

Subwavelength-Structured Waveguides for Free-Electron-Photon Interactions

Omer Emre Ates, Benjamin J. Slayton, and William P. Putnam

Department of Electrical and Computer Engineering, University of California, Davis,
Davis, CA 95616, USA (bputnam@ucdavis.edu)

The interaction between free electrons and photons in electron microscopes offers unique opportunities for microscopy and quantum science. For example, modulating electron beams with multiple laser excitations, researchers have demonstrated a novel near-field electron microscope, capable of probing electromagnetic excitations on the nanometer spatial scale and in the attosecond (10^{-18} s) temporal range [see D. Nabben *et al.*, *Nature*, **619**, 63 (2023)]. Additionally, it has recently been demonstrated that the interaction between free electrons and photons in an electron microscope can be quantum coherent, and furthermore, this quantum coherence could potentially be leveraged for heralded sources of single electrons and photons [see A. Feist *et al.*, *Science*, **377**, 777 (2022)]. Although promising, these innovations in free-electron-photon interactions have thus far suffered a significant limitation: they require high-energy (>100 -keV) electron beams. Accordingly, these demonstrations have taken place in energetic (and expensive) transmission electron microscopes (TEMs). TEMs are a logical setting for these experiments, as their high-energy electrons can be velocity-matched to co-propagating photons in dielectric waveguides. However, achieving such velocity-matching between photons in conventional dielectric waveguides and electrons is not feasible for the low electron energies (<30 -keV) in more common scanning electron microscope (SEMs).

To extend these exciting free-electron-photon interactions to SEMs, we explore subwavelength-structures that can enable the strong interaction between low-energy (<30 -keV) electrons and photons. Subwavelength-modulated silicon photonic waveguides have been shown to support low-loss modes over extended propagation lengths [see P. J. Bock *et al.*, *Opt. Express*, **18**, 20251 (2010)]. Furthermore, the periodic, subwavelength-structuring of these waveguides means that their propagating modes are composed of spatial harmonics. These spatial harmonics, with high longitudinal wavevectors, can travel at very slow phase velocities. We show that, much like in conventional vacuum electronics, these slow spatial harmonics can be used to enable strong interactions between slow electrons and co-propagating photonic modes. Specifically, we show that 23-keV electrons can be coupled to co-propagating photons with a coupling strength comparable to that achievable with high-energy (>100 -keV) electrons.