Generation of Non-Gaussian Quantum State in Telecommunication Band

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Abstract. We have implemented the non-Gaussian operation on the pulsed squeezed vacuum at telecommunication wavelengths. The non-Gaussian operation based on photon subtraction was carried out using a Titanium-based superconducting transition-edge-sensor that can resolve the photon number. We observed a dip in reconstructed Wigner functions of generated quantum states, which is the clear evidence that a non-Gaussian operation was realized.

Keywords: Non-Gaussian operation, pulsed squeezed light, telecomm-band, transition-edge-sensor, photon-number resolving detector.

1 Introduction

Non-Gaussian operation is one of the essential resources for continuous-variable based quantum information processing. It is well-known that we cannot realize entanglement distillation [1-3] and universal quantum computation without non-Gaussian operation [4]. In a practical application of quantum communication such as teleportation and dense cording, we must share highly entangled quantum states between distant parties using optical fibers. Because of unavoidable losses in a fiber, it is essential to distill the entangled states.

The conventional information theory gives transmission capacity bounds that depend on the number of channels and their noises [5]. These bounds are so-called "Shannon limit". However, quantum information theory allows us to overcome the Shannon limit and indicate novel bounds, "Holevo limit" [6, 7]. The implementation of ultimate-high-capacity optical communication which can reach the Holevo limit requires a quantum computation for coherent light pulses propagating in an optical fiber [8].

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Non-Gaussian operation can be realized by utilizing the third or higher order optical nonlinearity. However, the higher order optical nonlinearity in the existing materials is so small for a single-photon that it is difficult to use the nonlinearity in materials to implement quantum gates. Alternatively Gottesman et al., have proposed the cubic-phase gate that consists of Gaussian operations (e.g., the squeezer, the displacement operation and the homodyne detection) and the photon-number resolving detector (PNRD) [9]. The measurement-induced nonlinearity with the PNRD, which is effective as a non-Gaussian operation in the cubic-phase gate, because the rest of cubic-phase gate is substantially composed of Gaussian operations. Recently several experiments on the non-Gaussian operation have been demonstrated in the visible light region [10-12]. However, all of them have implemented non-Gaussian operations by using avalanche photodiodes instead of the PNRD. Using avalanche photodiodes, we cannot measure the number of photons and can only know the arrival of photons. They are inefficient in detecting two or more photons, because the corresponding number of detectors is necessary and each detector must catch only a single photon.

In this paper, we present an experimental demonstration of non-Gaussian operations at a telecommunication wavelength. Employing the PNRD based on a superconducting transition-edge-sensor (TES)[14, 15], the one- or two-photon-subtracted squeezed state at a telecommunication wavelength was generated. As mentioned above, the non-Gaussian operation with the PNRD at a telecommunication wavelength is one of the challenging tasks, and the experimental demonstration will lead to the practical application of the quantum information technologies to the conventional optical communication systems.

2 Experimental Setup

Schematic diagram of the experimental setup is shown in Fig. 1. The pulsed squeezed vacuum was generated by the spontaneous parametric downconversion (SPDC) process in a Type-0 periodically poled lithium niobate adhered-ridge-waveguide (PPLN-ARW) [15]. The Nearly Fourier-limited ∼5 ps laser pulse from

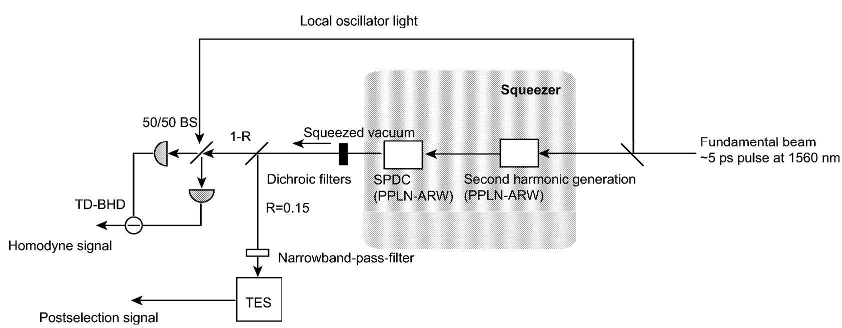

Fig. 1. Experimental setup

an Erbium-doped fiber laser was used as a primary source of the fundamental beam at 1560 nm. It is also used as the local oscillator light for the time-domain balanced homodyne detector (TD-BHD: the overall homodyne efficiency was ~ 0.3). The fraction ($R = 0.15$) of the squeezed vacuum beam was taken out from the homodyne detection mode. The subtracted photons (reflected beam) led to the Ti-TES after passing through the (single-mode) fiber based narrow band pass filter with a pass-band of 0.5 nm. The Ti-TES has a quantum efficiency of 65% and an energy resolution of 0.3 eV with which the Ti-TES can resolve the photon number at 1560 nm (0.8 eV) well. The dark count rate of the Ti-TES was $\sim$ 1000 cps when the discrimination level at a discriminator was set to the level for one-photon detection. To improve the signal-to-noise ratio, the 100 ns gate synchronized with the laser pulse was applied to the DSC. In this way, the dark count rate was decreased to 40 cps, corresponding to a dark count probability of 10^{-4} per 100 ns gate. As regards discrimination level for two-photons detection, a dark count probability was $< 10^{-5}$ per 100 ns gate. For every postselection signals from the Ti-TES, a digital oscilloscope registered homodyne signals. Such postselection procedure provides the non-Gaussian operation. In this experiment, the conditional homodyne detections were carried out in case of not only one-photon but also two-photon subtraction, since the Ti-TES can resolve the photon number. The data segment was stored one after another until the 4000 data segment filled up the oscilloscope's memory. The data acquisition time was $1 \sim 10$ seconds since the trigger photon detection rate was $0.4 \sim 5$ kHz, which depended on the threshold for the Ti-TES. The relative phase between the LO light and the measured beam was changed from 0 to π during the single data acquisition by the piezo transducer (PZT) located in 50/50 beamsplitter (BS). Since the interferometer in the setup was substantially stable during the data acquisition time, it is not stabilized actively. For each data segment, the quadrature amplitude was evaluated from a peak value of the homodyne signal and the time when the homodyne signal was registered, then the Wigner function was reconstructed from $\sim$ 10,000 of the quadrature amplitudes using the iterative maximum-likelihood estimation algorithm [16].

3 Experimental Results

Figure 2 shows experimental Wigner functions (left panel), their contour plots (middle panel), and the theoretical Wigner functions (right panel), when the initial quantum state was a -1.25 dB squeezed vacuum (anti-squeezed level was 4.1 dB). The experimental Wigner functions are not corrected for measurement imperfections, that is, the homodyne efficiency and dark counts of the detectors. Figure. 2(a) show a Wigner function of a measured quantum state when the threshold level was set to one-photon detection. We observed the dip in the center of the Wigner functions, which obviously indicates that the non-Gaussian operation was realized. Figure. 2(b) shows a Wigner function when the threshold level was set to two-photon detection. We observed the Wigner function that was clearly different from the case of one-photon detection as shown in figure.

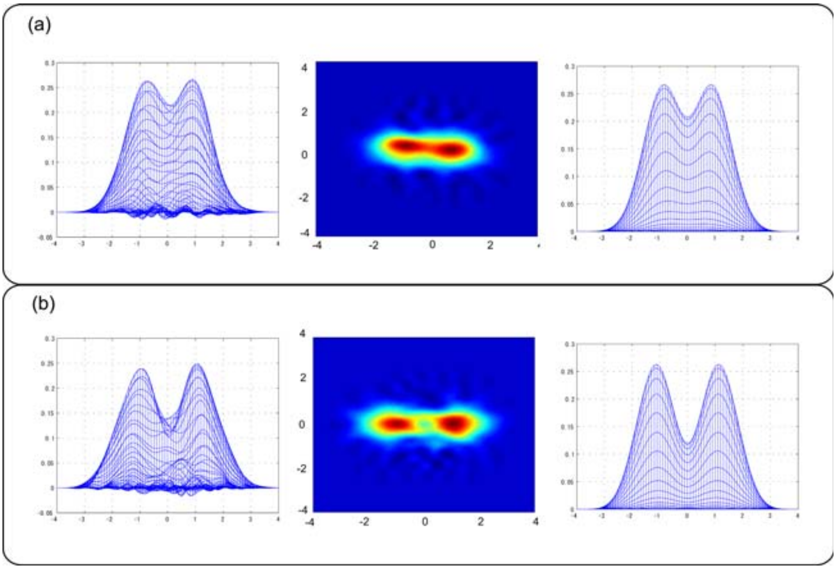

Fig. 2. Experimental results. (a) Wigner functions of one-photon-subtracted squeezed state. (b) Wigner functions of two-photon-subtracted squeezed state.

In our experiments, although we could demonstrate the presence of the dips into the measured Wigner functions, we could not observe the negative value in the measured Wigner functions. In general, the prepared state before the homodyne measurement can be evaluated by correcting the homodyne efficiency. We were not able to observe the negative value in Wigner functions even after the correction of the measurement imperfections. It turns out that the modal purity (the mode matching efficiency of the trigger photon against the mode of LO light for the homodyne measurement) was low to get the ideal Wigner function. We cannot observe the negative value with a modal purity of less than $\sim$0.7, even if the homodyne efficiency is perfect. If the modal purity is imperfect, a fraction of the trigger photons is out of the mode for the homodyne measurement. Such photons become noise photons that trigger the attenuated squeezed vacuum. Therefore, the fidelity of the generated photon-subtracted squeezed state is degraded. The right panels of Fig.2 (a) and (b) show the theoretical Wigner functions of one- and two-photon-subtracted squeezed states, respectively, taking a modal purity of 0.69, and other experimental conditions into account. The shapes of the experimental Wigner functions are in good agreement with these theoretical ones. According to the numerical result, the modal purity in this experiment is not perfect and the negative values can not be obtained in the corrected Wigner functions.

To improve the fidelity of the non-Gaussian operation, it is essential to improve the modal purity. Using a narrower band-pass-filter in front of the trigger detectors, the modal purity would be improved. In the condition, the trigger detection rate becomes lower. Therefore, the signal-to-noise ratio of the trigger detector must be improved to observe the negative value in the Wigner functions. In use of TES for the trigger detector at a telecommunication wavelength, the signal-to-noise ratio will be improved by reducing the noise counts mainly originating from the black body radiation in the fiber that guides the trigger photons to TES. To get a pure non-Gaussian state, the purity of initial squeezed state should be improved as well. Specifically, the homodyne efficiency and optical losses of setups must be improved.

4 Conclusion

In conclusion, we have demonstrated the non-Gaussian operation against a pulsed squeezed vacuum at a telecommunication wavelength using the photon-number-resolving detector based on the titanium transition-edge-sensor. Improving the imperfect modal purity and homodyne efficiency, the high-purity non-Gaussian operation will be realized, and eventually, it will contribute to progress of a squeezing enhancement and the entanglement purification for a quantum repeater of continuous-variable-based quantum key distribution system over optical fiber networks.

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