ELECTRON-PHOTON INTERACTIONS IN A SCANNING ELECTRON MICROSCOPE

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ABSTRACT

In this work, we describe a testbed for studying free-electron photon interactions in a 1 to 20-keV scanning electron microscope. The setup includes an ultrafast emitter, optical modulators for structuring the electron beam, a nanostructured interaction zone, and electron and optical spectrometers with time-tagging electronics to characterize these interactions. Through this work we aim to understand these interactions at electron energies orders-of-magnitude lower than used in most previous work, enabling their more widespread adoption and potentially leading to chip-scale technologies.

KEYWORDS

Electron Microscopy, Quantum Optics

INTRODUCTION

In recent years, there has been an explosion of interest in the use of free-electrons to herald photons or other electrons, and to generate quantum light [1]-[5]. While these experiments are highly promising, they require beam energies in the range of hundreds of kilo-electron-volts, and have thus so far only been achieved in transmission electron microscopes (TEMs). If these interactions hope to find wide-scale application, the energy of these interactions must be substantially reduced. In this work, we outline our efforts to generate and study these interactions in a significantly lower energy scanning electron microscope (SEM), the various challenges associated with this approach, and how we are addressing these challenges.

An overview of the apparatus, along with an example conceptual experiment is shown in Fig. 1. First, an ultrafast electron packet is generated by exciting a Schottky source with an 80-fs, 400-nm laser pulse. The electron is then focused through an aperture aligned to the optical axis via a 3-axis stage (Fig. 1a). This aperture is excited by a 800 nm, 2 ps laser, which modulates the momentum of the initial electron packet, $|\psi(0)|^2$ (Fig. 1b). After propagation over distance L, the electron bunches into an attosecond structured packet, $|\psi(L)|^2$, as described in previous work [6].

We then pass this structured electron packet over a nanostructured fiber optic cable (Fig. 1c). A micrograph of this structure is shown in Fig. 1i. For an unstructured packet, the proximal electron induces polarization in the grating that travels with the electron packet, oscillating and producing light via the Smith-Purcell effect [7]. Recent work has hypothesized that such interactions involving structured electron wavepackets could lead to superradiant emission [8] as well as Cat and Gottesman-Kitaev-Preskill states of quantum light [9], which are difficult to generate with other nonlinearities and may provide fault tolerance in continuous variable optical quantum computing. The active edge detector (Fig. 1d) is used for calibration of the beam position and cancellation of beam vibrations and drift, and is critical for disentangling varying coupling due to changes in the impact parameter of the beam. We show the physical realization of this in Fig. 1g, and a micrograph of the close proximity of the edge to the fiber in 1h.

We then pass the electron through a lens (Fig. 1e) and into a spectrometer, which filters the electron by energy (Fig. 1f). Using a slit and channel electron multiplier, we count electrons at various energies. Simultaneously, we count generated photons passing through an optical spectrometer, and we time-tag and correlate these photon counts with the electron events. By measuring an electron with $n\hbar\omega$ photons of energy loss, we can herald the arrival of *n* photons of energy $\hbar\omega$, or vice-versa. By performing interferometry with the resulting light, as well as interacting the electrons with a second laser, we will study the dynamics of this interaction with unprecedented detail.

While the full experiment is still in progress, many milestones have been reached to realize and study these interactions. The ultrafast triggering, stages, edge detector, modulator stage, time-tagger, and photon spectrometer are all complete and fully operational. We have also demonstrated our nanofabricated fiber tip (Fig. 1i) and have calibrated the electron spectrometer (Fig. 2a-c), including in counting mode. In this work, we detail the submodules that are currently under development and our progress on them.

SUBMODULES

Nanostructured Fiber Tips

The core experiment revolves around a nanoscale grating pattern that is fabricated directly on top of the tip of a fiber-optical cable. The nano-patterned fiber is used to simplify light collection. Since the depth of focus of the beam is on the order of 10 μm, the nanostructure protrudes to allow close impact of the beam. These fibers were fabricated via a customized process of hydrofluoric acid vapor etching, polishing a flat 10-μm plateau onto the tip, gold evaporation, and ion beam milling of nanostructures on the plateau. In Fig. 1i we show a micrograph of a patterned fiber structure. The fiber is covered with a thin (~50-nm) gold layer that prevents the build-up of electric charge on the otherwise electrically insulating fiber and acts to favor the radiation

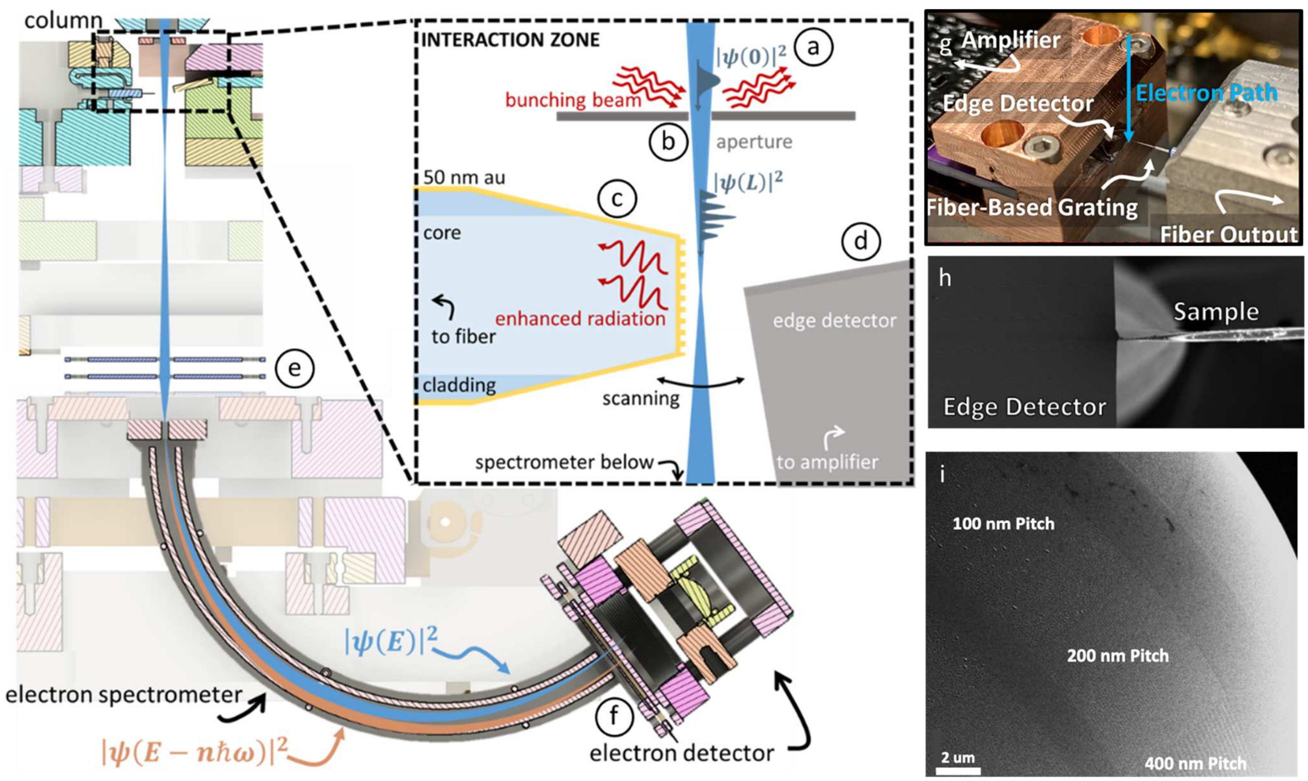

Figure 1: Experimental apparatus and results. (a) The incident ultrafast electron pulse. Pulse is modulated by a (b) laser excited aperture before passing near a (c) nanostructured grating on a fiber. (d) An edge detector that is used to calibrate beam position. After interaction, the beam is focused with a lens (e) into an electron spectrometer (f), which separates electrons by the number of photons gained or lost. (g) Physical realization of the interaction zone, with the modulator removed for clarity. (h) SEM micrograph of a fiber and the edge detector. Note the charging of the fiber can be compensated for with the edge detector. (i) SEM micrograph of the fiber with multiple grating patterns from a 100 nm – 400 nm pitch.

ofphotons into the fiber rather than into free-space. We calculate up to 25-fold improvements in the photon collection efficiency at targeted wavelengths compared to conventional free-space approaches.

Laser Triggering and Modulators

Our experimental configuration enables us to study spontaneous emission of Smith-Purcell radiation into the optical fiber. In a more involved configuration, we will propagate the electron across a modulated electric field before passing aloof to the fiber pattern. With this approach, as the electron bunch (or wave function in the case of a single electron wavepacket) exits the modulation field, it obtains a spatial probability distribution with local maxima that coincides with the period of the nanosized patterned structure. The modulating electric field is generated by illuminating a metallic aperture grid (the '*modulator*') with a pulsed laser. The addition of a modulator to the experimental configuration enables us to study stimulated and super-radiant Smith-Purcell radiation into the fiber. So far we have integrated the modulator grid (shown in Fig. 1b) as well as demonstrated ultrafast electron emission required for such a process (see Fig. 2d). Our next step is to check that we generate modulated sidebands using the electron spectrometer, described below.

Electron Spectrometer and Counter

We also have designed, constructed, and tested an electron spectrometer to allow us to verify the generation of electron bunching, as well as to characterize the electrons after superradiant emission. The spectrometer is integrated into our SEM as shown in Fig. 1. Early results from the spectrometer are shown in Fig. 2a-c. Our results indicate we can measure electrons with sub-eV energy resolution (Fig. 2b), and nanosecond temporal resolution (Fig. 2c). This time and energy resolution will allow us to directly observe single-photon loss and gains.

Active Beam Alignment

The intensity of the generated radiation decreases exponentially as a function of the separation distance between the pattern and the passing electron. This separation, referred to as the impact parameter, must be calibrated and controlled in measurement with nanometer-scale accuracy for proper data interpretation in order to ensure superradiant light enhancement is not due to a varying impact parameter. Furthermore, beam impact with the sample can lead to incoherent background radiation in the form of cathodoluminescence which must be either avoided or accounted for properly during the experiment or in post-analysis. To this end, we have developed a form of active

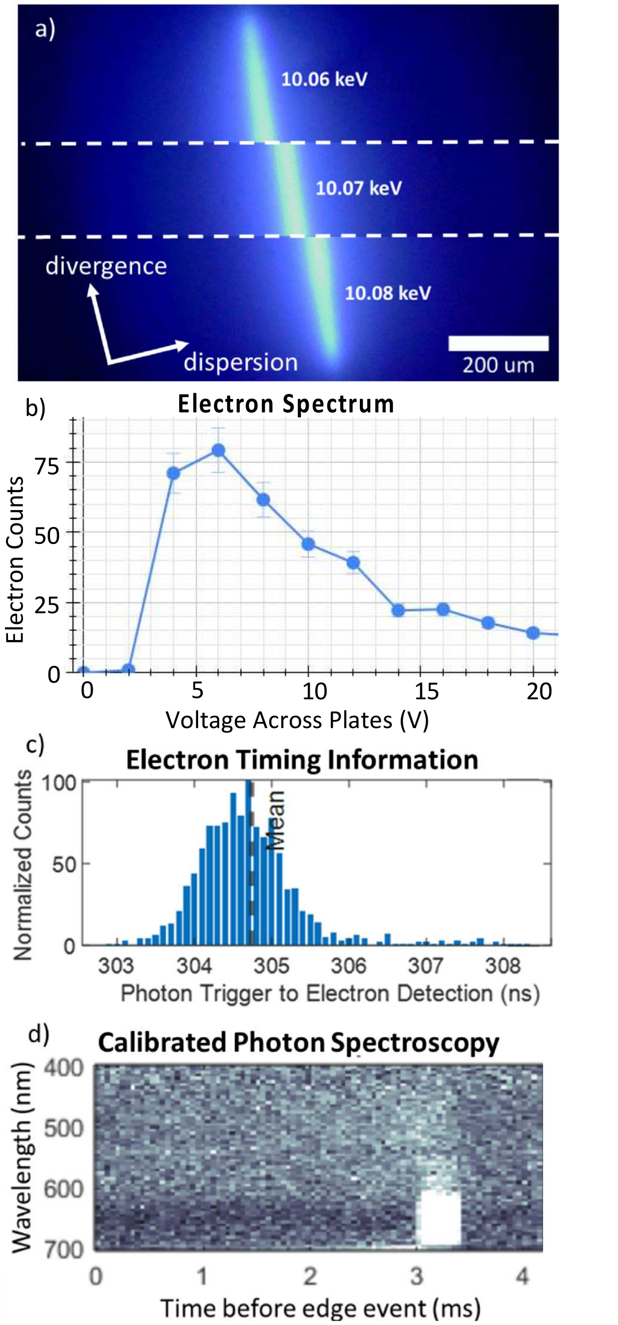

Figure 2: Module Data - (a) Phosphor image of the electron spectrometer beam for various energies. (b) Electron spectrometer in counting mode, with a slit incorporated to give superior energy resolution. (c) Electron counts from the same detector when an ultrafast triggered tip is used, showing ~1 ns timing resolution on the spectrometer. (d) Photon counts vs. delay from photon detection to electron detection event, demonstrating ultrafast triggering of our electron source, as evidenced by varied delay times when propagating down the column. White corresponds to more counts.

scan synchronization, in which a cleaved semiconducting edge is used to detect the presence of a constantly scanned electron beam, shown in Fig 1g-h. By repeatedly scanning the beam over the edge of the sample faster than vibrations and instabilities of the system, we can use the edge detector signal to calibrate all of our output photon and electron signals to when we know the beam exited the edge. Synchronized photon counts from this setup, as a function of time from the edge detection, are shown in Fig. 2d.

FUTURE PLANS

Our next goal is to generate attosecond bursts of the electron beam by combining the ultrafast triggering, modulator grid, and spectrometer, to observe many-photon sidebands characteristic of attosecond bunching [6]. Simultaneously, we are seeking to combine the nanostructured tip with our scan calibration system and optical spectrometer/counter to realize the collection of Smith-Purcell with unprecedented control over the impact parameter. When these are complete, we will then begin our push to generate quantum states of light from structured electron beams, and thus realize a long-sought after goal of free-electron light sources.

ACKNOWLEDGEMENTS

This material is based upon work supported by the National Science Foundation under Grant No. 2110535 and 1745302. Part of this material, in particular the construction of the electron energy spectrometer, is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences, under Award Number(s) DE-SC0022054.

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