Inverse AC Josephson Effect in Ballistic Multiterminal Graphene Josephson Junctions

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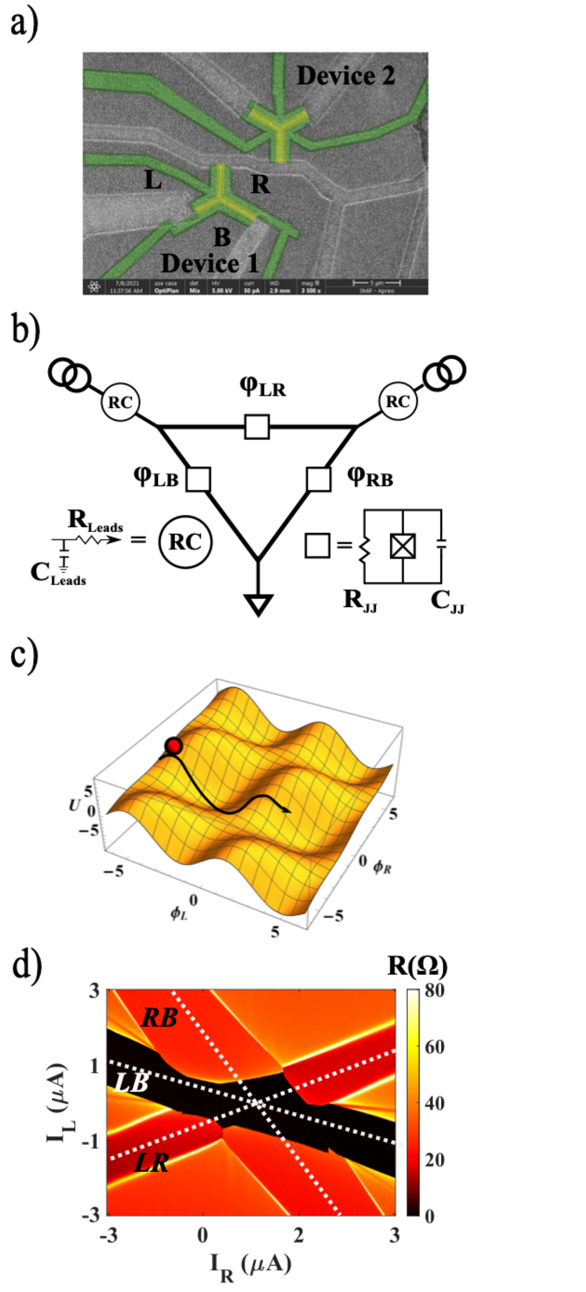
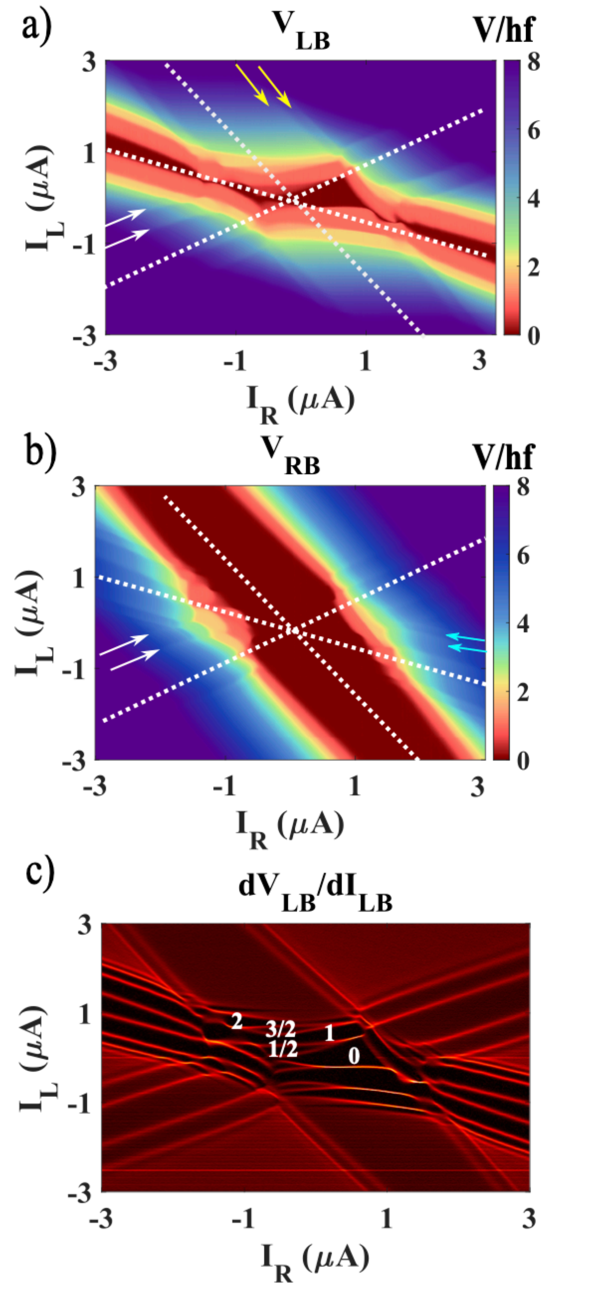
In multi-terminal Josephson junctions, the superconducting coupling is established between each pair of contacts across a common normal channel. The state of such junction is described by N-1 independent phase differences between pairs of contacts, where N is the number of terminals. The added complexity makes multi-terminal junctions an ideal medium for engineering novel quantum phenomena. For example, the energy spectrum of multi-terminal Josephson junction has been predicted to effectively emulate the band structure of topologically non-trivial materials. This exciting prospect led to renewed interest toward experimental realizations of multi-terminal Josephson junctions.

Figure 1a shows a scanning electron microscope image of a three-terminal junction, in which the normal region is made of ballistic graphene encapsulated in hexagonal boron nitride. Biasing the individual junctions, we observe three superconducting branches, corresponding to pair-wise coupling between pairs of junctions (Figure 1d). We further explore the phase dynamics of these junctions when exposed to microwave radiation. The microwave drive causes inverse AC Josephson effect, which has been explored in detail in conventional Josephson junctions. In this phenomenon, the phase of the junction locks to the drive frequency, and the I−V curves acquire "Shapiro steps" of quantized voltage $V=nhf/2e$ with integer n. If the junction has three or more superconducting contacts, coupling between different pairs of terminals must be taken into account, resulting in a complicated energy landscape (Figure 1c).

Experimentally, we observe robust Shapiro steps with fractional n (Figure 2). We demonstrate that these steps cannot be attributed to non-sinusoidal current-phase characteristics of the junctions. Instead, they can be explained by considering the device as a completely connected Josephson network. We explore the stability of these steps and related phenomena, such as correlated switching events between different junctions. We successfully simulate the observed behaviors using a modified two-dimensional resistively and capacitively shunted junction model (Figure 1b). Our results suggest that multi-terminal Josephson junctions may be a highly-tunable playground for possible applications in quantum information processing.



a) An SEM image of the studied device. A 500 nm channel of monolayer graphene is contacted by three MoRe leads ~7 microns wide . Currents I_L and I_R are sourced from contacts L and R. Voltages are measured between these contacts and the grounded contact B. b) A circuit model of the device. All three superconducting contacts are connected via Josephson junctions, resistors and capacitors. c) An illustration of the trajectory of the phase particle through the two-dimensional washboard potential. d) The differential resistance map of the left junction vs I_L and I_R at zero microwave power and Vgate = 10 V. The three branches corresponds to supercurrent between three pairs of contacts.



a,b) DC voltage maps for junctions LB and RB at 5.2 GHz, 15 dBm, and Vgate = 10 V. White dashed lines indicate the biasing conditions which result in zero voltage across one of the three junction. At high bias, imprints of other junctions emerge as ripples on each map parallel to the white dashed lines (arrows mark the location of the ripples, cyan from LB, yellow from RB, white from RL). c) Differential map of panel (a) which highlights the plateau boundaries. Half integer Shapiro steps emerge in the LB (and LR) junction at the intersection of the ripples induced by the RB junction. These half integer steps disappear for high applied biases, where only the single junction behavior is effectively present.