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Gate tunable edge magnetoplasmon resonators

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Quantum Hall systems are platforms of choice to study topological properties of condensed matter systems and anyonic exchange statistics. In this work we have developed a tunable radiofrequency edge magnetoplasmonic resonator controlled by both the magnetic field and a set of electrostatic gates, meant to serve as a versatile platform for future interferometric devices designed to evidence non-abelian anyons. In our device, gates allow us to change both the size of the resonant cavity and the electronic density of the two-dimensional electron gas. We show that we can continuously control the frequency response of our resonator, making it possible to develop an edge magnetoplasmon interferometer. As we reach smaller sizes of our resonator, finite size effects caused by the measurement probes manifest. In the future, such device will be a valuable tool to investigate the properties of non-abelian anyons in the fractional quantum Hall regime.

Under strong perpendicular magnetic fields, two-dimensional electron gases (2DEGs) enter the quantum Hall regime. One important feature of this effect is the appearance of edge states with quantized conductance. Edge state transport can be described in terms of free collective bosonic modes called edge magnetoplasmons (EMP)^{1–6} that propagate along the edge with velocity v ^{7–13}.

When two counter propagating edges are brought together at the level of a quantum point contact (QPC), the granularity of charge carriers comes into play. In the regime of the integer quantum Hall effect (IQHE), the excitations tunneling at the QPC are quasi-electrons that obey the Fermi statistics. However, in the case of the fractional quantum Hall effect, these excitations are no more fermionic but anyonic and follow an anyonic statistics.

Unlike fermions, anyons are quasiparticles with fractional charge and non-trivial exchange statistics. This means that the system acquires a non trivial braiding phase when two anyons are exchanged. Such properties were recently demonstrated experimentally in collider^{14–16} and interferometer^{17,18} experiments. Those experiments focused on the anyonic nature of the abelian, i.e., commutative, states $\nu = 1/3$ and $\nu = 2/5$. However, other fractional fillings are expected to host non-abelian anyonic excitations; in particular the $\nu = 5/2$ filling factor¹⁹. The braiding of such non-abelian anyons has been proposed as a promising platform for topologically protected quantum computing protocols^{20,21}.

One proposal to evidence these non-abelian properties is to study the absorption of microwave radiation by EMPs in an isolated Hall island²². Because of its isolated nature, the Hall island is a resonant cavity for the EMPs. In this cavity, a resonance at $f = v/L$ (in the GHz range) is defined by the ratio between the velocity v of the EMPs and the perimeter L of the island^{7,8,12}. By adding a QPC, the resonator becomes a quasiparticle interferometer operated in the microwave domain. It is predicted that the statistics of the quasiparticles involved in the tunneling process determine the amplitude and period of the oscillations of the absorption with respect to the magnetic field. Cano et al.²² theorize that non-abelian properties, particularly expected to be observed at the $\nu = 5/2$ filling, modulate this absorption depending on the parity of the number of quasiparticles present in both lobes of the interferometer. One of the main advantages of such a system is that the amplitude of the interferometric signal has a first-order dependence in the strength of the tunnel coupling. By contrast, other experiments relying on an open geometry of anyonic interferometers^{17,18,23,24} make use of two QPCs and the interferometric signal only has a second order dependence on the tunnel coupling. Such a detection scheme thus increases the sensibility of the experiment and serve as an alternative route for the study of anyonic properties of quasiparticles in quantum Hall systems.

Aiming toward the realization of such an interferometer, we study here the microwave absorption of a bare Hall island, in a simple resonator regime, i.e., not in the interferometer mode. Contrary to previous works on

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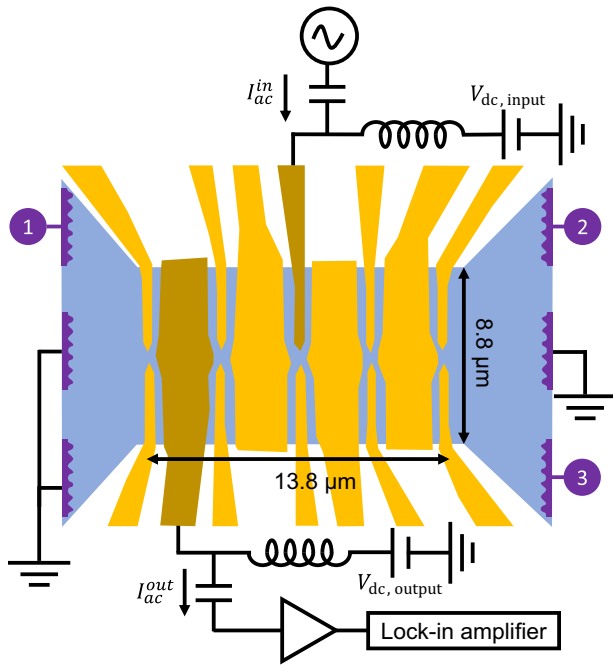


Fig. 1 | Edge magnetoplasmon resonator. Schematics of the sample. The 2DEG is shown in blue and the electrostatic gates are indicated in yellow. Two gates, shown in brown, are used both for electrostatic gating and microwave measurement. The injection of the microwave signal is done through the thin central brown gate and detection by the large brown pad on the left of the structure. Ohmic contacts (in purple) are also present on the sample far ($\approx 100 \mu\text{m}$) from the resonator area, in order to probe the dc properties of the sample (see Supplementary Note 2).

EMP resonators^{1,2,7–13}, we define the cavity by a combination of electrostatic gates and chemical etching. This allows us to continuously change the shape of the cavity²⁵, making it possible to fully control the frequency of the resonant mode. We focus on micrometer-sized structures, approaching the dimensions required for interferometric experiments^{23,24}, much smaller than previously considered EMP resonators^{7,12,25}. In this configuration, we observe a deviation from the $f = v/L$ relation and we reach a regime in which the microwave measurement gates act as frequency filters of the resonant signal. We explore the finite size effect of the probes on the resonance frequency of the structure. We also consider the role of top gates on the propagation of magnetoplasmons and compare our results with a theoretical description based on an EMP scattering matrix formalism^{3,5,26}.

Results

Sample description

The Hall island considered here is based on an AlGaAs/GaAs heterostructure hosting a high mobility 2DEG. Ti/Pt/Ti/Au gates are evaporated on this structure. These gates are coupled only capacitively to the 2DEG (see Fig. 1). This geometry allows us to realize islands of controllable sizes, from $8 \times 7 \mu\text{m}^2$ ($L = 30 \mu\text{m}$) to $8 \times 13 \mu\text{m}^2$ ($L = 42 \mu\text{m}$), by choosing which QPC to open or to close (see insets of Fig. 2a–c).

The injection and detection of the microwave signal is done through two bias-tees connected respectively to the top gate of the central QPC and to the left pad gate (in brown in Fig. 1). These two gates can also be addressed in dc and thus allow us to tune the perimeter of the structure as well as the local electronic density inside the resonator. Ohmic contacts are also present (shown in purple in Fig. 1). Their purpose is to control the opening and closing of the gates in the dc regime in the calibration stage of the experiment.

The large gates deposited on top of the structure have two roles: first, they allow us to tune the density of the 2DEG and second, they screen the inter-channel coupling, leading to a decrease of the velocity v of EMPs by approximately one order of magnitude^{7,27,28}. Reducing the velocity brings the

resonance frequency f_{res} into our experimental frequency window of 0.5–8.5 GHz for magnetic fields between 0 and 8 T.

Discrete control of the cavity size

Figure 2a–c. present the result of the measurement of the microwave signal $s(f, B)$ transmitted through the cavity in three different electrostatic configurations of the same sample. The quantity plotted in this figure is the square of the normalized transmitted intensity $|s|^2$ (see methods section for details about the normalization procedure). In this figure, the frequency varies from 1.5 to 8 GHz and the magnetic field is swept between 0 and 5 T, corresponding to filling factors $\nu \geq 2$. Each color map corresponds to the electrostatic configuration drawn in the inset of the figures where the QPCs used to define the cavity are represented in red. The main feature of these transmission maps (Fig. 2a–c) are the resonances whose frequency decreases with the magnetic field, following the magnetic field behavior of $\nu \propto 1/B^{29}$. In Fig. 2g, the resonance frequency is plotted as a function of $1/B$ for three different cavity sizes (perimeters of $30 \mu\text{m}$, $35 \mu\text{m}$ and $42 \mu\text{m}$). The extrapolation of the linear fits down to 0 T^{-1} demonstrates the inverse proportionality between the frequency and the magnetic field.

The full maps of the transmitted signal (Fig. 2a–c) exhibit discontinuities in the line shape following the resonance. These discontinuities are caused by the transitions between various plateaus of the IQHE¹². This is particularly visible around 2 T. Within a plateau, the edge states are well defined thanks to the conductance suppression through the bulk of the resonator. However, between two plateaus, the bulk becomes conducting and the edge states cease to exist as 1D chiral conducting regions. Consequently, there is no well defined resonance frequency anymore and this manifests as discontinuities in our experimental maps. Figure 2d–f. present the corresponding numerical simulations that will be detailed below.

In the largest cavity ($L = 42 \mu\text{m}$), we observe a second mode present at twice the frequency of the fundamental. This mode is not observed for smaller cavities. As we will show with our theoretical description, this is due to the finite-size of the detection gate that leads to “blind spots” in the EMP detection. When decreasing the size of the cavity, the frequency of the resonance increases and so does that of the first harmonic. The harmonic is then pushed into the blind spot of the detection and thus disappears in Fig. 2b, c.

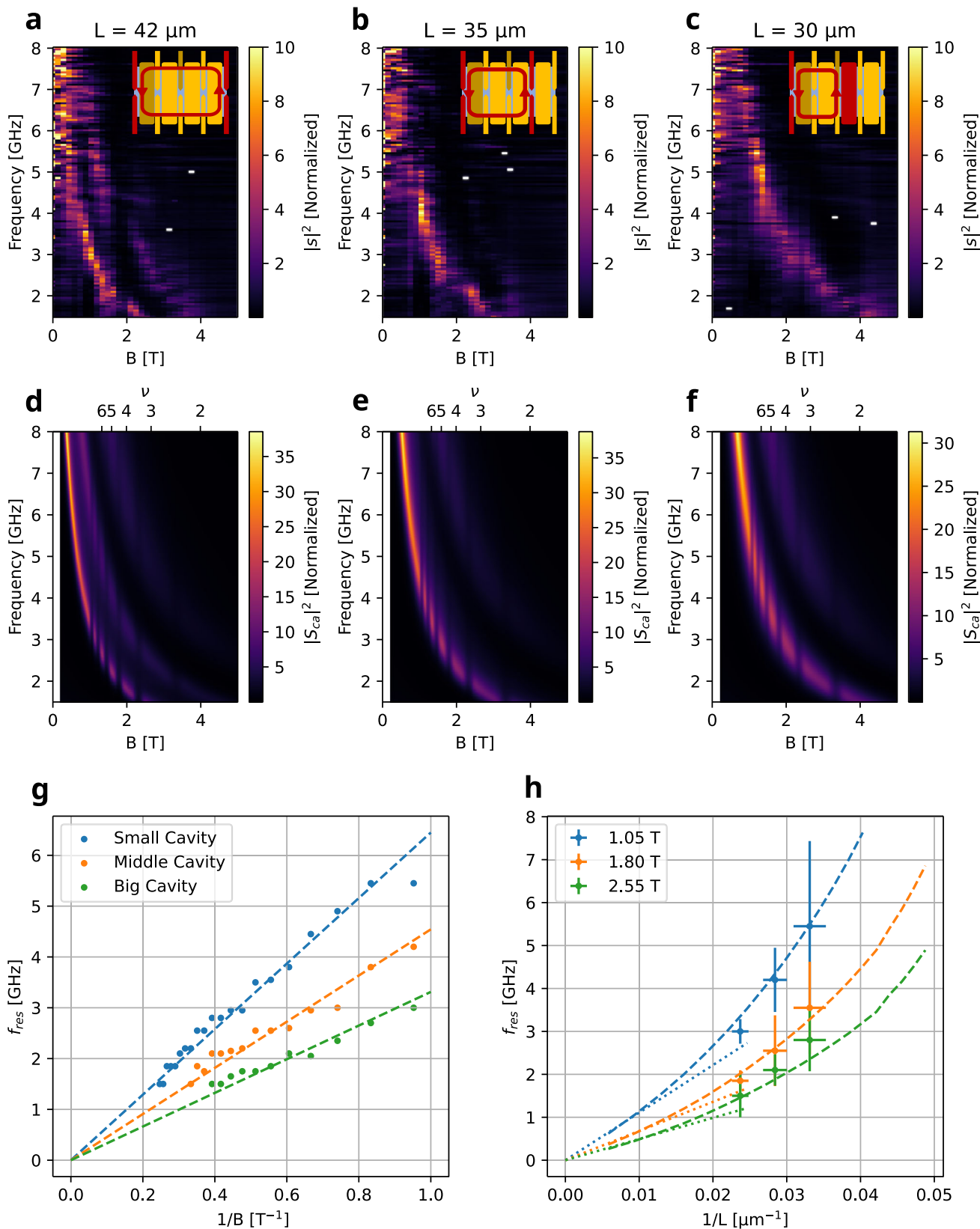
For a fixed magnetic field B , reducing the perimeter of the cavity increases the resonance frequency. This is better seen by extracting the frequency at a given field and plotting it as a function of the inverse of the total perimeter L of the cavity under study as shown on Fig. 2h for the fields 1.05 T, 1.8 T and 2.55 T. If the frequency were proportional to the inverse of the total length of the cavity, we would observe a proportionality relation between f_{res} and $1/L$ (dotted lines). However, linear fits to the data do not converge to 0. This peculiar behavior is caused by finite size effects of the input and output gates that will be explored theoretically in the next sections.

Propagation of the EMPs

The theoretical description of the system is done in two steps. First, we consider the propagation of magnetoplasmons in the presence of a gate following the description of ref. 28. We consider a 2DEG separated from the gate by a distance d (see Fig. 3a). In between the 2DEG and the gate, the AlGaAs layer is described by a dielectric of relative permittivity ϵ_r , approximately equal to 12.4 at low temperature^{30–32}. The density $n_0(x)$ on the edge of the system vanishes over a length a where it connects to the vacuum.

The transmission amplitude for the charge EMP at frequency $\omega/2\pi$ propagating over a distance l is of the form $e^{jk(\omega)l}$. The real part of $k(\omega)$ describes the accumulated phase or equivalently the charge EMP effective velocity ($\text{Re}(k(\omega)) = \omega/v$), whereas its imaginary part $\text{Im}(k(\omega)) \geq 0$ describes the charge magnetoplasmon attenuation along propagation.

In ref. 28, [Sec. IV.A.2], dissipation is associated with the dc longitudinal resistance, which is non-vanishing between the plateaus of the quantum Hall effect. However, this is not the only source of dissipation in quantum Hall systems. Dissipation also arises from the capacitive coupling to charge puddles within the bulk of the 2DEG, thereby taking energy away from the charge EMP mode and ultimately dissipating it into the phonon



bath^{11,33}. Such dissipation is present even when the longitudinal dc resistance vanishes within quantum Hall plateaus. At the lowest order, a contribution to $\text{Im}(k(\omega))$, proportional to ω^2 can be added to describe the damping of EMP along their propagation²⁵. Adding this capacitive dissipation to the expressions of ref. 28, [Sec. IV.A.2] for the complex valued $k(\omega)$ for a wide

edge leads to:

$$k(\omega) = \frac{\omega}{v} + i \left(\frac{r^2}{4\omega_c \tau a} + \frac{\xi \omega^2}{v^2} \right) \tag{1a}$$

Fig. 2 | Effect of the magnetic field and the size of the cavity. **a–c** Color maps of the microwave transmission $|s(B, f)|^2$ of the sample as a function of the magnetic field and the excitation frequency for three different electrostatic configurations. From left to right the size of the cavity decreases (the electrostatic configuration is schematically represented in the inset of the figures) and, reciprocally, the resonance frequency increases. **d–f** Numerical simulations performed with the same cavity sizes as in (a–c). The top horizontal axis indicates the values of the filling factors associated to the density and field used in the simulations. **g** Frequency of the resonant mode as a function of the inverse of the magnetic field for the three cavities presented in (a–c). These points were obtained by extracting the maximum of the

transmission signal at each value of the magnetic field. The dashed lines correspond to the linear fit of the experimental points. **h** Frequency of the resonant mode as a function of the inverse of the perimeter of the cavity for three different magnetic fields. The experimental data is presented with error bars and the dashed lines correspond to the result of the simulation. The dotted lines indicate the expected $f = v(B)/L$ behavior, only valid for large cavities, using for v the values used to plot figures (d–f). The error bars shown in this graph correspond, in the frequency axis, to the fitted width of the resonance. Those in the $1/L$ axis were taken by estimating the uncertainty on L and propagating the error to $1/L$.

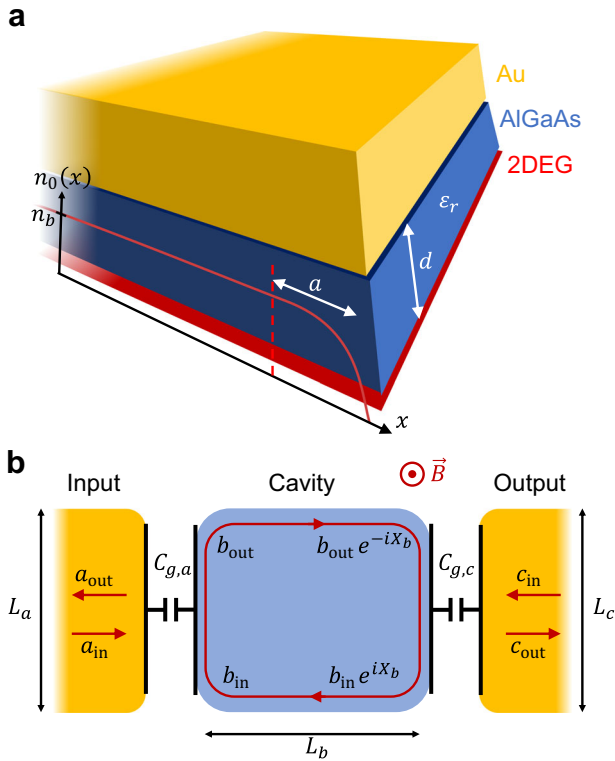


Fig. 3 | Theoretical description of the system. **a** The Au gate (in yellow) is positioned at a distance $d \approx 105$ nm above the 2DEG (in red) separated by the AlGaAs layer (in blue) with relative dielectric permittivity ϵ_r . The electronic density $n_0(x)$ is constant in the bulk and decreases to zero on a scale a on the edge. **b** The radio-frequency transport through the system is described in terms of three different sections. The input (resp. output) gate is described by the incident and reflected amplitudes a_{in} and a_{out} (resp. c_{in} and c_{out}). The cavity is connected capacitively to these two input and output gates of respective lengths L_a and L_c through capacitances $C_{g,a}$ and $C_{g,c}$. The magnetoplasmons acquire an amplitude e^{iX_b} where $X_b = k(\omega)L_b$ when propagating along the edge of the cavity on a length L_b . The transmission amplitude is given by the term S_{ac} in the magnetoplasmon scattering matrix. For readability reasons, the top gates are not represented here. Their effect is already taken into account by Eq. (1a).

$$v = \frac{\gamma \omega_c a}{1 + \gamma(r^2/4) + (1/\omega_c^2 \tau^2)} \quad (1b)$$

where $r \approx 2.405$ is the first zero of the Bessel function J_0 , $\omega_c = eB/m$ is the cyclotron pulsation and $\gamma = l_0 d/a^2$ with the characteristic length $l_0 = e^2 n_b / \epsilon m \omega_c^2$. In our experiment, n_b denotes the bulk electronic density and $\epsilon = \epsilon_r \epsilon_0$ with ϵ_0 the dielectric permittivity of vacuum and $\epsilon_r = 12.4$ the relative dielectric permittivity of GaAs³⁴. The effective mass m of electrons in the 2DEG is taken to be 0.067 times the mass of free electrons^{35,36}. d is the distance from the top gates to the 2DEG, $d = 105$ nm. As we will discuss later, we obtain a best fit of our data by using $a = 2.8 \mu\text{m}$. It leads to $\gamma = 1.4 \times 10^{-2}$ with $l_0 = 1.1 \mu\text{m}$ at 1 T and makes Eq.s (1a) and (1b) valid

since $\gamma \ll 1$ and $d \ll a$. We reach a maximal value of $ka \approx 1$ for the smallest cavities which should limit the relevance of some approximation made in ref. 28 and therefore impact our calculation. However, as we will see the final agreement with our data remains good.

The relaxation time of the Drude model τ is related to the dc longitudinal resistance and thus depends on the magnetic field (see Supplementary Note 5). Finally, the length ξ , which has to be fitted from the experimental data, accounts for dissipation through capacitive couplings via the $\xi \omega^2/v^2$ contribution to $\text{Im}(k(\omega))$ where v , given by Eq. (1b) is the effective velocity of the magnetoplasmonic charge mode.

Transmission model

Assuming that dissipative propagation of the charge EMP is described according to the previous paragraph, we can now turn our attention to the coupling of the resonator to the probing gates. These two gates are described as two microwave transmission lines, capacitively coupled to the 2DEG. The microwave propagation along these lines is treated within the input/output formalism for the setup depicted on Fig. 3b.

This corresponds to a plasmonic Fabry-Perot (FP) cavity with extended mirrors corresponding to the region where its resonant modes couple to the external transmission lines through a capacitive coupling $C_{g,a}$ at the input gate of length L_a and $C_{g,c}$ to the output gate of length L_c . Propagation along the uncoupled parts of the island over a distance L_b leads to an amplitude e^{iX_b} with $X_b = k(\omega)L_b$ (dissipation being contained in $\text{Im}(k(\omega))$).

Microwave propagation across the FP cavity can then be described using an EMP scattering matrix connecting the incoming to the outgoing modes

$$\begin{pmatrix} c_{out} \\ a_{out} \end{pmatrix} = \begin{pmatrix} S_{cc} & S_{ca} \\ S_{ac} & S_{aa} \end{pmatrix} \begin{pmatrix} c_{in} \\ a_{in} \end{pmatrix} \quad (2)$$

involving four scattering amplitudes whose explicit forms are given in Supplementary Note 6. The resonant mode of interest is accessible through the full transmission amplitude connecting a_{in} to c_{out} :

$$S_{ca} = \frac{t'_a t_c e^{iX_b}}{1 - r'_a r'_c e^{2iX_b}} \quad (3)$$

In this equation, t_j and r_j respectively denote the EMP transmission and reflection coefficients at the input ($j = a$) and output ($j = c$) mirrors of the FP cavity. For simplicity, these expressions assume that the distance traveled by the magnetoplasmons between the input and output gates and vice-versa are the same, as depicted on Fig. 3b. For an asymmetric sample and with the propagation amplitude discussed in the previous paragraph, the expressions are almost the same: first of all, the product of the two amplitudes in the denominator is e^{2iX_b} where X_b is computed from L_b being the average of the propagation distances from a to c and c to a . However, the exponential at the numerator has to be replaced by $e^{ik(\omega)L_{ac}}$ where L_{ac} is the actual length of the path from a to c .

To obtain the expressions of the transmission and reflection coefficients, we model the mirrors of the FP by a capacitive coupling between a transmission line with characteristic impedance $Z = 50 \Omega$ and the edge channel of the Hall island³⁷. We introduce dissipation for the charge EMP mode beneath the metallic input and output gates as discussed in the

previous paragraph. We assume total electrostatic mutual influence between the two gates and the resonator within each mirror of the FP cavity. This hypothesis is reasonable for our sample and ensures maximal coupling between the resonator and its left and right ports. As shown in supplementary note 6, this leads to the plasmonic transmission and reflection amplitudes:

$$t'_j = -\text{Re}(k(\omega))L_j\sqrt{\mathcal{R}} \text{sinc}\left(k(\omega)\frac{L_j}{2}\right)D_j^{-1}, \quad (4)$$

$$t_j = -k(\omega)L_j\sqrt{\mathcal{R}} \text{sinc}\left(k(\omega)\frac{L_j}{2}\right)D_j^{-1}, \quad (5)$$

$$r'_j = e^{-\text{Im}(k(\omega))\frac{L_j}{2}}\left[1 + e^{-ik(\omega)\frac{L_j}{2}} \times \alpha_j \text{sinc}\left(k(\omega)\frac{L_j}{2}\right)\left(1 - \text{Re}(k(\omega))\frac{\mathcal{R}L_j}{2\alpha_j}\right)\right]D_j^{-1}, \quad (6)$$

with D_j being the denominator coefficient

$$D_j = e^{\text{Im}(k(\omega))\frac{L_j}{2}}\left[1 + e^{ik(\omega)\frac{L_j}{2}} \times \alpha_j \text{sinc}\left(k(\omega)\frac{L_j}{2}\right)\left(1 - \text{Re}(k(\omega))\frac{\mathcal{R}L_j}{2\alpha_j}\right)\right],$$

where $\mathcal{R} = 2e^2Z/h$. The dimensionless coupling

$$\alpha_j = \frac{e^2}{h} \frac{L_j}{\nu C_{g,j}} \quad (7)$$

depends on the magnetic field via the EMP velocity ν and characterizes the importance of Coulomb interactions within the mirrors.

Note that dissipative propagation of the charge EMP introduces a non-reciprocity in the scattering matrix between the transmission line and the edge channel (i.e., $t'_j \neq t_j$). This comes from the fact that when the transmission line is driven, it imposes a uniform potential all along the edge channel beneath the gate whereas, when an ac current is injected into the edge channel, the associated charge density wave is damped while propagating beneath the metallic gate and therefore induces a smaller voltage drop at the capacitor and thus a smaller drive on the transmission line. The non-reciprocity is a consequence of dissipation of the charge EMP along its propagation and may be used to probe it.

Now equipped with this theoretical description, we come back to the experimental data in which $|s|^2$ can be compared to $|S_{cal}|^2$. Fig. 2d–f depict the result of the calculation for three cavities with sizes equal to those of the cavities studied experimentally. In order to better compare the amplitude of the signal, we apply the same normalization procedure to the numerical simulations and to the experimental data (see methods section). We observe that we reproduce well the experimental data by considering a lineic capacitive coupling $c_g = 3 \text{ nF m}^{-1}$ ($C_{g,j} = c_g L_j$). The electronic density is fixed by the dc transport data that indicates the position of the plateaus and leads to $n_b = 1.93 \times 10^{11} \text{ cm}^{-2}$ (see supplementary note 2). Finally, the best fit to the resonance frequency was obtained by using the value $a = 2.8 \text{ }\mu\text{m} \gg d$ for the length over which the electronic density falls to zero on the edge of the sample. This value is compatible with the ones obtained in refs. 27,38. The value of the dimensionless coupling α_j at $B = 1 \text{ T}$ is $\alpha_j \approx 0.12$. It should be noted here that, in order to obtain a good agreement between data and theory, we consider edge modes propagating 400 nm inwards compared to the lithographically defined edges. This condition can be justified by the fact that we are in the wide edge limit given the value of a : the EMP modes emerge from the topological edge channels that are spatially separated from each other and are not found on the exact lithographic edge of the structure³⁹. Using these parameters, we obtain velocities varying from

$1 \times 10^5 \text{ m s}^{-1}$ at 1 T to $2.1 \times 10^4 \text{ m s}^{-1}$ at 5 T (see Appendix D) and wavevectors whose maximum value in our experimental range is $2.4 \times 10^6 \text{ m}^{-1}$.

Relation between resonance frequency and cavity size

As previously mentioned, we do not have a proportionality relation between the resonance frequency and $1/L$ (see Fig. 2h). This discrepancy can be accounted for by considering the total phase acquired by the EMPs propagating beneath the input and output gates. This phase becomes non-negligible compared to that associated to the propagation of EMPs across the cavity when it becomes small enough, as it is the case in our experiment. From our numerical simulations, shown in dashed lines in Fig. 2h, the ν/L behavior is recovered for large cavities. However the increase of the frequency faster than ν/L for small cavities is well reproduced by our theoretical model.

In the simulations presented on Fig. 2d–f, we observe the emergence of a higher frequency modes on top of the fundamental one for the larger island. The role of the FP's detection mirror is crucial when its dimension is comparable to that of the resonator. The gate then plays the role of filter. This can be mathematically observed through the sinc term that is present in the expression of the transmission and reflection terms (r_j, t_j, t'_j). Physically, this simply accounts for the relation between the wavelength $\lambda = 2\pi/k$ of the EMP and the size of the detection gate. For instance, if we consider the charge density associated to the fundamental mode of a magnetoplasmon propagating on the edge of our system, the detection power of our probes will be related to the integrated field underneath those probes. With λ the wavelength of the mode of interest, and considering a detection gate of size $\lambda/2$, we will be able to integrate a finite signal. However, the first harmonic of wavelength $\lambda/2$ and the associated signal integrated by the gate average to zero. This is the case for our smallest cavity shown in Fig. 2c. In this case, the total size of the cavity is $30 \text{ }\mu\text{m}$ while the detection gate overlaps the EMPs over a length $L_c = 11.3 \text{ }\mu\text{m} \approx \lambda/2$. For this reason, unlike previous works with large samples and gates of negligible size used for injection and detection^{7,8,11}, we are limited to the observation of only the fundamental and first harmonic of the cavity. This aspect is well reproduced in our theoretical modeling of the system.

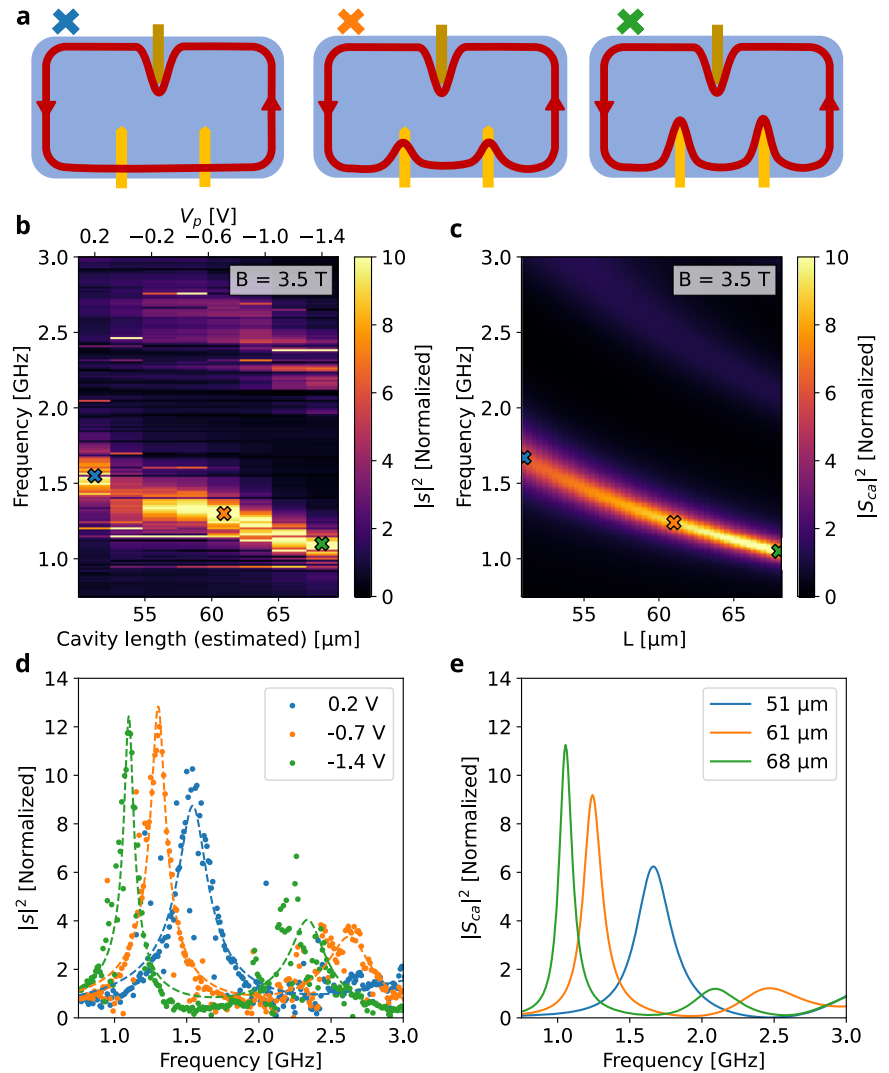
Our theoretical calculation also anticipates higher order modes that are not observed experimentally. Other than the relative low amplitude of these modes, making them difficult to detect experimentally, their absence in the experimental data could be attributed to dipolar effects. These effects, linked to the non-circular geometry of the cavity^{22,40}, are not taken into account in our theoretical description.

Continuous control of the cavity size

The continuous control of the geometry of the cavity is essential in order to realize a microwave EMP interferometer in the future. Another way to control the size of the cavity is to use individual gates²⁵ instead of completely closing QPCs as we did in Fig. 2. Figure 4 shows the result of this experiment. In this configuration the top gates are polarized to $V_G = 50 \text{ mV}$ (including the output gate, see methods section). The input gate is polarized to $V_G = -1.1 \text{ V}$ leading to an edge following the contour of the gates instead of the chemically defined edge. This has the effect of changing the strength of the coupling of the resonant mode to the input gate. We then tune two gates at the bottom of the structure (see Fig. 4a). By applying a negative voltage bias on these two gates we can increase the size L of the cavity from $54 \text{ }\mu\text{m}$ (for $V_G = 0.2 \text{ V}$) to $71 \text{ }\mu\text{m}$ (for $V_G = -1.4 \text{ V}$). The result of this procedure is presented on Fig. 4b. As shown in Fig. 4d, we can extract the line shape of the resonance that clearly shows the shift of the resonance frequency as well as that of the first harmonic mode. Using a Lorentzian fit, we extract a quality factor $Q = f/\Delta f$ for the main resonant mode of $|s|^2$ that varies between 8 (for $V_G = 0.2 \text{ V}$) and 18 (for $V_G = -1.4 \text{ V}$).

This experimental results can be well reproduced using the theory described previously as shown in Fig. 4c. In this figure, we plot the frequency as a function of the total length L of the cavity instead of the QPC voltage as we cannot access the precise electrostatic of the system and the way the edge states are deformed by the applied voltage. Because this data was taken after

Fig. 4 | Continuous control of the resonance frequency with electrostatic gates. Using two gates we can change continuously the perimeter of the structure and thus the frequency of the resonance. **a** At positive gate voltage the edge states go below the active gates (left). As the gate voltage is decreased, the edge states are moved towards the top of the gates (middle) and ultimately completely go around the gates (right). Doing so, the frequency of the resonant mode increases. **b** Frequency vs gate voltage map of the transmission amplitude of the sample. The markers correspond to the situations sketched in (a). **c** Theoretical computation of frequency vs inverse of perimeter **(d)** Line cut of the transmission amplitude as a function of the frequency for 3 different values of the gate voltage as indicated in (d). The dots represent the experimental data while the dashed lines correspond to a double Lorentzian fit of the data used to extract the quality factor Q . **e** Line cuts of the theoretical data shown in (c) taken at the same values as in (d).



thermally cycling the sample and for a different top-gate voltage compared to the data from Fig. 2, in this case we extract a density $n_b = 2 \times 10^{11} \text{ cm}^{-2}$ and we have different fitting parameters $c_g = 0.1 \text{ nF m}^{-1}$ and $a = 1.8 \text{ μm}$.

Conclusion

In conclusion, we have studied an electrostatically and magnetically tunable EMP resonator of very small size, such that the measurement probes are an integral part of the resonator and cannot be neglected in the theoretical description. We have shown that such resonator can be defined using electrostatic gates. Using top gates we are able to change the density of the 2DEG and screen the interaction between edge channels leading to a decrease of the velocity of the magnetoplasmons, a behavior well captured by our numerical simulations. We have compared our results to a theoretical description of our system and have found a good agreement between the two. In particular we find that the deviation from the expected $1/L$ trend of the EMP resonance frequency can be attributed to finite size effects of the input and output gates used in our experiment. We also explain the presence or absence of harmonics in our signal by frequency dependent filtering effects at the injection and detection gates. Finally, we have shown that we are able to change the size of the cavity at will by using fully or partially closed QPCs.

In future experiments, this electrostatic control should allow us to study resonances in a broad frequency range and, at the same time, reach surface areas that are small enough to control the magnetic field on the scale of the magnetic flux quantum. We will then be able to probe interference effects for elementary electronic or anyonic excitations within the resonator.

This experimental platform constitutes the basis for future interferometric microwave experiments aimed at studying the statistics of quasiparticles in exotic phases of the quantum Hall effect. This platform also opens new possibilities to investigate the screening role of the mirrors on the cavity in extreme limits where the combined size of the mirror is larger than the free propagation length of EMPs. Moreover, it opens the way to a direct investigation of the spatial dependence of dissipation effects by probing the non-reciprocity of the capacitive coupling between an edge channel and a transmission line. Finally, it also enables studying non-linear plasmonic effects in resonators as well as parametric resonance processes through a dynamical control of the resonance frequency via a time dependent electrical control of the cavity's geometry.

Methods

Base temperature

All measurements presented here were performed in a dry dilution cryostat at a maximal temperature of 30 mK. Other details about the methodology of this work, including data analysis and details of the theoretical modeling can be found in the supplementary information.

Data normalization procedure

Our experimental setup does not benefit from a low temperature calibration procedure that would allow us to extract the absolute value of the gain of our measurement chain. In order to overcome this difficulty and access a clear signal of the resonant modes present in our cavity we apply the following procedure to the raw signal amplified and collected.

Table 1 | Experimental gate configuration used in fig. 2 of the main text

V_G^{in}	V_G^{out}	Top gates	Density
0 V	0 V	20 mV	$1.93 \times 10^{11} \text{ cm}^{-2}$

Table 2 | Experimental gate configuration used in fig. 4 of the main text

V_G^{in}	V_G^{out}	Top gates	Density
-1.1 V	50 mV	50 mV	$2 \times 10^{11} \text{ cm}^{-2}$

Without such calibration, the gain of the whole rf setup and the background signal vary drastically over the 8 GHz bandwidth of our measurement. However, at a fixed frequency, the variation of the magnetic field B only affects the sample, leaving the whole rf setup unchanged. Thanks to this property, we can numerically fix the gain of each frequencies and remove the background signal.

With $s_{\text{raw}}(f, B)$ the complex signal measured (amplitude and phase), the normalization procedure we use is the following :

- First, at each frequency, we extract the average value and the standard deviation of s_{raw} over B ,

$$\overline{s_{\text{raw}}}(f) = \langle s_{\text{raw}}(f, B) \rangle_B$$

$$\sigma_{s_{\text{raw}}}(f) = \sqrt{\langle |s_{\text{raw}}(f, B) - \overline{s_{\text{raw}}}(f)|^2 \rangle_B}$$

- Then, we apply the transformation

$$s(f, B) = \frac{s_{\text{raw}}(f, B) - \overline{s_{\text{raw}}}(f)}{\sigma_{s_{\text{raw}}}(f)}$$

Since we measure on a wide range of magnetic field B and because the resonance width is small compared to this range, the mean value of $\overline{s_{\text{raw}}}(f)$ is a good (and systematic) approximation of the background signal at f . $\sigma_{s_{\text{raw}}}$ is the average modulus of the background-less signal. Apart from the resonance, the signal measured is just a background noise, so $\sigma_{s_{\text{raw}}}$ is a good (and systematic) approximation of the background noise amplitude at f . Assuming this noise does not depend on the frequency f , $\sigma_{s_{\text{raw}}}$ is then a measure of the gain of our setup at a given frequency f .

This means that, in order to compute $\langle s_{\text{raw}} \rangle_B$ and $\sigma_{s_{\text{raw}}}^2$, we need the full f, B map. For this reason, the data shown in fig. 4 of the main text (b) are extracted from eight complete f, B maps at various gate voltage V_p .

Gate configurations

In order to optimize the detection of the resonant mode of the cavity, the electrostatic environment is different between the data shown in Figs. 2, 4 of the main text. The values of the gate used to obtain Fig. 2 are presented in Table 1 while the gate configuration of Fig. 4 are presented in Table 2. In those two tables the column *Top gates* includes all gates except the QPCs or pads used to defined the limits of the cavity itself.

The densities are estimated from both the dc measurement of the Hall voltage and the rf maps.

Data availability

All data related to this paper are available on the zenodo platform under the following <https://doi.org/10.5281/zenodo.13644446>. Additional raw data is available from the corresponding author upon reasonable request.

Code availability

The code used to generate the figures in this paper is available on the zenodo platform under the following <https://doi.org/10.5281/zenodo.13644446>. Additional raw data analysis code is available from the corresponding author upon reasonable request.

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Author contributions

U.G. and A.C. grew the substrates, Y.J. fabricated the samples. E.F., M.R., G.F. and G.M. designed and performed the experiment. E.F., M.R., G.F., B.P., E.B., J.-M.B. and G.M. analyzed the data. G.R., H.S.-B., I.S. and P.D. developed the theoretical framework. E.F., G.R. and G.M. performed the numerical simulations. E.F., G.R. and G.M. wrote the manuscript with feedback from all the other authors.

Competing interests

The authors declare no competing interests.

Additional information

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