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Kjell Martin Mølster, Marie Guionie, Patrick Mutter, Jean-Baptiste Dherbecourt, Jean-Michel Melkonian, et al.. Tunable narrowband MIR ns-pulses at 5 kHz repetition from a 70% efficient backward wave OPO pumped at 1030 nm. 2022 Conference on Lasers and Electro-Optics (CLEO 2022), May 2022, San Jose, United States. pp.SM3O.3, 10.1364/CLEO_SI.2022.SM3O.3 . hal-04105499

HAL Id: hal-04105499

<https://hal.science/hal-04105499v1>

Submitted on 24 May 2023

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Tunable narrowband MIR ns-pulses at 5 kHz repetition from a 70% efficient backward wave OPO pumped at 1030 nm

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Abstract: Precision-tuned nanosecond pulses at 1981.1 nm and 2145.6 nm are generated from a PPKTP BWOPPO with 70% efficiency, pumped by an amplified single-frequency fiber laser at 1030 nm. It is free from mechanically-adjustable optical cavities. © 2022 The Author(s)

Introduction

The backward wave optical parametric oscillator (BWOPPO) is a parametric down-conversion device where positive feedback for oscillation is established by nonlinear interaction between counter-propagating waves. In order to realize that, quasi-phase matched (QPM) interaction is used with $\chi^{(2)}$ polarity structured with a period similar to the pump's optical wavelength inside the nonlinear material. It can deliver narrowband, coherent, and tunable electromagnetic radiation, satisfying similar needs as OPO would in, e.g., microscopy, LIDAR, spectroscopy, and others. The first demonstration of a BWOPPO [1] happened in 2007 in periodically poled KTiOPO_4 (PPKTP) over 40 years after the initial proposal [2]. Further developments in the structuring technology in PPKTP allow for the fabrication of efficient and low-threshold BWOPPOs suitable for high-power operation [3-4]. BWOPPO needs to satisfy a three-wave mixing QPM condition, $\Delta k = k_p - k_f + k_b - K_\Lambda = 0$, and energy conservation $\omega_p = \omega_f + \omega_b$. The subscripts b, f, and p denote the backward, forward, and pump fields, respectively. The grating vector $K_\Lambda = 2\pi/\Lambda$, is associated with the periodicity (Λ) of the $\chi^{(2)}$ structure. The counter-propagating nonlinear process and the phase-relation associated with the difference frequency mixing process enforce a self-seeded oscillation and phase-locking between the pump and the forward wave [4]. From the momentum and energy conservation conditions, one can show, to the first dispersion order, that the forward and the backward wave frequency tuning rates with respect to the pump frequency are given by the group velocities of the interacting pulses:

$$\frac{d\omega_f}{d\omega_p} = \frac{v_{gf}(v_{gb} + v_{gf})}{v_{gp}(v_{gb} + v_{gf})} = 1 + \varepsilon, \quad \frac{d\omega_b}{d\omega_p} = \frac{v_{gb}(v_{gp} - v_{gf})}{v_{gp}(v_{gb} + v_{gf})} = -\varepsilon. \quad (1)$$

The quantity ε is small, of the order of 10^{-3} , indicating that the frequency change of the forward wave closely follows that of the pump, while the backward wave frequency changes substantially lower. This is in contrast to the tuning behavior in standard OPOs. Such a tuning property, together with the high efficiency of the BWOPPO, would be highly beneficial in applications where fast and precise tuning is needed, e.g., differential absorption LIDARs (DIAL). A prerequisite for this is a tunable high-power pump capable of delivering transform-limited nanosecond pulses in near-infrared. This work combines a specially designed tunable nanosecond pump source at 1.03 μm [5] with a PPKTP BWOPPO, demonstrating a simple, robust and precision-tuned source in the 2 μm spectral region, with a conversion efficiency reaching 70%. The conversion efficiency is defined as the ratio between the parametric and the pump energy, $(E_{\text{forward}} + E_{\text{backward}})/E_{\text{pump}}$. The system is free from mechanically adjustable optical cavities, presenting a high potential for applications in airborne and space-borne environments where high stabilities are needed.

Experimental setup

The experiment was carried out using a pump similar to that originally described in [5]. A tunable single-frequency fiber laser at 1030 nm seeded a multi-stage Ytterbium amplifier where the first stages are fiber-based, and the following used bulk Yb:YAG crystals. The output laser pulses were 11 ns (FWHM) long and were delivered at a repetition rate of 5 kHz with a bandwidth close to 100 MHz [5]. It was focused to a Gaussian spot of 140 μm radius at $1/e^2$ into a BWOPPO crystal. The BWOPPO crystal had a grating period (Λ) of 580 nm, which results in a backward traveling idler with a center wavelength of 2145.6 nm and a forward traveling signal of 1981.1 nm. We synchronously monitored the pump and one of the parametric wavelengths with two wavemeters as the DFB seed laser wavelength was changed. In addition to these measurements, we measured the output power, bandwidths, and time traces of the interacting waves. Two different lengths of BWOPPO PPKTP crystals were employed, one

with a grating length of 7 mm, and one with a length of 17 mm. The longer samples are the largest PPKTP sample with sub- μm gratings produced to date. All nonlinear crystals were uncoated.

Results, Discussion, and Conclusion

Figure 1. (a) shows conversion efficiencies well over 50% and 70% for the short and long BWOPO crystal, respectively. For the 7 mm (17 mm) crystal, at a maximum of 1.92 (0.96) mJ pump energy, the crystal generated 0.53 (0.32) mJ of idler and 0.60 (0.36) mJ of signal. The threshold for the short crystal was at 0.37 mJ, whereas, for the long crystal, the threshold was reached at a pump energy of 70 μJ . The BWOPO pulse duration was about 12 ns (FWHM) at a pump of 10 W. As in all parametric oscillators, the pulse length depends on the pumping rate above the threshold. The significant pump depletion by the BWOPO leaves the remnant of the pump in a 19 ns (FWHM) flat-top pulse. The two crystals follow the same characteristic efficiency as the pump is increased above the threshold. The bandwidth of the idler and signal were estimated with a 10 GHz scanning Fabry-Perot (FP) cavity to be lower than 310 MHz and 407 MHz, respectively. In this measurement, the FP cavity finesse was >150 . The BWOPO tuning was investigated by modulating the DFB central wavelength in the pump setup. Figure 1 (b) shows both the theoretical and experimental data from tuning the pump by ± 5 GHz with a modulation period of 10 s. The changes in the BWOPO forward wave frequency follow very well that of the pump and are according to the expectations from Eq. (1). The frequency changes in the backward wave are beyond the resolution of our measurement. It can be inferred directly from the change in the forward wave that the excess energy to shift the backward bandwidth should be below 10 MHz, smaller than the measured bandwidth of the output pulses. This is also visible in the larger forward wave bandwidth as compared with the backward wave bandwidth. The relationship between forward and pump wavelength demonstrates that the forward wave acts as a cavity-free wavelength translator. This property is useful for, e.g., DIAL systems, where on and off absorption peak measurements require fast and precise tuning over a few-GHz frequency range. The modulation speed for the presented system is determined by the repetition rate of the pump source, as the seed laser for the MOPA system can tune within the pulse repetition rate, and BWOPO has an instant response, allowing for pulse-to-pulse modulation. However, in this demonstration measurement, we were limited by the wavemeter's sensitivity and thus the integration time, restricting our modulation rate to 0.1 Hz.

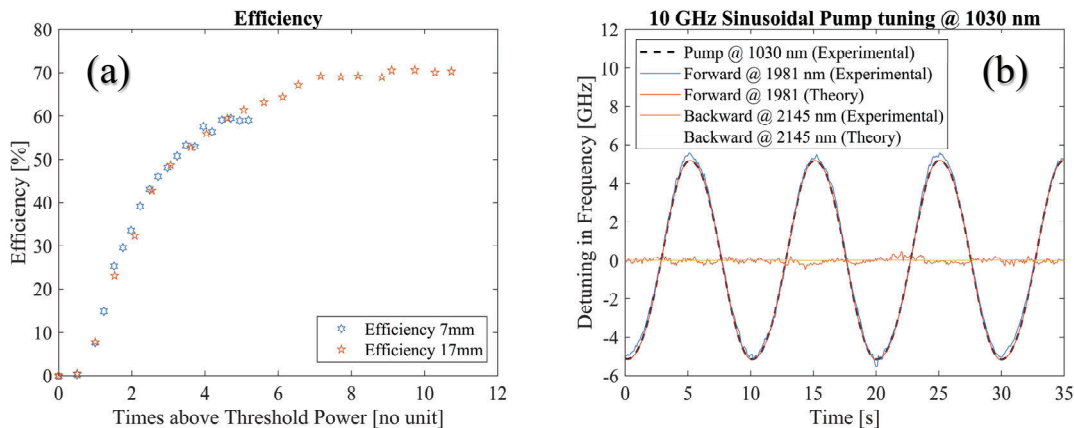


Figure 1 (a) BWOPO efficiencies at different levels above the energy threshold for both the crystals. The efficiency is the ratio between the parametric energies and the pump (b) BWOPO tuning for forward and backward traveling waves as the pump is tuned by ± 5 GHz.

In conclusion, we have demonstrated a high-energy, narrowband, mJ, nanosecond BWOPO with continuous tuning over 10 GHz in the MIR with a conversion efficiency exceeding 70%. The high average powers of 3 W at 1981.1 nm and 2.65 W at 2145.6 nm were obtained thanks to the long and well-poled PPKTP crystal. The BWOPOs excellently translated the bandwidth of the pump into the forward parametric wave while providing a stable, narrow line backward wave. This work has been done under the framework of the LEMON project, EC grant agreement No. 821868.

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