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Compact harmonic cavity optical parametric oscillator for optical parametric amplifier seeding

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Abstract: We present a broadly tunable highly efficient frequency conversion scheme, based on a low-threshold harmonic cavity optical parametric oscillator (OPO) followed by an idler-seeded power amplifier. By choosing the cavity length of the OPO equal to the 10^{th} harmonic of its 41 MHz Yb:KGW solid-state pump laser, a very compact optical setup is achieved. A singly-resonant cavity without output coupler results in a low oscillation threshold of only 28–100 mW in the entire signal tuning range of 1.37–1.8 µm. The 2.4–4.15 µm idler radiation is coupled out at the 41 MHz pump frequency and employed to seed a post amplifier with nearly Watt-level output power. In addition, the seeder plus power amplifier concept results in clean signal and idler pulses at the fundamental repetition rate of 41 MHz with a time-bandwidth product below 0.4 and a relative intensity noise 10 dB lower compared to the solid-state pump laser.

1. Introduction

Ultrafast mid-infrared laser systems are the backbone of a multitude of spectroscopy techniques. Besides their irreplaceability in (coherent) Raman spectroscopy [1] and frequency comb spectroscopy [2], also linear methods such as vibrational spectroscopy in the mid-infrared (MIR) spectral regime were found to benefit from high-performing laser sources [3].

For a range of applications that do not require ultrashort pulses, quantum cascade lasers (QCLs) are competing with optical parametric sources due to their compactness and robustness. However, their tunability is limited [4], even in the more environmentally sensitive external-cavity configuration, and multiple modules need to be operated and maintained to cover the mid-infrared spectral range [5]. Furthermore, QCL technology currently reaches its limits for wavelengths shorter than 3 µm [6]. Contrarily, mid-infrared vibronic lasers are limited in tuning range to no more than 6 µm and with mode-locking being available up to 3.5 µm [7,8].

Optical parametric frequency conversion, in contrast, is the most flexible technology to generate tunable radiation [9–15]. However, the parametric frequency converters could be sensitive to ambient and pumping conditions. This applies in particular for free-space optical parametric oscillators (OPOs) and becomes more significant with shorter pulse duration and higher output (and pump) powers. Often it is not even the OPO cavity itself that sensitively reacts to its environment, but minute changes in the pump laser intensity or beam pointing, which impact intensely on the OPO performance.

Difference frequency generation (DFG) sources [16–19] or high-repetition-rate optical parametric amplifiers (OPAs) [20,21] circumvent these cavity-induced instabilities, but at the cost of requiring a coherent seed. The latter is often difficult to provide, particularly if mode-locked oscillators are used that do not enable white-light continuum generation in crystals like sapphire, and might come with a limited tuning range and seed intensity.

It was shown that a combined seeder plus power amplifier concept can significantly improve the robustness of parametric frequency converters [22,23], ultimately resulting in extremely

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stable and low-noise sources suitable for further frequency conversion to the deep MIR without observing the typical stability issues of nonlinear converters [12,24]. In a simplified picture the seeding unit dictates the operating wavelength, tuning range, and high-frequency noise properties, while output power and drift stability are dominated by a saturated amplifier stage. The latter also leads to a moderate "cleaning" of the pulse properties.

In this Letter we advance this concept by reducing the complexity of the seeding unit further by employing a harmonic cavity OPO (HC OPO) with just a fraction of the resonator length compared to the pump laser [25,26] as a seeding unit. This results in an exponentially decaying intra-cavity signal, where every nth (here: 10^{th}) pulse serves as seed for the next frequency conversion process. Crucially, only the idler is used for seeding a subsequent optical parametric amplifier, as it is not resonantly propagating inside the harmonic cavity and hence leaves the OPO with the original pump repetition rate, as illustrated in Fig. 1. The resulting output pulses exhibit surprisingly low intensity noise, surpassing that of previous concepts with the same pump laser. The excellent long-term stability and reproducibility allows utilizing the system in a swept-source MIR spectroscopic experiment. Unlike other OPO systems, the system can be very easily adapted to different pump lasers, as the delay only needs to be adapted by a fraction of the oscillator cavity length and different harmonic orders can be picked. Finally, the harmonic cavity OPO shows a very low oscillation threshold due to the absence of an output coupler for the signal and the usage of only few optical components and it exhibits a footprint of only $30 \times 14\,\text{cm}^2$.

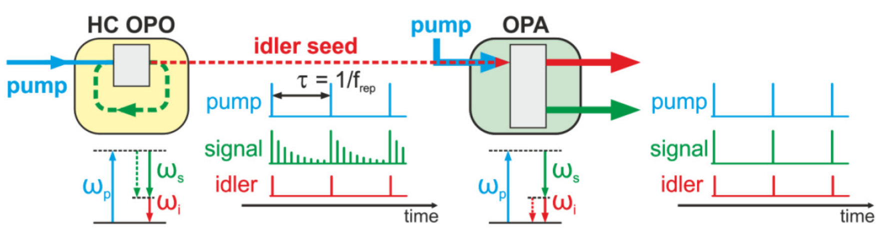

Fig. 1. Illustration of the frequency conversion concept. In a first step, a HC OPO is employed to generate tunable signal pulses at a multiple of the repetition rate of the pump laser. The generated idler, which is not resonantly oscillating inside the OPO cavity, then seeds a second nonlinear crystal that generates both signal and idler pulses at the fundamental repetition rate.

2. Harmonic cavity OPO

A detailed experimental setup is depicted in Fig. 2. A mode-locked Yb:KGW oscillator is employed as pump laser [27]. It delivers 7 W average output power at 41 MHz repetition rate and 425 fs pulse duration at a central wavelength of 1033 nm with 2.7 nm bandwidth.

A fraction of up to 400 mW is employed to pump the HC OPO (yellow), while up to 2.5 W are used for the post-amplification unit (green). The OPO cavity consists of a planar dichroic mirror, a curved (r = 150 mm) dichroic mirror, and a planar highly reflective mirror for the signal wavelength range (1370–1800 nm), mounted on a delay stage. Herein, the curved mirror transmits both the idler (2400–4150 nm) and the residual pump radiation. The pump beam is focused to a spot size of 40 µm ($1/e^2$ waist) in a 10-mm-long MgO-doped periodically-poled lithium niobate (PPLN) crystal. The cavity length is chosen to match the 10^{th} fraction of the pump oscillator cavity length, such that the oscillating signal pulse is amplified every 10^{th} round trip. Spectral tuning is achieved by both controlling the temperature of the PPLN crystal and the cavity length. Due to the high number of round-trips, the intracavity dispersion (up to 35000 fs^2 for 10 round trips by the crystal only) makes the system robust against temporal jitter and thermal

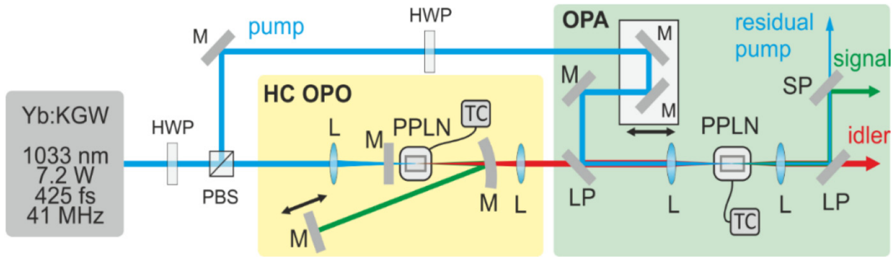

Fig. 2. Optical setup of the frequency conversion system consisting of a seeding unit (HC OPO) and a power amplifier (OPA). Abbreviations: HWP: half-wave plate; L: lens; M: mirror; LP: long-pass filter; PBS: polarizing beam splitter; PPLN: periodically-poled lithium niobate nonlinear crystal; SP: short-pass filter; TC: temperature controller.

drift, by stretching the intracavity signal pulse, while still not introducing large wavelength shifts that could occur for slight cavity length changes.

The collimated idler beam is coupled out from the HC OPO cavity and serves as a synchronous seed for the post-amplification unit (green). It is therefore collinearly combined with the second pump beam, which is synchronized in time by a delay stage. A second temperature-controlled 10-mm-long PPLN crystal is used for parametric amplification, but with a larger focus size of 50 µm. This spot size limits the applicable pump power to about 2.5 W, which is a good compromise between power extraction and small-signal gain. All beams are then collimated and separated by long- or short-pass filters.

First, we characterize the performance of the HC OPO over its tuning range of 1370–1800 nm in the signal beam or 2400–4150 nm in the idler beam, respectively. The intracavity signal pulse train is measured by detecting a leaking signal behind the planar delay mirror with a fast InGaAs photodiode (Hamamatsu) and a 4 GHz oscilloscope (Agilent DSO9404A). Figure 3(a) shows the measured decaying signal pulse train showing oscillation on the 10^{th} harmonic of the pump repetition rate, with very pronounced peaks for the amplified pulses. We attribute the deviation of this pulse train compared to the expected exponential decay pattern to transversal spatial mode changes of the oscillating signal. The high single-pass gain influences the spatial properties of the circulating pulse depending on whether the crystal is pumped (every 10^{th} round trip) or not (otherwise). Consequently, when detecting the signal with a fast small-area photodiode these spatial variations couple into the measured signal.

In the following, we analyze the idler output of the OPO, as it is the beam of interest that is later used for seeding the amplifier. In Fig. 3(b), the idler spectra (measured with the waveScan spectrometer from APE) and the measured pump threshold are shown in steps of 200 nm. Over a large tuning range (2600–4150 nm) gap-free and continuous tunability is observed. From short to long idler wavelengths, the spectral bandwidth varies from 25–52 nm, which corresponds to Fourier-limited pulse durations of 436–351 fs. Apart from atmospheric absorption, the spectra are very clean and free of the mode structure of the 410 MHz cavity. For 400 mW of pump power, a maximum output power of 73 mW at 3200 nm is observed, which corresponds to a photon efficiency of 56%, a remarkably high value for an OPO. While no operation below 2400 nm was achieved, the efficiency trend in Fig. 3(c) indicates that this is rather attributed to the unfavorable higher order dispersion of the cavity mirrors towards 2 µm signal wavelength rather than the parametric gain. On the upper end of the idler tuning range in contrast, the decrease of the single-pass gain due to the temporal walk-off of the idler pulse denotes the limit in tuning range.

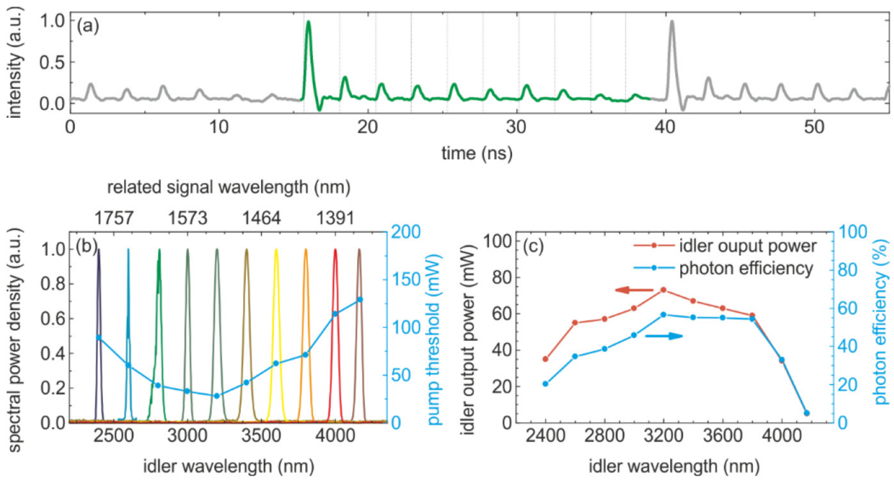

Fig. 3. (a) Measured pulse train of a parasitic intracavity signal from OPO at 1525 nm. (b) OPO idler spectra and corresponding pump threshold. (c) OPO idler output power at constant 400 mW pump power and corresponding photon efficiency.

3. Post-amplification scheme

In the next step, the performance of the idler-seeded post-amplification unit is evaluated. Figure 4(a) shows the signal output power at 1525 nm as a function of idler seed power at 3200 nm for five different pump power settings ranging from 0.5 W to a maximum of 2.5 W. To evaluate the seed saturation behavior, two linear fits are applied to the region of nearly linear amplification and the region of saturation. The crossing point of these two fits is defined as the "seed saturation power". It is evident that little seed power, typically well below 5 mW, is sufficient to achieve nearly the maximum output power due to the relatively high small-signal gain (typ. > 100). We note though, that for lower or higher wavelengths, the seed saturation power increases [24]. Furthermore, the saturation of the conversion efficiency as a function of pump power was measured (Fig. 4(b)) with the result that 1.25 W, about half of the available power, are sufficient to saturate the photon efficiency on the order of 50%. Hence, at the maximum pump power of 2.5 W, about 800 mW signal and 500 mW idler power are extracted. In principle, the remaining 4 W of the pump oscillator could be employed to further amplify these beams to the multi-Watt level [24].

The spectral and temporal properties of the seeding pulses are widely maintained during amplification. The efficiency of this concept is furthermore underlined by the autocorrelation shown in Fig. 4(c), indicating a temporally and spectrally clean pulse without satellites (time-bandwidth-product: 0.36).

Equal to the HC OPO, also the post-amplification unit is continuously tunable over a wide range and exhibits smooth output power in the idler window, as shown in Fig. 5(a). We make use of the excellent tuning characteristics and stability of this system in a swept-source experiment, measuring the vibrational bands of a 9-µm-thick photoresist (Clariant, AZ9260) on a CaF_2 substrate. Figure 5(b) shows excellent agreement between the measurements taken by sweeping the wavelength of the system at constant idler power and a reference measurement taken with a commercial FTIR spectrometer (Bruker VERTEX 80). All vibrational features are reproduced with bandwidth-limited resolution and very little excess noise due to the stability of the laser source.

As illustrated in Fig. 6, the long-term stability of both the seeding unit and the power-amplifier are excellent on the short and long timescales. Figure 6(a) depicts a 0.57% rms power fluctuation

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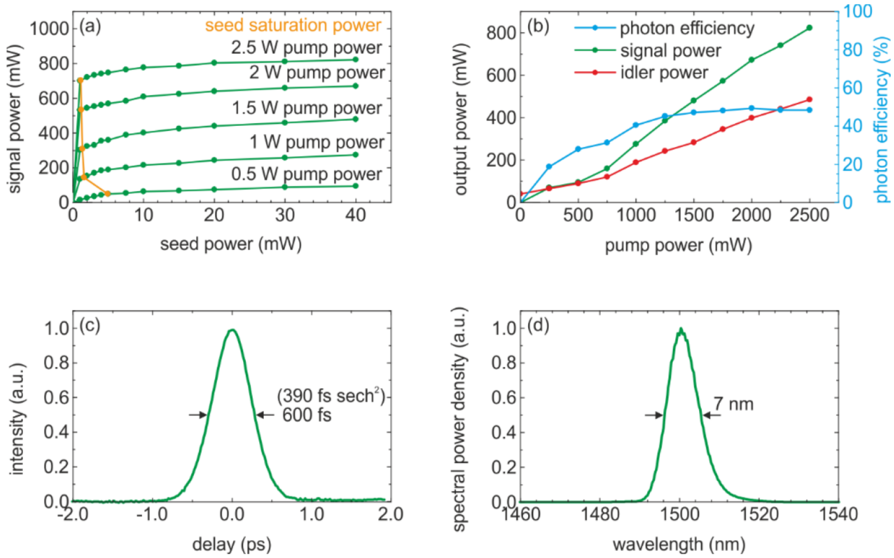

Fig. 4. Performance of the power amplifier. (a) OPA signal output power versus idler seed power, demonstrating very strong seed saturation of the amplifier stage. The orange line denotes a fit to emphasize the seed saturation power. (b) Signal and idler output power and photon efficiency versus pump power at an idler wavelength of 3200 nm and 40 mW seed power. The system shows saturation of the conversion efficiency at a level of 50% starting from about 1.25 W of pump power. (c) Intensity autocorrelation measurement and (d) corresponding signal spectrum at 1500 nm.

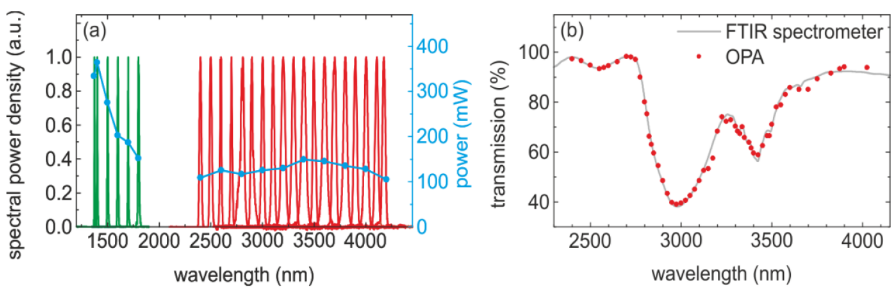

Fig. 5. Signal and idler spectra and corresponding output power of the OPA for a fixed pump power of 1 W in coarse steps of 100 nm (a). Transmission measurement of a 9 µm thick photoresist (Clariant AZ 9260), by fine tuning the idler wavelength (b).

of the power amplifier over 30 min. These values are achieved due to the stability of the pump laser in combination with both seed and pump saturation. Also the spectral stability of the idler radiation has been measured, resulting in 0.43 nm rms wavelength fluctuation at 3200 nm along with a stability of the bandwidth as good as 0.24 nm rms for 50 nm bandwidth. We note that these values are achieved with a passively stable setup, without any electronic stabilization, dry air purging, or thermal stabilization, except that of the nonlinear crystals.

At frequencies in the kHz and MHz range, the system shows even lower noise compared to the solid-state pump laser, as plotted in Fig. 6(b). Both the pump oscillator and the 1500 nm signal radiation are measured at 1.5 mA photo current with a home-built low-noise InGaAs detector with a detection bandwidth of 20 MHz and a lock-in amplifier (Zurich Instruments, UHFLI). Under these conditions, shot noise-limited operation is achieved at about 200 kHz. Compared

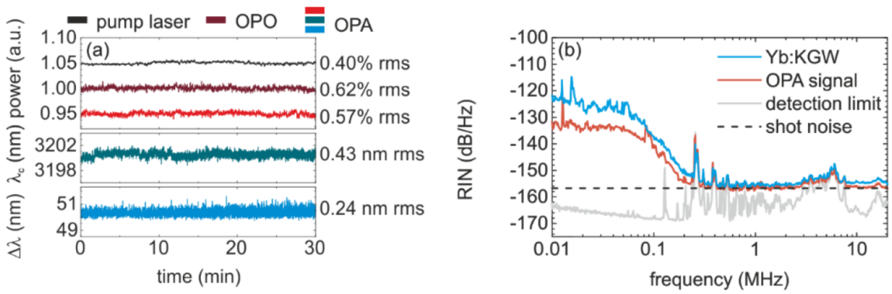

Fig. 6. (a) Simultaneously measured stability of output power of the pump laser, OPO and OPA stage (upper panel) and measured center wavelength and spectral bandwidth over 30 minutes. (b) Relative intensity noise (RIN) at a photocurrent of 1.5 mA of both the Yb:KGW pump laser and the OPA signal at 1525 nm. The frequency conversion chain results in a noise reduction of up to 10 dB.

to the pump laser, a noise reduction of 10 dB is observed in the 10–100 kHz region, which we attribute to the stabilizing effect of the OPO cavity in combination with the saturation in the power-amplification stage.

4. Summary and conclusion

In conclusion, we present a compact, low-noise seeding unit for optical parametric power amplifiers based on the idler of a harmonic cavity optical parametric oscillator. Compared to alternative approaches, the system is extremely energy efficient due to its low oscillation threshold (28 mW) and high photon efficiency (56%). Including the amplifier unit, the system provides continuous tunability in the 1370–1800 nm and 2400–4150 nm spectral range, which could be extended by the choice of suitable mirrors. Owing to the saturated operation of the post-amplification stage, the system exhibits excellent short and long-term stability well below 1% rms over 30 min, exhibiting even 10 dB lower relative intensity noise fluctuations than its solid-state pump oscillator.

Future ideas include employing an additional difference-frequency generation step between signal and idler to exploit the 5–20 µm range. Rapid tunability can be achieved by utilizing fan-out crystals instead of temperature tuning. The small number of optical components, its energy efficiency, and the simple adaption to different pump lasers with different MHz repetition rates make this system highly interesting to replace the widely used bulk optical parametric oscillators.

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Disclosures

The authors declare no conflicts of interest.

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