Femtosecond fiber-feedback optical parametric oscillator

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We demonstrate what is to our knowledge the first synchronously pumped high-gain optical parametric oscillator (OPO) with feedback through a single-mode fiber. This device generates 2.3–2.7 W of signal power in 700–900-fs pulses tunable in a wavelength range from 1429 to 1473 nm. The necessary high gain was obtained from a periodically poled $LiTaO_3$ crystal pumped with as much as 8.2 W of power at 1030 nm from a passively mode-locked Yb:YAG laser with 600-fs pulse duration and a 35-MHz repetition rate. The fiber-feedback OPO setup is compact because most of the resonator feedback path consists of a standard telecom fiber. Because of the high parametric gain, the fiber-feedback OPO is highly insensitive to intracavity losses. For the same reason, the synchronization of the cavity with the pump laser is not critical, so active stabilization of the cavity length is not required. © 2001 Optical Society of America

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Synchronously pumped optical parametric oscillators (OPO's) are interesting sources of broadly wavelength-tunable ultrashort pulses as required for many applications. Recently it was demonstrated[1] that power-scalable diode-pumped thin disk lasers[2] can be passively mode locked with a semiconductor saturable-absorber mirror.[3,4] Such mirrors generate multiwatt average output powers, even in the subpicosecond domain. In this Letter we show that the combination of such a pump laser with a fiber-feedback OPO, a novel type of synchronously pumped OPO in which a single-mode fiber represents most of the cavity length, results in a system with a number of attractive features. Our concept has led to a stable and compact OPO setup that is unusually insensitive to intracavity losses and drifts of the OPO cavity length. Even with nonoptimal optical components, we obtained as much as 2.7 W of average power in 900-fs pulses tunable around 1.45 μm. In contrast to many other OPO's in this pulse duration regime, the fiber-feedback OPO does not need active stabilization of the cavity length.

The incorporation of a fiber into a cavity that contains bulk components will, in general, introduce substantial losses, mainly at the fiber launch. Nevertheless, 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. We achieved a small-signal gain of the order of 90 dB by applying a high average pump power of as much as 8.2 W to a periodically poled $LiTaO_3$ (PPLT) crystal, which has a relatively high nonlinearity [$d_{\mathrm{eff}} \approx 9$ pm/V (Ref. 5)]. The Yb:YAG pump laser is slightly modified from that described in Ref. 1, generating pulses with a duration of 0.6 ps at a repetition rate of 35 MHz and delivering as much as $\approx$11 W of average power.

After passing an isolator and an attenuator, the pump beam is focused with a curved mirror (M_1) to a waist with 90-μm radius in the middle of the PPLT crystal (Fig. 1). The 22-mm long, uncoated crystal is operated at a temperature of $\approx$150 °C to prevent photorefractive damage. The OPO signal wavelength depends on the period of the poling pattern and the crystal temperature. Our 0.5-mm-thick crystal, fabricated by the same procedure as described for periodic poling of $LiNbO_3$,[6] has eight poled regions of transverse width 1.2 mm with different grating periods of 28.3–29 μm, resulting in signal wavelengths of 1429–1473 nm (for 150 °C crystal temperature). After the nonlinear crystal, the signal wave is collimated and separated from the pump and idler waves by a combination of three dichroic elements (mirrors M_3 and M_4 and a filter). One of the two reflected beams from an uncoated glass substrate is used for the signal feedback; the transmission of 82% represents the signal output. The feedback light at $\approx$1.45 μm is launched into a 4.6-m-long standard telecom fiber, which is single mode at the signal wavelength. The light emerging from the fiber is mode matched by lenses f_1 and f_2 and fed back into the crystal through dichroic mirror M_2, which is highly reflective for the pump wave and is transmissive (70%) at the signal wavelength.

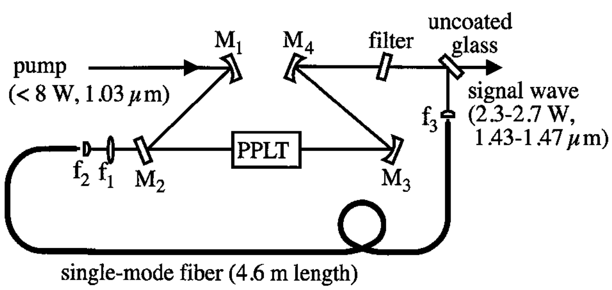

Fig. 1. Setup of the OPO ring cavity.

The different gratings permit generation of signal power output of 2.3–2.7 W (measured with a thermal powermeter) for a pump power of 8.2 W incident upon the crystal. Figure 2 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 nonoptimal optical components (filter, 5%; glass substrate, one 9% reflection suppressed; 15% at uncoated end faces of the PPLT crystal). The internal pump depletion is as much as ≈80% at full power. If required, an idler power (expected to be 1.0–1.1 W in the present experiment) in the range 3425–3670 nm could be extracted through an optimized mirror, M_3.

A notable feature of the fiber-feedback OPO, which results from the high gain and the strong output coupling, is the insensitivity of its 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 fiber launch between the glass substrate and lens f_3 (Fig. 1). Obviously it is not necessary 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 fiber 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 2.5-W signal power, the M^2 value increased to 2.5 in the tangential direction and 2.2 in the sagittal direction. A significant contribution to this beam quality degradation might arise from thermally induced bulging of various nonoptimal substrates (mirrors M_3 and M_4 and the filter) that are heated by idler absorption.

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

Despite the short pulse duration, adjustment of the fiber-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 temporally overlaps the pump pulse in the crystal, the high parametric gain still allows for efficient energy extraction. Also note that nonlinear effects in the fiber can lead to a substantial temporal broadening of the seed pulses. Figure 4 shows that varying the round-trip length of the resonator over a 0.5-mm range (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 less than 0.5 nm; the bandwidth, less than 0.3 nm. The operation of the fiber-feedback OPO system is stable over hours, and no signs of crystal damage were observed during all experiments.

Note that the signal pulse energy in the fiber is ~2 orders of magnitude higher than the soliton energy. As a result, we expect the temporal and spectral shape of the pulses after the fiber to be significantly distorted. Nevertheless we obtained near-bandwidth-limited output signal pulses because the short pump pulses create only a narrow time window for

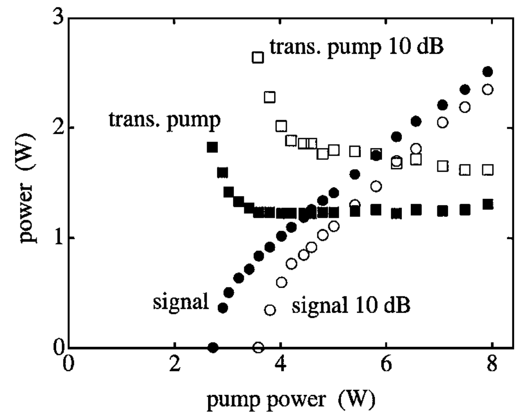

Fig. 2. Signal power (filled circles) and transmitted (trans.) pump (filled rectangles) versus pump power for a signal wave of 1429 nm (28.3-μm grating period). Open circles and rectangles, the same, with a 10-dB attenuator in the feedback loop.

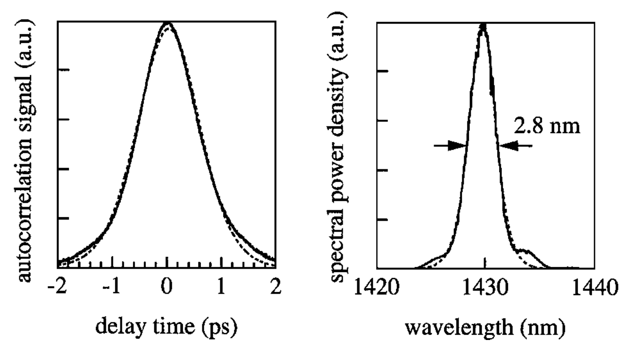

Fig. 3. Intensity autocorrelation and optical spectrum of the signal wave (1429 nm) with 2.5 W of average power. We determined the FWHM pulse duration, $\tau_p = 870$ fs, by assuming a sech^2 pulse shape (dashed curves, fitting function). The time–bandwidth product is 0.36.

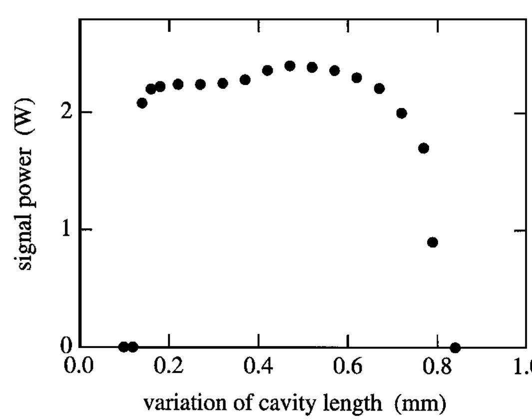

Fig. 4. Variation of signal output power with cavity length.

gain and the output spectral width is limited by the phase-matching bandwidth.

In conclusion, we have demonstrated a novel type of synchronously pumped OPO that is based on feedback through a single-mode fiber. This fiber-feedback OPO concept results in a powerful and efficient, compact and stable source of tunable subpicosecond pulses. A crucial point is the use of a high parametric gain and strong output coupling, which became possible by combination of high pump intensity and a crystal with high nonlinearity. Using nonoptimal components, we obtained as much as 2.7 W of signal power in subpicosecond pulses at a wavelength of 1429–1473 nm. Unlike for other subpicosecond OPO's, here the adjustment of the OPO cavity length is not critical (within a range of 0.5 mm). The operation is stable over hours. Also, the performance is insensitive to additional cavity losses.

In the near future we expect to generate other signal and idler wavelengths (e.g., signal wavelengths of $\sim 1.55\ \mu$m) by modifying the quasi-phase-matching period. Also, we plan to use fibers with greatly increased mode areas[7] to exploit soliton formation in the fiber. Signal pulses much shorter than the pump pulses and thus increased output peak powers, as previously reported,[8] should be achievable with a fiber-feedback OPO. We also envisage the generation of significantly higher signal and idler average powers because our pump source, a passively mode-locked Yb:YAG thin disk laser, is based on a power-scalable concept.

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