Quantized charge fractionalization at quantum Hall Y junctions in the disorder dominated regime

Chaojing Lin \(^{1,2}\) \(^{✉}\), Masayuki Hashisaka \(^{3}\), Takafumi Akiho \(^{3}\), Koji Muraki \(^{3}\) & Toshimasa Fujisawa \(^{1}\)

Fractionalization is a phenomenon where an elementary excitation partitions into several pieces. This picture explains non-trivial transport through a junction of one-dimensional edge channels defined by topologically distinct quantum Hall states, for example, a hole-conjugate state at Landau-level filling factor \(\nu = 2/3\). Here we employ a time-resolved scheme to identify an elementary fractionalization process; injection of charge \(q\) from a non-interaction region into an interacting and scattering region of one-dimensional channels results in the formation of a collective excitation with charge \((1-r)q\) by reflecting fractionalized charge \(rq\). The fractionalization factors, \(r = 0.34 \pm 0.03\) for \(\nu = 2/3\) and \(r = 0.49 \pm 0.03\) for \(\nu = 2\), are consistent with the quantized values of 1/3 and 1/2, respectively, which are expected in the disorder dominated regime. The scheme can be used for generating and transporting fractionalized charges with a well-defined time course along a well-defined path.
ne-dimensional electronic systems provide non-trivial many-body effects that cannot be explained with single-particle pictures. Theoretically, these effects can be calculated using bosonization techniques and the bosonic (plasmonic) scattering approach, which have been applied for both dc and ac responses even in inhomogeneous and disordered systems. Experimentally, many-body states can be investigated using electronic and optical techniques. Among them, one-dimensional edge channels in integer and fractional quantum Hall (QH) systems are attractive for studying non-trivial excitations in multiple channels by utilizing mesoscopic devices. The focus of this study is transport eigenmodes that govern the interacting edge channels.

For example, the charge and spin (dipolar) modes for copropagating channels in the integer QH system at \( \nu = 2 \) were investigated based on the Coulomb interaction in terms of the chiral Tomonaga-Luttinger liquid. At a Y-junction where two decoupled channels join to form an interacting region, an electronic excitation incident from the non-interacting region is fractionalized into non-trivial charge and spin excitations in the interacting region. In the absence of interchannel tunneling, the eigenmodes are determined by the interaction parameters and can hence deviate from the pure charge and spin modes. In this interaction-dominated regime, the fractionalization ratio assumes a non-universal interaction-dependent value, as demonstrated in frequency- and time-resolved measurements as well as noise measurements.

A similar class of coupled modes appears when disorder allows for significant tunneling between two edge channels. A well-known example is the charge and neutral modes in the ‘hole conjugate’ fractional QH state at \( \nu = 2/3 \), as suggested by noise measurements and transport properties for short interacting regions. We assume a reconstructed edge with counterpropagating integer and fractional channels, whereas alternative effective models can be considered. Theoretically, the charge and neutral modes appear at the Kane-Fisher-Polchinski fixed point in the renormalization group flow. In this disorder-dominated regime, an elementary excitation should be fractionalized into pure charge and neutral modes with a quantized ratio at a Y junction of interacting and non-interacting regions.

In this study, we have experimentally identified this quantized fractionalization ratio by employing time-resolved measurements for the hole-conjugate fractional state at \( \nu = 2/3 \). A similar quantized fractionalization is also found in the integer QH state at \( \nu = 2 \) in the presence of significant tunneling. The obtained feature is supported by a simulation involving a realistic model based on the plasmon scattering approach. The quantized charge fractionalization describes the dc characteristics as well.

**Results**

**Fractionalization processes.** We first consider the edge of the fractional state at \( \nu = 2/3 \), where the counterpropagating \( \Delta \nu = 1 \) and 1/3 one-dimensional channels are formed along the interface to the electronic vacuum (\( \nu = 0 \)), as shown in Fig. 1a. Here, \( \Delta \nu = |\nu_1 - \nu_2| \) denotes a channel along an interface between insulating (incompressible) regions with \( \nu = \nu_1 \) and \( \nu_2 \). Disorder-induced scattering renders them describable as a composite \( \Delta \nu = 2/3 \) channel with two counterpropagating transport modes, i.e., a charge mode carrying a charge and a neutral mode carrying heat. We address fractionalization processes at Y-junctions comprising \( \Delta \nu = 1, 2/3, \) and 1/3 channels, as shown in Fig. 1b–d. Two types of Y-junctions are possible, i.e., Y\(_C\) and Y\(_N\), which form depending on the cyclic order of the insulating regions and the direction of the magnetic field. For the configuration shown in Fig. 1b, a wave packet of charge \( q \) incident from the \( \Delta \nu = 1 \) channel is fractionalized with factor \( r (= 1/3 \) in the disorder dominated regime) at junction Y\(_C\) into fractional charges \( 1-r|q| \) and \( rq \), which propagate through the \( \Delta \nu = 2/3 \) and \( \Delta \nu = 1/3 \) channels, respectively. This occurs because the charge mode in the \( \Delta \nu = 2/3 \) channel is composed of charges \( q \) in the \( \Delta \nu = 1 \) channel and \(-rq \) in the \( \Delta \nu = 1/3 \) channel. The formation of this collective excitation requires a charge \( rq \) to be reflected back into the uncoupled \( \Delta \nu = 1/3 \) channel. A similar reflection is expected when a wave packet of charge \( q \) is injected from a \( \Delta \nu = 1/3 \) channel to junction Y\(_N\) shown in Fig. 1c, where neutral excitation in the \( \Delta \nu = 2/3 \) channel is formed by reflecting charge \( q \) in the downstream \( \Delta \nu = 1 \) channel. As shown in Fig. 1d, a charge wave packet in the charge mode of the \( \Delta \nu = 2/3 \) channel is decomposed into a charge in the \( \Delta \nu = 1 \) channel and heat in the neutral mode. We focus on the charge fractionalization by neglecting neutral excitations as the length of the \( \Delta \nu = 2/3 \) channel (\( L > 100 \mu \)) is much longer than the equilibration length \( L_{eq} \) (typically \( \sim 10 \mu \)).

**Quantized fractionalization in \( \nu = 2/3 \) case.** We demonstrate the charge fractionalization in time-domain measurements using several devices formed in a standard ALGaAs/GaAs heterostructure (see Methods and Supplementary Note 1). The following data were obtained at \( \sim 50 \) mK from devices \#1 and \#2 fabricated on the same chip, as schematically shown in Fig. 2a. For device \#1, two Y-junctions, Y\(_C\) and Y\(_N\), formed at the intersections of the three regions—the ungated region with bulk filling factor \( v_B = 2/3 \), the gated region with a tunable \( v_G (\sim 1) \) in Fig. 2a), and vacuum. An initial charge wave packet was excited by applying a voltage step to the injector gate \( G_I \), and the waveforms of the charge packets after passing through the junctions were investigated by applying a voltage pulse of width \( t_w \) (0.08-0.15 ns) to the detector gate \( G_D \). Charge waveforms were
obtained by measuring the detector current $I_D$ at various time delays $t_d$ of the voltage pulse with respect to the voltage step (see Methods\textsuperscript{38}). Trace (i) in Fig. 2b is a reference showing that a single charge packet was observed for $V_G = 0$ (the gate voltage $V_g = -0.3$ V), i.e., when a single $\Delta \nu = 2/3$ channel without Y-junctions is formed, as shown in the inset. This is a typical characteristic of the edge magnetoplasmon mode\textsuperscript{39–41} at $\nu = 2/3$. When the $Y_C$ and $Y_N$ junctions were activated by setting $V_G = 1$ ($V_g = +0.26$ V, $B = 11.5$ T), a clear charge fractionalization manifested as two distinct packets in trace (ii). The first packet is associated with the direct propagation through junction $Y_N$, $\Delta \nu = 1$ channel, and junction $Y_C$. The second one is delayed by the round trip around the gated region, as illustrated in the insets. Subsequent packets associated with further fractionalization processes are extremely small to be resolved. By assuming $r = 1/3$, the entire process yields a series of packets with $2q/3, 2q/9, \ldots$ toward the detector. We evaluated the charge $q_f$ in the reference wave packet in (i) as well as $q_{f1}$ and $q_{f2}$ in the first and second packets in (ii), respectively, from the area of the peaks. The obtained $q_f, q_{f1}$, and $q_{f2}$ are plotted in Fig. 3b as a function of $V_g$, with the vertical axis normalized by the $q_f$ value at $V_g = -0.3$ V ($V_G = 0$). The ratios $q_f/q_f$, $q_{f1}/q_f$, and $q_{f2}/q_f$ are similar to the expected values of $(1-r)/2$ and $(1-r)r/2$, respectively, when the $\Delta \nu$ and 1/3 channels are well defined at $V_G \geq 1$. In particular, $r = q_{f2}/q_f$ estimated from each $I_D$ profile yields $r = 0.34 \pm 0.03$ in the range of $V_g = -0.21 - 0.27$ V, as shown in the inset of Fig. 3b, consistent with the quantized value of $1/3$.

This observation is supported by the dc characteristics of device #2, which has Corbino geometry with ohmic contacts surrounded by a QH state, as shown in the lower part of Fig. 2a. Transport through the $\Delta \nu = 1/3$ channel formed between $V_G = 1$ and $V_g = -0.2$ regions involves the equilibration associated with scattering between the coupled $\Delta \nu = 1$ and 1/3 channels inside the composite $\Delta \nu = 2/3$ channels. Fig. 3a shows the two-terminal conductance $G$ between ohmic contacts $\Omega_1$ and $\Omega_2$ with other ohmic contacts floating. The clear plateau of $G \cong e^2/6h$ at $V_g \approx +0.2$ V ($V_G = 1$) ensures a full equilibration in the $\Delta \nu = 1/3$ channel and negligible backscattering in both $V_G = 1$ and $V_g = 2/3$ regions. This is a requisite for clear quantization of $r = 1/3$. Whereas the dc characteristics of systems involving composite $\Delta \nu = 2/3$ channels have been successfully explained in various ways\textsuperscript{32,33,37}, we herein demonstrate that the same can also be understood with the quantized charge fractionalization. As shown by the simplified channel configuration in the inset of Fig. 3a, a fictitious charge packet $q$ emanating from $\Omega_1$ is fractionalized into a series of charge packets through the paths shown by the dashed lines. Some of them reach $\Omega_2$ with the first charge $2q/9$ through path $\Omega_1 - \gamma_1 - Y_C - Y_N - Y_C - \Omega_2$, followed by others multiplied by the geometric ratio of $1/9$ associated with round trip $Y_C - Y_N - Y_C - Y_N$. The total charge $q/4$ reaching $\Omega_2$ explains $G = e^2/6h$ for the conductance $2e^2/3h$ of the source channels connected to $\Omega_1$ and $\Omega_2$. Hence, charge fractionalization provides a unified view of dc and time-dependent charge transport.

Quantized fractionalization in $\nu = 2$ case. We observed similar quantized fractionalization with integer QH states at $V_G = 2$ and $V_g = 1$, when the two $\Delta \nu = 1$ channels with up- and down-spins were prepared in the disorder-dominated regime. The two channels are coupled to form a composite $\Delta \nu = 2$ channel, as shown in the bottom inset of Fig. 2c. Significant scattering between them is allowed for example by coupling to nuclear spins\textsuperscript{42}. Separate experiments showed full equilibration for a channel length of ~300 $\mu$m in device #2 (see Supplementary Note 2). Our previous study showed a short equilibration length of ~10 $\mu$m in a similar device with a slightly lower electron
In this disorder-dominated regime, the transport eigenmodes of the $\Delta\nu = 2$ channel should be a pure symmetric charge mode and a short-lived antisymmetric neutral mode (see Methods). These modes are excited at junction YE and decomposed at junction YD with quantized charge fractionalization of factor $r = 1/2$. Namely, a single charge packet with $q$ in the symmetric mode splits into two packets with $(1-r)q$ and $rq$ in the up- and down-spin channels, respectively. Compared with the reference trace (i) in Fig. 2c for $(v_G, v_B) = (0, 1)$, trace (ii) shows charge fractionalizations for $(v_G, v_B) = (2, 1)$ at $v_g = +0.34\, V$ and $B = 7.5\, T$. A series of well-isolated packets, $q_{f1}$, $q_{f2}$, ... manifests the multiple fractionalization processes at YD. As plotted in Fig. 3e, the fractionalization factor $r = q_{f1}/q_{f2} = 0.49 \pm 0.03$ obtained in the range of $v_g = 0.31-0.37\, V$ is consistent with the quantized value of 1/2. This is in contrast to previous studies pertaining to the interaction dominated regime, where asymmetric modes with an interaction dependent factor of $r \approx 0.4$ were observed.

We observed a clear two-terminal conductance plateau $G = e^2/3\, h$ at $(v_G, v_B) = (2, 1)$ using device #2, as shown in Fig. 3d. This conductance is 1/3 of the original $G = e^2/h$ of the single integer channel emanating from the ohmic contacts. This can be understood as the sum of the first transmission coefficient (the square of the fractionalization factor 1/2) of a fictitious charge packet through path $\Omega_1 - Y_E - Y_D - Y_E - Y_D - \Omega_2$ followed by others with a geometric ratio of 1/4 associated with round trip $Y_D - Y_E - Y_D - Y_E - Y_D$, as shown in the inset. Hence, the quantized fractionalization also explains the dc characteristics of the integer channels.

**Plasmon velocities.** The velocity of the wave packet is an important parameter that reflects the interaction, as evident from chiral Tomonaga-Luttinger theories.\textsuperscript{2,10,19} We experimentally estimated the velocities from the time of flight, as summarized in Fig. 3c, f. The velocities of the edge channels ($\Delta\nu = 1$ channel between $v_G = 1$ and vacuum and $\Delta\nu = 2/3$ channel between $v_G = 0$ and $v_B = 2/3$ in Fig. 3c) are comparable to those in previous reports regarding edge magnetoplasmons\textsuperscript{38,39,43,44}. The velocity of the $\Delta\nu = 1/3$ interface channel between $v_G = 1$ and vacuum, and the $\Delta\nu = 2$ composite channel between $v_G = 2$ and vacuum are shown in f. Data in b, c, e, and f were obtained using device #1. Vertical dotted lines for representative $v_g$ and $v_B$ values were determined from a separate four-terminal measurement (see Supplementary Note 1).

**Fig. 3 Characteristics of charge transport.** a, d $v_g$-dependence of two-terminal conductance $G$ measured with ohmic contacts $\Omega_1$ and $\Omega_2$ of device #2 obtained at $v_B = 2/3$ in a and $v_B = 1$ in d. The insets show the channel configurations, where multiple charge fractionalizations at Y-junctions explain the plateau $G = e^2/6\, h$ at $v_G = 1$ in a and $G = e^2/3\, h$ at $v_G = 2$ in d. b, e The reference charge $q_r$ and fractionalized charges $q_{f1}, q_{f2}, ...$ in the respective packets normalized by $q_r$. A single reference packet typically involves $q_r \approx 240e$ in b and 30e in e. The clear plateaus of $q_r/q$ indicate the quantized fractionalization. The insets show fractionalization factor $r = q_{f1}/q_r$ with a constant region ($r = 0.34 \pm 0.03$ in b and $r = 0.49 \pm 0.03$ in e). c, f Charge velocities of the channels. The $\Delta\nu = 1/3$ interface channel between $\nu = 1$ and 2/3 regions, the $\Delta\nu = 1$ edge channel between $v_G = 1$ and vacuum, and the $\Delta\nu = 2/3$ composite channel between $v_G = 0$ and $v_B = 2/3$ in Fig. 3c, f. The velocities of the edge channels ($\Delta\nu = 1$ channel between $v_G = 1$ and vacuum and $\Delta\nu = 2/3$ channel between $v_G = 0$ and $v_B = 2/3$ in Fig. 3c) are comparable to those in previous reports regarding edge magnetoplasmons. The velocity of the $\Delta\nu = 1/3$ interface channel between $v_G = 1$ and vacuum, and the $\Delta\nu = 2$ composite channel between $v_G = 2$ and vacuum are shown in f. Data in b, c, e, and f were obtained using device #1. Vertical dotted lines for representative $v_g$ and $v_B$ values were determined from a separate four-terminal measurement (see Supplementary Note 1).
Fig. 4 Velocity of the interface mode. a Schematic cross-section around the interface channel \( \Delta \nu = |\nu_1 - \nu_2| \) (of width \( w_g + w_o \) (\( w_g \) in the gated region and \( w_o \) in the ungated region) between two QH states at \( \nu_1 \) and \( \nu_2 \). The interaction inside the channel can be described with geometric capacitance \( C \) to the gate. b Calculated capacitance \( C \) as a function of \( w_g \) for several \( w_o \) values. c Fractionalization factor \( r \) for junction \( \nu_2 = (2/3, 1) \) and \( (1, 2/3) \) showing \( r \sim 1/3 \) (circles), and junction \( \nu_2 = (1, 2) \) and \( (2, 1) \) showing \( r \sim 1/2 \). d Normalized charge velocities \( v_C/\Delta \nu \) for fractional \( \Delta \nu = 1/3 \) interface channels at \( (2, 3/1) \) and \( (1, 2/3) \) marked with circles, integer \( \Delta \nu = 1 \) interface channels at \( (1, 2) \) and \( (2, 1) \) marked with squares, and conventional edge channels at \( (0, 2) \) and \( (0, 1) \) marked with triangles. Data obtained after light irradiation are marked with solid symbols. Channel capacitance \( C \) is shown on the right scale.

Fig. 4a, this \( C \) is expected to depend on the width, \( w = w_g + w_o \) of the channel (compressible region), where \( w_g \) (\( w_o \)) is the spread under the gate (in the ungated region). Our numerical simulation (see Methods) shows that \( C \) is determined primarily by \( w_g \) rather than \( w_o \) (Fig. 4b). The normalized velocities, \( v_C/\Delta \nu \), obtained for various values of \( (\nu_2, \nu_1) \), are summarized in Fig. 4d. Here, the data for \( \nu_2 > \nu_1 \) and \( \nu_2 < \nu_1 \) were obtained using devices #1 and #2, respectively, with \( V_g > 0 \) and \( V_g < 0 \) (see Supplementary Notes 2 and 3). Except for \( (\nu_2, \nu_1) = (2/3, 1) \), \( v_C/\Delta \nu \) indicates similar values for all interface channels, i.e. \( \Delta \nu = 1/3 \) (circles) and \( 1 \) (squares), as well as edge channel \( \Delta \nu = 1 \) (triangles). This coincidence suggests that the velocities are determined by a similar \( C \sim 0.4 \text{ nF/m} \), as shown on the right axis. A comparison with Fig. 4b implies that \( w_g \) is sufficiently narrow, comparable to the depth \( d \sim 100 \text{ nm} \) of the electron system from the surface. This indicates that the velocity \( \sim 30 \text{ km/s} \) of the \( \Delta \nu = 1/3 \) channel obtained for \( (\nu_2, \nu_1) = (1, 2/3) \) is reasonable. Meanwhile, a significantly lower velocity of \( \sim 1 \text{ km/s} \) was observed for the \( \Delta \nu = 1/3 \) channels in the \( (2, 3/1) \) configuration. This suggests a wide \( w_g \sim 10 \mu \text{ m} \) in the crude model or quasi-diffusive transport in the presence of disorder potential. Whereas this might be related to the small energy gaps of the QH states at lower \( B \) in this configuration, the velocity did not increase significantly with \( B \) even after light irradiation (solid circle), which increased the electron density. The former \( (1, 2/3) \) configuration with a fractional state in an ungated region might be suitable for minimizing the time-of-flight and hence decoherence in a fractional-charge interferometer. It is noteworthy that the fractionalization factor \( r \) summarized in Fig. 4c remained at approximately 1/3 even when the velocity reduced significantly.

Discussion

The observation above suggests robust fractionalization factors in the disorder-dominated regime. This is consistent with the plasmon (charge density wave) transport model (see Methods) shown in Fig. 5a, where interaction and scattering are characterized by distributed capacitances and scattering conductances, respectively.\(^{46-48}\) The transport eigenmodes generally deviate from the pure charge and neutral modes at higher frequencies. However, the deviation is small in the low-frequency regime, where the wavelength \( \lambda \) of the plasmon is much greater than the equilibration length \( \lambda_{eq} \). This is observed in the numerical simulation of multiple charge fractionalizations with realistic parameters, as shown in Fig. 5b, c, where the distortion of the charge waveform is negligible. The obtained narrow width (a few nanoseconds) of the fractionalized wave packets encourages studying microscopic fractionalization processes including neutral modes and heat generation, which can be used to identify the appropriate effective model\(^{34-36,49}\). The deterministic fractionalization processes may benefit the search for non-trivial anyonic statistics of fractional charges\(^{48,50-53}\).

Methods

Device fabrication. The devices were fabricated from a standard GaAs/AlGaAs heterostructure with a two-dimensional electron gas (2DEG) located 100 nm below the surface having an electron density of \( 1.85 \times 10^{11} \text{ cm}^{-2} \) in the dark and \( 2.07 \times 10^{11} \text{ cm}^{-2} \) after light irradiation at low temperature. After patterning holes into the 2DEG for the Corbino geometry, ohmic contacts were formed by alloying Au-Ge-Ni metal films; subsequently metal gates were patterned using photolithography and electron-beam lithography (see Supplementary Note 1 for details).

Time-of-flight experiment. A charge wave packet was generated by depleting electrons near the injection gate \( G_0 \) of length \( l = 50 \mu \text{ m} \) by applying a voltage step \( \Delta V_{\text{i}} = 5-15 \text{ mV} \) to the static voltage of \( -0.2-0.3 \text{ V} \). This induced charge \( q_d = C_{0}(\Delta V_{\text{i}}) \) in the packet, where \( C_0 \) is the coupling capacitance. The charge waveform \( \rho (t) \) was evaluated by applying a detector pulse \( \Delta V_{\text{D}} = 20 \text{ mV} \) to the static voltage of...
 capacitance of interface channel. The interface channel is a compressible stripe of finite width $w$ between two incompressible regions. As the electrostatic potential for this situation is challenging, we assumed finite widths $w_p$ and $w_n$ in the gated and ungated regions, respectively, as shown in Fig. 4a. By considering the incompressible regions as insulators, the capacitance between the channel and the gate was calculated using commercial software COMSOL based on the finite-element method.

Fractionalization factor at high frequencies. We used the plasmon scattering approach to simulate the fractionalization process in the presence of disorder-induced tunneling. Consider two one-dimensional chiral channels ($n = 1$ and $2$) with conductance $v_{\pm}$ (positive for right movers and negative for left movers), as shown in Fig. 5a. The charge density $n$, electrochemical potential $V_{\pm}$ and current $I_{\pm} = v_{\pm}nV_{\pm}$ are related to each other with the Coulomb interaction characterized by the self-capacitance $C_0$ (to the ground) and coupling capacitance $C_g$ per unit length$^{[15,16,26]}$. The quantum capacitance was absorbed in those capacitances. Scattering between the channels was considered with scattering conductance $g$ per unit length$^{[22]}$. Based on current conservation, we derived the following wave equation:

$$\frac{\partial}{\partial x} I_1 = \left[ \begin{array}{cc} C_1 + C_2 & -C_1 C_2 \\ -C_1 C_2 & C_1 + C_2 \end{array} \right] \frac{\partial}{\partial t} + g \left[ \begin{array}{c} 1 \\ 1 \end{array} \right] V_1 \left[ \begin{array}{c} V_1 \\ V_2 \end{array} \right].$$

(1)

Transport eigenmodes $I_1 = \frac{I_1}{I_2}$ can be calculated for alternating current $I_L = I_L e^{i(\omega t-\nu t)}$ with amplitude $I_L$ at frequency $\omega$. The resulting $\nu$ (complex) for each mode measures the wavenumber in the real part and the decay rate in the imaginary part. For the fractional case with $\nu_1 = e^2/\hbar$, $\nu_2 = e^2/\hbar$, and $g > 0$, pure charge and neutral modes with $I_1/I_2 = -1/3$ and $-1$, respectively, appeared at $g > u(C_1 + 3C_2)$ in the disorder-dominated regime, and interaction-dependent modes appeared at $g < u(C_1 + 3C_2)$ in the interaction-dominated regime. Because the solution in the zero-frequency limit ($\omega \rightarrow 0$) provides the equilibrium length $L_0 = \omega/2g$, the disorder-dominated regime corresponds to the plasmon wavelength $\lambda$ much longer than $L_0$.

Our wave packet contains a long wavelength in the Fourier components ($\lambda > 800$ nm in the $\Delta = 2$ channel for the data in Fig. 2b and $\lambda > 300$ nm in the $\Delta = 3$ channel for the data in Fig. 2c). Hence, all data shown herein are obtained from the disorder-dominated regime for our sample $L_0 = 10$ nm. In this case, the charge mode exhibits a slight decay with an angle $\arg[k] = 2\pi \left( \frac{\omega}{\nu} + \frac{\nu}{\omega} \right)$ in the lowest order. This broadens the wave packet only slightly. The time evolutions of $I_1$ and $I_2$ in Fig. 5 were obtained by integrating Eq. (1) with current conservation at the boundaries of non-interacting ($C_0 = 0$ and $g = 0$) and interacting regions.

Data availability

The data and analysis used in this work are available from the corresponding author upon reasonable request.

Code availability

The codes that are used to generate results in the paper are available from the corresponding author upon reasonable request.

Received: 10 July 2020; Accepted: 2 December 2020;
Published online: 07 January 2021.
The authors thank T. Hata and Y. Tokura for their contributions.

Acknowledgements
The authors thank T. Hata and Y. Tokura for their beneficial discussions. This study was supported by the Grants-in-Aid for Scientific Research (JP15H05854, JP19H05603) and the Nanotechnology Platform Program of the Ministry of Education, Culture, Sports, Science and Technology, Japan.

Author contributions
T.F. designed and supervised this study. C.L. fabricated the device and performed the experiment with help from M.H and T.F. T.A. and K.M. grew the wafer. C.L. and T.F. analyzed the data and wrote the manuscript. All authors discussed the results and commented on the manuscript.

Competing interests
The authors declare no competing interests.

Additional information
Supplementary information is available for this paper at https://doi.org/10.1038/s41467-020-20395-7.

Correspondence and requests for materials should be addressed to C.L. or T.F.

Peer review information Nature Communications thanks the anonymous reviewers for their contribution to the peer review of this work.

Reprints and permission information is available at http://www.nature.com/reprints

Publisher’s note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Open Access
This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The images or other third party material in this article are included in the article’s Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article’s Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this license, visit http://creativecommons.org/licenses/by/4.0/.

© The Author(s) 2021