Highly-efficient generation of coherent light at 2128 nm via degenerate optical-parametric oscillation

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1. INTRODUCTION

Since the observation of the first black-hole coalescence in 2015, gravitational-wave detection has evolved from proof-of-principle experiments into the new field of gravitational-wave astronomy [1–3]. Further increasing the sensitivity of detectors not only allows the observation of weaker signals, but will also expand the detection range towards the entire universe. This promises new insights into cosmology and even the origin of the universe by statistical evaluation of the gravitational-wave background [4]. Especially the low-frequency regime is of interest in the context of multi-messenger astronomy, since merger events cross the gravitational-wave spectrum days to weeks before the coalescence, giving ample pre-warning for a precise sky localization of any electro-magnetic counterpart.

Enhancement of the detector sensitivity, however, is a highly complex task involving many fields of expertise. For instance, coating thermal noise poses a significant limitation of current detectors, particularly in the mid-frequency range from several tens of Hz to a few hundreds of Hz [5–7]. This will be solved by operation at cryogenic temperatures and a simultaneous change of the mirror substrate and coating materials. The most promising substrate candidate, crystalline silicon, excels with high mechanical Q-factor and thermal conductivity in the cryogenic regime, in contrast to the currently used fused silica [8, 9]. Latest research in coating technology, on the other hand, has shown promising mechanical loss results with amorphous silicon thin films [10]. Optimized coatings utilizing this material could show a thermal noise that is a factor of twelve below conventional silica-tantala coatings [11]. However, the operation wavelength with these novel coatings is restricted to above 1.8 μm. Otherwise the absorption would exceed the required order of a few ppm [9, 12, 13], which would lead to significant heating of the test masses, distortions from thermal lensing and hinder advanced quantum sensing techniques. As such, design studies for upcoming detector generations such as LIGO Voyager and Cosmic Explorer [12] feature wavelengths around 2 μm. Prototype facilities like ETPathfinder [14] are planning to investigate interferometry with this novel wavelength for gravitational-wave detection.

New laser schemes have to provide a comprehensive solution for high precision quantum metrology, including optics and detection devices [15–18]. In addition, the laser sources themselves have stringent requirements in terms of power stability, amplitude and phase noise, as well as spatial mode quality. It took decades of development effort to reach the technological maturity of laser sources at 1064 nm. Laser technologies at around 2 μm are most often based on either holmium- or thulium-doped laser media, but their maturity and performance levels still leave a lot to be desired [19], as their conventional use in medical and LIDAR applications does not require exceptional stability. In contrast, our approach employs laser sources at 1064 nm currently used in gravitational-wave detection and converts the light via optical parametric down-conversion to 2128 nm. This nonlinear process is known to retain the stability and noise properties of the pump [20, 21], allowing us to fully take advantage of the already optimized technology.

Prior optical parametric oscillators have been used e.g. to provide...
tunable continuous-wave laser sources [22], wavelength conversion of pumped lasers [23], or even to generate quantum random bits, exploiting their inherent bistability [24].

Here we report highly efficient generation of coherent light at 2128 nm employing an external degenerate optical parametric oscillator (DOPO) and verify the preservation of power stability, amplitude and phase noise, as well as spatial mode quality.

2. EXPERIMENTAL SETUP

Our setup for the generation of 2128 nm light was based on type 0 degenerate optical-parametric oscillation (DOPO) in a nonlinear resonator, pumped by 1064 nm light from a nonplanar ring oscillator (NPRO) [25] master laser, see figure 1. We chose a hemilithic resonator design around a periodically-poled potassium titanyl phosphate (PP-KTP) crystal, where one side of the crystal functioned as end mirror of the resonator. This side was highly reflective for both wavelengths, while the other side of the crystal was anti-reflective. The coupling mirror was mounted on a piezo to scan and stabilize the cavity length and was coated with a reflectivity of 96% at 1064 nm and 90% at 2128 nm. The overall cavity length has been simulated and optimized to suppress higher-order Gaussian modes. Further optical properties of the DOPO are summarized in table 1. Our cavity was coupled with a mode-matching efficiency of 94%, which was mainly limited by the beam shape of the pump laser. We used a modified Pound-Drever-Hall control scheme in transmission of the resonators together with a digital controller [26] to stabilize the DOPO cavity. To simultaneously achieve the degeneracy of signal and idler fields, as well as a high conversion efficiency, we precisely controlled the temperature of two regions of the crystal [27, 28]. The main temperature \( T_1 \) adjusted the quasi phase-matching for the degenerate process. About 1 mm of the crystal’s high-reflective (HR) end was separately temperature controlled \((T_2)\) to ensure resonance for 1064 nm and 2128 nm at the same time.

The 1064 nm and 2128 nm fields were separated from each other by a dichroic beam splitter and the power of the converted light was tracked by a photodiode. To determine the wavelengths of signal and idler fields, we used a Bruker Equinox 55 spectrometer with a resolution of 0.5 cm\(^{-1}\), which corresponds to 0.23 nm at \( \lambda = 2128 \) nm.

DOPOs are known to be highly sensitive to reflection of light back into the resonator [29], which is caused by a bistability allowing the randomly chosen phase states 0 and \( \pi \) for the converted light [21, 24]. For this reason, we tried to avoid back-reflections as much as possible by slightly tilting all optics after the DOPO. In addition, we found an operation above the point of maximum efficiency to be much less sensitive than below this point. An output power of about 80 mW has been shown to be stable for our configuration.

3. RESULTS/CHARACTERIZATION

We characterized our setup to validate the performance required for interferometric light sources in gravitational-wave detection. This includes temperature tuning behavior of the oscillation wavelength, conversion efficiency, interferometric visibility, and power stability. We would have liked to also include an amplitude noise spectrum of the DOPO output field, but were unable to obtain a sufficiently broadband, low-noise and high dynamic range photo detector for 2 \( \mu \)m.

| Wavelength (nm) | 1064 | 2128 |
|----------------|------|------|
| finesse        | 153  | 59.5 |
| waist radius   | 33.2 | 47.4 | \( \mu \)m |
| free spectral range | 3.80 | 3.83 | GHz |
| linewidth (FWHM) | 24.9 | 64.3 | MHz |
| coupler reflectivity | 96  | 90  | %  |

Table 1. Optical properties of the DOPO cavity for the pump and converted wavelengths.

Fig. 1. Simplified schematics of our experiment. The laser was a NPRO with 2 W output power at the wavelength \( \lambda = 1064 \) nm. An electro-optical modulator (EOM) provided phase-modulation sidebands at 28 MHz for a Pound-Drever-Hall locking scheme of the cavity. A combination of half-waveplate and polarizing beam-splitter (PBS) adjusted the pump power. The converted light was split from the pumping beam with a dichroic beam-splitter (DBS). For diagnostic purposes, the converted light could be sent towards a spectrometer and confocal cavity. A second, identical DOPO was installed together with a phase shifter and 50/50 beam-splitter for the interference measurement (sec. C).

Fig. 2. Measured signal and idler wavelengths versus crystal temperature \((T_1 = T_2)\). Below the temperature of degeneracy (about 45.1 °C for this crystal) the difference of the signal and idler wavelengths increased with decreasing temperature. In this region the power of the converted light was nearly constant. At degeneracy the output power dropped quickly when the temperature was further increased and the conversion stopped completely at temperatures exceeding 46 °C.
The conversion efficiency \( \eta \) result for the maximum external conversion efficiency was obtained by inserting a thermal power head into the pump and output fields, respectively. Figure 3 shows the measured power levels and the calculated external conversion efficiency, i.e. not corrected for power loss from mode-matching, reflection loss of the crystal’s AR coating, internal absorption, as well as residual transmission through the resonator. We fitted a numerical model to the measured data with the time-domain simulation program NLCS [32]. As free parameters for the simulation, we used the effective non-linearity \( d_Q \) and maximum external conversion efficiency \( \eta \). Here, \( d_Q \) is related to the nonlinear coefficient \( d_{33} \) of our crystal geometry by an additional Fourier factor introduced by the quasi phase-matching, \( d_Q = \frac{2}{3} d_{33} \).

We obtained \( d_Q = (4.75 \pm 0.18) \) pm/V for the harmonic transition from 1064 nm to 2128 nm in quasi phase-matched PPKTP. The result for the maximum external conversion efficiency was \( \eta = (88.3 \pm 1.4) \) % at an incident pump power of 52 mW. Correcting for the imperfect mode matching of the pump beam, we infer an internal conversion efficiency greater than 94 %.

Far above the pump power of optimal conversion of 50 mW, i.e. above 600 mW, the output power at 2128 nm was higher than predicted by the fit in Fig. 3. We assume that this was due to imperfect constructive interference of up-converted (re-converted) light with the pumped cavity mode, but operation at these powers should in any case be avoided to retain a stable and well controllable system.

### C. Interference of converted beams

In the next step, we duplicated the DOPO setup and measured the visibility between the two independently created light fields at 2128 nm. For this, the beams were overlapped on a 50/50 beam splitter. A piezo-mounted mirror allowed us to scan the relative phase between the two fields, cf. figure 1. The resulting interference fringes were monitored on a photodiode in one of the beam splitter output ports, see figure 4. We observed a stable and stationary interference pattern, indicating quasi-identical operation of the two DOPOs and high coherence between the two fields. A maximum interferometric visibility

\[
V = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}} = 0.975
\]

was achieved, where \( I_{\text{min}} \) and \( I_{\text{max}} \) are the light powers detected at the minimum and maximum of the interference fringe, respectively. The visibility is a measure for the coherence properties of light. Deviations from \( V = 1 \) are furthermore caused by non-perfect beam overlap, differing beam powers, as well as phase and amplitude fluctuations [33]. Our measured visibility is the sum of all these imperfections, which results in an upper limit for the coherence properties of the converted fields. We assume that our visibility value was limited by imperfect beam overlap and even higher values would be achievable with careful alignment. We conclude that the two individual wavelength conversions preserve coherence properties to a high degree and therefore that the conversion approach is suitable for interferometric applications.

### D. Power stability

Converting the wavelength should retain the stability properties of the pump beam, without introducing additional power drifts or amplitude noise. We measured the intensity of the pumped and converted...
We have reported on a stable, coherent light source at 2128 nm using a high-efficiency degenerate optical-parametric oscillation. We showed long-term stability over many hours and proved strong coherence between two individually converted fields, with a measured visibility of $V = 0.975$. While our setup was optimized for low pump powers, our obtained value for the non-linearity allows for the conversion maximum to be adapted to arbitrary powers, by changing the reflectivities of the DOPO mirrors. Our approach should thus enable the conversion of the highly stable 1064 nm lasers used in current gravitational-wave detectors with powers above 100 W with external conversion efficiencies greater than 80%. Furthermore, our scheme can be readily extended to create squeezed states of light, which have become an integral part of all current and future gravitational-wave detectors.

**4. CONCLUSION**

We have reported on a stable, coherent light source at 2128 nm using high-efficiency degenerate optical-parametric oscillation. We showed long-term stability over many hours and proved strong coherence between two individually converted fields, with a measured visibility of $V = 0.975$.

While our setup was optimized for low pump powers, our obtained value for the non-linearity allows for the conversion maximum to be adapted to arbitrary powers, by changing the reflectivities of the DOPO mirrors. Our approach should thus enable the conversion of the highly stable 1064 nm lasers used in current gravitational-wave detectors with powers above 100 W with external conversion efficiencies greater than 80%. Furthermore, our scheme can be readily extended to create squeezed states of light, which have become an integral part of all current and future gravitational-wave detectors.

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