*Article*

# Transferring of Continuous Variable Squeezed States in 20 km Fiber

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**Featured Application: In order to construct a useful quantum internet network in continuous variable region, the long distance transferring of nonclassical state of light is essential. Fiber is the best media for the transmission of light, but the guided acoustic wave Brillouin scattering (GAWBS) effect in the fiber would inevitably destroy the nonclassical characteristics of squeezed state or entangled state. Here, we propose and realize a suitable time multiplexing method for the transferring and measurement of nonclassical states. The influence of GAWBS can be greatly reduced and the quantum characteristics can be retained as much as possible.**

**Abstract:** Transferring of a real quantum state in a long-distance channel is an important task in the development of quantum information networks. For greatly suppressing the relative phase fluctuations between the signal beam and the corresponding local oscillator beam, the usual method is to transfer them with time-division and polarization-division multiplexing through the same fiber. But the nonclassical states of light are very sensitive to the channel loss and extra noise, this multiplexing method must bring the extra loss to the quantum state, which may result in the vanishing of its quantum property. Here, we propose and realize a suitable time multiplexing method for the transferring and measurement of nonclassical states. Only the local oscillator beam is chopped into a sequence of light pulses and transmitted through fiber with continuous orthogonal-polarized signal beam. Finally, when the local oscillator pulses are properly time delayed compared to the signal beam, the quantum state can be measured in the time sequences without the influence of extra noise in the fiber. Our work provides a feasible scheme to transfer a quantum state in relative long distance and construct a practical quantum information network in metropolitan region.

**Keywords:** squeezed states of light; transferring; fiber channel

## 1. Introduction

Nonclassical states of light, which include the squeezed state of light and entangled state of light, play a pivotal role in research of quantum information and quantum communication [1–4]. The squeezed state of light, whose quantum fluctuation of one quadrature component is reduced to a level below quantum noise limit (QNL), is widely applied in quantum teleportation, quantum computing, quantum metrology, and so on [5–14]. With the development of quantum information research, the construction of a practical quantum information network has been an important goal in related fields [15–17]. With the help of a low-Earth orbit satellite "Micius", quantum teleportation in discrete variables has been realized in a more than 1000 kilometer distance [18]. On the other hand, it has been pointed out that the high-efficiency unconditional quantum information network at a

metropolitan scale can be designed and built in continuous variables (CV) region with deterministic entangled or squeezed states of light [19]. But the nonclassical states of light are very sensitive to the loss and extra noise in the channel, the most protocols in CV region are demonstrated in very short distance [6,20–22]. Therefore, an effective way for transferring a quantum state in a long-distance channel is necessary for the construction of CV quantum information network. Optical fiber and free space are two main quantum channels used for the exchange of long-distance quantum information [23–28]. Optical fiber is the more suitable channel for the transmission of quantum information due to its lower loss and higher reliability. Recently, CV quantum key distributions (QKD) in ten-kilometer order have been realized with a modulated coherent state by several groups [29–33].

In the optical fiber channel, not only the loss but also the spurious noise in the fiber have to be considered for the transmission of a quantum state. Balance homodyne detection (BHD) is the most common detection method for measuring a CV quantum state, where the relative phase between quantum state and the corresponding local oscillator (LO) beam must remain relatively stable. Hence simultaneous transmission of a signal beam and the corresponding LO beam through a same fiber with orthogonal polarization has been widely implemented in many experiments [14,27]. Nevertheless, there is always some excess noise loaded on the signal beam in the transmission process, and the main noise source in radio frequency is derived from guided acoustic wave Brillouin scattering (GAWBS) [34]. The stimulation of GAWBS noise is mainly due to the fluctuation of the density of optical fiber in time and space caused by the acoustic field, which results from the continuous thermal motion of the particles in the optical medium [34,35]. In order to eliminate the influence of GAWBS noise as much as possible, the continuous signal beam and the corresponding LO beam are usually chopped into pulsed light by an amplitude electric–optic modulator (AM) and transmitted with time- and polarization-division multiplexing in CV QKD experiments [31,36–38]. When the signal pulse and time-delayed LO pulse are not simultaneously transmitted in the fiber, the influence of GAWBS can be greatly removed. For example, in CV quantum teleportation, the entanglement state and the LO beam are continuously transmitted in the fiber channel, thus the communication distance is seriously influenced by the GAWBS noise [14].

The usual chopper tools for the light beam are AM and acousto–optic modulators (AOM). When the signal beam is transferred through an AM or AOM, the efficiency cannot reach 100%, which means that the quantum characteristics will be inevitably destroyed when the nonclassical state is the signal beam and is transferred with this method. Here we present a more practical protocol for the transferring of quantum state without introducing the extra loss and noise to the signal beam. Only the LO beam is shaped to a sequence of light pulses with AM and transmitted through the fiber with the continuously polarization-perpendicular signal beam. In the output port of the fiber, the signal beam and the LO beam are separated with a polarization beam splitter (PBS), then the LO beam is sent into a optical path delay (OPD) for realizing the proper delaying compared with the signal beam. When the LO beam and the signal beam are interfered in the BHD system, only the part of the signal beam without the influence of spurious GAWBS noise is directly measured. If quantum information is loaded into the part of signal beam without the influence of GAWBS, the information can be transferred with fidelity as high as possible in this condition.

## 2. Theoretical Analysis

When vacuum noise and excess noise produced by the effect of the depolarized GAWBS is considered, the output ($\hat{a}_{out}$) and input ($\hat{a}_{in}$) relation of optical mode transmitted in the fiber is given by [25,30]:

$$\hat{a}_{out} = \sqrt{\eta}\hat{a}_{in} + \sqrt{1-\eta}\hat{a}_v + \sqrt{\eta_2}\hat{a}_g, \tag{1}$$

where $\hat{a}_g$ is the mode of GAWBS extra noise, $\hat{a}_v$ is the mode of vacuum noise induced by the transmission loss. $\eta = \eta_1\eta_2$ is the total transmission efficiency in the fiber, which includes the coupling efficiency of fiber coupler ($\eta_1$) and the fiber transmission efficiency ($\eta_2 = 10^{-al}$), $a$ denotes the transmission loss in fiber per kilometer (0.36 dB/km @ 1342 nm) and $l$ denotes the transmission

distance. The noise variances of quadrature amplitude ($\hat{x}_{a_{out}} = \hat{a}_{out} + \hat{a}_{out}^+$) and quadrature phase [$\hat{p}_{a_{out}} = (\hat{a}_{out} - \hat{a}_{out}^+)/i$] of the mode $\hat{a}_{out}$ over the fiber channel can be given by[25]:

$$
\begin{aligned}
\Delta^2 \hat{x}_{a_{out}} &= \eta \Delta^2 \hat{x}_{a_{in}} + 1 - \eta + \eta \varepsilon l I_{LO},\\
\Delta^2 \hat{p}_{a_{out}} &= \eta \Delta^2 \hat{p}_{a_{in}} + 1 - \eta + \eta \varepsilon l I_{LO},
\end{aligned}
\tag{2}
$$

where $\varepsilon l I_{LO}$ is the excess noise induced to the signal beam by the GAWBS processing on $\hat{a}_g$, $\varepsilon$ is the noise coefficient of GABWS in the fiber, $I_{LO}$ is the power of the corresponding LO beam before the fiber coupler. When the signal beam is a coherent state, i.e., $\Delta^2 \hat{x}_{a_{in}^C} = \Delta^2 \hat{p}_{a_{in}^C} = 1$, the variances of both two quadratures of the output state are the same:

$$
\Delta^2 \hat{x}_{a_{out}^C} = \Delta^2 \hat{p}_{a_{out}^C} = 1 + \eta \varepsilon l I_{LO}.
\tag{3}
$$

When the signal beam is changed to a quadrature amplitude squeezed state, i.e., the noise variance of quadrature amplitude is below the corresponding QNL. Here, we suppose that $\Delta^2 \hat{x}_{a_{in}^S} = e^{-2r}$ and $\Delta^2 \hat{p}_{a_{in}^S} = e^{2r}$, where $r$ is the squeezing factor. The variances of the output state from the fiber become:

$$
\begin{aligned}
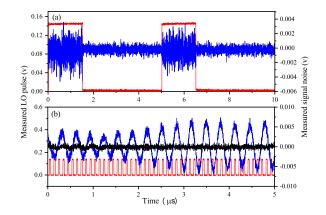\Delta^2 \hat{x}_{a_{out}^S} &= \eta e^{-2r} + 1 - \eta + \eta \varepsilon l I_{LO},\\
\Delta^2 \hat{p}_{a_{out}^S} &= \eta e^{2r} + 1 - \eta + \eta \varepsilon l I_{LO}.
\end{aligned}
\tag{4}
$$

It is obvious that the squeezing property can be greatly influenced in this processing. In some situation, the squeezing even can vanish due to the existance of GAWBS extra noise.

In the usual transmission processing through single-mode fiber, the signal beam and the corresponding LO beam are sent to the fiber with orthogonal polarization [24,25,28,38]. The LO beam stimulates additional noise on the polarization of the signal beam due to GAWBS when the LO beam and the signal beam are simultaneously transmitted. But if the LO beam is chopped to the periodic pulsed beam, the spurious GAWBS extra noise loaded on the signal beam only appears when the LO beam exists in the fiber, i.e., the noise of the signal beam in the time interval without the existing of LO beam maintain a normal level without the influence of GAWBS. In this condition, if the LO beam pulse sequence is properly time-delayed, it could overlap with the signal beam without the GAWBS extra noise. When these two light beams are injected into the BHD system, the noise of the pure signal beam without the influence of GAWBS can be measured. At the same time, the part of the signal beam with GAWBS extra noise is not measured because there is no LO beam when it is incident on the photodiodes of BHD system.

There are two schemes to choose for measuring the noise of quantum state with pulsed LO beam as shown in Figures 1a,b. Figure 1a shows the amplitude noise at 3.0 MHz analysis frequency of a coherent state when the LO pulse repetition rate is 200 kHz, where the red trace denotes the sequence of LO beam and the blue trace is the measured quadrature amplitude noise, which means that the pulse time is longer than the handling time for analysing at a certain frequency. When the LO beam is on for the first 1.5 μs in each period, the output of the BHD system can obtain the quadrature amplitude noise of the signal beam. When the LO beam is off for the last 3.5 μs in each period, the output of the BHD system is the corresponding electronic noise. This scheme is more efficient for the noise measurement at higher analysis frequency because the noise analyzing can be performed in each time sequence. Another scheme in Figure 1b shows the amplitude noise at 3.0 MHz of a coherent state when the LO pulse repetition rate is 10 MHz, which means that the pulse time is shorter than the handling time for certain frequency, which has a relatively short delay time for the LO pulse in the implementation of the experiment. The red trace denotes the sequence of the LO beam and the black trace is the corresponding electronic noise of the BHD. In this condition, the output of the BHD has to be filtered with a bandpass filter with central frequency of 3.0 MHz and bandwidth of 100 kHz

to obtain the quadrature noise at 3.0 MHz analysis frequency of the signal beam. In each scheme, the measured noise variance of the signal beam is not influenced by the GAWBS extra noise, thus the last terms of Equations (2)–(4) relative to GABWS noise can be ignored and the distance of the transferring quantum state can be markedly prolonged.
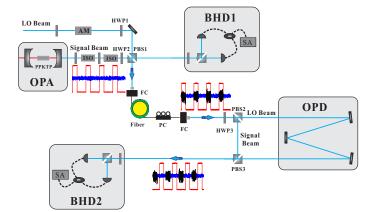


**Figure 1.** The schemes for measuring the noise of quantum state with pulsed local oscillator (LO) beam. (**a**) the pulse time is longer than the handling time. (**b**) The pulse time is shorter than the handling time. The red trace is the LO pulse sequence; the blue trace is the measured noise; and the black trace corresponds the electronic noise of detector.
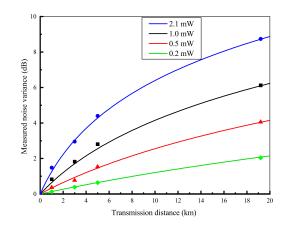
## 3. Experimental Setup and Results

Experimental setup for the generation and transferring of squeezed state of light is shown in Figure 2. An optical parametric amplifier (OPA) [39], which contained a pair of concave mirrors and a type-0 quasi-phase-matched periodically poled KTiOPO$_4$ (PPKTP) crystals with dimensions of $1 \times 2 \times 12$ mm$^3$, was used to generate the squeezed state of light at wavelength of 1342 nm pumped by a Nd:YVO$_4$ all-solid-state laser [40]. The diameters of both concave mirrors was 10 mm and the curvature radii were 50 mm. The input mirror was coated with high reflection at 1342 nm and transmission T = 20% at 671 nm, and the output mirror was coated with transmission T = 10% at 1342 nm and high reflection at 671 nm. When the OPA worked under deamplification conditions, i.e., the relative phase between the pump beam and the seeded signal beam is maintained at $\pi + 2k\pi$ ($k$ is an integer), amplitude squeezed state of light was generated. Because the backscattering noise from fiber can be coupled to OPA and affect its stability, two isolators (ISO) with a total loss of 10% were placed in the path of the output beam of the OPA. The LO beam which came from pump laser was chopped to a sequence of light pulses with repetition frequency of 10 MHz and duty ratio of 30%. Then, the continuous squeezed state of light and the pulsed LO beam were coupled on PBS1. By rotating half wavelength plates (HWP1 and HWP2) in each light path, we can control the paths of the signal beam and the LO beam which are sent to optical fiber for transmission or BHD1 for the measurement of squeezing. When the signal beam and the LO beam were all coupled to the BHD1, the squeezing properties of the output beam from OPA can be easily measured, which was $4.04 \pm 0.16$ dB below corresponding QNL. If two ISOs with the transmission efficiency of 90% was removed, the measured squeezing from the OPA was $5.08 \pm 0.16$ dB below corresponding QNL. On the output port of the fiber, the signal beam and the LO beam were separated by an adjusting polarization controller (PC) [41], HWP3 and PBS2. If the two beams were directly sent to the BHD2 for the measurement of noise, the squeezing may be deposited in the extra noise. In order to measure the part of the signal beam without the influence of GAWBS extra noise, the pulsed LO beam is delayed in a 15 m free space OPD. After the delay processing, when the signal beam coincided with the LO beam again after PBS3, only the pure squeezed state of light was coincident with the LO beam. Obviously, the quantum state measured by BHD2 is indeed squeezing of the generated state from the OPA. In the experiment, the mode matching between the continuous signal beam and the LO

beam was optimized through lenses in the light path, firstly. Then, the mode matching between can be maintained when the LO beam was chopped. Thus our proposal had no influence in the fidelity between the input and output signal beam, and can reduce the influence in the loss of extra devices added in the light path of the signal beam.
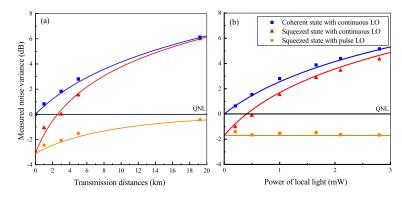


**Figure 2.** Schematic diagram of the experimental device. OPA: optical parametric amplifier. PPKTP: periodically poled KTiOPO$_4$. AM: amplitude modulator. HWP1-3: half wavelength plate. ISO: isolator. FC: fiber coupler. PC: polarization controller. OPD: optical path delay of the LO beam. BHD1–2: balanced homodyne detection. BHD1 was used to measure the noise variance of the quantum state before the fiber. BHD2 was used to measure the noise variance of the quantum state output from the fiber.

As is well known, the noise coefficient $\varepsilon$ of GABWS in the fiber was dependent on the analysis frequency [34,35]. In order to quantitatively evaluate the influence of GAWBS on the quantum state, the exact value of $\varepsilon$ should be known. The continuous LO beam was used to measure the noise variance of a coherent state, and the dependence of measured extra noise of the output state at usual analysis frequency range (1.0 MHz to 6.0 MHz) on the transmission distance of fiber is given in Figure 3. The green rhombuses, red triangles, black rectangles, and blue dots correspond to measured noise variance of a coherent state when the powers of LO beam in BHD2 are 0.2 mW, 0.5 mW, 1.0 mW and 2.1 mW, respectively. The traces in each color are the fitting results with the corresponding experimental data and these results showed that $\varepsilon = 0.16 \ \mathrm{m^{-1} \cdot W^{-1}}$ at this frequency range according to the Equation (3).



**Figure 3.** The dependence of the measured noise variance of a coherent state on the transmission distance in the fiber. The green, red, black, and blue traces correspond to the powers of LO beam in BHD2 of 0.2 mW, 0.5 mW, 1.0 mW and 2.1 mW, respectively.

In order to know the influence of GAWBS on the transmission of nonclassical state, the dependencies of measured noise variance of the signal beam with on the transmission distance are given in Figure 4a. The red and blue traces correspond to the measured noise variances of squeezed state and coherent state with a continuous LO beam, respectively. Here, the power of LO beam in BHD2 is kept at 1.0 mW. When the transmitted state was a −4.0 dB squeezed state, the calculated result shows that the squeezing vanished when the transmission distance was about 2.6 km. Thus the continuous LO beam must be changed to pulsed LO beam to eliminate the influence of GAWBS as the previous theoretical analysis. The second scheme as shown in Figure 1b was chosen in our experiment. The calculated result, which is given as the orange trace in Figure 4, shows that the squeezing property can be kept even when the transmission distance is very long. The dot, triangle and square are the corresponding measured results with different transmission distances. When the transmission distance was 19.2 km and the total transmission efficiency $\eta$ was 18%, the measured noise variance of squeezed state was still 0.42 dB below the corresponding QNL. The result shows that the transmission distances can be greatly improved if the pulsed LO beam is used in the BHD system.



**Figure 4.** The dependence of measured noise variances of the signal beam on the transmission distance (**a**) and the power of the LO beam in BHD2 (**b**) in the fiber. The square is the result when LO beam was continuous and the signal beam was a coherence state. The triangle is the result when LO beam was continuous and the signal beam is a quadrature amplitude squeezed state. The dot is the result when the LO beam was pulsed and the signal beam is squeezed state. The solid traces are the corresponding calculation results, which was in good agreement with the experimental data.

In order to verify the feasibility of our protocol, the dependence of the noise variances of coherent state and squeezed state on the different power of LO beams in BHD2 are given in Figure 4b when the fiber length was 5.0 km. It is obvious that when the LO beam was pulsed, the squeezing level of the transferred squeezed state still remained at −1.6 dB, which indicates that the influence of GAWBS noise can be completely eliminated with this transmission scheme. At this time, the transferring of the signal beam is only affected by the transmission loss in the fiber.

## 4. Results

In a summary, the transferring distance of the quantum state in the fiber can decide the range of constructed quantum information network with a nonclassical state. GAWBS extra noise in the fiber can destroy the quantum property of the entangled state or the squeezed state with the increasing of length of the fiber. With the transferring scheme we proposed, only the LO beam was shaped to a sequence of light pulses and transferred, the quantum property of nonclassical state can be totally reserved. Compared with our previous experiment, the transferring distance of nonclassical state has been enhanced to 20 km, the decreasing of squeezing degree was only caused by the transmission loss in the fiber. Thus the construction of a practical quantum network at the metropolitan scale is possible with this scheme [19].

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