# Broadly tunable femtosecond near- and mid-IR source by direct pumping of an OPA with a 41.7 MHz Yb:KGW oscillator

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**Abstract:** We generate over half a watt of tunable near-IR (1380-1830 nm) and several hundred milliwatts in the mid-IR (2.4-4.2 μm) as well as milliwatt level mid-IR (4.85-9.33 μm) femtosecond radiation by pumping an optical parametric amplifier directly with a 7.4 W Yb:KGW oscillator at 41.7 MHz repetition rate. We use 5 mm PPLN and 2 mm GaSe as downconversion crystals and seed this process by a supercontinuum from a tapered fiber. The system is extremely simple and very stable and could replace more complex OPOs as tunable light sources.



**OCIS codes:** (190.4360) Nonlinear optics, devices; (190.4970) Parametric oscillators and amplifiers.

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#185813 - $15.00 USD Received 6 Mar 2013; revised 18 Apr 2013; accepted 27 Apr 2013; published 3 May 2013

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## 1. Introduction

Laser sources delivering broadly tunable femtosecond pulses at high repetition rates enable a number of key applications in time-resolved spectroscopy. Optical parametric amplifiers (OPAs) [1] seeded with a white-light continuum are powerful tools for such applications. Due to their simple setup and spectral versatility, they have many advantages over optical parametric oscillators (OPOs) [2–4]. However, they require rather high pump energies, typically provided by amplified laser systems, limiting the repetition rate to a few hundred kilohertz [5–7]. Recently, the repetition rate of OPAs has been pushed to the MHz range by using laser oscillators with cavity dumping [8–10] or fiber amplifiers [11,12]. Later on, an OPA with 50 MHz repetition rate pumped by a frequency-doubled Yb:fiber amplifier and seeded by a supercontinuum has been demonstrated [13].

Especially the mid-IR spectral region has attracted great interest recently [14], because many molecules exhibit vibration bands in this spectral region. For example, broadband mid-IR sources can be combined with scattering-type scanning near-field optical microscopes, which give access to both spatial and spectral information on the nanoscale [15]. Among various methods of generating mid-IR radiation [16,17], difference frequency generation schemes are promising due to their simple setup [18–21].

## 2. Experimental setup

Here, we present an OPA that is directly pumped by a simple diode-pumped solid-state oscillator without the need for any amplifier or cavity dumping. We generate over half a watt of signal power in the near-IR (1380-1830 nm), several hundred milliwatts of mid-IR from 2.4 to 4.2 μm, and milliwatt level mid-IR radiation from 4.85 to 9.33 μm.

The experimental setup is shown in Fig. 1. We employ a passively mode-locked dual-crystal Yb:KGW oscillator [22] delivering up to 7.4 W average power with 425 fs pulse duration and 41.7 MHz repetition rate at 1040 nm as pump source. Approximately 600 mW of the laser power is used to generate a supercontinuum seed in an 8 cm long tapered fiber with 4 μm waist diameter [23], whereas the remaining light is used to pump the parametric amplifier. The tapered fiber exhibits a typical throughput of 50%. The signal beam and the pump beam are combined with a dichroic mirror in a collinear interaction geometry and focused separately into a 5 mm long periodically poled lithium niobate (PPLN) crystal. For focusing we employ lenses with 100 mm focal length for both beams, leading to mode radii of 15 μm (vertical) and 20 μm (horizontal).

#185813 - $15.00 USD Received 6 Mar 2013; revised 18 Apr 2013; accepted 27 Apr 2013; published 3 May 2013

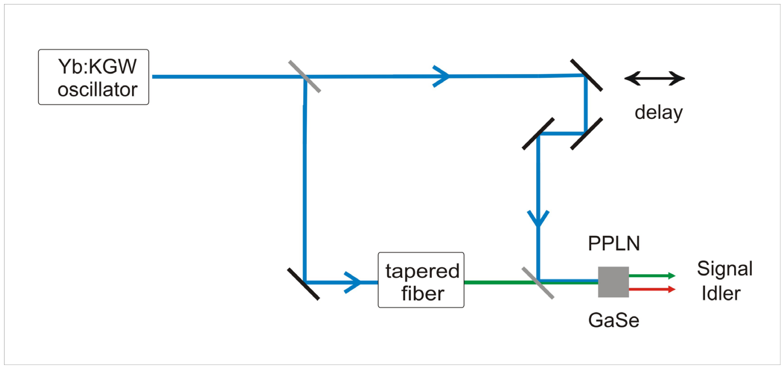


Fig. 1. Experimental setup of the OPA. For near-IR amplification we use a PPLN crystal and for mid-IR generation a GaSe crystal.

## 3. Experimental results

In Fig. 2 the signal power and the conversion efficiency (ratio of signal power versus pump power) of the optical parametric amplifier are shown as a function of pump power. At 2 W pump power, which corresponds to an intensity of 10.5 GW/cm$^2$, the conversion efficiency reaches saturation at 23.5%, whereas the signal power is still increasing at increasing pump power. However, we restrict the pump power to 2 W in order to remain well below the damage threshold of the PPLN crystal.

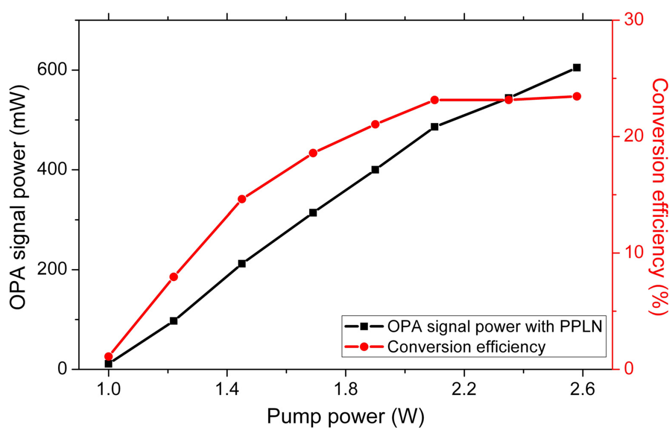


Fig. 2. OPA signal power and conversion efficiency (ratio of signal power versus pump power) vs. pump power.

The OPA signal wavelength is continuously tunable between 1380 and 1830 nm, which corresponds to idler wavelengths from 2.41 to 4.22 µm, by changing the poling period of the crystal (28.0 to 31.0 µm in 0.5 µm steps) and by changing the crystal temperature between 20 and 200 °C. The tuning behavior is shown in Fig. 3.

#185813 - $15.00 USD Received 6 Mar 2013; revised 18 Apr 2013; accepted 27 Apr 2013; published 3 May 2013

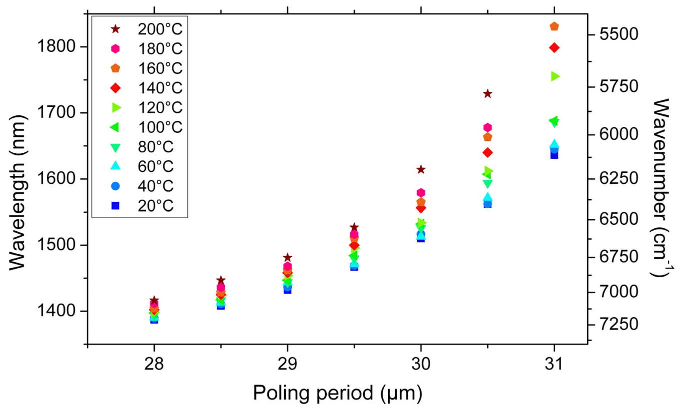


Fig. 3. Temperature tuning of signal wavelength. We used a 5 mm long PPLN crystal. The signal wavelength is continuously tunable between 1380 and 1830 nm.

The signal and idler spectra measured at room temperature are shown in Figs. 4 and 5, respectively. In Fig. 4 the supercontinuum seed of the tapered fiber is also depicted on a logarithmic scale. We exceed 325 mW over the whole signal range with a maximum power of 540 mW at 1400 nm, and we exceed 140 mW over the whole idler range with a maximum power of 220 mW at 3.06 µm. The pump power was set to 2 W to remain below the damage threshold of the PPLN crystal. However, using the maximum available pump power of 4 W, signal powers up to 800 mW were reached.

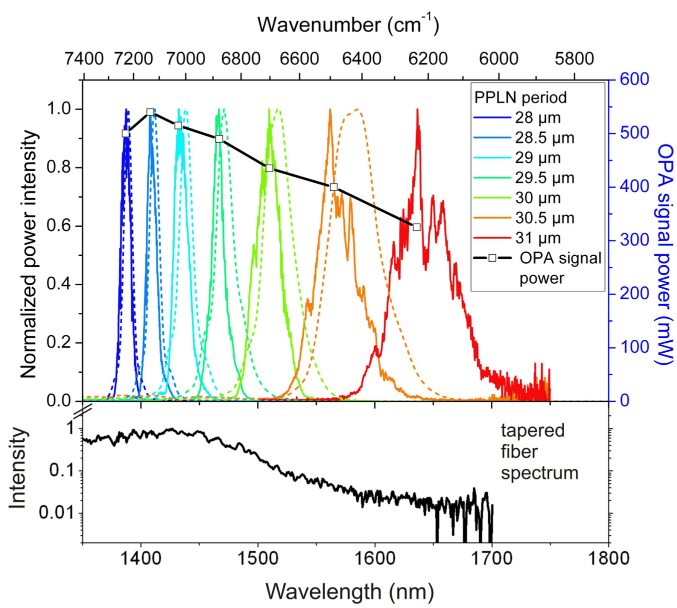


Fig. 4. OPA signal spectra and supercontinuum spectrum of the tapered fiber. The solid lines correspond to the experimental results. The dashed lines depict spectra from a numerical simulation. At room temperature the signal wavelength with PPLN is tunable between 1380 and 1640 nm.

The signal spectra are broader at longer wavelengths, with 9 nm FWHM at 1400 nm and 48 nm FWHM at 1640 nm. However, the width of the idler spectra is smaller at longer wavelengths (210 nm FWHM at 3000 nm and 110 nm FWHM at 4100 nm).

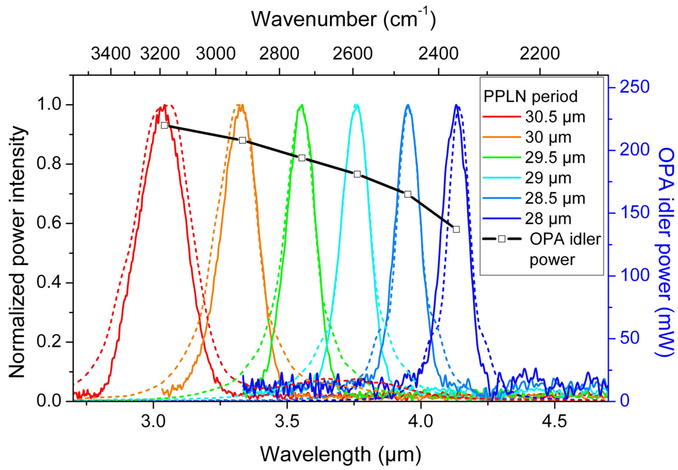


Fig. 5. OPA idler spectra. The solid lines correspond to the experimental results. The dashed lines depict spectra from a numerical simulation. At room temperature the idler wavelength with PPLN is tunable between 3.04 and 4.16 µm.

The dashed lines depict spectra from the numerical solution of a $\chi^{(2)}$ Nonlinear Envelope Equation [24]. The agreement between the simulation, which uses the actual experimental parameters, and the measurement is quite good. For the longer signal wavelengths the simulation predicts somewhat broader spectra than the measurements. Angular dispersion due to focusing into the crystal might account for this deviation.

The autocorrelation indicates chirped signal pulses with durations in the range of a few hundred femtoseconds, with shorter pulse durations at shorter wavelengths. An example of an autocorrelation is shown in Fig. 6. In this case, the signal pulse duration is 110 fs, while the Fourier-limited signal pulse duration is 45 fs. The chirp is introduced due to the propagation in the 8 cm long tapered fiber. We did not compress the pulses, but in principle the chirp could be compensated by a prism sequence or chirped mirrors.

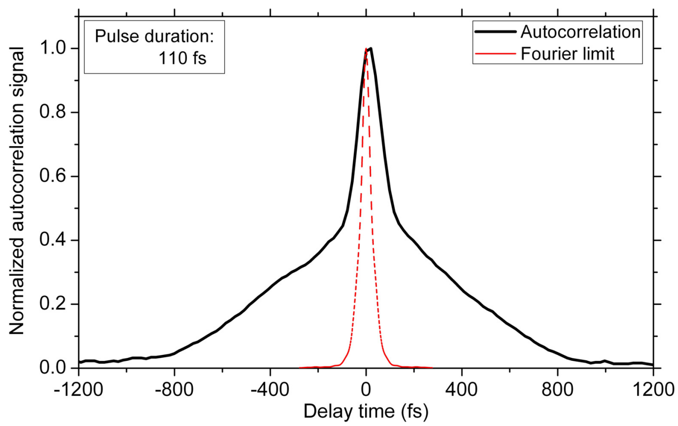


Fig. 6. Autocorrelation and Fourier limit for the signal pulse at 1470 nm (6800 cm$^{-1}$) wavelength.

To generate mid-IR radiation at longer wavelengths, we used a 1 mm or 2 mm long gallium selenide (GaSe) crystal instead of the PPLN crystal. We performed type I phase matching ($e - o \rightarrow o$) and the pump power was set to 4 W. Apart from that, the setup remains the same as shown in Fig. 1 and as described above.

Broadband mid-IR idler pulses tunable from 4.85 to 9.33 µm (2060-1070 cm$^{-1}$) are generated with up to 830 µW average power at 6.46 µm. The spectra are depicted in Fig. 7

#185813 - $15.00 USD Received 6 Mar 2013; revised 18 Apr 2013; accepted 27 Apr 2013; published 3 May 2013

and exhibit broadband behavior over the whole tuning range, with 130 nm (55 $cm^{-1}$) FWHM at 4.85 µm and up to 640 nm (72 $cm^{-1}$) FWHM at 9.33 µm. The dashed lines depict spectra from a simulation using the method described in [25]. The agreement between simulation and measurement is quite good.

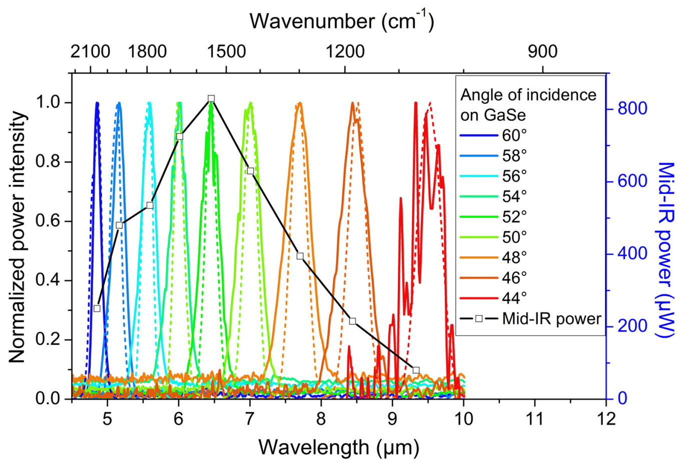


Fig. 7. The mid-IR idler spectra are tunable between 4.85 and 9.33 µm. The solid lines correspond to the experimental results. The dashed lines depict spectra from a numerical simulation. We used a 2 mm long GaSe crystal.

The output power and the spectra of both schemes are temporally stable, as shown in Fig. 8, where the measurement time was one hour.

The power fluctuations in the near-IR region at 1390 nm are equal to 0.9% rms and the corresponding wavelength fluctuations are equal to 0.025% rms (0.34 nm). The power fluctuations in the mid-IR region at 6.32 µm are equal to 3.3% rms and the corresponding wavelength fluctuations are equal to 0.14% rms (8.9 nm).

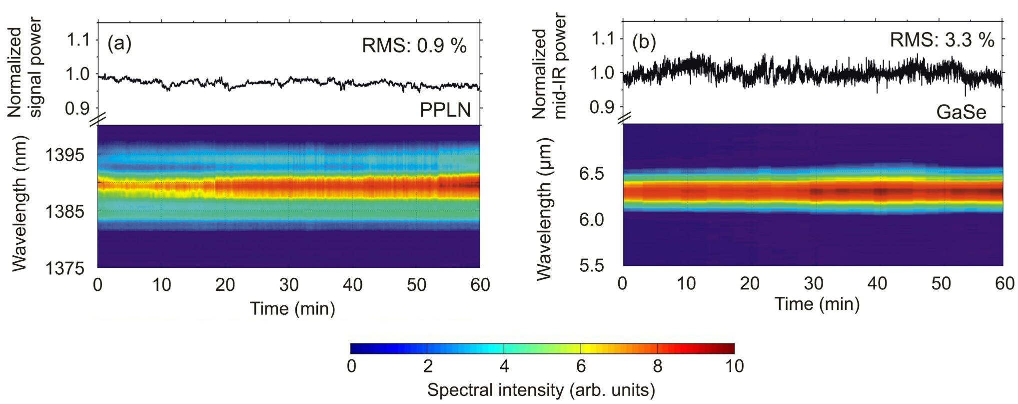


Fig. 8. Temporal stability of power and spectra (a) in the near-IR region using a 5 mm PPLN crystal and (b) in the mid-IR region using a 1 mm GaSe crystal. All measurements were performed over one hour.

## 4. Conclusion

To conclude, we demonstrated a femtosecond PPLN OPA with up to 540 mW average power and 41.7 MHz repetition rate that is tunable between 1380 and 1830 nm (signal) and 2.41 to 4.22 µm (idler), pumped by an Yb:KGW laser oscillator and seeded by a fiber-based supercontinuum. By using a GaSe crystal instead of PPLN, we generated broadband mid-IR idler radiation tunable between 4.85 and 9.33 µm. Our source is compact and cost-efficient and has the potential to replace more complex Ti:sapphire/OPO systems for ultrafast spectroscopy and mid-IR applications, such as broadband gas sensing and nano-spectroscopy.

**Acknowledgments**

We acknowledge financial support from Baden-Württemberg-Stiftung, MWK Stuttgart, Deutsche Forschungsgemeinschaft (SPP1391), and the Bundesministerium für Bildung und Forschung (3N10146). This work was supported by the German Research Foundation (DFG) within the funding program Open Access Publishing.