Fabry-Perot interferometry and Aharonov-Bohm oscillations in hybrid topological insulator-superconductor devices

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We study Fabry-Perot interference in hybrid devices, each consisting of a small superconducting disk deposited on the surface of a three-dimensional topological insulator. Such structures are hypothesized to contain protected zero modes known as Majorana fermions bound to vortices. The interference manifests as periodic conductance oscillations, tunable by both gate bias and magnetic field. The magnitude of the conductance oscillations shows no strong dependence on doping level or sample thickness, suggesting that they result from phase coherent transport in surface states. However, the Fabry-Perot interference can be tuned by both top and back gates, implying strong electrostatic coupling between the top and bottom surfaces. We observe a distinct checkerboard pattern in plots of conductance versus gate bias and magnetic field. The checkerboard pattern is consistent with a $\pi$ phase shift that occurs whenever the magnetic flux within the superconducting region changes by a single flux quantum $\Phi_0 = \hbar/2e$. This suggests an Aharonov-Bohm interference of counter-propagating states that lie near the boundary between the superconductor and the topological insulator.

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I. INTRODUCTION

At the surface of a topological insulator there are gapless states that behave as helical Dirac electrons,[1] with the electron spin constrained to point in a direction perpendicular to momentum. This spin-momentum locking generates a nontrivial Berry phase of $\pi$ as an electron moves in a complete circle around the Brillouin zone. In a topological insulator, an odd number Fermi surfaces exist at the Fermi energy, protecting the surface states from nonmagnetic disorder. If superconductivity is induced in the surface states of topological insulators, the resulting system will resemble a spinless $p_x + ip_y$ superconductor, with protected zero energy modes known as Majorana fermions bound to vortices.[2] These Majorana fermions possess non-Abelian exchange statistics that can be exploited to create a fault-tolerant topological quantum computer.[3,4]

While doping 3D topological insulators can result in superconductivity,[5] an alternative approach is through the proximity effect by directly coupling conventional s-wave superconductors to topological insulators such as $\text{Bi}_2\text{Se}_3$, $\text{Bi}_2\text{Te}_3$, or strained $\text{HgTe}$.[6,7,11] There has also been progress in inducing superconductivity in 2D topological insulators.[8,9,10] Although anomalous signatures have been reported in Josephson junctions constructed on the surface of topological insulators,[11,12,13,14,15] a “smoking gun” signature of Majorana fermions remains lacking.

A potential method of detecting Majorana fermions is through interferometric measurements.[20,22] In this approach, electrical current is flowed through chiral edge modes that are formed at the domain wall between a superconductor and a ferromagnet deposited on the surface of a 3D topological insulator. By creating chiral edge modes around a superconducting island with one or more Majorana fermions bound to vortices, one creates an interferometer that probes the $Z_2$ phase of the Majorana fermions. In the simplest proposals, the interferometer detects the number of vortices within the superconductor, with an odd number producing a $\pi$ phase shift with respect to the case for an even number. More elaborate interferometers could conceivably detect the fermion parity as well, thus allowing for the read-out of topological qubits. This detection strategy appears promising because there has been progress in inducing ferromagnetism in 3D topological insulators.[23,24] Furthermore, Fabry-Perot oscillations have recently been observed in hybrid $\text{Bi}_2\text{Se}_3$ devices with superconducting leads,[31] thus realizing the form of gate-tuned phase coherent transport that is necessary for interferometric searches of Majorana fermions in topological insulators. The complex geometry of the proposed interferometers,[20,22] as well as possible complications from bulk states encourage further experimental studies of phase coherent transport in hybrid superconductor - topological insulator devices in order to better understand realistic systems.

Here, we report on studies of hybrid devices consisting of a superconducting disk deposited on the surface of a 3D topological insulator. Two normal metal leads are connected to the topological insulator on opposite sides of the superconducting disk. By flowing current between the two normal metal leads, we probe phase coherent transport within the topological insulator as a function of chemical potential and magnetic field. We find clear signatures of gate-tuned Fabry-Perot oscillations, with higher frequency oscillations occurring at small source-drain biases. The magnitude of the oscillations are es-
sentially the same for lightly-doped and more heavily-doped devices, implying that they originate from surface states of the topological insulator rather than the bulk. However, the oscillations can be tuned by applying a bias either to the top gate or back gate, suggesting a strong degree of electrostatic coupling between the top and bottom surfaces. In the presence of a magnetic field applied perpendicular to the topological insulator surface, we find that the Fabry-Perot oscillations undergo a periodic phase shift of $\pi$. This phase shift occurs whenever a magnetic flux quantum $\Phi_0 = h/2e$ is added to the region enclosed by the superconducting lead. Unexpectedly, the phase shift is observed despite the lack of ferromagnetic regions surrounding the superconducting disk. Our results suggest the presence of edge states encircling the superconductor, with implications for more advanced interferometric searches for Majorana fermions.

This paper is organized as follows. In Sec. II, we describe our experimental methods, including sample fabrication and measurement techniques. In Sec. III, we consider phase coherent transport in our devices at zero magnetic field. In Sec. IV, we explore how geometric resonances respond to both top gating and back gating. In Sec. V, we report on Aharonov-Bohm-like oscillations from states encircling the superconducting lead. In Sec. VI, we cover a spectroscopic search for zero bias anomalies at high magnetic field. In Sec. VII, we summarize our conclusions.

II. EXPERIMENTAL METHODS

Single crystals of Bi$_2$Se$_3$ were grown by melting a mixture of pure Bi and Se in a stoichiometric ratio of 1.9975:3 (Bi:Se) in a vacuum quartz tube at 800 °C. Thin flakes (7-20 nm) of Bi$_2$Se$_3$ were exfoliated onto silicon substrates covered by a 300 nm thick SiO$_2$ layer. Such thin flakes typically have a 2D carrier density of $N_{2D} \approx 10^{13} - 10^{14}$ cm$^{-2}$ and low temperature mobility $\mu \approx 10^2 - 10^3$ cm$^2$/V-s, as determined from measurements of separate Hall bar devices. Order of magnitude variations in 2D carrier density of flakes of similar thicknesses suggest uneven Ca doping and thus variable bulk doping from sample to sample. Weak anti-localization measurements of the Hall bar devices give typical phase-coherence lengths of $\ell_\phi = 300 - 1000$ nm at 10 mK.

For the interferometer devices, normal metal leads were deposited through e-beam evaporation of 5 nm of Ti and 50 nm of Au. Brief Ar ion milling is employed before metallization in situ to ensure good contact between the Bi$_2$Se$_3$ and the leads. The normal metal leads are typically separated by a distance of 300 to 400 nm. A superconducting disk is inserted on the Bi$_2$Se$_3$ between the gold leads by a second step of e-beam lithography and a subsequent DC sputtering of 50 nm of Nb at room temperature. Measurements of Au/Al$_2$O$_3$/Nb tunnel junctions reveal a superconducting gap of $\Delta = 1.5$ meV for our Nb films immediately after sputtering; in Ti-Nb devices, the inverse proximity effect and additional nanofabrication processing will likely reduce the gap below this pristine value. Applying a bias to the silicon substrate permits back gating. A top gate is created by covering the sample with 33 nm of alumina via atomic layer deposition and evaporation of Ti/Au. By measuring the change in carrier concentration of a separate Hall bar device with top gate bias, we find that the relative permittivity of the top gate dielectric is 8.75.

The devices were thermally anchored to the mixing chamber of a cryogen-free dilution refrigerator equipped with a vector magnet and filtered wiring. We perform low frequency transport measurements with standard lockin techniques, typically with a 10 nA AC excitation at $f = 73$ Hz. Unless stated otherwise, all measurements were carried out at a base mixing chamber temperature of 20 mK. While the precise electron temperature is difficult to determine, we find that the samples’ transport signatures continue to evolve below 50 mK, suggesting reasonably sufficient heat-sinking and filtering of our DC lines.

A typical interferometer device can be seen in Fig. Ia. The separation between the gold leads is 350 nm and the niobium disk is designed to have a diameter of 200 nm (the true diameter of the actual disk on the sample is obscured by the alumina dielectric and top gate; bare niobium disks fabricated on identical silicon substrates with the same recipe possessed diameters of $\approx 200$ nm). For the device shown in Fig. Ia, the Bi$_2$Se$_3$ flake is 15 nm thick and 600 nm wide. We studied two sets of devices: the first set (Piece A, B, and C) possessed a gold lead separation of 350 nm and Nb disk diameter of 200 nm. The second set of devices (Piece D, E, F and G) were designed to have a lead separation of 800 nm and Nb disk diameter of 380 nm. The samples in each set differ in conductance despite similar lateral dimensions, suggesting varying number of bulk states due to differences in thickness or variations in overall doping that were also observed in Hall bar devices. Such discrepancies might be due to an uneven distribution of Ca doping. In the first set, two of the devices (Piece A and Piece B) had higher resistance (a few kΩ at base temperature) while the third (Piece C) had a lower resistance (roughly 250 Ω). The second set of devices possessed resistances of 500 to 1000 Ω. Despite the order of magnitude difference of conductance, all devices showed similar magnitude of conductance variations from gate-tuned phase coherent transport. Out of the three samples in the first set, we will focus on only one (Piece A); the other two showed qualitatively similar behavior. For the second set, we will focus on Piece D. We note that the TI flakes in Piece E and Piece G each consisted of $\approx 200$ nm wide nanoribbons.
FIG. 1. (a) SEM micrograph of topological insulator - superconductor interferometer. Bi$_2$Se$_3$ flake (not visible) is outlined with dashed line. (b) Conductance vs source-drain bias $V$ for a high resistance device (Piece A) at low and high temperature. (c) Conductance trace for low resistance device (Piece C).

III. FABRY-PEROT OSCILLATIONS AT ZERO FIELD

We first consider transport between the gold leads through the Bi$_2$Se$_3$ segment in the absence of a magnetic field. As shown in Figs. 1b and 1c, plots of conductance $dI/dV$ versus source-drain bias $V$ for Piece A and Piece C, respectively, reveal clear signs of non-linearity in the $I-V$ characteristics which become smeared out beyond $T = 1$ K. The peaks (dips) in conductance are signatures of Fabry-Perot resonances that occur due to constructive (destructive) interference between incident and reflected electrons in the topological insulator. For example, incident electrons can be reflected at the Bi$_2$Se$_3$-Au interface due to a finite barrier between the materials or Fermi velocity mismatch between the two materials. Restrictions on backscattering in the topological insulator due to spin-momentum locking could be evaded either due to spin flips within the metallic leads or scattering between top and bottom surfaces. Quantum interference originates from an additional phase that is accumulated by reflected electrons while traversing across the Bi$_2$Se$_3$ segment multiple times. In the lowest order case of a single reflection at each Bi$_2$Se$_3$-Au (i.e. reflected electrons travel an additional distance of $2L$, where $L$ is the separation between the Au leads), this corresponds to a WKB phase of $2k_F L$, where $k_F$ is the Fermi wave number. This interpretation is confirmed by the gate-tuning of the resonances, as the Fermi energy (and thus Fermi wave number) evolves with gate bias. In Fig. 2, we show a plot of conductance versus $V$ and top gate bias $V_{TG}$ from the high resistance sample Piece A, revealing the characteristic checkerboard pattern of Fabry-Perot resonances.

We note that while reports of Fabry-Perot oscillations typically have characteristic energy periods in the mV range, in our devices we are able to realize resonances with energy periods as small as 160 µV.

In Fig. 3 we plot conductance versus top gate bias $V_{TG}$ for a variety of fixed source-drain biases from Piece A. The traces show the sinusoidal behavior of Fabry-Perot resonances as the Fermi energy and wave vector change, superimposed on universal conductance fluctuations. At high source-drain bias (beyond the superconducting gap of niobium), the conductance oscillations have a characteristic peak-to-peak magnitude of $\approx 0.1 e^2/h$ and a top gate bias period of 32 mV. Using the slope of fea-
tions in plots of $dI/dV$ vs $V$ and $V_{TG}$ to convert top gate bias into changes in Fermi energy, the conductance oscillations of Piece A have an energy periodicity of $\approx 0.34$ mV. Based on the predicted periodicity of $\Delta E = \frac{h\nu_{FW}}{2\pi}$ and $L \approx 350$ nm, this implies a Fermi velocity of $5.75 \times 10^4$ m/s, which is an order of magnitude smaller than the value extracted from angle-resolved photoemission spectroscopy of macroscopic pieces of Bi$_2$Se$_3$.[30] The discrepancy could result from renormalization of the Fermi velocity due to electron-electron interactions or coupling to bosonic modes such as phonons or surface plasmons.[37] We note that the observed energy period of the Fabry-Perot oscillations is smaller than for topological insulator devices with smaller lead separation, but which lack superconducting disks in between the leads.[31] This helps to confirm that for the devices reported here, the quantum interference is determined by paths that travel completely from one gold lead to another, rather than being dominated by much shorter paths between one of the gold leads and the superconducting disk.

Similar to earlier results from hybrid topological insulator - superconductor devices,[31] we observe a bias-dependence of the oscillation period, with a frequency doubling occurring at a source-drain bias below the niobium superconducting gap. This frequency doubling results from an interplay of phase coherent transport and multiple Andreev reflections in a ballistic system in contact with a superconductor.[31,32] Low energy electrons in the topological insulator undergo Andreev reflection at the Bi$_2$Se$_3$-Nb interface, generating reflected holes that also traverse the Bi$_2$Se$_3$ segment. These reflected holes do not directly interfere with incident electrons. Instead, they reflect off the Bi$_2$Se$_3$-Au interface and impinge upon the Nb again to reflect as electrons through a second round of Andreev reflection. Such reflected electrons can interfere with incident electrons, but the phase difference is doubled to $4Lk_F$ as compared to conventional Fabry-Perot oscillations because quantum interference involves reflected particles that have traveled four times across the Bi$_2$Se$_3$ segment rather than merely twice. Interestingly, we see signs of another doubling of the frequency near zero source-drain bias (see Fig. 2). This could reflect higher order reflection processes[10,11] that is expected in relativistic Dirac systems, where specular Andreev reflection is permitted.[40,41]

**IV. DUAL GATING OF FABRY-PEROT OSCILLATIONS**

We next turn to simultaneous top and back gating of the Fabry-Perot oscillations in order to study their origin. Under standard experimental conditions, Bi$_2$Se$_3$ differs from an ideal topological insulator due to the presence of conducting bulk states[22] and trivial surface states from band bending[23], either of which can coexist with the topologically non-trivial Dirac surface states. The existence of both top and bottom surfaces with potentially different transport properties is an additional complication. Thus, identifying the individual types of carriers through transport measurements can be difficult. For example, studies[31,32] on Bi$_2$Se$_3$ films of varying thicknesses have extracted separate transport properties of bulk and surface states. Total depletion of bulk carriers through aggressive chemical or electrochemical doping have revealed an ambipolar field effect that was attributed to the Dirac electrons[44]. Although in principle quantum oscillations can reveal the nontrivial Berry phase of the topological surface states,[37] in reality the large Zeeman coupling of bulk states can complicate this interpretation.[35]

As we previously reported,[31] the Fabry-Perot oscillations have a peak-to-peak magnitude of $\approx 0.1 e^2/h$, independent of sample thickness or total conductance. This appears to rule out the bulk carriers as the source of the quantum interference. Here, we gain further insight into the origin of the oscillations by applying biases to both the top and back gates. One naïvely expects that screening by the bulk carriers would cause the top gate to primarily influence the top surface while the back gate would mainly tune the Fermi energy of the bottom surface. In Fig. 3 we show a series of conductance versus top gate traces for different biases applied to the back gate from Piece A; similar results were obtained from the
other two interferometers. We highlight two main observations from these data. First, the positions of the resonances are linearly shifted by the back gate. For Piece A, a 1 V bias applied to the back gate shifts the Fabry-Perot resonances by $\Delta V_{TG} = 78$ mV. Similar shifts were observed for Piece B ($\Delta V_{TG} = 72$ mV per $\Delta V_{BG} = 1$ V) and Piece C ($\Delta V_{TG} = 62$ mV per $\Delta V_{BG} = 1$ V). Note that the ratio $\Delta V_{BG}/\Delta V_{TG} \approx 15$ for the relative efficiency of the top and back gates is close to the ratio of the gate capacitances $C_{top}/C_{bottom} \approx 20$. Thus, the location of each Fabry-Perot resonance in most of our samples depends only on the total carrier density $n$, which can be tuned by either the top or back gate. This implies that there is strong electrostatic coupling between the top and bottom surfaces, such that applying a bias to the top gate will equivalently shift the Fermi level of the bottom surface and vice versa. We note that the shift in the Fabry-Perot resonances with back gate bias was also observed in the low resistance device, which presumably contained a higher amount of bulk doping.

A second observation from Fig. 4a is that certain features in the top gate traces can evolve in magnitude with back bias. That is, some of the peaks and dips related to the Fabry-Perot oscillations appear to grow either stronger or weaker as one tunes $V_{BG}$. An example is the conductance peak that occurs near $V_{TG} = -0.2$ V at zero back gate bias. As a negative voltage is applied to the back gate, this conductance peak becomes more and more prominent. Thus, the overall transport properties of Bi$_2$Se$_3$ is not purely a function of a single linear combination of $V_{TG}$ and $V_{BG}$, unlike the locations of the Fabry-Perot resonances. Instead, such features vary with the displacement field, $D$. Here, the displacement field is an antisymmetric function of $V_{TG}$ and $V_{BG}$ ($D = \alpha V_{TG} - \beta V_{BG}$ for some positive constants $\alpha$ and $\beta$) and is related to the interlayer voltage between the top and bottom layers. One possibility is that this reflects a tuning of the surface-to-bulk coupling by the displacement field, which will impact the lifetime of surface states and alter the visibility of the Fabry-Perot resonances. Alternatively, the background from universal conductance fluctuations from the bulk that might evolve in a nontrivial way with gating.

We further explore this second observation in Fig. 4b, where we show a plot of conductance vs top gate bias and back gate bias for Piece D. The arrows indicate the directions for either carrier density ($n$) or displacement field ($D$). As with Piece A, the Fabry-Perot resonances can be tuned by either top gate or back gate, as reflected by the parallel bands of lines, which we assume to be along lines of constant $n$. As hinted in Fig. 4a, we observe some features that also evolve with the displacement field.

We close this section by noting anomalous behavior in Piece E, which we show in Fig. 4c. One set of the resonances are perpendicular to the $n$ axis, having the same slope as the resonances in Fig. 4b. However, there is another set of resonances with a completely different slope. This second set of resonances appears to be more strongly tuned by the back gate than by the top gate. Such resonances might correspond to states that are partially screened from the top gate by either the metallic leads or other states within the topological insulator.

V. MAGNETIC FIELD TUNING OF FABRY-PEROT OSCILLATIONS

We consider the influence of a magnetic field on the phase coherent transport in our hybrid topological insulator devices. Here, we apply a magnetic field perpendicular to the topological insulator film. In a previous study we had found that in-plane fields up to at least 100 mT had negligible influence on the transport properties of similar topological insulator devices, suggesting a quasi-2D limit of the electrons. In this study, we apply strong enough fields such that the superconducting region would enclose multiple flux quanta if the Meissner
FIG. 5. Zero bias conductance vs magnetic field for Piece A at $V_{TG} = 0$.

When we measure zero bias conductance vs magnetic field, as shown in Fig. 5, we observe oscillations with a period of approximately 200 mT. This is suggestive of an Aharonov-Bohm effect. In Fig. 6, we plot conductance of the high resistance device Piece A versus top gate bias and magnetic field. Here, a constant source-drain bias of 0.2 mV is applied and a slowly-varying background is subtracted from each gate trace to reveal the Fabry-Perot oscillations. We find evidence for a checkerboard pattern of periodicities $(200 \text{ mT})/(60 \text{ mT}) \approx 3.3$ for Piece A and Piece D is very close to the inverse ratio of their areas $(380 \text{ nm})^2/(200 \text{ nm})^2 \approx 3.6$, helping to confirm that the frequency of the Aharonov-Bohm oscillations is governed by the area of the niobium disk.

We explore the magnetic field evolution in greater detail in Fig. 8, where we show a series of top gate traces for various fields from Piece A and Piece B. For Piece A, we present data corresponding to both low source-drain bias ($V = 0.2 \text{ mV}$). For Piece B, we show data with similar behavior at high source-drain bias ($V = 1.35 \text{ mV}$), beyond the gap of the niobium disk. We note that no such phase shifts were observed in topological insulator junctions at high source-drain bias without a superconducting disk.

There is evidence that the phase shift is rapid, yet smooth. For example, in Fig. 8, a local maximum in the conductance remains at $V_{TG} = -0.046 \text{ V}$ up until 50 mT. At 75 mT, this peak in the conductance splits into two and at 100 mT a local maximum has appeared at $V_{TG} = -0.056 \text{ V}$, where there was previously a conductance dip.

In many respects, the field evolution of the Fabry-Perot resonances mimics the anomalous Aharonov-Bohm oscillations that were predicted and recently observed in topological insulator nanowires with magnetic flux threaded through their core. While in the dirty limit this results in a topologically protected one-dimensional channel at a magnetic flux of $h/2e$, in the clean limit a phase shift of the Fabry-Perot resonances occurs.

It is curious that the observed periodicity of the phase shift corresponds to one magnetic flux quantum enclosed by the niobium disk rather than one flux quantum enclosed by the entire Bi$_2$Se$_3$ segment. We emphasize that we observe similar field periodicity in the other two devices ($\approx 150 \text{ mT}$ for Piece B and $225 \text{ mT}$ for Piece C), despite variations in topological insulator width (600 nm, 900 nm, and 1100 nm for Piece A, B, and C, respectively). Presumably, phase coherent transport is spread over most if not all of the Bi$_2$Se$_3$ film, so interference effects should be detectable when the electrons paths enclose an integer number of magnetic flux quanta. Thus, one would expect a much smaller field periodicity than observed. For example, a recent report found similar field modulations of Fabry-Perot oscillations in graphene nanoconstrictions. There, the field periodicity of tens of mT were consistent with one magnetic flux quantum enclosed by the large graphene leads on either side of the nano constriction. Smaller devices had a larger field periodicity, unlike our devices, in which the field periodicity is governed by the area of the superconductor rather than the Bi$_2$Se$_3$ segment.

One way to resolve this discrepancy is to propose that electron paths in the vicinity of or reflected off of the superconducting segment dominate the measured phase coherent transport. Such paths could be better protected from disorder due to the particle-hole symmetry imposed by the superconductor. The observation of anomalous Aharonov-Bohm oscillations just beyond the niobium energy gap in Fig. 5 suggests that residual Andreev reflections might still afford such protection. Because the protected paths closely follow the boundary of the superconductor, the quantum interference from such paths is sensitive to the magnetic flux enclosed by the superconductor. While any Meissner screening of the
superconductor will likely result in a spatially varying magnetic field within the niobium disk, the Aharonov-Bohm phase acquired by states beyond the superconductor should only be a function of the total flux enclosed by such states rather than the precise distribution. Similar phase shifts and field periodicity are observed for energies beyond the superconducting energy gap (see Fig. 8b), suggesting that normal reflection off of the superconductor also generate paths that encircle the superconductor. The precise details and trajectories of these paths are not clear at this time. One possibility is that they are related to the bound edge states that are thought to exist encircling nanoholes in massless Dirac systems such as graphene.\textsuperscript{55,56}

We strengthen this picture of counter-propagating states encircling the Nb disk as the source of the conductance oscillations by considering devices that do not have the multiply-connected geometry required for Aharonov-Bohm oscillations. The TI nanoribbons in Pieces E and G were narrower than the 380 nm Nb disk deposited on the top surface. Thus, the Nb disks in these devices are not completely surrounded by the TI and indeed these devices do not exhibit Aharonov-Bohm oscillations. In Piece E (shown in Fig. 9a), the Nb disk covers the whole width of the TI nanoribbon; any current flowing between the gold leads must pass through the region covered the superconductor. For Piece G (shown in Fig. 10a), the Nb disk is located on the edge of the nanoribbon, which has a single narrow segment passing alongside the disk. Thus, current can flow along one side of the superconductor but not the other. The Fabry-Perot oscillations in Pieces E and G (plotted in Figs. 9b and 10b) do not undergo periodic phase shifts, even in magnetic fields up to 0.5 T. Such a field is large enough to enclose multiple flux quanta within the bare TI segments. Although some features (likely related to universal conductance fluctuations) do evolve with field, the Fabry-Perot oscillations do not.

At this point, we discuss how these paths might be related to the gapless edge modes present in topolog-
FIG. 8. Top gate sweeps for various magnetic field, showing the $\pi$ phase shift of the Fabry-Perot oscillations. (a) Piece A with source-drain voltage 0.2 mV. (c) Piece B with source-drain voltage 1.35 mV. Magnetic field varies from 400 mT (top trace) to 560 mT (bottom trace), in steps of 20 mT. Traces are offset vertically for clarity for both graphs.

While we observe some features matching the prediction, one must be cautious due to the lack of sudden changes in phase relating to vortex entry within the superconductor. As discussed previously, the phase shifts in Fig. 8a and c are shown to be rapid, yet smooth. We conjecture that the superconducting disks that we employ in this experiment could be too small for them to favor vortex entry. Future experiments with larger disks would facilitate explicit vortex entry.

VI. SPECTROSCOPY AT HIGH MAGNETIC FIELD

Finally, we consider a spectroscopic search for Majorana fermions in our devices under high fields. Utilizing tunneling probes to study the density of states around the superconducting disk, one should observe a zero bias conductance peak whenever an odd number of vortices are present. We show in Fig. 11 a plot of conductance versus source-drain voltage and magnetic field for the featured high resistance sample Piece A. We find that for certain magnetic field ranges (centered on 175 mT and 350 mT), a peak near zero bias occurs. According to Fig. 6, these field ranges correspond to an odd number (1 and 3) magnetic flux quanta enclosed by the superconductor. No such peaks occur in the low resistance sample, where a conductance dip persists up to 800 mT.

While this behavior is consistent with zero energy modes from Majorana fermions, we note that the peaks are not stable to changes in chemical potential, as shown in Fig. 12. This is in contrast to the predicted robustness of the conductance peak from Majorana fermions.
However, we do not rule out the possibility that the zero energy modes at the top and bottom surfaces become hybridized through the bulk if the chemical potential exceeds a critical value \(58-61\). Such hybridization could be periodic with chemical potential, which tunes the wavefunction overlap of the Majorana states.\(^62\) Alternatively, the gap protected the zero energy modes could also be exceedingly small, possibly far smaller than the energy range that is swept in Fig. \(^12\).

VII. CONCLUSIONS

We have presented a study of Fabry-Perot interferometry in hybrid topological insulator - superconductor devices. We observe Fabry-Perot resonances with multiple gate frequencies, corresponding to higher order reflection processes, including those influenced by Andreev reflection at the topological insulator - superconductor interface. The magnitude of the Fabry-Perot resonances do not scale with bulk doping, suggesting that they originate from surface states. The resonances can be tuned by both top and back gates, providing evidence of strong electrostatic coupling between the top and bottom surfaces. When a magnetic field is applied perpendicular to the topological insulator film, the Fabry-Perot resonances undergo a distinctive and periodic \(\pi\) phase shift. These signatures persist even in the presence of significant bulk doping. The field periodicity of the \(\pi\) phase shift is associated with the superconductor enclosing an integer number of magnetic flux quanta \(\hbar/2e\), implying an anomalous Aharonov-Bohm effect from the unexpected presence of states near the interface of the superconductor and topological insulator. This confinement exists even in the absence of a ferromagnetic gap within the topological insulator beyond the superconductor. Our results improve the understanding of phase coherent transport in topological insulators and how it interplays with superconductivity and phase-winding magnetic fields. Further modifications in device geometry as well as reduced bulk doing could help to confirm the presence of Majorana fermions in hybrid topological insulator - superconductor devices.
FIG. 12. Conductance of Piece A vs source-drain bias and top gate bias. No stable zero bias anomalies are visible.

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