Optical Parametric Generation of Mid-Infrared Picosecond Pulses Beyond 6 μm in $CdSiP_2$

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Abstract: We report parametric generation of near- and mid-infrared picosecond pulses at 100 kHz in $CdSiP_2$ pumped at 1.064 μm, providing 154 mW of idler at 6.204 μm and 1.16 W of signal at 1.282 μm.

OCIS codes: 190.4400 Nonlinear optics, materials; 190.4970 Parametric oscillators and amplifiers

In the absence of widely available solid-state laser sources in the mid-infrared (mid-IR), optical parametric down-conversion has been established as an effective technique for the generation of coherent radiation in this spectral range. Using oxide-based birefringent materials such as $LiNbO_3$, $KTiOAsO_4$ and $RbTiOAsO_4$, and periodically-poled crystals such as PPLN and PPRTA, 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. $CdSiP_2$ (CSP) [1], is a recently discovered nonlinear material which offers unique properties for parametric down-conversion into the mid-IR. It offers a transparency above ~6.5 μm and a noncritical phase-matching (NCPM) capability with an effective nonlinear coefficient as high as $d_{\mathrm{eff}}=d_{36}=84.5$ pm/V [2]. Importantly, CSP has a band-gap well below 1 μm, which permits pumping at 1.064 μm, and under type I ($e\rightarrow oo$) parametric generation with NCPM can provide an idler wavelength beyond 6.4 μm, a spectral range of great interest for medical applications. In earlier studies, the potential of CSP for the generation of mid-IR radiation using direct pumping at 1.064 μm was demonstrated in pulsed nanosecond and pulsed picosecond optical parmetric oscillators [4-6]. Here, we report efficient generation of picosecond pulses in near- and mid-IR in CSP at 100 kHz using single-pass parametric generation (OPG) pumped by a mode-locked $Nd:YVO_4$ laser at 1.064 μm [7]. We demonstrate an average signal power of 1.16 W at 1.282 μm and idler power of 154 mW at 6.204 μm for 6.1 W of pump power.

A schematic of the experimental setup is shown in Fig. 1. The pump source is a commercial mode-locked $Nd:YVO_4$ laser at 1.0642 μm. It can deliver up to 40 W of average power at 100 kHz with a pulse energy of 400 μJ. The output beam has a diameter of 5 mm and the pulses have durations of 8.7 ps, with a spectral bandwidth of ~0.2 nm. The beam has a quality factor M^2~1.1 and the output power stability of <0.5% RMS over 13 hours. Using a telescope, the pump beam is collimated to a ~500 μm diameter before the CSP crystal. The pump power and polarization are controlled using two half-wave plates and a polarizing beam-splitter cube. Pumping is single-pass.

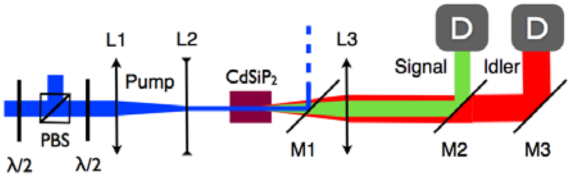

Fig. 1. Experimental setup for single-pass optical parametric generation in CSP pumped at 1.064 μm.
λ/2: half-wave plate, PBS: polarizing beam-splitter, L: lens, M: mirror, D: diagnostics.

The CSP crystal was grown from a stoichiometric melt by the horizontal gradient freeze technique [8]. It was cut at θ=90° (φ=45°) for type I ($e\rightarrow oo$) interaction under NCPM with a length of 8 mm and an aperture of 6.75 mm x 6 mm (along the *c*-axis). The residual loss of the crystal was measured to be 0.198 cm^{-1} for the pump at 1.064 μm, 0.114 cm^{-1} for the signal near 1.3 μm, and 0.014 cm^{-1} for the idler near 6.2 μm. Both crystal faces were antireflection (AR)-coated for the three wavelengths with an eight-layer coating, providing an average reflectivity per surface of ~0.35% at 1064 nm, ~0.4% at 1.275 μm, and ~0.5% at 6.2 μm. The overall single-pass transmission of the AR-coated sample was 83% at 1.064 μm.

We observed OPG output at 1.1 W of pump, corresponding to a pulse energy of 11 μJ and pumping intensity of 0.62 GW/cm^2. By further increasing the pump to 6.1 W, we generated an average signal power of 1.16 W at 1.282 μm with pulse energy of 11.6 μJ. This represents a power efficiency of ~19% and a photon conversion of ~23%. At 6.1 W of pump, we measured an average idler power of 154 mW at 6.204 μm with a pulse energy of 1.54 μJ. Therefore, the power efficiency from the pump to the idler was ~2.5%, with a photon conversion efficiency as much as ~15%. Beyond 6.1 W of pump, we observed the onset of lensing in the CSP crystal. To ascertain the origin of this lensing effect, we chopped the pump beam and performed power scaling measurements of OPG output. The results are shown in Fig. 2, where the signal pulse energy is plotted against pump pulse energy, in the absence of chopping (I), and when the pump is chopped at 100 Hz with duty cycles of 50% (II) and 5% (III). The results clearly confirm the origin of the saturation and lensing as thermal. Given the high pump repetition rate of 100 kHz, saturation in output energy occurs as a result of heating of the crystal, leading to thermal dephasing at higher average powers. With crystals of higher quality, larger aperture and longer length, we expect substantial increases in the signal and idler power to multiwatt and watt level, and at higher conversion efficiencies, by increasing the available pump power to 40 W, while minimizing saturation and thermal lensing.

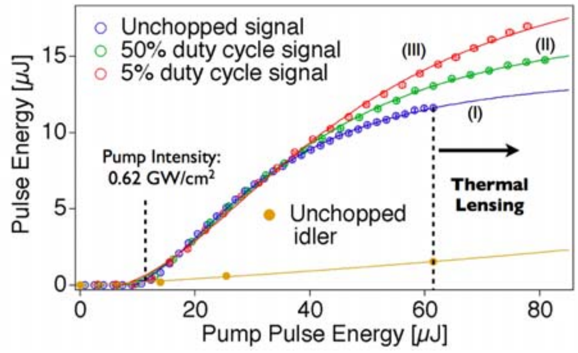

Fig. 2. Output signal pulse energy versus pump pulse energy at the input to the CSP crystal.
(I): Unchopped pump beam; (II), (III): Chopped pump beam. Also shown is the idler pulse energy versus pump pulse energy.

The measured autocorrelation of the signal pulse and the corresponding spectrum are shown in Fig. 3(a) and 3(b), corresponding a signal pulse duration of 6.36 ps, and a spectrum centered at 1.282 μm with a bandwidth of 8.5 nm, resulting in a time-bandwidth product of 9.3. The idler spectrum, shown in Fig. 3(c) centered at 6.204 μm, and has a bandwidth of 122 nm. The dips in the spectrum correspond to absorption lines of water, as verified by the HITRAN molecular database. The signal and idler peak wavelengths of 1.282 μm and 6.204 μm are in close agreement with the calculated values of 1.286 μm and 6.180 μm for a pump wavelength of 1.0642 μm based on the Sellmeier equations for the material [2].

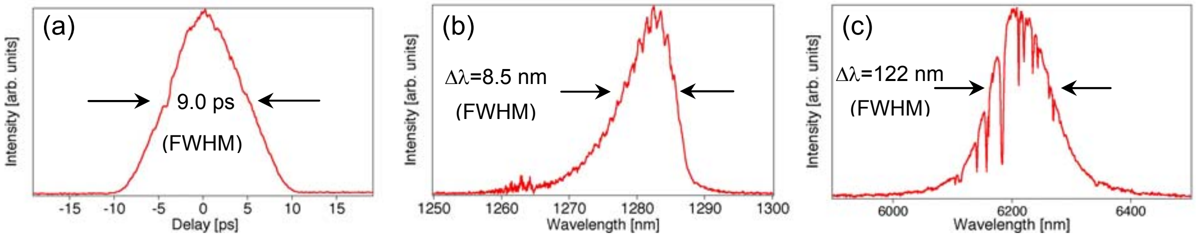

Fig. 3. (a) Intensity autocorrelation, and (b) spectrum of the signal pulses at 1.282 μm. (c) Spectrum of idler centered at 6.204 μm.

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