

Phd Thesis Defense: Free-electron interaction with nanophotonic excitations

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Free electrons provide a powerful platform to control optical excitations at the nanoscale because they carry electromagnetic fields that are tightly localized and contain large evanescent wave-vector components inaccessible to propagating light. Although this property makes electron beams uniquely suited to address confined optical modes, their full potential for technological applications is still being actively developed. This Thesis aims to contribute to this effort by exploring novel phenomena that arise when electron beams are incorporated into different optical systems.
As an introduction to the main concepts underlying this Thesis, Chapter 1 summarizes the theoretical frameworks used to describe electromagnetic excitations, with emphasis on linear and nonlinear optical phenomena, surface waves such as polaritons and waveguide

modes, and electron beams.

Chapter 2 explores electron-driven excitation of surface polaritons through resonant scatterers placed near polariton-supporting materials. The passing electron polarizes a small resonant particle, which then launches surface modes with a spectrum determined by the particle's response. Our semi-analytical model reveals an optimum scatterer-surface separation that maximizes polariton emission. This approach is extended to periodic arrays of scatterers, leading to a polaritonic analog of the Smith-Purcell effect, in which surface polaritons are emitted directionally into diffraction orders controlled by the array period, electron velocity, and polariton dispersion relation. Hexagonal boron nitride nanodisks coupled to graphene plasmons are identified as a realistic mid-infrared implementation for small resonant scatterers, with efficiency comparable to resonant lossless particles.

In Chapter 3, we introduce wave-mixing cathodoluminescence as a nonlinear spectromicroscopy technique for detecting low-frequency excitations through visible-range optical readout. In this mechanism, the evanescent field of a swift electron mixes with an external optical pump through the second-order nonlinear response of a specimen, generating sum- and difference-frequency photons. The method up-converts far-infrared spectral fingerprints into the visible range, avoiding the need for low-frequency light sources or detectors. Calculations for retinal-coated silver nanorods show that molecular vibrational signatures can be accessed with nanometer-scale spatial resolution under external illumination and visible-range detection.

Chapter 4 explores electrostatic control of electron trajectories as a means of tuning coupling to guided modes in silicon waveguides. By deflecting electrons into grazing trajectories using a static electron-repulsive field, the minimum electron-waveguide separation becomes a controllable parameter that governs both coupling strength and modal selectivity. In particular, we consider three doped silicon waveguides placed on a sapphire substrate, with the two side elements acting as lateral gating structures. Including image-force effects and collision thresholds, the analysis predicts voltage-tunable photon yields reaching several photons per electron in realistic integrated photonic geometries.

In Chapter 5 cylindrical waveguides are studied as mediators between free electrons and nanoscale absorbers. A gate-controlled grazing electron launches a guided wave packet that subsequently drives a nearby resonant particle. This waveguide-mediated channel concentrates the broadband electron field spectrally and spatially, producing strong absorption enhancements relative to direct bare-electron excitation.

In summary, this Thesis establishes free-electron-nanophotonic interactions as a versatile platform for nanoscale excitation, spectroscopy, and control of optical, polaritonic, and guided modes, with potential applications in integrated photonics, molecular sensing, and quantum nanophotonics.

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