Subnanosecond, mid-IR, 0.5 kHz periodically poled stoichiometric $LiTaO_3$ optical parametric oscillator with over 1 W average power

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We report a subnanosecond mid-IR tunable optical parametric oscillator based on periodically poled stoichiometric lithium tantalate (PPSLT), pumped by an amplified single frequency microchip laser at 1064 nm at a repetition rate of 0.5 kHz. Using a 20 mm long PPSLT crystal polled with three different domain periods (30.2, 30.3, and 30.4 μm) and changing the temperature of the crystal from 20°C to 265°C, we achieved wavelength tuning between 2990 and 3500 nm. The high nonlinearity of the used medium and the large aperture (3.2 mm) ensure maximum idler output energy of ~2 mJ in the whole tuning range, corresponding to 18% idler conversion efficiency and more than 1 W of average power. 270 ps idler pulse durations were obtained as a result of the 818 ps pulse duration of the pump. © 2013 Optical Society of America

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Subnanosecond coherent sources in the mid-IR spectral region (2.5–4 μm) that encompass high average power (>1 W) and high pulse energy (>1 mJ) 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 [1,2]. A simple and effective way for covering this spectral region is to utilize nonlinear frequency downconversion devices such as optical parametric oscillators (OPOs), pumped by well-established kilohertz-Q-switched microchip-based Nd-laser systems. However, this approach is limited in terms of achievable energy and efficiency due to the small number of roundtrips that 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 $CdSiP_2$ (CSP), used in a noncritical phase-matching configuration, can be implemented in a short cavity OPO to produce subnanosecond signal and idler pulses [3]. On the other hand, this material has a low damage threshold and exhibits residual absorption losses that limit the achievable output energy. Natural choices for such OPOs are periodically poled, quasi-phase-matched nonlinear materials, with their exceptionally large nonlinearity and complete absence of spatial walk-off. An attempt to develop kilohertz subnanosecond OPO has been made recently by using periodically poled potassium titanyl phosphate crystal (PPKTP) [4], but this system is limited in terms of output energy and average power and no wavelength tunability was demonstrated. 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) [5] or at low repetition rate (30 Hz) and high output energy (3.4 mJ), but consequently very modest average output power [6]. Additionally, the pump pulse durations that 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 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. This has been demonstrated for pump pulses with a few tens of nanoseconds pulse duration at 30 Hz and 10 kHz repetition rate, respectively [7,8]. Moreover, PPSLT presents an attractive opportunity to produce high-power/energy OPOs at high repetition rates, when it is pumped by high-power subnanosecond laser sources.

Here, we describe a compact subnanosecond, singly resonant mid-IR OPO based on PPSLT, which is pumped by an amplified, single frequency Nd:YAG microchip laser, and which offers high pulse energy at relatively high repetition rate and tunability around the peak absorption band of water at 3 μm. To our knowledge, this is the first subnanosecond PPSLT-based OPO that incorporates high-energy pulses with high repetition rate and tunability in this spectral region highly relevant for biomedical applications, and has inherent potential for additional energy scaling.

We employ a 20 mm long, 10 mm wide, and 3.2 mm (along the z axis) thick PPSLT crystal [manufactured by Deltronic Crystal Industries, Inc., New Jersey] with three polled zones with different 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, signal, and idler waves. The OPO cavity length is confined by the crystal oven design to 27 mm. 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 (OC) is a dielectric mirror with a reflection of >99.9% for the signal waves and transmission >98% for the idler waves. The PPSLT crystal is pumped through the OC, which transmits >99% at 1064 nm. The pump beam is slightly elliptical, and it is focused into the PPSLT crystal. The beam waist major/minor axes are 2.4/2.3 mm ($1/e^2$ level), respectively. The incident pump beam is separated from the idler wave by a dichroic mirror, which has 99% reflection for the pump (p-polarization) and transmits 97% at the idler wavelength. The pump source is a diode-pumped Nd:YAG microchip laser oscillator amplified in a two-stage rod amplifier emitting up to 13 mJ at 0.5 kHz, and with 818 ps pulse duration with high beam quality ($M^2 < 1.4$) [9]. 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 dichroic mirror, only the idler wave is measured; the residual pump radiation and the signal are blocked with a filter.

The measured OPO threshold was 1.4 mJ of pump energy (corresponding to 38 MW/cm^2 average pump intensity). This intensity threshold value is in agreement with the theoretically predicted value of 44 MW/cm^2 from the Brosnan and Byer theory [10] for the case of a singly resonant OPO with pump reflection. Compared with CSP OPO employed in a very similar cavity [3], the OPO threshold is more than 30 times higher, which should be attributed to the much higher nonlinearity of the CSP crystal. 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 2.2 mJ, at pump energy of 11.5 mJ, which corresponds to an idler conversion efficiency of 18.3% and overall quantum conversion efficiency (both idler and resonating signal) of nearly 52% (see Fig. 1). At the working pulse repetition rate (0.5 kHz), the generated average power at 3 μm was above 1 W. The average idler output power was 0.88 W at around 3.4 μm and 0.97 W at 3.25 μm.

Changing the temperature of the PPSLT crystal from room temperature up to 265°C, we were able to achieve continuous tuning from 3 to 3.5 μm employing the three domain inversion periods. The experimental results are in very good agreement with the theoretically calculated curves for the domain inversion periods (see Fig. 2). In the above calculations, we used the Sellmayer coefficients and the expression for thermal expansion of SLT derived by Dolev *et al.* [11].

In order to measure the idler pulse duration, we frequency doubled the idler pulse using birefringent phase-matched second-harmonic generation (SHG) in a 5 mm thick KTP crystal and measured the pulse duration of the generated SH signal, which was 400 ps. The pulse duration measurements have been done using an InGaAs photodiode connected to a 1.5 GHz digital oscilloscope. The response time of the measurement system is 350 ps. The instrument response function was measured with a signal-to-noise ratio better than 100, and the statistical errors and noise contributions are not substantial (e.g., the RMS of the FWHM of the record response functions is not greater than ~5 ps). After deconvolution, the pulse duration (FWHM) of the frequency doubled idler is found to be 190 ps, corresponding to 270 ps idler duration. The accuracy of the measurement is estimated to be ±25 ps. The undepleted temporal pulse shape profile is shown in Fig. 3, together with the SH idler pulse profile.

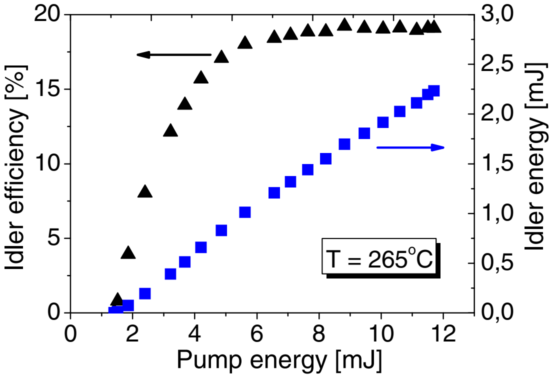

Fig. 1. Idler energy versus pump energy incident on the PPSLT crystal at crystal temperature 265°C (blue rectangles). The output idler energy is corrected with the transmission of the optical elements. Idler conversion efficiency (black triangles).

We measured the spectrum of the signal leaking from the OC of the OPO with an InGaAs spectrometer at a domain inversion period of 30.3 μm and a temperature of the PPSLT crystal 265°C [Fig. 4(a)]. In order to estimate the spectral width of the idler, we reconstructed the idler spectrum from the signal spectrum using the Manley–Row relation. In addition, we measured the spectrum of the idler wave with a monochromator and a PbSe detector. Both idler spectra show good consistency with each other [Fig. 4(b)]. The FWHM of the calculated idler spectra is 60 nm at 265°C.

The beam quality of the idler wave is measured to be $M_x^2 \times M_y^2 = 42 \times 46$ (Fig. 5). The relatively poor beam quality could be attributed to a couple of factors,

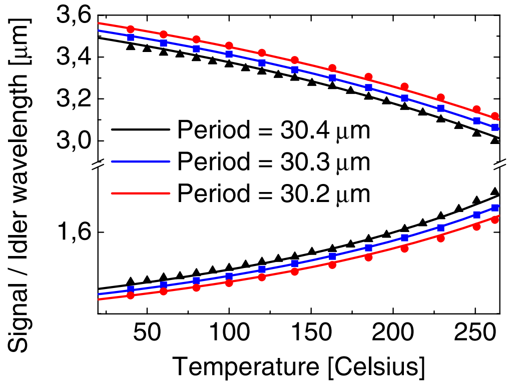

Fig. 2. OPO temperature tuning for three domain inversion periods, measured data (dots), and calculated tuning curves (solid curves).

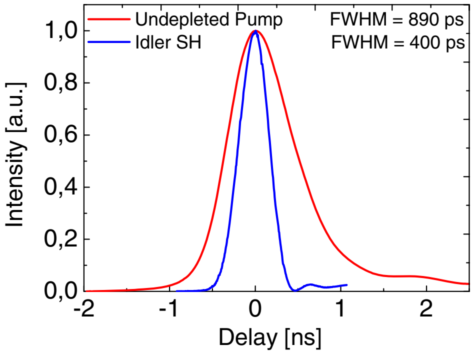

Fig. 3. Temporal pulse shapes of the incident pump and the second harmonic of the idler pulse. Maximum intensity of both pulses is given at the zero time position.

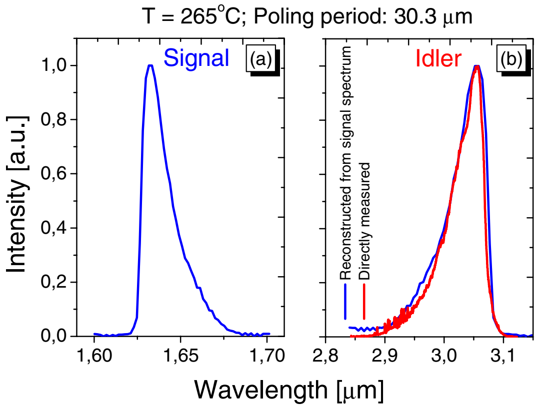

Fig. 4. (a) Directly measured signal spectrum, leaking through the OC (blue curve). (b) Idler spectra: reconstructed from signal spectrum (blue curve), directly measured (red curve). Experimental conditions are as follows: PPSLT crystal temperature 265°C, domain inversion period 30.3 µm, and pump intensity ≈300 MW/cm^2.

including the oscillator cavity with a large Fresnel number (∼100), pumping levels well above the threshold, and the small number of roundtrips in the cavity.

We have demonstrated tunable operation of subnanosecond 0.5 kHz OPO based on PPSLT, pumped by an amplified single-mode passively Q-switched microchip laser. We have achieved an output energy of 2.2 mJ and more than 1 W average power, tunable around the peak water absorption at 3 µm. An extension to even higher repetition rates and energies through larger aperture nonlinear materials and a second amplification stage is currently in progress.

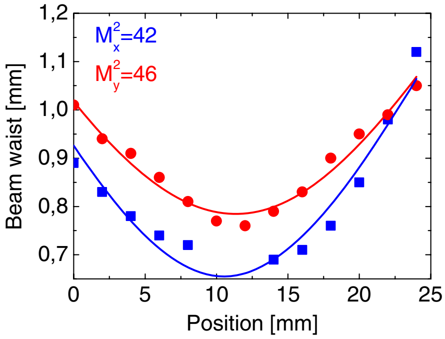

Fig. 5. Beam waist along the propagation axis for various positions behind an inserted lens (100 mm). The idler beam quality factor M^2 is measured at 3 µm wavelength and pump intensity ≈300 MW/cm^2.

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