spectra.

To summarize, we have measured the conductance of a suspended graphene sample with a high aspect ratio. Through Fourier analysis techniques, the differential conductance and the differential shot noise reveal two sets of clear resonances, which may be attributed to single-mode transverse and multimode longitudinal resonance. The analysis of the interference pattern yields a Fermi velocity that is significantly higher than the one usually reported for graphene on a substrate, thus indicating that close to the Dirac point, unscreened many-body interactions become significant in suspended graphene. Furthermore, we find that universal conductance fluctuations, the dominant mechanism for \( \delta G \) around the Dirac point, may coexist with Fabry-Pérot oscillations at \( |\mu| = 30–40 \text{meV} \) and their (quasi)periodicity yields specific signatures in the Fourier spectra.

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