Shaping Quantum Photonic States Using Free Electrons

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Abstract: We propose a new scheme for creating desired quantum photonic states using interactions of free electrons with optical cavities. We show how the choice of the initial electron state controls the resulting quantum light state. © 2021 The Author(s)

The ability to design and arbitrarily control quantum light sources has been a highly desirable (albeit hard to achieve) goal for many years, both at the level of a few photons and especially at the level of many photons. The realization of these non-trivial quantum states of light (e.g. Fock states, displaced Fock states, NOON states, and other entangled photon states) are inherently challenging. While entanglement can be realized with the use of optical nonlinearities, like in spontaneous parametric down conversion (SPDC), these techniques are limited to specific wavelengths, and even for those wavelengths, the relatively low efficiency of the nonlinear process limits the throughput of entangled pairs. A promising new direction for generation of quantum light can be found in the phenomenon of photon-induced nearfield electron microscopy (PINEM) [1]. In a PINEM interaction, a relativistic free electron passing through a sample interacts with a coherent optical field populated with many photons. Recent theoretical works generalized the PINEM theory to the domain of quantum optics – creating the quantum PINEM (QPINEM) theory [2-3]. These exciting prospects motivated a pursuit to increase the intrinsic electron–photon interaction strength by the design of specialized photonic structures and nanophotonic cavities [4-6]. Despite all this recent progress, the work on PINEM and QPINEM so far focused on manipulating the electron with light. The idea of instead manipulating the light with electrons has not been explored in theory or experiments.

Here we propose to use the electron–light interaction to purposefully control the quantum state of light. We present a framework for the creation of exotic photonic states, and show how the resulting light states depend on the coherent states of the electrons (illustrated in figure (1a)), which can be pre-shaped by PINEM interactions [4-5]. More specifically, we show how the electron interaction can generate photon-added states, Fock states, thermal states, displaced coherent states and displaced Fock states. For this purpose, we extend the current QPINEM theory [2-3] within a density matrix formalism, and present a robust scheme to handle multiple consecutive interactions of electrons with a common cavity mode. To precisely quantify the electron–photonic-cavity interaction in an arbitrary electromagnetic environment, we also employ the macroscopic quantum electrodynamic (MQED) [7-8] framework for the QPINEM interaction.

Figure 1: Creating photonic states of novel quantum statistics using free-electron–photon interactions. (a) Schematic for a realization of quantum photon-induced nearfield electron microscopy (QPINEM) interactions, which can be tested in an ultrafast electron microscope (UEM), resulting in (usually) entangled electron-photon states. The electron is measured by an electron energy loss spectrometer (EELS). Inset lists several photonic structures suitable for strong QPINEM interactions [4-6]. (b) Photoelectron probability map after a single QPINEM interaction, given an input coherent state $|\psi^0\rangle_p = |\alpha|^2 = 50$ and interaction strength $g_{Q\alpha} = 0.25i$ (intuitively, $g_{Q\alpha}$ is the coupling strength per one photon [2]). The stripes represent a post-selection process. (c) Fock state generation. Starting from an initially empty cavity, the process creates a target state of 100 photons using $g_{Q\alpha} = 1i$. (d) Thermal state generation over many interactions, given an initial state $|\psi^0\rangle_p = |\alpha|^2 = 10$ and $g_{Q\alpha} = 0.1i$. (e) Generation of displaced Fock states, given an input Fock state $|\psi^0\rangle_p = |N = 5\rangle$ and $g_{Q\alpha} = 0.5i$. 
In figures (1b) – (1e) we show four concrete results of QPINEM interactions leading to control over the quantum state of light. In figure (1b) we show the probability map of joint electron-photon energy states after an interaction. This is shown for a PINEM-like setup (a coherent state of light interacting with a monoenergetic free electron). The interaction moves the photon through the Fock ladder and the electron through an integer ladder of states with energies separated by $\hbar \omega$, with $\omega$ being the cavity frequency. The entanglement between the light and the electron is visibly shown, contrary to the conventional semiclassical PINEM theory, which always implies a separable product state. Let us now consider one procedure for controlling the output photonic state, which is post-selection. Upon post-selecting electrons of a given energy (which corresponds to horizontal linecuts of the probability map), the resulting light state is an infinite sum of photon-added coherent states.

In figure (1c), we demonstrate how measurement enables the generation of Fock states. It involves consecutive interactions of an empty cavity with free electrons. The photonic state after each electron measurement is a Fock state, and while this specific process is stochastic, we are guaranteed to reach our target Fock state given enough interactions. We can also produce photonic states without post-selection or measurement of the electron. For example, in figure (1d), we show the evolution of an initially coherent photonic distribution, after many interactions with free electrons, converging to a thermal distribution.

Lastly, in figure (1e) we demonstrate the generation of displaced Fock states, starting from a photonic Fock state (following our scheme for generating Fock states, for example). This interaction requires a unique electron quantum state - a “comb” electron, whose quantum state is (asymptotically) an equally distributed superposition of all possible energies in its ladder. An interaction with such an electron (or its approximation) implements a displacement operator $\hat{D}(\beta) \equiv \exp \left[ \beta a^\dagger - \beta^\ast a \right]$ on any photonic quantum state ($a, a^\dagger$ are the photonic annihilation and creation operators, respectively). Therefore, starting with a photonic Fock state, the interactions with comb electrons create a displaced Fock state.

To consider the experimental feasibility of the suggested schemes, we consider the cavity lifetime $\tau$ (the decay rate of the average number of photons in the cavity), and the rate of injection of electrons $\Delta t$ (proportional to the average current). Following a Lindblad master equation, we find that for a successful QPINEM experiment, the duration of the experiment needs to be much shorter than the loss time of the cavity. Mathematically, $\Delta t/\tau$ needs to be much smaller than unity, or the photonic state will decay and decohere. Recent PINEM works demonstrated free-electron interactions with cavities having a lifetime of up to 260/340 fs [4-5]. Our UTEM setup, and others, currently perform PINEM experiments with electron currents of less than 0.1 nA, which corresponds to $\Delta t > 1\text{ms}$. These values result in $\Delta t/\tau$ much greater than one, i.e., the photonic state in the cavity will decay before the next electron arrives. However, while designated experiments for our purpose of shaping the quantum statistics of light are still beyond immediate reach, there is significant progress in that direction in very recent experiments, and we are optimistic that a regime of sufficiently low loss and high interaction strength can be realized. Already along those lines, experiments with higher electron densities (up to thousands per pulse) have been shown, and higher electron numbers would become accessible with advances in photoemission physics and better tip designs. In addition, promising platforms for enhancing the electron–photon interaction strengths could combine recent experimental work of PINEM in photonic cavities [4-5], with PINEM in elongated structures for very strong phase-matched interactions [9-10].

To conclude, we have proposed a novel scheme for the generation of quantum photonic states of high-interest, using a setup already commonly used in electron microscopes – the interaction of free electrons with photonic cavities.

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