Supplementary Information for

Evidence of electronic cloaking from chiral electron transport in bilayer graphene nanostructures

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Fabrication and Methods

The studied devices were fabricated from homogenous bilayer graphene film synthesized by CVD method[1]. The BLG film was transferred onto a degenerately doped Si substrate with a 40 nm Al_2O_3 layer deposited by ALD as the back gate dielectric. Source and drain metal electrodes were defined using electron-beam lithography, with channel lengths between 50 to 200 nm, followed by e-beam evaporation of a Pd/Au (5 nm/25 nm), and lift-off processes. For top gate dielectric, a thin layer of aluminium (1.5~2 nm) was deposited and oxidized in the air, and repeated for three times. The top gate electrodes were defined by e-beam lithography, followed by metal deposition of Ti/Au (5 nm/25 nm). The conductance of BLG devices was measured in a cryogen-free closed cycle cryogenic probe station (CRX-4K, LakeShore) using standard lock-in technique with an AC bias current of 10 nA at 447 Hz. Unless otherwise specified, all measurements were done at 6 K.

Raman Spectrum of studied device

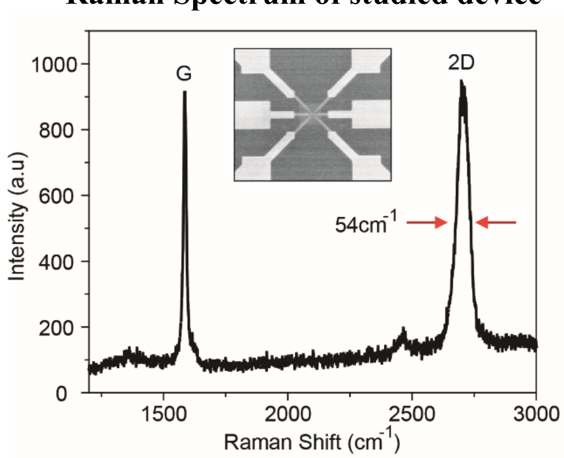


Figure S1. Raman spectroscopy of the studied BLG device. Typical Raman spectrum (514 nm excitation) and scanning electron microscopy image (inset) of CVD grown bilayer graphene device. Bilayer graphene was confirmed from FWHM (full-width-half-maximum) of 2D band peak (~54 cm^{-1}), and I_{2D}/I_G intensity ratio value (~ 1.03) of CVD BLG (light gray area in SEM image).

Resonance cavity in 150nm BLG device at monopolar regime

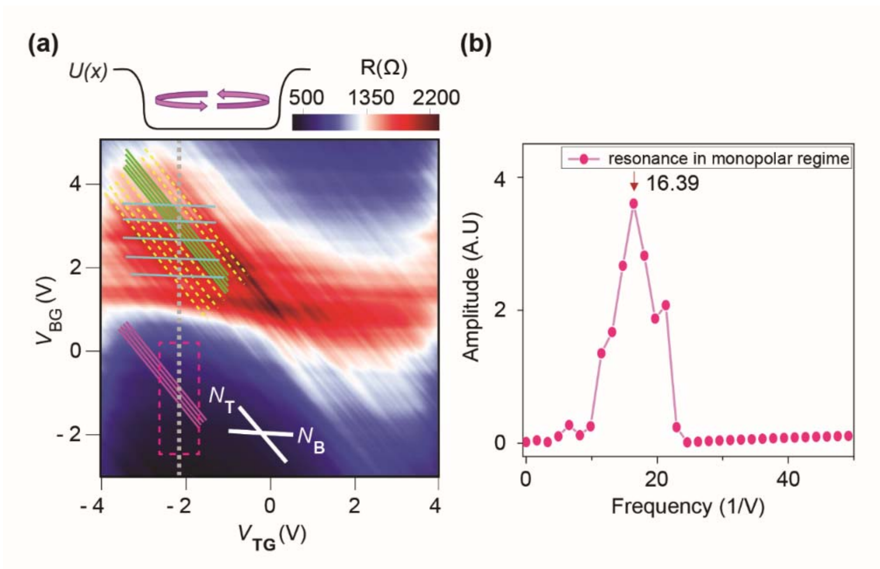


Figure S2. Fourier analysis of phase coherent transport for a 150nm BLG device in the monopolar regime. (a) Two dimensional color plot of differential conductance versus V and V_{BG}. Fabry-Perot conductance oscillations in the monopolar regime, highlighted by the purple lines, correspond to massive Dirac fermions trajectory shown in the top inset. (b) The Fourier transform spectrum performed along the grey dashed line (V_{TG} = -2.1V) in the highlighted pink dashed square region. The observed oscillation period is listed in Table 1.

Electrostatic potential profile

In our devices, electric potential between graphene and top gate seems to be strongly influenced by top gate voltage, but less influenced by global back gate voltage [2]. The oscillation patterns along the N_B direction are quasi-periodic with almost same interval at both low and high carrier density in all devices of different dimensions. For example, the oscillation period measured along at V_{TG} = 1.4V and at V_{TG} = 3V show 2.29V and 1.89V, corresponding to LGL cavity length of 51 nm and 46 nm, respectively (Figure S4a). This confirms our interpretation that variation of potential barrier width is not substantial, less than 10 nm range, as back gate voltage changed (Table 1). We attribute this behavior to the electric field screening of global back gate by top gate, source, and drain metal electrode [2-4] as well as to the nonlinear screening effect at p-n junction in our BLG devices [5].

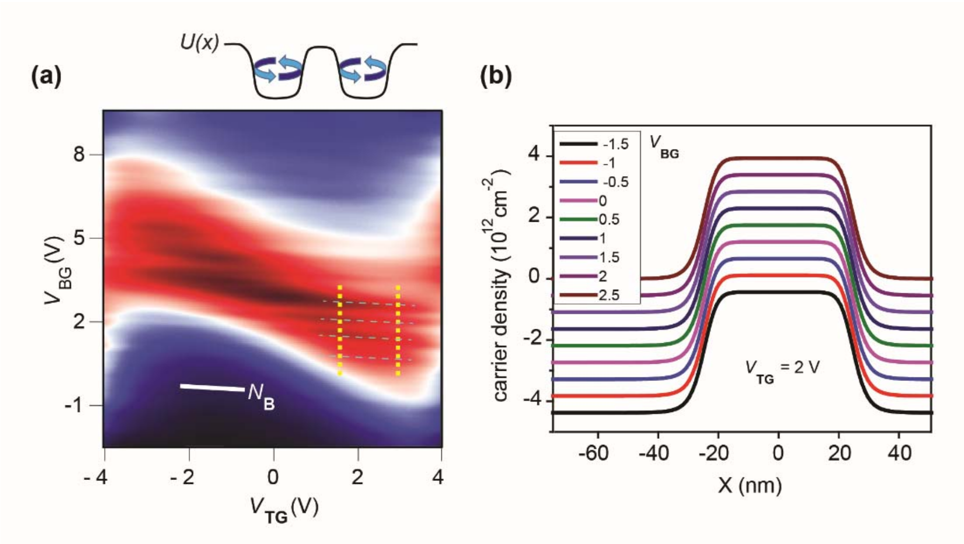


Figure S3. Electrostatic potential profiles. (a) Two dimensional color plot of differential conductance versus V_{TG} and V_{BG} (from Figure S4i). Fabry-Perot conductance oscillations along N_B were highlighted with dashed blue lines. Cavity lengths of GL are estimated from FFT results along vertical yellow lines at V_{TG} = 1.4V, and 3V. (b) Density profiles for V_{TG} = 2V over a range of back gate voltages around top gated region. We calculated carrier density profile by using commercial finite element simulation software (Comsol Multiphysics) [2,6].

Electronic cloaking effect in BLG devices (120nm/100nm)

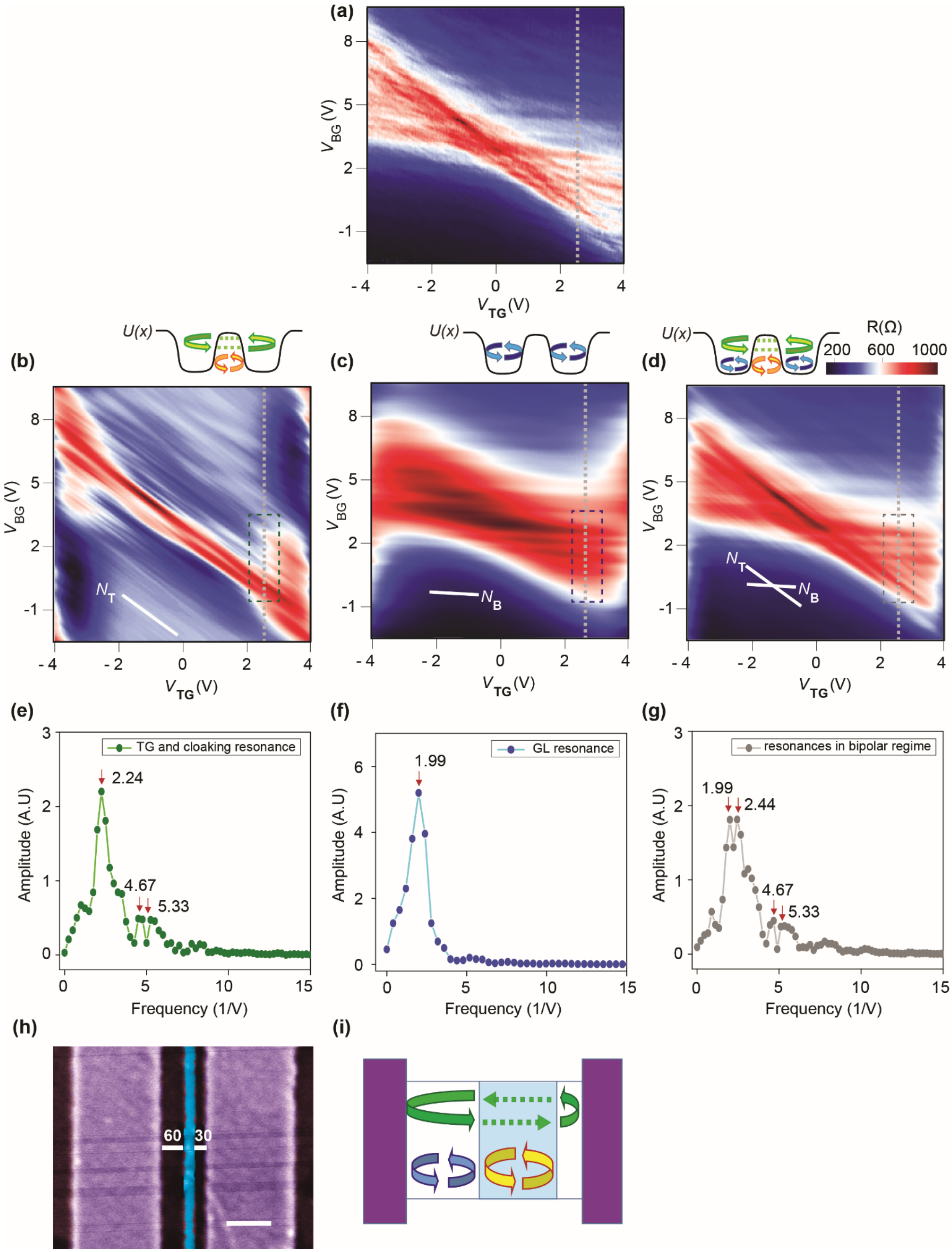


Figure S4. Electronic cloaking effect of massive Dirac fermions in a 120 nm BLG device. (a) 2D resistance map measured from 120 nm BLG device. (b), (c) Two fringing patterns observed along N_T (solid white line) and N_B (solid white line) after 2D FFT process performed on resistance map (a), respectively. (d) The sum of two resistance components from (b) and (c). Top insets describe quasiparticle trajectories for each individual oscillation in bipolar regime (b, c, d). (e), (f), (g), The Fourier transform spectra for (b), (c), and (d), respectively. The FFTs are performed along the grey dashed line (V_{TG} = 2.6 V) in the highlighted dashed square regions. The splitting of the resonant peak (4.67 V^{-1}, 5.33 V^{-1}) in (e) results from potential profile variation. The difference of estimated resonant cavity length corresponding to the two peaks is ~ 5 nm. (h) False-colour SEM image of a device with top gate (blue), source-drain electrodes (purple), and BLG (dark purple). The lengths of LGL(left graphene lead) and RGL(right graphene lead) are determined from the SEM image. The scale bar is 100nm. (i) The schematic view of resonant cavity lengths with trajectories is drawn for corresponding averaged-FFT results at 10 different top gate voltages within highlighted square area. At carrier density n = 3.8 × 10^{12} cm^{-2}, this device exhibits mobility $\mu \approx 7420$ $cm^2V^{-1}s^{-1}$, and mean free path $l_e \sim 170$ nm from two-terminal measurement. Note that these values are lower bound mobility and mean free path limited by contact resistance.

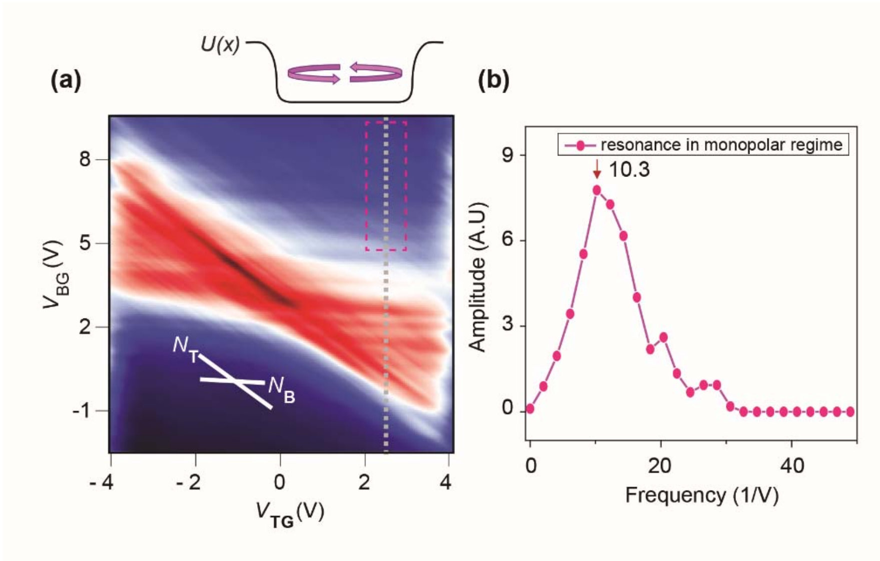
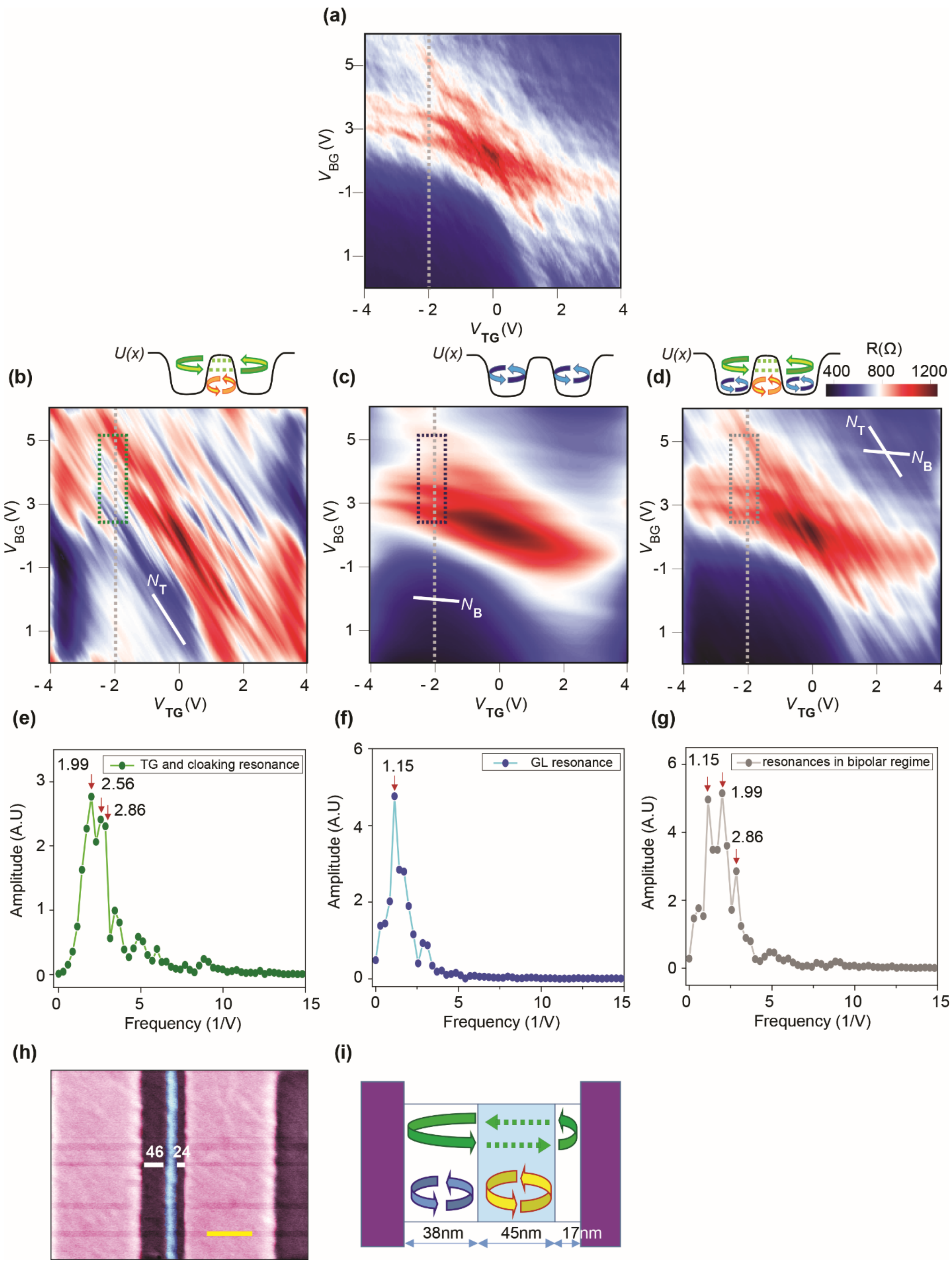


Figure S5. Fourier analysis of phase coherent transport for a 120nm BLG device in the monopolar regime. (a) Two dimensional color plot of differential conductance versus V_{TG} and V_{BG}. Fabry-Perot conductance oscillations in the monopolar regime correspond to massive Dirac fermions trajectory shown in the top inset. (b) The Fourier transform spectrum performed along the grey dashed line (V_{TG} = 2.6 V) in the highlighted pink dashed square region. The observed oscillation period is listed in Table 1.



(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
(i)
V_BG (V)
V_TG (V)
U(x)
R(Ω)
400
800
1200
N_T
N_B
1.99
2.56
2.86
TG and cloaking resonance
1.15
GL resonance
resonances in bipolar regime
Amplitude (A.U)
Frequency (1/V)
46
24
38nm
45nm
17nm

Figure S6. Electronic cloaking effect of massive Dirac fermions in a 100 nm BLG device. (a) 2D resistance map measured from a 100 nm BLG device. (b) and (c) Two fringing patterns observed along N_T (solid white line) and N_B (solid white line) after 2D FFT process performed on resistance map (a), respectively. (d) The sum of two resistance components from (b) and (c). Top insets describe quasiparticle trajectories for each individual oscillation in the bipolar regime. (e), (f), (g) The Fourier transform spectra for (b), (c), and (d), respectively. The FFTs are performed along the grey dashed line (V_{TG} = -1.9 V) in the highlighted dashed square regions. The splitting of the resonant peak (2.56 V^{-1}, 2.86 V^{-1}) in (e) results from potential profile variation. The difference of estimated resonant cavity length corresponding to the two peaks is ~ 3 nm. (h) False-colour SEM image of a device with top gate (blue), source-drain electrodes (purple), and BLG (dark purple). The lengths of LGL and RGL are determined from the SEM image. The scale bar is 100nm. (i) The schematic view of resonant cavity lengths with trajectories is drawn for corresponding averaged FFT results. At carrier density n = 4.2×10^{12} cm^{-2}, this device exhibits mobility $\mu \approx 3580$ $cm^2V^{-1}s^{-1}$, and mean free path $l_e \sim 85$ nm. Note that these values are lower bound mobility and mean free path limited by contact resistance.

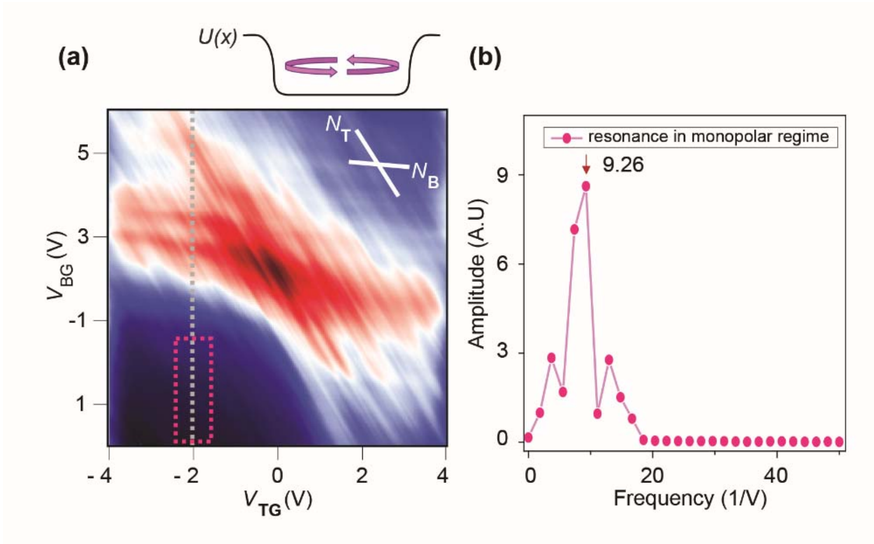


Figure S7. Fourier analysis of phase coherent transport for a 100nm BLG device in the monopolar regime. (a) Two dimensional color plot of differential conductance versus V_{TG} and V_{BG}. Fabry-Perot conductance oscillations in the monopolar regime correspond to massive Dirac fermions trajectory shown in the top inset. (b) The Fourier transform spectrum performed along the grey dashed line (V_{TG} = -1.9 V) in the highlighted pink dashed square region. The observed oscillation period is listed in Table 1.

Scaling of resonant cavity size in BLG devices

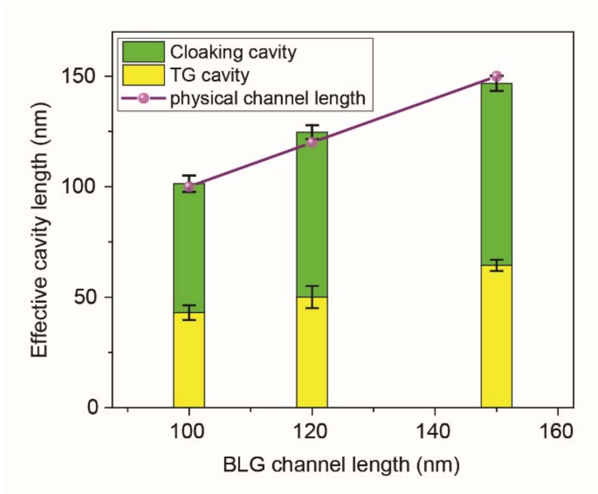


Figure S8. Sum of top gate resonant cavity (yellow) and cloaking cavity (green) length was plotted as a function of BLG physical channel length (100 nm/ 120 nm/ 150 nm).

We also examine the scaling of resonance cavity lengths due to different origins for three devices. As shown in Fig. S8, the "cloaking cavity" length scales linearly with the physical channel length, and the sum of the cloaking cavity length and top-gate cavity length is in good agreement with the physical length. These results again support the observation of electronic cloaking effect. We also note that the resonant cavity length for the top-gate confined cavity becomes slightly smaller for shorter channel length devices, despite a fixed top-gate length of 30 nm. This could be due to the increased fringing field screening effect from electrodes in the shorter devices [7].

References

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