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Conversion of 30 W laser light at 1064 nm to 20 W at 2128 nm and comparison of relative power noise

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Abstract
All current gravitational wave (GW) observatories operate with Nd:YAG lasers with a wavelength of 1064 nm. The sensitivity of future GW observatories could benefit significantly from changing the laser wavelength to approximately 2 μm combined with exchanging the current room temperature test mass mirrors with cryogenically cooled crystalline silicon test masses with mirror coatings from amorphous silicon and amorphous silicon nitride layers. Laser light of the order of ten watts with a low relative power noise (RPN) would be required. Here we use a laboratory-built degenerate optical parametric oscillator to convert the light from a high-power Nd:YAG laser to 2128 nm. With an

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input power of 30 W, we achieve an output power of 20 W, which corresponds to an external conversion efficiency of approximately 67%. We find that the RPN spectrum marginally increases during the wavelength conversion process. Our result is an important step in the development of low-noise light around 2 μm based on existing low-noise Nd:YAG lasers.

Keywords: gravitational wave detection, 2 μm laser wavelength, laser power noise, degenerate optical parametric oscillation

1. Introduction

The observation of gravitational waves (GWs) produced by merging black holes [1] gave birth to gravitational-wave astronomy [2]. A new generation of more sensitive GW observatories will lead to the observation of a wealth of astrophysical and possibly even cosmological events. Proposed observatories, such as the Einstein Telescope [3], LIGO Voyager [4], and Cosmic Explorer [5], demand the reduction of several kinds of noise sources. One of the fundamental sources of noise is a consequence of *thermally induced* movement of the highly reflective surfaces of the test mass mirrors, which is sensed by the laser light. It is a significant noise contribution at frequencies in the lower audio band. Its noise spectral density can be reduced by using materials with higher mechanical quality factors and by reducing the temperatures of the mirrors and their suspensions.

A currently very promising approach combines cryogenic temperatures with crystalline silicon as test mass material and amorphous silicon and silicon nitride as materials for the highly reflective coating [6]. In order to achieve low absorption of laser light in these coating materials, the operation wavelength of the interferometer needs to be changed to a wavelength around 2 μm [4]. Future GW observatories that are optimized for signals in the band from a few hertz to about 100 Hz will require an optical power of the order of ten watt, which is then resonantly enhanced in the arm resonators to a few tens of kilowatts. Higher powers are disadvantageous due to mirror heating and quantum radiation pressure noise. A review on quantum noise in laser interferometers is given in [7]. Around 2 μm, laser sources based on diode lasers, Ho:YAG, Ho:YLF, Tm:YAG, Tm:YAP, Tm:LiYF_4, and Ho:GdVO_4 [8–14] have been developed, showing high continuous-wave output powers [15] and compatibility with advanced quantum-measurement techniques such as squeezed states of light [7, 16, 17]. Another proposed wavelength is 2128 nm, which can be obtained by wavelength-doubling of the light of existing ultra-stable Nd:YAG laser systems [18]. Wavelength-doubling should be able to directly transfer the high stability and low-noise qualities of laser systems that have been developed for GW detectors, and is immediately extendable for the generation of squeezed light [19].

Here, we report on the generation of stable continuous-wave laser light in the 2 μm region with low power noise and a power sufficient for future cryogenic GW observatories like the Einstein Telescope. The light was produced by wavelength doubling through degenerate optical parametric oscillation (DOPO), where the pump light at 1064 nm came from a laser system similar to those used in the Advanced LIGO detectors [20]. We measured up to 29.0(9) W of 2128 nm light and an external conversion efficiency of up to 68.0(5)%. The relative power noise (RPN) was around $10^{-6}/\sqrt{\mathrm{Hz}}$ and close to the 1064 nm input light noise level for Fourier frequencies above 3 KHz. At lower frequencies we observed excess noise due to detection noise of the extended InGaAs photo diode.

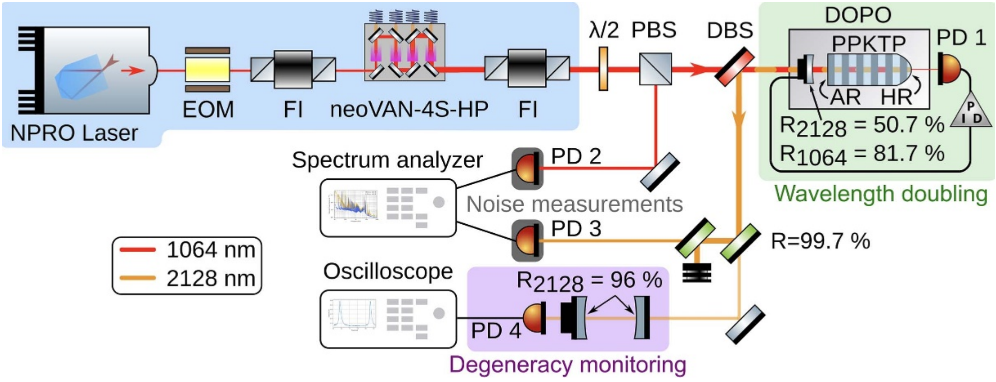

Figure 1. Schematics of the experiment. The NPRO laser and the neoVAN-4S-HP amplifier provided up to 70 W pump power at the wavelength 1064 nm (colored blue: Input light preparation) for the degenerate optical-parametric oscillator (DOPO) for wavelength doubling (colored green: Light conversion). To monitor the degeneracy (single frequency), a small portion of the converted light was adapted to a concentric resonator whose length was continuously changed (colored purple: Degeneracy monitoring). The relative power noises were detected with photo diodes PD2 and PD3 and spectrally analyzed (colored silver: Noise measurements). NPRO: non-planar ring oscillator laser; EOM: electro-optical modulator; FI: Faraday isolator; PBS: polarizing beam-splitter; DBS: dichroic beam-splitter; DOPO: degenerate optical parametric oscillator.

2. Experimental setup

Our pump laser at 1064 nm (figure 1) corresponded to the first amplification stage of the laser system scheme used in Advanced LIGO during the fourth observation run O4 [20]. The seed laser was a 2 W non-planar ring oscillator (NPRO). Its light was sent through an electro-optical modulator (EOM), which produced a phase modulation at 28 MHz required for Pound-Drever-Hall (PDH) locking of the resonator length. A Faraday isolator (FI) protected the seed laser from back-reflections and back-scattering. The light was then amplified by a neoLASE neoVAN-4S-HP laser amplifier up to power levels between 5 and 75 Watts [21]. A second Faraday isolator shielded the neoVAN amplifier from back-reflections. A fraction of the high power beam was detected on a photodetector (PD 2) to perform RPN analysis, while the remaining light was used to pump the parametric process.

Most of the 1064 nm light was coupled into the standing wave resonator of our self-built degenerate optical parametric oscillator (DOPO). It contained a plano-concave, periodically poled (type 0) potassium titanyl phosphate (PPKTP) crystal. The highly reflective coated curved end face of the crystal formed one end of the resonator, while the other end of the crystal was anti-reflective coated for both wavelengths. A detailed description can be found in [18, 19]. The resonator's coupling mirror had reflectivities of 81.7% at 1064 nm and 50.7% at 2128 nm (measured with an Agilent Cary 5000 spectrophotometer). The parameters of the DOPO cavity are summarized in table 1 for the pump and converted fields.

To stabilize the length of the DOPO on resonance, a PDH control scheme with the sensor placed in cavity transmission was used (PD 1). A digital controller [22] produced the actuator fed back signal for the piezo-mounted coupling mirror. The parametric process converted the pump field into the idler and signal fields. Here, we achieved degeneracy of these two fields by adjusting the temperatures of two separate regions of the nonlinear crystal [23, 24]. We continuously monitored (PD 4) the degeneracy with a length-varied confocal cavity

Table 1. Overview of the degenerate optical parametric oscillator cavity parameters.

	1064 nm	2128 nm	
Waist radius	31.5	44.9	μm
Finesse	31.0	9.2	
Free spectral range	3.63	3.65	GHz
Linewidth (FWHM)	117	399	MHz
Coupler reflectivity	81.7	50.7	%
Power built-up	19.2	5.9	

(length: 25 mm; mirror reflectivities: 96%). As observed previously, the degeneracy was an intrinsically stable point of operation. Temperature drifts in the laboratory prevented long-term-stable degenerate operation, however, a gentle mechanical impulse always brought the system quickly back into degenerate operation [18]. A dichroic beam-splitter (DBS) separated the 1064 nm and 2128 nm light. The RPN of the generated 2128 nm output field was measured with an extended InGaAs photo diode (PD 3; Thorlabs FD05D) with custom transimpedance amplifier, and evaluated with a spectrum analyzer.

3. Results

Figure 2 shows the conversion efficiency η as a function of the 1064 nm input power P_{in}, as well as the measured 2128 nm power P_{out}. We did not correct P_{out} or η neither for power loss from imperfect mode matching nor for reflection loss of the crystal's anti-reflection coating, internal absorption, and residual transmission through the crystal's end surface coating. An analytical fit has been made using the formula

$$P_{\text{out}} = 4\eta_{\text{max}} P_{\text{in}}^{\text{th}} \left(\sqrt{\frac{P_{\text{in}}}{P_{\text{in}}^{\text{th}}}} - 1 \right),$$

which is derived from [25, 26]. The best fit was achieved for an OPO threshold power $P_{\text{th}} = 9.73(12)$W. The maximum external conversion efficiency was $\eta_{\text{max}} = 67.8(5)\%$ where 32.5(12) W of pump power was converted into 22.0(8) W of output power. The maximum measured power of converted light was 29.0(9) W at an input pump power of 50.6(15) W. The uncertainty in these values are given by the 3% relative measurement error of our thermal power meter head, as specified by the manufacturer. Figure 3 shows the RPN in the input and output light beams, as simultaneously measured by two (extended) InGaAs photo diodes and a spectrum analyzer. Electronic dark noise was negligible and not subtracted. The noise peaks in the 1064 nm light are due to ground loops, which we were unable to eliminate during our measurement campaign. If we compare the spectra of the RPN at both wavelengths, we find both are in the same order of magnitude above 100 Hz. Above 3 kHz it can be seen that the RPN of the converted light is about 50% higher. Below 100 Hz, on the other hand, the RPN is significantly higher. This is due to electronic artefacts of the extended InGaAs photo diode and mechanical resonances, e.g. from mirror mounts, which couples into the RPN of the DOPO via pointing. During the experiment, two effects were noted. First, the DOPO PDH error signal became increasingly distorted with higher pump powers, such that above a pump power of about 30 W it was no longer possible to use this signal to control the resonator length electronically. Instead, we opted to manually adjust the feedback voltage to hold the DOPO resonator on resonance. Secondly, the conversion efficiency dropped quicker after the point of maximum

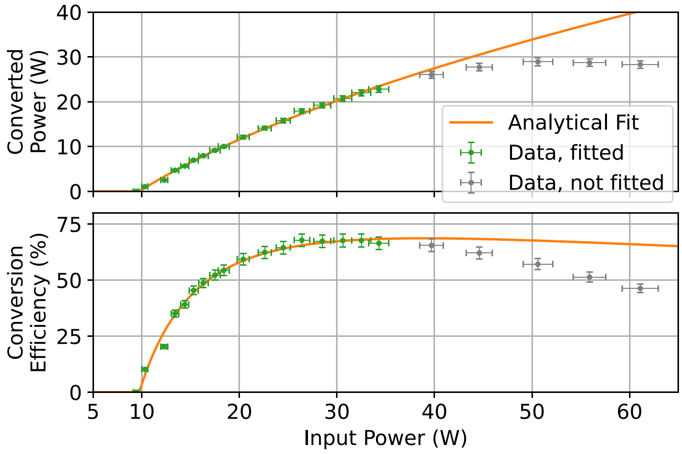

Figure 2. Power of the converted light at 2128 nm (top) and external conversion efficiency (bottom) as a function of the input power at 1064 nm. The indicated error bars correspond to the measurement accuracy of the thermal power meter, which was 3%. The orange line shows a fit of the analytical formula. Above 34 W of input power, the error signal for the DOPO length control was distorted; therefore, those points were excluded from the fit (see main text).

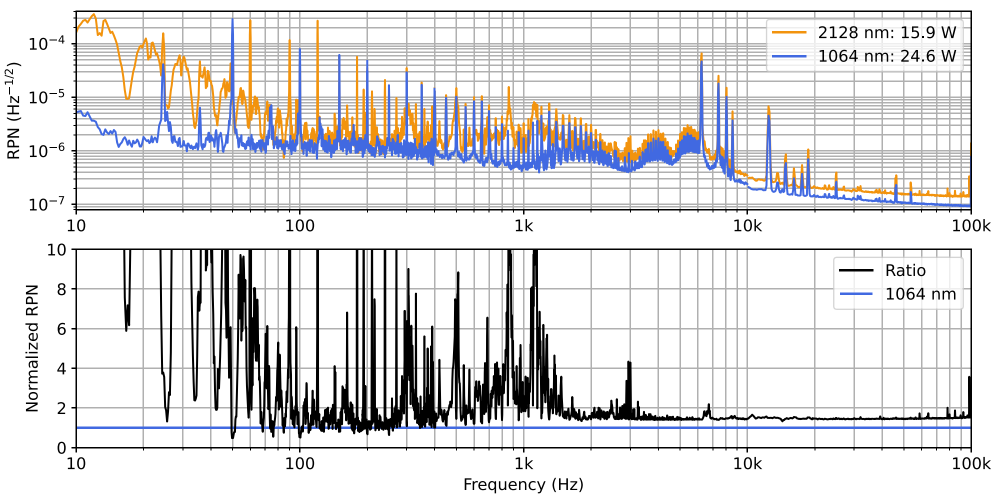

Figure 3. (Top) Relative power noise (RPN) measurements of the 1064 nm laser beam (blue) and the converted 2128 nm laser beam (orange). The light at 1064 nm showed unusual noise peaks due to ground loops, which we could not eliminate during the measurement campaign. The relative power noise at 2128 nm was generally somewhat higher than that of the input beam. Below 100 Hz this was due to detection noise from the extended InGaAs photo diode (Thorlabs FD05D). At higher frequencies, we measured only slightly increased relative noise. This was caused by the positive slope of the conversion efficiency. Indeed, the effect reduced when the conversion efficiency approached its loss-limited maximum. (Bottom) RPN level of the converted beam (black) normalized to the RPN of the input (blue).

conversion than expected from the theory. We presume this was due to the imperfect length control of the resonator, combined with the increased thermal load on the resonator, which could have led to an onset of thermal lensing and a resulting decrease in mode matching.

4. Conclusion

Our experiment proves that a few tens of watts of stable light at 1064 nm can be efficiently converted into light at 2128 nm without strongly increasing the RPN. The required frequency degeneracy of the generated light by the optical parametric conversion process was achieved by fine-tuning the temperature of the DOPO crystal. Degenerate operation was a point of stability but sensitive to disturbances. We conclude that arbitrarily long periods of precise degenerate operation is possible even for optical powers in the 10 W-range as realized here, if the crystal is not exerted to vibrations and its temperature along the optical axis does not show any drifts. The latter is caused by drifting pump powers. Long term stability can be realized with a power stabilization as realized in the GEO 600 squeeze laser [27].

We produced up to 29 W of stable laser light at 2128 nm. This is higher than the power level required for the low-frequency interferometer of the Einstein telescope [3]. It is less than required for LIGO Voyager [28], however, higher powers should be achievable when using a DOPO cavity that is optimized for higher powers, for instance having a larger waist size [29].

Our RPN measurements above 3 kHz show that degenerate parametric down-conversion far above oscillation threshold roughly preserves the noise figure of the pump light. We consider this as another positive result of our work presented here.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://10.25592/uhhfdm.16144.

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Conflicts of interest

The authors declare no conflicts of interest.

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