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Observation of continuous-wave squeezed light at 1550 nm

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We report on the generation of continuous-wave squeezed vacuum states of light at the telecommunication wavelength of 1550 nm. The squeezed vacuum states were produced by type I optical parametric amplification (OPA) in a standing-wave cavity built around a periodically poled potassium titanyl phosphate (PPKTP) crystal. A non-classical noise reduction of 5.3 dB below the shot noise was observed by means of balanced homodyne detection. © 2008 Optical Society of America

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Squeezed states of light were proposed to improve the sensitivity of laser interferometers for the detection of gravitational waves [1], and to establish quantum communication channels [2], e.g. for quantum key distribution [3–5]. For any application of squeezed states of light, a low decoherence level is required, i.e. optical loss and thermally driven noise sources need to be minimized. The laser wavelength of 1550 nm has emerged highly interesting. Firstly, at this wavelength conventional silica based telecom glass fibers show low optical loss and can be used for the transmission of squeezed states. Losses of as low as 0.2 dB/km were already measured in the late 70's [10], and ultra low loss (ULL) fibers with an attenuation of 0.17-0.18 dB/km are commercially available today [11]. Secondly, at this wavelength crystalline silicon constitutes an excellent test mass material for interferometric applications with low optical loss and high mechanical quality [9].

Gravitational wave detectors require the generation of squeezed states in a single spatial-temporal mode of continuous-wave light, whereas quantum channels can also be established in the pulsed laser regime. In the past years squeezed states at wavelengths above 1.5 μm were mainly generated in the latter regime. Noise powers of 4.1 dB below vacuum noise at 1505 nm [6], 3.2 dB at 1535 nm [8], and 1.7 dB at 1550 nm [7] were observed. Very recently, continuous-wave squeezed vacuum states at 1560 nm were generated by an optical parametric oscillator based on periodically poled $\mathrm{LiNbO_3}$ (PPLN), and a nonclassical noise suppression of 2.3 dB was observed [12].

Here, we report on the generation of continuous-wave squeezed vacuum states at a wavelength of 1550 nm based on periodically poled potassium titanyl phosphate (PPKTP). Squeezing of -5.3 dB was observed by balanced homodyne detection. The visibility of the mode-matching between the squeezed field and a spatially filtered local oscillator beam was measured to 99 % proving high spatial mode quality of the squeezed states. The squeezing strength observed was not limited by the squeezed light source but was limited by the quantum efficiency of the photo diodes used.

The light source in our setup, as schematically depicted in Fig. 1, was a high power erbium micro fiber laser providing about 1.6 W of continuous-wave radiation at 1550 nm. The laser beam was first send through a ring mode cleaner (MC) cavity with a finesse of 350 and a line width of 1.2 MHz for p-polarized light. Thus reducing mode distortions of the laser's $\mathrm{TEM_{00}}$ spatial mode profile as well as its phase and amplitude fluctuations at frequencies above the MC linewidth. Approximately 10mW of the transmitted light served as local oscillator (LO) for balanced homodyne detection, while the remaining power of about one 1 W was used to generate the second harmonic pump field for the OPA. Both, second harmonic generation (SHG) and squeezed light generation were realized in single-ended standing-wave cavities formed by two mirrors and the non-linear crystal. In either cavity we employed a PPKTP crystal of dimension $10\times2\times1\,\mathrm{mm}^3$ with flat, anti-reflection (AR) coated front and end faces. Inside a polyoxymethylene (POM) housing, each crystal is embedded in a copper fixture mounted on a Peltier element. Together with an integrated thermistor this enabled us to actively fine-tune the crystal temperature, thereby adjusting the thickness of the alternating domains of poling and hence minimizing the phase mismatch and enabling efficient nonlinear coupling. A high-reflection (HR) mirror with a power reflectivity r >99.98 % for both the fundamental and harmonic wavelengths faces one AR-side of the crystal and a piezo-driven out coupling mirror was mounted on the opposite side. This mirror was of 90 % power reflectivity for 1550 nm and has 20 % and some marginal reflectivity at 775 nm for the OPA and SHG, respectively. All cavity mirrors were spherical with 25 mm r.o.c. and measured 12.7 mm in diameter. The mirrors and the ring-piezo were mounted inside aluminum blocks that were rigidly attached to the POM housing. The distances between

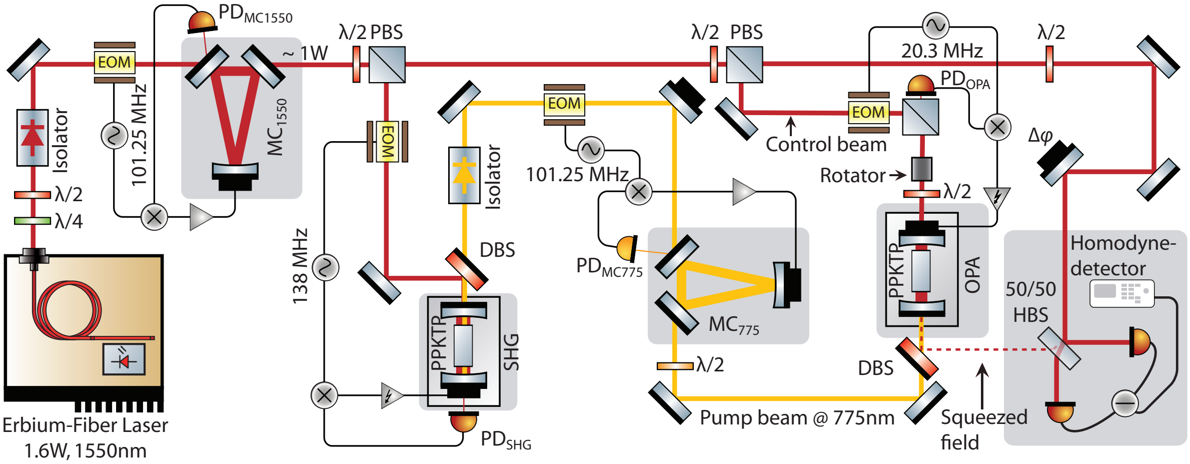

Fig. 1. Schematic of the setup. After being send through a mode cleaner (MC) cavity one part of the light is used as control beam for the OPA and local oscillator for balanced homodyne detection. The other part is frequency doubled in a SHG cavity to provide the 775 nm field to pump the OPA. The squeezed field leaves the OPA in counter direction of the pump and is measured with the homodyne detector. PBS: polarizing beam splitter; DBS: dichroic beam splitter; HBS: homodyne beam splitter; MC: mode cleaner cavity; PD: photo diode; EOM: electro-optical modulator.

crystal end faces and mirrors were 20 mm. Considering the refractive index of n=1.816 for PPKTP at 1550 nm, calculating the cavity waist size w_0 and free spectral range FSR yields ω_0=60 μm and FSR=2.6 GHz, with a line width (FWHM) of 43 MHz. When the SHG cavity was locked on resonance it produced up to 800 mW at 775 nm, which were separated from the fundamental by a dichroic beam splitter (DBS). Having passed the combination of a half waveplate and a polarizing beam splitter for pump power adjustment, an optical diode to prevent the SHG from back reflected light, and an electro optical modulator (EOM), the harmonic beam was eventually mode matched to the TEM$_{00}$-mode of the filter cavity (MC$_{775}$). The transmitted beam was then carefully aligned to match the OPA-cavity TEM$_{00}$ mode. The lengths of the four resonators in our setup were controlled to resonate with the respective carrier by means of a modulation/demodulation (Pound-Drever-Hall, PDH) scheme utilizing custom made EOMs and matched photo detectors. For details on the particular implementation, please refer to Fig. 1.

The squeezed states leave the OPA in counter direction to the second-harmonic pump, where another DBS separates the two. The measurement of field quadratures variances was accomplished by means of balanced homodyne detection, for which the squeezed field is subsequently brought to interference with the LO on a 50/50-beam splitter. A piezo actuated steering mirror was employed to shift the LO phase relative to the squeezed field. To adjust the visibility we injected a control beam through the HR back side of the OPA. Matching this auxiliary beam to the TEM$_{00}$ mode, i.e. congruent to the mode to be squeezed, the transmitted light was used to overlap with the LO on the homodyne beam splitter (HBS). We reached a fringe visibility of 99.0,%. The two outputs of the 50/50-beam splitter were each focused down and detected by a pair of Epitaxx ETX-500 photodiodes. The difference current was fed to a spectrum analyzer.

To verify our detectors linearity we took measurements of the vacuum noise power against the incident LO power at 5 MHz as depicted in Fig. 2. Changing the LO power by a factor of two, entailed a 3 dB shift of the corresponding noise trace, showing that the detector was quantum noise limited and operated linearly in the measurement regime.

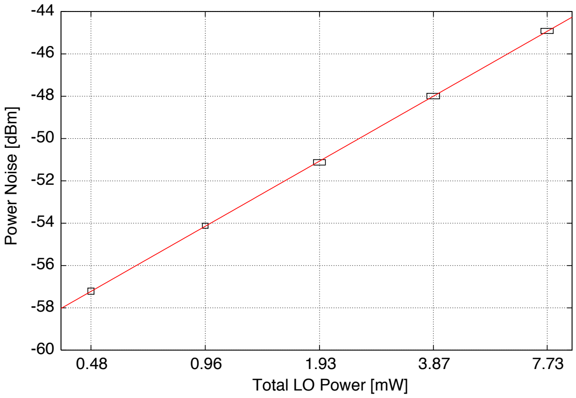

Fig. 2. Homodyne detector noise power levels measured at different LO powers at a frequency of 5 MHz with the signal port blocked. All values were extracted from a linear fit to averages of 5 traces each. Boxes indicate the standard deviation of the fit including an estimated ±5% uncertainty of the power meter used. The graph shows that our homodyne detector was quantum noise limited and operated linearly within our measurement regime.

We found the optimum pump power for our OPA to be 300 mW, yielding a noise reduction of 5.3 dB in the squeezed quadrature. This entailed an increase of 9.8 dB in the anti-squeezed quadrature. To switch between the two, a piezo-actuated mirror was used to phase shift the LO with respect to the squeezed field . The measured noise curves are depicted in Fig. 3. Trace (a) is the measured shot noise when the signal port of the HBS is blocked. The associated power of the incident LO was approximately 4 mW. Opening the signal port and injecting the field leaving the resonant OPA, trace (d) was recorded by linearly sweeping the LO-phase, thereby changing the measured quadrature from anti-squeezed to squeezed values. Holding the homodyne angle fixed, continuous traces of the squeezing (b) and anti-squeezing (c) were recorded. All traces were recorded at a side band frequency of 5 MHz and are, apart from (d), averaged twice. The contribution of electronic dark noise of our detector was negligible and was not subtracted from the measured data.

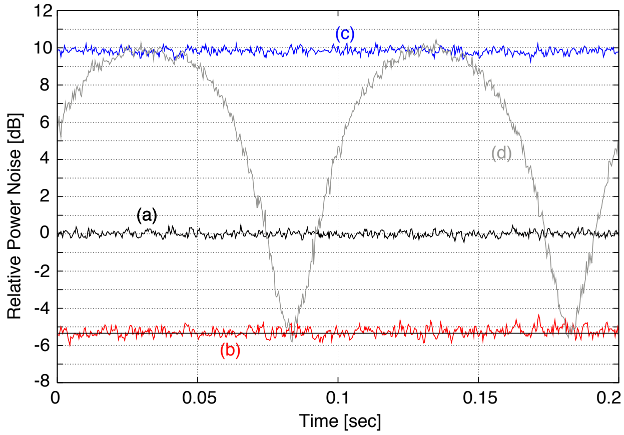

Fig. 3. Quantum noise powers at a frequency of 5 MHz normalized to the shot-noise level (trace (a)). All traces were recorded with a resolution bandwidth of 300 kHz and a video bandwidth of 300 Hz. Squeezing (b) and anti-squeezing (c) curves are averages of 2 traces each. Curve (d) was recorded by linearly sweeping the LO-phase which continuously rotates the measured quadrature from anti-squeezing to squeezing.

The observed squeezed noise power was 5.3 dB below shot noise, however, the observed anti-squeezing was about 10 dB above shot noise, revealing an uncertainty product of about a factor of three above the minimum uncertainty. With an increased pump power we observed further increased anti-squeezing, but a constant squeezing level. From this observation we conclude that our measurement was not limited by phase noise [14,19] but by optical losses. With 0.25% residual reflectance of our crystal AR coatings and 0.1%/cm absorption loss within the crystal we estimate the escape efficiency due to 10% transmittance of the out coupling mirror to be 90%. Together with a propagation loss of approximately 3% we estimate the quantum effiecency of our photo detectors to be 90%±4% and therefore expect that higher levels of squeezing from PPKTP will be observed in future utilizing better photo diodes and escape efficiency optimized OPA. We note that PPKTP has already been successfully applied for the generation of squeezed and entangled states at wavelengths between 532 nm and 1064 nm [13–17] with the maximum squeezing strength of 9 dB observed at 860 nm in [14]. The strongest squeezing to date was reported in [18] where a MgO:LiNbO$_3$ crystal enabled the observation of a noise reduction of 10 dB below shot noise at 1064 nm. However, at 1550 nm the phase matching condition of this material is uncomfortably highand temperature gradients significantly complicate the stable operation of a squeezed light source. This makes PPKTP the preferable material for the generation of squeezed light at 1550 nm.

In conclusion, we have demonstrated strong squeezing at the telecommunication wavelength of 1550 nm. Our experiment proved that PPKTP is an efficient material for the generation of squeezed states at this wavelength.

The states generated are compatible with applications in laser interferometers for gravitational wave detection. Current gravitational wave detectors are operated at 1064 nm [16], however, future detector designs might consider silicon as test mass material and the laser wavelength of 1550 nm in order to the reduce the thermal noise floor.

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