An Electronic Mach-Zehnder Interferometer

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Direct phase measurements of electrons, customarily done in double-slit interferometers [1–4], are difficult to perform under strong magnetic fields. Electrons are being diverted by the Lorentz force, perform chiral skipping orbits, and prefer one slit to the other - thus breaking the symmetry of the interferometer. At the extreme quantum limit, namely, in the quantum Hall effect (QHE) regime, the interferometers do not function in a high magnetic field, namely, in the quantum Hall effect (QHE) regime [8], since it destroys the symmetry between left and right slits. Here, we report on the fabrication and operation of a novel, single channel, two-path electron interferometer that functions in a high magnetic field. It is the first electronic analog of the well-known optical Mach-Zehnder (MZ) interferometer [9]. Based on single edge state and closed geometry transport in the QHE regime the interferometer is highly sensitive and exhibits very high visibility (62%). However, the interference pattern decays precipitously with increasing electron temperature or energy. While we do not understand the reason for the dephasing we show, via shot noise measurement, that it is not a decoherence process that results from inelastic scattering events.

Direct phase measurements of electrons, customarily done in double-slit interferometers [1–4], are difficult to perform under strong magnetic fields. Electrons are being diverted by the Lorentz force, perform chiral skipping orbits, and prefer one slit to the other - thus breaking the symmetry of the interferometer. At the extreme quantum limit, namely, in the QHE regime, the skipping orbits quantize to quasi-one-dimensional like states, named chiral edge states. We exploited the chiral motion of the electrons and constructed an electronic analog of the ubiquitous optical Mach-Zehnder (MZ) interferometer [9] (described schematically in Fig. 1a). A beam splitter BS1 splits an incoming monochromatic light beam from source S into two beams, which, after reflection by mirrors M1 and M2, recombine and interfere at BS2 to result in two outgoing beams (collected by detectors D1 and D2). When the phase along one of the paths varies both signals in D1 and in D2 oscillate out of phase, and since no photons are being lost the sum of both signals stays always equal to the input in S. In the electronic counterpart, depicted in Fig. 1b, quantum point contacts (QPC) function as beam splitters and Ohmic contacts serve as detectors. A QPC is formed in the 2DEG by depositing a split metallic gate on the surface of the semiconductor and biasing it negatively with respect to the 2DEG. The induced potential in the 2DEG creates a barrier under the gate bringing the two oppositely propagating edge currents to the small opening in the barrier, allowing thus backscattering. As shown schematically in Fig. 1b QPC1 splits the incoming edge current from S to two paths, a transmitted inner path and a reflected outer path, both later recombine and interfere in QPC2, to result with two edge currents (collected by D1 and D2).

The actual device, seen in Fig. 1c, was fabricated in a high mobility 2DEG embedded in a GaAs-AlGaAs heterojunction. A ring-shaped mesa, 3μm in width, was defined by plasma etching with Ohmic contacts (for S, D1, and D2) connected to the inner and outer edges of the ring. The inner contact, D2, and the two QPCs are connected to outside sources via air bridges that float above the mesa. A phase difference φ between the two paths is introduced via the Alaronov-Bohm (AB) effect [10,11], φ = 2πBA/φ0, with B the magnetic field, A the area enclosed by the two paths (≈ 45μm²), and φ0 = 4.14 × 10⁻¹⁵Tm² the flux quantum. A few modulation gates, MG, are added above the outer path in order to tune the phase φ by changing the area A. We briefly review the operation of the interferometer. At filling factor 1 in the QHE regime a single chiral edge state carries the current. The interfering current, in turn, is proportional to the transmission probability from source to drain TSD. Neglecting dephasing processes and having the transmission (reflection) amplitude ti (ri) of the ith QPC fulfilling ti|2 + |ri|2 = 1, then [7] I1D1 ∝ TSD1 = |t1t2 + r1r2eiφ|2 = |t1t2|2 + |r1r2|2 + 2|t1t2r1r2|cosφ and I2D2 ∝ TSD2 = |t1r2 + r1t2eiφ|2 = |t1r2|2 + |r1t2|2 - 2|t1t2r1r2|cosφ. Note that ideally the two currents oscillate out of phase as function of φ while TSD1 + TSD2 = 1. The visibility of the oscillation is defined as: v = (I1max - I1min)/(I1max + I1min) and, for example, when QPC2 is tuned so that T2 = 0.5, the visibility is v = 2√T1(1 - T1).

Measurements were done at filling factor 1 (magnetic field ∼5.5T) and also at filling factor 2 with similar results. With a refrigerator temperature ∼6mK the electron temperature was determined by measuring the equilibrium noise [12] to be ∼20mK. High sensitivity measurement of the interference pattern was conducted at ∼1.4MHz with a spectrum analyzer. Current at D1 (or D2) was filtered and amplified in situ by LC circuit and a low noise home-made pre-amplifier, both placed near the sample and cooled to 1.5K.
FIG. 1. The configuration and operation of an optical Mach-Zehnder interferometer and its actual realization with electrons. (a) Schematics of an optical Mach-Zehnder interferometer. D1 and D2 are detectors, BS1 and BS2 are beam splitters, and M1 and M2 are mirrors. With 0(π) phase difference between the two paths, D1 measures maximum (zero) signal and D2 zero (maximum) signal. The sum of the signals in both detectors is constant and equals to the input signal. (b) Schematics of the electronic Mach-Zehnder interferometer and the measurement system. Edge states are formed in a high perpendicular magnetic field. The incoming edge state from S is split by QPC1 (quantum point contact) to two paths, of which one moves along the inner edge and the other along the outer edge of the device. The two paths meet again at QPC2, interfere, and result in two complementary currents in D1 and in D2. By changing the contours of the outer edge state and thus the enclosed area between the two paths, the modulation gates (MG) tune the phase difference between the two paths via the Aharonov-Bohm effect. A high signal-to-noise-ratio measurement of the current in D1 is performed at 1.4MHz with a cold LC resonant circuit as a band pass filter followed by a cold, low noise, preamplifier. (c) SEM picture of the device. A centrally located small Ohmic contact (3 × 3µm²), serving as D2, is connected to the outside circuit by a long metallic air-bridge. Two smaller metallic air-bridges bring the voltage to the inner gates of QPC1 and QPC2 - both serve as beam splitters for edge states. The five metallic gates (at the lower part of the figure) are modulation gates (MG).

A standard lock-in technique, with a low-frequency signal (7Hz, 10µV RMS), gave similar results, however, the measurement lasted much longer and was prone to samples instability. Since at 5.5T each flux quantum occupies and area of some 10^{-15}m² (some 60,000 flux quanta thread the area A), a minute fluctuation in the superconducting magnet (being in the so called, persistent current mode). In this mode the magnetic field decays smoothly at a rate of ~0.12mT/hour (~1 flux quantum every 50 minutes). The second was via scanning the voltage on a modulation gate at a rate much faster than the decay rate of the magnetic field, thus changing the area A, the enclosed flux, and consequently the AB phase.

FIG. 2. Interference pattern of electrons in a Mach Zehnder interferometer and the dependence on transmission. (a) Two dimensional color plot of the current collected by D1 as function of magnetic field and gate voltage at an electron temperature of ~20mK. The magnet was set in its persistent current mode (B ~ 5.5T at filling factor 1 in the bulk) with a decay rate of some 0.12 mT/hour, hence time appears on the abscissa. The two QPCs were both set to transmission $T_1 = T_2 = 0.5$. Red (blue) stands for high (low) current. (b) The current collected by D1 plotted as function of the voltage on a modulation gate (red plot) and as function of the magnetic field (blue plot) - along the cuts shown in a. The visibility of the interference is 0.62. (c) The visibility of the interference pattern as a function of the transmission probability $T_1$ of QPC1 when QPC2 is set to $T_2 = 0.5$. Dashed line is a fit to the experimental data with visibility=$2\eta\sqrt{T_1(1-T_1)}$. The normalization coefficient $\eta=0.6$ accounts for possible decoherence and/or phase averaging.

We first test the ideality of the Ohmic contacts and the validity of the edge states picture. For both QPCs open a nearly ideal Hall plateau was observed in $I_{D1}$ while no current was measured in D2 ($I_{D2}=0$). That
validated that current was confined to the outer edge with no backscattering across the 3µm wide mesa. We then pinched off QPC1 or QPC2 and found again a Hall plateau in $I_{D2}$ with zero current in $D1$ ($I_{D1} = 0$). This proved that the small Ohmic contact of $D2$ was ideal and fully absorbed the current. Setting then both QPCs to $T_1 = T_2 \sim 1/2$ and varying the magnetic field $B$ (actually the time) or the area $A$ (the voltage on a MG) lead to pronounced interference signal in $D1$ (or in $D2$) with visibility as high as 0.62 (Fig. 2). Since the field decays linearly with time and the area (or electron density) vary proportional to the gate voltage changing these parameters leads to the diagonal straight color lines (of constant phase) seen in Fig. 2a. Figure 2b shows similar data taken along two cuts (the dotted lines shown in Fig. 2a) - one for constant $B$ and one for constant $A$. The cleanliness of the interference pattern and the high visibility prove the nearly ideal nature of the interferometer.

In order to further verify the two-path nature of the interference the visibility was measured as function of $T_1$ for a constant $T_2 = 0.5$ (see Fig. 2c). It agrees well with the expected expression for the visibility $v = 2\eta\sqrt{T_1(1-T_1)}$, with $\eta \sim 0.6$ a normalization factor that accounts for dephasing (either due to phase averaging in the energy window of the electrons or due to inelastic scattering processes). Moreover, the period of the oscillations, in time and in MG voltage, agrees well with one flux quantum being added (or subtracted) in the rings area. The time period is $\sim 50\text{min}$, which is the time needed for one flux quantum decay in the superconducting magnet, while the voltage period agrees approximately with that needed to deplete one electron (hence, one flux quantum for filling factor 1) under the MG gate.

While the visibility is very high it is still smaller than unity ($v \sim 0.6$). An obvious reason is the finite energy spread of the electrons at the edge (due to their finite temperature) and the unavoidable dependence of the AB area on the energy (hence, the AB phase) - leading to phase averaging (thermal smearing). Indeed, the visibility was found to drop precipitously with increasing temperature or applied voltage at $S$, as seen in Fig. 3. In this example, a mere increase of the temperature to 100mK (some 9µeV) reduced the visibility from $v \sim 0.53$ to $v \sim 0.01$ (plotted in red in Fig. 3a). If indeed phase averaging is the cause for the dephasing, it could, in principle, be eliminated with monoenergetic electrons.

A minute AC signal ($\sim 0.5µV$) at 1.4MHz was added to a variable DC voltage $V_{DC}$ and the synchronous AC part of the interfering signal was measured at 20mK. This signal leads to a differential visibility $v_\Delta$, resulting only from the electrons in an energy window $\sim 0.5µeV$ around an energy $eV_{DC}$. Surprisingly, as seen in Fig. 3a (plotted in blue), the energy dependent differential visibility at $T=20\text{mK}$ is strikingly similar to the temperature dependent visibility with a relation between the scales $eV_{DC} \sim 4k_BT$. The visibility (in color scale) is plotted as function of both $T$ and $V_{DC}$ in Fig. 3b. The clear symmetry across the diagonal suggests that the dephasing processes due to temperature and voltage are similar. Unfortunately this contradicts our previous assertion of phase averaging taking place in a wide window of energy and points at decoherence, induced by inelastic scattering events, as the main source of dephasing. In other words, for an increased temperature or for high energy monoenergetic electrons, empty states are being created allowing energy loss via scattering.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig3.png}
\caption{The dependence of the visibility of the interference pattern on temperature and applied voltage. (a) Visibility as function of temperature at small excitation voltage for $V_{DC} = 0$ (red plot), and as function of $V_{DC}$ with a small AC voltage $V_{AC}$ superimposed on it at electron temperature 20mK (blue plot). Both QPCs were set to $T_1 = T_2 = 0.5$. (b) A 2D color plot of the visibility as function of temperature and applied DC voltage. Red (blue) stands for high (low) visibility.}
\end{figure}

In order to test this hypothesis current shot noise was measured. Its spectral density, defined as the averaged square of the current fluctuations per unit of frequency, $S = \langle (i^2) \rangle / \Delta f$, and for stochastic partitioning at zero temperature $S \propto eV_{DC}TSD(1 - TSD)$ [13]. Introducing a phenomenological parameter $k$ that accounts for decoherence in the interferometer with $T_1 = 1/2$ and $T_{SD} = 0.5 + \sqrt{T_2(1-T_2)}\cos\phi$, we find that for complete phase averaging or for a complete decoherence $T_{SD} = 0$. On the other hand shot noise in $D1$ is
$S_{D1} \propto T_{SD1}(1 - T_{SD1}) = 1/4 - k^2 T_2(1 - T_2) \cos^2 \varphi$, with $S_{D1} =$ const. for $k = 0$ but $S_{D1} = 1/4 - k^2 T_2(1 - T_2)/2$ for complete phase averaging (resulting from an integration of $\cos^2 \varphi$ in the range $\varphi = 0...2\pi$). Hence, noise is expected to exhibit a parabolic dependence on $T_2$ in a coherent system. Shot noise was measured (see Refs. 12 and 13 for details) with a relatively large $V_{DC}$ applied at $S$ so that interference signal was quenched (negligible visibility). The dependence of $S$ on $T_2$, shown in Fig. 4, followed the above expression with $k \sim 0.9$, proving that indeed phase averaging is dominant while decoherence is negligibly small.

FIG. 4. Shot noise measurement (at filling factor 2) as function of $T_2$ when the transmission of QPC1 was set to $T_1 = 0.5$. A 30$\mu$V DC voltage (under which the AB interference pattern was quenched) was used to measure shot noise. The shot noise of the current collected by $D1$ is shown by the black dots (normalized to a maximum), while the two solid lines are the expected noise for $k = 0$ and $k = 0.9$, respectively, according to the simple model described in the text. The agreement with the simple model indicates that the electrons are coherent even at the DC voltage where the interference pattern fades away. Inset: the current at $D_1$ as function of $T_2$ at $V_{DC} = 30\mu$V. As expected from the lack of the interference pattern, the current is independent of $T_2$ (see text).

A single particle, namely, a non-interacting model would lead to the following dependences of the visibility on energy: for $V = 0$ and finite $T$, $\nu \propto \beta T / \sinh(\beta T)$, with $\beta$ a constant; for finite $V$ but $T = 0$, $\nu \propto \sin[(\pi/2\pi) V] / [(\pi/2\pi) V]$, while the differential visibility at $T = 0$ is expected to be voltage independent. Since the experimental results contradict these projections we propose (with no proof yet) two possible reasons for the dephasing. One might be due to low frequency noise (say, $1/f$ type due to moving impurities), which might be induced by a higher current, leading to fluctuation in the area and consequently, phase smearing. The other could be related to the self consistent potential contour at the edge. Since it depends on the local density of the electrons in the edge state [14], fluctuation in the density due to partitioning are expected to lead to fluctuation in the AB area enclosed by the two paths and hence to phase randomization. For example, for $B \sim 5.5T$ a merely $1\sim 2$ angstroms shift of the edge suffices to add one flux quantum into the enclosed area.

Our aim here was to present a novel and powerful electron interferometer, which might to be used as a powerful tool for future interferometry studies of electrons. One exciting possibility is the study of coherence and phase of fractionally charged quasiparticles in the fractional quantum Hall effect regime [15].

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