Compact, High-Energy, Picosecond Optical Parametric Oscillator at 450 MHz near 6 μm

S. Chaitanya Kumar,[1,*] A. Agnesi,[2] P. Dallocchio,[2] F. Pirzio,[2] G. Reali,[2] K. T. Zawilski,[3] P. G. Schunemann,[3] and M. Ebrahim-Zadeh[1,4]

[1]*ICFO-Institut de Ciencies Fotoniques, Mediterranean Technology Park, 08860 Castelldefels, Barcelona, Spain*
[2]*Laser Source Laboratory - University of Pavia, Department of Electronics, via Ferrata 1 – 27100 Pavia, Italy*
[3]*BAE Systems, Inc., MER15-1813, P.O. Box 868, Nashua, New Hampshire 03061-0868, USA*
[4]*Institucio Catalana de Recerca i Estudis Avancats (ICREA), Passeig Lluis Companys 23, Barcelona 08010, Spain*
Author e-mail address: chaitanya.suddapalli@icfo.es

Abstract: We report a compact, efficient, 1.5 mJ, 450 MHz, mid-IR picosecond OPO based on $CdSiP_2$, synchronously-pumped at 1064 nm and tunable across 6091–6577 nm, covering the technologically important wavelength range for surgical applications.
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1. Introduction

Mid-infrared (mid-IR) spectral range, 5900-6600 nm, constituting absorption bands of amide-I (6000 nm), water (6100 nm) and amide-II (6450 nm), is of great interest for human surgery, due to simultaneous absorption by both proteins and water. The choice of these wavelengths minimizes the collateral damage, while maintaining an effective ablation rate of the tissue, enabling minimally invasive human surgery [1]. However, it is difficult to generate such longer wavelengths using conventional lasers where the emission wavelength depends on the transitions between the quantized energy levels in the laser gain medium. The only laser source available at these wavelengths is the free-electron laser [2]. But its complexity precludes its use for many practical applications. On the other hand, by now, it is well-accepted that nonlinear frequency conversion devices such as optical parametric oscillators are powerful solid-state sources of coherent radiation providing access to mid-IR spectral region with wide tunability. By exploiting oxide-based birefringent materials, such as $LiNbO_3$, $KTiOAsO_4$, and $RbTiOAsO_4$, or periodically poled crystals, such as periodically poled $LiNbO_3$ and periodically poled $RbTiOAsO_4$, spectral regions up to ~5 μm can be accessed, but the onset of multiphonon absorption sets a practical upper limit of ~4 μm for wavelength generation in such materials. Chalcogenide nonlinear crystals with transparency in the mid-IR, such as CdSe and $AgGaSe_2$, can provide coherent light at longer wavelengths, but their low bandgap energy precludes pumping near ~1 μm due to two-photon absorption, thus requiring long wavelength laser sources with limited availability near ~2 μm, or the deployment of cascaded pumping schemes. Hence, it is imperative to explore viable alternative materials for the generation of mid-IR radiation beyond 4 μm pumped by the well-established Nd-based lasers at 1064 nm. The newly discovered nonlinear material Cadmium Silicon Phophide, $CdSiP_2$ (CSP) offers unique linear and nonlinear optical properties for parametric down-conversion and is one of the very few nonlinear materials that enables pumping at 1 μm for the direct generation of mid-IR wavelengths beyond 6 μm [3-5]. Its large band gap, high optical quality, improved thermal and optical properties with high effective nonlinear coefficient (d_{eff}~84.5 pm/V), and noncritical phase-matching (NCPM) make it an attractive nonlinear material candidate for generating mid-IR wavelengths in the 6-6.5 μm range [6].

Here, we report a compact, high-repetition-rate OPO based on CSP, synchronously-pumped by a master oscillator power amplifier (MOPA) system at 1064 nm, generating an idler energy as high as 1.5 mJ at 6246 nm with a photon conversion efficiency of 29.5%. The OPO is tunable over 486 nm, with more than 1.2 mJ over >68% of the tuning range in good beam quality. To our knowledge, this is the first high-repetition-rate picosecond OPO based on CSP, synchronously pumped at 1064 nm in collinear geometry [5].

2. Experimental setup

The schematic of the experimental setup is shown in Fig. 1(a). The high-energy MOPA pump laser system is seeded by a 450 MHz passively mode-locked oscillator providing 5.4 ps micro-pulses. An acousto-optic modulator selects a train of micro-pulses with 1μs duration (macro-pulse) at a repetition rate of 20 Hz and the successive amplifier stages increase the macro-pulse energy up to 50 mJ, corresponding to an average power of 1 W. This represents a single micro-pulse energy of 0.1 mJ with a measured pulse width of 8.6 ps at a central wavelength of 1064 nm. The output beam from pump laser has a diameter of 2 mm and a beam quality factor of M^2<1.1 [7]. The nonlinear material is a CSP crystal, grown from stoichiometric melt by the horizontal gradient freeze technique [8].

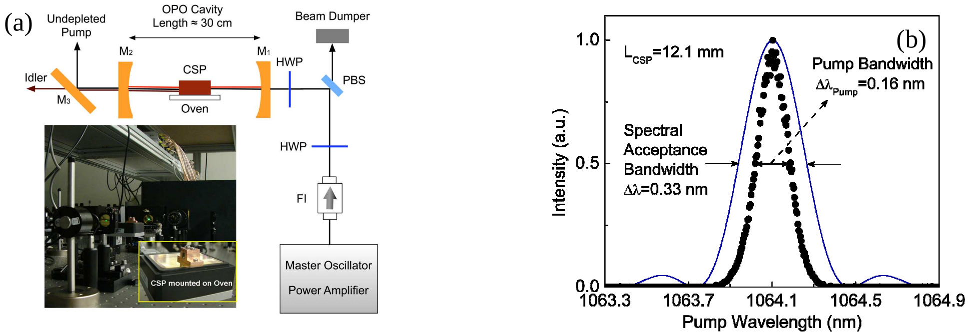

Fig. 1. (a) Experimental setup of high-energy CSP OPO. Inset: Laboratory setup and CSP crystal mounted on an oven. (b) Parametric gain bandwidth relative to pump bandwidth at 1064 nm.

The CSP crystal is 12.1-mm-long, 4-mm-wide (along the c-axis), 5-mm-thick sample and is cut at θ=90°, Φ=45° for Type-I (*e*→*oo*) interaction under NCPM. The pump laser operates at a central wavelength of 1064 nm and has an FWHM spectral bandwidth of 0.16 nm. This is shown in Fig. 1(b), relative to the parametric gain bandwidth of 0.33 nm for 12.1-mm-long CSP crystal, estimated using the relevant Sellmeier equations [8]. The CSP crystal is housed in an oven with temperature stability of ±0.1°C. Both crystal faces are antireflection coated with a single layer sapphire coating, providing high transmission (T>98.7%) for the pump and signal over 1064-1300 nm and T>76% for the idler over 6000-6500 nm. The residual loss at 1064 nm is estimated from the transmission of the crystal. The measured data for linear absorption coefficient, resulted in a value of α=0.075 cm^{-1}, for extraordinary (*e*) and α =0.15 cm^{-1}, for ordinary (*o*) polarizations. These values indicate the improved quality of this crystal as compared to the earlier samples [3,4]. The OPO is configured as a singly-resonant oscillator in a compact linear standing wave cavity comprising two curved mirrors, M_1 and M_2, with radius of curvature r=3 m (ZnSe substrate). Both mirrors are highly reflecting (R>99%) for signal over 1200-1400 nm, and highly transmitting at 1064 nm (T>97%) and for the idler over 5500-7500 nm (T>98%). The pump beam has a waist radius of w_0 ~1.5 mm after the input mirror to avoid any damage, while using the maximum aperture of the crystal. A dichroic mirror, M_3, highly reflecting (R>99%) at 1064 nm and highly transmitting (T>95%) for idler, separates the generated idler from the undepleted pump. In the measurements of energy and efficiency, all the data were corrected for transmission and reflection coating losses. The total round-trip optical length of the cavity, including the CSP crystal, is 666 mm, corresponding to a 450 MHz repetition rate, ensuring the synchronization with the pump laser.

3. Results

We characterized the OPO with regard to output pulse energy and tunability by varying the crystal temperature at constant pump energy of 30 mJ. Figure 2(a) shows the extracted idler energy as well as the transmission of CSP crystal across the tuning range. By changing the CSP crystal temperature from 30 ºC to 180 ºC, we could tune the idler wavelength from 6091 to 6577 nm, corresponding to a total tuning range of 486 nm. The generated idler energy varies from 1.3 mJ at 6091 nm to 1 mJ at 6577 nm, reaching a maximum of 1.5 mJ at 6275 nm, with >1.2 mJ over >68% of the tuning range. This represents a maximum idler energy conversion efficiency of 5% and a photon conversion efficiency of 29.5%. The drop in the idler energy towards the longer wavelengths is attributed to the

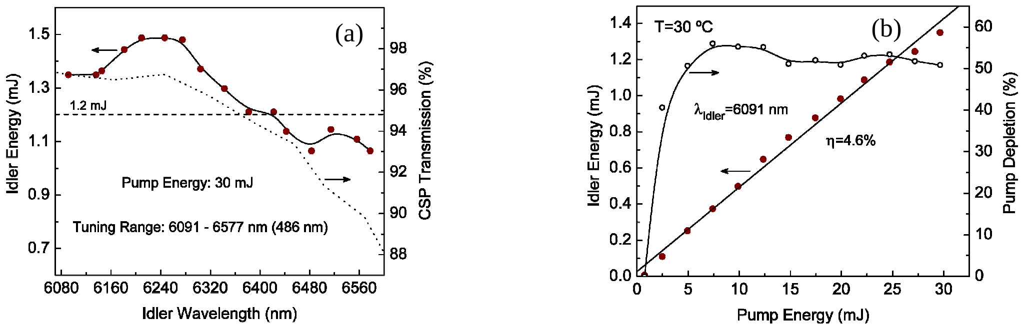

Fig. 2. (a) mid-IR idler power across the tuning range, (b) mid-IR idler energy scaling and pump depletion.

water absorption peak near 6.4 μm and residual multi-phonon absorption in the CSP crystal, resulting in reduced transmission, as evident from Fig. 2(a). The corresponding pump depletion is recorded to be >42% over more than 64% of the tuning range with a maximum pump depletion of 51% at 6483 nm.

We also performed idler energy scaling measurements at different wavelengths across the OPO tuning range. The variation of the idler energy and pump depletion as a function of the pump energy obtained at a temperature of 30ºC corresponding to an idler wavelength of 6091 nm is shown in Fig. 2(b). As evident from the plot, 1.35 mJ of idler is obtained for a pump energy of 30 mJ at a slope efficiency, η=4.6%, implying a peak idler energy efficiency of 4.5%, representing a photon conversion efficiency of 25.7%. The threshold pump energy is measured to be 0.7 mJ, corresponding to single micro-pulse energy of 1.5 μJ and strong pump depletion reaching >50% is achieved above input pump energy of 5 mJ.

Further, we have measured the duration of the signal pulses extracted from the OPO using a home-made autocorrelation setup. Figure 3(a) shows the measured autocorrelation profile at 1289 nm, where the amount of signal energy extracted from the cavity was >1.3 mJ for an incident pump energy of 30 mJ. The FWHM of the trace is 16.3 ps, resulting in the signal pulse duration of 10.6 ps, assuming a sech^2 pulse shape. This value of pulse duration was confirmed by repeating the measurement several times, and similar pulse duration is expected across the tuning range. Also shown in the inset of Fig. 3(a) is the signal beam profile at 1289 nm, measured a pyroelectric camera (Spiricon, Pyrocam-III). The corresponding idler beam profile at 6091 nm, recorded at the full output energy, is shown in Fig. 3(b). Both signal and idler beam profiles confirm good beam quality in TEM_{00} spatial mode, which is important for surgical applications.

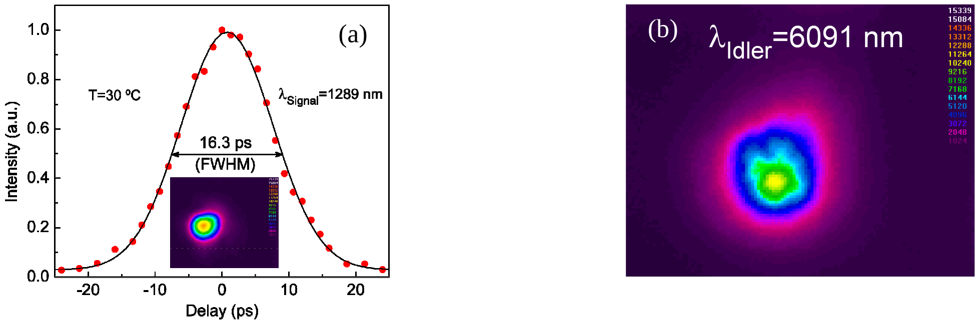

Fig. 3. (a) Signal autocorrelation, (Inset: Signal beam profile) (b) Spatial beam profile of the mid-IR idler.

4. Conclusions

In conclusion, we demonstrated a compact, efficient, high-energy, and high-repetition-rate mid-IR picosecond OPO based on the new nonlinear material CSP. The OPO is synchronously pumped by a master oscillator power amplifier system at 1064 nm, providing 1 μs long macropulses constituting 8.6 ps micropulses at 450 MHz, and it can be tuned over 486 nm across 6091–6577 nm, covering the technologically important wavelength range for surgical applications. Using a compact (~30 cm) cavity and improved, high-quality nonlinear crystal, idler macropulse energy as high as 1.5 mJ has been obtained at 6275 nm at a photon conversion efficiency of 29.5%, with >1.2 mJ over more than 68% of the tuning range, for an input macropulse energy of 30 mJ. Both the signal and idler beams are recorded to have good beam quality with a Gaussian spatial profile, and the extracted signal pulses are measured to have durations of 10.6 ps.

5. References

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