High energy kHz Mid-IR tunable PPSLT OPO pumped at 1064 nm

A. Gaydardzhiev, D. Chuchumishev, D. Draganov, I. Buchvarov

Abstract

We report a single frequency sub-nanosecond optical parametric oscillator (OPO) based on periodically poled stoichiometric lithium tantalate (PPSLT), pumped by an amplified microchip laser at 1064 nm at a repetition rate of 0.5 kHz. Using a 11 mm long PPSLT crystal polled with three different domain periods (30.2, 30.3, 30.4 µm) and changing the temperature of the crystal from 20°C to 265°C, we have achieved wavelength tuning between 2990 nm and 3500 nm. The high nonlinearity of the used medium and the large aperture (2 mm) ensure maximum idler output energy of ~0.5 mJ in the whole tuning range, corresponding to average ~10.5% idler conversion efficiency and ~250 mW of average power. Sub-nanosecond pulse durations were obtained for the idler as a result of the 1 ns pulse duration of the pump.

Keywords: Nonlinear optical materials and devices, optical parametric oscillators, periodically poled nonlinear materials

1. Introduction

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 and wide-ranging medical applications based on the high water absorption around 3 μm [1]. A simple and effective way of covering this spectral region is with nonlinear frequency down-conversion devices such as OPOs, pumped by well established Q-switched neodymium lasers. However, this approach is limited in terms of achievable energy and efficiency due to the small number of roundtrips which are possible in the OPO cavity for the duration of the pump pulse. One possible way of overcoming this inherent deficiency is by employing nonlinear crystals 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 have low damage threshold, thus limiting the achievable output energy. Natural choices for such OPOs are periodically poled nonlinear crystals, with their exceptionally large nonlinearity and complete absence of spatial walk-off. Recently, there have been studies with periodically poled lithium niobate (PPLN) based nanosecond-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 power. However, due to its low photorefractive damage threshold, PPLN only finds limited applications: at very low power levels. MgO doping of periodically poled lithium niobate (PPMgOLN) crystal elements can expand the applications to a medium power level only. Among the nonlinear crystals transparent between 1-4 microns with relatively high nonlinearity, periodically poled stoichiometric $LiTaO_3$ (PPSLT) possesses higher photorefractive damage threshold and lower coercive field (1.7 kV/mm in comparison of 2 kV/mm for PPMgOLN). Hence, PPSLT crystal is a promising candidate for efficient and high pulse-energy devices working at kHz repetition rate. Although PPSLT crystal has been used successfully for high-energy nanosecond OPO tunable around 2 microns, its performance at higher average power i.e kHz repetition rate has not been studied yet. Moreover the OPO operation around 3 microns is much more interesting due to the peak water absorption in this spectral region. It has been suggested that a PPSLT crystal is a suitable candidate for more efficient and high pulse-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 average 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 energy and repetition rate and inherent potential for energy scaling.

2. Experimental setup

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 (fig. 1). Figure 1 shows photographs of the structure of the PPSLT with domain inversion period 30.4 μm. The relatively good uniformity of the crystal structure can be seen in Y-cut cross section, the X axis of the crystal is along the optical axis.

The crystal is antireflection coated for the pump, the signal and idler waves. The OPO cavity length is 23 mm with plane parallel mirrors (fig.2a). As a rear mirror for the OPO we used a silver coated mirror (with reflection of 96-97% at each of the three wavelengths). The output coupler is a dielectric mirror on a 3-mm thick YAG substrate 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 dichroic 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). The maximum pulse energy used for OPO pumping was up to 4.5 mJ which value is determined by the damage threshold of the OPO rear mirror. By 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. Additional set of mid-IR filters have been used after the dichroic mirror in order to avoid detection of the residual pump radiation during measurements of the idler output power.

3. Results and discussion

The measured OPO threshold was 800 μJ of pump energy (corresponding to around 100 MW/cm^2 pulse pump intensity), Fig. 2b. 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 12.6 % 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 pump intensity applied in the present work is ~550 MW/cm^2 (four times below the PPSLT damage threshold). The maximum idler output energy at ~3 μm reached 470 μJ which corresponds to idler conversion efficiency of 10.5% and overall quantum conversion efficiency of 30 %. The developed system is limited in terms of repetition rate by the optimal operation frequency of the microchip laser (at 0.5 kHz we have obtained the highest output power) and in terms of output power by the damage threshold of the rear (silver) mirror (damage occurs due to the average power not the peak intensity). Although our amplifier can work at higher repetition rates we have chosen 0.5 kHz as the best compromise between repetition rate and output energy.

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 derived by Dolev at. al. [7].

In other to obtain the idler pulse duration we have frequency doubled the idler pulse in a 5 mm thick KTP crystal and we have measured the pulse duration of the produced second harmonic. Its duration (FWHM) amounted to 0.69 ns (Fig. 4), measured with a fast photodiode (InGaAs with response time ~75 ps) 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. At low SHG conversion efficiency this corresponds to 714 ps idler duration which is shorter as expected than the undepleted pump pulse duration (~1 ns), Fig.4. The depleted pump pulse shape together with the undepleted pulse profile can be seen in Fig. 4, together with the second harmonic idler pulse profile.

We 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 of the PPSLT crystal (Fig.5a.). 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.

In order to estimate the spectrum width of the idler we have reconstructed its spectrum from the signal one using the Manley-Row relation. The calculated spectra are shown on Fig.5b. The FWHM of the calculated spectra changes from 15.3 nm at 100ºC to 22.5 nm at 240 ºC, whilst central wavelength of the spectrum changes from 3415 nm to 3101 nm. The behavior both of the signal and idler wave is consistent with the gain bandwidth calculated for quasi phasematching in PPSLT 11 mm long pumped at 1064 nm, with pump intensity of ~250 MW/cm^2 as employed in the current measurement, shown on Fig.5c.

4. Conclusions

In conclusion, we have demonstrated 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 energy pulsed output - 0.5 mJ with 714 ps pulse duration, tunable around the peak water absorption between 2.9-3.4 microns. Further development to higher energies is in progress through using larger aperture nonlinear crystal and dielectric coated rear mirror.

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Figure Captions

FIGURE 1 Photographs of the structure of the PPSLT with domain inversion period 30.4 µm. (the SLT crystal and the poling is made by Deltronic Crystal Industries, NJ, USA)

FIGURE 2 (a) Schematic of the optical parametric oscillator. (b) Idler energy versus pump energy, incident on the PPSLT crystal at crystal temperature 250 ºC, output idler energy is corrected with the transmission of the optical elements

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

FIGURE 4 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.

FIGURE 5 (a) measured signal spectra (first spectrum on the left corresponds to 100ºC, temperature increase with step of 20 ºC to the right); (b) reconstructed idler spectra (first spectrum on the left corresponds to 250ºC, temperature decrease with step of 20 ºC to the right); (c) Gain bandwidth of PPSLT analytically calculated for crystal length 11 mm, pump intensity ~250 MW/cm^2 and temperature of the crystal corresponding to the experimental conditions in the signal measurements above

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A. Gaydardzhiev, D. Chuchumishev, D. Draganov, I. Buchvarov

Address: Department of Physics, Sofia University, 5 James Bourchier Blvd., BG-1164, Sofia, Bulgaria

A. Gaydardzhiev: a.gaydardzhiev@phys.uni-sofia.bg

D. Chuchumishev: d.chuchumishev@phys.uni-sofia.bg

D. Draganov dimitar@phys.uni-sofia.bg

I. Buchvarov: ivan.buchvarov@phys.uni-sofia.bg

Corresponding author:

Ivan BUCHVAROV, Assoc. Prof
Department of physics, Sofia university
5 J. Bouchier Blvd.
Sofia 1164, BULGARIA
FAX: +359 2 962 5276
Phone: +359 2 8161708
Web page: www.phys.uni-sofia.bg/~ibuch
Email: ivan.buchvarov@phys.uni-sofia.bg

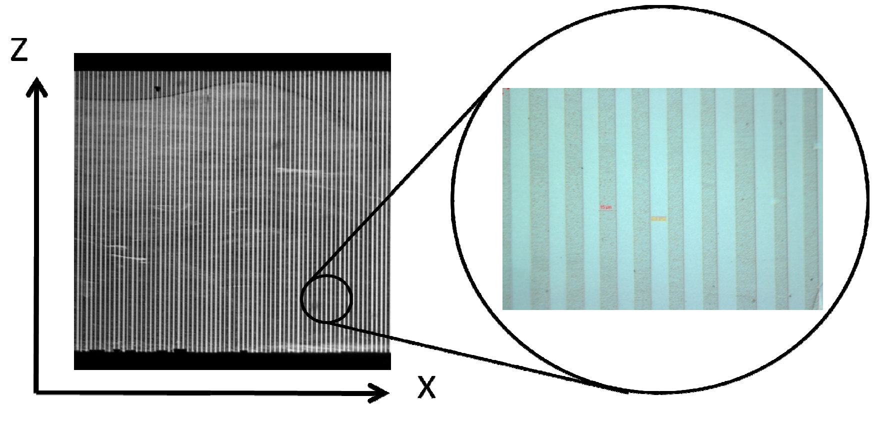

FIGURE 1
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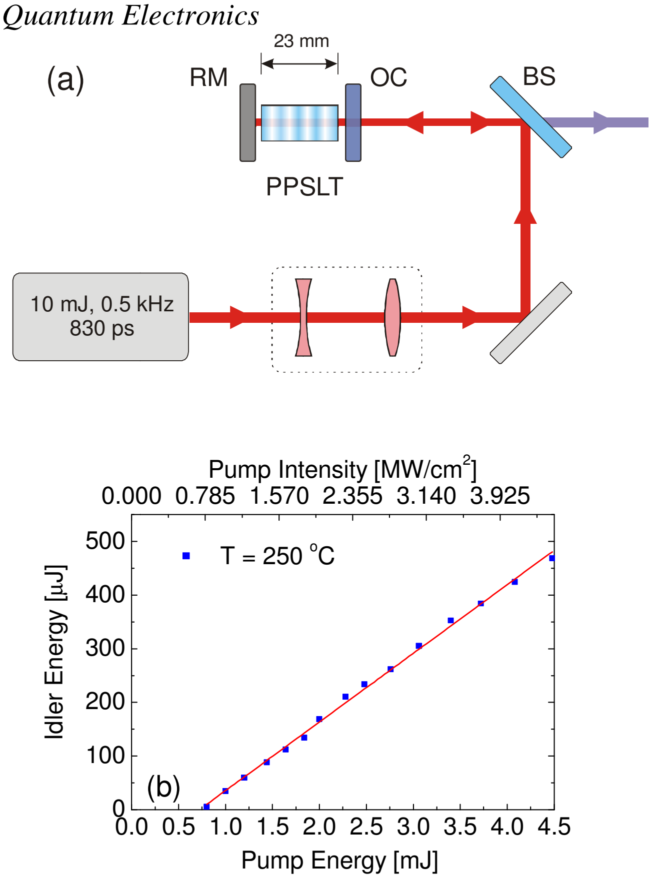

FIGURE 2
A. Gaydardzhiev *Quantum Electronics*

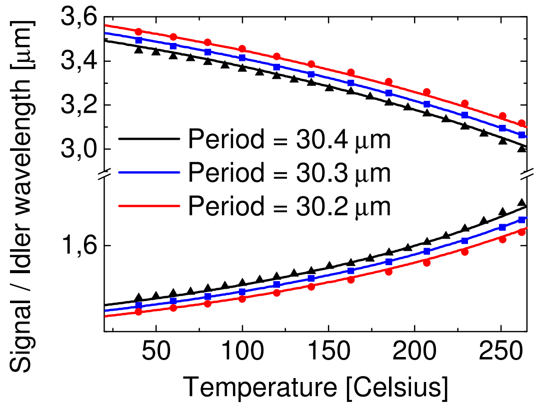

FIGURE 3

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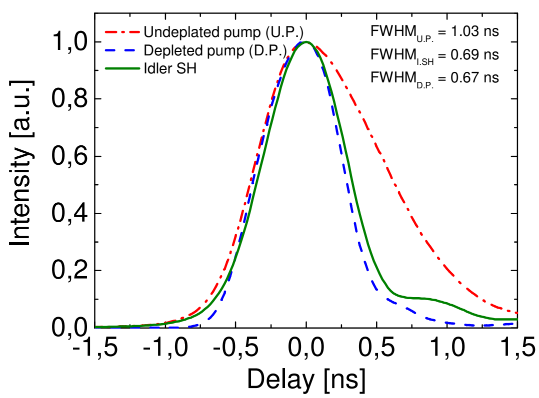

FIGURE 4

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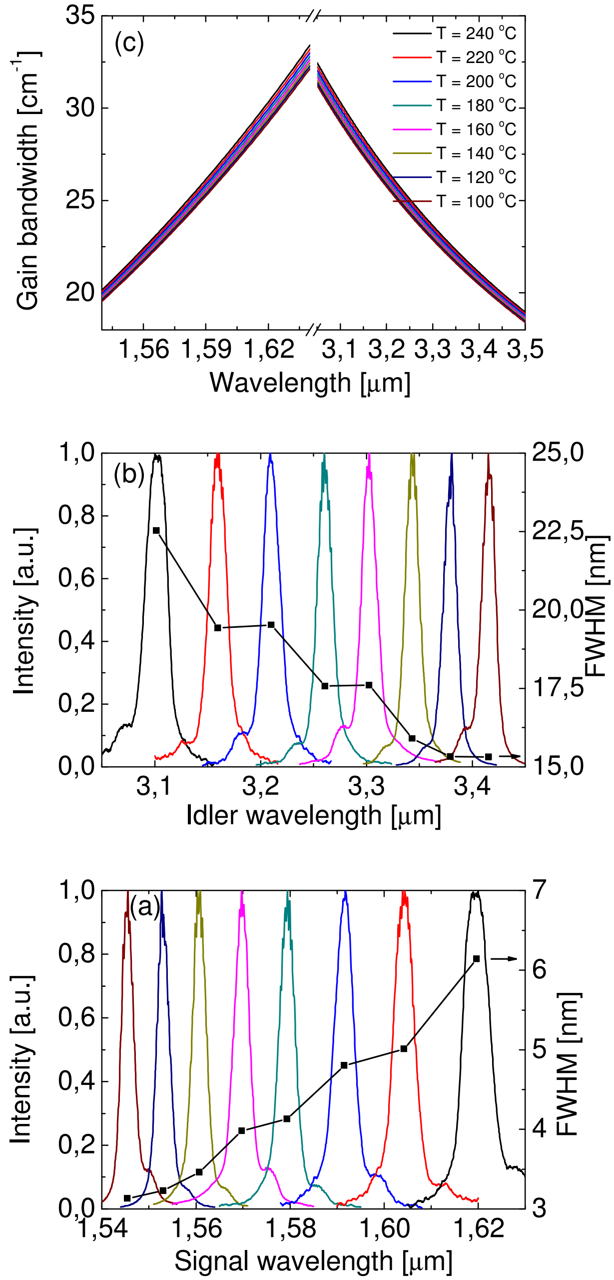

FIGURE 5
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