Nonlocal phase modulation of continuous-variable twin beams

Zhifan Zhou[1], Luis E. E. Araujo[1,2], Matthew DiMario[1], B. E. Anderson[3], Jie Zhao[1], Kevin M. Jones[4], Paul D. Lett[1]

1. Joint Quantum Institute, National Institute of Standards and Technology and the University of Maryland, College Park, MD 20742, USA

2. Institute of Physics "Gleb Wataghin," University of Campinas (UNICAMP), 13083-859 Campinas, São Paulo, Brazil

3. Department of Physics, American University, Washington DC 20016, USA

4. Department of Physics, Williams College, Williamstown, MA 01267, USA

Author e-mail address: zhifan@umd.edu

Abstract: We experimentally investigate the nonlocal phase modulation of spatially separate continuous-variable twin beams via a four-wave mixing process. Two separated phase modulators interfere nonlocally to modify the beam correlations, resulting in the various covariance matrices.

1. Introduction

Quantum nonlocality, such as demonstrated by the Einstein-Podolsky-Rosen (EPR) paradox, figured prominently in the prolonged Bohr-Einstein debates on the completeness of quantum theory. The EPR thought experiment later inspired Bell's theorem [1] and various schemes for quantum engineering [2]. Recent years have witnessed the rapid developments of quantum computing and the realization of quantum cluster states [3]. Many of these are manifested in discrete-variable (DV) regimes [4,5]. Motivated by the subtle role that quantum nonlocality may play in the continuous-variable (CV) regime [6], we have sent CV twin beams through a nonlocal phase modulation process.

The CV twin beams, labeled as the probe and the conjugate, pass through two spatially separated electro-optical phase modulators (EOMs). We experimentally investigate that the beam correlations depend on the relative phase between the two EOMS, although the twin beams are not coincident locally. This proof-of-principle manifestation of quantum nonlocality in the CV regime may have implications for further study of the CV cluster states and on fundamental effects such as the Bell inequality and tests of quantum steering and quantum erasing.

2. Experimental setup and results: CV nonlocal phase modulation

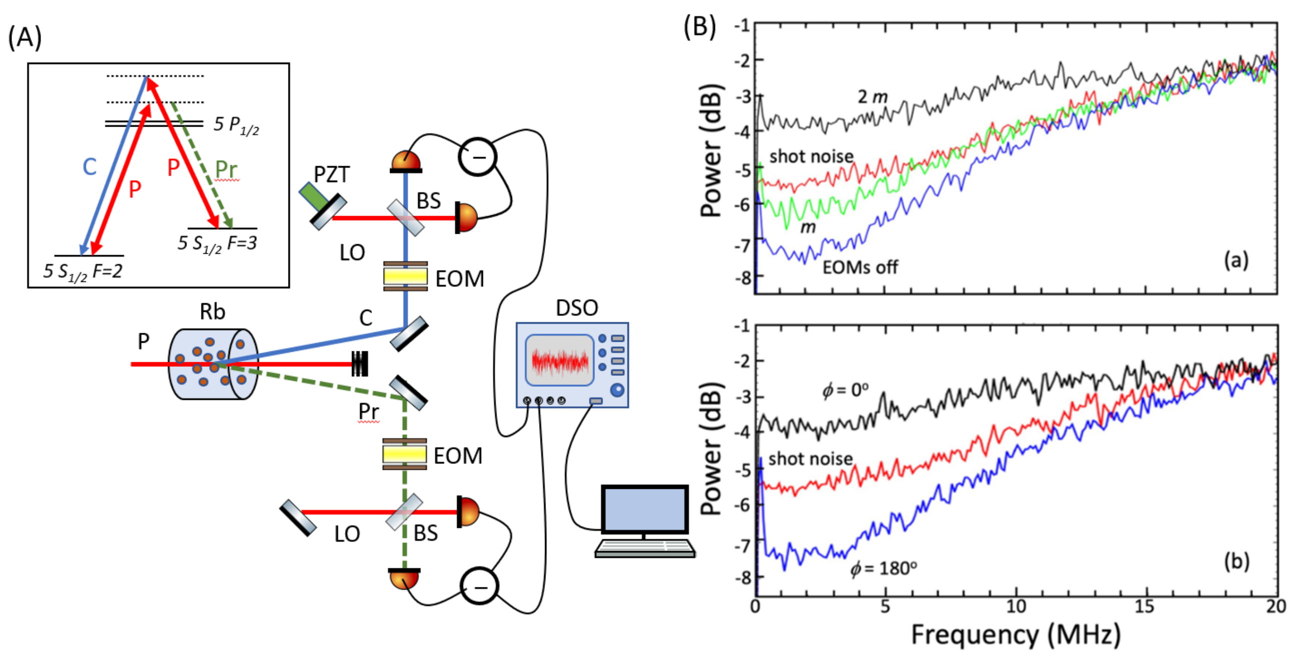

Fig.1. (a) Experimental setup and energy level diagram (inset) of the FWM process in 85Rb. P, pump; Rb, rubidium 85; Pr, probe; C, conjugate; LO, local oscillators; BS, beam splitter; DSO, digital storage oscilloscope. (B) (a) Squeezing spectra obtained with both EOMs turned off (blue line) and with one EOM on, but at different modulation depths: m (green line) and 2m (black line); (B) (b) Squeezing spectra for both EOMs running, at a modulation depth m, in phase (ϕ = 0◦, black line) and out of phase (ϕ = 180◦, blue line). In all cases, m = 0.12, and the red line is the shot noise.

The general scheme of the CV nonlocal phase modulation is shown in Fig.1. To prepare the twin beams, we used the previously demonstrated free-space four-wave mixing (FWM) in hot rubidium vapor [7], creating a strongly correlated two-mode squeezed vacuum without any cavity confinement and propagate the beams away from one another. The probe and the conjugate beams are detected with two homodyne detectors (HD) with an efficiency higher than 97%. The EOMs are inserted into the paths before the HD beam splitters.

We now show that the phase modulations interfere with each other nonlocally (Fig.1B). For two EOMs driven in phase, the beam correlations reduce the direct two-mode entanglement as they interfere constructively (Black curves in Fig.1B(a) and Fig.1B(b)). In contrast, the squeezing signal between the two beams is restored for two EOMs being out of phase as they cancel the effect of each other (Blue curves in Fig.1B(a) and Fig.1B(b)). Figure 2 shows the resulted various covariance matrices. When the beams are not modulated, the X and P quadratures of the probe and conjugate beams are not coupled. We do not observe any correlations when the EOMs are operated at 180° phase difference either. However, at 0° phase difference, the X and P quadratures are coupled, and positive correlations can be seen. The double diagonal structure in the covariance matrix corresponds to the frequency sidebands introduced by the EOMs. A single EOM, at twice the modulation depth, produces similar correlations to those produced by the two in-phase EOMs. This phenomenon holds when modulated within LO or hybridlike.

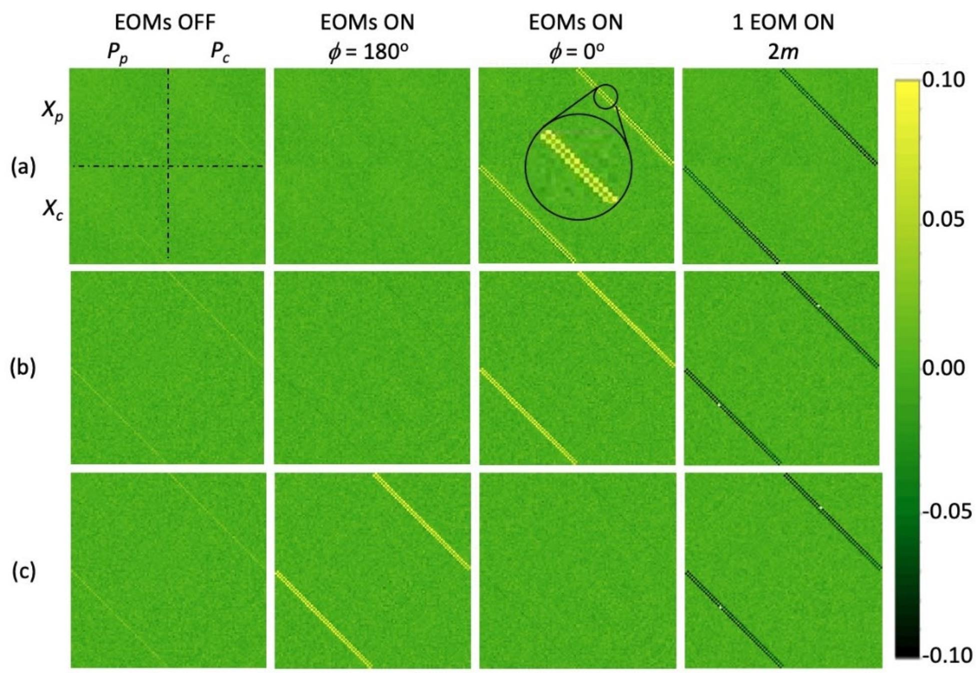

Fig. 2. Measured XP covariance matrices for (a) both EOMs on the twin beams, (b) both EOMs on local oscillator beams and (c) one EOM in the probe beam and the other EOM on conjugate local oscillator. The dashed crossed lines in the left-most matrix in (a) are a visual aid to help label and identify the Xp,c, and Pp,c sub-quadrants. In the two cases where both EOMs are on, their modulation depth is m = 0.1. In (b) and (c), when the EOMs are off, residual correlations between the X and P quadratures can be seen that are due to suboptimal locking of the homodyne detector phase θ. The inset in a row (a) shows a double diagonal structure of the correlations corresponding to the first-order frequency sidebands due to the periodic modulation of the beams by the EOMs.

3. References

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