Available online at www.sciencedirect.com
SCIENCE DIRECT®
Optics Communications 240 (2004) 185–190
OPTICS COMMUNICATIONS
www.elsevier.com/locate/optcom

Squeezed light at sideband frequencies below 100 kHz from a single OPA

R. Schnabel [a,*], H. Vahlbruch [a], A. Franzen [a], S. Chelkowski [a], N. Grosse [a], H.-A. Bachor [b], W.P. Bowen [b], P.K. Lam [b], K. Danzmann [a]

[a] *Max-Planck-Institut für Gravitationsphysik (Albert-Einstein-Institut), Institut für Atom- und Molekülphysik, Universität Hannover, Callinstrasse 38, 30167 Hannover, Germany*

[b] *Department of Physics, Faculty of Science, The Australian National University, ACT 0200, Australia*

Received 14 April 2004; received in revised form 15 June 2004; accepted 15 June 2004

Abstract

Quantum noise of the electromagnetic field is one of the limiting noise sources in interferometric gravitational wave detectors. Shifting the spectrum of squeezed vacuum states downwards into the acoustic band of gravitational wave detectors is therefore of challenging demand to quantum optics experiments. We demonstrate a system that produces nonclassical continuous variable states of light that are squeezed at sideband frequencies below 100 kHz. A single optical parametric amplifier (OPA) is used in an optical noise cancellation scheme providing squeezed vacuum states with coherent bright phase modulation sidebands at higher frequencies. The system has been stably locked to a reference laser beam for half an hour limited by thermal stability of our laboratory.

PACS: 04.80.Nn; 42.50.Dv; 42.65.Yj
Keywords: Gravitational wave detectors; Squeezed states

Currently, an international array of first-generation, kilometer-scale laser interferometric gravitational-wave detectors, consisting of GEO 600 [1], LIGO [2], TAMA 300 [3] and VIRGO [4], targeted at gravitational-waves (GW) in the acoustic band from 10 Hz to 10 kHz, is going into operation. These detectors are all Michelson interferometers. Intense laser light is injected from the bright port, whereas the output port is locked to a dark fringe. The anti-symmetric mode of arm-length oscillations (e.g., excited by a gravitational wave) yields a sideband modulation field in the anti-symmetric

* Corresponding author. Tel.: +49-511-762-19169; fax: +49-511-762-2784.
E-mail address: roman.schnabel@aei.mpg.de (R. Schnabel).

0030-4018/$ - see front matter
doi:10.1016/j.optcom.2004.06.030

(optical) mode which is detected at the dark output port. In general, several technical noise sources, and more fundamentally, thermal noise and quantum noise (radiation pressure and shot-noise [5,6]) contribute to the signal noise floor. Recently it has been shown that thermal noise and radiation pressure noise might be sensed by additional short high-finesse cavities and subsequently reduced [7,8]. Shot-noise on the other hand can be reduced by squeezed vacuum states of light injected into the dark port of the interferometer ([9] and references therein). Experimental progress has been reported in [10] where the shot-noise of a power-recycled table-top interferometer has been reduced by squeezed states at about 5 MHz.

Squeezed states of light, when used to improve the (quantum noise limited) sensitivity of GW interferometers over a broad spectrum, need to meet stringent requirements. First of all GW interferometers require squeezed vacuum states at frequencies in the acoustic detection band (10 Hz to 10 kHz). Such states have not been demonstrated so far (see last paragraph of this paper) since controlled demonstration of squeezed light involves a reference laser source which is in general classically noisy in the kHz-regime and below. Noise cancellation schemes have been proposed to enhance squeezing utilizing Kerr non-linearity in fibers [11], laser diodes [12] and second harmonic generation [13]. In a recent experiment, continuous wave squeezing at frequencies as low as 220 kHz was demonstrated [14] utilizing two squeezed beams from two independent optical parametric amplifiers (OPAs). A second requirement on squeezed states is that a phase reference still has to be present to enable a stable lock to the interferometer. Squeezed vacuum states from noise cancellation schemes as mentioned above are generally capable of carrying phase modulation sidebands at some higher frequency. Thirdly, for a broad band improvement of GW interferometers, frequency dependent squeezing is required [5].

In this paper, we report the observation of a squeezed vacuum state at a sideband frequency of 80 kHz utilizing a single dim squeezed beam and a classically correlated bright coherent laser beam in a Mach–Zehnder configuration. Broadband vacuum squeezing from 130 kHz up to several MHz was also measured. Consider a Mach–Zehnder interferometer with independently adjustable beamsplitter reflectivities (ε_1,ε_2) and an OPA in one arm of the interferometer (Fig. 1). We theoretically and experimentally show that this configuration can be operated as a common mode noise cancellation experiment providing a squeezed vacuum with phase modulation sidebands at the interferometer output. First let us derive the expression for the amplitude quadrature operator in frequency space $\hat{X}^+_{\text{out}}$. We consider amplitude noise from our laser source ($\hat{X}^+_{\text{src}}$) and vacuum fluctuations entering lossy ports of our set-up ($\hat{X}^+_{\text{vac}}$, $\hat{X}^+_{\text{loss}}$, $\hat{X}^+_{\text{oc}}$). A bright coherent state represented by the quadrature operator $\hat{X}^+_{\text{src}}$ encounters the first beamsplitter, with reflectivity ε_1 that couples in the vacuum state entering through the unused input port, thereby producing two fields

$$\hat{X}^+_{\text{ic}} = \sqrt{\varepsilon_1}\hat{X}^+_{\text{vac}} + \sqrt{1-\varepsilon_1}\hat{X}^+_{\text{src}} \quad \text{and}$$
$$\hat{X}^+_{\text{ref}} = \sqrt{1-\varepsilon_1}\hat{X}^+_{\text{vac}} - \sqrt{\varepsilon_1}\hat{X}^+_{\text{src}}.$$

The field $\hat{X}^+_{\text{ic}}$ is used to seed a single OPA consisting of a $\chi^{(2)}$ non-linear medium inside a highly under-coupled optical resonator. In our scheme the OPA acts as a de-amplifier resulting in a dim amplitude squeezed transmitted output field $\hat{X}^+_{\text{sqz}}$. In

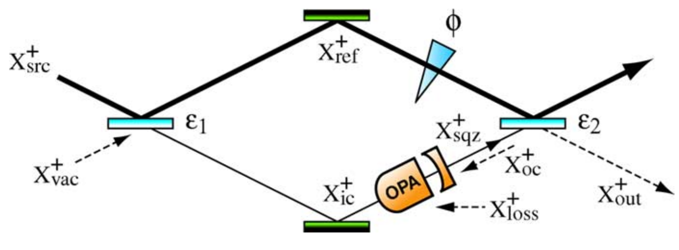

Fig. 1. Schematic of our experiment to produce squeezed vacuum states of light below 100 kHz utilizing a single OPA.

this configuration the overall non-linearity g of the OPA resonator, which is dependent on the crystal non-linearity, second harmonic pump power and mode matching of fundamental and pump beams, becomes real and negative. We follow the treatment of optical parametric oscillation and amplification which uses the linearized formalism of quantum mechanics and the mean field approximation as given in [15] yielding the OPA transfer function

$$\hat{X}^{+}_{\mathrm{sqz}} = \left\{ \sqrt{4\kappa_{\mathrm{ic}}\kappa_{\mathrm{oc}}}\hat{X}^{+}_{\mathrm{ic}} + \sqrt{4\kappa_{\mathrm{loss}}\kappa_{\mathrm{oc}}}\hat{X}^{+}_{\mathrm{loss}} + (2\kappa_{\mathrm{oc}} - \mathrm{i}\Omega - \kappa + g)\hat{X}^{+}_{\mathrm{oc}} \right\} / (\mathrm{i}\Omega + \kappa - g), \tag{1}$$

where κ_{ic}, κ_{oc}, κ_{loss} are the input, output and loss coupling rates, respectively, for the OPA resonator with total decay rate $\kappa = \kappa_{\mathrm{ic}} + \kappa_{\mathrm{oc}} + \kappa_{\mathrm{loss}}$. The sideband frequency of detection is set by $\Omega/2\pi$. The reference beam $\hat{X}^{+}_{\mathrm{ref}}$ is given a phase shift ϕ before being interfered with the squeezed beam $\hat{X}^{+}_{\mathrm{sqz}}$ on the second beamsplitter ε_2 to give $\hat{X}^{+}_{\mathrm{out}} = \sqrt{\varepsilon_2}\hat{X}^{+}_{\mathrm{sqz}} + \mathrm{e}^{-\mathrm{i}\phi}\sqrt{1-\varepsilon_2}\hat{X}^{+}_{\mathrm{ref}}$ on the chosen output port. Fully expanding this expression and collecting terms it becomes clear that

$$\begin{aligned}\hat{X}^{+}_{\mathrm{out}} = \Big\{ & \hat{X}^{+}_{\mathrm{src}} \Big[\sqrt{(1-\varepsilon_1)\varepsilon_2}\sqrt{4\kappa_{\mathrm{ic}}\kappa_{\mathrm{oc}}} - \sqrt{\varepsilon_1(1-\varepsilon_2)} \\ & \times (\mathrm{i}\Omega + \kappa - g)\mathrm{e}^{-\mathrm{i}\phi} \Big] + \hat{X}^{+}_{\mathrm{vac}} \Big[\sqrt{\varepsilon_1\varepsilon_2}\sqrt{4\kappa_{\mathrm{ic}}\kappa_{\mathrm{oc}}} \\ & + \sqrt{(1-\varepsilon_1)(1-\varepsilon_2)}(\mathrm{i}\Omega + \kappa - g)\mathrm{e}^{-\mathrm{i}\phi} \Big] \\ & + \hat{X}^{+}_{\mathrm{oc}} [\sqrt{\varepsilon_2}(2\kappa_{\mathrm{oc}} - \mathrm{i}\Omega - \kappa + g)] \\ & + \hat{X}^{+}_{\mathrm{loss}} \Big[\sqrt{\varepsilon_2}\sqrt{4\kappa_{\mathrm{loss}}\kappa_{\mathrm{oc}}} \Big] \Big\} / (\mathrm{i}\Omega + \kappa - g). \end{aligned} \tag{2}$$

The value of ϕ is set to zero to ensure that complete cancellation of the coherent amplitude at the chosen output port is possible. The sideband detection frequencies are assumed to be within the linewidth of the OPA resonator such that the approximation $\Omega \ll \kappa$ is valid. From the above equation the noise spectrum of the output field as measured by a homodyne detector may be calculated using $V^{+}_{\mathrm{out}} = \langle (\hat{X}^{+}_{\mathrm{out}})^2 \rangle - \langle \hat{X}^{+}_{\mathrm{out}} \rangle^2$. The input vacuum states are assumed to be uncorrelated amongst themselves and with variances set to $V^{+}_{\mathrm{vac}} = V^{+}_{\mathrm{oc}} = V^{+}_{\mathrm{loss}} = 1$. The laser source contribution ($\hat{X}^{+}_{\mathrm{src}}$) to the output field may be completely removed provided that the following condition, consisting of a relation between both beamsplitter reflectivities and OPA resonator properties, is satisfied

$$\varepsilon_1^{+} = 1 - \left[1 + \frac{\varepsilon_2}{(1-\varepsilon_2)} \frac{4\kappa_{\mathrm{ic}}\kappa_{\mathrm{oc}}/\kappa^2}{(1-g/\kappa)^2} \right]^{-1}. \tag{3}$$

This condition can be interpreted as ε_1 compensating for the classical OPA gain in order to achieve perfect interference visibility. With ε_1 suitably adjusted, the output noise spectrum becomes a squeezed vacuum of variance V^{+}_{sqzvac}. Here the superscript $^{+}$ describes the fact that a phase reference might still be given by a modulation field at higher frequencies.

$$V^{+}_{\mathrm{out}}(\varepsilon_1 = \varepsilon_1^{+}) = V^{+}_{\mathrm{sqzvac}} = 1 + \varepsilon_2 \frac{4\kappa_{\mathrm{oc}} g}{(\kappa - g)^2}. \tag{4}$$

It can be seen that ε_2 should be close to one to keep losses on the squeezing as small as possible. In the experiment described below we chose $1-\varepsilon_2 = 1\%$, which is already a small value in comparison with typical losses in current squeezing experiments. Note that the noise variance in Eq. (4) is identical to that of a single OPA seeded with a quantum noise limited input and detected with $1-\varepsilon_2$ intensity loss. However, here a modulation performed in only one interferometer arm will endow the squeezed vacuum with bright modulation sidebands outside the squeezing band of interest, thereby facilitating phase locking of any downstream applications.

Figs. 3 and 4 show experimental results from the single OPA noise cancellation scheme according to Fig. 2. The OPA was constructed from a non-critically phasematched $MgO{:}LiNbO_3$ crystal inside a hemilithic resonator of input and output power reflectivities of 0.9997 and 0.95, respectively. The laser source of the experiment was a monolithic non-planar Nd:YAG ring laser of up to 2W single mode output power at 1064 nm. Intensity noise below 2 MHz was reduced by a servo loop acting on the pump diode current. The OPA was seeded with a coherent beam of 30 mW at the fundamental wavelength and pumped with 300 mW of the second harmonic (532 nm). The second

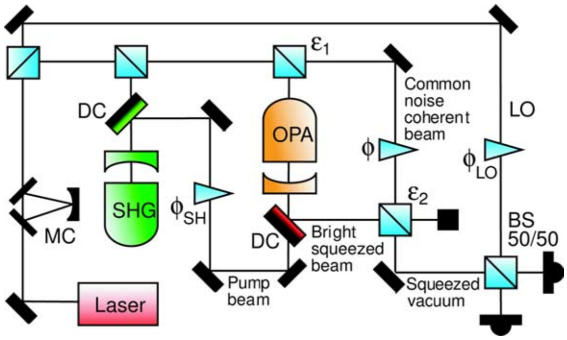

Fig. 2. Schematic diagram of the experiment. BS, beam splitter; DC, dichroic; MC, mode-cleaner; $\lambda/2$: half-wave plate, ϕ_{SH}, ϕ, ϕ_{LO}: actively controlled phase shifts on second harmonic beam, reference beam and homodyne local oscillator.

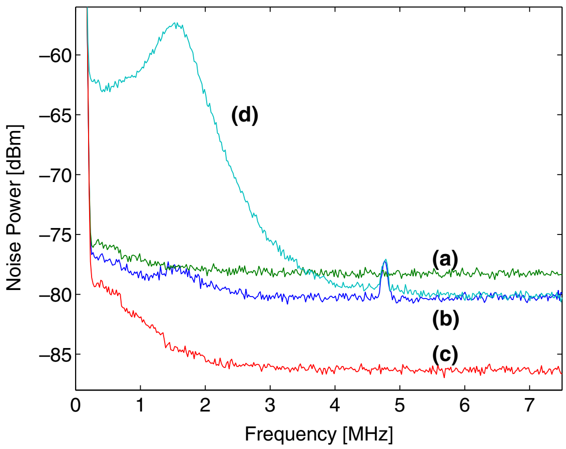

Fig. 3. Measured noise power spectra at sideband frequencies $\Omega/2\pi$; (a) shot noise, measured with blocked squeezed beam; (b) squeezing including optical noise cancellation due to interference with a coherent beam on beamsplitter ε_2; (c) squeezing when coherent beam at ε_2 was blocked, i.e., squeezing without additional noise cancellation; (c) dark noise on the detector. The distance between curves (b) and (d) represents the optical cancellation of technical noise achieved in our system.

harmonic beam was generated in a cavity which was similar to the OPA cavity. Conversion efficiency of 65% was achieved. The length of the OPA cavity was electronically controlled to be on resonance for the seed beam. We used a sideband modulation technique based on an (intra-cavity) refractive index modulation on the $MgO{:}LiNbO_3$ crystal. This was achieved by a radio-frequency (19.8 MHz) electric field applied to two copper

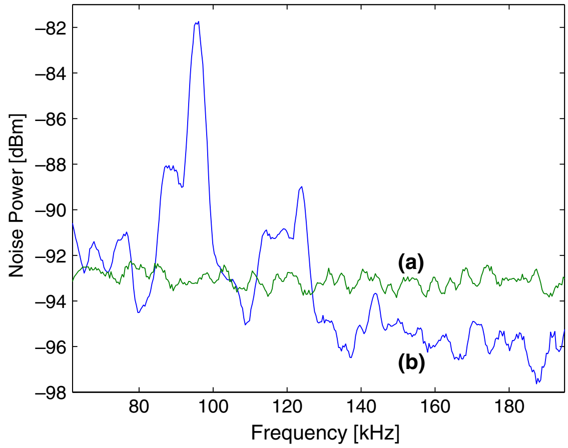

Fig. 4. Measured noise power spectra. Squeezing was observed where curve (b) was below the shot-noise curve (a).

plates that were placed on opposite sides of the nonlinear crystal. The error signal was deduced by mixing down the photodetected reflected seed beam. From the same beam we also generated an error signal for the phase difference of fundamental and second harmonic waves inside the OPA. This enabled a stable lock to deamplification of the seed beam generating a dim amplitude quadrature squeezed beam of about 200 μW at 1064 nm. This control loop used a phase modulation on the second harmonic pump at about 19.7 MHz that modulated the amplification of the OPA. Note that both control locking loops did not require any measurement on the squeezed beam leaving the OPA. The noise power spectrum was measured in a homodyne detector constructed from two optically and electronically matched ETX 500 photodiodes. Amplitude quadrature squeezing was observed at sideband frequencies from 4 MHz up to the 29 MHz OPA cavity linewidth. Curve (d) in Fig. 3 shows the noise power spectrum of the amplitude quadrature stably locked to the homodyning local oscillator. The locking loop error signal was extracted from the homodyne detector using the 19.8 MHz phase-modulation sidebands on the squeezed beam. The shot-noise reference given by curve (a) was measured by blocking the squeezed beam before the homodyne detector. The apparent increase in shot-noise level at lower frequencies is due to higher homodyne detector dark noise, cf. curve (c). In a second step the dim squeezed beam was overlapped on a beamsplitter of reflectivity $\varepsilon_2 = 99\%$ with a coherent beam from the same laser source. The intensities and the relative phase of both inputs were adjusted to provide a dark output of less than 6 μW. The amplitude noise spectrum of the dark port is shown in Fig. 3 curve (b). The spectra in Fig. 3 were recorded on a spectrum analyzer with resolution bandwidth (RBW) set to 100 kHz and video bandwidth (VBW) set to 100 Hz. In Fig. 4 the RBW was reduced to 3 kHz and the VBW to 10 Hz. Here, measured shot-noise (a) and squeezed vacuum noise (b) are shown after Gaussian weighted averaging within the RBW. The detector dark noise was at least 2.5 dB below the squeezed trace before being subtracted. Squeezing at 80 kHz and broadband squeezing from 130 kHz upwards were observed. Between 80 and 130 kHz the squeezing was partly masked by residual technical noise. Both, squeezing at 80 kHz and technical noise as shown in Fig. 4 were stationary features in our experiment and were observed in stable locks of up to half an hour. We point out that the squeezed beam still carried the phase-modulation sidebands at 19.8 MHz providing the phase reference required for an application in GW interferometers.

Within the assumptions of the presented theory, perfect cancellation of technical laser source noise is possible, provided that anti-correlated noise contributions are kept to zero, and matching of the coherent amplitudes and the spatial modes at the combining beam splitter are perfect. A flat spectrum of a constant level of squeezing inside the cavity linewidth is then expected. As mentioned above, residual classical noise at some frequencies still limited the observation of squeezing to the lowest frequency of 80 kHz. Our results, however, were not limited by the strength of optical noise cancellation. Classical noise was suppressed by 25 dB at the 1.5 MHz laser relaxation oscillation (Fig. 3). The strength of the optical noise cancellation was due to 94.4% visibility at the 99/1 combining beamsplitter which also led to the residual power of 6 μW at the dark output port. Classical noise from the homodyne local oscillator was electronically suppressed by 60 dB and was not significant for our measurements. Our results were limited by anti-correlated classical noise, possibly arising from acoustic noise coupling into the optical scheme, locking noise of the OPA, electronic pickup of stray RF fields in the electrodes applied to the OPA crystal, or even noise coupled into the system via the second harmonic pump. The signal at 4.8 MHz was identified to be the beat of two modulation frequencies and indeed picked up by the OPA. In both figures the lower boundary of noise power was set by the squeezing achieved in the OPA and subsequent losses. Photodiode efficiencies of $(92 \pm 3)\%$, homodyne detector visibility of 0.975 ± 0.003, propagation losses of $(5 \pm 0.5)\%$ and OPA escape efficiency of $(88 \pm 2)\%$ give an overall loss of 27%.

In conclusion, we have reported the observation of squeezing at low sideband frequencies down to 80 kHz from a single OPA. The wavelength of the carrier laser field was 1064 nm which is compatible with current GW detectors. In total, just 600 mW laser power was necessary to generate the squeezed states. We note that power requirements linearly scale up with the number of OPAs employed in the scheme. One goal of further investigations will be the reduction of losses for increasing the squeezing strength. Residual classical noise contributions at low frequencies will also be identified in further investigations that aim to reach the acoustic band of gravitational wave detectors.

During the refereeing process two new experiments were performed demonstrating squeezed light at even lower frequencies [16,17]. In both systems optical parametric oscillators (OPOs) were applied. Such systems are naturally free from laser noise but generally show a poorer control capability. The absence of a laser beam at the (fundamental) reference frequency doesn't provide length control of the OPO cavity, nor can phase modulation sidebands be therefrom induced to accompany the vacuum squeezed states. In [16] locked vacuum squeezing down to 50 kHz has been demonstrated using the second harmonic laser beam for OPO cavity length control and a noise dither locking technique for quadrature angle control at the homodyne detector. In [17] squeezing at 200 Hz has been demonstrated; their system also used a noise dither locking technique, the OPO length was not controlled.

Acknowledgement

This work has been supported by the Deutsche Forschungsgemeinschaft and is part of Sonderforschungsbereich 407.

References

[1] B. Willke, et al., Class. Quantum Grav. 19 (2002) 1377.
[2] A. Abramovici, et al., Science 256 (1992) 325.
[3] M. Ando, et al., Phys. Rev. Lett. 86 (2001) 3950.
[4] B. Caron, et al., Class. Quantum Grav. 14 (1997) 1461.
[5] H.J. Kimble, Y. Levin, A.B. Matsko, K.S. Thorne, S.P. Vyatchanin, Phys. Rev. D 65 (2001) 022002 and references therein.
[6] J. Harms, Y. Chen, S. Chelkowski, A. Franzen, H. Vahlbruch, K. Danzmann, R. Schnabel, Phys. Rev. D 68 (2003) 042001.
[7] P.-F. Cohadon, A. Heidmann, M. Pinard, Phys. Rev. Lett. 83 (1999) 3174.
[8] J.-M. Courty, A. Heidmann, M. Pinard, Phys. Rev. Lett. 90 (2003) 083601.
[9] R. Schnabel, J. Harms, K.A. Strain, K. Danzmann, Class. Quantum Grav. 21 (2004) S1045.
[10] K. McKenzie, D.A. Shaddock, D.E. McClelland, B.C. Buchler, P.K. Lam, Phys. Rev. Lett. 88 (2002) 231102.
[11] M. Shirasaki, H.A. Haus, J. Opt. Soc. Am. B 7 (1990) 30.
[12] Y. Lai, H.A. Haus, Y. Yamamoto, Opt. Lett. 16 (1991) 1517.
[13] T.C. Ralph, A.G. White, J. Opt. Soc. Am. B 12 (1995) 833.
[14] W.P. Bowen, R. Schnabel, N. Treps, H.-A. Bachor, P.K. Lam, J. Opt. B 4 (2002) 421.
[15] P.K. Lam, T.C. Ralph, B.C. Buchler, D.E. McClelland, H.-A. Bachor, J. Gao, J. Opt. B. 1 (1999) 469.
[16] J. Laurat, T. Coudreau, G. Keller, N. Treps, C. Fabre, submitted (2004), quant-ph/0403224.
[17] K. McKenzie, N. Grosse, W.P. Bowen, S.E. Whitcomb, M.B. Gray, D.E. McClelland, P.K. Lam, submitted (2004), quant-ph/0405137.