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Creating and Probing Graphene Electron Optics with Local Scanning Probes[1]

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Ballistic propagation and the light-like dispersion of graphene charge carriers make graphene an attractive platform for optics-inspired graphene electronics where gate tunable potentials can control electron refraction and transmission. In analogy to optical wave propagation in lenses, mirrors and metamaterials, gate potentials can be used to create a negative index of refraction for Veselago lensing and Fabry-Pérot interferometers. In circular geometries, gate potentials can induce whispering gallery modes (WGM), similar to optical and acoustic whispering galleries [1] albeit on a much smaller length scale. Klein scattering of Dirac carriers plays a central role in determining the coherent propagation of electron waves in these resonators. In this talk, I examine the probing of electron resonators in graphene confined by linear and circular gate potentials with the scanning tunneling microscope (STM). The tip in the STM tunnel junction serves both as a tunable local gate potential, and as a probe of the graphene states through tunneling spectroscopy. A combination of a back gate potential, $V_{\rm g}$, and tip potential, $V_{\rm b}$, creates and controls a circular pn junction that confines the WGM graphene states. The resonances are observed in two separate channels in the tunneling spectroscopy experiment: first, by directly tunneling into the state at the bias energy $eV_{\rm b}$, and, second, by tunneling from the resonance at the Fermi level as the state is gated by the tip potential. The second channel produces a fan-like set of WGM peaks, reminiscent of the fringes seen in planar geometries by transport measurements. The WGM resonances split in a small applied magnetic field, with a large energy splitting approaching the WGM spacing at 0.5 T. These results agree well with recent theory on Klein scattering in graphene electron resonators [2]. [1]. Y. Zhao, J. Wyrick, F. D. Natterer, J. F. Rodriquez-Nieva *et al.*, Science **348**, 672 (2015). [2]. J. F. Rodriguez-Nieva, L. S. Levitov, *arXiv:1508.06609* .

[1]This work is done in collaboration with Y. Zhao, J. Wyrick, F.D. Natterer, J. F. Rodriquez-Nieva, C. Lewandoswski, K. Watanabe, T. Taniguchi, N. B. Zhitenev, and L. S. Levitov