Time-Domain Analysis of the Coupling between Free-Electrons and Photonic Waveguides

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Abstract: We investigate how free-electrons can excite modes in nearby photonic waveguides. Using particle-in-cell simulations, we explore how a free-electron packet can couple energy into multiple, velocity-matched modes of an adjacent silicon waveguide.
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Interactions between keV-energy free electrons and photons have attracted significant research attention in recent years. These interactions offer promising scientific and technological opportunities, ranging from electron microscopy to quantum-coherent applications. Early experiments in this area often involved the interaction of an electromagnetic near field, supported by a localized, nanoscale structure, with a passing, energetic electron. For example, the original photon-induced near-field electron microscopy (PINEM) experiments exploited the acceleration and deceleration of electrons passing through the near-field around a nanostructure excited by a femtosecond laser [1]. More recently, researchers have begun to explore these interactions with co-propagating electromagnetic waves in nearby waveguides [2, 3]. However, despite this new geometry, the essential computational mechanism for predicting electron-photon coupling has remained the same. Here, we present a new, time-domain simulation approach for studying the coupling of free electrons to waveguide photons. We use this time-domain simulation to demonstrate the energy exchange between free electrons and photonic modes in an air-top silicon waveguide. This time-domain simulation platform could help further extend the understanding of the coupling dynamics between free electrons and photons.

Our time-domain simulations are based on a particle-in-cell (PIC) solver. These PIC simulations account for the effects of electromagnetic fields on moving charges, as well as the effects of moving charges on fields, *i.e.* radiation. Our PIC simulations are carried out in CST, and in Fig. 1a, we provide an illustration of the essential simulation geometry. (We should note that Smith-Purcell radiation has recently been similarly analyzed via PIC simulations in CST [4].) In the simulation we inject a pulse of macroparticles 50 nm above a uniform silicon waveguide. The macroparticles have varying charge, and together, these macroparticles form a Gaussian-shaped pulse of charge (as illustrated in Fig. 1a). The Gaussian pulse has a total charge equal to that of a single electron, $e = 1.6 \times 10^{-19}$ C. Additionally, for the initial simulations, the Gaussian pulse has a standard deviation of 133 nm.

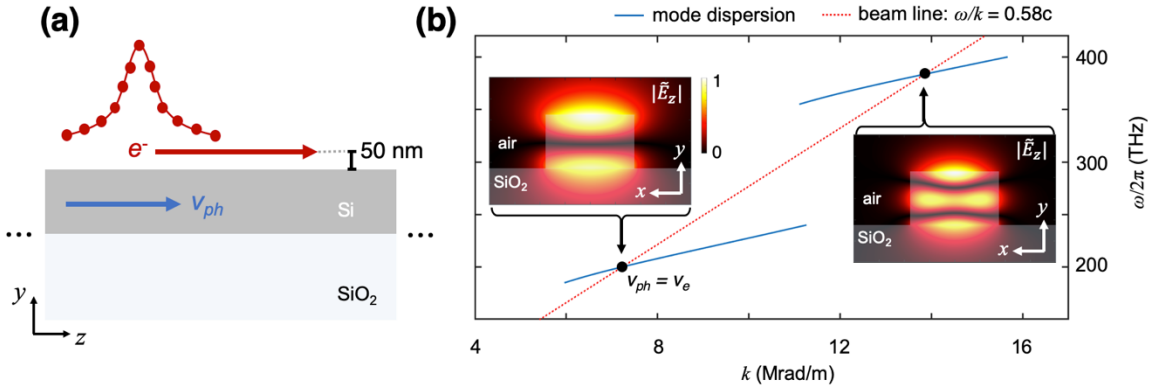

Figure 1: Time-domain simulations of free-electron and waveguide mode interactions. **(a)** Schematic representation of the simulation setup. A Gaussian-shaped pulse of macroparticles, traveling in the z direction, is injected above a Si waveguide. The waveguide sits on an SiO_2 substrate. The waveguide has a (foundry-compatible) cross section of 350 nm by 250 nm. **(b)** The waveguide width is designed so that a lower-order mode velocity-matches with the electron ($v_e = 0.58c$) at approximately 200 THz and is close to the cut-off frequency. A higher-order mode can also velocity-match the electron. The normalized longitudinal (z-directed) electric field profiles are illustrated in the insets for each mode. Since the electron is moving on top of the waveguide, it tends to couple with the modes that have a high longitudinal field above the waveguide.

The Gaussian pulse of charge can excite modes in the adjacent silicon waveguide. In Fig. 1b, we show sections of the dispersion curves for two modes of the waveguide. Additionally, in Fig. 1b we also plot the beam line. The beam line corresponds to all points with a phase velocity that matches that of the electron beam. In our case, we set the electron pulse velocity to v_e = 0.58c (that is, the electron energy is 116 keV). For efficient coupling, the phase velocity of a photon in the waveguide (v_{ph}) must match that of the electron. As shown in Fig. 1b, the electron pulse velocity-matches with the two illustrated modes at f_1 = 200 THz and f_2 = 384 THz. (Here, the refractive index of the silicon and silicon dioxide are assumed to be wavelength-independent, and they are set to 3.48 and 1.45, respectively.)

A snapshot of the results of our time-domain simulation are included in Fig. 2. In Fig. 2a, the normalized instantaneous power density (S_z) in the z-direction is shown at t = 56 fs. (t = 0 is the time the electron pulse enters the simulation.) From the power density plot, we see that the electron pulse (with velocity 0.58c) is coupling to velocity-matched photonic modes. In Fig. 2b, the instantaneous power density in the z-direction is integrated over the simulation cross section at z = 10 μm and plotted as a function of time. The total average power is computed as 0.13 μW (after excluding the power associated carried only by the electron, *i.e.* the beam power). We should note that due to the difference in the electron velocity and the group velocity of the modes, the power associated with the modes (unshaded region in Fig. 2b, t > 60 fs) is easily separated from that associated with the electron beam (shaded region in Fig. 2b, t < 60 fs). Additionally, it is important to note that the total coupled power accounts for all velocity-matched photonic modes that are excited by the electron. In the inset of Fig. 2b, we include the Fourier transform of the power. The spectrum of the power shows four distinct peaks. Two peaks clearly correspond to the two modes illustrated in Fig. 1b; these peaks occur at $2f_1$ and $2f_2$. The other two peaks correspond to the mixing products of these two modes. Lastly, we should note that, interestingly, the energy coupled into the waveguide, as calculated via our time-domain simulation, does not agree with the expectations from conventional, frequency-domain approaches. Further modeling is required to explain this disagreement.

In summary, we have used time-domain PIC simulations to investigate the coupling between free electrons and waveguides. These studies are particularly interesting as they furnish information on higher-order mode and radiative coupling mechanisms.

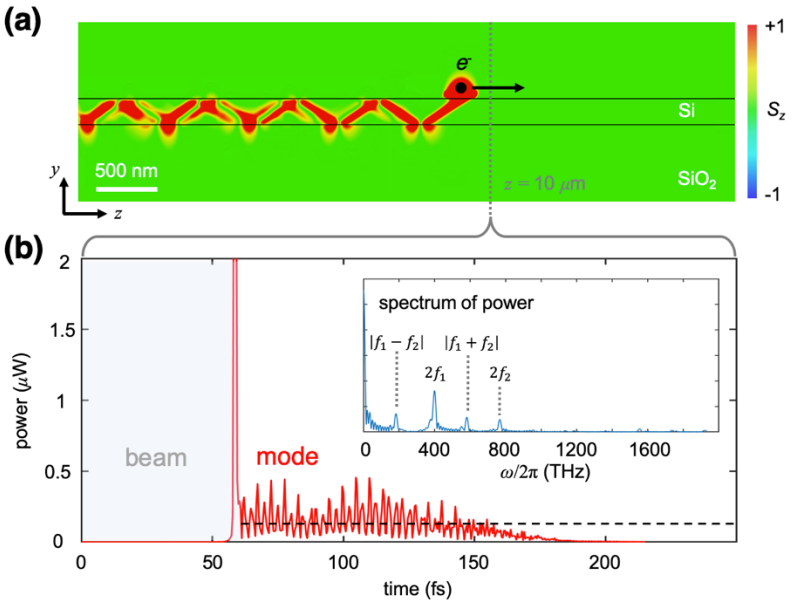

Figure 2: Time-domain PIC simulation results for the uniform waveguide. **(a)** Normalized instantaneous power density in the z-direction at the x = 0 plane (center of the waveguide). The electron is moving above the waveguide and the plot is at t = 56 fs. Electron velocity is equal to 0.58c. **(b)** Total power flow in the z-direction versus time. The Fourier transform (inset) is evaluated after excluding power associated only with the near field of the electron packet. The peaks at 400 THz ($2f_1$) and 768 THz ($2f_2$) confirm that the electron is coupling with the waveguide modes demonstrated in Fig. 1b.

References

[1] B. Barwick *et al.*, *Nature,* **462**, 902–906 (2009).
[2] A. Feist *et al., Science,* **377**, 777–780 (2022).
[3] G. Huang *et al., PRX Quantum,* **4**, 020351 (2023).
[4] D. Konakhovych *et al.,* arXiv:2105.07682 (2021).