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RAPID COMMUNICATION

Narrowband, mid-infrared, seeded optical parametric generator based on non-critical $CdSiP_2$ pumped by 120-ps, single longitudinal mode 1,064 nm pulses

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Abstract In this work, we present low-threshold, efficient optical parametric generation in $CdSiP_2$ pumping at 1,064 nm with 120-ps-long, single longitudinal and transverse mode pulses at 230-kHz repetition rate provided by a microchip passively Q-switched master-oscillator power amplifier laser system. Seeding at the signal wavelength with a laser diode, we generated bandwidth-limited idler pulses at 6,100 nm.

1 Introduction

Pulsed coherent radiation sources operating in the mid-IR are very attractive devices for many scientific, industrial and biomedical applications, such as time-resolved spectroscopy, material processing and minimally invasive human surgery [1, 2]. This important spectral region can be accessed through nonlinear frequency down-conversion processes based on parametric amplification, with the cost-effectiveness and reliability of the whole laser system mainly determined by the pump laser characteristics. The well-established diode-pumped solid-state laser technology at 1,064 nm can be exploited to pump optical parametric oscillators (OPO) and optical parametric generators (OPG) based on oxide nonlinear materials to access mid-IR up to ~4 μm, with this limit mainly set by materials transparency. Beyond this limit, matured chalcopyrite crystals such as $AgGaSe_2$ and $ZnGeP_2$ can be employed to generate mid-IR radiation, but they cannot be directly pumped at 1 μm due to the onset of two-photon absorption (TPA). The new chalcopyrite nonlinear crystal $CdSiP_2$ (CSP) recently proved to be a very interesting candidate to overcome such limitations thanks to a favorable combination of properties such as an energy band gap sufficient to avoid to a great extent TPA under direct pumping at 1,064 nm, non-critical phase-matching capability, a clear transparency range that extends up to 6.5 μm and an extremely high (84.5 pm/V) second-order nonlinear coefficient [3]. Such a high nonlinearity can be exploited for generation of sub-nanosecond pulses either employing short crystals in short cavity OPO [4] or relying on direct parametric generation in longer crystals taking advantage of the non-critical phase-matching configuration. Beside intrinsic simplicity, one of the OPG advantages in comparison with OPO is that seeding is much easier to apply in this configuration, yielding a straightforward method for achieving narrowband, single-frequency operation [5]. Recently, we demonstrated extremely low-threshold optical parametric generator (OPG) pumping a $CdSiP_2$ (CSP) crystal with 500-ps-long pulses from a Nd-laser system [6]. Diode laser seeding allowed narrowband non-critical OPG operation at 1-10 kHz repetition rate with the idler at ~6,100 nm. In comparison with [7], with a simpler Q-switching-based pump system, a fourfold improvement of the time-bandwidth product of the mid-IR pulses was obtained. Further reduction in this product, which was still ~5 times above the Fourier limit, is reported in this work. While short or ultrashort pulses are essential for efficient frequency conversion in any nonlinear process, Fourier-limited pulses are desirable on all timescales, from

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femtosecond to nanosecond, because any application, in science, medicine or material processing [1], based on resonant interaction, will profit from the as narrow as possible spectral extent of the coherent mid-IR source.

2 Experimental setup and results

The experimental setup for the OPG experiments is shown in Fig. 1.

The pump source was a passively Q-switched (PQS) laser system in master-oscillator power amplifier (MOPA) configuration. The master oscillator was a microchip PQS laser emitting at 1,064 nm and providing a train of single longitudinal mode, 120-ps-long pulses, at a repetition rate of 230 kHz, with 4-mW average power. The average power was increased up to 5.5 W, corresponding to a single pulse energy of ~24 µJ and a peak power of about 0.2 MW, in a two stage Nd:YVO_4 amplification module. The output beam profile was well preserved by the amplifier, and we measured a beam quality factor $M^2 = 1.2$ at the maximum output power level. Further details about very similar pump laser system can be found in [8].

The OPG was based on a 21.4-mm-long CSP crystal, cut for non-critical (90°), type-I (oo-e) phase matching. Both 4.1 × 6.1 mm^2 crystal facets were AR-coated with a single layer of Al_2O_3, optimized only for the pump and signal wavelengths resulting in a residual reflectivity at the idler wavelength (~6.1 µm) of about 20 % per surface. A $f = 400$ mm spherical lens focussed the pump beam in the CSP crystal to a diameter 2w ≈ 0.62 × 0.53 mm^2 along the horizontal and vertical (parallel to crystal *c*-axis) directions, respectively. In these conditions, we measured an unseeded OPG threshold as low as ≈ 6.5 µJ incident pump pulse energy, corresponding to a on-axis peak fluence of ~5 mJ/cm^2, lower with respect to previous results in double-pass configuration reported in [6]. The average output power at the signal (~1,290 nm) and idler (~6,100 nm) wavelengths as a function of the incident pump power is reported in Fig. 2.

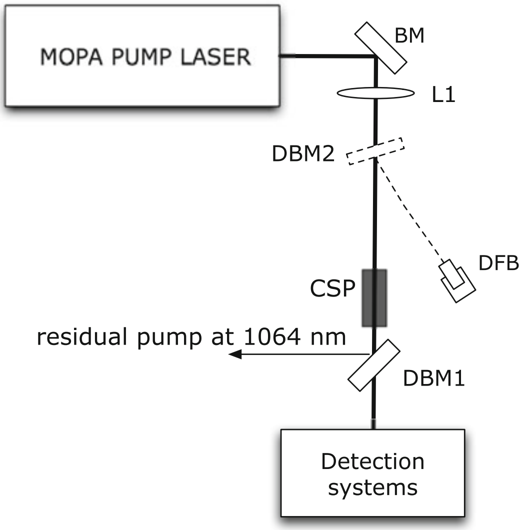

Fig. 1 Experimental setup. BM: Bending mirror HR at 1,064 nm; L1: $f = 400$ mm spherical lens, AR at 1,064 nm; DBM1: dichroic bending mirror HR at 45° at 1,064, AR at signal and idler wavelength; DBM2: dichroic bending mirror AR at 1,064 nm, HR at 1,290 nm; DFB: seeding DFB diode laser

A maximum idler output power of ~120 mW, corresponding to a single pulse energy of 0.52 µJ, was obtained. The maximum average power at the signal wavelength was ~1.04 W, resulting in a total (signal + idler) external conversion efficiency of 21 %. The quantum conversion efficiency calculated from the signal energy is ~23 %. The lower quantum conversion efficiency calculated from the idler energy is mainly attributed to additional reflection losses at the crystal surface due to non-optimized crystal coatings. No surface damage occurred on the CSP facets up to the maximum on-axis pump intensity applied which exceeded 150 MW/cm^2.

We measured the signal pulse duration with a commercial autocorrelator (FR103-XL, Femtochrome Inc.). Assuming a Gaussian temporal profile, from the autocorrelation trace, we derived a pulse duration of 42 ps, as shown in Fig. 3. The signal spectrum FWHM was ~1.2 nm (see inset of Fig. 3). One may conclude that both signal pulse duration and linewidth (~7 cm^{-1}) are well representative also for the idler, which is inherent property of an OPG.

For the signal, the beam quality measurement was performed by means of a CCD camera moved along the focal region of a spherical lens. Up to 4 W incident pump power, the beam quality was reasonably good ($M^2 < 1.5$) and only slightly inferior compared to the pump. At higher average pump power, thermal load in the CSP crystal contributed to

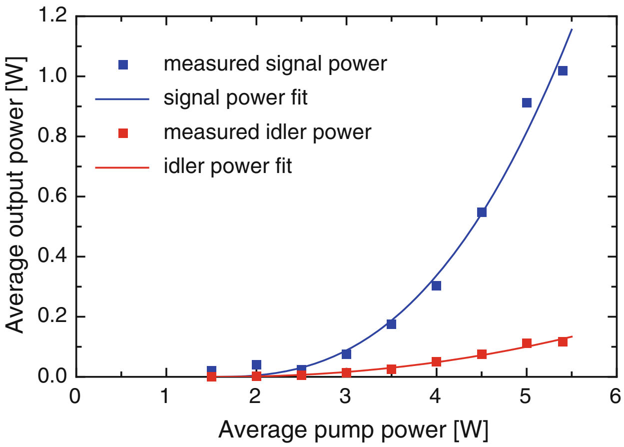

Fig. 2 Average output power as a function of the average incident pump power for signal (~1,290 nm) and idler (~6,100 nm)

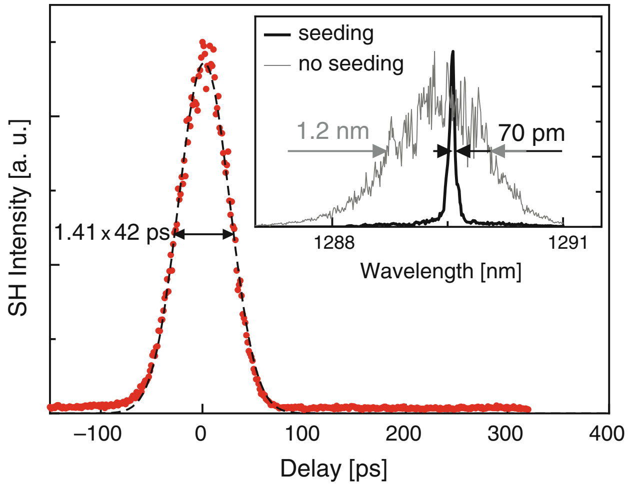

Fig. 3 Signal pulse autocorrelation trace (*dots*) and Gaussian fit (*line*). In the inset, both the unseeded and the seeded pulse spectra in normalized amplitude scale are shown

a significant signal beam quality degradation ($M^2 \approx 6$ at the maximum incident pump power). This is due mainly to residual CSP absorption (we measured a pump absorption of $\approx$ 14 % at low incident intensity) and partly to the onset of TPA at 1,064 nm [9]. The idler beam quality was also characterized at different average pump power levels with the knife-edge method. The measurement was performed only along the horizontal (uncritical for CSP) x-plane, since the beam was symmetric. At an average incident pump power level of 4 W, we measured $M^2 = 21$, compared to $M^2 = 1.4$ for the signal, as shown in the inset of Fig. 4. To better clarify the role of average incident pump power in signal (as well as idler) beam quality degradation, we placed a chopper (duty cycle 4 %) in the path of the pump beam (see Fig. 1) and operated the OPG at the maximum pump pulse energy. In these conditions, signal beam quality was close to diffraction limit ($M^2 < 1.2$), as shown in Fig. 4.

In order to obtain narrowband operation, we also performed seeded OPG experiments. The seeder was a fiber-coupled wavelength stabilized distributed-feedback (DFB) laser diode (QPHOTONICS). The output beam of the diode was collimated and combined with the pump beam through a dichroic bending mirror (see Fig. 1). We measured a maximum incident seed power on the CSP crystal of 40 μW. Due to unpolarized nature of the fiber-coupled diode emission, only 50 % of the total power was effectively seeding the parametric process. The seed diode output wavelength was matched to the parametric fluorescence peak through temperature wavelength tuning of both the CSP crystal and the diode laser. In our working conditions, we estimated a single pass small signal parametric gain of $\sim 5 \times 10^4$. At such extremely low continuous wave power level, seeding did not significantly improved the efficiency, but was very effective in narrowing the signal spectrum down to ~70 pm FWHM (see inset of Fig. 3), resulting in a time-bandwidth product of 0.53, very close to the Fourier limit (0.441) for Gaussian-shaped pulses. The same product should be representative also for the generated idler pulses. This represents a significant improvement (by a factor 17.5) with respect to results previously reported in [7] with 8.7 ps pump pulses.

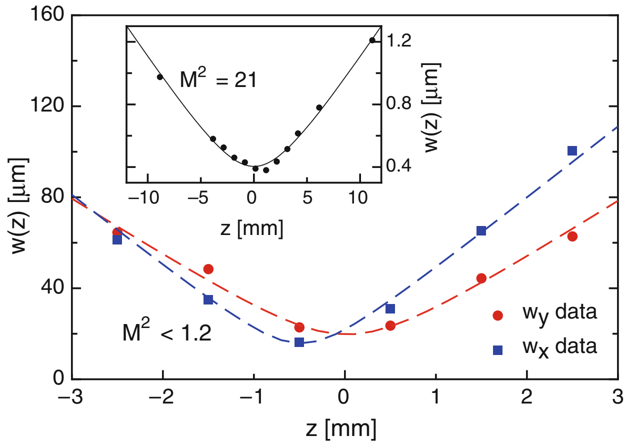

Fig. 4 Signal beam quality at maximum incident pump pulse energy with chopped pump beam (duty cycle 4 %). In the *inset*, idler beam quality at 4 W of average pump power measured without the chopper

3 Conclusions

In conclusion, we demonstrated efficient optical parametric generation in the mid-IR by pumping a CSP crystal with a train of diffraction limited, single longitudinal mode, 120-ps pulses at 230-kHz repetition rate, provided by a microchip PQS MOPA laser at 1,064 nm. The relatively short pulse duration and spectral purity of the pump allowed to access a temporal regime usually covered by OPG pumped by much more complicated and costly ps mode-locked MOPA lasers. Moreover, by seeding the OPG at the signal wavelength with a DFB laser diode, we demonstrated the possibility to achieve idler spectral purity close to the Fourier transform limit, which is an additional bonus for many applications in the mid-IR spectral region.

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