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Novel ultrafast parametric systems: high repetition rate single-pass OPG and fibre-feedback OPO

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Abstract
We describe two novel parametric systems for wavelength-tunable ultrashort pulse generation in the spectral range around 1.5 μm. We demonstrate the first single-pass optical parametric generator (OPG) that is directly pumped by a mode-locked laser at the full laser repetition rate of 35 MHz, obtaining up to 500 mW of average signal power with a pulse duration of 300 fs. We also report on a novel type of synchronously pumped high-gain optical parametric oscillator (OPO) with feedback through a single-mode fibre. We compare two fibre-feedback OPO systems, generating multi-watt average signal powers in 10 ps and 800 fs pulses. Both the OPG and fibre-feedback OPO system require a high parametric gain, which is achieved in periodically poled nonlinear crystals of $LiNbO_3$ and $LiTaO_3$, pumped with recently developed passively mode-locked all-solid-state lasers with very high average output power.

1. Introduction

Ultrafast laser systems in the near infrared are interesting for many applications in spectroscopy and telecommunications. In recent years, optical parametric generators (OPG) and optical parametric oscillators (OPO) have proven to be attractive sources of ultrashort pulses which are tunable over a broad wavelength range.

Optical parametric generators allow simple and robust systems, operating without external resonators. However, to exceed the threshold for parametric generation, high-energy pump pulses are required. For this reason, ultrafast parametric generators have so far always required amplified pump sources [1, 2], typically involving a seed laser and a regenerative amplifier, which leads to a complex overall system despite the inherent simplicity of parametric generation. Moreover, the low repetition rates of such systems limit the obtainable average output power. In the first part of this paper, we report on what is, to our knowledge, the first single-pass parametric generator that is directly pumped with a mode-locked laser at full repetition rate. With this simple configuration, we obtain up to 0.5 W of average output power in 300 fs pulses at a repetition rate of 35 MHz.

Compared to OPG systems, synchronously pumped OPOs offer a lower pump threshold, typically a better efficiency, and better spectral and spatial properties of the generated beams. However, an external cavity is then required, which has to be precisely synchronized to the mode-locked pump laser. In the second part of this paper, we present two different fibre-feedback OPOs. This novel type of synchronously pumped OPO is based on feedback through a single-mode fibre in combination with a very high parametric gain and strong output coupling. This concept leads to compact, stable and powerful systems in the femtosecond and picosecond regimes. We demonstrate a picosecond device generating up to 4.4 W of average signal power in $\approx$10 ps pulses tunable from 1485–1582 nm. We also present a femtosecond version that generates up to 2.7 W average signal power tunable from 1429–1473 nm in 700–900 fs pulses [3]. In contrast to many other OPOs in this pulse duration regime, this system is very insensitive to drifts of the OPO cavity length and does not require active stabilization. Because of the high parametric

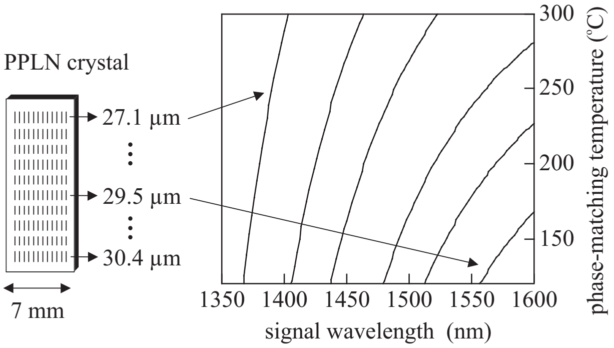

Figure 1. The 7 mm long and 0.5 mm thick $LiNbO_3$ crystal has ten periodically poled regions with grating periods from 27.1–30.4 μm. The calculated phase-matching temperatures of the different channels are shown for a pump wavelength of 1030 nm.

gain, fibre-feedback OPOs are also unusually insensitive to intracavity losses. Even at low repetition rates, the set-up is very compact since most of the resonator feedback path consists of the fibre.

Both the OPG and the fibre-feedback OPO systems require a high parametric gain (tens of decibels). Recently, it was demonstrated that high-power all-solid-state lasers can be passively mode-locked with semiconductor saturable absorber mirrors (SESAMs) [4, 5]. These laser systems generate multi-watt average output powers in the picosecond and sub-picosecond domains [6–8]. The combination of such pump lasers with periodically poled $LiTaO_3$ (PPLT) and periodically poled $LiNbO_3$ (PPLN) crystals allows high parametric gain to be achieved.

2. Femtosecond optical parametric generator

The femtosecond optical parametric generator is based on a 7 mm long PPLN crystal. PPLN is attractive for OPG experiments because of its high effective nonlinearity (d_{eff} up to ~17 pm V^{-1}) and because the phase-matching wavelengths can be controlled with the period of the poling pattern. Our 0.5 mm thick PPLN crystal was produced by electric field poling [9]. It contains ten periodically poled channels with poling periods between 27.1–30.4 μm. Switching between the channels (by translating the crystal) allows different ranges of signal wavelengths to be addressed. For a given channel, temperature tuning allows coverage of a continuous range of several nanometres (figure 1).

The high parametric gain needed for an OPG, together with the high repetition rate of mode-locked lasers, means that a pump laser with multi-watt average power is required. In the last few years, diode-pumped continuous-wave Yb:YAG thin disk lasers with multi-watt TEM_{00} output power have been demonstrated [10, 11]. Recently, we demonstrated the passive mode locking of such a laser with a SESAM, obtaining 730 fs pulses at 35 MHz repetition rate with as much as 16.2 W average power and 0.47 μJ pulse energy [7]. For the experiments described in this paper, we used a slightly modified version, generating pulses with a duration of 0.6 ps at a repetition rate of 35 MHz and delivering up to ≈11 W of average power.

The 1030 nm output beam of the Yb:YAG laser is first sent through a variable attenuator and an optical isolator. Then

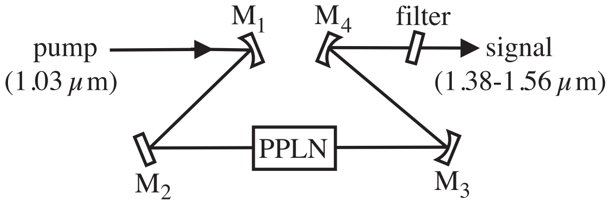

Figure 2. A schematic diagram of the OPG set-up.

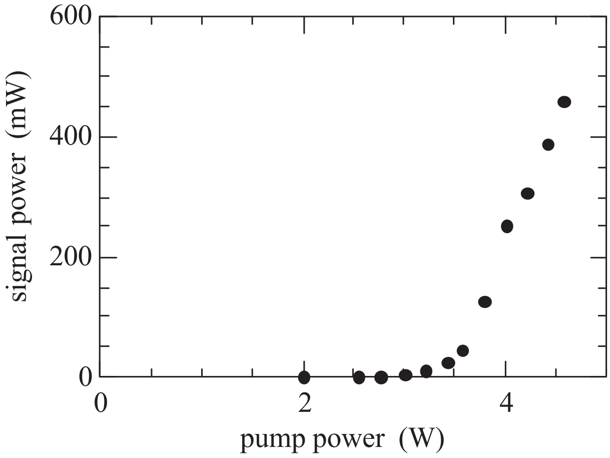

Figure 3. Signal output power as function of pump power incident on the uncoated PPLN crystal (for 28.4 μm grating period and 1.46 μm signal wavelength).

it is focused to a waist with a 40 μm radius in the middle of the PPLN crystal (figure 2, M_1 and M_2—highly reflective mirrors for 1030 nm). The crystal is operated in an oven at a temperature above 150 °C to avoid photorefractive damage. The generated signal is separated from the pump and idler waves by a combination of two dichroic mirrors (M_3, M_4) and a filter.

For different crystal temperatures in the range between 150–250 °C and grating periods from 27.1–29.2 μm, we obtain signal wavelengths from 1.38–1.56 μm. The spectrum is broader for longer grating periods (from 15 nm FWHM for 27.1 μm grating period and 1.38 μm signal wavelength, up to 40 nm for a 29.2 μm grating period and 1.56 μm signal wavelength), as can be expected from the broader phase-matching bandwidth at given temperature for longer grating periods (see figure 1).

The signal output power was measured with a thermal powermeter and corrected for losses at the filter (9%). The different poled channels allow generation of signal output power between 0.25–0.5 W in the spectral region of 1.38–1.56 μm for a pump power of less than 5 W incident on the crystal. In figure 3, the average signal power for a 1.46 μm wavelength is shown as a function of the pump power (for a 28.4 μm grating period). The idler power was not measured but is expected to be up to 0.25 W in the range of 3.03–4.06 μm.

We also observed several additional nonlinear processes. We measured up to ≈0.1 W of green light at 515 nm (second harmonic of the pump beam), in addition to the outputs, whose powers were not measured, in the red spectral region (second harmonic of the signal beam, sum frequency of the signal and the pump beam) and in the UV at 343 nm (third harmonic of

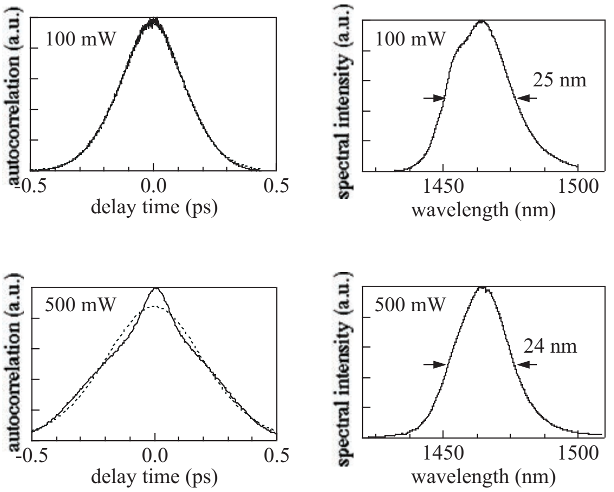

Figure 4. Intensity autocorrelation and optical spectrum of the signal wave for signal powers of 100 mW and 500 mW (for 28.4 μm poling period and 1.46 μm signal wavelength).

the pump beam).

The duration of the signal pulses was measured by intensity autocorrelation assuming a sech^2 pulse shape. For the 28.4 μm grating period, a signal wavelength of 1.46 μm and 100 mW signal output power, we obtain a FWHM pulse duration of 198 fs, which is approximately three times shorter than the 600 fs pump pulses (figure 4, dotted curve is the fitting function). The spectral width is 25 nm (FWHM), leading to a time-bandwidth product of $\sim$0.7, which is not far from the transform limit ($\approx$0.315 for the ideal sech^2 pulse shape). At 0.5 W signal power, we obtain a spectral width of 24 nm and a pulse duration of 307 fs, leading to a time-bandwidth product of $\sim$1.1.

The M^2 value was measured for a similar set-up with a 60 μm pump-waist radius in the PPLN crystal. For a signal wavelength of $\lambda = 1.5$ μm and a signal output power of 150 mW, the M^2 value was 2.8 in the sagittal and 2.0 in the tangential direction (the M^2 value of the pump beam was 1.5).

Some channels have been operated with output powers of $\approx$0.2–0.3 W for several hours (with a 60 μm pump-waist radius). At higher pump powers, the onset of damage was observed. For signal powers around 0.5 W, in most gratings damage was observed after minutes. The damaged regions can be seen under a microscope and are located in the middle or at the exit face of the PPLN crystal. No regions of damage were observed at the entrance face. For gratings generating a high level of parasitic green light (which occurs when the grating period is suitable for second-harmonic generation via high-order quasi-phase-matching), damage occurs at a significantly lower pump power. We believe that the damage is linked to green-light-induced infrared absorption [12], which leads to high levels of absorbed infrared pump light, particularly at the end of the crystal, where the maximum amount of green light occurs. Photorefractive damage and direct thermal effects are not likely to be important at these power levels because such effects should be greatly reduced by chopping the pump beam with a low duty cycle (10%), whereas we did not observe a significant reduction of damage under such conditions. These problems might be removed in future by using stoichiometric

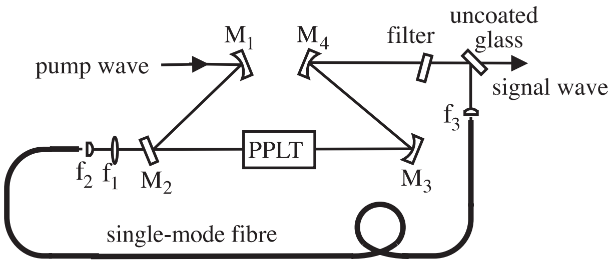

Figure 5. Set-up of the OPO ring cavity: M_1–M_4, mirrors; f_1–f_3, lenses; PPLT, crystal of periodically poled $LiTaO_3$.

(rather than congruent) $LiNbO_3$ or $LiTaO_3$ material [13, 14] which has recently been demonstrated to exhibit much weaker GRIIRA effects. This should allow long-term operation of such crystals in a parametric generator, even at higher power levels where the conversion efficiency would be greater. As these crystals also have a higher photorefractive damage threshold, even room temperature operation may be possible.

3. Fibre-feedback OPO

The availability of high parametric gain in periodically-poled crystals pumped by high-power mode-locked lasers has also allowed demonstration of the fibre-feedback OPO. In this novel type of synchronously pumped OPO, a single-mode fibre represents most of the OPO cavity length. The incorporation of a fibre into a cavity containing bulk components will, in general, introduce substantial losses, mainly at the fibre launch. Nevertheless, a high power conversion efficiency can be achieved if a large parametric gain is available and most of the power of the resonant wave is coupled out directly after the nonlinear crystal. Other intracavity losses then affect only a small portion of the generated power. Because of the feedback, the required gain in a fibre-feedback OPO is significantly lower than the gain needed for an OPG, so the intensities in the crystal can be reduced well below the damage threshold.

We compare two fibre-feedback OPO systems, working in the picosecond and femtosecond regimes. Both systems generate multi-watt average signal output powers around 1.5 μm.

Femtosecond fibre-feedback OPO

In this section, we briefly summarize the results obtained from the first fibre-feedback OPO [3], operating in the femtosecond regime. This OPO is based on a 22 mm long uncoated PPLT crystal, pumped with up to 8.2 W average power at 1030 nm from the passively mode-locked Yb:YAG thin disk laser presented in section 2.

The set-up of this system is shown in figure 5. After passing through an optical isolator and a variable attenuator, the pump beam is focused with a curved mirror (M_1) to a waist with a 90 μm radius in the middle of the PPLT crystal. The uncoated crystal is operated at a temperature of $\approx$150 °C to avoid photorefractive damage. Our 0.5 mm thick crystal, fabricated by the same procedure as described for periodic poling of lithium niobate [9], has different grating periods, from 28.3–29 μm, resulting in signal wavelengths between 1429–1473 nm. After the nonlinear crystal, the signal wave is

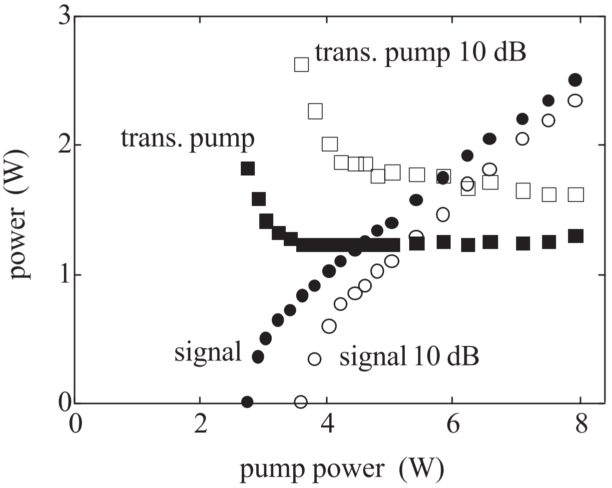

Figure 6. Signal power (full circles) and transmitted pump (full rectangles) versus pump power for a signal wave of 1429 nm (grating period 28.3 μm). Open circles and rectangles are the same but with a 10 dB attenuator in the feedback loop.

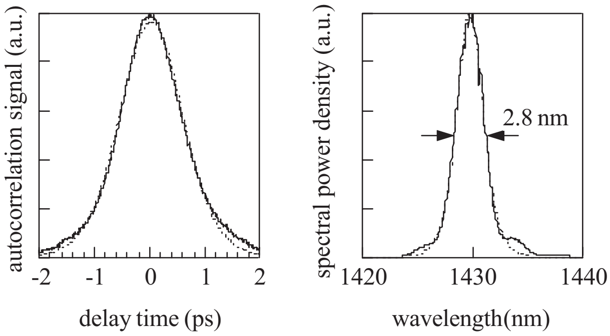

Figure 7. Intensity autocorrelation and optical spectrum of the signal wave (1429 nm) with 2.5 W average power. The FWHM pulse duration $\tau_p = 870$ fs was determined by assuming a sech^2 pulse shape (dotted curve is the fitting function). The time-bandwidth product is 0.36.

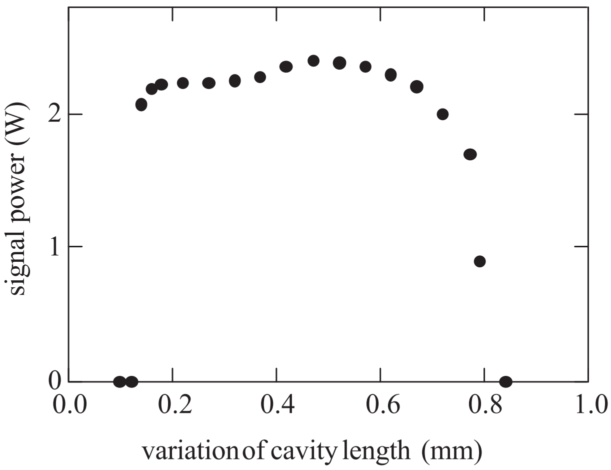

Figure 8. Variation of signal output power with cavity length.

collimated and separated from the pump and idler waves by a combination of three dichroic elements (mirrors M_3 and M_4, filter). An uncoated glass substrate with 82% transmission is used as an output coupler. One of its reflected beams is launched into a 4.6 m long standard telecoms fibre which is single-mode at the signal wavelength (mode field diameter 9.2 μm). The light emerging from the fibre is mode-matched by the lenses f_1 and f_2 and fed back into the crystal through the dichroic mirror M_2, which is highly reflective for the pump wave and transmissive (70%) at the signal wavelength.

The different gratings allow generation of signal output powers between 2.3–2.7 W (measured with a thermal powermeter) for a pump power of 8.2 W incident on the crystal. Figure 6 shows the typical performance for one grating. We would expect to obtain even higher signal output powers, of the order of 4 W, by reducing the losses of several non-optimized optical components. If required, the idler power (expected to be 1.0–1.1 W in the range 3425–3670 nm in the present experiment) could be extracted through an optimized mirror M_3.

A notable feature of the fibre-feedback OPO, which results from the high gain and strong output coupling, is the insensitivity of the performance to cavity losses; the maximum output power is reduced by only 6% if an additional filter with 10 dB loss at the signal wavelength is inserted at the fibre launch between the glass substrate and lens f_3 (figure 5). Obviously there is no critical need to minimize the losses in the feedback loop after the output coupling (lenses f_1–f_3 were uncoated and the polarization of the signal light emerging from the fibre was not controlled).

For a signal wavelength of 1429 nm and an output power of 1 W, the M^2 value was 1.2 in the tangential and 1.3 in the sagittal direction (the M^2 value of the pump beam was 1.1). For a 2.5 W signal power, the M^2 value increased to 2.5 (tangential) and 2.2 (sagittal direction). There might be a significant contribution to this beam quality degradation arising from thermally-induced bulging of various non-optimized substrates (mirrors M_3 and M_4, and the filter) which are heated by idler absorption.

For all poled channels and pump powers, the FWHM pulse duration, measured with an autocorrelator (assuming a sech^2 pulse shape), is typically around 700–900 fs. The spectral width is around 3–4 nm (FWHM), leading to a time-bandwidth product of 0.36–0.53. For 2.5 W signal power at 1429 nm (grating period 28.3 μm), we obtain 870 fs pulses with a spectral width of 2.8 nm, leading to a time-bandwidth product of 0.36 (figure 7), which is not far from the Fourier limit.

Despite the short pulse duration, the adjustment of the fibre-feedback OPO cavity length is not critical because of the high parametric gain. For example, even if only the leading edge of a signal pulse is temporally overlapped with the pump pulse in the crystal, the high parametric gain still allows for efficient energy extraction. Also note that nonlinear effects and dispersion in the fibre can lead to a substantial temporal broadening of the seed pulses. Figure 7 shows that varying the round-trip length of the resonator over a range of 0.5 mm (corresponding to more than one FWHM pulse width) led to an output power reduction of less than 10%. Within this range, the pulse duration did not change significantly. The central wavelength of the optical spectrum changed by less than 0.5 nm, the bandwidth by less than 0.3 nm. The operation of the fibre-feedback OPO system is stable over hours, and no signs of crystal damage were observed during all experiments.

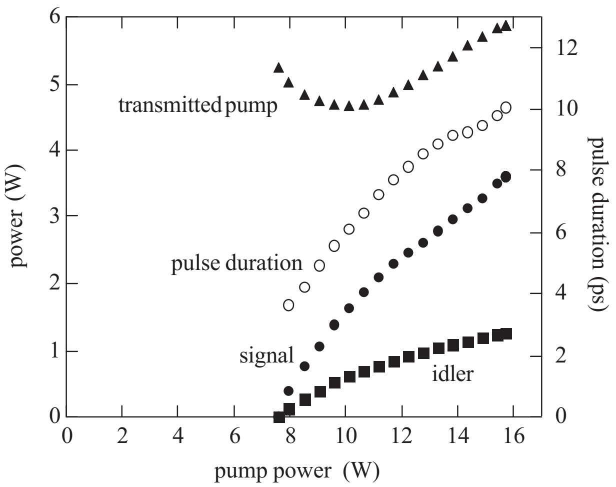

Figure 9. Variation of signal power (full circles), idler power (full rectangles), transmitted pump power (full triangles), and signal pulse duration (open circles, right axis) versus pump power for a signal wave of 1545 nm (grating period 29.5 μm). The FWHM pulse duration was determined by assuming a sech^2 pulse shape.

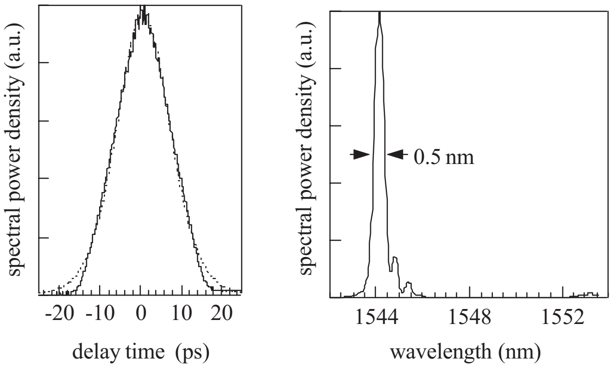

Figure 10. Intensity autocorrelation and optical spectrum of the signal wave (1545 nm) with 3.6 W average power. The FWHM pulse duration $\tau_p = 10$ ps was determined by assuming a sech^2 pulse shape (dotted curve is the fitting function). The time-bandwidth product is 0.63.

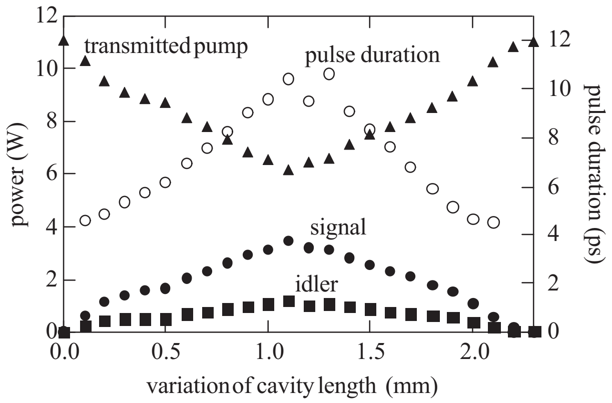

Figure 11. Signal power (full circles), idler power (full rectangles), transmitted pump power (full triangles), and signal pulse duration (open circles, right axis) versus variation of the cavity length for a signal wave of 1545 nm (grating period 29.5 μm). The FWHM pulse duration was determined by assuming a sech^2 pulse shape.

Picosecond fibre-feedback OPO

The second fibre-feedback OPO, working in the picosecond regime, is pumped with a passively mode-locked Nd:YAG laser with up to 17 W of average power at 1064 nm. The laser is a modified version of the laser described in [6], with two rather than three laser heads. The pump pulse duration is 16 ps at a repetition rate of 59 MHz.

The OPO set-up is similar to the set-up of the femtosecond system (figure 5), but instead of separating the signal wave with two dichroic mirrors (M_3, M_4) and a filter, we use three dichroic mirrors, which enable us to extract the idler power. As a nonlinear medium, we use an uncoated, 19 mm long and 0.5 mm thick multi-grating PPLN crystal (from Crystal Technology, Inc), which was again operated at 150 °C to prevent photorefractive damage. The pump mode radius was 40 μm, and the parametric gain with 17 W incident on the crystal (14.5 W in the crystal) is estimated to be ~50 dB.

We use seven gratings with a transverse width of 1.2 mm and poling periods of 28.7–29.9 μm, resulting in signal wavelength of 1485–1585 nm. Feedback is provided through a 2 m long large mode area fibre (effective mode area 311 μm^2) [15]. The uncoated glass substrate, which serves as an output coupler, has a transmission of ~91% (again, one of the two reflected beams is launched into the fibre).

The different gratings permit generation of 3.7–4.4 W of average signal output power for a pump power of up to 18 W incident on the crystal. Due to some degradation of the laser (probably related to the pump diodes), we used a maximum pump power of 16 W in most experiments. Figure 9 shows the typical performance for the grating with a 29.5 μm poling period (for a signal wavelength around 1545 nm). The autocorrelation and optical spectrum for the highest signal power are shown in figure 10. Note that the slight modulation on the autocorrelation results from beating with a weak longer wavelength component at ≈1553 nm, which occurs only for the highest pump power and in a small range of cavity length adjustments (see below). When the pump power is ramped up, the signal pulse duration changes from 3.6 ps near threshold to 10 ps at full power, and particularly for lower pump powers the autocorrelation is well fitted assuming a sech^2 pulse shape. The centre wavelength of the signal steadily changes from 1545.5 nm to 1544 nm, and the pulse bandwidth decreases from 1 nm to 0.5 nm.

We measured the beam quality factor M^2 of the signal output for the maximum signal power of 3.7 W (at 16 W pump power) with two different gratings and obtained values below 1.2 for both the horizontal and vertical direction. The overall performance is very similar for the different gratings, except for the signal and idler wavelengths.

When we inserted a filter with a 10 dB attenuation before or after the fibre, the signal output power at full pump power dropped from 3.6 W to 3.1 W, i.e. by 15%. This effect is somewhat stronger than for the femtosecond OPO, because the parametric gain is smaller. At full pump power, the OPO could typically be operated over a range of cavity lengths covering ≈2 mm. Roughly in the middle of this range, the maximum signal and idler power is obtained, and the pulse duration also reaches its maximum value. Close to this optimum, there is a narrow region of cavity lengths for which the signal and idler output powers drop by a few per cent and the signal spectrum

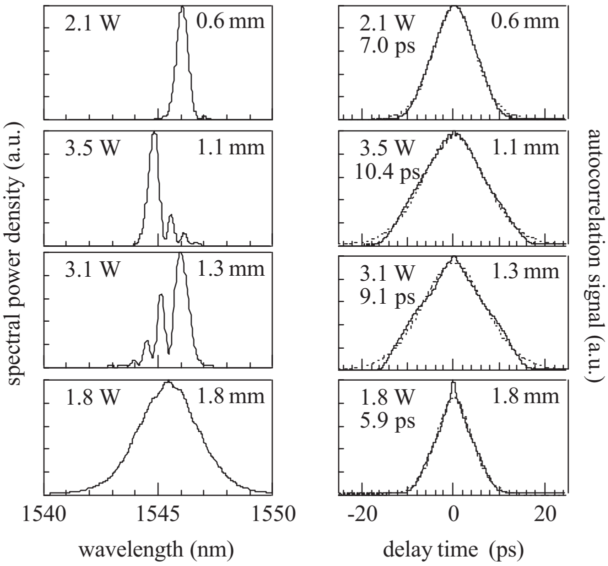

Figure 12. Signal spectral power density and intensity autocorrelation for four different cavity length variations. The average signal power is indicated in the upper left corner, the relative cavity length is shown in the upper right corner. The FWHM pulse duration was determined by assuming a sech^2 pulse shape and is also shown in the upper left corner of the autocorrelation.

exhibits significantly stronger side peaks than normal. For a slightly shorter cavity length, these side peaks occur at longer wavelengths, and for longer cavity at shorter wavelengths (see figure 12). On the side corresponding to short cavity lengths, the pulses are close to bandwidth-limited, while on the side of longer cavities the spectra are broader.

Comparison of picosecond and femtosecond OPO

Although the set-ups of the picosecond and the femtosecond OPOs are very similar, the operating characteristics are quite different in some respects. The first aspect concerns the insensitivity of both systems to cavity length adjustments. For the femtosecond OPO, the allowed range of cavity lengths is 0.5 mm wide, which corresponds to about twice the FWHM signal pulse width at full power. This remarkable insensitivity mainly results from the very high parametric gain, which allows efficient energy extraction even if only the far wing of the seed pulse overlaps with the pump pulse. Also note that the signal pulse experiences significant nonlinearity and dispersion in the fibre, so that the seed pulse may be temporally broadened.

For the picosecond OPO, the parametric gain is roughly 30 dB lower (due to the lower peak pump power), and the effects of fibre nonlinearity and dispersion are very weak. For these reasons, the allowed range of cavity lengths (2 mm) is shorter than the FWHM spatial length of the signal output pulse (3 mm). Therefore, the sensitivity of the femtosecond OPO to cavity length changes is not much stronger than for the picosecond OPO, particularly if one takes into account the fact that the signal output power was nearly constant within the 0.5 mm wide range.

Another important aspect concerns the phase-matching bandwidth. In the case of the femtosecond OPO, the bandwidth is just enough to allow for a signal pulse bandwidth of up to a few nanometres. This effect limits the signal bandwidth and also prevents any changes of the signal wavelength when the cavity length is changed. On the other hand, the short pump pulse creates only a short time window with gain, which limits the signal pulse duration. (Note that, in this high-gain situation, significant energy transfer occurs only over a part of the crystal length, within which the pump/signal group delay difference mismatch is not significant.) As both bandwidth and duration are limited, we always obtain close to bandwidth-limited pulses.

In the picosecond OPO, the phase-matching bandwidth was somewhat wider (mainly because of the longer signal wavelengths and the slightly shorter crystal), while the pulse bandwidth is significantly smaller ($\approx$0.5 nm at full power). Therefore, the phase-matching bandwidth is not a limiting factor in this case, and changes of signal wavelength and output bandwidth are possible.

4. Summary

We have presented three different parametric systems for ultrashort pulse generation in the spectral range around 1.5 μm. The first system is a parametric generator (OPG) based on a PPLN crystal which is directly pumped with a mode-locked high-power laser at the full laser repetition rate. From this extremely simple tunable wavelength converter for ultrashort pulses we obtained up to 0.5 W of signal average output power in 300 fs pulses, the maximum achievable power being limited by crystal damage. We envisage that the damage problem may soon be eliminated by the use of stoichiometric PPLN or PPLT crystals [13, 14].

We have also demonstrated two different synchronously pumped parametric oscillators, where the feedback is provided through a single-mode fibre. These devices have generated multi-watt signal average powers around 1.5 μm, with 700–900 fs signal pulse duration in one case and up to 10 ps in the other. Operation is stable over hours, and crystal damage is not observed. These fibre-feedback OPOs have a number of attractive features, including a compact and stable set-up and an unusually small sensitivity for cavity losses, so that the demands on the quality of the optical components are rather low. Even with uncoated nonlinear crystals we obtained a respectable efficiency. Furthermore, the femtosecond OPO is unusually insensitive to changes of the cavity length, so that, in contrast to other femtosecond OPOs, an active stabilization is not required.

As the thin disk pump lasers appear to be power-scalable [7], we expect to generate significantly higher signal and idler powers in the near future. Such sources are attractive for a number of interesting applications.

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