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A narrow-bandwidth optical parametric oscillator

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Abstract

A narrow-bandwidth, singly resonant, picosecond optical parametric oscillator based on a non-critical phase-matched lithium triborate crystal and synchronously pumped by the second-harmonic of a Nd:YLF laser mode-locked at 76 MHz is described. An intracavity birefringent filter reduces the spectral bandwidth and allows fast scanning of the output wavelength within the phase-matched bandwidth. A signal output of 1.6 W in Fourier transform limited pulses with a duration of 22 ps and a bandwidth of 0.06 nm has been obtained. The signal and idler wavelengths were tunable from 750 to 930 nm and from 1220 to 1770 nm, respectively. © 1998 Elsevier Science B.V. All rights reserved.

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Optical parametric oscillation (OPO) is an efficient technique to obtain laser emission with a broad tunability and very high conversion rates [1]. The bandwidth of the OPO output results from the phase-matching conditions for the parametric process and the presence of wavelength selective devices in the cavity. Introduction of a grating allows for very narrow-bandwidth output of the OPO. A disadvantage of a grating is that high losses are introduced in the cavity. As a result high demands are placed on the gain of the parametric process. Sufficient gain can easily be achieved in Q-switched [2] and Q-switched and mode-locked [3] operation but is not straightforward in only mode-locked operation. Mode-locked operation is favorable for applications where low-energy pulses are desired with still adequate peak powers.

Synchronously pumped systems based on potassium titanyl phosphate (KTP) and its isomorphs [4–7], β-barium borate (BBO) [8], and lithium triborate (LBO) [9–12] crystals have been developed. The pulse duration of the pump laser pulses varied from a few picoseconds down to a few tens of femtoseconds. Fourier transform limited pulses were obtained in all of these systems. Obviously, these short pulses lead to broad bandwidths. Generation of narrow-bandwidth pulses can be performed using lasers with a pulse length of a few tens of picoseconds. However, these pulses have relatively low peak intensities. Therefore, tightly focused beams and long interaction lengths are needed to obtain enough gain. This can be achieved by using a temperature-tuned, non-critical phase-matching (NCPM), non-linear crystal like LBO. Besides its ability of NCPM over a wide frequency range, LBO has a very high damage threshold and a low group velocity walk-off among the interacting fields which allows the use of long crystals.

In this Letter we present the first synchronously pumped, narrow-bandwidth, 76 MHz repetition rate OPO based on a LBO crystal and a birefringent filter.

The experimental layout of the OPO is depicted in Fig. 1. The pump source was a mode-locked Nd:YLF laser (Antares, Coherent Inc.). It generated 18 W in 50 ps pulses at 1.053 μm with a repetition frequency of 76 MHz. Second harmonic generation in a LBO crystal yielded an average output power of 5.6 W at 527 nm in 35 ps pulses.

The OPO cavity was singly resonant for the signal wave. The cavity was formed by two concave mirrors, two flat mirrors, and a plane output coupler (OC). The mirrors were highly reflecting ($R > 99.9\%$) over the range from 750 to 930 nm. The transmission at 527 nm was higher than 98%. Two output couplers with a transmission of

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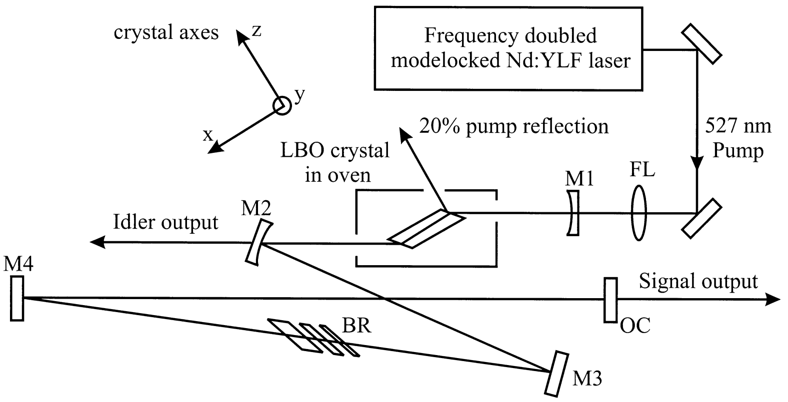

Fig. 1. Schematic of the narrow bandwidth OPO. FL: focusing lens 200 mm; M1: 100 mm ROC; M2: 250 mm ROC; M3, M4: flat; OC: 9% output coupler; BR: birefringent filter.

~ 9% were used to cover the spectral range from 750 to 930 nm. The output coupler was placed on a precision translation stage with a motor-controlled micrometer and a piezoelectric transducer for coarse and fine adjustments of the cavity length.

The LBO crystal (Casix Inc.) placed in a temperature-controlled oven was located at the intracavity focus between the two concave mirrors. It was Brewster-angled and cut for NCPM type I ($e \rightarrow o + o$) in the xy plane ($\theta = 90°$ and $\phi = 0°$). The signal and idler beams were polarized along the z-axis and the pump beam was polarized along the y-axis of the crystal. The three beams propagated in the x direction. The crystal dimensions were $3 \times 6 \times 30$ mm^3 ($y \times z \times x$) and its temperature could be varied between ambient temperature and 200°C with stability of better than 0.1°C.

The angle of incidence on the center concave mirror was 18° to compensate for the astigmatism introduced into the resonator by the brewster-angled LBO crystal [13]. The calculated waist radius of the resonated signal wave was 33 μm in the z direction and 53 μm in the y direction. The pump beam was focused into the crystal with a lens ($f = 200$ mm) through the input concave mirror to a radius of 26×42 μm ($z \times y$ direction), which corresponds to a optimum focusing configuration. This optimum was determined by evaluating the focusing parameters in case of elliptical beam profiles [14]. The signal bandwidth was reduced by a three-plate birefringent filter placed inside the cavity.

The threshold for oscillation was found to be 1.75 W of average power incident on the LBO crystal at a resonator wavelength of 792 nm. Inside the crystal this corresponds to an average power of 1.4 W and a peak intensity of 15 MW/cm^2. With a pump power of 4 W inside the crystal a signal output of 1.6 W was obtained corresponding to a conversion efficiency of 40% at the signal frequency only. The average signal output power remains approximately constant over the major part of the tuning range, as shown in Fig. 2. The idler was tunable between 1220 and 1770 nm with an average power of about 800 mW. The total power conversion including both the signal and idler is better than 55%. Tuning of the frequency was accomplished by adjusting the crystal temperature between 116 and 156°C and simultaneous rotation of the birefringent filter around its axis.

The pulse duration and bandwidth of the signal output were measured, respectively, with a second-order intensity autocorrelator and a Fabry-Perot spectrometer with a free spectral range (fsr) of 0.32 nm and a finesse of 150. The results are shown in Fig. 3a, 3b at a signal wavelength of 792 nm. The trace of the intensity autocorrelation fits well a Gaussian profile with a full width half maximum

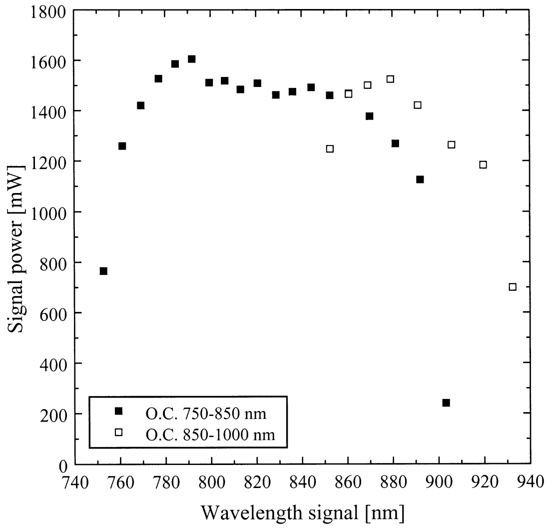

Fig. 2. The average signal output power as function of the frequency for the OPO. Two different output couplers were used to cover the whole spectral range.

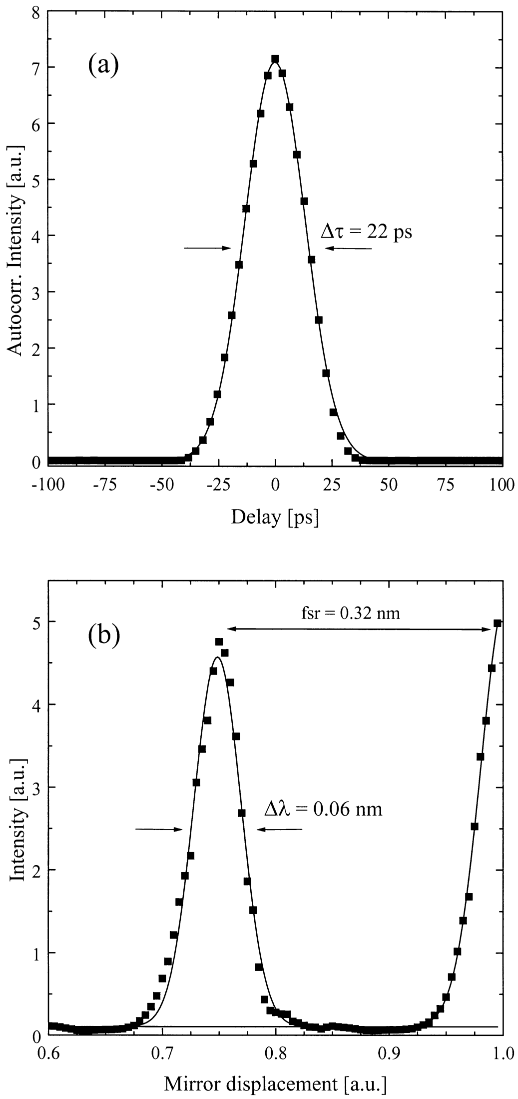

Fig. 3. (a) Intensity autocorrelation and (b) corresponding Fabry-Perot spectrum of the signal output at 792 nm. The deconvoluted pulse width is 22 ps and the spectral bandwidth is 0.06 nm.

(FWHM) of 26 ps corresponding to a deconvoluted pulse duration of 22 ps. The spectral width was measured to be 0.06 nm FWHM. This gives time–bandwidth product of 0.63 for these signal pulses which is 1.4 times the Fourier transform limit for Gaussian profiles [15].

The signal wavelength was tunable by changing the angle of the birefringent filter only. The observed FWHM spectral scanning range was 4.3 nm at 792 nm and 5.4 nm at 853 nm. These values are in good agreement with the calculated spectral bandwidth obtained with the Sellmeier equations for LBO given by Lin et al. [16]. The birefringent filter gives the opportunity of quickly scanning the OPO output wavelength in a moderate tuning range without changing the crystal temperature. The scanning velocity only depends on the rotation speed of the birefringent filter. Therefore, although NCPM is used the scanning speed is the same as in the case of critical phase-matching. Another advantage of the birefringent filter is the very high spectral stability, because the oscillation frequency is fixed by its orientation. No influence of small mechanical vibrations and temperature disturbances on the output frequency were observed [17].

In conclusion, we have demonstrated a highly efficient, widely tunable, narrow-bandwidth OPO synchronously pumped by mode-locked pulses. Tunable signal output over the range from 750 to 930 nm with up to 1.6 W average power in 22 ps pulses was obtained. With the use of a birefringent filter the spectral bandwidth was 0.06 nm and fast scanning is possible within the phase-matched bandwidth of the non-linear crystal by rotating the filter only. The combination of a low pulse energy, a high repetition rate, and moderate peak powers make this OPO a suitable source for non-linear spectroscopy such as coherent Raman spectroscopy (CARS and SRS), sum frequency spectroscopy, and two-photon fluorescence microscopy.

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