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10-dB squeeze laser tuneable over half a nanometer around 1550 nm

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Abstract: Lasers for generating monochromatic light beams with sideband spectra in strongly squeezed vacuum states are the basis for aspired optical continuous-variable quantum computers. We have developed a "squeeze laser" that produces 10 dB squeezed vacuum states at a wavelength of 1550 nm, the latter being tunable by 0.5 nm without losing the high squeeze factor. Several identical squeeze lasers can thus be combined to realise wavelength-division multiplexing. Our squeeze laser uses the mature technology of parametric down-conversion in a periodically poled KTP crystal placed in a cavity that resonates both the squeezed field and the second harmonic pump field. Unlike previous realisations, we achieve the double resonance and phase matching by individually optimising and controlling the temperatures of two sections of the crystal body. The wavelength range is currently limited by the tuneability of the 1550 nm master laser.

1. Introduction

Quasi-monochromatic laser light with its sideband spectrum in a squeezed vacuum state is a pillar of quantum technology [1]. It has been improving the sensitivities of gravitational-wave detectors [2], [3], [4], [5], and table-top experiments proved the principles of one-sided device independent quantum key distribution (QKD) [6], calibrating photo sensors without a standard lamp [7], and extending eye-save laser sensing into otherwise impossible regimes [8].

Squeezed light with a tuneable wavelength allows for quantum-enhanced spectroscopy [9]. The work cited achieved a 5 dB squeeze factor at 855 nm with a 5 pm tuning bandwidth. Squeeze factors below 2 dB were observed in the wavelength ranges of (836 ± 5) nm [10], (472 ± 4) nm [11], 389.5 ± 0.5 nm [12]. Tuneable squeezed light around 1550 nm ensures compatibility with existing 1550 nm network infrastructure and can be used for wavelength division multiplexing (WDM) [13], e.g. in QKD or continuous-variable optical quantum computation [14].

Here we report on the realisation of a tuneable 1550 nm "squeeze laser" [15] – a parametrically pumped laser resonator providing continuous quasi-monochromatic laser light in a TEM00 mode, with a MHz sideband spectrum in squeezed vacuum states. The squeeze factor achieved was greater than 10.5 dB. This high level was maintained even when the wavelength of the squeeze laser was tuned to 23 different sample wavelengths, which together covered almost half a nanometre around 1550 nm. At each wavelength, double resonance of the squeezed light at 1550 nm and the pump light at 775 nm were fine-tuned along with phase matching of the non-linear conversion.

2. Setup

The experiment is illustrated in Fig. 1. 1550 nm continuous-wave laser light provided by a an NKT Basik + NKT Boostik fiber laser system was partly upconverted to 775 nm by cavity-enhanced second-harmonic generation (SHG). The second harmonic field was separated from the 1550 nm field by a dichroic beam splitter (DBS) and directed to pump the cavity-enhanced parametric

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downconversion (PDC) to generate squeezed vacuum states at 1550 nm. The cavity consisted of a 9.3 mm long periodically poled KTP crystal and a coupling mirror mounted on a piezo-electric element (PZT). The coupling mirror had a reflectivity of 83% at 1550 nm and 97.5% at 775 nm, the crystal end face was highly reflective coated for both wavelengths, resulting in a FWHM linewidth of 106.6 MHz for 1550 nm and 15.4 MHz for 775 nm. The cavities were stabilized on resonance by the Pound-Drever-Hall locking method [16]. To generate an error signal, a 51 MHz phase modulation was imprinted on the 1550 nm pump field which was upconverted to the 775 nm field in the SHG. The crystal was placed on a split heating pad with two Peltier elements underneath to separately heat the crystal center and coated end face in order to achieve phase matching and to compensate for the reflection phase mismatch. The latter arose from the Gouy phase [17], different penetration depths of the 775 nm and the 1550 nm light in the reflection coatings, and the position of the crystal cut in the last poling domain. Temperatures were monitored with NTC elements and kept stable to a manually adjusted set points with a control loop actuating the Peltier elements' currents. The squeezed vacuum was separated from the second harmonic pump field via a DBS and guided to a balanced homodyne detector. A control beam could be injected through the back of the PDC cavity for alignment of the squeezed vacuum beam path and its overlap with a coherent local oscillator on a beam splitter for the balanced homodyne detection. Photo diodes detected the signal in the output ports. The resulting photo currents were subtracted and amplified by a transimpedance amplifier, whose voltage was fed to a spectrum analyser. The measured quadrature depended on the phase between the local oscillator and squeezed vacuum, which could be varied by applying voltage to a PZT holding a mirror in the local oscillator beam path.

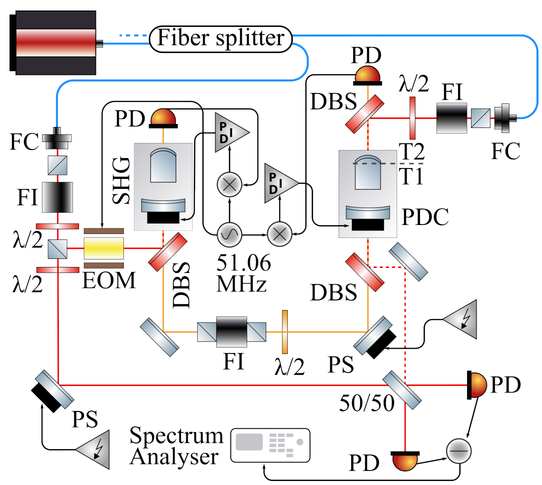

Fig. 1. Schematic of optical setup. Part of the tunable continuous-wave light was upconverted in a second-harmonic generation (SHG) cavity, pumping the cavity-enhanced degenerate parametric downconversion (PDC) process. The generated squeezed vacuum field was reflected by a dichroic beam splitter (DBS) onto a balanced homodyne detector. To adjust the readout phase, a mirror on a piezo-electric element acted as a phase shifter (PS). The two temperature ranges of the ppKTP crystal T1 and T2 served to optimise the phase matching in the case of simultaneous double resonance of the PDC resonator. EOM= electro-optical modulator, FC= fiber output coupler, FI= Faraday isolator, PD= photo diode.

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3. Results

Figure 2 shows a zero span measurement at a Fourier frequency $f = 2\,\text{MHz}$ with a squeeze factor $(11.0 \pm 0.1)\,\text{dB}$ below the vacuum shot noise level. The corresponding anti-squeeze factor was $(19.8 \pm 0.1)\,\text{dB}$ above the vacuum noise which corresponds to a loss of 6.4% [7] mainly contributed by the interference contrast at the beam splitter of $\approx 98.3\%$ and the photo diodes' quantum efficiency of $\approx 99\%$ stated by the manufacturer. The dark noise clearance was $(22.3 \pm 0.1)\,\text{dB}$ at a local oscillator power of $(5.0 \pm 0.3)\,\text{mW}$. The squeeze factor was measured at a pump power of $P_{\text{pump}} = (15.2 \pm 0.7)\,\text{mW}$. Slowly shifting the local oscillator phase scans the entire phase space between squeezed and anti-squeezed state, which is shown in the orange trace.

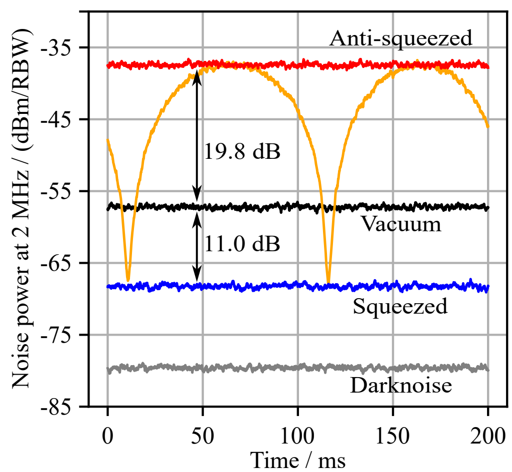

Fig. 2. Zero span measurements at Fourier frequency $f = 2\,\text{MHz}$. A squeeze factor of $(11.0 \pm 0.1)\,\text{dB}$ below the shot noise and an anti-squeeze factor of $(19.8 \pm 0.1)\,\text{dB}$ above was observed at a pump power of $P_{\text{pump}} = (15.2 \pm 0.7)\,\text{mW}$. Slowly shifting the local oscillator phase resulted in the orange curve. The dark noise was $(22.3 \pm 0.1)\,\text{dB}$ below the shot noise for a local oscillator power of $(5.0 \pm 0.3)\,\text{mW}$ and was not subtracted from the data. The resolution bandwidth was set to RBW = 300 kHz, the video bandwidth to VBW = 300 Hz.

Each data point in Fig. 3 represents such a zero span measurement with a tuned wavelength in the range of 1549.9 nm to 1550.34 nm in 0.02 nm steps. The wavelength was changed at the NKT laser system with a subsequent frequency stabilization time of at least 20 minutes and cavity temperatures were adjusted accordingly to maximize the squeeze factor. Squeeze factors were all $>(10.5 \pm 0.1)\,\text{dB}$ with a maximum of $(11.0 \pm 0.1)\,\text{dB}$ and an average of $(10.8 \pm 0.1)\,\text{dB}$, at pump powers of about $P_{\text{pump}} = 15\,\text{mW}$. Fluctuations in the anti-squeeze factors were a result of slightly different intra-cavity pump powers of the PDC due to mode matching changes due to the wavelength tuning and measurements taken on different days. Those fluctuations are less visible in the squeeze factors as they were dominated by the overall optical loss in the system.

The optimized temperatures in the crystal's centre for phase matching (T1) and end face for reflection phase mismatch compensation (T2) showed a non-monotonic behaviour. This was unexpected since dn/dT of KTP does not change sign in the temperature range applied. An explanation for this behaviour could be found in the compact design of the cavity itself. Firstly, NTC sensors are mutually influenced by both Peltier elements, and secondly, the thermal baths are not decoupled from each other. In addition the crystal itself acted as a thermal bridge. Further measurements on reproducibility with different crystals and different cavity designs will give more insight.

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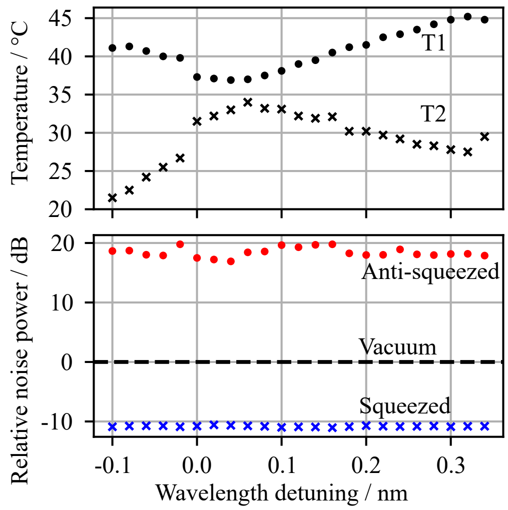

Fig. 3. Crystal temperatures and squeeze factors at detuned wavelengths. Zero span measurements were taken for detunings between −0.1 nm and 0.36 nm in 0.02 nm steps around 1550 nm. For each step, phase matching and reflection phase tuning temperatures were adjusted. A squeeze factor >10.5 ± 0.1 dB was achieved for each point, with an average a squeeze factor of 10.8 ± 0.1 dB. The temperatures for phase macthing (T1) and reflection phase mismatch compensation (T2) show a non monotonous behaviour, see discussion in the main text. Measurements were performed with a pump power $P_{\text{pump}} = 15$ mW, a resolution bandwidth of RBW = 300 kHz and a video bandwidth of VBW = 300 Hz.

Our tuning range is limited by the tuning range of the NKT laser system and the temperature range. We set a lower bound for the temperatures to be 20° C (room temperature) to avoid condensation inside the cavity. The upper temperature limit in the system is the maximum heating power of 70° C.

4. Conclusion

Highly efficient frequency conversion or frequency mixing of quasi-monochromatic continuous wave light fields requires a non-linear optical medium in a cavity. The medium must be phase-matched for all wavelengths involved and the cavity resonant for as many of these as possible. We have considered here the case of a quasi-phase-matched KTP crystal in a half-monolithic cavity that is doubly resonant to laser light and its first harmonic. We have shown that these conditions can be maintained by fine-tuning two temperature regions of the medium when the fundamental wavelength is tuned over almost half a nanometer around 1550 nm. This shows that a larger number of identical squeeze lasers are suitable for wavelength multiplexing, which could be profitably used in future optical quantum computers, for example.

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Disclosures. The authors declare no conflicts of interest.

Data availability. Data is available on request

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