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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. This Letter aims to reuse the existing high-performance lasers at 1064 nm. Here we report the realization of a squeeze laser at 2128 nm that uses pump light at 1064 nm. We achieve the direct observation of 7.2 dB of squeezing as the first step at megahertz sideband frequencies. The squeeze factor achieved is mainly limited by the photodiode's quantum efficiency, which we estimated to (92 ± 3)%. 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, to the best of our knowledge, cost-efficient wavelength of GWOs.

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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 10-fold increased reach for sources producing signal frequencies around 100 Hz and with hundred times larger range around 10 Hz are being proposed [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 using 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]. One of the proposed wavelengths in this region is 2128 nm [6]. Increasing the signal requires ultra-stable laser radiation, which is not absorbed or scattered by the test mass mirrors. Reducing the quantum noise of the radiation requires squeezing the optical quantum uncertainty [7–9] over the entire spectrum of expected signals, as first achieved in [10]. Current GWOs use well-proven ultra-stable laser devices with powers up to 160 W and squeeze lasers with a nonclassical noise suppression between 7 and 12 dB [11,12]. Optical resonators increase the light powers to up to 750 kW in the 4 km arms in the case of Advanced LIGO [13]. Optical loss reduces the squeeze factor to 6 dB in the case of GEO 600 [14–16] and around 3 dB in LIGO and Virgo [17,18].

A first squeeze laser for the 2 μm region was previously reported in [19,20]. Squeeze factors 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 realization of a squeeze laser at 2128 nm that uses 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 ± 0.2)dB at sideband frequencies around 2 MHz. The squeezed field uncertainty was observed by a balanced homodyne detector (BHD) that used a bright stable local oscillator beam at 2128 nm that was produced by degenerate optical parametric oscillation (DOPO), which we reported previously [21].

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 have a half-monolithic (hemilithic) design and are composed of periodically poled potassium titanyl phosphate crystals, with highly reflective coating on the curved end face and an anti-reflective coating on the

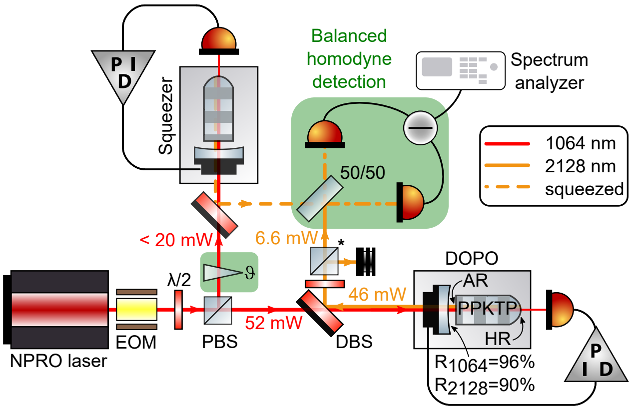

Fig. 1. Schematics of the experiment. The NPRO laser provided up to 2 W output power at the wavelength $\lambda = 1064$ nm for the two identical nonlinear cavities: squeezer and DOPO. The squeezed light was detected with a BHD. EOM, electro-optical modulator; PBS, polarizing beam splitter; DBS, dichroic beam splitter; $*$ upward pointing PBS with a beam dump, providing s-polarized light.

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 [22] 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 [21]. 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 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 BHD could be adjusted with a phase shifter, i.e., a piezo-mounted mirror, which 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 $(92 \pm 3)\%$ with a thermal power meter (accuracy 3%) and precise multimeters.

Figure 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 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 megahertz 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 be ± 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

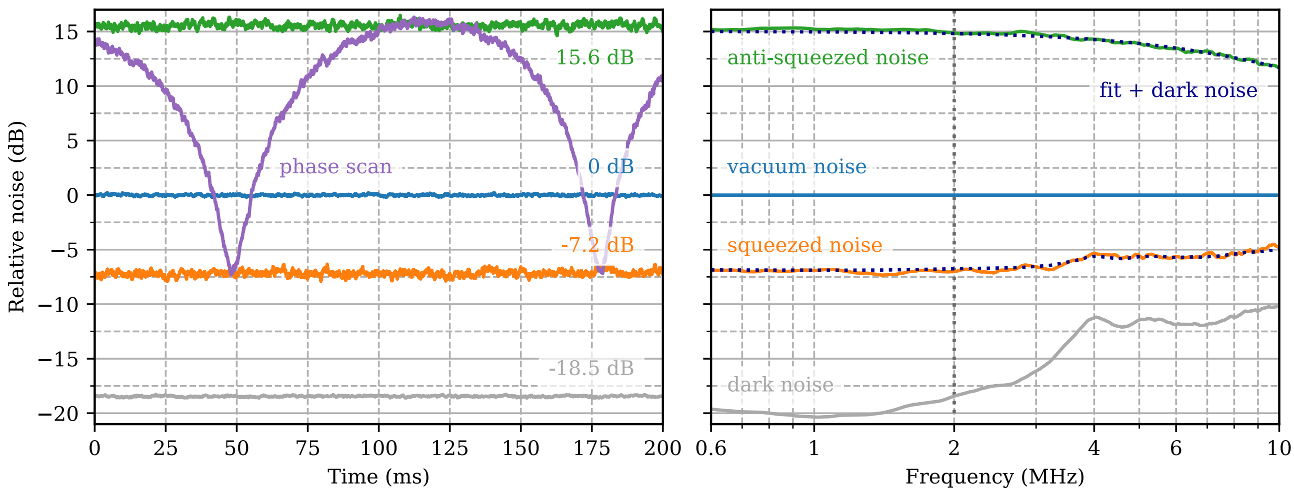

Fig. 2. (Left) zero-span noise measurement at a sideband frequency of 2 MHz. We achieved a squeezed noise reduction of (7.2 ± 0.2)dB below the vacuum noise, accompanied with an anti-squeezed noise in the orthogonal quadrature of (15.6 ± 0.2)dB. The noise arches were obtained by scanning the BHD readout 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 to 10 MHz, fitted with Eqs. (1) and (2), where the dark noise was added to the fitting curves. All traces were averaged 10 times.

of Θ, the measured quadrature variances $\Delta^2\hat{X}^m_{1,2}$ are given by [23]

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

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 $P_{\mathrm{thr}} = 20$ mW. The quadrature variances themselves can be described by [23]

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

where the upper sign corresponds to $\hat{X}_1$, and the lower sign corresponds to to $\hat{X}_2$. Here the variance of the vacuum ground state has been normalized to 1; η 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 Eqs. (1) and (2), we fitted our measurements (see Fig. 3) and obtained an rms phase noise of $\Theta = 7(1)$ 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 η 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):

$$1-\eta = \frac{1-\Delta^2\hat{X}_1\Delta^2\hat{X}_2}{2-\Delta^2\hat{X}_1-\Delta^2\hat{X}_2}. \quad (3)$$

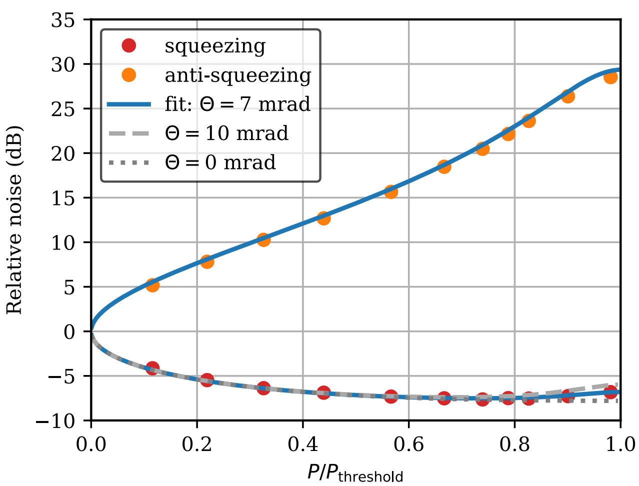

Fig. 3. Dependence of squeezed and anti-squeezed noise levels on the pump power, as a fraction of threshold power. The data points were taken by using maximum hold for anti-squeezing and minimum hold for squeezing, compared to the respective maximum/minimum hold vacuum noise reference. At high pump powers,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

Table 1. Overview of Optical Efficiencies

Source	Efficiency (%)
Resonator escape efficiency	98(1)
Propagation efficiency	>99
BHD visibility 98(1)%	96(2)
Photodiode quantum efficiency	92(3)
Total value as product of estimated efficiencies	85(4)
Total value from squeeze and anti-squeeze values	83.9(5)

Inserting the measured values of −7.2 dB squeezing and 15.6 dB anti-squeezing, we arrive at a an efficiency of $\eta = 83.9(5)\%$.

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 Table 1.

The escape efficiency of the squeeze resonator is given by $T/(T+L)$, where T is the coupling-mirror transmissivity, and L is the 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. The values for residual reflectivities were taken from the coating manufacturer measurements, while we estimated scattering and absorption loss within the cavity to be 1% to 2%, based on our own experience with high-quality squeeze resonators at different wavelengths.

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 BHD contributes quadratically, and therefore has a high impact. We measured a visibility of $V = 98(1)\%$. Finally, we include the non-perfect quantum efficiency of our photodiodes in the estimate, around 92% according to our measurements. 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.

We have reported on a novel approach to combine squeezed-light generation at 2128 nm via parametric downconversion with DOPO pumped by a highly stable Mephisto laser at 1064 nm. We currently reach a squeeze level of (7.2 ± 0.2)dB in the megahertz 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 promising, cost-efficient candidate for all next-generation gravitational-wave detectors such as Cosmic Explorer [3], Einstein Telescope [24], NEMO [25], and Voyager [6]. In these GWOs, a squeeze level of 10 dB is usually targeted. A reduction of optical loss within the detector to around 6.3% may be within reach for realistic technological advances (Table 6.1 [26]). The squeeze light source 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 2µm.

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Disclosures. The authors declare no conflicts of interest.

Data Availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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