Sub-nanosecond, 1-kHz, low-threshold, non-critical OPO based on periodically-poled KTP crystal pumped at 1064 nm

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ABSTRACT

We employed a 9-mm long periodically-poled $KTiOPO_4$ (PPKTP) crystal with a domain inversion period of 37.8 μm in an optical parametric oscillator (OPO) to generate sub-nanosecond pulses around 2.8 μm. With a 1-cm long OPO cavity in a singly resonant configuration with double pass pumping the OPO threshold was 110 μJ at 1064 nm (1-ns pump pulses at 1064 nm). The maximum idler output energy reached 110 μJ (quantum conversion efficiency of 32.5%). The signal pulse duration (FWHM) was 0.72 ns and the estimated idler pulse duration was 0.76 ns. At room temperature the signal and idler wavelengths were at 1722 and 2786 nm.

Key words: optical parametric oscillators; mid-infrared; sub-nanosecond pulses; PPKTP

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 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 periodically poled $KTiOPO_4$ (PPKTP) with 2.3-ns pump pulses at 1064 nm resulted in ~1 ns long signal pulses, both with a 10-mm long crystal in an OPO cavity (with only very few round trips) and with a 20-mm long crystal in a quasi-OPG (optical parametric generator) configuration (low-finesse doubly-resonant OPO cavity parasitically formed by residual reflections of the crystal AR-coatings).[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, $d_{eff}=d_{36}=84.5$ pm/V, which permitted to use crystal lengths not exceeding 1 cm, while pumping with relatively short 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.

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.

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2. EXPERIMENTAL SET-UP

The periodically-poled $KTiOPO_4$ (PPKTP) sample (d_{eff}~8 pm/V) used in the present study was 9 mm long, with a 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 and Fig. 2). The rear total reflector, TR, was an Ag-mirror with a reflection of ~97% at all three wavelengths. The output coupler, OC, a dielectric mirror on a 3-mm thick YAG substrate, had a reflection of >99.9% between 1410 and 1800 nm (signal wave), transmitting >95% between 2750 and 4200 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 1064 nm. The beams were separated by the pump bending mirror, BM, which had 98% reflection for the pump (p-polarization) and transmitted 89% (p-polarization) at the idler wavelength, respectively. The pump source was a diode-pumped laser system consisting of an 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 was about 1.4 mJ, of which 0.89 mJ were incident on the PPKTP crystal. A combination of a half-wave plate, $\lambda/2$, and a polarizer, P, 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 BM, the residual pump radiation and the signal were blocked by a 2.3 µm cut-on filter.

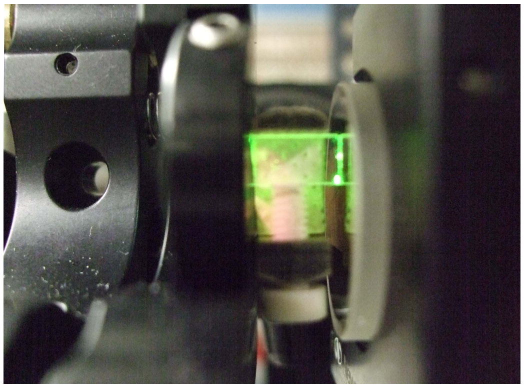

Fig. 1. Photograph of the operating short-cavity OPO.

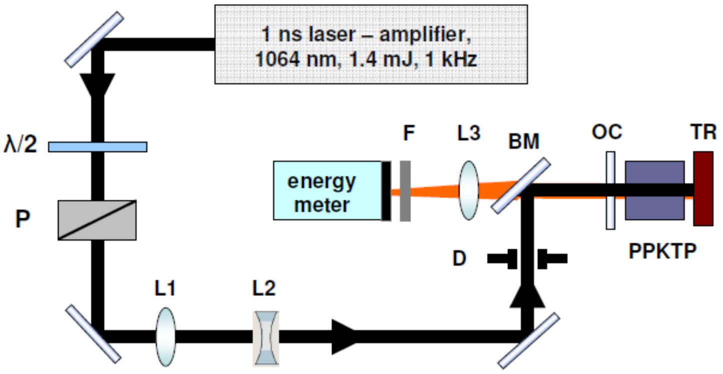

Fig. 2. Schematic of the OPO set-up: $\lambda/2$: half-wave plate, P: polarizer, F: 2.3 µm cut-on filter, L1: 20-cm lens, L2: -10 cm lens, L3: 10 cm MgF_2 lens, D: diaphragm, BM: bending mirror, OC: output coupler, TR: total reflector.

3. RESULTS AND DISCUSSION

The measured OPO threshold was as low as ~110 µJ of pump energy (~10 MW/cm^2 average pump intensity), Fig. 3. This intensity threshold value is >40 times lower than the one given in Ref. 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, the OPO threshold is only 6 times higher with the present PPKTP OPO, although the figure of merit of PPKTP is about 15 times lower – this can be attributed to the additional residual (linear) losses of CSP. In terms of pump fluence the present PPKTP OPO threshold amounts to ~10 mJ/cm^2 (average) or ~20 mJ/cm^2 (peak on axial).

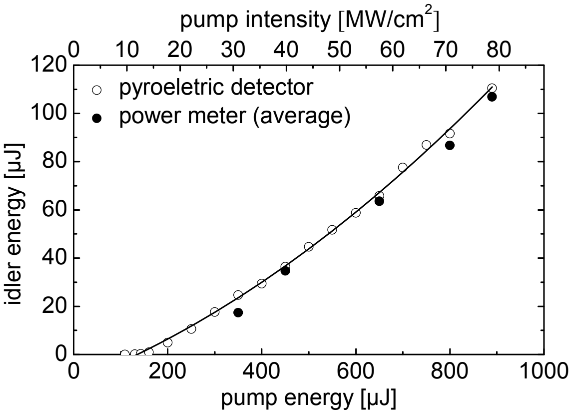

Fig. 3. Idler pulse energy versus pump pulse energy incident on the PPKTP crystal. The pump intensity represents a spatially averaged value equal to ½ of the peak on-axis value.

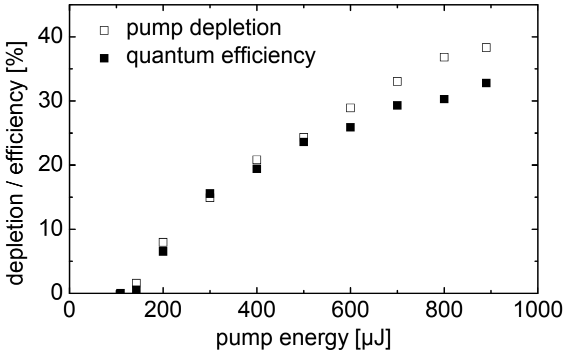

Fig. 4. Comparison of the measured pump depletion and calculated quantum efficiency versus pump energy.

As can be seen from Fig. 3, there is good agreement between the idler pulse energy measurements by a pyroelectric detector 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%. The latter closely follows the measured by a power meter pump depletion (Fig. 4), though at higher pump levels, additional nonlinear losses could be present.[2] The depleted pump pulse shape together with the undepleted pulse profile (measured by misaligning the OPO), can be seen in Fig. 5, together with the signal pulse profile, all recorded by a 70 ps response InGaAs photodiode and a 2 GHz oscilloscope.

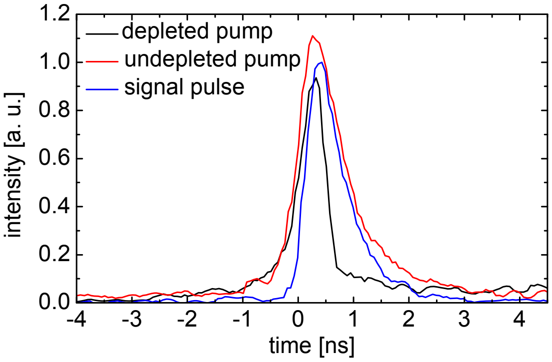

Fig. 5. Pulse shapes of the incident (undepleted) pump, depleted pump, and signal pulses. The relative intensity scale is true only for the undepleted and depleted pump pulses.

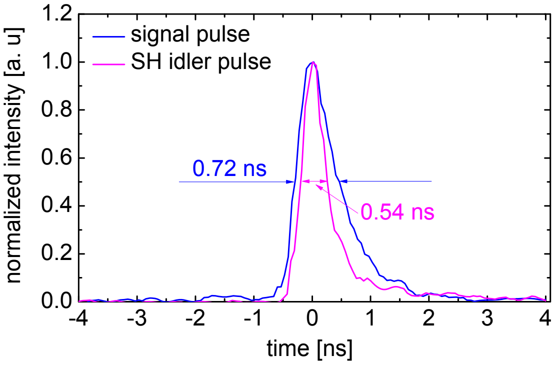

Fig. 6. Comparison of the pulse duration of the second harmonic of the idler pulse with the signal pulse.

The signal pulse duration (FWHM) amounted to 0.72 ns (Fig. 6), 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 (θ=0° cut, tilted for type-I phase-matching) and measured the pulse duration of the second-harmonic, also shown in Fig. 6. Multiplying the result by $\sqrt{2}$, the second-harmonic generation shortening factor for Gaussian pulse shapes, gives an idler pulse duration estimation of 0.76 ns, very close to the signal pulse duration.

4. CONCLUSION

In conclusion, we demonstrated sub-ns pulse durations for the signal and idler pulses of a 1 kHz OPO based on PPKTP. At room temperature the signal and idler wavelengths were at 1722 and 2786 nm, respectively. Tuning is possible by temperature and/or multiple gratings. Extension to yet higher repetition rates and energies is in progress.

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