

# Quantum metrology with frequency up-converted squeezed vacuum states

Christoph Baune,<sup>1,2</sup> Jan Griesmer,<sup>2,3</sup> Axel Schönbeck,<sup>1,2</sup>  
Christina E. Vollmer,<sup>2,4</sup> Jaromír Fiurášek,<sup>5</sup> and Roman Schnabel<sup>1,2,\*</sup>

<sup>1</sup>*Institut für Laserphysik und Zentrum für Optische Quantentechnologien,  
Universität Hamburg, Luruper Chaussee 149, 22761 Hamburg, Germany*

<sup>2</sup>*Institut für Gravitationsphysik, Leibniz Universität Hannover and Max-Planck-Institut für  
Gravitationsphysik (Albert-Einstein-Institut), Callinstrasse 38, 30167 Hannover, Germany*

<sup>3</sup>*Institut für Festkörperphysik, Leibniz Universität Hannover,  
Appelstrasse 2, 30167 Hannover, Germany*

<sup>4</sup>*Present address: PTB Braunschweig, Bundesallee 100, 38116 Braunschweig and Institut für  
Quantenoptik, Leibniz Universität Hannover, Welfengarten 1, 30167 Hannover, Germany*

<sup>5</sup>*Department of Optics, Palacký University, 17. listopadu 12, 77146 Olomouc, Czech Republic*

\* [roman.schnabel@physnet.uni-hamburg.de](mailto:roman.schnabel@physnet.uni-hamburg.de)

**Abstract:** Quantum metrology utilizes nonclassical states to improve the precision of measurement devices. In this context, strongly squeezed vacuum states of light have proven to be a useful resource. They are typically produced by spontaneous parametric down-conversion, but have not been generated at shorter wavelengths so far, as suitable nonlinear materials do not exist. Here, we report on the generation of strongly squeezed vacuum states at 532 nm with 5.5 dB noise suppression by means of frequency up-conversion from the telecommunication wavelength of 1550 nm. In addition, we report on the sub-shot noise sensitivity of a Mach-Zehnder interferometer at 532 nm, which is the first demonstration of practicability of frequency up-converted squeezed states in quantum metrology.

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**OCIS codes:** (270.6570) Squeezed States; (190.7220) Upconversion; (190.4970) Parametric oscillators and amplifiers; (120.3180) Interferometry

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## 1. Introduction

The improvement of measurement devices with nonclassical states has been widely explored in many experiments. Squeezed vacuum states of light [1–3] in particular have successfully been employed in quantum metrology; they were used to enhance the sensitivity in spectroscopy [4], imaging [5] and gravitational wave detectors [6–10]. So far, squeezed states were only used to enhance the sensitivities in experiments, where the operating wavelength was in the near-infrared regime. However, spectroscopic measurements are performed at various optical wavelengths – including the visible regime. Consequently, squeezed states are an interesting resource for nonclassical sensitivity improvements, too. In addition, the shot-noise sensitivity of interferometric measurement devices generally increases with the inverse of the wavelength giving another motivation to generate squeezed vacuum states at short wavelengths.

Squeezed vacuum states of light are most successfully generated at near-infrared wavelengths by degenerate parametric down-conversion [11] from a strong second-harmonic field. However, the generation of squeezed states at visible wavelengths by using parametric down-conversion exhibits technical difficulties. Intense second harmonic fields at ultraviolet wavelengths would be required, which leads to high absorption and photorefractive damage [12]. Other techniques like four-wave mixing [13] also have not been successful to produce strongly squeezed vacuum states at short wavelengths so far. Furthermore, self-phase modulation [14] and second-harmonic generation [15] techniques are not able to produce squeezed vacuum states, i.e. squeezed states without a carrier field.

Frequency up-conversion of squeezed states from near-infrared wavelengths into the visible spectrum evades the problem of intense ultraviolet fields. The signal combines with a strong idler beam via sum-frequency generation to generate a signal at a higher optical frequency. The up-converted signal's wavelength is the shortest one involved in the process and crys-

tal damage is avoided because its intensity is very low. If this frequency conversion is very efficient, the quantum statistics are maintained [16, 17]; it was shown that this *quantum* up-conversion maintains features like  $g^{(2)}$ -functions with values smaller than unity [18] or quantum non-Gaussianity [19].

The up-conversion of squeezed vacuum states of light from 1550 to 532 nm was shown for the first time in [20], where nonclassical noise suppression of 1.5 dB below shot noise was achieved. Here, we present the design of nonlinear cavities optimized for low pump powers and demonstrate significantly higher squeezing in the up-converted field. We furthermore show a sensitivity enhancement of a Mach-Zehnder interferometer by using quantum up-converted states for the first time.

## 2. Efficient frequency up-conversion of squeezed vacuum states

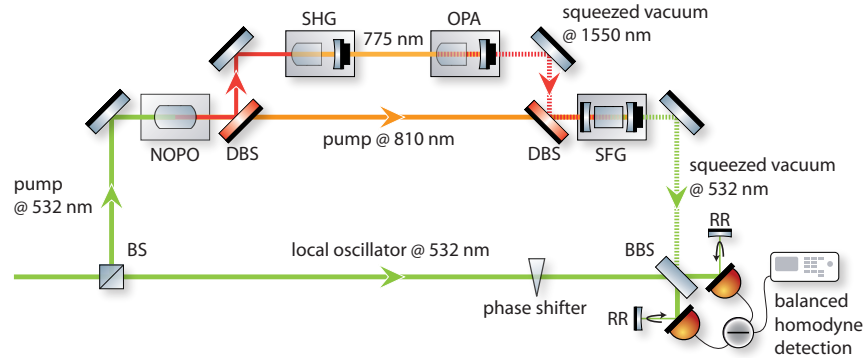


Fig. 1. Schematic of the experimental setup. A 532 nm beam of about 1 W power was split at a low transmission beam splitter (BS). Bright 810 and 1550 nm fields were produced via non-degenerate optical parametric oscillation (NOPO). Squeezed vacuum states at 1550 nm were produced in a degenerate optical parametric amplification cavity (OPA) and up-converted in the sum-frequency generation cavity (SFG) to 532 nm. The local oscillator for homodyne detection was provided by the second output port of the BS to ensure frequency stability with the up-converted state. SHG: second harmonic generation, DBS: dichroic beam splitter, BBS: balanced beam splitter, RR: retro-reflector.

The setup for quantum up-conversion of squeezed vacuum states from 1550 to 532 nm is schematically shown in Fig. 1. A continuous-wave 532 nm beam was used to pump a non-degenerate optical parametric oscillator (above threshold, NOPO). The generated fields at 1550 and 810 nm pumped a second harmonic generation cavity (SHG) and the sum-frequency generation cavity (SFG), respectively. The SFG was the same as used in [19] and showed a maximum conversion efficiency of 90.2 %.

Both the SHG and the optical parametric amplification cavity (OPA) were optimized for small pump powers. The nominal reflectivities of the incoupling mirrors were chosen to be 85 % at 1550 nm and 97.5 % at 775 nm for both cavities. Therefore, the cavities were doubly resonant at both the fundamental and harmonic wavelength. Simultaneous resonance of the two wavelengths was achieved by carefully choosing the cavity lengths, and the temperature of the periodically poled potassium titanyl phosphate (PPKTP) crystal was fine tuned to maintain quasi-phase matching conditions.

We estimated that more than 10 dB of squeezing at 1550 nm was coupled into the SFG. This could not be directly verified due to the compactness of our setup. Our homodyne detector at 1550 nm only achieved a fringe visibility slightly below 95%. However, we still measured

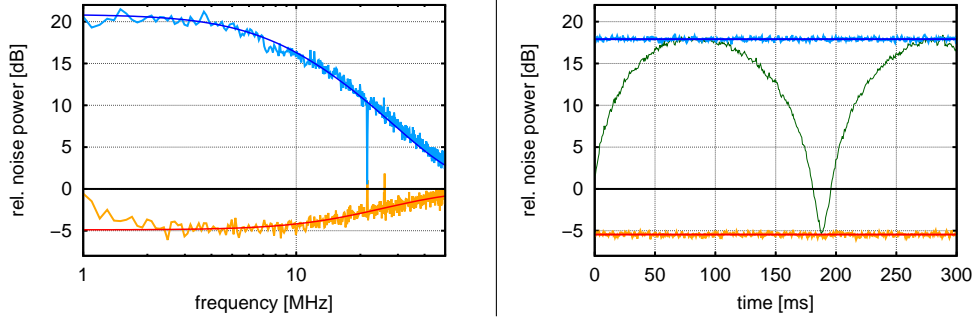


Fig. 2. Measurement of the up-converted squeezed vacuum states at 532 nm. On the left hand side, we show a power spectrum of the squeezed (orange) and anti-squeezed (cyan) quadrature noise normalized to the vacuum noise reference as well as a theoretical model (red and blue). It was recorded with a resolution bandwidth of 100 kHz. The dark noise was subtracted from the data to allow for a comparison with the theory. For frequencies below 2 MHz the dark noise of our homodyne detector dominated the measurement and the dark noise correction was too poor to reveal the full squeezing strength. The spikes at 21 MHz and 26 MHz were due to electronic pick-up in the dark noise caused by a modulation frequency used for cavity locking. On the right hand side, our best zero-span measurement at a Fourier frequency of 5 MHz is shown, recorded with a resolution bandwidth of 300 kHz and without corrections for dark noise. Here, also a continuous phase scan of the signal quadrature (green) is shown. The variance of the squeezed quadrature dropped 5.5 dB below the shot noise, whereas the anti-squeezed quadrature variance was 18 dB above.

more than 8.4 dB nonclassical noise suppression with a respective anti-squeezing of 19 dB, which indicates the presence of significantly higher values.

The homodyne detector at 532 nm was built with two photodiodes from Hamamatsu (Type S5973-02). The protection windows were removed and the diodes were tilted horizontally by about 45 degrees. Surface reflections were decreased by using p-polarized light. Residual reflections were re-focused onto the photodiodes with highly reflective concave mirrors (focal length 25 mm). The detection efficiency of the photodiodes could thereby be increased to up to 90 %, which was determined independently by directly measuring the photocurrent when a diode was illuminated with a well known light power.

Figure 2 shows a measurement of a power spectrum and a zero-span measurement of the signal field. We demonstrated a non-classical noise suppression over a wide frequency range from 1 to 50 MHz. About 5.5 dB shot noise reduction was measured at a sideband frequency of 5 MHz with a respective anti-squeezing of 17.9 dB. This state corresponded to an initial squeezing value of 19.3 dB subject to 27 % optical loss. (To calculate the optical loss, the dark noise was subtracted from the data, which led to slightly higher squeezing and anti-squeezing values; -5.55 and 17.94 dB, respectively.) We estimated the contribution of phase noise to be negligible in our experiment. The major optical loss sources were the up-conversion efficiency and the quantum efficiency of the photodiodes in the homodyne detector (both about 10 % losses). Minor contributions came from non-perfect mode-matchings (2.5 % loss), a limited visibility at the homodyne detector (2 % loss), and propagation losses (5 % loss, mainly induced by an optical isolator in the path between the OPA and the SFG).

The theoretical fits for the (anti-)squeezed power spectra  $S^-$  ( $S^+$ ) were obtained with the

formulae (based on [21])

$$S^+(\omega) = 1 + \eta \frac{\kappa^2}{\kappa^2 + \omega^2} \frac{4\gamma|\varepsilon|}{(\gamma - |\varepsilon|)^2 + \omega^2}, \quad (1)$$

$$S^-(\omega) = 1 - \eta \frac{\kappa^2}{\kappa^2 + \omega^2} \frac{4\gamma|\varepsilon|}{(\gamma + |\varepsilon|)^2 + \omega^2}, \quad (2)$$

where  $\omega/2\pi$  is the sideband frequency,  $\eta$  is the detection efficiency,  $\gamma/2\pi$  and  $\kappa/2\pi$  are the bandwidths (HWHM) of the OPA and SFG, respectively, and  $\varepsilon$  is the pump parameter. The parameters ( $\gamma = 2\pi 60$  MHz,  $\kappa = 2\pi 40$  MHz,  $\varepsilon = 0.77\gamma$ ) were in good agreement with independently determined values.

### 3. Quantum enhancement of a Mach-Zehnder interferometer at 532 nm

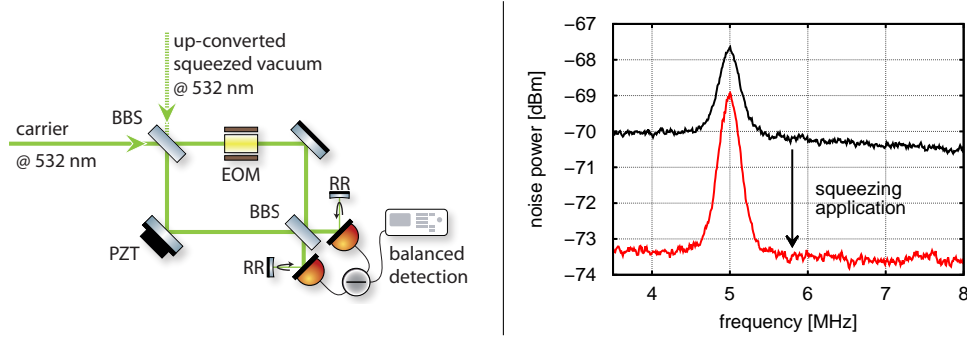


Fig. 3. Setup (left) and experimental results (right) of a squeezed light enhanced Mach-Zehnder interferometer. The carrier at 532 nm and the up-converted squeezed vacuum were the inputs of the interferometer, that consisted of two highly reflective mirrors and two balanced beam splitters (BBS). The two output ports were analyzed with a balanced detector. An electro-optic modulator (EOM) in one of the interferometer arms generated a phase modulation at 5 MHz, which is clearly visible in the spectrum (right). When the up-converted squeezing was applied, the noise floor dropped and the signal-to-noise ratio improved. The resolution and video bandwidth were 300 kHz and 300 Hz, respectively, and no dark noise subtraction was performed. PZT: piezo-electric transducer to lock the interferometer at mid-fringe, RR: retro-reflector.

The Mach-Zehnder interferometer consisted of two beam splitters and two highly reflective mirrors. A schematic of the device is shown in Fig. 3. An electro-optic modulator (EOM) generated a phase modulation at 5 MHz. The output was measured with a balanced detector. Again, the reflected light was re-focused onto the photodiodes to increase the detection efficiency. We mounted one of the highly reflective mirrors of the Mach-Zehnder interferometer onto a piezo-electric transducer. This enabled us to scan the interferometer's phase to adjust the visibility and eventually lock it to mid-fringe. The signal could be detected with a higher signal-to-noise ratio compared to vacuum (black), when squeezed vacuum (red trace) was injected into the signal port of the interferometer. The observation of about -3.3 dB squeezing improves the phase sensitivity by the equivalent of a 2.1-fold increase in coherent light power, i.e. by a factor of  $\sqrt{2.1} = 1.46$ . A slightly lower conversion efficiency (80 %) and additional optics (including the EOM) increased the optical loss, which degraded the observable squeezing from 5.5 dB to 3.3 dB.

#### 4. Conclusion and outlook

We demonstrated frequency up-conversion of strongly squeezed vacuum states of light with a conversion efficiency of up to 90.2 %. The up-converted states at a wavelength of 532 nm were measured with a noise suppression of up to 5.5 dB below shot noise, when the alignment, servo phase control as well as the temperature for phase matching of all subsystems – which included four nonlinear cavities – were optimized. A squeezing resonator that was also resonant for the pump light (doubly resonant) helped to produce good squeezing levels, even for the low pump power available. The linewidth of the up-conversion cavity was increased to minimize the effect of intra-cavity loss for given pump powers [24]. Furthermore, the detection efficiency of the homodyne detector was optimized by re-focussing reflected light onto the chip. The observed squeezing spectrum is in excellent agreement with our theoretical model that incorporates transfer functions of not only the squeezing resonator but also the up-conversion cavity.

The compatibility of the up-converted states with a Mach-Zehnder interferometer was demonstrated by an improvement of the signal-to-noise ratio by a factor of 1.46. This result verified that highly efficient up-conversion of squeezed vacuum states opens the possibility of sensitivity enhancements of phase measurements, such as those for gravitational wave detectors, where the operating wavelength is reduced to 532 nm [25]. Furthermore, spectroscopic measurements might greatly benefit from this technique, as in principle the entire visible wavelength regime can be covered by means of quantum up-conversion.

The optimum working point of our experiment was difficult to maintain, as infrequent mode hops of the NOPO slightly changed the precise wavelengths of the pump fields at 810 and 1550 nm. Consequently, the phase matching conditions of the subsequent nonlinear cavities varied and the conversion efficiencies decreased. This problem could possibly be circumvented by amplifying the 1550 nm pump field for the SHG with a fiber amplifier to ensure that enough pump power for the OPA is always available to produce strongly squeezed states. In this case, only the NOPO and SFG have to be adjusted to provide high up-conversion efficiency.

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