Propagation of a bipartite entangled state through a negative refractive index medium

Quentin Glorieux*, **Jeremy B. Clark, Ryan T. Glasser, Ulrich Vogl, and Paul D. Lett**
Quantum Measurement Division, National Institute of Standards and Technology
and Joint Quantum Institute, NIST and University of Maryland,
100 Bureau Dr., Gaithersburg, MD 20899-8424, USA
**quentin.glorieux@nist.gov*

Abstract: We generate entangled twin beams using four-wave-mixing and investigate its propagation through a negative refractive index medium. Anomalous dispersion is generated near a gain line induced by a pump beam in an atomic vapor.

OCIS codes: 270.0270, 270.6570.

1. Introduction

Quantum states of light have been shown to provide improvements in a variety of systems, resulting in better imaging resolution [1], sub-shot noise interferometry, and computation schemes that scale better with resources than when using classical means. A key aspect of these entangled and squeezed states of light is that they exhibit correlations that are stronger than allowed classically [2, 3]. Due to the important role entanglement plays in the field of quantum optics, numerous investigations into its fundamental behavior have taken place. Experiments investigating how entanglement evolves when propagating through a slow light medium, in which the group velocity of light is less than the speed of light in vacuum, c, have been conducted in the past [4, 5].

Here, we seek to investigate how quantum correlations and entanglement behave when propagating through a medium exhibiting anomalous dispersion [6]. In such a medium, optical pulses may propagate with group velocities that are larger than c, or even negative [6]. In this paper, we demonstrate that the dispersion associated with non-degenerate four-wave mixing process in warm rubidium vapor may be used to generate pulses with record negative group velocities. Additionally, we will discuss recent results involving the combination of fast light and quantum entanglement and their application for secure quantum key distribution.

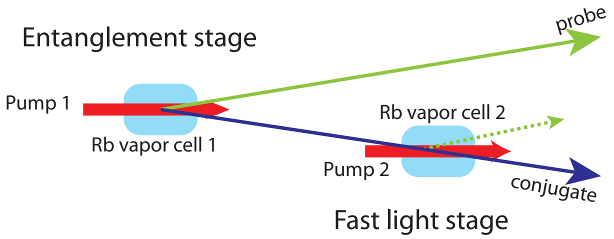

Fig. 1. Experimental setup of entanglement generation and fast light medium preparation.

2. Experimental setup

In this experiment, we generate an entangled state using four-wave mixing in a hot atomic vapor of ^{85}Rb, which converts two photons from an intense pump beam into a pair photons emitted into twin fields referred to as the probe and the conjugate [7, 8]. To characterize the entanglement, we measure the fluctuations of two orthogonal quadratures X and Y. Homodyne detection provides experimental access to these fluctuations, enabling us to confirm the entanglement of our twin beams. Subsequently, we add a medium with anomalous dispersion in the path of the conjugate beam, producing a group velocity faster than c for a pulse of light in this beam. To do so we use a second vapor cell with a separate four-wave mixing process driven by second, independent pump beam. We then check that a pulse propagating through this medium experiences an effective negative group velocity by measuring the cross correlations between the probe and conjugate photocurrent time traces [6]. We have measured an advancement relative to c of up to 3.7 ns in the configuration used for this experiment for fluctuations in the bandwidth of 100 kHz to 3 MHz.

3. Results

We have investigated the persistence of two-mode squeezing after passing one beam through a fast light medium. To quantify that effect we calculate a quantity often used in the verification of continuous-variable bipartite entanglement: the inseparability I. The inseparability is the sum of the X and Y quadrature noises (for the phases that minimize each of the terms), and a value below 2 guarantees bipartite entanglement.

When the negative dispersion medium is absent from the conjugate beam path, we observe -3 dB of squeezing below the shot noise limit, with an associated inseparability $I \simeq 1$ (see Fig 2.a). When we add an anomalous dispersion medium by unblocking the second pump beam, the squeezing is reduced to -2.3 dB (see Fig 2.a) and I increases to 1.2, but it is still below the threshold required to show entanglement ($I < 2$). This measurement shows for the first time the possibility of preserving entanglement after propagation through a fast light medium.

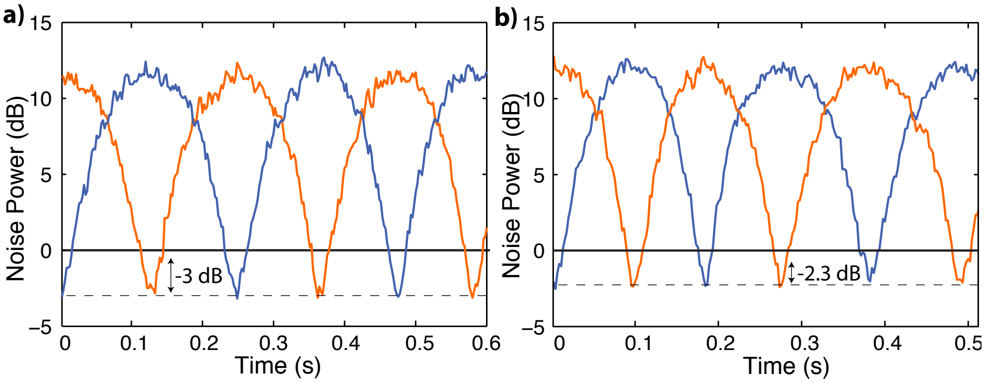

Fig. 2. Noise power compared to shot noise limit for the X (sum - blue traces) and Y (difference-orange traces) quadratures. a) In the absence of fast light medium. b) In presence of fast light medium corresponding to an advancement of 3.7 ns.

References

1. J. B. Clark, Z. Zhou, Q. Glorieux, A. M. Marino, and P. D. Lett, Optics Express, **20**, 15, 17050-17058 (2012).
2. Q. Glorieux, R. Dubessy, S. Guibal, L. Guidoni, J-P. Likforman, T. Coudreau, Physical Review A **82**, 3, 033819 (2010).
3. Q. Glorieux, S. Guibal, L. Guidoni, J-P. Likforman, T. Coudreau, Physical Review A, **84**, 5, 053826 (2011).
4. A. M. Marino, R. C. Pooser, V. Boyer, and P. D. Lett, Nature **457**, 859 (2009).
5. G. Htet, B. C. Buchler, O. Gleckl, M. T. L. Hsu, A. M. Akulshin, H. A. Bachor, and P. K. Lam. Optics Express, **16**, 10,7369-7381 (2008)
6. R. T. Glasser, U. Vogl, and P. D. Lett, Physical Review Letters **108**, 173902 (2012).
7. V. Boyer, A. M. Marino, R. C. Pooser, and P. D. Lett, Science **321**, 544 (2008).
8. Q. Glorieux, J. B. Clark, N. Corzo-Trejo, and P. D. Lett, New Journal of Physics **14**, 123024 (2012).