High-power femtosecond fiber-feedback optical parametric oscillator based on periodically poled stoichiometric $LiTaO_3$

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We demonstrate a synchronously pumped high-gain optical parametric oscillator with feedback through a fiber, using a passively mode-locked Yb:YAG thin-disk laser as a pump source. We obtain as much as 19-W average signal power at a wavelength of 1.45 μm in 840-fs pulses and 7.8 W of idler power at 3.57 μm. The repetition rate of the pulses is 56 MHz, and the transverse beam quality of the generated signal is $M^2 < 1.6$. © 2004 Optical Society of America

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During the past few years, enormous progress has been achieved in the development of high-average-power femtosecond laser systems. Numerous ultrafast systems operating with different gain materials were demonstrated, hugely extending the range of accessible wavelengths. Also, substantial progress has been achieved in the scaling of the average output power. To date, up to 77 W of average power can be directly obtained from a passively mode-locked laser[1,2] and up to 76 W from a fiber-based chirped-pulse amplification system.[3] However, the available laser gain materials for high-average-power (>10-W) femtosecond operation strongly limit the obtainable range of wavelengths: so far such sources have operated only near a wavelength of 1 μm. Synchronously pumped optical parametric oscillators (OPOs) can overcome these limitations, allowing the generation of tunable ultrashort pulses at different wavelengths, which are required for many applications, such as large-scale RGB laser display systems.[4] Recently, Südmeyer *et al.* demonstrated what is believed to be the first fiber-feedback OPO, a novel type of synchronously pumped OPO.[5] In this device a single-mode fiber represents most of the OPO cavity length. Although the fiber feedback introduces substantial losses (mainly at the fiber launch), high conversion efficiency can be achieved by employment of a high parametric gain and strong output coupling directly after the nonlinear crystal. Additional intracavity losses then only weakly influence the generated power. This concept led to compact, stable, and efficient systems in the femtosecond and picosecond regimes.[6] The femtosecond versions are unusually insensitive to drifts of the OPO cavity length and do not require active stabilization. In this Letter we present a high-power version of the fiber-feedback OPO that generates femtosecond pulses with what is believed to be a record high 19-W average output power in the 1.5-μm spectral region. This output power was achieved by combination of a high-power mode-locked Yb:YAG thin-disk laser[7] with a periodically poled stoichiometric $LiTaO_3$ crystal (PPSLT). Compared with standard congruent crystals, PPSLT exhibits high photorefractive damage resistance and negligibly small green-induced infrared absorption.[8] Also, it has a low coercive field, which allows one to pole thicker samples,[9] so there is a potential for operating similar devices at much higher power levels with increased mode areas.

The fiber-feedback OPO (Fig. 1) is based on a 17.5-mm-long PPSLT crystal pumped with up to 58 W at 1030 nm from a passively mode-locked thin-disk Yb:YAG laser, which is a modified version of the one described in Ref. 1. It generates up to 68 W in

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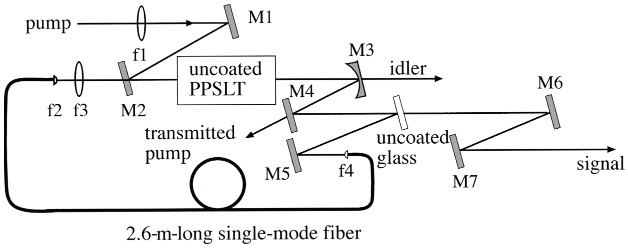

Fig. 1. Setup of the OPO ring cavity: M1–M7, mirrors; f1–f4, lenses.

780-fs pulses at a pulse repetition rate of 56 MHz. The pump beam radius inside the 1-mm-thick PPSLT crystal is 160 μm in the horizontal and 130 μm in the vertical direction. The calculated parametric gain is ≈60 dB. The crystal is operated at ≈150 °C to avoid photorefractive damage. The poling period is 29 μm, leading to a signal wavelength of 1.45 μm (for 150 °C). For simplicity we used an uncoated crystal and accepted the relatively high reflection losses (≈13% per surface). The different wavelength components are separated with dichroic mirrors (M3–M7). The power levels of the remaining pump and idler waves were slightly corrected for transmission losses in the dichroic mirrors (transmission of idler mirror M3, 95%; transmission of residual pump mirror M4, 94.5%). Only a weak reflection (≈4% of the power) from an uncoated glass substrate is used for the signal feedback, while the transmission (≈92%) of this glass substrate represents the signal output. The feedback light at ≈1.45 μm is launched into a 2.6-m-long large-mode-area fiber[10] that is single mode at the signal wavelength (mode area in the fiber, 436 μm^2). The dispersion of the fiber is determined mainly by the material dispersion of fused silica; the zero-dispersion wavelength is ≈1.3 μm. The light emerging from the fiber is mode matched with lenses f2 and f3 and fed back into the crystal through dichroic mirror M2, which is highly reflective for the pump wave and is transmissive at the signal wavelength. The repetition rate of the OPO cavity is matched to the pump laser. The propagation in the fiber corresponds to ~71% of the total optical path for one round trip.

We obtained up to 19 W of average signal power at 1.45 μm for a pump power of 58 W incident on the crystal (Fig. 2). We would expect to obtain even higher signal powers by reducing the losses of several nonoptimized optical components. In particular, an antireflection coating on the PPSLT crystal would greatly reduce the losses; it would basically remove ≈13% of pump losses at the crystal input face and a similar amount of signal loss at the exit face. Also, the transmission of the output coupler could be optimized. In addition, we would expect to obtain wavelength tuning by changing the operating temperature of the PPSLT crystal in a certain wavelength range. The change in wavelength at the operating point of the OPO would be 0.23 nm/K.

The duration of the signal pulses was measured by intensity autocorrelation. Assuming a sech^2 pulse shape, the pulse duration (FWHM) is typically near 840 fs (Fig. 3). The width of the optical spectrum (Fig. 4) is approximately 3.3 nm (FWHM), leading to a time–bandwidth product of ≈0.4.

One of the main advantages of such a fiber-feedback OPO is the unusual insensitivity to adjustment of the cavity length: the cavity length can be varied over a range of 0.4 mm (corresponding to more than one pulse width), while the output power is reduced by only less than 10% (Fig. 5). Over this range, the central wavelength changes only slightly from 1447.9 nm

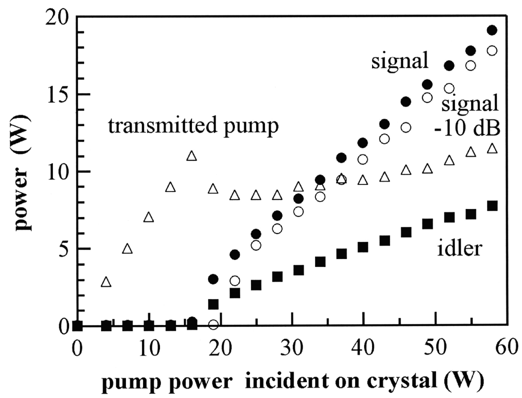

Fig. 2. Signal power without attenuator (filled circles), signal power with additional 10-dB attenuator (open circles), idler power (filled rectangles), and power of the transmitted pump (open triangles) versus pump power.

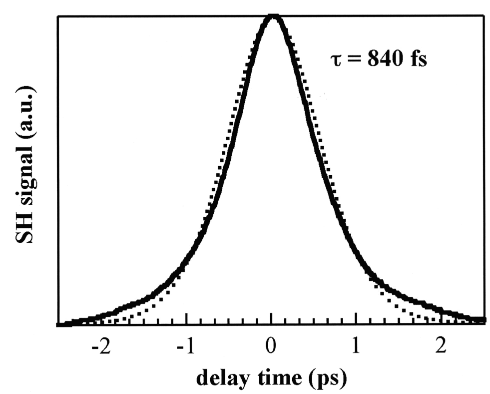

Fig. 3. Measured intensity autocorrelation (solid line) of the signal wave with 19-W average power. The dashed curve represents the sech^2 fit with a pulse duration of 840 fs. SH, second harmonic.

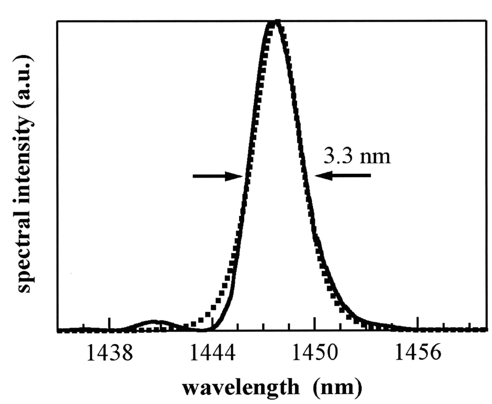

Fig. 4. Optical spectrum of the signal wave with 19-W average power.

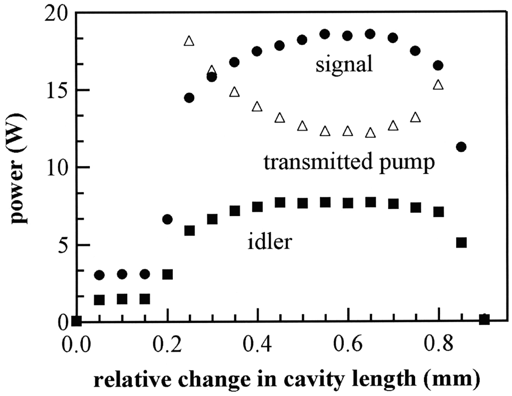

Fig. 5. Average output power of the signal (filled circles), idler (filled rectangles), and transmitted pump (open triangles) as functions of the relative change of the cavity length.

for a shorter cavity to 1447.5 nm for a longer cavity (with a FWHM bandwidth varying in the range 3.3–3.8 nm). The pulse duration changes from 650 fs (for a shorter cavity) to 940 fs. Therefore, stable operation over hours is achieved without the need for active cavity length stabilization. In addition, the fiber-feedback OPO is very insensitive to cavity losses in the feedback loop: when an additional attenuator with 10-dB loss was inserted in front of the fiber launch (between M5 and f4), the maximum signal output power was reduced by less than 5%.

Note that the phase-matching bandwidth of the crystal is significantly smaller than the pulse bandwidth. This, however, poses no problem in the high-gain regime, where even a temporally stretched signal pulse is compressed again by the action of the temporally limited gain. Also, note that the small phase-matching bandwidth explains the weak dependence of the signal wavelength on the cavity length.

Recently we found that high-gain OPOs operated with very high peak powers and high conversion efficiency cannot provide a perfect transverse beam quality of the output beams.[11] This is because gain guiding leads to a reduced mode size of the signal beam near the end of the crystal, where most of the power conversion occurs. The small signal beam area results in backconversion occurring in the center of the transverse profile in situations with strong saturation, as is necessary for good conversion. The OPO described here is already operating in this regime. Nevertheless, the transverse beam quality factor M^2 of the signal beam has been measured to be <1.6 at full power, i.e., not too far from the diffraction limit. For a reduced pump power of 37 W and 10.5 W of signal output power, we measured the M^2 value to be below 1.3.

After the fiber of the feedback loop, the average power of the fed-back signal was measured to be 90 mW at full power. This leads to only moderate nonlinear phase shifts in the large-mode-area fiber. With a standard telecom fiber we would expect significant nonlinear phase shifts, but numerical simulations indicated no strong effect of these phase shifts on the OPO performance.

In conclusion, we have demonstrated a fiber-feedback OPO with an unprecedented signal average output power of 19 W in 840-fs pulses in the 1.5-μm spectral region. This OPO also generates an idler average output power of 7.8 W at a wavelength of 3.57 μm. With an antireflection-coated OPO crystal, significantly higher powers would be expected.

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