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LETTER

High-energy picosecond OPO based on PPKTP

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Abstract
Output energy of 1 mJ is obtained for the 380 ps long idler pulses at 2800 nm from a short cavity singly resonant 500 Hz optical parametric oscillator employing PPKTP and a near-diffraction-limited, single frequency, sub-nanosecond pump source at 1064 nm.

(Some figures may appear in colour only in the online journal)

1. Introduction

When laser radiation is converted to longer wavelengths the efficiency of the down-conversion nonlinear process is normally enhanced by inserting the nonlinear crystal into a resonant cavity forming an optical parametric oscillator (OPO), which ensures feedback and multiple round trips for the resonated wave (signal or idler, or both) reaching in the best case depletion of the pump wave [1]. This works, however, only on time scales which ensure a sufficient number of round trips, i.e. from continuous wave (cw) down to a few nanoseconds (1 ns is equivalent to 30 cm in free space) and corresponds, obviously, to relatively low peak power pump sources, e.g. cw or short pulse (Q-switched) lasers [1]. The parametric gain can be increased by using longer nonlinear crystals but crystal growth restrictions normally set an upper limit of a few centimeters. Longer crystals automatically mean a smaller number of round trips which reduces the OPO feedback effect in the short pulse limit. Thus development of highly nonlinear materials is of increasing importance in this limit. In particular, periodically poled crystals provide substantially higher effective nonlinearities; therefore, they are compatible with shorter pulse durations and cavity lengths.

The generated signal and idler pulses from a pulsed OPO exhibit durations that are shorter compared to the pump pulse due to the temporal gain narrowing effect (the parametric gain depends on the instantaneous intensity). One finds only a few examples in the vast OPO literature of pulse generation in the short pulse limit. For instance, using a 9 mm long periodically poled $KTiOPO_4$ (PPKTP) crystal in an OPO cavity with only very few round trips, pumped by 2.3 ns pulses at 1064 nm, resulted in ~1 ns long signal pulses [2]. Sub-nanosecond idler pulses from a short cavity OPO employing a highly nonlinear material used in a non-critical phase-matching configuration were reported only recently [3]. Cadmium silicon phosphide, $CdSiP_2$ (CSP), with its exceptionally high effective nonlinearity, $d_{eff} = d_{36} = 84.5$ pm V^{-1}, permitted us to use crystal lengths not exceeding 1 cm, while pumping with 1 ns pulses near 1 μm [3]. These results could be extended towards shorter pulse durations, <300 ps at 6.15 μm corresponding to <3 cavity round trips, with a 7 mm long crystal, but this was in the high repetition rate (1–10 kHz) regime corresponding to low pulse energies, which does not utilize the available crystal aperture of a bulk nonlinear material [4]. In addition, the idler tuning range of this exceptional nonlinear crystal is limited under non-critical phase-matching to 6.1–6.5 μm, because with increasing temperature the transparency limit of 6.5 μm, set by intrinsic multi-phonon peaks, is reached.

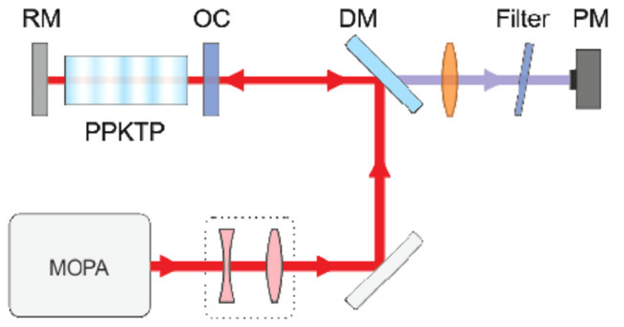

Figure 1. Experimental set-up of the PPKTP OPO.

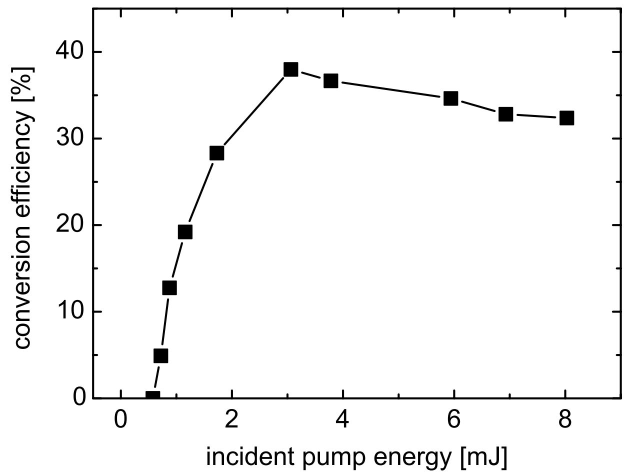

Figure 2. Quantum conversion efficiency of the PPKTP OPO calculated from the idler output.

We investigated also PPKTP based sub-nanosecond and picosecond OPOs for idler pulse generation around 2.8 μm with the same pump sources achieving very low thresholds and high conversion efficiency [5, 6]. Such coherent sources in the 1.5–3 μm spectral region are of interest e.g. in solar cell processing as the metal contacts are shifted to the backside of the cell in order to avoid the shadowing effect. With a 1 cm long OPO cavity in a singly resonant configuration and double pass pumping by 1 ns pulses at 1064 nm, the maximum idler energy reached 110 μJ at 1 kHz [5]. Pumping with 500 ps pulses at 1–10 kHz resulted in an idler energy of ∼50 μJ and pulse duration of ∼250 ps [6]. The corresponding quantum conversion efficiencies were 32.5% and 34.9%, respectively. However, also with PPKTP, energy scaling has not been studied yet and the potential of thick periodically poled samples has not been utilized. In the present work we extend these results to the millijoule energy range for the idler by utilizing the full crystal aperture with a powerful pump source specially designed for this purpose. This represents a significant energy scaling by almost an order of magnitude.

2. Experimental set-up and results

More information on the fabrication of thick PPKTP can be found in [7]. The same PPKTP sample described in [5, 6], $d_{\mathrm{eff}} \sim 8$ pm V^{-1}, 9 mm long, with a domain inversion period of 37.8 μm, was used now in the cavity shown in figure 1. It was 3 mm thick along the *z*-axis, and 5 mm wide along the *y*-axis, with a grating pattern of 8 mm (along *x*-axis) to 2 mm (along *y*-axis). The PPKTP sample was antireflection coated for the pump and signal with low reflectivity (∼4%) in the idler spectral range. The rear mirror RM was a plane Ag reflector while the plane output coupler OC was a dielectric mirror reflecting 99.9% at the signal wave and transmitting >93% at the idler wave (∼2.8 μm). Hence, the OPO can be considered as singly resonant with double pass pumping. The physical cavity length was 16 mm. This is longer than the minimum possible but the only reason was to protect the PPKTP crystal if damage to the RM occurs. The PPKTP crystal was pumped through the OC, which transmitted more than 98% at 1064 nm. The beams were separated by a dichroic mirror DM, which had 99.5% reflection for the pump (π-polarization) and transmitted 94% (π-polarization) at the idler wavelength.

The near-diffraction-limited, single frequency Nd:YAG based MOPA pump system is described in detail elsewhere [8]. It is based on amplification of pulses from a near-diffraction-limited, single frequency, passively *Q*-switched Nd:YAG laser in a two stage diode-pumped amplifier and delivers up to 13 mJ output pulses at 1064 nm at a repetition rate of 500 Hz. For the present experiment the pump pulse duration was 714 ps and the pump beam was down-collimated to a diameter of ∼2 mm in the position of the PPKTP crystal. Only the idler pulse energy was measured by a power meter (PM). The filter in front of the power meter was a 2.4 μm cut-on filter on Ge. The results were corrected for the transmission of the filter, the collimating lens and the dichroic mirror (figure 1).

The OPO threshold was at 0.58 mJ of pump energy, corresponding to a peak (on-axial) intensity ∼50 MW cm^{-2}. It should be outlined that optical parametric generation (or low finesse OPO operation due to residual reflectivity of the AR coatings at the idler wave) was observed with a three times higher threshold if the output coupler is removed. In the presence of the output coupler, however, depletion normally suppresses such parametric generation. The maximum OPO external quantum conversion efficiency reached 38%, figure 2, which in fact exceeds the best values achieved in the low-energy regime [5, 6].

Maximum idler energy of 1 mJ was extracted at the maximum pump level of 8 mJ (figure 3). This is the highest energy ever reported from a sub-nanosecond OPO at any wavelength.

The pulse durations were obtained by deconvolution of the recorded curves (figure 4) with the time response of the detection system (InGaAs photodiode and 1.5 GHz oscilloscope) which was measured to be 350 ± 5 ps, assuming Gaussian functions. For the pulse duration (FWHM) of the signal we obtained 550 ps, while for the frequency doubled idler the result was 270 ± 20 ps (figure 4). Hence, the idler pulse duration at 2.8 μm is estimated to be 380 ps (FWHM), again assuming a Gaussian pulse shape. Thus, the peak idler power amounts to 2.6 MW.

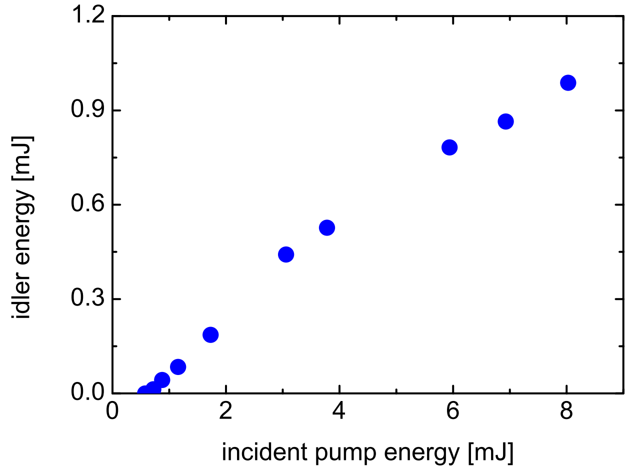

Figure 3. Idler energy at the OPO output versus pump energy incident on the PPKTP crystal.

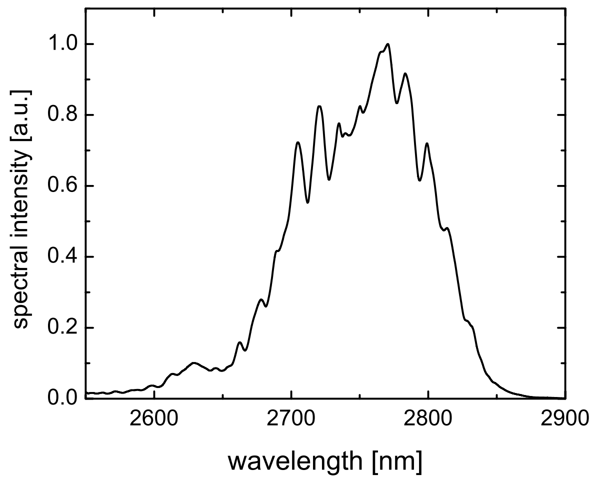

Figure 5. Idler spectrum measured at pump energy of 4 mJ.

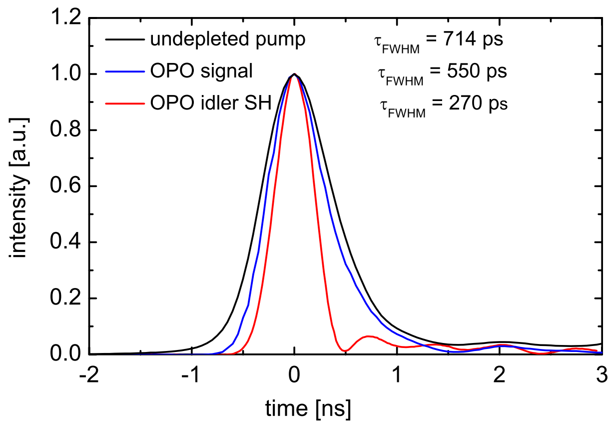

Figure 4. Temporal pulse profiles of the undepleted pump, signal and frequency doubled idler pulses.

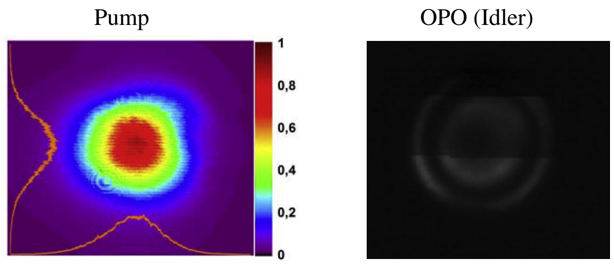

Figure 6. Spatial profiles of the pump beam in the position of the PPKTP crystal (a) and of the idler beam recorded close to the OPO output. The line artifact in (b) is due to the external chopper used because the pyroelectric camera is limited to repetition rates up to 50 Hz.

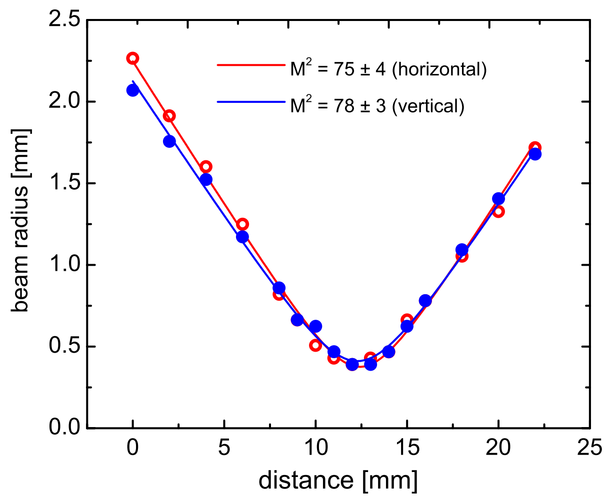

Figure 7. Idler beam quality evaluated at a pump energy of 4 mJ with a 25 mm lens.

The measured idler spectrum is shown in figure 5. Its FWHM amounts to ∼110 nm, which is broader than the spectral acceptance bandwidth due to the high parametric gain regime. The corresponding signal spectral FWHM was measured to be 27 nm.

The beam profiles of the pump and idler waves were measured with a CCD and a pyroelectric camera, respectively. As can be seen from figure 6, even though a near-diffraction-limited pump beam is used, the idler output from the OPO is highly multimode. This can be attributed to the large Fresnel number of the cavity (∼100) and the low number of signal round trips within the short duration of the pump pulse. The M^2 parameters obtained in the two planes and the corresponding fits used are shown in figure 7.

The present limitation for further energy scaling of the described short cavity OPO looks quite trivial because it occurred as damage to the rear Ag total reflector. Even though the PPKTP crystal was separated by 3 mm from the rear mirror after close inspection with a microscope, tiny traces of silver could be observed on its AR-coated surface. In practice, it was very difficult to find a supplier of more damage resistant metal coatings for such a mirror.

One possibility to reduce the damage susceptibility related to the high signal intracavity power is to reduce the reflectivity of the output coupler at the signal wave. Note that in the present set-up about 1.6 mJ of signal energy (according to the photon number conservation) is dissipated in the cavity due to parasitic absorption/scattering. According to figure 2, the maximum output energy is achieved when the quantum efficiency is already decreasing, at about 14 times above threshold. Obviously, higher output energy could be achieved at maximum quantum efficiency, i.e. increasing the OPO threshold and slope efficiency with an output coupler partially transmitting the signal wave. This will simultaneously reduce the risk of optical damage to the mirrors and the nonlinear crystal.

3. Conclusion

In conclusion, we achieved idler energy as high as 1 mJ at 2.8 μm from a PPKTP OPO in the picosecond regime. At a repetition rate of 500 Hz this gives an average power of 0.5 W. Higher conversion efficiency can be expected by decreasing the output coupler signal reflectivity in order to avoid intracavity optical damage and pumping with the full available pump energy.

Acknowledgments

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