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0.7 mJ, 0.5 kHz Mid-IR Tunable PPSLT Based OPO Pumped at 1064 nm

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Abstract: We report up to 0.72 mJ at 0.5 kHz, temperature tunable (3-3.5 μm) radiation from a sub-nanosecond PPSLT based singly resonant OPO, pumped by an amplified microchip laser at 1064 nm.
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Sub-nanosecond coherent sources in the mid-IR spectral region (2.5-4 microns) combining high average power and high pulse energy with broad tunability are of fundamental interest for both scientific and industrial applications, e.g. remote sensing, molecular spectroscopy, resonant infrared pulsed-laser deposition and wide-ranging medical applications based on the high water absorption around 3 μm [1]. A simple and effective way to obtain the required radiation is with nonlinear frequency down-conversion devices such as OPOs, pumped by well established Q-switched neodymium lasers. However at sub-nanosecond pump pulse duration, this approach is limited in terms of achievable energy and efficiency due to the small number of roundtrips which are realizable in the OPO cavity for the duration of the pump pulse. One possible way of overcoming this inherent deficiency is by employing nonlinear media with higher nonlinearity. Recently, it was demonstrated that a highly nonlinear material ($CdSiP_2$) used in a non-critical phase-matching configuration, can be implemented in a short cavity optical parametric oscillator to produce sub-ns signal and idler pulses [2]. However this material has low damage threshold, thus limiting the achievable output energy. Natural choices for such OPOs are periodically poled quasi phase-matched (QPM) nonlinear materials, with their exceptionally large nonlinearity and complete absence of spatial walk-off. Lately, there have been studies with periodically poled lithium niobate (PPLN) based OPOs in the mid-IR, which are either at high repetition rate (10 kHz) and very modest output energy (few microjoules) [3] or at low repetition rate (30 Hz) and high output energy (3.4 mJ), but consequently very modest output power [4]. Additionally, pump pulse durations which are usually used are above 10 ns, thus limiting the peak energy and power. Even though MgO doping of LN has increased its photorefractive damage threshold and decreased its originally very high coercive field, periodically poled stoichiometric $LiTaO_3$ (PPSLT) have lower coercive field (2 kV/mm and 1.7 kV/mm respectively) and higher photorefractive damage threshold and is transparent up to 5 μm. Therefore, it has been suggested that LT is a suitable candidate of material for more efficient and high power/energy devices and this has been demonstrated for a 10 ns pump pulses at 30 Hz repetition rate [5]. Finally, PPSLT presents an attractive opportunity to produce high power OPOs at high repetition rates, when used with high power sub-nanosecond laser sources.

Here, we describe a compact sub-nanosecond, short cavity, singly resonant OPO based on PPSLT for the mid-infrared, pumped by a single frequency Nd:YAG microchip laser amplified in a two stage rod amplifier, which offers high pulse energy at relatively high repetition rate and tunability around the peak absorption band of water. To our knowledge, this is the first sub-nanosecond PPSLT based OPO, tunable in this highly interesting for biological applications spectral region, with such high energy and repetition rate and inherent potential for energy scaling.

We employ a 11 mm long, 10 mm wide, and 2 mm (along z axis) thick PPSLT crystal (manufactured by Deltronic Crystal Industries Inc., NJ) with three different polled zones with domain inversion periods (30.2, 30.3 and 30.4 μm respectively), equally spaced along the width of the crystal. The crystal is antireflection coated for the pump, the signal and idler waves. The OPO cavity length is 23 mm with plane parallel mirrors. As a rear mirror we have used a dielectric mirror (with reflection > 99% at 2.8-3.4 μm, 1550-1700 nm, 1064 nm). The output coupler is a dielectric mirror on a 3-mm thick YAG substrate (Layertec Inc.) with a reflection of >99.9% between 1410 and 1830 nm (signal wave) and transmission >98% between 2875 and 4050 nm (idler wave). The PPSLT crystal is pumped through the OC which transmits >99% at 1064 nm. The pump beam is collimated to a beam diameter of 1.3 mm in the position of the PPSLT crystal. The incident pump beam is separated from the idler wave by a separation mirror, which has 98% reflection for the pump (p-polarization) and transmits 80% at the idler wavelength, respectively. The pump source is a diode pumped Nd:YAG microchip laser oscillator amplified in a two stage rod amplifier emitting up to 10 mJ at 0.5 kHz, 1 ns pulse duration with high beam quality (M^2<1.4). From the maximum available pump energy (10 mJ) up to 7 mJ were incident on the PPSLT crystal. Varying the delay between the pump pulses of the amplifier and the microchip oscillator output we were able to continuously change the energy output of the amplifier without affecting the beam profile. After the separation mirror only the idler wave is measured, the residual pump radiation and the signal are blocked with a set of filters depending on the wavelength of the idler wave (2.6-3.2 wide band-pass filter and 3.2 µm long pass filter).

The measured OPO threshold was 800 µJ of pump energy (corresponding to around 100 MW/cm^2 average pump intensity), Fig. 2. This intensity threshold value is in agreement with the theoretically predicted value of 83 MW/cm^2 from the Brosnan and Byer theory [6] for the case of a singly resonant OPO with pump reflection. The OPO has 10% slope efficiency. Comparing with CSP employed in a very similar cavity by Petrov at al., the OPO threshold is over 30 times higher, which should be attributed to the much higher nonlinearity of CSP. The maximum idler output energy around ~3.1 µm reached 0.72 mJ which corresponds to idler conversion efficiency of 10% and overall quantum conversion efficiency of 30 %. The maximum achievable idler energy is limited by the rear mirror damage and it was in order of 1 mJ. Using a 3.2 mm thick PPSLT crystal sample a further scaling is possible and currently under development.

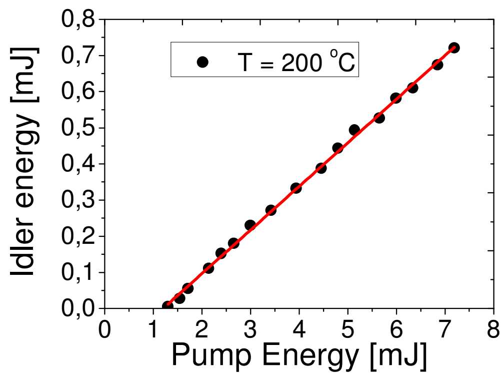

Fig.1 Idler energy versus pump energy, incident on the PPSLT crystal at crystal temperature 200 ºC, output idler energy is corrected with the transmission of the optical elements

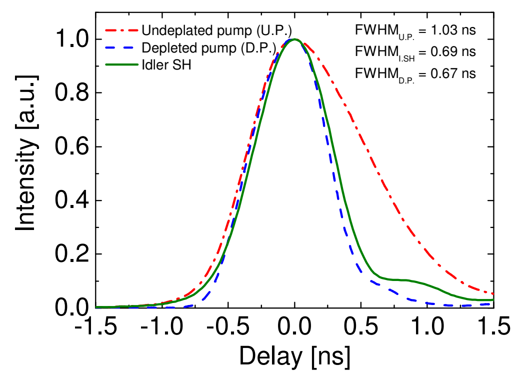

Fig. 2. Pulse shapes of the incident pump, depleted pump, and the second harmonic of the idler pulse. Maximum intensity of all pulses is given at the zero time position.

In other to measure the idler pulse duration we frequency doubled the idler pulse in a 5 mm thick KTP crystal and measured the pulse duration of the produced second harmonic. Its duration (FWHM) amounted to 0.69 ns (Fig. 2), measured with a fast photodiode (ET-3500, Electro Optics Technology Inc.) and 1.5 GHz digital oscilloscope (DDA 125, Lecroy Inc.). After deconvolution with the measurement setup response function (470 ps), the pulse duration (FWHM) of the frequency doubled idler is found to be 505 ps, corresponding to 714 ps idler duration, shorter as expected than the undeleted pump pulse duration (1.03 ns), Fig. 2. The depleted pump pulse shape together with the undeleted pulse profile can be seen in Fig. 2, together with the second harmonic idler pulse profile.

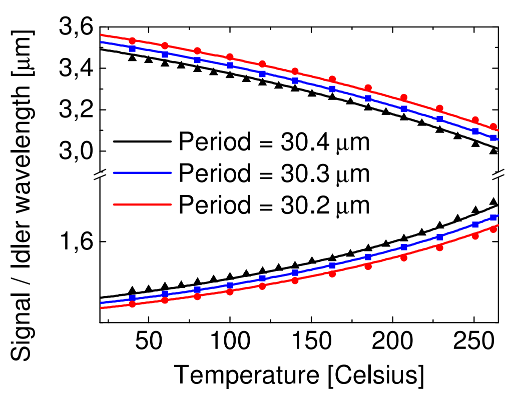

Fig. 3 OPO temperature tuning versus domain inversion period, measured data (dots) and calculated tuning curves (solid curves)

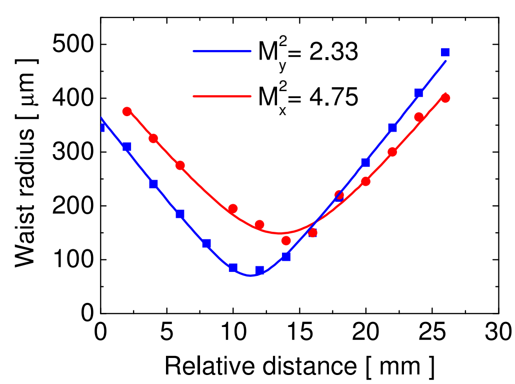

Fig. 4. Measured M^2 of the output radiation

Changing the temperature of the PPSLT crystal from room temperature up to 265 degrees Celsius we were able to achieve a continuous tuning from 3 to 3.5 µm employing the three domain inversion periods respectively, Fig. 3. The experimental results (dots on Fig. 3) are in very good agreement with the theoretically calculated curves for the domain inversion periods (solid curves). In the above calculations we have used the Sellmayer equations and the expression for thermal expansion of SLT was derived by Dolev at. al. [7]. Furthermore, we have measured the spectrum of the signal leaking from the output coupler of the OPO with a spectrum analyzer (Anritsu, MS9710B) at a domain inversion period of 30.3 µm. The FWHM of the measured spectra changes from 3.1 nm at 100ºC to 6.14 nm at 240 ºC, whilst central wavelength of the spectrum changes from 1545 nm to 1619 nm. Additionally, we have measured the beam quality of the idler was found it to be $M_x^2 = 4.75$ and $M_y^2 = 2.33$ (fig. 4).

In conclusion, we have demonstrated a tunable operation of sub-nanosecond 0.5 kHz OPO based on PPSLT, pumped by amplified single mode passively q-switched laser. We have achieved high (almost constant in the whole tuning range) energy output of 0.72 mJ tunable around the peak water absorption at 3 microns. Extension to yet higher repetition rates and energies is in progress.

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