

Development of Josephson Spectroscopy for Low-dimensional Materials

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Principal Investigator(s): Valla Fatemi

User(s): Luojia Zhang, Andrew Pierce

Affiliation(s): Cornell Applied and Engineering Physics and Physics

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Contact: vf82@cornell.edu, lz282@cornell.edu, atp66@cornell.edu

Website: <https://fatemilab.aep.cornell.edu/>

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Abstract:

Low-dimensional layered materials including graphene exhibit intriguing electrodynamic properties in the THz frequency range, including correlation-driven energy gaps and plasmonic cavity modes. However, these phenomena are difficult to access experimentally because of the mismatch between sample sizes (typically a few to a few tens of microns) and the wavelengths of THz photons (typically a few hundred microns to a few mm). In this project, we made use of Josephson junctions as on-chip photon sources as an alternative route to accessing THz electrodynamics. By fabricating circuits incorporating Josephson junctions and layered materials, we observed plasmonic collective excitations in graphene and demonstrated their hybridization with modes of a proximal superconducting cavity, thus paving the way for studies of hybrid cavity quantum matter.

Summary of Research:

We fabricated circuits in which a Josephson junction is connected in parallel to a graphene heterostructure. The graphene heterostructure includes NbN top and bottom layers which serve both as gates and to define a confined superconducting cavity mode (Fig. 1A). When the Josephson junction is operated in the voltage-biased state, it emits photons that probe the high-frequency loss of the graphene heterostructure. The high-frequency loss in the circuit is in turn encoded in the DC current across the Josephson junction as required by energy conservation. Thus, by measuring the DC current-voltage characteristic of the Josephson junction, we can probe high-frequency response in graphene

from approximately 10 to 190 GHz.

The loss measured for an NbN/graphene/NbN device, expressed as the real part of the input impedance $\text{Re}(Z_{\text{in}})$, is shown as a function of frequency and of gate voltage (proportional to carrier density) in Fig. 1B. Numerous peaks and dips in the spectrum correspond to different cavity modes of the multi-layered structure, including modes of the superconducting cavity (nearly-vertical features) and plasmon modes of graphene (those that shift with gate voltage). Notably, avoided crossings between modes are visible at 93 and 170 GHz (Fig. 2). These features indicate strong light-matter coupling (hybridization) between different modes in the structure, which raises the possibility of engineering hybrid cavity-matter ground states and degrees of freedom in cavities based on low-dimensional materials.

Conclusions and Future Steps:

Our approach to defining cavities raises the possibility of controlling the effective dielectric function of electrons in low-dimensional materials like graphene. Such engineered dielectric functions serve to modify electronic interactions and have been proposed as a route toward realizing novel correlation-driven ground states. However, cavity-induced ground states are generally expected to be fragile, likely requiring measurements at sub-Kelvin temperatures. The approach to spectroscopy developed to this project is thus ideally suited to probing such novel ground states, as it imposes heat loads on devices that are orders of magnitude smaller than for comparable optics-based THz spectroscopy methods.

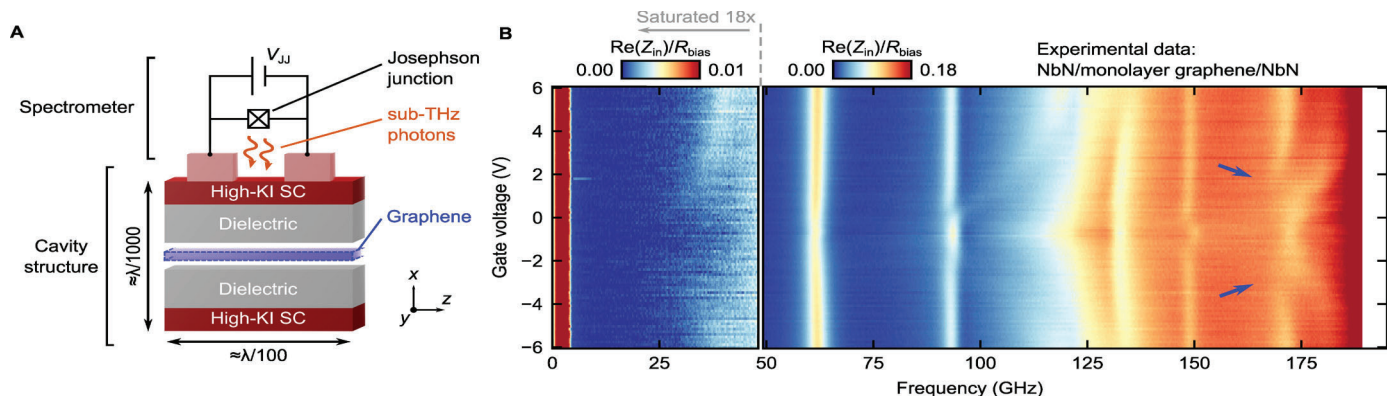


Figure 1: (A) Schematic of device geometry in which a Josephson junction acts as a photon emitter connected to an NbN/ graphene/NbN heterostructure. (B) Measured loss, expressed as $\text{Re}(Z_{\text{in}})$, of an NbN/graphene/NbN device as a function of frequency and gate voltage exhibiting numerous resonant modes. Blue arrows highlight an avoided crossing near 170 GHz.

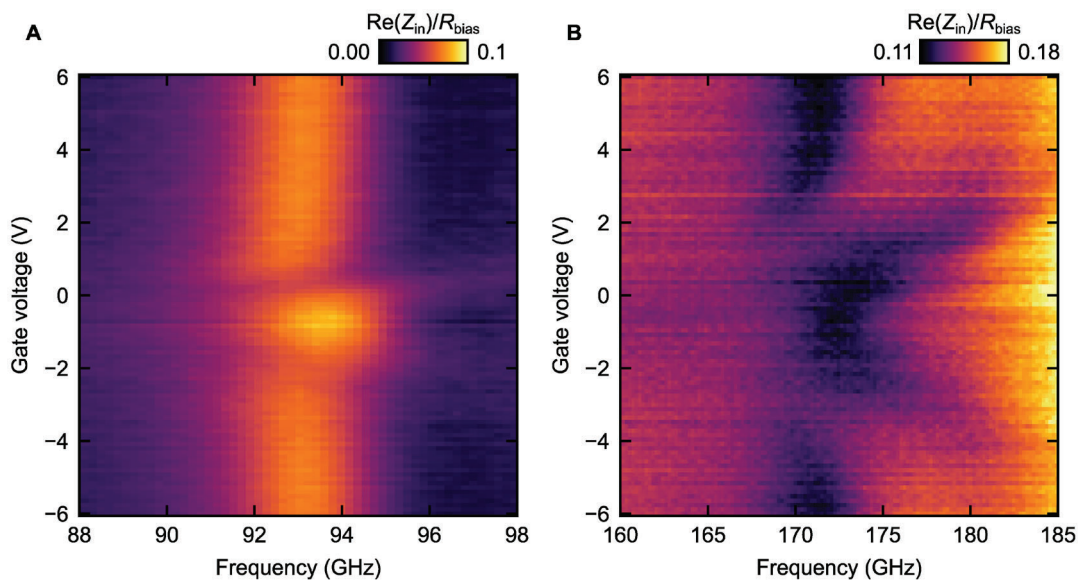


Figure 2: Zoom-in on avoided crossings from Fig. 1B near 90 GHz (A) and 170 GHz (B).