Multi-Watt femtosecond optical parametric master oscillator power amplifier at 43 MHz

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Abstract: We present a high repetition rate mid-infrared optical parametric master oscillator power amplifier (MOPA) scheme, which is tunable from 1370 to 4120nm. Up to 4.3W average output power are generated at 1370nm, corresponding to a photon conversion efficiency of 78%. Bandwidths of 6 to 12 nm with pulse durations between 250 and 400 fs have been measured. Strong conversion saturation over the whole signal range is observed, resulting in excellent power stability. The system consists of a fiber-feedback optical parametric oscillator that seeds an optical parametric power amplifier. Both systems are pumped by the same Yb:KGW femtosecond oscillator.

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1. Introduction

Tunable near-infrared femtosecond laser sources are advancing to become the backbone for spectroscopic techniques such as multi-photon fluorescence [1,2], coherent Raman scattering microscopy [3], as well as time-resolved measurements and frequency comb spectroscopy [4]. To provide this versatility, broadband tunability has to come along with high repetition rate, high pulse energy, good noise performance, and high reliability with similar pulse properties on all time scales.

While lasers are ultimately limited in the tuning range by their gain bandwidth, optical parametric oscillators provide tunability into the mid-infrared [5–7]. Based on near-infrared parametric sources the mid-infrared spectral range from 2 to 20 μ m can be exploited by difference frequency generation (DFG) of signal and idler [8,9].

With the aim to lower complexity and cost, optical parametric amplifiers (OPAs) [10–13] and optical parametric generators (OPGs) [14] have become powerful tools for infrared light generation [15]. However, they suffer from intrinsic shot-to-shot amplitude and phase noise that limits their applicability for precision measurements in modulation and comb spectroscopy. By using a phase-preserving $\chi^{(3)}$ process such as the Raman soliton shift, the shot-to-shot noise issues can be overcome, however at the cost of long term power and spectral stability [16, 17]. Highly nonlinear bulk fibers have been shown to provide coherent broadening at low power levels [18] and very short pulses.

We demonstrate that using a fiber-feedback optical parametric oscillator (OPO) [19, 20] as a seed source leads to excellent shot-to-shot stability, long term average power stability, and a broad tuning range, whereas a parametric power amplifier adds high output power without degradation of the beam profile. This approach decouples the degrees of freedom compared to a classical synchronously-pumped OPO, since the pulse properties can be configured independently from the final output power and pulse energy, which avoids balancing intracavity nonlinearities. Therefore this system is highly suited for spectroscopic applications that require excellent stability [21], as well as for pumping mid-IR DFG stages and OPOs [22] at arbitrary wavelengths or for MIR supercontinuum generation in fibers [23].



2. Experimental setup

Fig. 1. Experimental setup. An Yb:KGW oscillator is used to pump a fiber-feedback OPO (I) at a maximum power of 1.5 W. The OPO supplies radiation between 1370 and 2000 nm with wavelength dependent power of 25 - 320 mW that is applied to seed an OPA (II). Up to 6.25 W pump power is used to synchronously pump this power amplifier at the oscillator repetition rate. Both signal (1370 - 2000 nm) and idler (2100 - 4120 nm) of the post amplifier can be used for further experiments. HWP: Half-wave plate, BS: Beamsplitter, DC: Dichroic mirror, TC: Temperature control.

Figure 1 depicts the experimental setup. Both the fiber-feedback OPO [21] and the OPA are pumped by the same Yb:KGW oscillator [24]. It delivers up to 8W average output power at 43 MHz repetition rate and 500 fs pulse duration at a central wavelength of 1030 nm.

Two identical 10 mm long periodically-poled magnesium oxide doped (5%) congruent lithium niobate (MgO:PPLN) crystals with poling periods between 27.91 and 31.59 μ m are used as nonlinear gain media for both the OPO and the OPA. A broadband AR-coating minimizes the losses for idler, pump and signal wavelengths. As a feedback fiber a 4.2 m long SMF-28 silica fiber is employed in the OPO, in which pulses between 1370 and 2000 nm are generated. Coupling objectives with an effective focal length of 12.5 mm are used. Tuning is achieved by changing the resonator length and adjusting the phase-matching condition by changing the PPLN poling period and temperature. A maximum OPO average output power of 1.5 W at 1400 nm is achievable at 4.5 W pump power. However, the OPO is operated at rather low power in order to save pump power for the OPA. Between 25 and 320 mW signal power is generated in the whole tuning range depending on the wavelength with a maximum pump power of 1.5 W. Despite missing compensation of the dispersion that is inherent in the propagation through the feedback-fiber, the OPO produces nearly transform-limited pulses (250 - 400 fs) with typical time-bandwidth products (TBP) of 0.4 - 0.5 in the range up to 1650 nm.

The OPO signal is further used as seed source for an OPA, in which it is amplified and an idler between 2100 and 4120 nm is generated. The OPA is pumped with up to 6.25 W at a beam waist of about 85 μ m. Thus, a maximum pump intensity of about 1.13 GW/cm² is accessible.

This two-stage concept offers a variety of advantages. The OPO provides an extremely

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broad gap-free tuning range with high spectral stability, as well as a good shot-to-shot stability compared to alternative seeding concepts based on $\chi^{(3)}$ processes. Except for a dichroic beam combiner, only standard optical components such as silver mirrors are required. On the other hand, the OPA provides extremely high photon conversion efficiency, high average output power and excellent long term average power stability. The flexibility of the OPO seeder is preserved during the power amplification process. Finally, this two stage setup combines and maintains the OPO and OPA properties in an advantageous manner.

3. **Experimental results**

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Figure 2 shows the OPA tuning range and the average output power. A typical spectral width between 6 and 12 nm at pulse durations between 250 and 400 fs in the range of 1370 - 1650 nm has been observed, assuming sech² pulse shapes. For higher signal wavelengths longer pulse durations are expected. Nearly Fourier-limited pulses are achievable for lower signal wavelengths. The measured time-bandwidth products of 0.4 to 0.5 show that the pulse properties of the OPO are well conserved during the post-amplification. All spectra have been measured with a Yokogawa AQ6375 spectrometer. The pulse durations have been measured with an APE pulse check autocorrelator.

For increasing signal wavelengths, thus decreasing idler wavelengths, the OPA output power decreases. This is due to increasing temporal walk-off effects and an effectively decreasing damage threshold of PPLN due to higher order second harmonic generation (SHG) phasematching of the 1030 nm pump beam in longer poling periods (> $31 \,\mu$ m). Therefore, the conversion efficiency decreases and less OPO and OPA power is achievable. Only 3.3 - 4 W pump power is applicable to amplify wavelengths higher than 1750nm without increasing the pump and seed beam diameters.



Fig. 2. Tuning range and average output power of the OPA (a). Watt-level output power is achieved over almost the whole tuning range of 1370 to 4120nm, with maximum output power of 4.3 W. The OPA is pumped with 6.25 W at 1370 - 1500 nm. The pump power is then constantly reduced to 3.3 W at 2000 nm. Assuming sech² pulse shapes, the signal pulse duration is on the order of 250 and 400fs between 1370 and 1650nm (b). Typical time bandwidth products are on the order of 0.4 - 0.5.

In order to investigate the OPA conversion efficiency as a function of the pump power, the maximum available seed power achievable with 1.5W OPO pump power has been utilized. Figure 3(a) depicts this measurement for 1400nm using 320mW seed power. The OPA output power increases nearly linearly with the pump power. At 1400 nm up to 3.8 W signal power is achieved at 6.25 W pump power, whereas the corresponding idler reaches

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up to 1.1W. Note that the experimentally accessible power was approximately 10% lower when compared to the here reported overall generated power due to the requirement to separate pump, signal, and idler after the crystal. This was achieved with broadband longand short-pass filters. Furthermore, the signal power shown in Fig. 3(a) contains no seed power and denotes the bare generated power. The photon efficiency will finally saturate at about 78%. The onset of saturation is calculated by fitting the initial linear increase for low power and by linearly fitting the saturated power. The intersection of these lines denotes the beginning saturation. Thus the saturation starts at 1.5 W. The corresponding photon efficiency is 64%. We expect this concept to be scalable to significantly larger spot sizes in the nonlinear crystal for further power scaling. A similar behavior has been observed for other wavelengths. However, the overall photon efficiency decreases for higher seed wavelengths, which can be explained by the temporal walk-off in PPLN crystals with longer poling periods and the lower applicable pump power due to parasitic SHG. These effects could be lowered by employing periodically-poled lithium tantalate instead of lithium niobate, which exhibits reduced temporal walk-off effects, does not suffer from higher order second-harmonic phase matching for these specific wavelengths, and has a higher damage threshold, at the cost of lower nonlinearity.



Fig. 3. Signal and idler power dependencies on the OPA pump power (a). A nearly linear relation of signal, idler power, and pump power is shown. Up to 78% photon conversion efficiency is achieved at 1400 nm. Note that the seed and idler power denote the bare generated power, i.e., no seed power is included in these values. Figure (b) depicts the long term average power stability at 1400 nm without active stabilization, which reaches 0.1 % RMS in 45 min, and the corresponding spectral properties. The central frequency exhibits a standard deviation of 24.2 pm RMS, whereas the bandwidth varies by 12.7 pm RMS. The corresponding shot-to-shot stability is 0.6%, limited by detection electronics (c). Figure (d) shows the collimated idler beam profile at 3500 nm at 400 mW. Minor changes may occur at other wavelengths and slight deformations may occur near the maximum output power of about 1 W.

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Figure 3(b) shows the long term stability at 1400 nm. The output power varies only by about 0.1 % RMS in 45 min at 10 Hz measurement bandwidth. This value has been confirmed at multiple arbitrary power levels, at which the OPA has been operated in saturation. The long term stability is significantly better compared to the OPO, which reaches 1 % RMS at identical conditions. We attribute this significant increase in stability to the later discussed saturation effects. Also, excellent spectral stability is achieved with this MOPA concept as depicted in Fig. 3(b). A passive wavelength stability of 24.2 pm RMS has been observed in 45 min. The bandwidth deviates by about 12.7 pm RMS. In Fig. 3(c) a typical pulse train is shown. The peak intensity fluctuations due to electronic background noise are on the order of 0.6%. This holds for the pump source, the OPO, and the power amplifier. The data has been obtained with an Agilent Infiniium DSO9404A oscilloscope and a reverse-biased 1 mm² InGaAs photodiode. The long term stability and power have been measured with a Gentec UP12E-10S-H5 powermeter. Figure 3(d) displays a beam profile of the collimated OPA idler at 3500 nm at an output power of 400 mW. A Gaussian intensity distribution is observed for both the horizontal and vertical axis. A $1/e^2$ waist of 0.584 mm is measured in the former direction, whereas 0.578 mm is measured in the latter direction. At higher power the profile is slightly broadened but maintains a Gaussian distribution. Similar beam profiles have been measured at other idler and signal wavelengths. The beam profiles have been recorded with a *Spiricon Pyrocam III*.

In order to investigate the OPA signal dependence on the seed power, the OPO seed has been attenuated using multiple neutral density filters to approximately zero. The pump power has been kept constant during this measurement. Figure 4(a) and 4(b) show the obtained results. Saturation of the signal output power at extremely low seed power is clearly visible for a signal wavelength of 1400 nm as well as 1750 nm. The minimum required seed power for saturation is again calculated by linearly fitting the initial linear increase and the approximately constant part of the signal power and by calculating the lines intersection. It is displayed by the orange data points. Before the signal starts saturating, a linear increase as a function of seed power is visible, which agrees well with the expected behavior of optical parametric amplification in the case of neglected pump depletion. This behavior has been observed at different wavelengths as well as different pump power.

Until now, the dependence of the OPA signal power on the seed power at constant pump power has been investigated. In the following, the dependence of the seed power that is required to drive the OPA into saturation on the pump power will be discussed. Figure 4(c) displays the saturation seed power over the pump peak intensity. For increasing pump intensity, the seed power seems to drop very fast. This has been observed for different wavelengths and is shown for 1400 and 1750 nm. The seed power used in this figure is taken from the saturation calculations done for Fig. 4(a) and 4(b). The lowest observed saturation seed power at 1400nm is about $0.15 \,\mathrm{mW}$ at a pump power of 6W, corresponding to $1.08 \,\mathrm{GW/cm^2}$, whereas a seed power on the order of 1 mW is required at 1750 nm. Figure 4(d) depicts the single pass gain over wavelength for operating the OPA in saturation. The seed power has been kept constant at 18 mW during the measurement. For different pump power similar characteristic wavelength dependence occurs. The single pass gain decreases monotonically. This behavior is again due to walk-off and parasitic SHG generation for higher wavelengths. Temporal walk-off becomes more important for wavelengths higher than 1500nm, since the group velocity of both signal and idler is smaller than the pump group velocity. For wavelengths lower than 1460nm the signal and idler group velocities have opposite sign relative to the pump beam group velocity, which counters temporal walk-off at the cost of higher pulse duration for signal and idler, as also visible in the autocorrelation traces shown in Fig. 2(b).



Fig. 4. Signal power dependence on seed power at constant pump power. The seed power has been attenuated by several neutral density filters. Figure (a) shows the signal power as a function of seed power for pump powers of 1 to 6 W. Due to a high and nearly constant photon conversion efficiency the signal power saturates at extremely low seed power. Figure (b) displays the same measurement for 1750 nm. The seed power required to drive the OPA into saturation is depicted in Fig. (c) as a function of the applied pump power. Further details concerning the calculation are given in the main text. Figure (d) shows the single pass gain at different wavelengths by applying a seed power of 18 mW that drives the OPA into saturation. This is shown for 1 W, 2 W, and 3 W pump power.

4. Conclusion

In conclusion, we have reported a high-repetition rate parametric MOPA scheme that combines the advantages of OPO and OPA properties while maintaining an ultra-compact footprint due to the fiber-feedback concept. High average power of up to 4.3 W at 43 MHz repetition rate, good conversion efficiency up to 78%, as well as excellent long term average output power stability of 0.1% RMS have been achieved with the parametric power amplifier, while preserving the spatial beam quality, tuning range, and spectral stability of the synchronously-pumped OPO. We have shown quantitatively that the system is operating in an extremely saturated regime regarding both seed and pump power. Temporal walk-off and decreasing damage threshold of PPLN have been identified as limiting factors at signal wavelengths above 1750nm. The precise gap-free tunability and power scalability make this system highly attractive as a pump source for mid-infrared difference frequency generation, but also for linear and nonlinear spectroscopic applications such as coherent Raman spectroscopy and multi-photon fluorescence imaging.

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