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Distribution of polarization squeezed light through a 20 km fiber channel

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Polarization squeezed light plays a key role in quantum memory by transferring quantum information between atoms and photons [1], and has potential applications in quantum precision measurement [2]. For polarization squeezed light, the quantum variance of at least one Stokes operator is smaller than that of the coherent state. Compared with the quadrature squeezed state, polarization squeezed light has the following advantages: one is that it is a bright beam, and the other is that it can be measured directly without using a local oscillator.

In terms of the application, it is essential to distribute the quantum resource through quantum channels to achieve quantum-enhanced information processing. The squeezed light has been transmitted over a 40 km fiber [3], and furthermore, the polarization squeezed light has been distributed through an atmospheric channel 1.6 km in length [4]. However, the distribution of polarization squeezed light through a fiber channel has not been reported on previously, and the evaluation of polarization squeezing in a fiber channel is unclear.

In this study, we prepare a polarization squeezed light at a telecommunication wavelength of 1550 nm and distribute the prepared polarization squeezed light through a 20 km fiber channel. By measuring the quantum variances of three Stokes operators of the output state, we demonstrate that the squeezing of the Stokes operator $\hat{S}_3$ and the antisqueezing of $\hat{S}_2$ decreases, while the variance of $\hat{S}_1$ increases, concomitant with the increase in the fiber length. The result thereby provides a significant reference point for future practical applications of polarization squeezed light.

As shown in Figure 1(a), the polarization quantum state of light can be characterized by four Stokes operators on a Poincaré sphere, where $\hat{S}_0$ represents the intensity of the light field, $\hat{S}_1$, $\hat{S}_2$, and $\hat{S}_3$ are horizontal, linear at 45°, and right-circular polarizations, respectively. When the polarization squeezed light is distributed through a fiber channel, the inevitable loss and noise in the fiber channel lead to its decoherence. Following distribution through a fiber channel with the attenuation of α, the output mode is then described by $\hat{O}' = \sqrt{\eta}\hat{O} + \sqrt{1-\eta}(\hat{\nu} + \hat{w})$, where $\eta = \eta_1 \times \eta_2$ is the total efficiency, including the transmission efficiency of $\eta_1 = 10^{-\alpha L/10}$ in the fiber channel with L kilometer and the fiber coupling efficiency of $\eta_2 = 94\%$, $\hat{\nu}$ and $\hat{w}$ represent a vacuum mode introduced by loss in the quantum channel and excess noise, respectively. The theoretical predicted quantum variances of the Stokes operators after the transmission can be found in Appendix A.

As is shown in Figure 1(b), an optical parametric amplifier (OPA) cavity is a semimonolithic structure, which consists of a 10 mm type 0 periodical poled potassium titanyl phosphate (PPKTP) crystal and a concave mirror. The convex face of the PPKTP crystal with a curvature radius of 12 mm is coated with high reflectivity at 1550 nm and transmissivity of 20% at 775 nm and thereby serves as the input coupler of the OPA. The plane face of the PPKTP crystal is coated with antireflectivity for both wavelengths. With a curvature radius of 25 mm, the concave mirror is mounted on a piezoelectric transducer serving as the output mirror. The mirror is coated with a transmissivity of 12.5% at 1550 nm and high reflectivity at 775 nm. The seed and pump beams of the OPA are combined on a dichroic mirror and then enter the OPA. When the relative phase between the seed and pump beams of the OPA is controlled to $(2n+1)\pi$, the OPA is operated in the deamplification status and an amplitude-squeezed state is thereby prepared. When the flip mirror (FM) is flipped up, the prepared amplitude-squeezed state is reflected into the homodyne detector (HD), where the quantum efficiency of the photodiode is 99% to measure the variance of the amplitude-squeezed state.

To prepare the polarization squeezed light, the FM is flipped down. In this case, the amplitude-squeezed state in vertical polarization is combined with a 900 μW coherent beam in horizontal polarization on the polarization beam splitter (PBS2), where the relative phase between two input beams is controlled to $\pi/2$. Thus, the polarization squeezed light with the squeezing of $\hat{S}_3$ is obtained. Then, the prepared polarization squeezed light is distributed over an isotropic single-mode fiber (SMF-28e+), which is coated with an antireflectivity of 0.25% at both the input and output end faces, with the attenuation of $\alpha = 0.2$ dB/km. The polarization controller placed at the end of the fiber ensures that the polarization direction of the output beam, therefore, remains unchanged. Finally, the Stokes operators of the output polarization squeezed light are measured.

In our experiment, a 6 μW amplitude-squeezed state is prepared by the OPA with the pump power of 42 mW gen-

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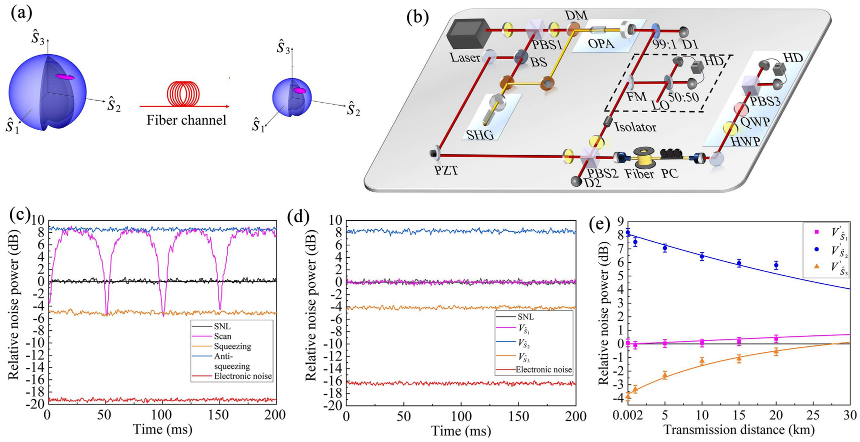

Figure 1 (Color online) (a) Schematic; (b) experimental setup; (c) relative noise power of the amplitude-squeezed state; (d) relative noise power of the three Stokes parameters of the prepared polarization squeezed light; (e) dependence of the relative noise power of distributed polarization squeezed light on the transmission distance of the fiber channel. Error bars represent one standard deviation and are obtained based on the statistics of measured noise variances. The measurement frequency, resolution bandwidth, and video bandwidth of the spectrum analyzer are 6 MHz, 100 kHz, and 300 Hz, respectively.

erated by the second harmonic generator, which is below the threshold of 63 mW. By deploying homodyne detection, as shown in the dashed box in Figure 1(b), we measure the noise of the amplitude-squeezed state using the HD. As shown in Figure 1(c), the squeezing of -5.06 dB (orange line) and the antisqueezing of $+8.62$ dB (blue line) for the amplitude and phase quadratures of the squeezed state are observed, when the relative phase between the squeezed state and local oscillator is locked to 0 and $\pi/2$, respectively.

To measure the variances of the Stokes operators, the polarization squeezed light is projected onto the different Stokes operators by a combination of a half-wave plate, a quarter-wave plate, and the PBS3 [1]. The measured relative noise powers of the Stokes operators $\hat{S}_1$, $\hat{S}_2$, and $\hat{S}_3$ of the prepared polarization squeezed light before distribution are shown in Figure 1(d), which indicates that a polarization squeezed light with -4.12 dB squeezing of $\hat{S}_3$ and $+8.42$ dB antisqueezing of $\hat{S}_2$ is thereby obtained.

In the distribution of the polarization squeezed light in the fiber channel, it is essential to estimate the excess noise, which leads to the decoherence of the polarization squeezed light [5,6]. By replacing the amplitude-squeezed state with a weak coherent beam with the same power, the transmission efficiencies and excess noises are estimated by the variance of $\hat{S}_2$. The total efficiencies η are 0.94, 0.89, 0.72, 0.59, 0.48, and 0.40 at transmission distances of 0.002, 1, 5, 10, 15, and 20 km, and the corresponding excess noises are 0.01, 0.03, 0.10, 0.12, 0.18, and 0.19 shot noise unit, respectively.

After the distribution, the squeezing (antisqueezing) levels of the polarization squeezed light are -3.88 dB ($+8.21$ dB), -3.34 dB ($+7.50$ dB), -2.30 dB ($+7.06$ dB), -1.26 dB ($+6.44$ dB), -1.09 dB ($+5.96$ dB), and -0.57 dB ($+5.79$ dB) at transmission distances of 0.002, 1, 5, 10, 15, and 20 km, respectively. The detailed error bars of each Stokes operator are to be found in Appendix B. The dependence of the relative noise power of $\hat{S}_1$, $\hat{S}_2$, and $\hat{S}_3$ on the transmission distances of the fiber is shown in Figure 1(e). The theoretical curves are then calculated based on (3), where the relationship between the excess noise and transmission distance $W = 0.047 \times L^{0.462}$ is then applied, which is obtained by fitting the measured excess noise. We show that the squeezing of $\hat{S}_3$ and antisqueezing of $\hat{S}_2$ decrease with the increase in the transmission distance, while the variance of $\hat{S}_1$ increases because of the effect of the loss and excess noise. In particular, the squeezing disappears when the transmission distance is larger than 27.7 km, according to the theoretical prediction.

Conclusion. We prepared and distributed the polarization squeezed light through a 20 km fiber channel. After this distribution, a polarization squeezed light with -0.57 dB squeezing is still observed. We demonstrate that the quantum variance of $\hat{S}_3$ and $\hat{S}_2$ decreases with the increase in the fiber length, while the variance of $\hat{S}_1$ increases, because of the increase in the loss and excess noise. By introducing the technique of suppressing decoherence into the distribution experiment, the transmission distance of the polarization squeezed light can be extended further. Our work thus takes a crucial step toward enabling future practical applications based on polarization squeezed light.

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Supporting information Appendixes A and B. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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