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Sub-nanosecond, 1–10 kHz, low-threshold, non-critical OPOs based on periodically poled KTP crystal pumped at 1,064 nm

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Abstract We employed a 9-mm long periodically poled $KTiOPO_4$ (PPKTP) crystal in an optical parametric oscillator (OPO) to generate sub-nanosecond idler pulses around 2.8 μm. With a 1-cm long OPO cavity in a singly resonant configuration and double pass pumping by 1-ns pulses at 1,064 nm, the maximum idler energy reached 110 μJ at 1 kHz. Pumping with 500 ps pulses at 1–10 kHz, resulted in an idler energy of ~50 μJ and the shortest pulse duration of ~250 ps, ever reported for an OPO. The corresponding quantum conversion efficiencies were 32.5 and 34.9 %, respectively.

1 Introduction

Optical parametric oscillators (OPOs) consist of a resonant cavity which is in general, necessary for low peak pump powers, normally associated with pulses of duration from few nanoseconds to continuous-wave in which case many round trips of the resonated wave (signal or idler, or both) ensure sufficiently high parametric gain to reach the threshold [1]. With the development of periodically poled materials which provide substantially higher effective nonlinearities and thus require lower pump powers, shorter pulse durations and cavity lengths can be used. In general, the signal and idler pulse durations obtained are shorter than that of the pump, due to the temporal gain narrowing effect. Thus, using a 9-mm long periodically poled $KTiOPO_4$ (PPKTP) crystal in an OPO cavity with only few round trips pumped by 2.3-ns pulses at 1,064 nm resulted in ~1-ns-long signal pulses [2].

Recently, we demonstrated that a highly nonlinear material used in a non-critical phase-matching configuration can be implemented in a short cavity OPO to produce sub-nanosecond signal and idler pulses [3]. In the case of cadmium silicon phosphide, $CdSiP_2$ (CSP), this was possible due to the very high effective nonlinearity, $d_{\mathrm{eff}} = d_{36} = 84.5$ pm/V, which permitted to use crystal lengths not exceeding 1 cm, while pumping with 1-ns pulses near 1 μm [3]. However, the idler tuning range of CSP in such a non-critical phase-matching configuration is limited 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. In this work we demonstrate that periodically poled oxide materials can also be employed in short cavity, singly resonant OPOs, to cover shorter mid-IR idler wavelengths, at very low thresholds, with sufficiently high conversion efficiency and potential for energy scaling. Pulse durations as short as ~250 ps are obtained for the idler wave near 2.8 μm. To our knowledge these are the shortest pulses ever achieved with an OPO. Such sub-nanosecond coherent sources in 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 shadowing effect.

2 Experiments

The periodically poled $KTiOPO_4$ (PPKTP) sample ($d_{\mathrm{eff}} \sim 8$ pm/V) used in the present study was 9-mm long, with a

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domain inversion period of 37.8 μm. It was 3-mm thick along the *z*-axis, and 5-mm wide along the *y*-axis. However, the grating pattern was 8 mm (along *x*-axis) to 2 mm (along *y*-axis). This made it possible to build a plane–plane OPO cavity with a mirror separation of 1 cm (Fig. 1). The PPKTP sample was antireflection coated for the pump and signal with low reflectivity (∼4 %) in the idler spectral range. The rear total reflector RM was an Ag-mirror with a reflection of ∼97 % at all three wavelengths. The output coupler OC was a dielectric mirror on a 3-mm thick YAG substrate, with a reflection of >99.9 % between 1,410 and 1,800 nm (signal wave), transmitting >95 % between 2,750 and 4,200 nm (idler wave). Hence, the OPO can be considered as singly resonant with double pass pumping. The PPKTP crystal was pumped through the OC which transmitted >98 % at 1,064 nm. The beams were separated by a pump bending mirror, BM, which had 98 % reflection for the pump (p-polarization) and transmitted 89 % (p-polarization) at the idler wavelength, respectively.

First we used a pump source based on a diode-pumped electro-optically Q-switched, 1-ns Nd:YVO$_4$ microlaser, a cw pumped Nd:YVO$_4$ regenerative amplifier, and a double pass Nd:YAG post amplifier with pulsed pumping, optimized for a repetition rate of 1 kHz. The maximum available pump energy from this system was about 1.4 mJ, of which 0.89 mJ were incident on the PPKTP crystal. A combination of a half-wave plate and a polarizer served to adjust the pump energy. The pump beam from the amplifier was down-collimated using a telescope to a Gaussian diameter of 2w ∼ 1.2 mm in the position of the OPO. Only the idler energy was measured behind the bending mirror and the residual pump radiation and the signal was blocked by a 2.3-μm cut-on filter.

The measured OPO threshold with this pump source was as low as ∼110 μJ of pump energy (∼10 MW/cm^2 average pump intensity), as shown in Fig. 2a. This intensity threshold value is >40 times lower than the one given in [2] using focused beams, with the main difference related to the double pass pumping in the present scheme. Comparing with CSP employed in a very similar cavity [3], the OPO threshold is only 6 times higher with the present PPKTP, although its figure of merit is about 15 times lower; this can be attributed to the additional residual (linear) losses of CSP. In terms of pump fluence the PPKTP OPO threshold amounts to ∼10 mJ/cm^2 (average) or ∼20 mJ/cm^2 (peak on axis).

As can be seen from Fig. 2a, there is good agreement between the idler pulse energy measurements by a pyroelectric detector (Newport 818 J-09B) and the values derived from average power measurements with a power meter. The maximum idler output energy at ∼2.8 μm reached 110 μJ which corresponds to idler conversion efficiency of 12.4 % and quantum conversion efficiency of 32.5 % (Fig. 2b). The latter closely follows the conversion efficiency measured by power meter through pump depletion, though at higher pump levels, additional nonlinear losses could be present [2].

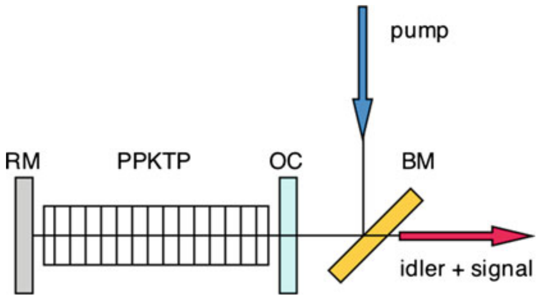

Fig. 1 OPO setup: RM broadband reflective silver mirror, OC dielectric output coupler on YAG substrate (high reflectivity for the signal wavelength), BM coated ZnSe bending mirror (high reflectivity for pump beam, high transmissivity for idler beam)

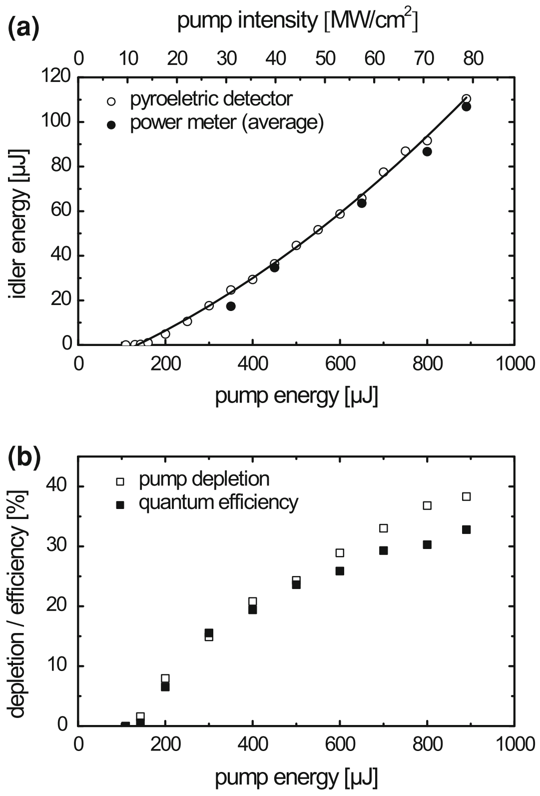

Fig. 2 Idler pulse energy versus pump pulse energy incident on the PPKTP crystal pumped by 1-ns pulses (**a**). The pump intensity represents a spatially averaged value, equal to half of the peak on-axis value. Comparison of the measured pump depletion and calculated quantum efficiency versus pump energy (**b**)

The depleted pump pulse shape together with the undepleted pulse profile (measured by misaligning the OPO), can be seen in Fig. 3a, together with the signal pulse profile, all recorded by a 70-ps response InGaAs photodiode and a

2-GHz oscilloscope. The signal pulse duration (FWHM) amounted to 0.72 ns (Fig. 3b), shorter as expected, than the pump pulse duration (1 ns). No such fast detectors exist above ~2 μm but we frequency doubled the idler pulse in a 4.5-mm thick $GaS_{0.4}Se_{0.6}$ crystal [4] ($\theta = 0°$ cut, tilted for type-I phase-matching) and measured the pulse duration of the second-harmonic (SH), also shown in Fig. 3b. Multiplying the result by $\sqrt{2}$, the SH generation shortening factor for Gaussian pulse shapes, gives an idler pulse duration estimation of 0.76 ns, very close to the signal pulse duration.

The second pump source we employed to pump the same OPO cavity was a diode-pumped laser system consisting of a passively Q-switched Nd:YAG oscillator and double pass side pumped $Nd:YVO_4$ amplifier described in detail elsewhere [5]. The maximum available pump energy was about 0.5 mJ (0.38 mJ incident on the PPKTP crystal). The pump pulse duration was ~500 ps and the repetition rate could be varied between 1 and 10 kHz. The pump beam from the amplifier was shaped by a sequence of two cylindrical telescopes and then down-collimated using a spherical telescope to a Gaussian diameter of 2w ~ 0.7 mm in the position of the OPO.

The measured OPO threshold with this pump source was as low as 76 μJ of pump energy (~40 MW/cm^2 average pump intensity) at 1 kHz, Fig. 4a. The maximum idler output energy at ~2.8 μm reached 50.7 μJ which corresponds to idler conversion efficiency of 13.3 % and quantum conversion efficiency of 34.9 %. The conversion efficiency achieved (Fig. 4b) is very similar to the one with the 1-ns pump pulses although in the present case the number of cavity round trips within the pump pulse FWHM is only about four. The conversion efficiency follows the measured pump depletion (Fig. 4b), again with some additional nonlinear losses at pump levels exceeding 50 MW/cm^2. The depleted and undepleted pump pulse shapes can be seen in Fig. 5a, together with the signal pulse profile, all measured by the 70-ps response InGaAs photodiode and a 6-GHz oscilloscope.

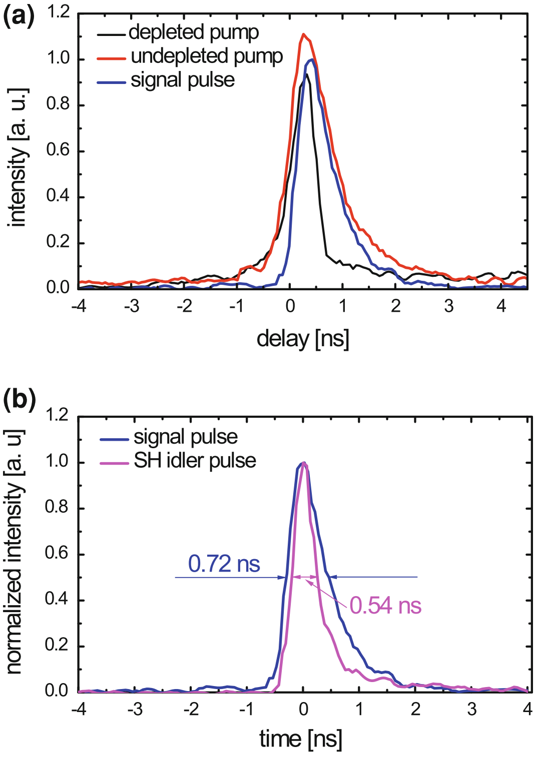

Fig. 3 Pulse shapes of the incident (undepleted) pump, depleted pump, and signal pulses (**a**). The relative intensity scale is true only for the undepleted and depleted pump pulses. Comparison of the pulse duration of the idler SH with the signal pulse (**b**)

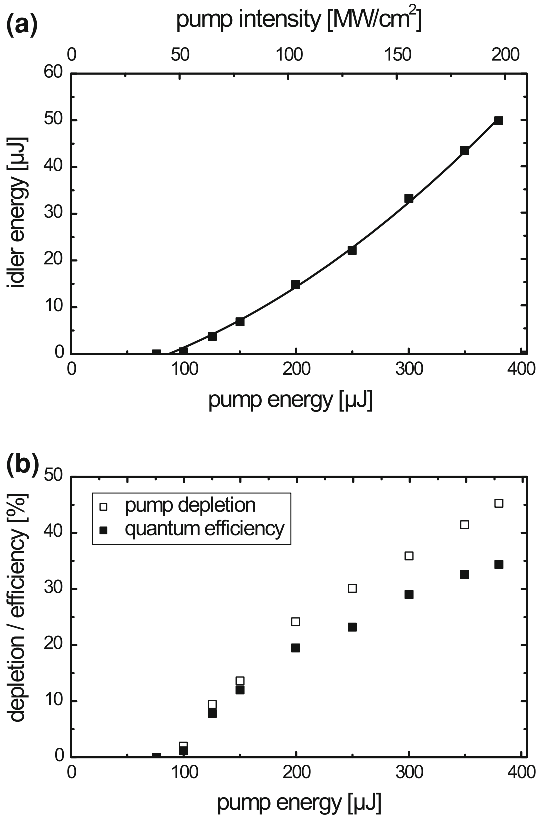

Fig. 4 Idler energy versus pump energy, incident on the PPKTP crystal pumped by 500 ps pulses at 1 kHz (**a**) and comparison of the measured pump depletion and calculated quantum efficiency versus pump energy (**b**)

The signal pulse duration (FWHM) amounted to 316 ps, again shorter, as expected, than the pump pulse duration (~500 ps). From the pulse duration of the idler SH, see Fig. 5a, multiplying the result by a factor of $\sqrt{2}$, an idler FWHM of 274 ps is obtained, again very close to the signal pulse duration. Autocorrelation measurement of the idler pulse using non-collinear SH generation in the same $GaS_{0.4}Se_{0.6}$ crystal gave a very similar result of 234 ps (Fig. 5b).

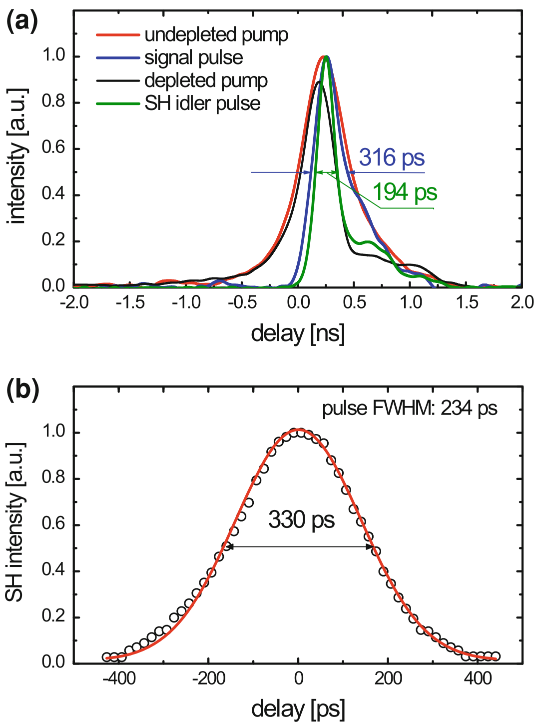

Fig. 5 Pulse shapes of the incident pump, depleted pump, signal and frequency doubled idler pulses (**a**) and autocorrelation of the idler pulses, fitted by Gaussian pulse shape (**b**). In (**a**) the relative intensity scale is true only for the undepleted and depleted pump pulses. The repetition rate is 1 kHz

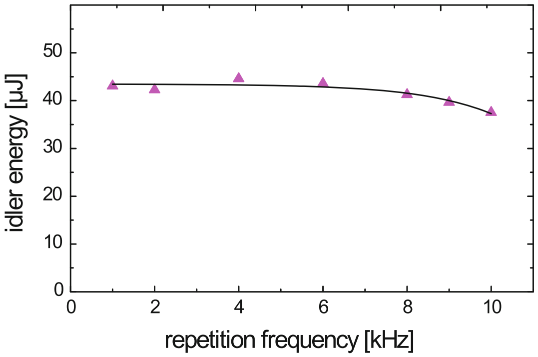

Fig. 6 Idler energy versus repetition rate at constant incident pump energy of 340 μJ

The dependence of the idler energy on the repetition rate is shown in Fig. 6. Some reduction is observed only at the highest repetition rates ~10 kHz, related to changes observed in the pump beam spatial profile. The highest idler average power obtained at 10 kHz repetition rate was 375 mW at 3.4 W of average pump power.

3 Conclusions

We demonstrated sub-nanosecond pulse durations down to ~250 ps for the signal and idler pulses of 1–10 kHz OPOs based on PPKTP and pumped at 1,064 nm. Maximum idler energies of 110 and 50 μJ near 2.8 μm were achieved with the 1-ns and 500-ps pump pulse sources, respectively. At room temperature the signal and idler wavelengths were at 1,722 and 2,786 nm, respectively. Tuning is in principle possible by temperature and/or multiple gratings and extension to higher pulse energies is in progress. Finally we notice that the idler wavelength can be affected by significant water vapor absorption in air; the OPO by itself is completely immune, owing to the extreme compactness and the very thin air gaps in the cavity, furthermore all measurements have been accomplished with detectors placed as close as possible to the output. However, for general applications such laser sources would require careful air purging to avoid strong absorption and related beam pointing disturbances.

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