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Disappearance and revival of squeezing in quantum communication with squeezed state over a noisy channel

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Squeezed state can increase the signal-to-noise ratio in quantum communication and quantum measurement. However, losses and noises existing in real communication channels will reduce or even totally destroy the squeezing. The phenomenon of disappearance of the squeezing will result in the failure of quantum communication. In this letter, we present the experimental demonstrations on the disappearance and revival of the squeezing in quantum communication with squeezed state. The experimental results show that the squeezed light is robust (squeezing never disappears) in a pure lossy but noiseless channel. While in a noisy channel, the excess noise will lead to the disappearance of the squeezing, and the squeezing can be revived by the use of a correlated noisy channel (non-Markovian environment). The channel capacity of quantum communication is increased after the squeezing is revived. The presented results provide useful technical references for quantum communication with squeezed light. *© 2016 AIP Publishing LLC.*
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Squeezed state of light has wide applications in quantum information and quantum metrology.[1,2] For example, it has been used in quantum communication,[3,4] quantum key distribution (QKD),[5–8] preparation of entangled state,[9–11] detection of gravitational waves,[12–14] measurements of small displacement[15,16] and transmittivity of optical samples,[17] and optical phase estimation.[18,19] There are several methods to generate squeezed state, such as four-wave mixing,[20,21] optical parametric amplifier,[22–26] atomic ensembles,[27] and waveguide.[28–30]

Since the noise of squeezed light is lower than the shot-noise-level (SNL), i.e., the noise of the coherent light, squeezed optical light can be used to increase the signal-to-noise ratio in quantum communication. However, the unavoidable losses and noises in quantum channels will lead to decoherence of the squeezed light. The behavior of squeezed state in a pure lossy channel was studied for the measurement of transmittivity of optical samples, in which the dependence of photon numbers on channel loss was theoretically and experimentally analyzed.[17] The features of squeezed state and two-mode entangled state in noisy channel with the Markovian[31] and non-Markovian environments[32,33] have been investigated theoretically. For a QKD scheme with squeezed state, the decoherence is a main factor that limits the secret key rate and transmission distance of QKD.[34] In quantum communication, the decoherence can lead to the disappearance of the squeezing and the failure of the communication. Thus, it is necessary to investigate the physical conditions of reducing and destroying of squeezing in quantum channels and to explore the feasible schemes of reviving the squeezing after it disappears.

Generally, there are two types of quantum channels, the lossy channel and the noisy channel. In a lossy but noiseless quantum channel, the noise induced by loss is nothing but the vacuum noise (corresponding to a zero-temperature environment).[34] In a noisy channel, the noise induced by loss is higher than the vacuum noise, which is called excess noise.[34] In this letter, we experimentally study the transmission features of an amplitude-squeezed state in a lossy and a noisy channel, respectively. In a lossy channel, the squeezing never disappears totally but gradually decreases. While in a noisy channel, the disappearance of the squeezing is observed. It has been shown that the noise in today's communication system exhibits correlations in time and space, thus it will be relevant to consider channels with a correlated noise (non-Markovian environment).[35–37] For example, a correlated noisy channel has been used to complete Gaussian error correction.[37] By applying an ancillary optical beam and establishing a correlated noisy channel, we successfully revive the squeezing after it has disappeared in a noisy quantum communication channel. We also implement the quantum communication with modulated squeezed state over a noisy channel in two cases, before and after squeezing is revived, respectively.

Figure 1 shows the schematic of our experimental setup. A continuous wave intracavity frequency-doubled and frequency-stabilized Nd:YAP/LBO (Nd-doped $YAlO_3$ perorskite/lithium triborate) laser produces the laser beams at both wavelengths of 540 nm and 1080 nm, which are used as the pump and seed beams of a nondegenerate optical parametric amplifier (NOPA), respectively. Two mode cleaners, MC1 and MC2, are inserted between the laser and the NOPA to filter noise and higher order spatial modes of the laser beams at 540 nm and 1080 nm, respectively. The NOPA consists of an α-cut type-II KTP crystal and a concave mirror. The front face of the KTP is coated to be used as the input coupler, and

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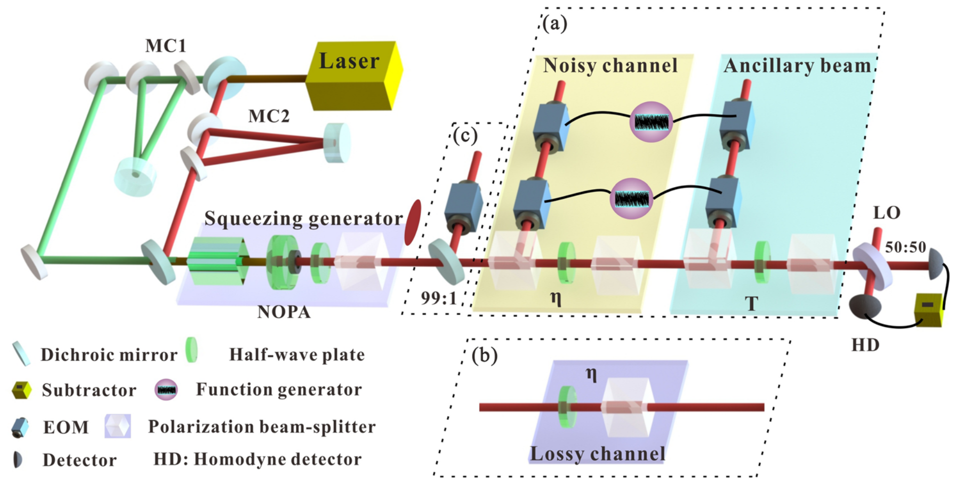

FIG. 1. Schematic of experimental setup. An amplitude-squeezed state is distributed over a noisy (a) and lossy (b) channel. The part (c) shows the modulation of the Gaussian signal on the squeezed state. LO: the local oscillator for homodyne detector.

the concave mirror serves as the output coupler of the squeezed states. The transmittances of the input coupler at 540 nm and 1080 nm are 99.8% and 0.04%, respectively. The transmittances of the output coupler at 540 nm and 1080 nm are 0.5% and 5.2%, respectively. The NOPA is operated at deamplification condition, which corresponds to lock the relative phase between the pump laser and the injected signal to $(2n+1)\pi$ (n is the integer). An amplitude-squeezed state and a phase-squeezed state in two orthogonal polarizations are simultaneously produced by the NOPA, and then, they are separated by a half-wave plate and a polarization beam-splitter (PBS). The amplitude-squeezed state with -3.5 dB squeezing and 8.5 dB anti-squeezing at sideband frequency of 2 MHz is used as the resource state to implement the quantum communication.

The squeezed state is transmitted in noisy and lossy channels, respectively. A noisy channel with channel efficiency η is mimicked by adding a Gaussian noise on a coherent beam through electro-optic modulators (EOMs) and coupling it with the transmitted mode on a beam-splitter (composed of a PBS, a half-wave plate and another PBS) as shown in Fig. 1(a). The lossy but noiseless quantum channel is mimicked by a beam-splitter as show in Fig. 1(b). The optical mode transmitted over the noisy channel is written as

$$\hat{a}' = \sqrt{\eta}\hat{a} + \sqrt{(1-\eta)g_a}\hat{N}_c + \sqrt{1-\eta}\hat{v}, \tag{1}$$

where $\hat{v}$ is the vacuum noise, $\hat{N}_c$ and g_a represent the Gaussian noise in the channel and the magnitude of noise, respectively. When the variance of the noise equals to zero, it corresponds to the transmission in a lossy but noiseless channel. The excess noise in the environment will lead to the disappearance of the squeezing of the transmitted mode. To revive the squeezing, an ancillary beam ($\hat{b}_{an}$) with correlated noise and a beam-splitter with the transmission coefficient T are applied. The ancillary beam carrying correlated noise is expressed by $\hat{b}'_{an} = \hat{b}_{an} + \sqrt{g_b}\hat{N}_c$, where g_b describes the magnitude of the correlated noise, which is assumed to be controllable. By sharing the correlated noise on the signal and ancillary optical beams, the correlation between the quantum system and environment is established. In this way, a non-Markovian environment is applied.

The transmitted and reflected modes from the revival beam-splitter are $\hat{a}_{out} = (\sqrt{(1-\eta)g_aT} - \sqrt{(1-T)g_b})\hat{N}_c + \sqrt{\eta T}\hat{a} + \sqrt{(1-\eta)T}\hat{v} - \sqrt{1-T}\hat{b}_{an}$, and $\hat{c} = (\sqrt{(1-\eta)(1-T)g_a} + \sqrt{Tg_b})\hat{N}_c + \sqrt{\eta(1-T)}\hat{a} + \sqrt{(1-\eta)(1-T)}\hat{v} + \sqrt{T}\hat{b}_{an}$, respectively. If choosing the parameters g_b and T to satisfy the following formula

$$\frac{g_a}{g_b} = \frac{1-T}{T(1-\eta)}, \tag{2}$$

the expression of $\hat{a}_{out}$ becomes

$$\hat{a}_{out} = \sqrt{\eta T}\hat{a} + \sqrt{(1-\eta)T}\hat{v} - \sqrt{1-T}\hat{b}_{an}. \tag{3}$$

It is obvious that the excess noise on the transmitted mode of the revival beam-splitter $\hat{a}_{out}$ is removed totally, and all excess noises are transferred to the unused reflected mode $\hat{c}$. In this case, the squeezing is revived. Finally, the output state is measured by a homodyne detection system. The output optical beam and the local oscillator are combined on a beam-splitter with 50% reflectivity. The output modes of the beam-splitter are detected by two photodetectors, and then, the photocurrents of two photodetectors are subtracted and amplified. The fluctuation variances of the amplitude and phase quadratures of output squeezed state are measured, when the relative phases between the measured optical field and the local oscillator are fixed to 0° and 90°, respectively.

Figure 2(a) shows the transmission of a squeezed state over a lossy channel. It is obvious that the squeezed (black line) and anti-squeezed (blue line) noises trend to the SNL along with the decreasing of the transmission efficiency of quantum channel. The squeezed noise is always below the shot-noise-limit (red line), until the transmission efficiency of the channel reaches to zero. Thus, the squeezed light is robust in a pure lossy quantum channel.

In Fig. 2(b), when the squeezed state is transmitted over a noisy channel (the variance of the noise is five times of the vacuum noise), the squeezing still exists when $0.9 < \eta \leq 1$, while it disappears when $\eta \leq 0.9$ (dash lines), which means that the excess noise in such a channel will destroy squeezing. To revive the destroyed squeezing, we perform the revival

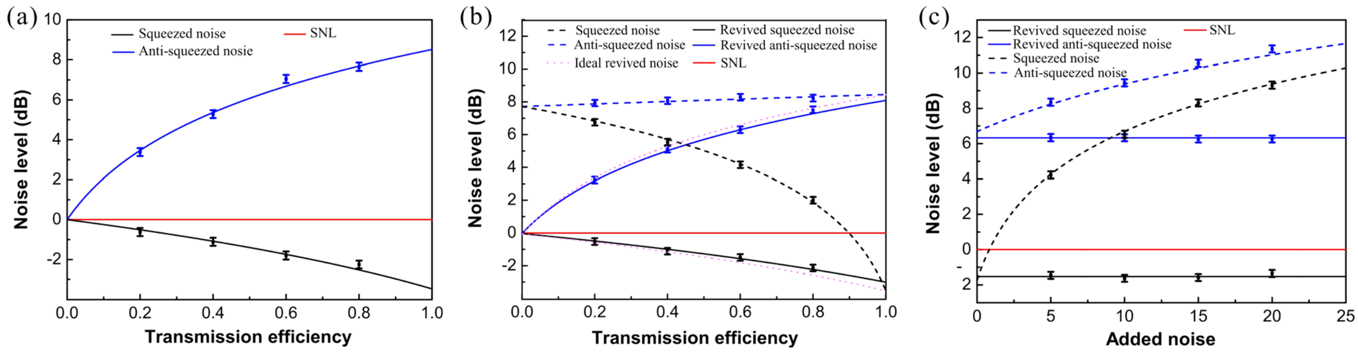

FIG. 2. Noise levels of a squeezed light transmitted in different quantum channels. (a) and (b) are the noise levels of a squeezed state in a lossy and noisy channel, respectively. (c) shows the transmission of a squeezed state with different excess noise in a noisy channel with $\eta = 0.6$. Error bars represent $\pm$ 1 standard deviation and are obtained based on the statistics of the measured noise variances.

operation. Two parameters, g_b and T, are adjustable in the revival procedure. For different channel efficiencies, we may fix one of them and adjust the other one to revive the squeezing according to Equation (2). Generally, T cannot be taken too small because it corresponds to add a linear loss on the transmitted optical mode, which will degrade the squeezing. In the experiment, we fix $T = 90\%$ and adjust g_b to revive the squeezing. The parameters g_a/g_b are chosen to be 0.14, 0.18, 0.28, and 0.56 for channel efficiencies of 0.2, 0.4, 0.6, and 0.8, respectively. The squeezing is revived after the revival operation is implemented, and the results are shown by the solid lines in Fig. 2(b), which are quite close to the case of transmitting the squeezed state in a lossy channel (dot lines). Thus, we say, that the excess noise in the noisy channel has been compensated by the revival operation. The small differences between the solid lines and dot lines derive from the loss introduced by the revival beam-splitter.

The dependence of squeezing on the excess noise is shown in Fig. 2(c). We can see that the boundary of disappearance of squeezing depends on the excess noise, when the variance of the excess noise is higher than 0.83, the squeezing disappears at the transmission efficiency $\eta = 0.6$ (dash lines). The corresponding experimental parameters in revival operation are $T = 90\%$ and $g_a/g_b = 0.28$, respectively. After the revival operation, the squeezing is revived (solid lines) and it is independent of the excess noise as indicated by Equation (3).

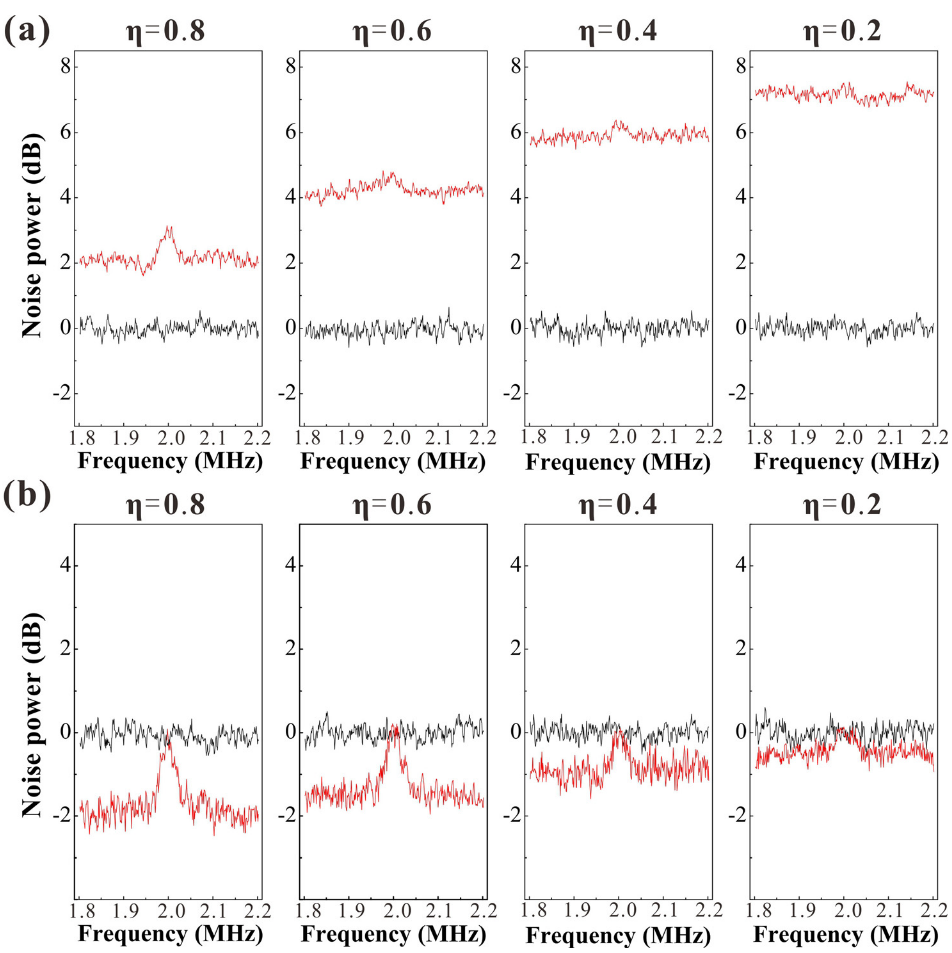

FIG. 3. Noise power spectrum of amplitude quadrature of the optical mode carrying the signal in frequency domain. (a) The squeezed optical mode with a modulated signal transmitted in a noisy channel. (b) The mode after the revival operation. The black and red lines are the SNL and measured noise power spectrum of amplitude quadrature, respectively.

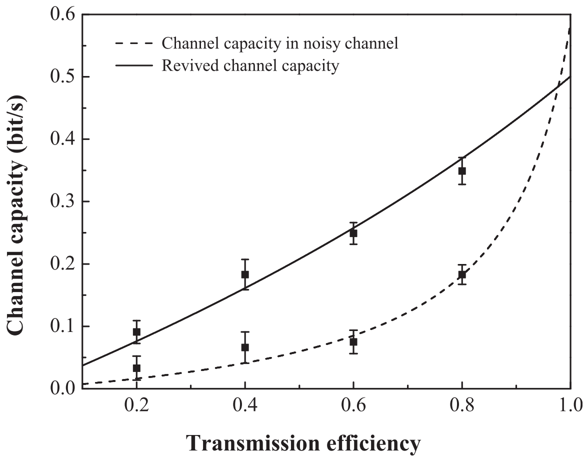

FIG. 4. Channel capacity of quantum communication with the squeezed state. The data are calculated with the measured results shown in Fig. 3.

We also use the squeezed state of light as a carrier to transmit information in a noisy channel. The signal is modulated first on a coherent beam by an amplitude EOM, and then, the modulated beam is coupled with the squeezed state of light on a beam-splitter with a transmittance of 99% [as shown by part (c) in Fig. 1]. The optical mode carrying the signal transmitted over the noisy channel is expressed by

$$\hat{a}'_s = \sqrt{\eta}\hat{a} + \sqrt{\eta}\hat{s} + \sqrt{(1-\eta)g_a}\hat{N}_c + \sqrt{1-\eta}\hat{v}, \quad (4)$$

where $\hat{s}$ is the Gaussian signal operating at the bandwidth of 2 MHz.

Figure 3 shows the noise power spectrum of quadrature amplitude of the transmitted optical mode with a modulated signal in frequency domain, and the signal decreases along with the reduction of the transmission efficiency and, finally, is immerged in the large background noise as shown in Fig. 3(a). Fig. 3(b) shows the noise power spectrum of quadrature amplitude after the revival operation is implemented, in which the noises are compensated, the signal becomes higher than the noise background, and thus, the signal-to-noise ratio is improved.

The channel capacity of quantum communication is expressed by[38]

$$C = \frac{1}{2}\log_2\left[1 + \frac{V_s}{V_N}\right], \quad (5)$$

in which V_s and V_N are the variance of Gaussian signal and noise, respectively. The channel capacities over a noisy channel without and with the revival operation are shown in Fig. 4 by the dash and solid line, respectively. It is obvious that the channel capacity is improved after the revival operation.

In summary, we experimentally studied the quantum communication using the squeezed state of light in two types of channels. In a pure lossy channel, the squeezing is robust, and in a noisy channel, the disappearance of squeezing is observed. By applying a correlated noisy (non-Markovian) environment, the squeezing can be revived. Our investigation provides concrete references for implementing the quantum communication with the squeezed light.

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