Pulse-resolved measurement of continuous-variable EPR entanglement with shaped local oscillators

Ami Shinjo[1], Takuya Katayama[1], Yujiro Eto[2] and Takuya Hirano[1]

[1]Gakushuin University, [2] National Institute of Advanced Industrial Science and Technology
E-mail: shinjo@qo.phys.gakushuin.ac.jp

1. Introduction

The generation of strong entanglement is important not only for the fundamental physics such as demonstrating EPR paradox [1] and steering [2] but also for applications such as the quantum information processing and quantum key distribution.

To demonstrate the EPR paradox and steering in a continuous variable (CV) experiment using the quadrature amplitudes *X* and *P* of the electromagnetic field, the conditional variance $\Delta^2_{B|A}X$ and $\Delta^2_{B|A}P$ must satisfy the EPR-Reid criterion [3] $\varepsilon^2 = \Delta^2_{B|A}X\ \Delta^2_{B|A}P < 1$, where $\hat{X} = \hat{a}^\dagger + \hat{a}$, $\hat{P} = i(\hat{a}^\dagger - \hat{a})$, $\hat{a}^\dagger$ and $\hat{a}$ are the creation and annihilation operator of the field mode, and $\Delta^2_{B|A}$means Bob's variance conditioned by Alice's value.
Several demonstrations of EPR paradox and steering have been reported [3, 4], but most of them performed in the frequency domain measurement. On the other hand, the time-domain measurement [5] in which one quadrature amplitude value is read for each one pulse using a pulsed LO light enables measurement of entanglement correlation directly from each measurements. However, there have been no reports that satisfy the EPR-Reid criterion in the experiment of time domain measurement using a pulsed light source.

We generated CV entanglement with a pulsed light source and measured in the time domain and also in the frequency domain. We used periodically poled lithium niobate (PPLN) waveguides to generate broadband squeezing, which is necessary for the time-domain measurement. In the pulsed light experiment it is important to improve temporal mode matching between entangled beams and the local oscillator (LO) beams. To resolve this problem, we shorten the duration of the LO pulse via optical parametric amplification (OPA) to improve temporal mode matching. In order to measure both in the frequency domain and the time domain, we used handmade homodyne detectors composed of high-speed operational amplifier and high-speed photodiodes [5]. Measurement results were quantified in term of the EPR-Reid criterion.

2. Experiment

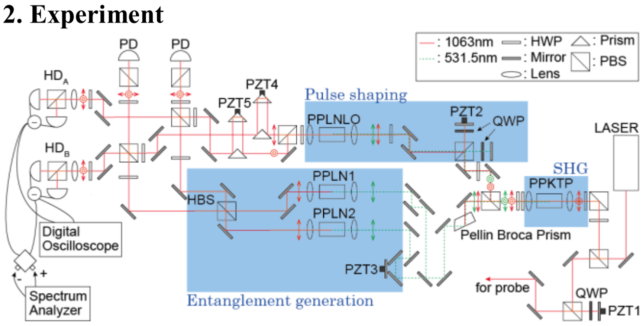

Figure I Experimental setup

Figure I shows the experimental setup. The laser source is a cw mode locked Nd:YVO₄ laser operating at 1063 nm with a pulse duration of 9 ps and a pulse repetition rate of 86.6 MHz. The laser output is frequency doubled in a periodically poled KTiOPO₄ (KTP) crystal to produce second harmonic (SH) beams. The SH beams are directed to two setup areas (Pulse shaping area and Entanglement generation area). In the Pulse shaping area, PPLN waveguide (PPLNLO) is used to shorten the duration of the pulses by OPA [6]. In Entanglement area, SH beams are directed to two PPLN waveguides (PPLN1 and PPLN2) to generate squeezed beams by OPA. Two squeezed beams, *x*-squeezed beam and *p*-squeezed beam are combined at the half beam splitter (HBS). The signals from two homodyne detectors (HD_A and HD_B) are directed to both a digital oscilloscope and a spectrum analyzer to observe homodyne signals in the time-domain measurement and in the frequency-domain measurement.

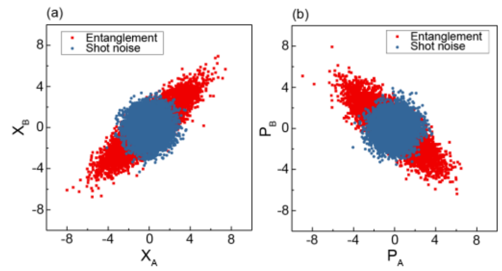

Figure II Measured correlation for approx. 8600 pulses. (a) X quadratures (b) P quadratures.

Figure II shows the results of time-domain measurement. From these measured quadratures, we calculated all elements of covariance matrix and estimated the EPR-Reid criterion. We obtained $\varepsilon^2 = 0.949 \pm 0.076$ that satisfied the EPR-Reid criterion.

3. Conclusions

In this work, we have demonstrated CV entanglement satisfying the EPR-Reid criterion in the time-domain measurement for the first time to our knowledge. We shortened the duration of the LO pulse by using OPA to improve the temporal mode matching between the LO pulse and the entanglement pulse. The product of conditional variances calculated from measured quadrature values is 0.949 which satisfies EPR-Reid criterion.

References

[1] A. Einstein, B. Podolsky, and N. Rosen: Phys. Rev. **47** (1935) 777.
[2] E. Schrödinger: Proc. Cambridge Pilis. Soc. **31** (1935) 555.
[3] M. D. Reid, P. D. Drummond, W. P. Bowen, E. G. Cavalcanti, P. K. Lam, H. A. Bachor, U. L. Andersen, and G. Leuchs: Rev. Mod. Phys, **81** (2009) 1727.
[4] S. Ast, M. Ast, M. Mehmet, and R. Schnabel: Opt. Lett. **41** (2016) 5094.
[5] Y. Zhang, R. Okubo, M. Hirano, Y. Eto, and T. Hirano: Sci. Rep. **5** (2015) 13029.
[6] Y. Eto, T. Tajima, Y. Zhang and T. Hirano: Opt. Express **16** (2008) 10650.