Squeezed light at 2128 nm for future gravitational-wave observatories

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All gravitational-wave observatories (GWOs) have been using the laser wavelength of 1064 nm. Ultra-stable laser devices are at the sites of GEO 600, Kagra, LIGO and Virgo. Since 2019, not only GEO 600 but also LIGO and Virgo have been using separate devices for squeezing the uncertainty of the light, so-called squeeze lasers. The sensitivities of future GWOs will strongly gain from reducing the thermal noise of the suspended mirrors, which involves shifting the wavelength into the 2 µm region. Our work aims for reusing the existing high-performance lasers at 1064 nm. Here, we report the realisation of a squeeze laser at 2128 nm that uses ultra-stable pump light at 1064 nm. We achieve the direct observation of 7.2 dB of squeezing, as the first step, at MHz sideband frequencies. The squeeze factor achieved is mainly limited by the photodiode’s quantum efficiency, which we estimated to $\left(92 \pm 3\right)\%$. Reaching larger squeeze factors seems feasible, also in the required audio and sub-audio sideband, provided photo diodes with sufficiently low dark noise will be available. Our result promotes 2128 nm as the new, cost-efficient wavelength of GWOs.

INTRODUCTION

The third observing run of LIGO and VIRGO gravitational-wave observatories (GWOs) produced a plethora of varied and unique astrophysics events, limited by fundamental noise sources [1]. GWOs with a tenfold increased reach for sources producing signal frequencies around 100 Hz and with hundred times larger range around 10 Hz seem feasible [2, 3]. Such high sensitivities will expand the detection range toward the entire universe for some sources, will result in a quasi permanent observation of mutually overlapping signals, and will promise new insights into cosmology and even the origin of the universe.

Current GWOs are limited by residual seismic noise, control noise and photon radiation pressure noise at sub-audio frequencies, by thermally excited internal movement of the mirror coatings (coating thermal noise) in the lower audio-band, and by photon counting noise in the higher audio-band [4]. Changing the laser wavelength from 1064 nm to around 2 µm will allow the usage of crystalline silicon as the bulk material of the test mass mirrors that are cryogenically cooled to about 18 K, potentially in combination with high-quality silicon-based coatings [5]. Increasing the signal requires ultra-stable laser radiation, that is not absorbed or scattered by the test mass mirrors. Reducing the quantum noise of the radiation requires squeezing the optical quantum uncertainty [6–8] over the entire spectrum of expected signals, as first achieved in [9]. Current GWOs use well-proven ultra-stable laser devices with powers of up to 160 W and squeeze lasers with a non-classical noise suppression between 7 dB and 12 dB [10, 11]. Optical resonators increase the light powers to up to 750 kW in the 4 km arms in the case of Advanced LIGO [12]. Optical loss reduces the squeeze factor to 6 dB in the case of GEO 600 [13–15] and around 3 dB in LIGO and Virgo [16, 17].

A first squeeze laser for the 2 µm region was previously reported in [18, 19]. Squeeze factors of up to 4 dB were measured. The value was limited by the quantum efficiency of the photo detectors, as well as noise of the 1984 nm thulium fiber laser and subsequently its second harmonic pump field at 992 nm.

Here, we report the realisation of a squeeze laser at 2128 nm that uses ultra-stable 1064 nm pump light from a Nd:YAG nonplanar ring oscillator (NPRO), which is also used as the master laser in current GWOs. We directly observed a squeeze factor of $(7.2 \pm 0.2)$ dB at sideband-frequencies around 2 MHz. The squeezed field uncertainty was observed by a balanced homodyne detector that used a bright stable local oscillator beam at 2128 nm that was produced by degenerate optical parametric oscillation (DOPO), which we reported previously [20].

EXPERIMENTAL SETUP

Our experimental setup (Fig. 1) is based on two identical nonlinear resonators that are optimized for wavelength-doubling via degenerate optical-parametric amplification. The two resonators were pumped with continuous-wave 1064 nm light from an NPRO laser. The resonators had a half-monolithic (hemilithic) design and were composed of periodically-poled potassium titanyl phosphate (PPKTP) crystals, with highly-reflective coating on the curved end face and an anti-reflective coating on the flat front face, and separate coupling mirrors with reflectivities of 96 % at 1064 nm and 90 % at 2128 nm. An electro-optical modulator provided phase-modulation sidebands at 28 MHz for a modified Pound-Drever-Hall control scheme in transmission of the resonators together with a digital controller [21] to stabilize the length of...
the DOPO cavity on resonance by feeding back to the piezo-mounted coupling mirrors. One resonator was pumped above the lasing threshold for DOPO (around 20 mW) and produced about 46 mW at 2128 nm from about 52 mW at 1064 nm; detailed information on this setup can be found in a previous publication [20]. The other resonator was pumped below the threshold power and therefore produced a well-defined light beam with a TEM$_{00}$ mode in a squeezed vacuum state at 2128 nm.

The generated squeezing was analyzed with a balanced-homodyne detector (BHD). For this, it was overlapped with a bright beam from the DOPO on a 50% beam splitter and both outputs were sent to photodiodes (extended InGaAs, Thorlabs FD05D), whose photocurrents were then subtracted from each other. The readout angle of the balanced-homodyne detector could be adjusted with a phase shifter, i.e., a piezo-mounted mirror, that was located in front of the squeezed-light cavity to suppress induced pointing loss. Our self-made electronics operated the photodiodes at a reverse bias voltage of 1 V and achieved a detection bandwidth of 30 MHz. The quantum efficiency of the extended-InGaAs photodiodes slightly increases with higher reverse voltage, but the dark-current and noise rises rapidly. We have found a reverse voltage of 1 V to be a useful balance between quantum efficiency and noise. With the photodiodes’ windows removed, we measured a quantum efficiency of (92 ± 3)% with a thermal power-meter (accuracy 3%) and precise multimeters.

RESULTS

Fig. 2 presents noise variances from BHD measurements recorded with a spectrum analyzer, normalized to the vacuum noise. The left panel shows a zero-span measurement at 2 MHz, while the right panel shows the spectrum in the range 0.6 MHz to 10 MHz. Electronic dark-noise was not subtracted from these traces. We obtained a non-classical noise suppression of (7.2 ± 0.2) dB at a sideband frequency of 2 MHz and a local-oscillator power of 6.6 mW. This squeezing level extended to lower frequencies, as shown in Fig. 2 (right), before the dark-noise clearance quickly decreased as the BHD’s transfer function was optimized for the MHz regime. At our measurement frequency, electronic dark-noise was dominated by the dark-current of the photodiodes. It was not subtracted from the measurements and reduced the achieved noise suppression by about 0.3 dB. We estimate the error on the squeezed/anti-squeezed noise levels to ±0.2 dB, as the BHD readout angle was not yet servo controlled and therefore prevented longer measurements at the optimal quadratures.

Random fluctuation of the phase between the squeezed-light beam and the local oscillator in the setup leads to a coupling between the squeezed and anti-squeezed light-field quadratures, which we denote here as $\hat{X}_1$ and $\hat{X}_2$, respectively. For a small amount of gaussian-distributed phase noise with an rms value of $\Theta$, the measured quadrature variances $\Delta^2 \hat{X}_1$, $\Delta^2 \hat{X}_2$ are given by [22]

$$\Delta^2 \hat{X}_{1,2} = \Delta^2 \hat{X}_{1,2} \cos^2 \Theta + \Delta^2 \hat{X}_{2,1} \sin^2 \Theta. \quad (1)$$

As phase noise becomes particularly relevant for large variances of the anti-squeezed quadrature, an upper bound can be determined by a measurement of the squeezing and anti-squeezing levels for various pump powers $P$ up to the threshold power $P_{\text{thr}} = 20$ mW. The quadrature variances themselves can be described by [22]

$$\Delta^2 \hat{X}_{1,2} = 1 \mp \eta \frac{4 \sqrt{P/P_{\text{thr}}}}{(1 \pm \sqrt{P/P_{\text{thr}}})^2 + 4(\Omega/\gamma)^2}, \quad (2)$$

where the upper sign corresponds to $\hat{X}_1$ and the lower sign to $\hat{X}_2$. Here, the variance of the vacuum ground state has been normalized to 1; $\eta$ is the overall detection efficiency; $\gamma = 2 \pi \times 64$ MHz is the linewidth of our squeezed-light cavity; and $\Omega = 2 \pi \times 2$ MHz is the measurement sideband frequency. Combining equations (1) and (2), we fitted our measurements Fig. 3 and obtained an rms phase noise of $\Theta = (7 \pm 1)$ mrad. This phase noise is likely dominated by high-frequency fluctuations introduced by the locking loops of the cavities, as well as residual high-frequency fluctuations of the main laser beam. However, it is not limiting our squeezing results and we therefore did not yet implement steps to reduce it.

**Optical loss analysis** State of the art squeeze lasers are entirely limited by optical loss, which arises from absorption, scattering, imperfect mode matching and imperfect quantum efficiency of the photodiodes. The total optical efficiency $\eta$ can be derived from a combination of the squeezed and anti-squeezed variances $\Delta^2 \hat{X}_1$ and $\Delta^2 \hat{X}_2$ (with dark noise subtracted).

$$1 - \eta = \frac{1 - \Delta^2 \hat{X}_1 \Delta^2 \hat{X}_2}{2 - \Delta^2 \hat{X}_1 - \Delta^2 \hat{X}_2}. \quad (3)$$
FIG. 2. (Left) Zero-span noise measurement at a sideband frequency of 2 MHz. We achieved a squeezed noise reduction of $(7.2 \pm 0.2)\, \text{dB}$ below the vacuum noise, accompanied with an anti-squeezed noise in the orthogonal quadrature of $(15.6 \pm 0.2)\, \text{dB}$. The noise arches were obtained by scanning the BHD readout angle. All traces were recorded with a resolution bandwidth of 300 kHz and a video bandwidth of 300 Hz. Dark noise and vacuum noise were additionally averaged 10 times. (Right) Spectrum of the generated squeeze light in the regime 0.6 MHz to 10 MHz, fitted with the equations (1) and (2), where the dark noise was added to the fitting curves. All traces were averaged 10 times.

FIG. 3. Dependence of squeezed and anti-squeezed noise levels on the pump power, as a fraction of threshold power. The data points were taken by using max hold for anti-squeezing and min hold for squeezing, comparing to the respective max/min hold vacuum noise reference. At high pump powers, the observed squeeze noise level degraded due to phase noise.

Inserting the measured values of $-7.2\, \text{dB}$ squeezing and $15.6\, \text{dB}$ anti-squeezing, we arrive at an efficiency of $\eta = (83.9 \pm 0.5)\%$.

We have estimated the loss contributions in our setup from the measured quantum efficiency of the photodiodes and manufacturers’ specifications of the optics. These are summarized in Tab. I.

The escape efficiency of the squeeze resonator is given by $T/(T+L)$, where $T$ is the coupling-mirror transmissivity, and $L$ is a sum of all round-trip losses, such as from an imperfect anti-reflective coating on the crystal, scattering and absorption loss, as well as residual transmission through the non-perfect reflecting back face of the crystal.

Propagation loss towards the homodyne detector is likely small, due to the use of high-quality optics and infrared-grade fused silica substrates, and has been estimated to $<0.1\, \%$ per surface. The beam overlap (visibility) between the local oscillator and squeezed beam at the balanced-homodyne detector contributes quadratically, and therefore has a high impact. We measured a visibility of $V = (98 \pm 1)\%$. Finally, we include the non-perfect quantum efficiency of our photodiodes, around 92% according to our measurements, in the estimate. This is the therefore the largest individual contribution.

Within its relatively large error bars, our estimated value for the overall efficiency is in agreement with the one obtained from the squeezing and anti-squeezing measurement.

| Source                        | Efficiency (%) |
|-------------------------------|----------------|
| Resonator escape efficiency   | 98 $\pm$ 1     |
| Propagation efficiency        | $>99$          |
| BHD visibility $(98 \pm 1)\%$ | 96 $\pm$ 2     |
| Photodiode quantum efficiency | 92 $\pm$ 3     |
| Total value as product of estimated efficiencies | 85 $\pm$ 4 |
| Total value from squeeze and anti-squeeze values | 83.9 $\pm$ 0.5 |

TABLE I. Overview of optical efficiencies
CONCLUSION

We have reported on a novel approach to combine squeezed light generation at 2128 nm via parametric down-conversion with degenerate optical parametric oscillation pumped by an ultra-stable Mephisto laser at 1064 nm. We currently reach a squeeze level of (7.2 ± 0.2) dB in the MHz sideband frequencies, being mainly limited by the quantum efficiency of the available photodiodes. The concept of wavelength-doubling, combined with squeezing, makes the wavelength 2128 nm a promising, because cost-efficient candidate for all next-generation gravitational-wave detectors like Cosmic Explorer [3], Einstein Telescope [23], NEMO [24] and Voyager [25]. In these GWOs, a squeeze level of 10 dB is usually aimed at. A reduction of optical loss within the detector to around 6.3 % may be within reach, for realistic technological advances [26, tab. 6.1]. The squeeze light source itself will then need to produce a measured squeeze level of 15 dB, which has been demonstrated at a wavelength of 1064 nm [27]. Further research into low-noise photo detectors with a quantum efficiency of 99 % is required to achieve this goal also at 2 μm.

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