Characterization of high-purity, pulsed squeezed light at telecom wavelengths from pp-KTP for quantum information applications

Thomas Gerrits[1], Burm Baek[1], Martin J. Stevens[1], Brice Calkins[1], Adriana Lita[1], Scott Glancy[1], Emanuel Knill[1], Sae Woo Nam[1], Richard P. Mirin[1], Robert H. Hadfield[2], Ryan S. Bennink[3], Warren P. Grice[3], Sander Dorenbos[4], Tony Zijlstra[4], Teun Klapwijk[4], Val Zwiller[4]

[1]National Institute of Standards and Technology, 325 Broadway, Boulder, CO 80305, USA
[2]Heriot-Watt University, Edinburgh, EH14 4AS, UK
[3]Center for Quantum Information Science, Oak Ridge National Laboratory, Oak Ridge, TN, 37831, USA
[4]Kavli Institute for Nanoscience, Delft University of Technology, Lorentzweg 1, 2628 CE Delft, The Netherlands
Author e-mail address: gerrits@boulder.nist.gov

Abstract: We characterize a pp-KTP crystal designed to produce pure single mode squeezed vacuum at 1570 nm. Measurements show Hong-Ou-Mandel interference with 97% visibility and a circular joint spectral distribution with a Schmidt number of 1.08.

OCIS codes: (270.6570) Squeezed States; (270.1670) Coherent optical effects

Pure optical squeezing in a single mode is highly desirable for quantum information applications such as continuous variable quantum computing and the generation of optical Schrödinger cat states. To generate optical cat states, photons are subtracted from squeezed light. Both the created quantum state and the subtracted photons must overlap with all modes (spatial, spectral, temporal) of the measurement apparatus, *i.e.* the homodyne detector and the photon-subtraction-arm single-mode fiber. This implies that the squeezed state must be in a single mode, allowing for *all* the subtracted photons to match the mode of the local oscillator. To date, high levels of mode-matched squeezing (matched to the mode of the local oscillator) have been achieved with cavity squeezing using a cw laser source [1]. However, no pure squeezing in a single mode that qualifies for unambiguous photon subtraction has been shown so far. In pulsed experiments, which allow for true heralding of the created state, the purity and intensity of the measured squeezing is generally low due to mode-matching difficulties. Recent theoretical predictions have held that a squeezing in a single mode can in principle be achieved by engineering a parametric down-conversion source in which the spatial and spectral output modes are exactly tailored to match the local oscillator modes of the homodyne detection apparatus [2]. Here, we describe the experimental realization and characterization of such a source at telecom wavelengths.

Our periodically poled-KTP down-conversion source is designed to produce a circular joint spectral distribution centered at λ = 1570 nm when pumped with a ~150 fs pulse centered at 785 nm. The pp-KTP should produce the degenerate two-mode squeezed state $|\xi\rangle = \exp\left(\xi^* \hat{a}_H \hat{a}_V - \xi \hat{a}_H^\dagger \hat{a}_V^\dagger\right)|0\rangle$, where V and H denote vertical (signal) and horizontal (idler) polarization modes. To characterize the source we employ several methods using low-jitter superconducting nanowire single-photon detectors (SNSPDs) and a photon number-resolving transition edge sensor (TES); both types of detector are fiber-coupled.

Figures 1a-c show joint spectral distributions measured with a fiber spectrometer [3] and SNSPDs. A more tightly focused pump beam generally produces more squeezing, but at the expense of a less circular joint spectral distribution. Spectral decomposition of the joint spectral amplitude yields a Schmidt number of 1.08, indicating that the two photon wave functions are factorizable and that this *unfiltered* source is useful for pure squeezing. Next, we measure the indistinguishability of photons in H and V via Hong-Ou-Mandel interference: H and V are separated by a polarizing beamsplitter, H is rotated 90° to V, and the two beams enter two ports of a 50/50 beamsplitter. Figure 1e shows two-photon interference measured using two TESs. The corrected (solid blue) curve indicates a visibility of 97% when subtracting multi-pair events.

Finally, we use two methods to measure the second-order intensity correlation between modes i and j, $g_{ij}^{(2)} = \left\langle \hat{a}_i^\dagger \hat{a}_j^\dagger \hat{a}_j \hat{a}_i \right\rangle / \left\langle \hat{a}_i^\dagger \hat{a}_i \right\rangle \left\langle \hat{a}_j^\dagger \hat{a}_j \right\rangle$. The first method uses a standard photon-correlation scheme with SNSPDs and time-to-amplitude histogramming electronics. The second method uses photon number statistics measured with the TES and the approximation $g^{(2)} \approx 2p_2/p_1^2$, where p_1 (p_2) is the probability of detecting one (two) photon(s). As shown Figure 1f, the two methods give remarkably similar results that agree well with theory. The cross-correlation between the two modes of the two-mode squeezer should scale as $g^{(2)}_{HV} = 2 + 1/\langle n \rangle$ (black dotted line), where $\langle n \rangle$ is the mean generated photon number. The corresponding data (black circles) align well with this prediction. The blue and green circles show $g^{(2)}_{HH}$, obtained by measuring the autocorrelation of one mode; as expected, the photon statistics of this mode follow a thermal distribution, independent of mean photon number ($g^{(2)}_{HH} = 2$, dashed blue line). The red circles show the cross-correlation between the two output ports of the 50/50 beamsplitter in the Hong-Ou-Mandel configuration described above. The result is a single mode squeezed vacuum in either output port of the beam splitter whose $g^{(2)}_{cc}$ and $g^{(2)}_{dd}$ values scale as 3+1/<n>. Note that all $g^{(2)}_{ij}$ data sets were scaled with just one common fitting parameter, the conversion efficiency between pump pulse energy and mean output photon number, $\langle n \rangle$.

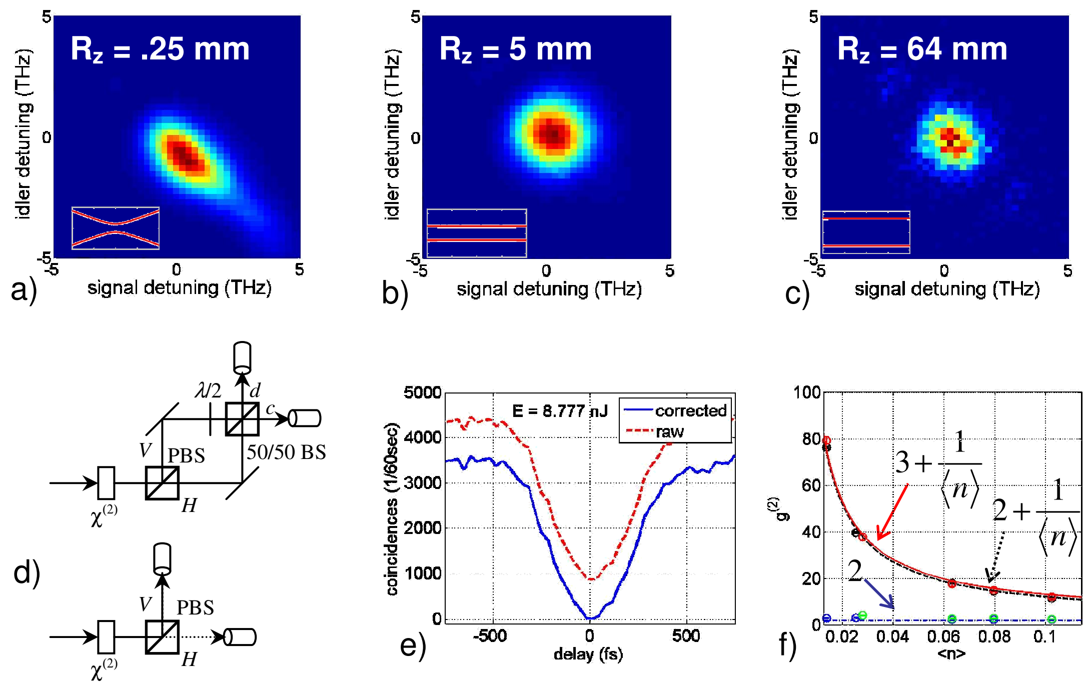

Fig. 1. a-c. Joint spectral distributions of the output of the pp-KTP two-mode squeezer at 1570 nm for different pump beam waists. R_z is the Rayleigh length of the pump beam and the insets correspond to the pump beam geometry inside the crystal. d. Experimental geometries for measuring the Hong-Ou-Mandel interference and $g^{(2)}_{cc}$ (upper graph) and $g^{(2)}_{HH}$ and $g^{(2)}_{HV}$ (lower graph) e. Hong-Ou-Mandel interference of both photons on a 50/50 beamsplitter, measured with <*n*> = 0.105. f. Measured and fitted $g^{(2)}$ values for different correlation configurations; red and green circles measured with two TESs; black and blue circles measured with the SNSPDs. Excess noise photons outside the main central lobe filter (some of which are barely visible in a-c) are blocked with a bandpass filter for the measurements in e and f.

In summary, we have created a periodically poled KTP squeezing source that delivers circular joint spectral distributions and a Hong-Ou-Mandel interference visibility of 97% when corrected for multi-pair events. The measured $g^{(2)}$ values fit the theoretical predictions of single mode outputs (thermal and squeezed vacuum) very well. These results suggest that the squeezed vacuum produced after interference of the two-mode squeezed state on a 50/50 beam splitter is close to the spatial mode of the collection optics, *i.e.* single mode fiber. We have presented various photon counting techniques to characterize the single mode character of two-mode and single-mode squeezed states. These techniques are useful tools for investigating the spatial mode properties of the squeezing. In the near future, we plan to map the local oscillator mode-matching characteristics of this source using homodyne detection.

References

[1] Y. Takeno *et al.*,Optics Express **15**, 4321-4327 (2007), H. Vahlbruch *et al., Phys. Rev. Lett.* **100**, 033602 (2008)

[2] W. P. Grice *et al*., *Phys. Rev. A* **64**, 063815 (2001), R. S. Bennink *et al*., *Phys. Rev. A* **66**, 053815 (2002), Xiaojuan Shi *et al*., *Optics Letters* **33,** 875 (2008), P.J. Mosley *et al*., *Phys. Rev. Lett.* **100**,133601 (2008)

[3] M. Avenhaus *et al*., *Optics Letters* **34**, 2873 (2009)