13 dB Squeezed Vacuum States at 1550 nm from 12 mW external pump power at 775 nm

Axel Schönbek¹, Fabian Thies², and Roman Schnabel¹

¹Institut für Laserphysik und Zentrum für Optische Quantentechnologien, Universität Hamburg, Luruper Chaussee 149, 22761 Hamburg, Germany
²Max-Planck-Institut für Gravitationsphysik (Albert-Einstein-Institut) and Institut für Gravitationsphysik, Leibniz Universität Hannover, Callinstraße 38, 30167 Hannover, Germany
*Corresponding author: axel.schoenbeck@physik.uni-hamburg.de

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Strongly squeezed light at telecommunication wavelengths is the necessary resource for one-sided device-independent quantum key distribution via fibre networks. Reducing the optical pump power that is required for its generation will advance this quantum technology towards efficient out-of-laboratory operation. Here, we investigate the second-harmonic pump power requirement for parametric generation of continuous-wave squeezed vacuum states at 1550 nm in a state-of-the-art doubly-resonant standing-wave PPKTP cavity setup. We use coarse adjustment of the Gouy phase via the cavity length together with temperature fine-tuning for simultaneously achieving double resonance and (quasi) phase matching, and observe a squeeze factor of 13 dB at 1550 nm from just 12 mW external pump power at 775 nm. We anticipate that optimizing the cavity coupler reflectivity will reduce the external pump power to 3 mW, without reducing the squeeze factor. © 2020 Optical Society of America

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1. INTRODUCTION

Allocating suitable low-noise laser light of sufficient power in a well-defined spatial mode contributes most to the rather large footprint of current sources for strongly squeezed light. These sources use cavity-enhanced degenerate parametric down-conversion [1–3] in optically nonlinear crystals such as periodically poled potassium titanyl phosphate (PPKTP), for a review see also [4]. Reducing the required external pump power will allow for smaller laser devices, with smaller footprints and less power consumptions and is a significant step towards a compactification of squeezed-light sources. Sources for strongly squeezed light form the basis of the, so far, only existing, experimentally proven concept of quantum key distribution (QKD) that does not need to trust the remote receiver. In such one-sided device independent QKD, any attacks on the receiver site, including flaws of receiver implementation and operation, are discovered during channel characterization, as demonstrated in [5].

In [6], 12.3 dB of squeezing at 1550 nm was observed using a PPKTP squeezing cavity that was only resonant at 1550 nm but not at the pump wavelength of 775 nm, of which 171 mW was required. It is well known that squeezing cavities that are not only resonant for the squeezed field but also for the pump field allow for lower external pump powers [3]. In [7], a doubly-resonant traveling-wave squeezing resonator was realized and a squeeze factor of 11.6 dB at audio sideband frequencies around 1064 nm observed, using a pump power of 90 mW. In [8], a doubly-resonant standing-wave squeezing resonator was realized and a squeeze factor of 15 dB at MHz sideband frequencies around 1064 nm observed, using a pump power of 16 mW. The experimental challenge is to simultaneously achieve double resonance as well as (quasi) phase matching, since the Gouy phase [9] and dielectric mirror coatings (and a crystal length not being an integer multiple of the poling period) cause differential phase shifts. One solution is the introduction of an adjustable dispersive component into the cavity, such as a rotatable anti-reflection (AR) coated window [7] [10] [11] or adjustable gas pressure [12]. Both examples, however, increase the complexity of the system, and, if the light needs to propagate through additional windows, additional optical loss is introduced, which reduces the achievable squeeze factor. Another possibility is to use a wedged crystal. Its translation perpendicular to the cavity mode changes the differential path length and allows for achieving double resonance and phase matching simultaneously [13] [14]. This approach, however, is not feasible if one crystal surface is used as a (spherical) cavity mirror for realising a compact 'half-monolithic' design.

Here, we report on the observation of a 13 dB squeezed vacuum state at 1550 nm from a doubly-resonant quasi-phase-
matched standing-wave half-monolithic cavity that was pumped with just $12 \pm 1$ mW of light at 775 nm. The nonlinear medium inside the cavity was a 9.3 mm long PPKTP crystal. Double resonance and close to optimum quasi-phase-matching was achieved simultaneously without introducing an additional dispersive component. Coarse trial and error adjustment of the Gouy phase via the cavity length together with fine tuning of the crystal temperature turned out to be sufficient. Compensation of differential phase shifts from e.g. mirror coatings is possible because the Gouy phase translates to different additional optical path lengths for the two fields [9].

### 2. EXPERIMENTAL SETUP

Figure 1 shows the schematic of the experiment. Continuous-wave monochromatic laser light at 1550 nm was filtered by a standing-wave mode-cleaner cavity and partly up-converted to 775 nm with a second harmonic generation (SHG) cavity. The latter field pumped cavity-enhanced type I degenerate spontaneous parametric down-conversion (PDC). Thus, a squeezed vacuum state at sideband frequencies around 1550 nm was generated. A dichroic beam splitter (DBS) deflected the squeezed field towards a balanced homodyne detector (BHD). (B)BS: (balanced) beam splitter; PD: photo diode; FI: Faraday isolator.

![Schematic of the experiment](image)

Figure 1. Schematic of the experiment. The continuous-wave monochromatic laser light at 1550 nm was filtered by a standing-wave mode-cleaner cavity and partly up-converted to 775 nm with a second harmonic generation (SHG) cavity. The latter field pumped cavity-enhanced type I degenerate spontaneous parametric down-conversion (PDC). Thus, a squeezed vacuum state at sideband frequencies around 1550 nm was generated. A dichroic beam splitter (DBS) deflected the squeezed field towards a balanced homodyne detector (BHD). (B)BS: (balanced) beam splitter; PD: photo diode; FI: Faraday isolator.

### 3. EXPERIMENTAL RESULTS

Figure 2 shows zero span measurements at Fourier frequency $f = 5$ MHz taken with a resolution bandwidth of $\Delta f = 300$ kHz. The squeezing level is $13.1 \pm 0.05$ dB below shot noise and an anti-squeeze factor of $25.8 \pm 0.05$ dB was observed. (The error bars of these factors were due to imperfect stability of the local oscillator power during the measurement cycle.) The peaked curve was recorded with a slowly shifted local oscillator phase. The BHD dark noise was $24.9$ dB below the shot (vacuum) noise of the local oscillator power of $12$ mW and was not subtracted from the data. The resolution bandwidth was $\Delta f = 300$ kHz and the video bandwidth $300$ Hz.

Figure 2. Zero span measurements at Fourier frequency $f = 5$ MHz. With a pump power of $P_{\text{pump}} = (12 \pm 1)$ mW at 775 nm, a squeeze factor of $13.1 \pm 0.05$ dB below shot noise and an anti-squeeze factor of $25.8 \pm 0.05$ dB was observed. (The error bars of these factors were due to imperfect stability of the local oscillator power during the measurement cycle.) The peaked curve was recorded with a slowly shifted local oscillator phase. The BHD dark noise was $24.9$ dB below the shot (vacuum) noise of the local oscillator power of $12$ mW and was not subtracted from the data. The resolution bandwidth was $\Delta f = 300$ kHz and the video bandwidth $300$ Hz.

For balanced homodyne detection, the squeezed field was overlapped with the local oscillator on a balanced beam splitter (BBS). A photo diode (PD) was placed in each output port of the BBS. The photocurrents from the two PDs were subtracted from each other and the resulting voltage was fed to a spectrum analyser. The quadrature that is read out by the homodyne detector is defined by the input phase difference. For that reason, a phase shifter, consisting of a mirror that is mounted on a PZT, was placed in the local oscillator path. Applying a voltage to the PZT allowed us to detect the squeezed or anti-squeezed quadrature, respectively.
ated below threshold [16, 17] assuming $f << \Delta f$:

$$\Delta^2 X_{f+\Delta f/2} = 1 - \eta - \frac{4\sqrt{\epsilon}}{(1+\sqrt{\epsilon})^2 + 4(2\pi f/k)^2}, \quad (1)$$

$$\Delta^2 \tilde{V}_{f+\Delta f/2} = 1 + \eta - \frac{4\sqrt{\epsilon}}{(1-\sqrt{\epsilon})^2 + 4(2\pi f/k)^2}, \quad (2)$$

where $\eta$ represents the overall detection efficiency of the initially pure quantum states; $\epsilon = P_{\text{pump}}/P_{\text{thres}}$ is the pump parameter with pump power $P_{\text{pump}}$ and oscillation threshold power $P_{\text{thres}}$, and $k$ is the decay rate of the PDC cavity at 1550 nm.

Fitting the model in Eqs. (1) and (2) to the eight spectra in Fig. 3 resulted in a full-width-half-maximum linewidth of $\kappa/(2\pi) = 109.8 \text{MHz}$, a total efficiency of $\eta = 0.952$, and pump parameters of 85.7%, 47.6%, 26.3% and 8.6% of the oscillation threshold power, respectively. In this figure, the dark noise was subtracted from the data allowing for a straight forward comparison with our model. The fits were plotted for a PDC cavity resolution bandwidth of 300 kHz, and the video bandwidth 300 Hz. All traces were recorded with a local oscillator power of 12 mW, except for the one at $\epsilon = 85.7\%$. Here, the local oscillator power was reduced to 1 mW to extend the linear response of the homodyne detector to large anti-squeezed noise powers (at the expense of a lower dark noise clearance).

The remaining loss was due to imperfect photo diode quantum efficiency, imperfect propagation efficiency, and imperfect cavity escape efficiency. According to manufacturer specifications, the InGaAs photo diode quantum efficiency was $\eta_{\text{ph}} \approx 0.99$ (Laseroptik GmbH), the propagation efficiency was mainly limited by the transmission through altogether seven anti-reflection coated surfaces of three lenses and the PDC cavity coupler, yielding $\eta_{\text{pr}} \approx 0.99$, and the PDC cavity escape efficiency could be estimated to $\eta_{\text{esc}} = T_1/(T_1 + L) \approx 15%/(15% + 0.1%) \approx 0.99$ (Laseroptik GmbH). Here $T_1$ is the transmission of the PDC cavity coupler at 1550 nm and $L$ is the cavity round trip loss at this wavelength, which includes two reflections from the anti-reflection coated surface of the PPKTP crystal, one transmission through the high-reflection coated back of the crystal and a small contribution from crystal absorption [18].

The larger the PDC cavity built-up factor of the pump field, the lower is the required external pump power. The PDC cavity built-up factor is given by [19, 20]

$$\frac{P_{\text{cav}}}{P_{\text{Pump}}} = \frac{(1 - R_1)}{(1 - \sqrt{R_1 R_2 V})^2} \approx \frac{(1 - 99.8\%)}{(1 - \sqrt{99.95\% \times 99.98\%})^2} \approx 140.\%$$

Here, $P_{\text{cav}}$ and $P_{\text{Pump}}$ are the intra-cavity and the external powers of the 775 nm pump field. $R_1$ is the respective power reflectivity of the input mirror, and $R_2$ the respective power reflectivity of the second cavity mirror. $V$ represents the propagation efficiency per half roundtrip at 775 nm incorporating all losses from absorption and scattering. In our setup, $R_1 = (97.5 \pm 0.3\%)$, $R_2 = (99.955 \pm 0.004\%)$, and $V = V_{\text{AR}} \times V_{\text{KTP}} = (99.935 \pm 0.05\%)$, with a transmission through the AR coating of $V_{\text{AR}} = (99.95 \pm 0.05\%)$, and a transmission through the PPKTP crystal of $V_{\text{KTP}} = (99.985 \pm 0.005\%)$ [18], which also takes into account scattering and absorption. These values we deduced from the measurement protocol of the coating company (Laseroptik GmbH) and our own independent measurements. According to Eq. (3) they result in an intra-cavity power built-up factor of about 140. Increasing the in-coupling reflectivity to $R_1 = 99.8\%$ would result in a built-up factor of about 570. Thus, the external pump power can be reduced by a factor of 570/140 ≈ 4 to about 3 mW simply by increasing the reflectivity of the PDC coupler at 775 nm.

4. DISCUSSION AND CONCLUSION

We demonstrated that the simultaneous conditions of double-resonance and quasi-phase-matching of a PPKTP squeezing resonator can be improved by coarse adjustment of the cavity length together with temperature fine-tuning. For a given squeezing resonator - with given waist size and given optical loss - the external pump power required for achieving a certain squeeze factor, can be minimized by selecting the input coupler reflectivity close to impedance matching of the pump light. Our experimental setup was not optimized in such a way but still reached oscillation threshold at moderately low pump power of 14 mW. Increasing the coupler reflectivity to $R_1(775\text{nm}) = 99.8\%$ will increase the pump power built-up from 140 to 570: an external pump power of just 3 mW can then produce the same spectrum with a squeeze factor of up to 13 dB. Further increasing the built-up factor at 775 nm is straightforward. The AR- and the HR coating of the crystal in our setup were also not optimized for low external pump power. For instance, an improved AR coating that enables $V_{\text{AR}} = 99.98\%$, an improved HR coating with $R_2 = 99.98\%$, and a coupler reflectivity of $R_1 = 99.9\%$ lead to $P_{\text{cav}}/P_{\text{Pump}} = 1100$, and the required external pump power reduces to 1.5 mW, again without affecting the squeeze spectrum.

At a level of just a few milliwatts of pump power the overall requirement of optical power is already dominated by the balanced homodyne detector. Some minimum optical power at the fundamental wave length is required for detecting the squeezed uncertainty of the quadrature amplitudes [4]. If the power is too low, the dark noise of the homodyne detector electronics limits the observable (useful) squeeze factor. Our experiment used
up to 12 mW for balanced homodyne detection. Since highly efficient second-harmonic generation from 1550 nm to 775 nm has been demonstrated [21] we conclude that the light power consumption for generation and efficient detection of squeezed quadrature uncertainties can be below 15 mW and clearly dominated by the detection scheme. To further reduce the required power, detection electronics with less dark noise need to be developed.

5. FUNDING INFORMATION

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