Quantum engineering of squeezed states for quantum communication and metrology

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We report the experimental realization of squeezed quantum states of light, tailored for new applications in quantum communication and metrology. Squeezed states in a broad Fourier frequency band down to 1 Hz has been observed for the first time. Non-classical properties of light in such a low frequency band is required for high efficiency quantum information storage in electromagnetically induced transparency (EIT) media. The states observed also cover the frequency band of ultra-high precision laser interferometers for gravitational wave detection and can be used to reach the regime of quantum non-demolition interferometry. And furthermore, they cover the frequencies of motions of heavily macroscopic objects and might therefore support the attempts to observe entanglement in our macroscopic world.

Squeezed states of light constitute a rather peculiar form of light [1]. Their statistical properties cannot be explained by arrival times of independent photons, and some of their field measures show less quantum noise than those of the vacuum state, which is the light's ground state with *zero* average photon number. Squeezed states were first demonstrated by Slusher *et al.* in 1985 [2]. Later, experimental techniques for the complete characterization of squeezed states have been demonstrated [3]. Squeezed states have been used to construct entangled states of light and to demonstrate quantum teleportation [4, 5]. Recently, they have been used to engineer Schrödinger kitten states for quantum information networks [6, 7]. Applications in the field of metrology and high precision measurements have been demonstrated in several proof of principle experiments [8, 9, 10]. In all these experiments squeezed states on rather short time scales below a microsecond, corresponding to Fourier frequencies above a megahertz, were employed. But, many applications require engineering of squeezed states defined on much longer time scales. High precision laser interferometers can be turned into quantum non-demolition (QND) measurement devices by employing squeezed states, thereby entering the field of *quantum* metrology. Possible examples for such interferometers are the currently operated gravitational wave detectors [11]. Here stably controlled squeezed states in the gravitational wave detection band of several kilohertz down to a few hertz will be required. Squeezed states in the same low frequency regime can be used to create entanglement between light and atoms to push a *light-atom* interferometer beyond its standard-quantum limit [12]. In the field of quantum communication, the coherent delay and the storage of nonclassical states of light are desired. Recently it has been theoretically shown that this can be achieved with electromagnetically induced transparency (EIT) [13]. Due to the narrow transparency windows, squeezed states at and below kilohertz frequencies are required [14]. In quantum information science, the creation of entangled states of macroscopic objects is of great scientific interest [15, 16]. They allow the study of quantum decoherence and the transformation from the microscopic quantum world to our macroscopic classical world. It has been theoretically shown that squeezed states of light can be used to entangle two suspended macroscopic mirrors [17]. The quantum variables of the entanglement will be the positions and momenta of vibrational or pendulum modes of the mirrors. For massive, macroscopic objects of hundreds of grams or even kilograms, these modes will also occur at rather low frequencies. *Quantum engineering* is therefore demanded to prepare new states of light, whose nonclassical properties reveal themselves on time-scales directly graspable for human beings.

In two pioneering experiments, squeezed states at audio frequencies were first generated [18], and a coherent control scheme for stable application of such states demonstrated [19]. However, at Fourier frequencies below one kilohertz the overall noise level of the optical states increased in both experiments, for reasons that, up to now, had not been understood. Here we report the observation of squeezed quantum states of light at Fourier frequencies below the kilohertz regime down to 1 Hz. The measured quantum noise levels were in perfect agreement with theoretical predictions. *Parasitic interferences* were identified to be responsible for the previously observed discrepancy at low frequencies.

Quantum states of optical fields can be detected and fully characterized with a *balanced homodyne detector* [3]. The measurement quantities are the field quadratures, e.g. amplitude or phase quadratures, and their variances. A rather impressive property of such a detector is its capability to measure even fluctuations of fields that do not contain *any* photons on average, i.e. fields in so-called vacuum states. These vacuum fluctuations contribute to the zero point energy which is a manifestation of quantum physics after which any oscillator, like a single-mode state of light, cannot have zero energy, otherwise Heisenberg's uncertainty relation would be violated [20]. A balanced homodyne detector is also a perfect device for the detection of squeezed states of light. In this case the variance of a certain field quadrature is found to be *squeezed* below the variance of the corresponding vacuum field.

In balanced homodyne detection dim quantum states of the signal beam are interfered with an intense auxiliary laser beam (local oscillator, LO) on a beam splitter with 50% power re-

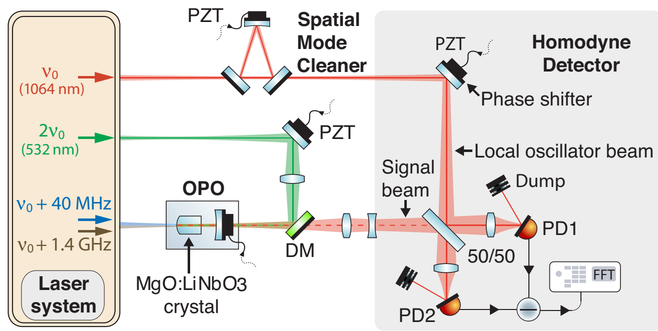

Figure 1: Schematic of the experiment utilizing four continuous wave laser beams. Squeezed states at low Fourier frequencies around carrier frequency $\nu_0 = c/1064\,$nm (with c the speed of light) were produced utilizing optical parametric oscillation (OPO). This parametric process was initiated inside a birefringent crystal made from MgO:LiNbO$_3$ by pumping the system with a green laser beam at 532 nm. Two additional laser beams were also focussed into the crystal. They served as control beams for piezo-electric length control of the cavity and phase control of the green beam. The fourth laser beam at 1064 nm was used as the local oscillator (LO) to observe the squeezed states by balanced homodyne detection. DM: dichroic mirror; PD: photo diode; PZT: piezo-electric transducer for positioning of mirrors.

flectivity, as shown in Fig. 1. The interference with the LO leads to an optical amplification of the measured signal field quadrature by a large factor, which is necessary to reach levels far above electronic noise of photodiodes and subsequent electronic circuits. Each output field from the 50/50 beam splitter is focussed onto a semiconductor photodiode. The final signal is derived from the difference of the two photocurrents, which is spectrally analyzed, for example using a Fast-Fourier-Transformation (FFT). Please note that noise contributions from the LO beam cancel in balanced homodyne detection. If the signal field and the LO interfere *in* phase, the balanced homodyne detector measures the signal state's *amplitude* quadrature $\hat{q}_1(\Omega, \Delta\Omega, t)$ where $\Omega/2\pi$ is the Fourier frequency and $\Delta\Omega/2\pi$ is the detection resolution bandwidth (RBW). If the LO's optical path length is changed by a quarter wave length the homodyne detector measures the phase quadrature $\hat{q}_2(\Omega, \Delta\Omega, t)$. The amplitude, together with the phase quadrature, form a set of two non-commuting observables. The simultaneous precise knowledge of both their values is limited by Heisenberg's uncertainty relation.

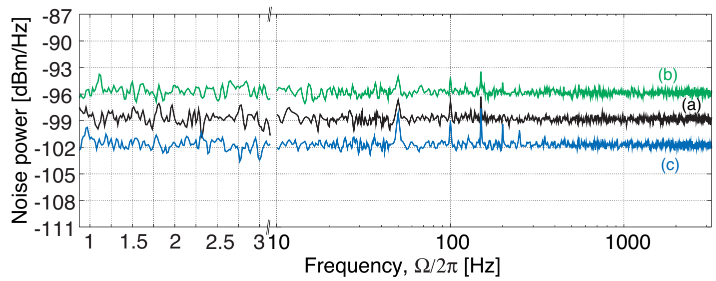

Figure 2: Noise powers (variances) of field quadratures for a spectrum of vacuum states at different sideband frequencies. Three different local oscillator powers were used: (a) 464 μW, (b) 928 μW, and (c) 232 μW. All traces are pieced together from five FFT frequency windows: 0.8–3.2 Hz, 10–50 Hz, 50–200 Hz, 200–800 Hz, 800 Hz–3.2 kHz with resolution bandwidths (RBW) of $\Delta\Omega/2\pi$=15.63 mHz, 250 mHz, 1 Hz, 2 Hz and 4 Hz, respectively. Each measurement point is the averaged root mean square value of 75, 100, 100, 400 and 400 measurements, again respectively for the five FFT windows. Peaks at 50 Hz and harmonics were due to the electric mains. Here, the electronic dark noise has been subtracted from the data.

Since the vacuum state sets the reference for squeezed states, we first present measurements of vacuum fluctuations. Vacuum states were produced by carefully blocking the signal input beam of the balanced homodyne detector without introducing scattered fields, while keeping the LO beam. Fig. 2 shows the spectral noise powers of optically amplified vacuum fluctuations of an optical field mode at 1064 nm for three different LO powers measured with our homodyne detector. We plot the spectral decomposition of the vacuum noise for sideband frequencies $\Omega/2\pi$ between 800 mHz and 3.2 kHz. For all three LO powers the signal port of our homodyne detector was empty and the observation of pure vacuum noise was confirmed in the following way. Firstly, the measured spectral noise powers scaled linearly with LO power. Secondly, the noise spectra were white, i.e. independent of Fourier frequency $\Omega/2\pi$. Both properties of vacuum noise are predicted from theory and were clearly found in our observations as presented in Fig. 2. Thirdly, independent measurements of the amplification factors of all electronic components used confirmed *quantitatively* within $\pm$0.5 dB uncertainty, that indeed pure vacuum noise was observed. We point out that the measurement of the frequency interval in Fig. 2 lasted for more than half an hour for each LO power, thereby demonstrating long term stability of our detector-setup. Our results in Fig. 2 represent the first successful detection of vacuum states at sub-audio and audio frequencies below one kHz with a white (flat) spectrum.

We now discuss how an optical field with less fluctuations than vacuum states at sideband frequencies down to 1 Hz was generated. A simplified schematic of the experiment is shown in Fig. 1. In total four linearly polarized, continuous-wave laser beams were used. They originated from two monolithic non-planar Nd:YAG continuous wave ring laser devices operating at 1064 nm. One of the laser devices provided the reference frequency ν_0. Parts of this field were converted into laser radiation at $2\nu_0$ and ν_0+40 MHz, utilizing a birefringent crystal and an acousto-optical modulator, respectively, (crystal and modulator are not shown in Fig. 1). The second laser device was phase locked to the first one and was operated at a frequency of ν_0+1.4 GHz. The frequency-doubled and frequency-shifted beams were all mode-matched into a nonlinear standing-wave cavity which housed a 6.5 mm long, 7% doped MgO:LiNbO$_3$ crystal. The frequency-doubled beam was horizontally polarized and served as the pump field for type I degenerate optical parametric oscillation (OPO) below threshold. This process deamplified the quadratures, $\hat{q}_1$, of all sideband fields of the vertically polarized cavity resonance mode at the fundamental frequency ν_0, defined at Fourier frequencies up to the cavity linewidth of approximately 27 MHz. Due to the OPO process and in accordance with Heisenberg's uncertainty relation, the orthogonal quadratures $\hat{q}_2$ were then complementarily amplified.

Since no laser radiation around the frequency ν_0 was injected into the OPO cavity, the parametric process only acted on vacuum fluctuations and produced squeezed vacuum states for all frequencies within the OPO cavity linewidth. The squeezed states were coupled out in the backwards direction of the injected pump field via a dichroic mirror and were sent to the balanced homodyne detector. The frequency-shifted beams were used to sense the two essential degrees of freedom of our experiment. The first one was the length of the OPO cavity. Only if the OPO cavity was kept on resonance for the reference frequency ν_0 (half the pump field frequency) squeezed states were produced. The second one was the relative phase of the second harmonic OPO pump field with respect to the local oscillator of the downstream experiment. Only when this relative phase was zero could the squeezed amplitude quadrature $\hat{q}_1$ be observed by our homodyne detector. The OPO cavity length was sensed by the beam at ν_0+1.4 GHz. This beam was orthogonally polarized with respect to the squeezed cavity mode and its frequency shift exactly compensated the birefringence of the OPO crystal. The phase of the pump field was sensed by the beam at ν_0+40 MHz; the procedure has been described in much detail in [19, 21]. The information from the two frequency shifted beams were then used to fix both degrees of freedom by precisely positioning of the relevant mirrors using piezo-electric transducers and electronic feedback loops. The special and important property of the scheme was that solely *frequency shifted* beams were used. If a field directly at the reference frequency ν_0 was used, an observation of squeezed states at low frequencies would not be possible, as shown in [18].

The observed variances of squeezed states between 1 Hz and 3.2 kHz are presented in Fig. 3, trace (e). For a significant portion of the shown spectrum the quantum noise variance was squeezed by an average value of 6.5 dB, i.e. 4.5 times smaller than the vacuum noise variance, trace (d). This value exactly matched the theoretical prediction for our experiment as discussed below. Trace (f) shows the dark-noise contribution of the homodyne detector itself.

The strength of the observed squeezing was limited by the finite optical parametric gain of the OPO cavity and the total optical loss the squeezed states suffered before being detected. For the measurements shown in Fig. 3 a gain of $g = 12 \pm 0.5$ was used and which was achieved with a pump power of 100 mW. Optical losses inside the OPO, in the beam path and in the homodyne detector added up to $l = 0.15 \pm 0.04$. The error bar was mainly due to the uncertainty in the quantum efficiency of the homodyne detector photodiodes (PD1, PD2 in Fig. 1, type: ETX500). Both values (g, l) were deduced from separate measurements. They can be used to estimate the expected strength of squeezing (for Fourier frequencies much smaller than the OPO

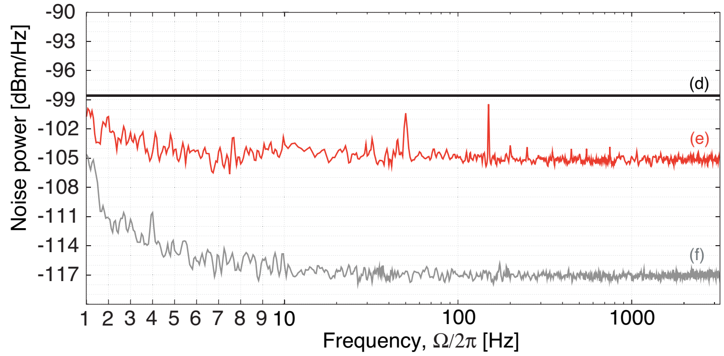

Figure 3: Trace (d) shows the (theoretical) vacuum noise level of our homodyne detector with 464 μW local oscillator power as confirmed in Fig. 2. Trace (e) shows the noise powers of squeezed states measured with the same local oscillator power. Squeezed vacuum noise was observed throughout the complete spectrum from 1 Hz to above 3 kHz. A nonclassical noise suppression of up to 6.5 dB below vacuum noise was observed here. FFT frequency windows: 1–10 Hz, 10–50 Hz, 50–200 Hz, 200–800 Hz, 800 Hz–3.2 kHz. RBW: 62.5 mHz, 250 mHz, 1 Hz, 2 Hz and 4 Hz. Averages: 30, 100, 100, 400 and 400. The dark noise (f) was not subtracted from the measured data.

cavity line width) and indeed provide the observed value: $-10\cdot\log_{10}(l+(1-l)/g)\approx$6.5 dB.

Compared with other experiments at audio frequencies, see for example Ref. [19], the squeezing strength reported here has been considerably increased. The improvement was enabled by a spatial mode cleaning cavity in the LO beam path right before the homodyne detector 50/50 beam splitter. With this cavity the spatial overlap, i.e. the interference contrast between LO and signal beam, could be increased up to a fringe visibility of 98.3%. We note that the squeezed variances shown in Fig. 3 represent typical results with high long term stability of the setup. With an increased second harmonic pump power the classical OPO gain changed from approximately 12 to 40±4 and up to 7.2 dB squeezing could be directly observed (7.5 dB when the dark noise was subtracted). In this regime stable operation of the OPO cavity was still possible for several minutes. However, for longer periods thermal fluctuations inside the OPO crystal due to absorption and power fluctuations of the pump beam moved the frequency shift between the fundamental mode and the coherent control beam away from its required value of 1.4 GHz.

Long term stable operation with high parametric gain should be possible with an electro-optical stabilization of the second harmonic pump power. At sub-audio frequencies below 5 Hz, trace (e) shows degraded squeezing strengths. An averaged value of 1.5 dB below vacuum noise was observed at 1 Hz. The degradation was partly due to a rising electronic dark noise level (trace (f)). By subtracting the dark noise, the nonclassical noise suppression recovered to 3.5±0.5 dB which was, however, still significantly lower than 6.5 dB as observed at other frequencies. This degradation was due to remnant parasitic interferences as described in the next paragraph.

The generation and observation of squeezed vacuum states of light at (sub-) audio frequencies reported here, were made possible by a significant reduction of *parasitic interferences*. Parasitic interferences are typically produced by moving surfaces that scatter photons into the low frequency detection band of the homodyne detector. Scattered light fields were identified to originate from the micro-roughness of the optical surfaces, non-perfect anti-reflection coatings and residual transmissions of high reflection mirrors. They were partly transmitted through the OPO cavity and entered our homodyne detector via its signal port. Other scattered fields were found to directly hit the photodiodes of the homodyne detector from other directions. In all cases these fields sensed multiple scattering processes from various optics and optic mounts. The scattering surfaces of these objects continuously moved through thermal expansion and acoustic vibrations. During the scattering processes optical sideband fields were produced at corresponding Fourier frequencies and higher harmonics. For any such scattered field which interfered with the homodyne local oscillator the whole setup acted like a sensitive interferometer measuring the motions of the scattering surfaces. These parasitic interferences easily masked the vacuum noise. Given a great number of such sources of scattered light with increasing motion amplitudes towards lower frequencies but low mechanical quality factors, a rather smooth monotonic increase was produced as observed for example in [19]. We reduced the parasitic interferences firstly, by carefully shielding our homodyne detector against scattered light fields and secondly, by reducing air turbulence, vibrations and temperature fluctuations of our experiment. The success of our experimental improvements proved, that the previous limitations to the observation of squeezed states were purely optical and were not due to any type of noise related to the photodiodes' semiconductor material. We could further validate that noise of the LO, amplified by a residual signal port field at optical frequency ν_0, gave no significant contribution to the experiment reported in [19]. Therefore, previously reported homodyne detector noise spectra were, most likely, not vacuum noise dominated below one kilohertz. In the same way squeezed variance spectra at these frequencies were also contaminated by additional noise from scattered fields.

In conclusion, our experiments expanded the range of Fourier frequencies at which squeezed states of light have been engineered by two decades. We reached the frequency regime in which vibrations and rotations of real macroscopic objects of human's everyday experience occur opening new avenues for high precision optical measurements of quantum metrology, as well as for quantum memories as a key element of many quantum communication protocols. A nonclassical noise suppression of up to 7.2 dB below vacuum noise variance at audio Fourier frequencies was achieved. Based upon our investigations we believe that squeezed states at even lower frequencies with also higher degrees of squeezing can be allocated by further protection against parasitic interferences and reduction of optical losses.

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