Generation of 1.5 µm Squeezed Vacuum Pulse Using a Sagnac Loop Interferometer

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Photon-number squeezing and quadrature squeezing were studied using ultrafast fibre nonlinear optics pumped by 1.5 µm femtosecond laser pulses. To obtain quadrature squeezing using an Erbium doped fibre amplifiers (EDFA) light source, we developed temporal homodyne technology to exclude the excess noise of an EDFA light source. We also performed a quadrature squeezing experiment using an optical parametric oscillator light source in stead of an EDFA light source exhibiting substantially high excess noise. Although the photon-number squeezing of –3dB was obtained from an asymmetric Sagnac fibre loop, the quadrature noise could not decrease to less than the Shot noise level without cooling the fibre, which is presumably due to GAWBS. To suppress guided acoustic wave Brillouin scattering, we refrigerated the fibre loop by liquid nitrogen, and squeezing at –0.7 dB was obtained by cooling the fiber at liquid nitrogen temperature.

Key Words: Squeezed state, Ultrafast nonlinear optics

1. Introduction

Quantum information and quantum computing technologies have been the subjects of an increasing number of studies. Quantum entanglement in photonics is of particular importance for achieving a practical quantum information network. Generation of squeezed light using optical components, available in classical optical communication, such as optical fibres, is attractive to create and distribute continuous variable entanglements. However, due to excessive noise caused by amplified spontaneous emission (ASE), Erbium doped fibre amplifiers (EDFA) have been rarely used in squeezed pulse generation. It is, therefore, important to examine coherence of various 1.5 µm laser sources and to evaluate their applicability. Currently, a novel scheme has been proposed to effectively improve coherence of pulsed lasers by utilizing a post-selection based on temporal homodyne detection.[1)]

On the other hand, quadrature squeezing using an optical fibre is still challenging despite many reports of quadrature squeezing experiment.[2-6)] An optical fibre carries noise from coherently excited phonon process, especially guided acoustic wave Brillouin scattering (GAWBS) [7)] brings large phase noise and prevents us from obtaining squeezing. To suppress GAWBS, various techniques have been reported. For example, GAWBS can be suppressed at very low temperatures,[2, 3)] by using a GHz reputation rate pulse lasers,[5)] or by using a photonic crystal fibre (PCF) instead of a conventional optical fibre.[8)]

In this paper, we report quadrature squeezing experiment using a coherent light source instead of EDFA sources. To purify the excessive noise, we developed a temporal homodyne technology and applied for the post-selection scheme.

2. Photon Number Noise in Light Source

First, we measured optical noise of various 1.5 µm laser sources, such as a homemade optical parametric oscillator (OPO) pumped by a Ti: sapphire laser, a fibre laser (IMRA femtolite 780) with an EDFA, and a gain-switched diode laser amplified by an EDFA. Some of light sources using an EDFA carry a substantial excessive noise and the noise prevents us from obtaining squeezed state, whereas the noise of the OPO corresponded to a standard quantum limit. As shown in Fig. 1, photon number noise of these light sources was experimentally measured. Output power of the fibre laserwas ~ 70 mW, and the EDFA can amplify up to ~50 mW. From Fig. 1, the fibre laser, the OPO amplified by EDFA, and the gain-switched

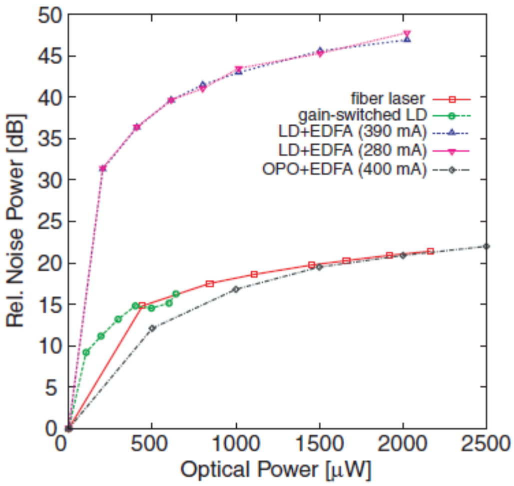

Fig.1 Photon number noise of various light sources.

diode laser show the similar level of photon number noise. Much higher noise level was measured for the gain-switch diode laser amplified by the EDFA. Although the EDFA gain is adjustable with the injection current of the pump laser diode, the gain shows little effect on the photon number noise. If we use these light sources for squeezing, the penalty of more than 100 times (20 dB) higher noise than the shot noise level (SNL) is serious problem because more than 2 mW optical power is usually needed to generate squeezed state using optical fibre nonlinearity. Therefore, fibre-lasers and EDFAs, widely used in classical optical communication, are not useful for squeezed state generation.

3. Squeezing Experiments using a Sagnac loop fibre

As a coherent 1.5 µm pulse laser source, Cr: YAG laser or OPO is widely used. We constructed an OPO pumped by a Ti: sapphire laser. A birefringence filter, which is used to widely select the centre wavelength and spectrum width, is placed in the OPO cavity. The laser pulses were launched into a 30-m-long Sagnac loop fibre interferometer with a variable coupler. We narrowed the spectrum width by inserting a birefringence filter in the OPO cavity so that the 30-m-long Sagnac loop fibre corresponded to several soliton lengths. The OPO generated optical pulses centred at 1513 nm with a spectrum width of 5 nm (FWHM), which corresponds to approximately ~700 fs for Fourier transform limited (FTL) pulse. Without the birefringence filter, the spectrum width of ~20-nm was obtained. The Sagnac loop fibre interferometer with an asymmetric splitting ratio, e.g. 93:7, generates amplitude squeezing.[9] We measured the magnitude of squeezing using balanced homodyne detection. We initially examined the amplitude squeezing without the birefringence filter and obtained –1.6 dB squeezing. The squeezing was improved to > –3 dB with the birefringence filter. Figure 2 shows the variation in amplitude noise as a function of various input laser powers launched to the Sagnac loop.

When the splitting ratio of the Sagnac loop fibre was set to 50:50, quadrature squeezing can be generated in a Sagnac loop fibre.[3] This set up are shown in Fig. 3. We plotted the minimum and the maximum quadrature noise in Fig. 4 for the various laser powers launched into the Sagnac loop fibre. The minimum quadrature noise did not decrease to less than the SNL. In general, the product of minimum and maximum quadrature noise corresponds to SNL in a pure state. Therefore, it seemed that the phase noise of GAWBS prevented us from obtaining quadrature squeezing.

To suppress this GAWBS, we refrigerated the Sagnac fibre loop by soaking more than 90 % of the fibre loop into liquid nitrogen. In this experiment, we used a 30-m-long Sagnac loop fibre with a fixed coupling ratio of 50:50. Figure 5 shows the comparison of noise level at room temperature and 77 K. The launched laser power was 3 mW. The phase noise was suppressed by ~3 dB, and small squeezing was observed.

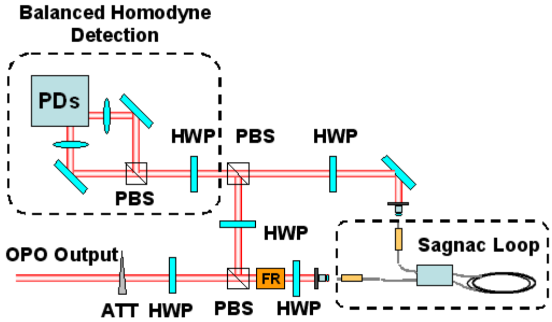

Fig.3 The schematic set up of the quadrature squeezing experiment using the Sagnac loop fibre. The differences from photon number squeezing are the ratio of coupler and the light pass of the local oscillator. PDs are KDPE330SL (KYOSEMI). Visibility between the squeezed ray and the local oscillator was >80 %. Overall efficiency was estimated to be about 60 %.

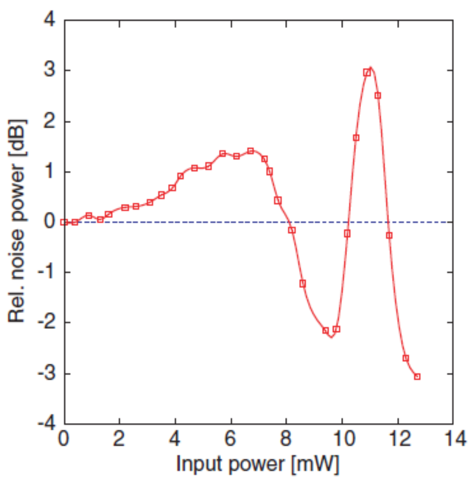

Fig.2 Dependence of photon number squeezing on input power using the asymmetric Sagnac loop fibre.

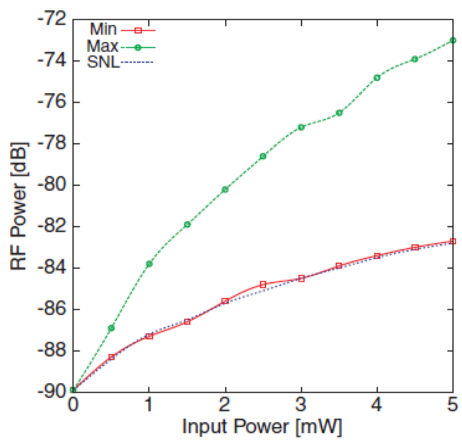

Fig.4 Dependence of quadrature noise dependence on input power using the symmetric Sagnac loop fibre. Upper curve is the anti-squeezing, and the lower curve is the minimum noise. The dotted curve is the SNL.

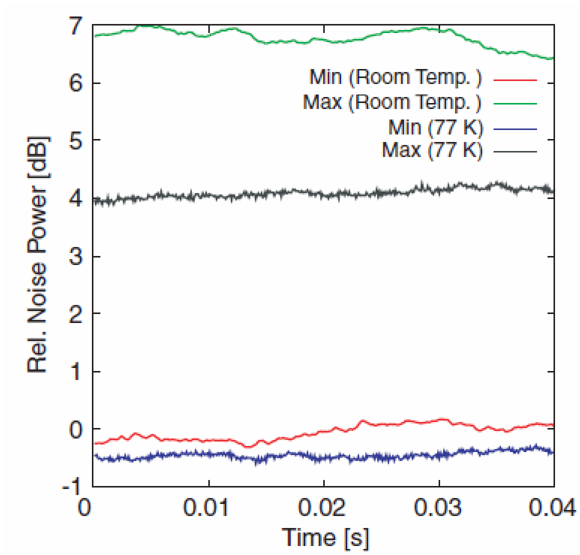

Fig.5 Quadrature noise using the 50:50 Sagnac loop fibre at room temperature and 77 K.

We also measured the quadrature noise dependence on input power. The highest squeezing of –0.7 dB was obtained at a launched laser power of 6 mW. The squeezing level was not improved at higher launched powers. To obtain higher magnitude of squeezing, additional techniques to suppress GAWBS are needed such as cooling down to lower temperature, using shorter fibers, adopting a PCF or post-selection schemes.

4. Temporal homodyne measurement

To suppress the excessive noise of a light source, the post-selection scheme using temporal homodyne detection will be useful. In this scheme, each signal pulse must be temporally resolved by detectors, which have sufficiently fast response time, to obtain the actual distribution of signal amplitude fluctuation. Therefore, we used a fast photodiodes (KPDE330SL (KYOSEMI)), a low noise RF amplifier

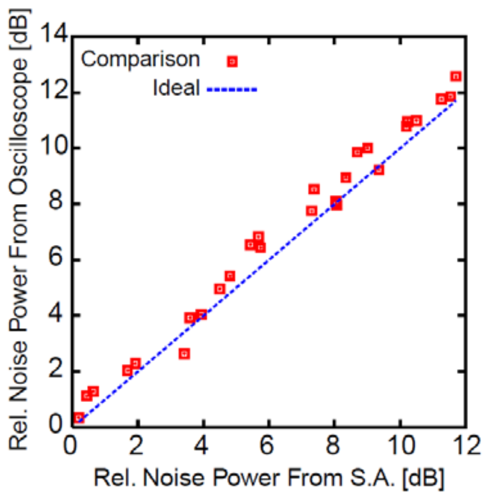

Fig.6 Comparison between the temporal homodyne detection and the conventional RF spectrum analyser detection.

(SA-230F5 (NF)), and an oscilloscope (DPO7054 (Tektronix)). To prevent the amplifier from saturation, a low-pass filter at 60 MHz was used.

We first compared the results of the temporal homodyne detection with that of a conventional RF spectrum analyser. Figure 6 shows the quadrature noise from the Sagnac loop fibre measured by the temporal homodyne detection and by the RF spectrum analyser. Our temporal measurement was in good agreement with the RF measurement.

Then, we performed the quadrature noise suppression using the post-selection scheme. The signal ray and local oscillator were split into two branches, and each optical pulse was measured by the temporal homodyne detections. The one branch was used as a tap, and the other was used as a signal. To purify the quadrature noise, we selected the signal pulses whose quadrature phase amplitude is close to the average value in the tap pulse distribution. The narrower the threshold for this process, the more quadrature noise can be removed. However, since the pulses of a certain number are necessary for the analysis of variance, we set the threshold (minimum) of

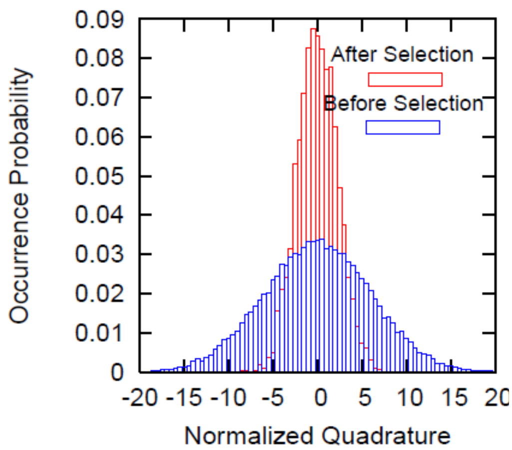

Fig.7 Histograms of signal pulses before and after selection using the post-selection scheme. The quadrature noise was 12.6 dB before filtering and 4.0 dB after filtering.

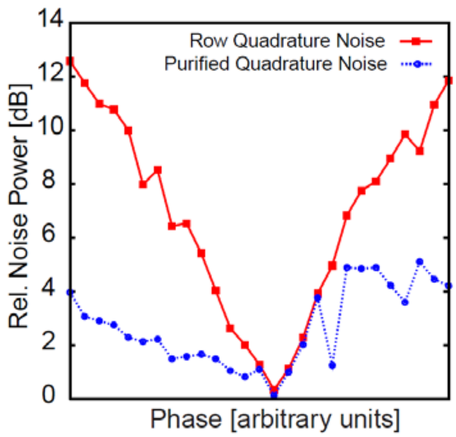

Fig.8 Suppression of quadrature noise at the various relative phase between the signal and local-oscillator. Horizontal axis corresponds to arbitrary relative phase between the signal pulse and

the selected pulse number to 3,000. The signal pulses, corresponding to the selected tap pulses, were selected, and used to calculate the variance. If the tap pulses and the signal pulses do not correlate with each other, no suppression would be obtained. Therefore, we confirmed the cross-correlation function between the signal and tap pulses. Figure 7 shows an example of the histogram before and after the post-selection. The probability distribution narrowed by the post-selection scheme remained to be a Gaussian shape. In this case, ~ 40000 pulses were processed before filtering and the quadrature variance was ~ 12 dB. After filtering, ~3000 pulses were selected and the quadrature variance was ~ 4 dB. The suppressions of the quadrature noise of various phase quadratures are displayed in Fig. 8. The quadrature variance was suppressed below 5 dB. If we can resolve the experimental imperfection, for example the disagreement of two homodyne efficiency and imperfect phase shifter, more suppression could be expected.

5. Conclusion

We performed quadrature squeezing experiment using a coherent femtosecond OPO light source, and developed temporal homodyne technology to eliminate GAWBS noise caused from the optical fiber. Due to the GAWBS noise, the quadrature squeezing was not obtained at room temperature, whereas squeezing at –0.7 dB was obtained by cooling the fiber at liquid nitrogen temperature. We also succeeded in reducing the quadrature noise with the post-selection scheme based on the temporal homodyne measurement. We may be able to purify the excessive noise of EDFA fibre lasers with the same post-selection scheme.

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