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Electrostatic tuning of plasmonic cavities for edge magnetoplasmons

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1. Introduction

Collective excitations of electron density in quantum Hall edge states, which are called edge magnetoplasmons (EMPs), have attracted much attention since 1980's [1-3]. One can extract electronic properties of quantum Hall edges, for example, width of edge channels from the group velocity and charge relaxation from the attenuation of EMPs. There are experimental attempts to tune the EMP transport by utilizing artificial structures. Muravev *et al*. demonstrated plasmonic band structures by periodically modulating the geometry of the edge channels [4]. The presented possibility to control the high-frequency transport opens a new direction of designing "high-frequency functions" of quantum Hall devices.

Recently, we reported the group velocity of EMPs along the edge channels defined by gate electrodes [5]. The velocity was controlled by the gate voltages through the modulation of the distance between the edge channel and the gate electrode. This electrostatic technique to tune the transport properties of EMPs might be a key technique for designing high-frequency response of quantum Hall systems. Here, we report the frequency-domain measurement for the resonance of EMPs in plasmonic cavities defined by gate electrodes. We measured transmission spectra of a single plasmonic cavity and evaluated the resonant frequency. As the group velocity of EMPs depends on the gate voltage, we find that the resonant frequencies can be tuned electrostatically. Moreover, we tried to tune the coupling of series cavities connected through a quantum point contact (QPC) by controlling the QPC transmission [6]. By these experiments, we examined the electrostatic controllability of high-frequency EMPs in quantum Hall systems.

2. Experimental setups

Figure 1 (a) shows the optical micrograph of the device and the experimental setup. The metallic electrodes to form QPCs and side gate electrodes were fabricated on an AlGaAs/GaAs heterostructure with the two dimensional electron gas (2DEG: electron density: 1.27×10^{11} cm^{-2}, and the mobility: 2.11×10^{6} cm^{2}/Vs at 4.2 K). The experiments were performed on the device at 300 mK. We applied a constant magnetic field of B = 5.3 T, which corresponds to a bulk filling factor $\nu = 1$. In this magnetic field, chirality of edge states leads electric signals to travel clockwise in the 2DEG. We measured DC and RF currents propagating from the Ohmic contact Ω_1 to Ω_2 simultaneously by the standard lock-in technique at 33 Hz and by the RF amplifier followed by the vector network analyzer.

Figure 1 (b) shows a sketch of a QPC beam splitter for EMPs. In the quantum Hall regime at $\nu = 1$, only one edge channel runs along the edge of the 2DEG. While DC transport property through the QPC is described solely by the transmission (T) and reflection (R) probabilities for electrons as illustrated by solid arrows, EMPs can also interact with each other through the interedge capacitance C. In the following experiments, the left and right QPCs in Fig. 1 (a) were completely closed to achieve capacitive couplings ($T = 0$, $C \neq 0$).

3. Single plasmonic cavity

The schematic diagram of a single plasmonic cavity is shown in Fig. 2 (a). We used one of the gate electrodes (V_1) to tune the group velocity of EMPs. As displayed in Fig. 2 (b), the measured scattering parameter S_{21} shows clear resonant peaks corresponding to the fundamental (n = 1) and second and third (n = 2 and 3) harmonics of the resonant modes. The observed highest quality factor (Q-factor) of the fundamental resonance was about 20. We expect that the Q-factor will be improved by optimizing the geometry of the edge channels. The fundamental resonant frequency can be tuned from 80 to 110 MHz by sweeping the gate voltage V_1, according to the change in the velocity of EMPs along the gate electrode. This is the direct evidence of the tunable resonant frequencies in gate-defined plasmonic cavities. The electrical tuning of the resonant frequency is essential for

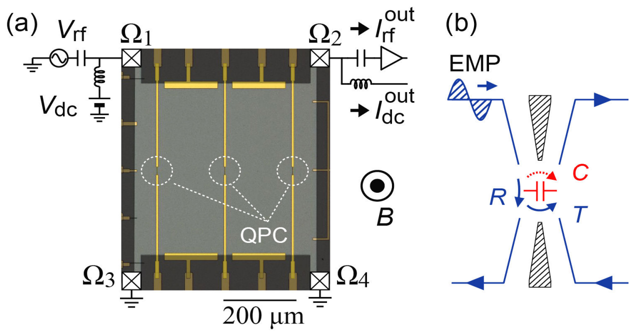

Fig. 1 (a) Optical micrograph of the device and the schematic diagram of the experimental setup. (b) QPC beam splitter for EMPs, where both transmissive and capacitive coupling coexist.

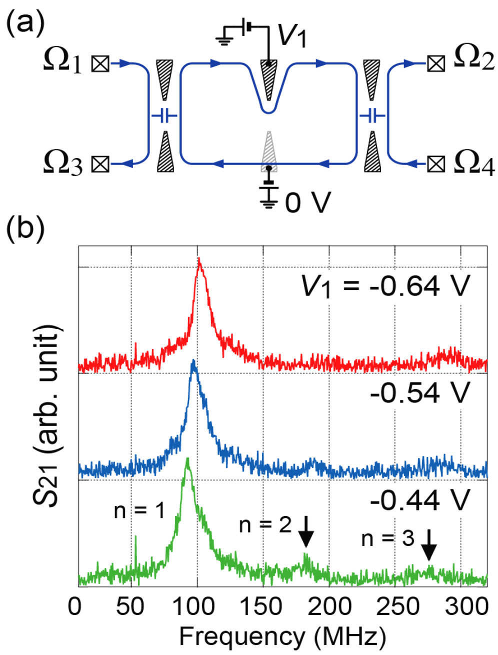

Fig. 2 (a) Schematic diagram of a single plasmonic cavity defined by two QPCs. (b) Scattering matrix element S_{21} as a function of the frequency measured at input RF power -50 dBm (700 μV). We observed shift of the fundamental peak by sweeping the gate voltage V_1.

studying coupled cavities.

4. Coupled plasmonic cavities

Figure 3 (a) illustrates a double cavity connected in series through the central QPC. The transmission probability of the QPC for electrons was controlled by the gate voltage V_2. The resonant frequencies of the left and right cavities can be individually controlled with the gate voltages V_A and V_B. We observed resonant peaks only when the two cavities have an identical resonant frequency. Figure 3 (b) shows the transmission spectra of the coupled cavity for the transmission probability of $T = 0$, 0.3, and 0.6 in this situation. The obtained Q-factor (~10) is similar to those of the single cavities, which implies that the two cavities are weakly coupled through the central QPC. We find that the peak vanishes as T is increased, as seen in Fig. 3(b). When the transmission is finite ($T > 0$), non-equilibrium charges are generated in the channels, which leads to significant dumping of EMPs.

Recently, energy relaxation of non-equilibrium electrons in edge states was experimentally evaluated [8]. The non-equilibrium electrons injected from a QPC to edge states redistribute their energies towards equilibrium states during the propagation (< 100 μm). In the present system, the EMPs split at the QPC ($0 < T < 1$) consist of non-equilibrium electrons and they completely relax their energies in the cavities, since the cavities have long perimeters (~1.5 mm). While we observed strong smearing of resonant peaks at $T > 0$, we found the clearest resonant peak at $T = 0$. This is because the electrostatic interaction through the capacitance is free from dissipation. We expect

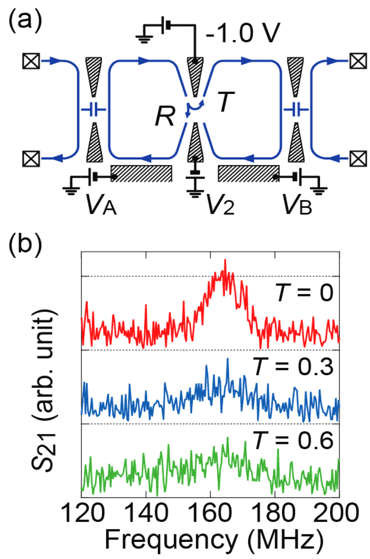

Fig. 3 (a) Coupled plasmonic cavities through a QPC. The coupling strength can be tuned by the gate voltage V_2. The resonant frequencies of two cavities can be tuned individually by V_A and V_B. (b) Transmission spectra of the coupled system at various transmission probabilities controlled by the gate voltage V_2.

that EMP devices with improved quality will be achieved by designing the capacitive couplings between edge channels, where effects of screening due to gate electrodes will be an essential ingredient.

5. Summary

We investigated the transmission characteristics of EMPs through single and double plasmonic cavities. We observed clear resonant peaks for the single cavity and demonstrated that the resonant frequencies are tuned by the gate voltages. In the coupled system, the coupling strength of these cavities was tuned by the transmission probability of the QPC. We observed higher Q-factor of the resonant peaks when the QPC is completely closed, indicating the dissipationless interaction of EMPs through the capacitance.

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