Toward Single Photon Detection using Nanophotonic Parametric Amplifiers

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Abstract: Ultra-intense parametric amplification can be used for amplifying single photons to macroscopic levels. We experimentally detected coherent states with $\langle N \rangle = 4.86$ with 17% efficiency and 2.5% dark count probability.

Detecting quantum states of light is necessary for applications such as quantum metrology [1], quantum state generation [2], and photonic quantum computation [3]. Using a lithium niobate (LN) nanophotonic optical parametric amplifier (OPA), we experimentally detected the presence of coherent states with average photon number $\langle N \rangle = 4.86$ and 1.72 with 17% and 5.2% efficiency, respectively, and 2.5% vacuum click chance (dark count probability) with an extended InGaAs photodetector, in shot-to-shot measurements at 250 MHz at room temperature and pressure. By showing how low-photon-number states can be amplified to classically detectable levels, this experiment indicates a path towards ultrafast detection of single photons based on intense parametric amplification.

The concept of the OPA-based detector is shown in Fig. 1a. The OPA amplifies the signal state through degenerate parametric down-conversion and amplifies the quadrature of the signal in phase with the pump while de-amplifying the other. The photocurrent detected after the signal is amplified by the OPA is proportional to the square of the quadrature in phase with the pump. In this way, the quantum state's in-phase quadrature is imprinted onto the macroscopic signal at the output, and the state can be interrogated with a variety of detectors which operate at macroscopic levels. For instance, the presence or absence of a quantum state, such as a single photon, could be probed by setting a threshold for the power seen at a classical photodiode.

The experimental setup is detailed in Fig. 1b. The OPA is a 5-mm long periodically poled thin-film LN waveguide on a chip [4], placed on a thermal controller for fine-tuning of phase matching. We used a Menlo Systems Orange A mode-locked laser generating 75-fs nearly transform-limited pulses at a 250-MHz repetition rate at 1 μm to pump both the OPA and the tabletop optical parametric oscillator (OPO) which provided the 2 μm signal. The signal states in the measurement were therefore coherent states. To determine the amplitude of the signal field inside the chip, we measured the output signal with the pump off using a superconducting nanowire single photon detector from ID Quantique optimized for 2 μm photons. The pump's off-chip average power was 145 mW for all measurements, which led to a measured gain of over 60 dB. Since coherent states are phase-sensitive, the amplified quadrature varies with the relative phase of the pump and signal. We modulated the phase with a piezoelectrically driven delay stage on the signal's path and locked it using an active feedback system. We used a variable attenuator to adjust the amplitude of the signal field. We measured the output signal by first rejecting the pump using a long-pass filter and then coupling it into a single-mode fiber connected to an extended InGaAs photodetector with a bandwidth of 18 GHz.

Nanophotonics is an ideal platform for realizing the amplification needed to detect a single photon with a macroscopic detector. The intense gain of our system is due to the high peak power density of the pulses of light

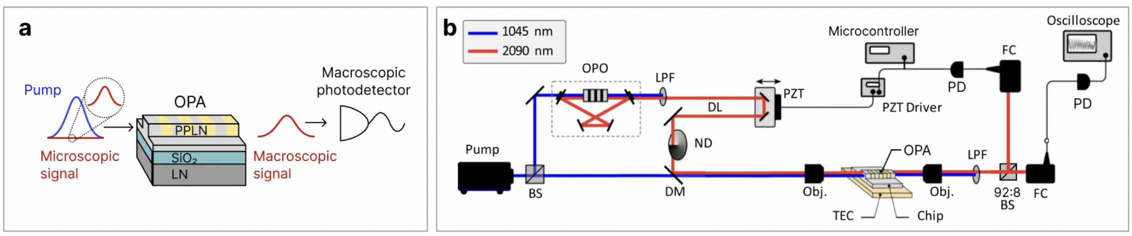

Fig. 1. (a) Simplified diagram of the detection scheme. The microscopic signal is intensely amplified by the nanophotonic OPA to macroscopic levels, at which point a variety of photodetectors may be used. PPLN, periodically poled LN. (b) Diagram of the setup used to amplify 2 μm low-photon number coherent states. BS, beam splitter; OPO, optical parametric oscillator; LPF, long-pass filter; DL, optical delay line; PZT, piezoelectric transducer; ND, variable neutral density filter; DM, dichroic mirror; Obj., reflective objective; TEC, thermoelectric cooling stage; FC, fiber coupler; PD, photodetector.

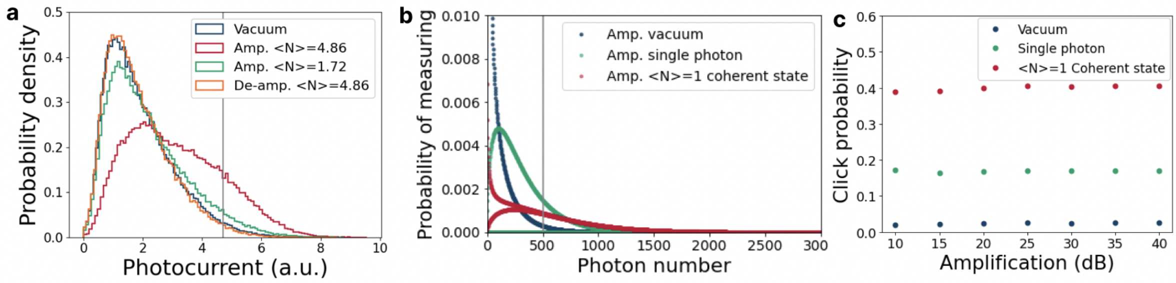

Fig. 2. (a) Photocurrent vs. probability density of amplified vacuum and amplified and de-amplified coherent states with $\langle N\rangle$=4.86 and 1.72. The photocurrent is proportional to the photon-number of the amplified state. Amp. stands for amplification of the coherent state, and De-amp. for de-amplification. The gray line denotes the threshold above which 2.5% of vacuum instances will result in a click. (b) Photon number distributions, from simulations, of amplified vacuum, single photon, and coherent state with $\langle N\rangle$=1. The gray line is the same as in (a). The amplification was 26 dB. (c) Plot of click probability vs. amplification for vacuum a click probability of 2.5%, calculated from simulations.

propagating in the dispersion engineered PPLN waveguide [4]. In addition, this detection scheme is not overly sensitive to output coupling losses and its speed is limited by the detector used outside of the chip, since there is no intrinsic dead time.

Measurement results from the experiment can be seen in Fig. 2a. The photocurrent is proportional to the square of the quadrature value being amplified and the photon number ($I \propto X_\phi^2 \propto N$) [5]. As expected, the distributions of amplified $\langle N\rangle = 1.72$ and 4.86 are distinct from each other and amplified vacuum. In addition, the de-amplified $\langle N\rangle = 4.86$ state distribution is almost identical to vacuum, indicating locking to deamplification of the coherent state. The photon number distributions, calculated using a quantum simulation Python library called QuTiP, for 26 dB of amplification, are shown in Fig. 2b.

To show an example of the system's ability to act as a click detector, we implement a threshold on the detector photocurrent which leads to a dark count probability of 2.5%, shown as a gray line in Figs. 2a and b. This threshold leads to a detection efficiency of coherent states with $\langle N\rangle = 4.86$ of 17% and of those with $\langle N\rangle = 1.72$ of 5.2% . Although we amplified and detected coherent states with a remarkable efficiency and dark count instead of single photons, our simulations show that the ability to detect low-photon-number coherent states is an indicator of the ability to detect single photons. As seen in Fig. 2b, both amplified coherent states and amplified single photons have distributions with higher photon numbers than amplified vacuum, with simulated detection efficiencies of 14% and 37% for single photons and $\langle N\rangle = 1$ coherent states, respectively, for a dark count probability of 2.5%. These efficiencies remain constant between 10 and 40 dB of OPA gain (the upper limit of our current computational abilities) as the threshold is adjusted to maintain a constant dark count rate, as shown in Fig. 2c, suggesting that even at our much higher gain levels, detecting a coherent state with high efficiency is indicative of the ability to detect single photons.

Our high-gain OPA-based photodetection system promises a path towards ultrafast room temperature on-chip single photon detectors. The detection of low-photon-number coherent states is a clear indicator of the ability to detect single photons, and we have achieved the detection of coherent states with a low dark count rate. Such a detector can be integrated in LN nanophotonic circuits, adding to the wealth of functionalities required for photonic quantum information processors. Our detection scheme could potentially be used for on-chip non-Gaussian quantum state engineering.

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