Merging Integrated Photonics and Electron Beams:

µeV-Electron-Spectroscopy and Single-Particle Heralding

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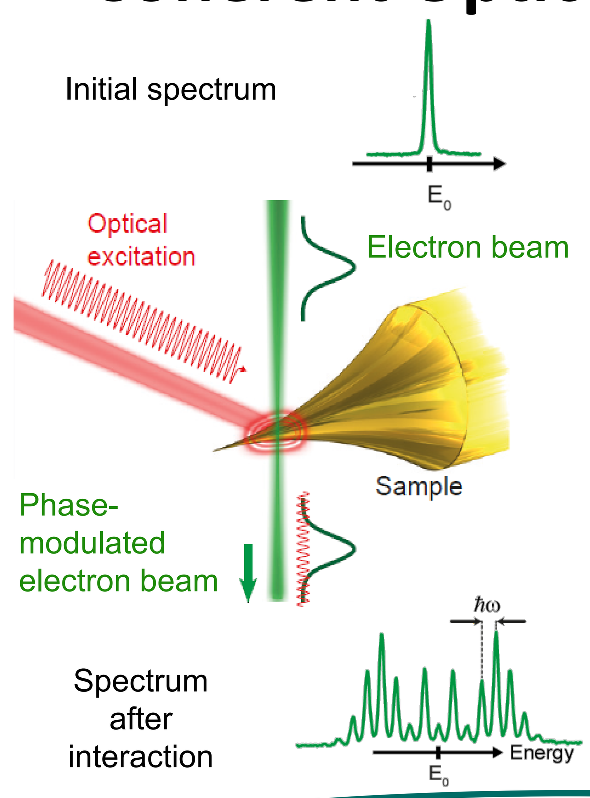
Motivation

Electron microscopy provides unique insights into heterogeneous nanomaterials and integrated circuits[1,2], but it does not yet harness many advanced capabilities from photon science, including programmable optics, coherent spectroscopy, or quantum-enhanced imaging.

Merging these two realms defines a new frontier in nanometrology and promises a novel class of light-enhanced electron microscopes[3,4]. However, this requires concepts and technology to interact and detect electrons and photons at the single-particle level.

Here, we present the coupling and manipulation of electron beams with light at an unprecedented efficiency using integrated photonics[5-7]. These advances may contribute to the in-situ metrology of functional silicon photonic devices.

Coherent Optical Phase Modulation & Laser-Driven Electron Optics



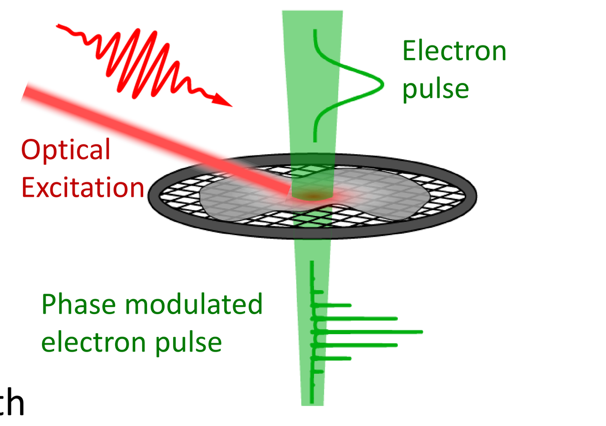
- Absorption and emission of photons in intense optical near-fields[8,9]
  → Formation of energy sidebands
- Final electron state:

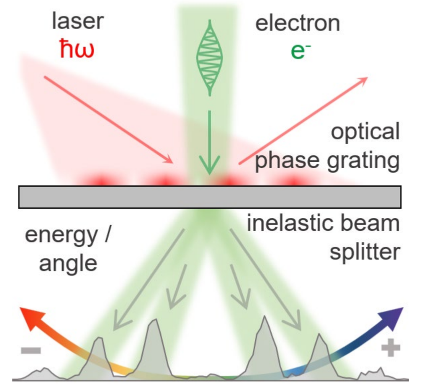
$$|\Psi_f\rangle = \sum_N J_N(2|g|)e^{i\arg(g)}|E_0 + N\hbar\omega\rangle$$

depends on electron-light coupling strength

$$g(R,\omega) = \frac{e}{2\hbar\omega}\int_{\mathbb{R}} E_z(R,z,\omega)\, e^{i\frac{\omega}{v}z} dz$$

Electron-light interaction is typically weak, required intense optical pulses





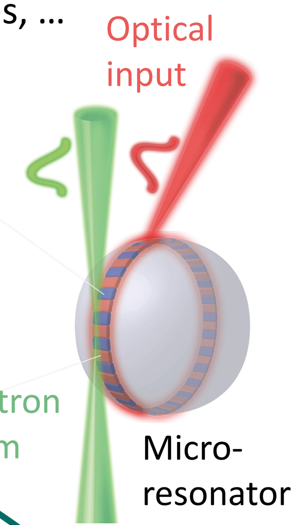
coherent optical phase modulation in space & time[10,11]

$$\varphi(z,x) = -2i|g|\sin\left(\frac{\omega}{v_e}z + k_{||}x + \varphi_0\right)$$

→ Aberration correction, beam chopping & dose control, beam splitters & phase plates, …

enhancing the interaction[5]

- Resonant cavity field enhancement
- Electron-light velocity phase matching



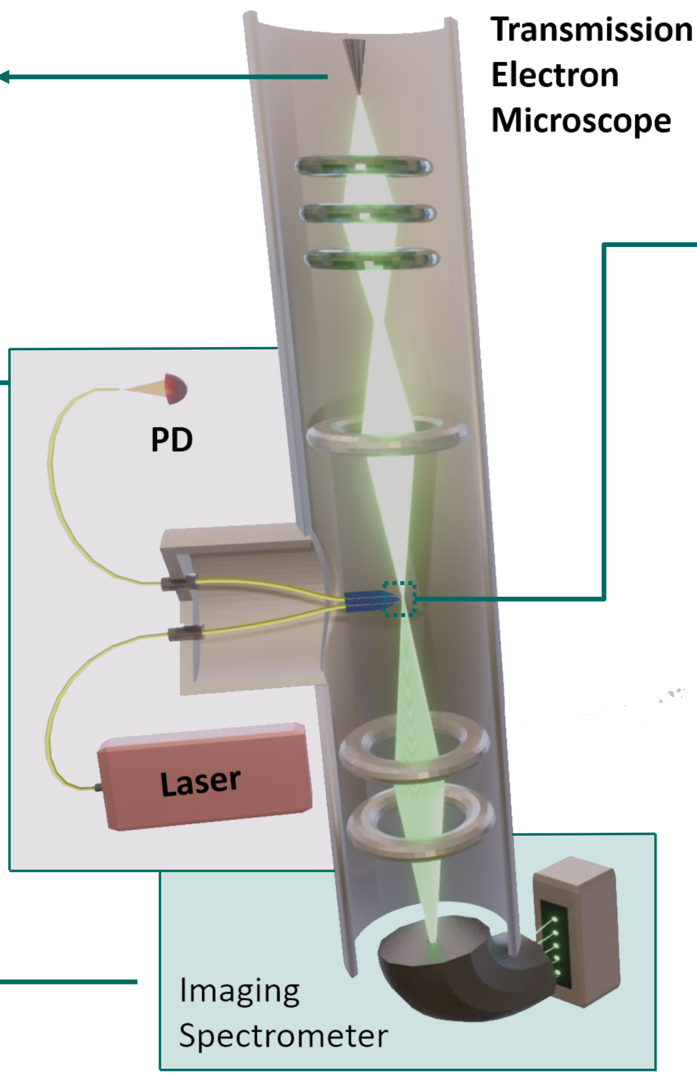
Integrated Photonics Platform for Efficient Electron-Light Coupling

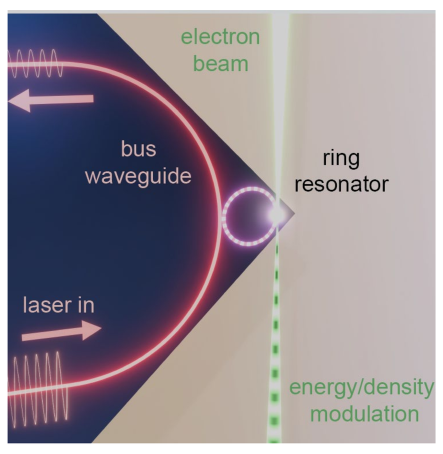
Electron beam properties[4]

- Nanometer spatial resolution
- Sub-eV energy spread in initial beam

Continuous-wave optical pump setup[5]

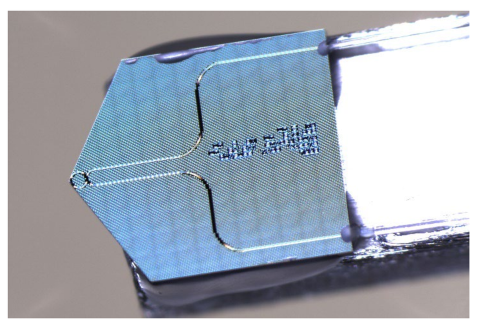
- Narrow line-width frequency-tunable CW fiber laser
- Control over input power and polarization
- Optical analysis of transmitted light





Si_3N_4 Microresonators

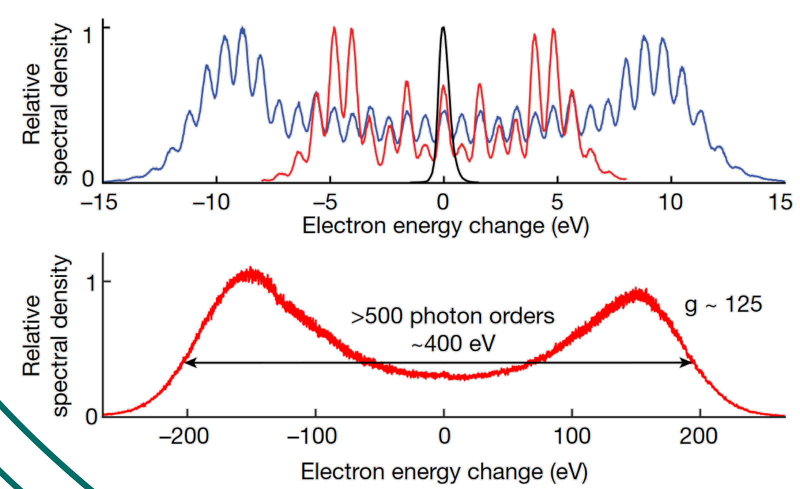
- Fiber-coupled, chip-based microresonators
- Top air cladding to facilitate electron-light coupling
- High internal Q factor $Q_0 \sim 0.74 \times 10^6$ at 1550nm
- Modes with strong coupling to electrons and anomalous dispersion



designed & fabricated by Kippenberg group and Center of MicroNanoTechnology (CMi) at EPFL[12]

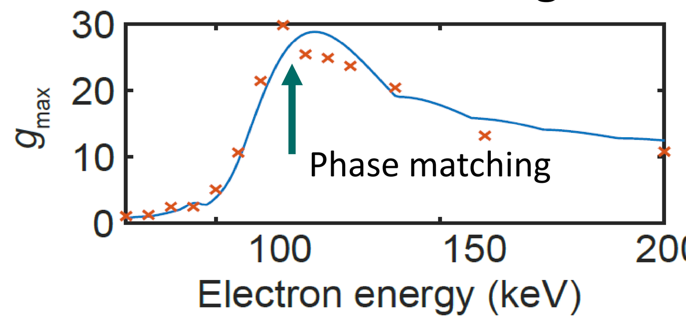
Efficient continuous electron beam modulation by CW laser

Electron energy spectra

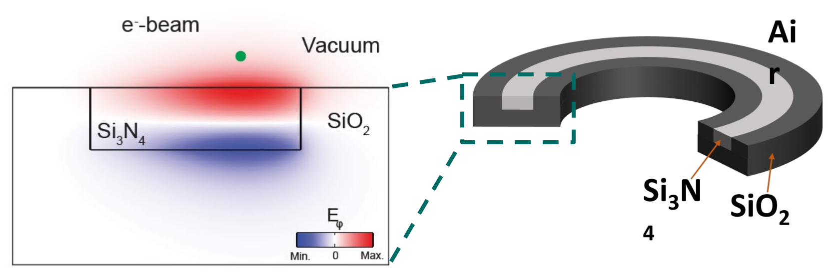


- Observe inelastic scattering for low CW input powers
- Efficient interaction

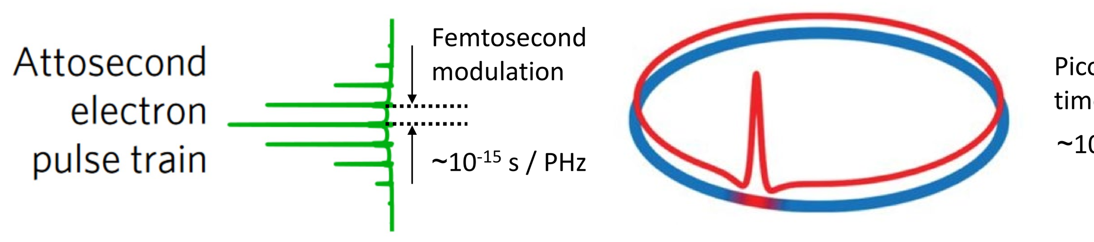
Phase Matching



- Vary electron energy
- determine the maximum coupling



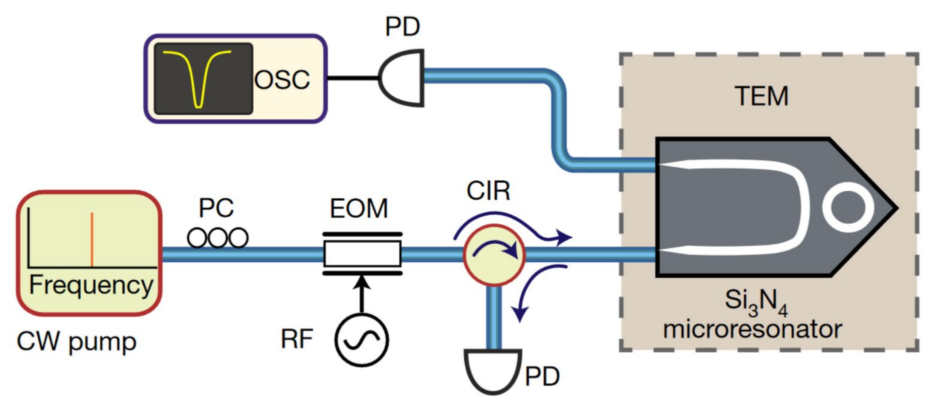
Electron Beam Modulation at GHz-PHz Frequencies



- Modulation of the electron beam at the optical frequency (PHz)[10]
- Soliton pulses allow for deep sub-harmonic modulations (GHz-THz)[7]

In-situ Metrology of Integrated Photonic Devices

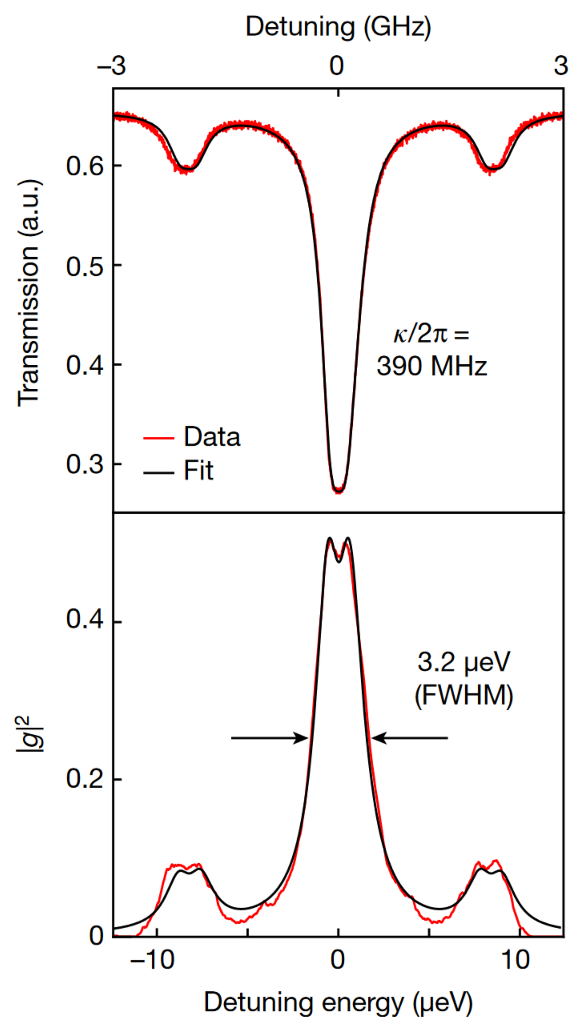
J.-W. Henke *et al.*, Nature **600**, 653 (2021). & Y. Yang *et al.*, Science **383**, 168–173 (2024).

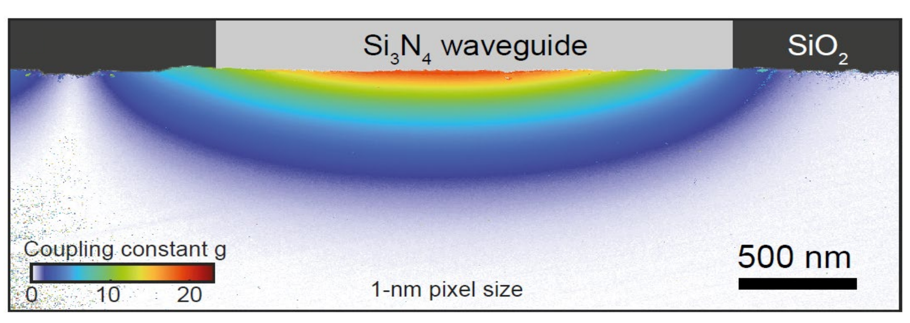


Electron energy-gain spectroscopy of a cavity mode

- optical transmission as a function of detuning
- electron energy spectra recorded with fast detector (100-µs binning)

→ energy resolution (sub-neV) decoupled from ZLP width (~500 meV)
→ in-situ resonator mode characterization





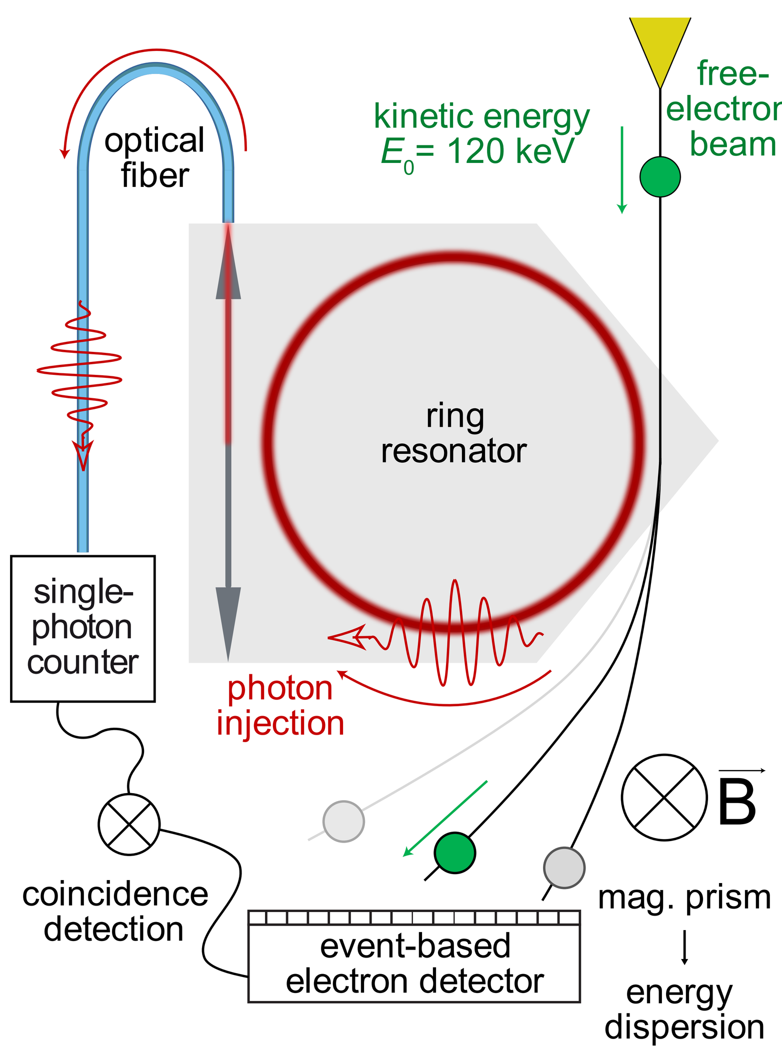
photon-induced near-field electron microscopy (PINEM)

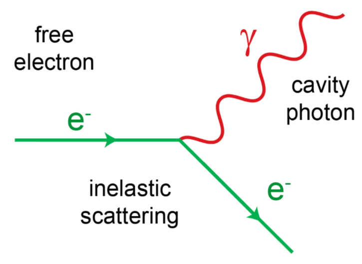
- energy-filtered image stack of individual photon sidebands
- Quantitative reconstruction of mode profile

→ combined nm-µeV spatial and spectral in-situ characterization of an integrated photonics circuit

Free-Electron Cavity-Photon Pairs & Single Particle Heralding

A. Feist *et al.*, Science **377**, 777 (2022).



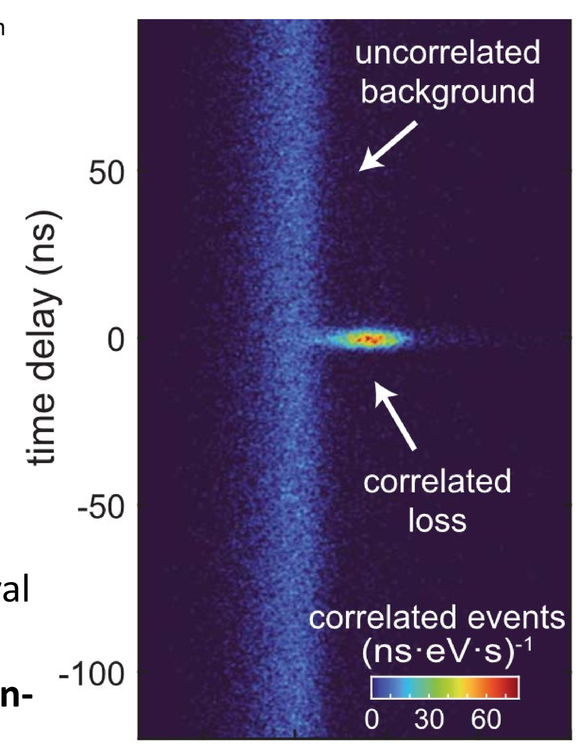


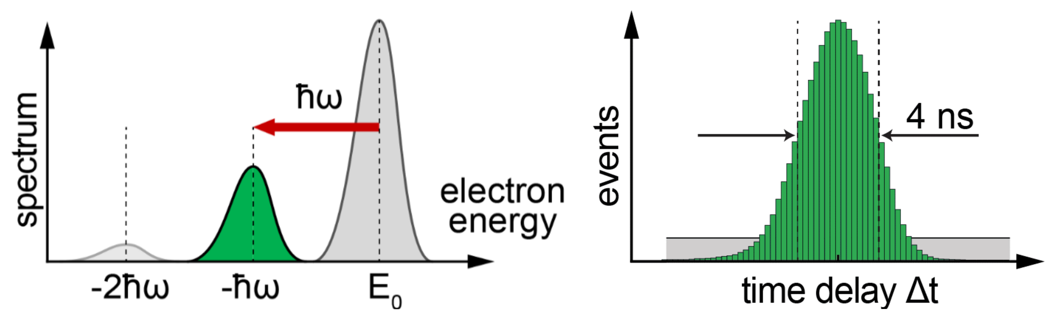
Inelastic scattering at the resonator creates single photons[13]

Coincidence Histogram

- Correlation of electron energy and relative photon arrival

→ **Correlated electron-photon pairs[6]**
→ detection of either particle heralds the other





→ Shot-noise reduced electron source (countable number of electrons)

→ Contrast enhancement by correlative imaging

Acknowledgments

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