1.3 W femtosecond mid-IR source at 8.5 μm wavelength

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***Abstract*— 1.3 W of average power at 8.5 μm central wavelength are generated through collinear optical parametric amplification in $LiGaS_2$. The crystal is pumped by a 45 W femtosecond oscillator operating at 1.03 μm wavelength. The seed is generated by a normally dispersive photonic crystal fibre. This ensures passive carrier-envelope-offset stability of the idler. The concept is expected to be peak and average power scalable, opening an exciting perspective towards applications in spectroscopy of molecular fingerprints as well as in high field physics.**

I. Introduction

A huge variety of molecules exhibits vibrational resonances in the mid-infrared (mIR) and thus the wavelength region is extremely attractive for spectroscopic applications like human breath or trace gas analysis. In particular, mIR frequency combs provide on the one hand the unique opportunity to precisely measure rovibrational transitions with high sensitivity and within a short measurement time [1]. On the other hand, mIR femtosecond (fs) pulses lead to high peak powers which give rise to strong ponderomotive forces for possible applications in high harmonic generation (HHG) [2]. A key feature for frequency and time domain applications is employing light sources with high average power. Femtosecond laser oscillators operate only at wavelengths shorter than 2.5 μm [1]. For longer wavelengths fs optical parametric amplifiers (OPAs) [3] and oscillators (OPOs) [4] are capable of exceeding the Watt average power level but only up to the oxygen absorption edge at about 5 μm wavelength. Longer wavelength fs sources could just recently reach an average power of 100 mW [5]. However, only about 0.1 % of the initial 90 W oscillator were transferred into the mIR. Here, an OPA-based approach is presented which enabled an increase of conversion efficiency by an order of magnitude. The source is tuneable from 5.5 μm to 11.5 μm and allows bandwidths that support few-cycle pulses.

II. Results

The experimental setup is shown in Fig. 1 (a). The Kerr-lens mode-locked (KLM) thin-disk (TD) oscillator emits 1.2 μJ, 250 fs pulses with an average power of 45 W and a 38 MHz repetition rate [6]. About 15 % of the total power is sent into a large mode area photonic crystal fibre (LMA 12) to generate the OPA seed. Among normally dispersive photonic crystal fibres, LMA 12 is suited best for providing a powerful seed in the amplified wavelength range from 1130 nm to 1260 nm [7]. About 400 mW are transferred into this spectral region. The OPA is directly pumped with the KLM TD oscillator output centred at 1030 nm which leads to a passive carrier-envelope-offset frequency stabilization of the idler. A

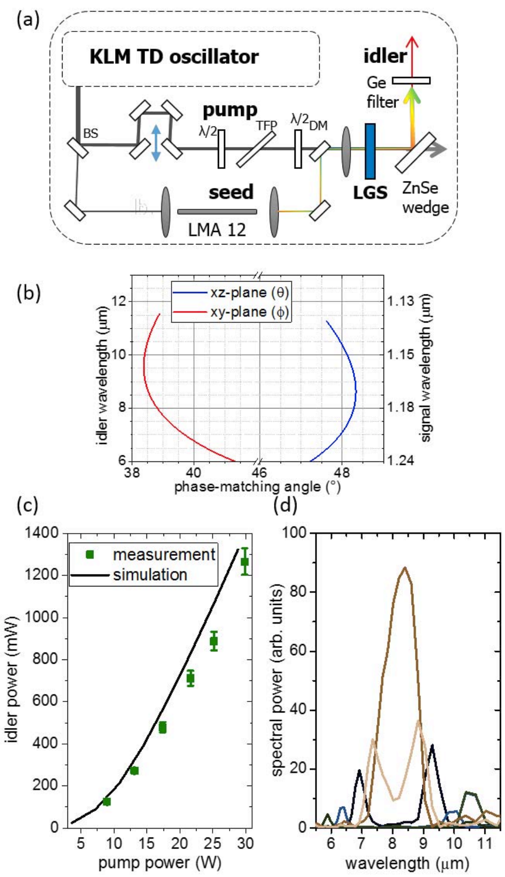

Fig. 1 (**a**) OPA setup: BS – beam splitter (15 % transmission), λ/2 – half-wave plate, TFP – thin film polarizer, DM – dichroic mirror (50 % transmission at 1080 nm) **(b)** Phase-matching curves for type I and type II phase-matching in the principal planes. Both show a turning point. The curves were predicted by means of the Sellmeier equations taken from [8]. (**c**) Generated idler power. Simulation (black line) and measurement after correcting for Fresnel reflections (green dots) **(d)** Angle tuning curve with the maximum at 8.5 μm and the idler wavelength splitting for smaller phase-matching angles.

collinear wave mixing geometry avoids spatial chirp. The biaxial crystal $LiGaS_2$ (LGS) was chosen because it exhibits two distinct advantages over other non-oxide crystals. Firstly, it was shown that it can withstand average powers of 50 W at peak irradiances of 50 GW/cm^2 [5]. Secondly, it exhibits a broad phase-matching bandwidth centred between 8.5 μm and 9 μm, the turning points of the phase matching angles in the tuning curve (fig. 1 (b)). Two possible cuts of the crystal are investigated. If the pump pulses propagate in the xy principle plane (type II phase matching, $n_x<n_y<n_z$, n is the index of refraction) the effective nonlinearity is higher ($d_{eff} \approx 6.0$ pm/V) than for phase-matching in the xz plane (type I, $d_{eff} \approx -4.6$ pm/V). In the presented experiments a 7 mm long LGS crystal was used which was cut for phase-matching in the xy plane. At the tuning angle for the most efficient down-conversion, it

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generated 25 % more mIR power than a comparable 8 mm long crystal cut for type I phase-matching. The idler FTL was in both cases about 110 fs.

The generated idler power was deduced from the measured power of a ZnSe wedge reflection passing through a germanium filter. By the time the experiments were performed, no beam splitter was available which transmitted the mIR efficiently and could handle the high pump power without detrimental thermal effects. Up to 1.3 W of mIR were generated if the full pump power was used. This corresponds to 34 nJ pulse energy. The quantum efficiency of the OPA is about 35 % and about 4 % of the pump power are down-converted to the idler wavelength centred at 8.5 μm. The experiment is in excellent agreement with 3d simulations [9] (Fig. 1(c)) and therefore marks an upper limit for the conversion efficiency of the single stage setup. For pumping with higher peak irradiances crystal damage is expected. The angle tuning curve of the OPA is shown in Fig. 1(d). As expected, a splitting of the idler wavelengths is observable if slightly detuned from the amplitude maximum. This allows generating very broadband mIR pulses despite using fairly long nonlinear crystals. Simulations predict bandwidths supporting pulses with durations of less than 2 optical cycles at about 10 percent of the maximal conversion efficiency. The so-far measured Fourier limits correspond to a duration of 3 cycles. This is attributed to the uncompressed seed which emerges from the LMA fibre. Additional seed pulse compression is expected to lead to lower Fourier limits.

III. SUMMARY

In conclusion, an OPA-based concept to generate high-power mIR femtosecond pulses has been presented. To the best of the authors' knowledge, an average power of more than 1 W has been reached for the first time at wavelengths longer than 5 μm. The power conversion efficiency is more than 25 times higher than in previous comparable studies [5]. No detrimental thermal effects were observed which promises the scalability of the concept to even higher average powers. Moreover, idler bandwidths supporting few-cycle pulses are directly reached. The presented approach is transferable to large-scale amplifier systems which operate with GW to TW peak power levels [10]. This promises high peak power mIR sources driven by standard 1 μm lasers. Therefore, the OPA concept is attractive for applications that require waveform-control as well as for spectroscopic applications.

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