doi:10.1017/S1431927622007735
Microsc. Microanal. 28 (Suppl 1), 2022

The Prospect of Quantum-Optical Information Transfer using an Electron Microscope Beam

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The recent few years have seen a surge of novel microscopy techniques combining the best of two worlds – the ultrahigh temporal and spectral precision of photonics with the superb resolution of electron microscopy [1]. When the electron is confined to a picosecond pulse (1 ps = 10^{-12} s), it can be fully overlapped with the intense optical fields that such short pulses can have. Thus, photon-induced nearfield electron microscopy (PINEM) [2–4], for example, allows electrons to image laser-pumped optical modes. Laser-driven mechanisms such as PINEM and electron energy gain spectroscopy (EEGS) [5–7] append standard methodologies as electron energy loss spectroscopy (EELS) and cathodoluminescence (CL) by providing polarization sensitivity and access to weakly interacting modes. Furthermore, actively enhancing the cross-talk between light the electron brought about an interest in the possible manipulations of the electron itself, dressing its wavefunction with optical phase [8] and structuring it as unprecedently short attosecond pulses [9–12] (1 as = 10^{-18} s). However, determining the physics carried by such modulated electron states and the utility they may bring is still an open challenge.

This work presents recent novel conceptual and experimental aspects of the interaction of electrons in a TEM that are strongly or moderately coupled to photons. We describe the possibility of imprinting electron beams with two types of quantum-optical information. If the electron-photon coupling is sufficiently strong, entangling these physical entities will create an inseparable quantum state, analogous to a Bell-pair [13,14]. Alternatively, in the weak coupling regime, PINEM can be used to dress the electron with the optical-frequency coherence of the driving laser. The electron carries the laser's phase information downstream to a sample and can emit temporally coherent radiation. Its coherence makes CL from laser-dressed electrons susceptible to quantum optics tools such as homodyne detection and homodyne quantum-state tomography [15], with a replica of the driving laser acting as a local oscillator. Interestingly, coherence carried by electrons is profoundly different from its photonic analogs. For example, the electron has longitudinally polarized fields, and the degree of coherence (DOC) transmissible to CL depends on the electron dispersion in vacuum. Furthermore, the electron acts as a nonlinear medium, where a significant degree of coherence is expected at the driving frequency and its integer-multiple harmonics, spanning the maximal possible bandwidth when the electron probability density forms attosecond pulses.

To approach the experimental conditions for these unique regimes, we have designed silicon-photonics circuits comprising micro-ring cavities and waveguides with several unique properties [16,17] (see Figure 2): (i) fiber-based laser injection for an efficient optical pumping through the TEM sample holder, (ii) high-quality factor (high-Q) and finesse enabling a resonant optical field enhancement, (iii) velocity matching of the optical mode's phase with the electron for an increased quantum coupling constant g_{Qu} [13], and (iv) a clad-less flat top waveguide, allowing the modal field to permeate the vacuum and interact with the electron beam. This structure enables the observation of PINEM at ultralow laser powers, <6 µW, in continuous wave (CW) mode. With quality factors of Q~10^6, the resonators offer an exquisite frequency selectivity. Using EEGS, the microscope reaches 3.2 μeV resolution, the finest spectral feature achieved with EEGS to date, surpassing previous values by three orders of magnitude.

In conclusion, this work presents concepts that may enable the transferring of phase or entanglement information from macroscopic systems, such as light and photons in a waveguide, to a target as small as the microscope can resolve. In state-of-the-art TEMs, this may reach atomic precision. The fiber-coupled silicon-nitride resonators show their merit by breaking two records simultaneously: facilitating PINEM with record-low power CW laser and demonstrating ultrahigh-resolution EEGS. This approach promises ever-larger electron-photon coupling and functionality. Specifically, this work opens a path for standardizing light-enhanced microscopy, using photonic circuits within continuous-beam TEMs, with the optical fibers entering and exiting through the sample-holder port. Thus, interest from the vast electron microscopy community can drive a leap forward within this paradigm and fulfill its still-unraveled potential.

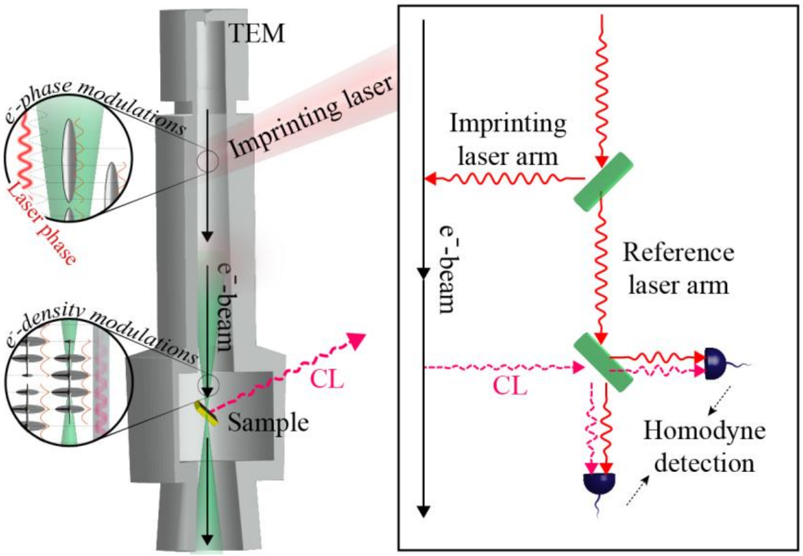

Figure 1. Laser-dressed electrons can form modulations with an optical-cycle periodicity and emit CL phase-coherent radiation. Thus, methodologies such as homodyne quantum-state tomography can be used to analyze the electron-sample interaction. The laser is marked red, CL purple, and the phase of the electron wavefunction orange.

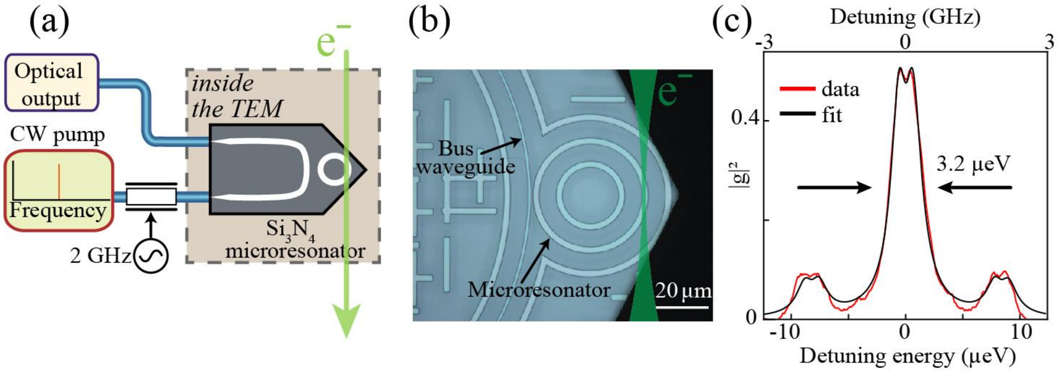

Figure 2. Silicon photonics for increased narrowband electron-photon coupling. (a) The intensity of a continuous wave (CW) laser injected to an in-TEM resonator. A modulator set to 2 GHz references the laser's spectral detuning. (b) Light is guided in a bus channel coupled to a high-Q ring microresonator based on silicon nitride (Si_3N_4) embedded in silica. The electrons co-propagate with the optical mode and exchange energy and momentum efficiently. (c) EEGS of the high-Q mode (0.39 MHz) is only 3.2 µeV, far below the zero-loss width, and surpasses previous EEGS measurements by three orders of magnitude. The sidelobes originate from the 2-GHz modulation. $|g|^2$ is the electron energy gain- and loss probabilities, where g is the PINEM parameter, also called the Rabi-parameter.

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