Generation of strongly squeezed continuous-wave light at 1064 nm

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Abstract: A compact and efficient source of amplitude-squeezed light is described. It employs a semi-monolithic degenerate MgO:$LiNbO_3$ optical parametric amplifier pumped by a frequency-doubled Nd:YAG laser at 532 nm. Injection-seeding of the amplifier by a 1064 nm wave permits active stabilization of the cavity length and stable operation. At a pump power of 380 mW, a maximum noise reduction of 6.5 dB in the amplitude fluctuations of the 0.2 mW 1064 nm wave was detected. The average detected noise reduction in continuous operation over 14 minutes was 6.2 dB. Taking the detection efficiency into account, this corresponds to a squeezing of 7.2 dB in the emitted wave.

OCIS codes: (270.6570) Squeezed states; (190.4970) Parametric oscillators and amplifiers.

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Although squeezed light was first generated more than a dozen years ago,[1] progress in the development of practical sources of strongly squeezed continuous-wave light has been slow because of technical difficulties. This development is to be continued, however, if squeezed light is to become a flexible and useful tool for applications. Aside the improvement of the degree of noise suppression, a central issue is long-term stability, since

#2987 - $10.00 US
Received October 27, 1997; Revised January 29, 1998

many applications of squeezed light will be in precision experiments which require long integration times. These are the ones which would benefit most from an improvement in signal-to-noise ratio by use of squeezed light.

Nonlinear optical devices as sources of squeezed light have the advantage of being relatively simple, both in terms of their structure and in their theoretical description. In particular, the squeezed light emitted from an optical parametric amplifier is close to the simple model of two-mode squeezed light, the two modes being spaced by a r.f. frequency up to the cavity bandwidth (on the order of 10 MHz). The light state is typically well described by a minimum uncertainty state that has undergone loss, i.e. the anti-squeezed quadrature has a quantum noise power relatively close to that required by the uncertainty relation. In contrast, laser diodes, where strong squeezing has also been reported,[2] are much more complex devices. Here, a subtle interplay of many modes, widely spaced in the frequency domain has been shown responsible for amplitude squeezing [3].

The development of sources of strongly two-mode squeezed light started 1986 with the seminal work of Wu et al. who achieved 4 dB at 1064 nm in scanned operation with a MgO:LiNbO$_3$ OPA pumped by an intracavity doubled, lamp-pumped Nd:YAG laser [4]. Taking propagation, homodyne and detection efficiencies into account, the actual noise reduction in the beam was 7.0 dB. Polzik et al.[5] reported 6 dB (6.6 dB in the beam) stabilized squeezed vacuum at 856 nm using a KNbO$_3$-OPA pumped by an externally resonantly frequency doubled Ti:Sapphire laser. With a type-II KTP OPA pumped by a doubled Nd:YAP laser, Ou et al.[6] obtained 4 dB (6.6 dB in the beam) squeezed vacuum at 1.08 μm.

The commercial availability of diode-pumped monolithic miniature Nd:YAG lasers (NPROs)[7] with their high intrinsic frequency stability opened up new opportunities for squeezed light generation at 1064 nm and its harmonic.[8,9,10] Following this line, 6.0 dB squeezed vacuum were reached in 1996 with an all-solid-state system consisting of an externally doubled NPRO, and a monolithic MgO:LiNbO$_3$ OPA.[15] The actual degree of noise reduction in the beam was 6.9 dB, taking into account the 94% detection efficiency. Long-term measurements of squeezing were not pursued.

The present work follows an approach recently developed to obtain very reliable and long-term stable squeezed light.[11] Again a mononlithic Nd:YAG laser is used, but for increased flexibility, the OPA is a semi-monolithic resonator, whose cavity length is slaved to the laser frequency via injection-seeding. The source emits bright squeezed light which can be tuned in frequency by tuning the pump laser frequency.[12] Continuous squeezing for 36 hours was demonstrated [13]. A practical advantage of this method is that the bright squeezed light generation does not require a beam overlap whose mode matching efficiency would directly limit the degree of detectable quantum noise reduction. When the device is operated as an amplitude-squeezer, the quantum noise reduction can be measured with a self-homodyne detector, without the need of a local oscillator.

According to theory, the squeezing factor (quantum noise power relative to shot noise) for an OPA pumped just below threshold power is, at zero frequency,

$$V_{sq,min} = 1 - T_2/A \ , \tag{1}$$

where T_2/A is the cavity escape efficiency for the squeezed wave, T_2 being the output coupler transmission and $A = L + T_2$ the total losses per round trip, L being the dissipation loss. A high escape efficiency is necessary for good squeezing. Two approaches can be followed: reducing L, which is quite difficult since it is limited by the crystal loss, or increasing T_2. In the latter case, the price to pay is a quadratic increase in threshold power, $P_{th} \sim A^2$, requiring the use of a higher power pump source. This approach was used in the present work. We employed a recently developed powerful single-frequency 532 nm pump source, capable of emitting up to 1.1 W.[14]

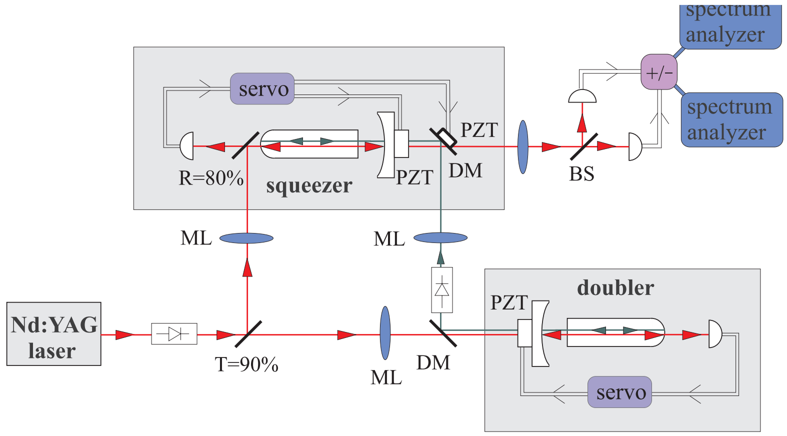

Fig. 1. Schematic of the squeezer. The laser is a 1.5 W monolithic nonplanar Nd:YAG laser. Both doubler and OPA employ MgO:$LiNbO_3$ crystals. Crystal temperatures are accurately controlled by ovens (not shown). The crystals are electro-optically modulated by r.f. sources via electrodes (not shown). PZT: piezoelectric actuator.

Fig. 1 shows the basic set-up. The OPA cavity contains a 7.5 mm long MgO:$LiNbO_3$ crystal heated to the phasematching temperature of about 120°C. It is polished flat and coated AR on the inner face and is spherically polished ($R = 10\,\mathrm{mm}$) and coated HR(532 nm, 1064 nm) on the other. The external mirror, placed at 24 mm from the crystal has transmission $T_2(1064\,\mathrm{nm}){=}7.2\%$ and is AR coated for the pump. The dissipative loss $L = 0.41\%$ of the cavity for 1064 nm was determined by replacing the output coupler by a HR mirror and measuring the finesse. The escape efficiency of 0.95 would imply a theoretical squeezing of 13 dB at threshold. The high outcoupling T_2 and the short cavity lead to a high cavity bandwidth, 50 MHz, which is also reflected on the squeezing bandwidth and allows to measure the squeezing at frequencies in the MHz range without significant penalty in the noise reduction.

Stable operation of the squeezer is achieved by injection of a seed wave into the OPA. An intense wave from the laser, 108 mW, is modematched (90%) into the cavity from the HR side. The 0.01% transmission is sufficient to couple a small part into the cavity, and about 0.6 mW exits the output coupler. The cavity optical path length is electrooptically modulated at a crystal resonance, here 40.3 MHz. The reflected wave carries information about the detuning of the OPA cavity from the laser frequency, and is read out, after optical attenuation, by a r.f. photodetector (Pound-Drever-Hall technique). The error signal is fed back via a servo to a piezo stack that controls the cavity mirror position and keeps the cavity locked on-resonance.

The pump wave from the frequency doubler passes through an isolator and is carefully modematched (90%) into the OPA, which it traverses in a double-pass. The oscillation threshold was $P_{th} = 500\,\mathrm{mW}$. Operating below threshold and scanning the pump phase with the PZT one observes phase-sensitive parametric amplification/attenuation of the transmitted IR wave. The maximum attenuation was close to 1/4 [15], and amplification factors up to 50 were observed. Phase locking was implemented by dithering the pump wave phase at 5 kHz and lock-in detection of the amplitude modulation imparted to the reflected IR wave. The pump phase can be stabilized on parametric deamplification or on amplification, although only the former was pursued for the squeezing measurements.

Under parametric deamplification the transmitted IR wave has a power of about 180 μW and is amplitude-squeezed. This noise reduction can be detected with a homodyne detector without local oscillator. A pair of Epitaxx ETX500 InGaAs photodiodes with removed covers and low-noise amplifiers are employed. A hybrid junction pro-

#2987 - $10.00 US
Received October 27, 1997; Revised January 29, 1998

vides sum and difference photocurrents i_-, i_+, which indicated the shot noise reference and the intensity noise levels, respectively. Squeezing measurements were performed at 6.5 MHz. The noise powers for the available light power are so low that the electronic noise floors of our spectrum analyzers (HP 8591A) dominate. However, they can be subtracted, including the electronic noise of the detectors, from the signal noise powers. Fig. 2 shows that this subtraction procedure yields results accurate to within 0.2 dB for light powers above 30 μW. This is the light power that yields a i_+ (amplitude) noise power equivalent to that of a 7 dB amplitude-squeezed wave with 180 μW power.

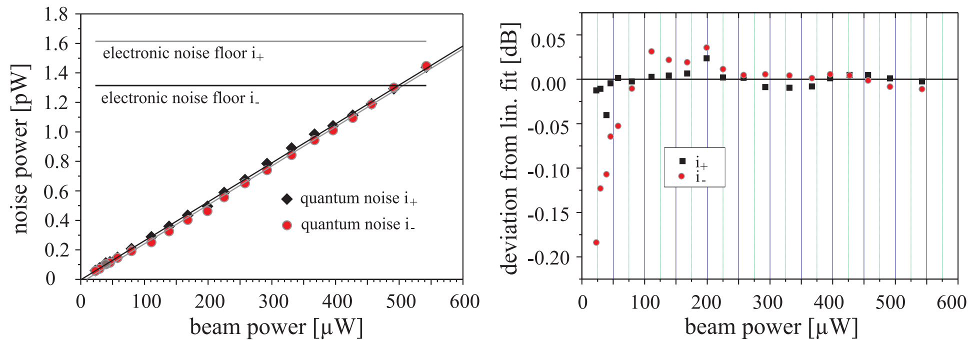

Fig. 2. Accuracy of the homodyne detector. Left: noise powers for the transmitted seed wave, with pump wave off and OPA cavity length locked. Spectrum analyzer noise floors including the electronic noise of the detectors (horizontal lines) have been subtracted. Resolution bandwidth 30 kHz. The equality of the i_- and i_+ noise powers (vacuum noise and amplitude noise respectively) shows that the transmitted seed wave is shot-noise limited. Right: deviation from linearity.

Good squeezing is obtained after careful optimization of modematchings, crystal temperature, and the various locks.

The best results achieved are displayed in Fig. 3. The noise reduction, averaged over 1 s, is 6.5 dB. Over longer periods we obtained an average noise reduction of $V_{sq,det} = 6.2$ dB, see Fig. 4. Here the spectrum analyzers were set to zero-span mode with an averaging time of 1 s, and every 1 s a data point was recorded.

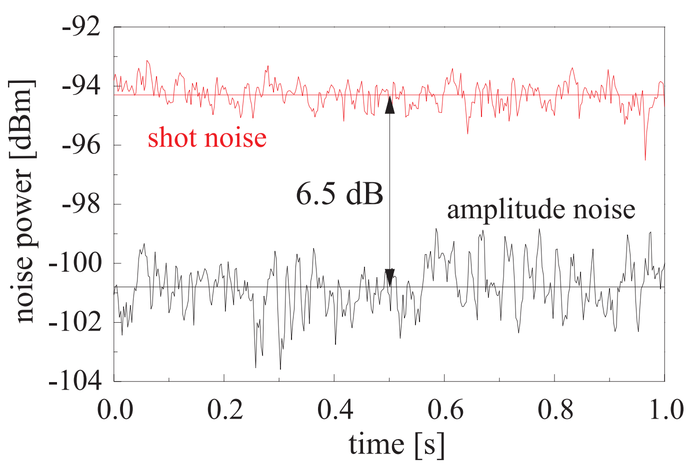

Fig. 3. Amplitude squeezing at 1064 nm at a pump power of 380 mW. Resolution bandwidth 30 kHz, video bandwidth 30 Hz.

#2987 - $10.00 US
Received October 27, 1997; Revised January 29, 1998

The present results are limited by the detection efficiency. Propagation loss of the squeezed light through the dichroic mirror, a focusing lens and the 50-50 beam splitter amounts to 1.4%. The quantum efficiencies of the photodiodes are 95.5% and 94.5%, determined by comparison with a Laser Instrumentation thermopile power meter accurate to 2%. The overall detection efficiency is thus $\eta \simeq 94\%$. Correcting the observed noise power one obtains the quantum noise reduction in the beam $V_{sq} = (V_{sq,det} + \eta - 1)/\eta = 7.2\,\mathrm{dB}$.

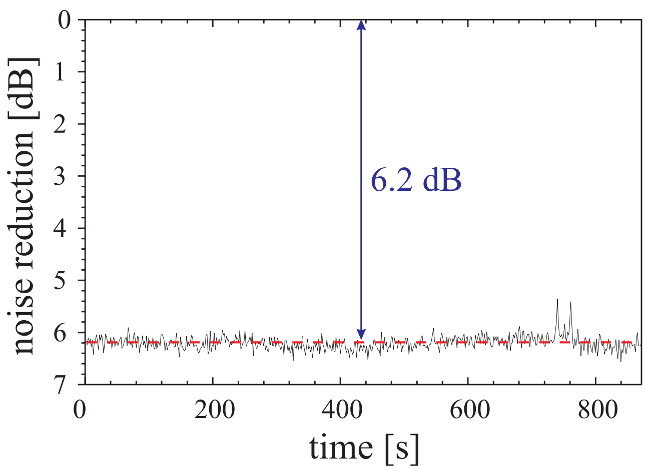

Fig. 4. Medium-term noise reduction. The standard deviation of the noise reduction is 0.13 dB.

Although high, the noise reduction falls short of the theoretically expected value. To study this we have measured the squeezing as a function of pump power, Fig. 5. The noise reduction improves slower than expected. Possible reasons for the discrepancy are: transfer of pump noise to the subharmonic wave, increase of subharmonic loss under pump power illumination, inaccuracy of locks, etc. These issues will have to be carefully adressed in future work.

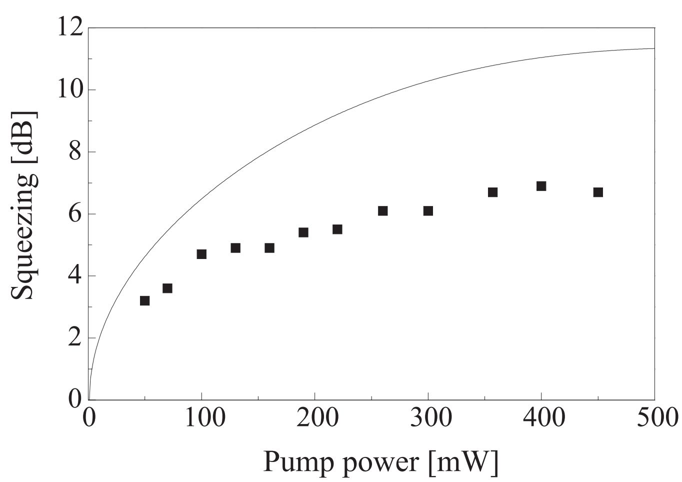

Fig. 5. Typical dependence of the squeezing on pump power. Line is theory with measured cavity parameters, points are data corrected for detection efficiency. Above 450 mW stable operation was not possible any more.

#2987 - $10.00 US Received October 27, 1997; Revised January 29, 1998

In conclusion, we have described a reliable and compact system for generation of strongly squeezed 1064 nm light, reaching 7.2 dB of medium-term stable noise reduction in the beam. We believe that potential of further improvement exists, both on the present system, and by employing quasi-phasematched nonlinear materials having substantially higher nonlinearity, thus permitting a further increase of output coupling.

We thank A.-C. Etile for her participation in the early stage of this work. We profited from stimulating discussions with R. Bruckmeier and G. Breitenbach. This work is part of ESPRIT project LTR 20029 ACQUIRE. Financial support by the Optik-Zentrum Konstanz is also gratefully acknowledged.

#2987 - \$10.00 US

Received October 27, 1997; Revised January 29, 1998