Picosecond Energy Scalable kHz OPO/OPA Tunable in 3-3.5 µm mid-IR Spectral Range

D. Chuchumishev[1], A. Trifonov[1], B. Oreshkov[1], N. Belashenkov[2], I. Buchvarov[1,2,*]
[1] Department of Physics, Sofia University, 5 James Bourchier Blvd., BG-1164 Sofia, Bulgaria
[2]ITMO University, 197101St.-Petersburg, Russia
**corresponding author: ivan.buchvarov@phys.uni-sofia.bg*

Abstract: We demonstrate 740 ps, 4.1-mJ tunable mid-IR PPSLT based OPO/OPA pumped by 38-mJ, 800 ps, Nd-laser system operated at 0.5-1kHz repetition rate.

OCIS codes: (190.4970) Parametric oscillators and amplifiers; (140.3070) Infrared and far-infrared lasers; 140.3600 Lasers, tunable

Picosecond Mid-IR laser sources combining high average power (>1 W) and high pulse energy (>1 mJ) are essential for a number of scientific and industrial applications, e.g., high harmonic generation, molecular spectroscopyand wide-ranging medical applications based on the high water absorption around 3 µm.Initially the main sources of such radiation have been the Mid-IR Free Electron Lasers[1]. Despite its great advantages the FEL system possesses serious drawbacks that are intrinsic to its underlying physical principles. These disadvantages prohibit the broad applications of such facilities and present the need of a compact laser system that will generate tunable mid-IR radiation with high energy at high repetition rates. Nonlinear frequency conversion devices, pumped by Q-switched Nd-laser systems, operating around 1 kHz repetition rates are effective way to cover 3-4 microns spectral range ensuring high energy/power of the laser output. Although the mid-IR OPO output can be scaled significantly in energy by employing an optical parametric amplification (OPA) stage, its successful operation in sub-nanosecond pulse range requires use of highly nonlinear optical media in order to compensate the limited resonant wave build-up time [3]. In recent years, exceptionally large nonlinearity and complete absence of spatial walk-off are provided by quasi phase-matched nonlinear materials. Systems based on periodically poled lithium niobate (PPLN) have been presented but they are either at high repetition rate (10 kHz) and very modest output energy (few microjoules) [4] or at low repetition rate (10 Hz) and high output energy (3.4 mJ), but consequently very modest average output power [5]. Even though MgO doping of LN has increased its photorefractive damage threshold and decreased its originally very high coercive field, periodically poled stoichiometric lithium tantalate (PPSLT) has a lower coercive field (~2 kV/mm for PPLN and 0.8 kV/mm for PPSLT) and a higher photorefractive damage threshold, while being transparent up to 5 µm. Therefore, it has been suggested that PPSLT is a suitable candidate for more efficient devices, with either high energy or high average power output.

In this work we present a tabletop picosecond mid-IR system that is tunable near the water absorption peak at 3µm. It consists of a OPO/OPA frequency conversion stage pumped by a Nd based MOPA generating 38 mJ pulses at 0,5-1 kHz repetition rate. The mid-IR energy after OPA reaches 4.1 mJ and is continuously tuned from 3 to 3.5µm with pulse duration of 740 ps.

The schematic architecture of the proposed sub-nanosecond pumped short-cavity-OPO/OPA system is shown on Fig.1a. The pump source for the two frequency conversion stages is a diode-pumped microchip-design oscillator and power amplifier providing 38 mJ pulses with high beam quality (M_x^2 x M_y^2=1.5 x 1.2) and short pulse duration (800 ps), at 0.5-1 kHz repetition rate. The pump beam is slightly elliptical and it is focused to a beam sizeof 1.9×2.0 mm and 2.7×2.8 (1/e^2- level) in the position of the PPSLT crystals in the OPO and OPA stages respectively. The OPO/OPA employs 3.2 mm (along z axis) thick PPSLT crystals (made by Deltronic Crystal Industries), 10 mm wide, with three polled zones with different domain inversion periods (30.2, 30.3 and 30.4 µm). The lengths of the nonlinear crystals used in OPO/OPA stages are 20 mm and 37 mm respectively, both are antireflection-coated for the pump, signal and idler waves. The OPO cavity is ~30 mm long with plane-parallel mirrors, highly reflective for the signal wave. The maximum idler energy at the output of the OPO is 0.47 mJ (at 3.1 µm idler wavelength), when pumped with 4.4 mJ, corresponding to idler conversion efficiency of 11% (Fig. 1b). The beam quality of the idler wave was measured to be $M_x^2 = 31$ and $M_y^2 = 32$. In order to measure the mid-IR idler pulse duration we frequency doubled it in 3-mm thick KTP crystal. The pulse duration of the SH of the idler waves, measured directly after the OPO, is 320 ps, which corresponds to 390 ps after deconvolution with the response time (160 ps) of the detection system (see Fig. 1b). The spectral width of the idler generated from the OPO is measured to be 45 nm (Fig. 2b).

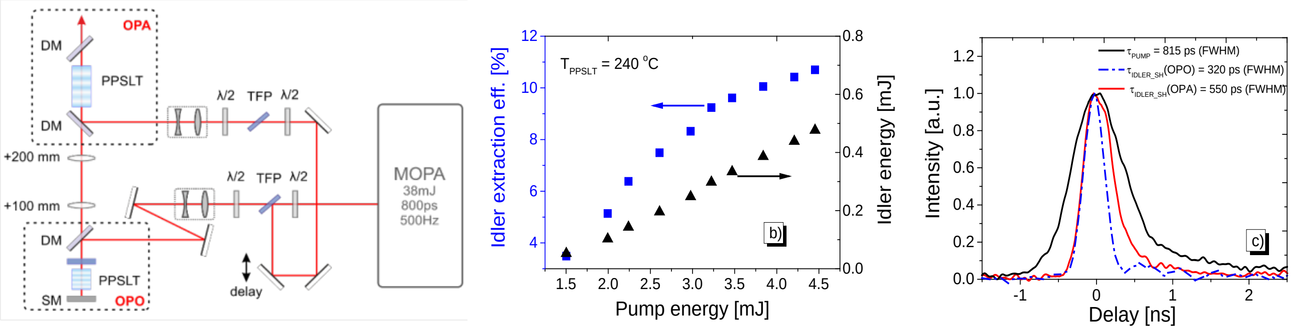

Fig. 1 (a) OPO/OPA optical scheme ; (b) OPO idler energy vs. pump energy and total idler conversion efficiency at different pump energies (output wavelength is 3.1μm);(c) Oscilloscope traces of the incident pump, the second harmonic (SH) of the idler wave after the OPO and the OPA.

The output idler wave is collimated and then focused in the OPA by two CaF_2 lenses with focal lengths of 100 mm and 200 mm respectively. In the OPA crystal collinear interaction of the signal from the OPO with the pump at 1064 nm is ensured. The residual pump after the OPA is reflected with a dichroic mirror and only the idler wave is analysed. The maximum achieved output idler energy from the amplifier is 4.1 mJ, when seeded with 0.39 mJ at 3.1 μm, at 29 mJ pump energy, corresponding to idler conversion efficiency of 13 % and total conversion efficiency of 51 % (Fig. 2a). By changing the temperature of the two PPSLT crystals from 40°C up to 265°C and employing the three domain inversion periods, we were able to achieve continuous tunability from 3 to 3.5 μm (Fig. 2c). After deconvolution with the response function of the detection system, we obtain 530ps for the SH of the idler after the OPA, corresponding to an idler pulse duration of 740ps, which is comparable with the pump pulse duration (see Fig1.c). The spectral width of the OPA idler is changed substantially and is close to 45 nm (Fig. 2b).

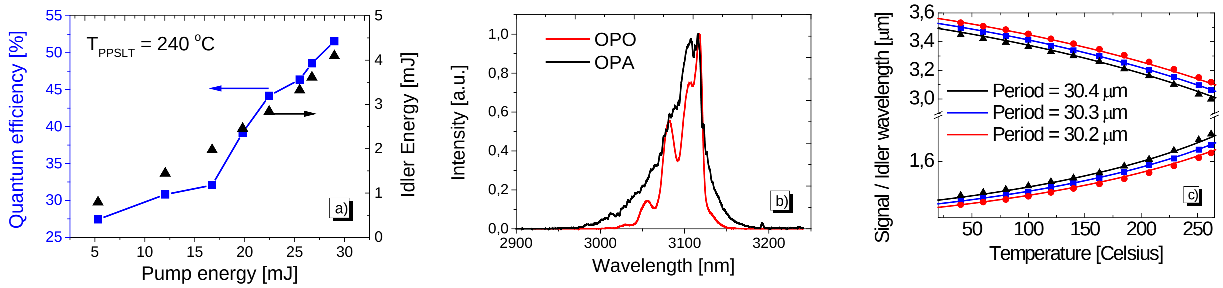

Fig. 2 (a) OPA idler output energy (seed is 0.39 mJ at 3.1 μm) and total conversion efficiency vs. pump energy; (b) idler spectra at the output of the OPO(red) and OPA(black); (c) temperature tunability – calculations (curves), measured data (dots).

In conclusion, we have demonstrated picosecond (740 ps) OPO/OPA system which incorporates high energy pulses (> 4 mJ) with high repetition rate (0.5 kHz) and tunability in highly relevant for biomedical applications spectral region around 3 microns. Although the two stage frequency conversion is more complex than a single OPO the utilized approach offers more reliability and further scaling of the energy.

We acknowledge support from Bulgarian National Science Fund grant number DO-02/134 and Deltronic Crystal Industries for manufacturing of the PPSLT crystals.

[1]. G. S. Edwards, R. H. Austin, F. E. Carroll, M. L. Copeland, M. E. Couprie, W. E. Gabella, R. F. Haglund, B. A. Hooper, M. S. Hutson, E. D. Jansen, K. M. Joos, D. P. Kiehart, I. Lindau, J. Miao, H. S. Pratisto, J. H. Shen, Y. Tokutake, A. F. G. van der Meer, and A. Xie, "Free-electron-laser-based biophysical and biomedical instrumentation," Rev. Sci. Instrum. **74**, 3207-3245 (2003).

[2]. Solid-State Mid-Infrared Laser Sources (Springer-Verlag, Berlin Heidelberg, 2003).

[3]. D. Chuchumishev, A. Gaydardzhiev, T. Fiebig, and I. Buchvarov, "Subnanosecond, mid-IR, 0.5 kHz periodically poled stoichiometric LiTaO3 optical parametric oscillator with over 1 W average power", Opt. Lett. 38, 3347-3349 (2013)

[4]. N. Dixit, R. Mahendra, O. P. Naraniya, A. N. Kaul, and A. K. Gupta, "High repetition rate mid-infrared generation with singly resonant optical parametric oscillator using multi-grating periodically poled MgO:LiNbO3," Optics & Laser Technology **42**, 18-22 (2010).

[5]. J. Saikawa, M. Miyazaki, M. Fujii, H. Ishizuki, and T. Taira, "High-energy, broadly tunable, narrow-bandwidth mid-infrared optical parametric system pumped by quasi-phase-matched devices," Opt. Lett. **33**, 1699-1701 (2008).