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► **To cite this version:**

Kjell Martin Mølster, Marie Guionie, Patrick Mutter, Jean-Baptiste Dherbecourt, Jean-Michel Melkonian, et al.. Precisely tunable narrowband mid-infrared mJ pulses from a backward wave optical parametric oscillator. Optica High-brightness Sources and Light-driven Interactions Congress 2022, Mar 2022, Budapest, Hungary. pp.MF4C.2, 10.1364/MICS.2022.MF4C.2 . hal-04059690

HAL Id: hal-04059690

<https://hal.science/hal-04059690>

Submitted on 5 Apr 2023

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Precisely tunable narrowband mid-infrared mJ pulses from a backward wave optical parametric oscillator.

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Abstract: Precision-tunable mJ, nanosecond pulses at 1981.1 nm and 2145.6 nm are generated at 5kHz repetition with an efficiency of 70% in a cavity-free arrangement using a PPRKTP BWOPO pumped by a narrowband DPSSL at 1030nm. © 2022 The Author(s)

Introduction

Rotational-vibrational spectroscopy using mid-infrared (MIR) absorption lines in small molecules is at the basis of diagnostic and analytical tools benefiting medical diagnostics, environmental monitoring, and providing crucial input to climate models. For the latter applications, long-distance differential absorption MIR LIDARs (DIAL) operating on mobile platforms require high MIR photon flux delivered in Fourier transform-limited nanosecond pulses generated using mechanically robust coherent source designs. The detection protocols typically require rapid and precise switching between on- and off- wavelengths of the Doppler broadened absorption line. This switching range encompasses a few GHz for small molecules in the atmosphere. Tunable optical parametric oscillators (OPOs) employing type-II quasi-phase-matching (QPM) in PPLN can provide sufficient output energy for seeding power amplifier chains in MIR LIDAR [1]. However, a typical type-II PPLN OPO acceptance bandwidth of about 300 GHz×cm in the 2 μm spectral range mandates doubly-resonant OPO designs, single-longitudinal mode pumping, and active mechanical stabilization of the OPO cavity length. In this work, we investigate a robust arrangement for the generation of narrowband, mJ-level radiation around 2 μm, which offers rapid and precise tuning without the need for optomechanical adjustments or cavity alignment. The highly efficient source relies on a precise and rapid tuning of a single-frequency fiber laser seeded master oscillator power amplifier (MOPA) pump source at 1030 nm [2] and the frequency translation properties of a backward wave optical parametric oscillator (BWOPO) [3-5].

Concept and experimental setup

BWOPO operation relies on a three-wave mixing (TWM) process with counter-propagating signal and idler waves. The three-wave mixing process involved in BWOPO needs to satisfy energy conservation ($\omega_p = \omega_f + \omega_b$) and momentum conservation ($\Delta k = k_p - k_f + k_b - K_\Lambda = 0$). Here, the subscripts p, b, and f represent the pump, backward, and forward propagating fields, respectively, and $K_\Lambda = 2\pi/\Lambda$ is the wavevector of the QPM grating with the period Λ . The grating vector has to be similar in size to that of the pump wave vector inside the crystal to achieve phase matching, implying sub-μm periodicity of the QPM structure. Counter-propagating TWM geometry ensures that the QPM structure starts oscillating once the pump threshold intensity is exceeded. The material of choice is periodically poled KTiOPO₄ (PPKTP), the only bulk crystal to produce BWOPO oscillation so far. The parametric output wavelengths in the BWOPO are determined by dispersion and QPM grating period. For a changing pump frequency, the changes in the parametric frequency are given by:

$$\Delta\omega_f = (1 + \varepsilon) \Delta\omega_p \text{ and } \Delta\omega_b = -\varepsilon \Delta\omega_p, \quad (1)$$

where $\varepsilon = v_{gb}(v_{gf} - v_{gp})/[v_{gp}(v_{gb} + v_{gf})]$ is of the order of 10^{-3} and is given by the group velocities of the interacting waves [4]. Then Eq. (1) implies that the frequency of the forward-generated (codirected with the pump) wave tunes approximately at the same rate as the pump, while the frequency changes in the backward wave are small [5]. Group velocity dispersion (GVD) introduces only a minor correction which can be neglected in the 2 μm region where GVD for z-polarized waves is close to zero in KTP. For a given pump wavelength, either signal or idler can be generated in the backward direction, depending on the QPM period. Although these configurations might appear equivalent at the threshold, they are not at higher pumping rates when the device is far from degeneracy. When the BWOPO has the period which enforces forward signal generation, the efficiency is fundamentally limited due to cascaded BWOPO processes, akin to the cascades observed in stimulated Raman scattering [6]. The same signal wavelength can be generated backward for a shorter QPM period. In such BWOPO, the cascaded processes are prohibited by momentum conservation, and higher efficiencies can be obtained at target wavelengths. Closer to degeneracy, however, when signal and idler are less than an octave apart, the cascading will not be possible even when signal is generated in the forward direction. Therefore in this work, we chose PPKTP crystals with a period of 580 nm, resulting in a forward-traveling signal at 1981.1 nm and a

backward-traveling idler of 2145.6 nm. A stable and narrowband ytterbium based pump at 1030 nm with a maximum tuning ($\Delta\omega_p$) exceeding 10 GHz, specially designed for DIAL systems [2], was used to pump BWOPO PPKTP crystals. The pump system consisted of a single-frequency fiber MOPA system followed by two free-space Yb:YAG based amplifiers. It produced 11 ns (FWHM) long millijoule pulses at a repetition rate of 5 kHz. The typical frequency bandwidth was 100 MHz. The pump wavelength tuning was obtained by modulating the central wavelength of the seed fiber laser. The pump beam $1/e^2$ radius in the BWOPO crystal was 140 μm . The wavelengths of the pump and the BWOPO output were simultaneously measured using an optical spectrum analyzer and a wavemeter. We also measured the waves' powers, bandwidths (by Fabry-Perot interferometer), and temporal traces. The PPKTP crystals had two different QPM grating lengths, one of 7 mm and one of 17 mm. The latter is by far the longest grating length of sub- μm gratings to date. The crystals were uncoated.

Results and Discussion

Fig.1(a) shows the measured and calculated frequency tuning for different pump frequency modulation amplitudes. The experiment results agree well with the dependencies calculated using Eq.1. Tuning of the forward BWOPO wave closely follows pump modulation, while the modulation of the backward wave was below the resolution of the wavemeter. Moreover, the BWOPO tuning is free of discrete jumps and tunes continuously with the pump. Thus, using this simple and mechanically robust arrangement, precise tuning over several GHz, suitable for targeting the on- and off- absorption line resonances, has been realized. The available fiber seed laser limited the tuning range of the pump. The pump can be tuned within the repetition rate of the laser, allowing pulse-to-pulse frequency targeting. In this measurement, the modulation rate was restricted by the integration time of the MIR wavemeter. The above-discussed characteristics do not come at the expense of efficiencies, as shown in Fig.1 (b-c). The conversion efficiencies (Signal+Idler) are above 70% and 50% for the long and short QPM grating, respectively. The efficiency corresponds to the combined parametric energy of 1.13 mJ (1.92 mJ pump) and 0.68 mJ (0.96 mJ pump), respectively. The threshold of the 7-mm BWOPO was 0.37 mJ, while it dropped to 70 μJ in a 17-mm long BWOPO crystal. Pulse durations of the parametric waves were about 12 ns at the average pump power of 10W. As a consequence of a high conversion efficiency, the temporal profile of the depleted pump pulse was a flat-top of 19 ns.

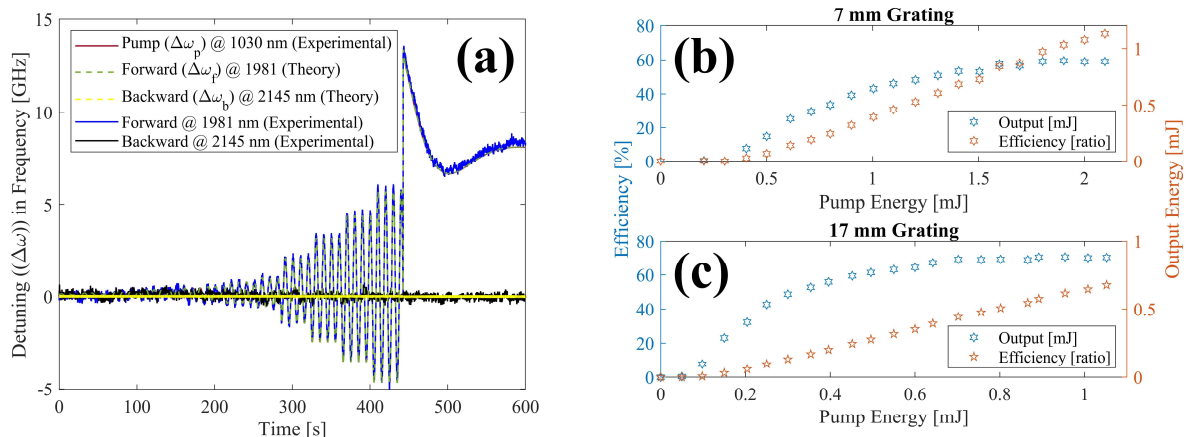


Figure 1 (a) Tuning of the backward and forward wavelengths resulting from a detuned pump. (b-c) The efficiency and parametric output energies for the two different QPM grating lengths used in the experiment. The efficiency is the ratio between the parametric energy and the pump.

In summary, we have demonstrated a narrowband mJ source with continuous and precise tuning over several GHz at 2 μm , with energy conversion efficiency reaching 70%. Average powers of up to 3W and 2.65W were generated at the signal and idler wavelengths, respectively. The mechanically robust, the cavity-free arrangement would be beneficial for stable performance in challenging environments, e.g., space and airborne applications. This work has been done under the framework of the LEMON project, EC grant agreement No. 821868.

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