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High-Q photonic chip-based temporal phase plates for electron microscopy

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The active optical shaping of free-electron beams enables a broad range of applications, from efficient free-space acceleration [1] and attosecond bunching of electrons [2-4] to the implementation of laser-driven phase plates [5,6] and beam splitters [7].

Recent experiments on inelastic electron-light scattering (IELS) [8,9] with dielectric microcavities such as microspheres [10] or photonic crystal cavities [11] have demonstrated the potential of using resonant field enhancement for increasing the interaction between electrons and photons. However, bringing IELS to state-of-the-art continuous-beam electron microscopes is challenging, due to the optical transition probabilities normally being far below unity, thus requiring the use of femtosecond high-intensity laser pulses.

In this work, we demonstrate IELS on a CW-pumped Si_3N_4microresonator with a *Q*-factor of $>10^6$, achieving an unprecedented high coupling to a continuous electron beam.The interaction strength between the electrons and the evanescent cavity field is spatially mapped and we discuss the potential application as a versatile temporal phase plate for electrons.

In an ultrafast transmission electron microscope (UTEM) [12], a continuous electron beam passes by a CW pumped Si_3N_4microresonator (see Fig. 1.a)), which is installed in a custom-designed TEM sample holder. The air-cladded microresonator chips (Fig. 1.b)) are fabricated using the photonic Damascene process [13] and exhibit a linewidth of ~70 MHz (Fig. 1.c)), as well as a free spectral range of ~1 THz for the quasi-TM fundamental mode. The electron beam interacts with the whispering gallery mode, confined in the fiber-coupled photonic chip.

When the CW laser is tuned to a resonance of the cavity, the initially narrow energy distribution is significantly broadened up to about 50 eV, with a shape typical for multi-order absorption and emission of photons(Fig. 1.a,d)). We retrieve a spatial map of the electron-light coupling parameter g, which exhibits a pronounced modulation along the structure (Fig. 1.e)), due to Ramsey-type interference [14] between the two crossings of the electrons and the resonator ring.

In conclusion, we demonstrate strong inelastic electron scattering off a CW optical field, enabled by high-*Q*microresonators. Hereby, new opportunities arise in electron microscopy, from optical beam structuring with state-of-the-art integrated photonics, to the exploration of free-electron cavity quantum optics[15].

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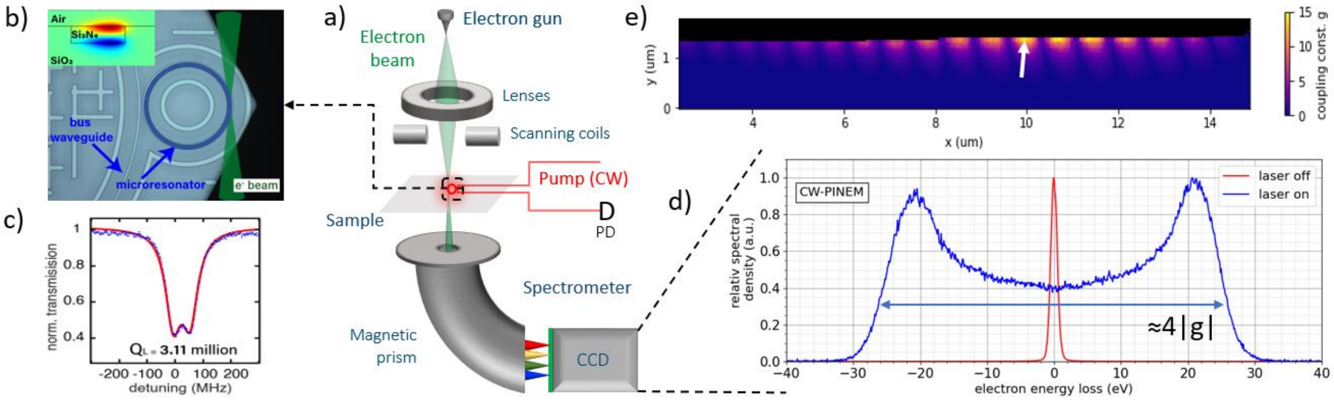

Figure 1. Figure 1. a) Inside of a transmission electron microscope (TEM), an electron beam passes close to a CW-pumped integrated Si3N4 microresonator in aloof geometry (b, SEM image: side view of the chip, Inset: Electric field component parallel to the electron beam.) c) Optical transmission spectrum of a typical microresonator resonance exhibiting a linewidth of ~70 MHz (Q-factor of 3.11·106). d) Electron energy distribution of the transmitted beam recorded with a magnetic-prism spectrometer. Tuning the CW laser to a cavity resonance, a spectral broadening up to ~50 eV is observed (probing position indicated by the white arrow in e)). e) Spatial map of the electron-light coupling constant g, obtained from scanning the electron beam across the resonator.

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