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Continuous-wave mode-locked singly resonant optical parametric oscillator synchronously pumped by a laser-diode-pumped Nd:YLF laser

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We describe a continuous-wave synchronously pumped, singly resonant, KTP optical parametric oscillator (OPO). The pump source is a frequency-doubled additive-pulse mode-locked Nd:YLF laser pumped by a laser diode. An average pump power threshold of 61 mW is observed for the OPO. At ~3.7 times threshold, the pump depletion is 79%, and the oscillator converts 16% of the pump into external signal output in bandwidth-limited picosecond pulses with 42 mW of average power. The OPO has been tuned over the range of 1.002–1.096 μm.

The wide bandwidth of the parametric interaction in nonlinear crystals makes the synchronously pumped optical parametric oscillator (OPO) potentially the most widely tunable source of ultrashort pulses. Much research has been done on such systems using *Q*-switched mode-locked lasers pumped by flash lamps.[1-3] For practical use, a cw pump source is desirable, so that each pulse in the train is identical. Two cases of cw synchronously pumped OPO's have been reported. Piskarskas *et al.*[4] achieved this using a doubly resonant oscillator, which has the benefit of a much lower threshold than a singly resonant oscillator (SRO). However, the requirement for simultaneous resonance for both of the generated waves places stringent stability requirements on the pump laser and OPO cavities and generally results in poor amplitude and frequency stability. This problem is exacerbated in the case of ultrashort-pulse operation, where material dispersion and birefringence of the nonlinear crystal prevent maintenance of the resonance condition over a wide comb of modes for significantly different signal and idler wavelengths, or group-velocity matching for the signal and idler pulses (round-trip synchronization). By resonating only one of the generated waves in a SRO, the tolerances on the pump laser and OPO cavities can be relaxed, but with typically over an order of magnitude increase in the threshold. The requirements of high enough peak power for operation of a SRO, together with cw pumping, can be met by using ultrashort pulses. Edelstein *et al.*[5] achieved stable, reliable operation of a cw synchronously pumped SRO using a colliding-pulse mode-locked dye laser as the pump source. However, the limited average output power available from such systems necessitated the complicating feature of the OPO's being sited at an intracavity focus so that sufficiently high peak intensities could be attained.

A desirable feature of a practical and reliable system would be the use of laser-diode-pumped sources. To get sufficient peak power for cw synchronous pumping of a SRO from the present generation of mode-locked diode-pumped lasers, somewhat shorter pulses are needed than those typically generated by active mode locking.[6-8] In particular, self-starting additive-pulse mode locking in laser-diode-pumped Nd:YAG and Nd:YLF lasers has resulted in pulse durations as short as 1.5 ps, but at low average power.[9,10] Utilizing the techniques of self-starting additive-pulse mode locking and efficient second-harmonic generation in an external resonant enhancement cavity, we have developed an ultrashort-pulse cw mode-locked source pumped by a diode laser, with sufficiently high peak powers for synchronous pumping of a SRO in an extracavity configuration. Thus we report here what we believe to be the first demonstration of such a device. Pulses of ~1-ps duration tunable over ~90 nm near ~1 μm have been achieved. The stable diffraction-limited and bandwidth-limited performance, with high conversion efficiency, indicates the potential usefulness of such a device.

The laser pump source was a frequency-doubled, self-starting additive-pulse mode-locked Nd:YLF laser pumped by a laser diode. A similar configuration has been described in an earlier study on Nd:YAG.[11] Here, the laser diode was a 3-W AlGaAs array (Spectra Diode Laboratories SDL 2482 P1) temperature tuned to the Nd:YLF absorption at 798 nm. The Nd:YLF rod was oriented for operation at 1047 nm. The 600-mm radius-of-curvature fold mirror was set for astigmatic compensation, and the laser cavity was completed with a plane 17% transmission output coupler.

The external cavity was formed by a 33% reflectivity beam splitter and an ~1.1-m length of single-mode, non-polarization-preserving optical fiber. Coupling of light into the fiber with ~65% efficiency was achieved using a 0.25-pitch gradient-index lens. This was antireflection coated at 1047 nm on the front face and index matched to the fiber at the rear

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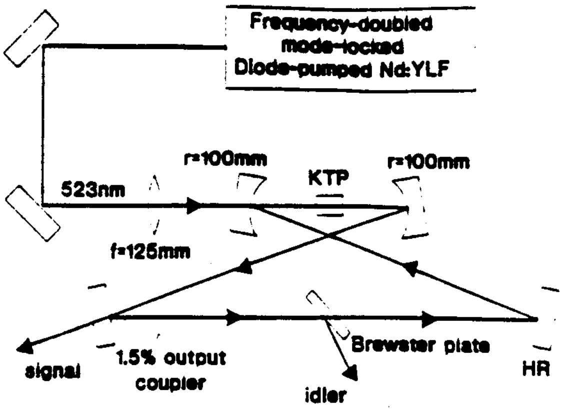

Fig. 1. Schematic diagram of the pump laser and the OPO cavity.

face to suppress étalon effects that would prevent mode-locked operation. An identical arrangement was used to couple light out of the fiber onto a plane mirror mounted on a piezoelectric transducer for cavity-length stabilization.

With the cavity lengths correctly matched and stabilized, stable long-term cw mode-locked operation was achieved. The mode-locking threshold corresponded to an average power of ~80 mW coupled into the fiber. With 2.4 W of diode pump power incident upon the Nd:YLF crystal, ~540 mW of average output power through the beam splitter was obtained in pulses of ~2.4-ps duration FWHM at a repetition rate of 125 MHz. This corresponds to a pulse peak power of ~1.7 kW.

Efficient frequency doubling of low-power mode-locked lasers can be achieved through the use of resonant enhancement cavities.[12,13] A configuration similar to the one used here has been described in detail in Ref. 11. Here the input coupler was 30% transmitting at 1047 nm. A 3-mm-long $MgO:LiNbO_3$ crystal, antireflection coated at 1047 and 523 nm, was mounted in an oven operated at 75.3°C for noncritical phase matching of 1047-nm frequency doubling to 523 nm.

With ~440 mW of average power at 1047 nm incident upon the enhancement cavity input coupler, a maximum of ~330 mW of average power at 523 nm was obtained as usable output from the enhancement cavity. This represents an external conversion efficiency of ~75%. More typical day-to-day operation gave ~300 mW of average output power. The output was in a clean circular TEM_{00} beam, in pulses of ~2-ps duration FWHM. This represents a peak output power of ~1.1 kW at 523 nm.

The OPO cavity was a ring configuration as shown schematically in Fig. 1. A ring configuration was chosen so that the KTP crystal loss was only experienced single pass. The two curved mirrors of 100-mm radius of curvature were highly reflecting (HR) (99.7%) at 1047 nm and highly transmitting (90%) at 523 nm. The cavity was completed by a plane high reflector mounted on a piezoelectric transducer for fine cavity-length adjustments and a plane 1.5% transmitting output coupler mounted on a micrometer-driven translation stage. The angle of incidence on the curved mirrors was kept to ~2.5° to minimize astigmatism in the cavity. The KTP crystal was 5 mm × 5 mm × 5 mm and antireflection coated at 1047 and 523 nm on both faces. The crystal had been cut for quasi-noncritical type II collinear phase matching in the *xy* plane for 1064-nm frequency doubling to 532 nm ($\theta = 90°$, $\phi = 26°$). The crystal loss was measured to be ~0.6% per single pass at 1047 nm. Including the output coupling of 1.5%, a further loss of ~1.0% from the other cavity mirrors gave a total cavity loss of ~3.1% at the resonated wavelength.

The KTP crystal was placed at the intracavity waist between the two curved mirrors, designed to be of 20-μm radius for the resonated beam. With a lens of 125-mm focal length, the incident 523-nm pump beam was focused down to an ~16-μm waist in the KTP crystal. The waist sizes used gave confocal parameters in the KTP crystal at the pump and signal wavelengths approximately equal to the KTP crystal length. With the OPO cavity length matched to that of the pump laser, mode-locked parametric oscillation was achieved. Oscillation could be achieved on either of the orthogonally polarized generated waves. The OPO cavity-length mismatch between operation on the two waves was ~0.3 mm, in close agreement with that calculated from the birefringence of KTP.[14] As the OPO would only oscillate over an ~40-μm region about exact length matching to the pump laser for either polarization, singly resonant operation could be enforced without recourse to discrimination against one of the polarizations. The singly resonant nature of the OPO was verified by the insertion of a Brewster plate to discriminate against the nonresonated wave, with no noticeable increase in threshold. The Brewster plate also usefully served to couple out the nonresonated wave. Oscillation threshold corresponded to ~61 mW of average power at 523 nm incident upon the KTP crystal. This represents a pulse peak power of ~230 W and a peak power density of ~57 MW cm^{-2}. The OPO yielded a slope efficiency of ~21% with respect to the power incident upon the OPO cavity, which gave rise to an average signal output power of ~42 mW at the maximum available pump power of ~255 mW incident

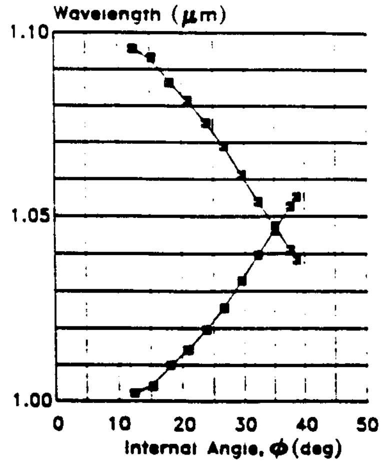

Fig. 2. Tuning behavior of the KTP OPO. The curves are drawn as a guide to the eye.

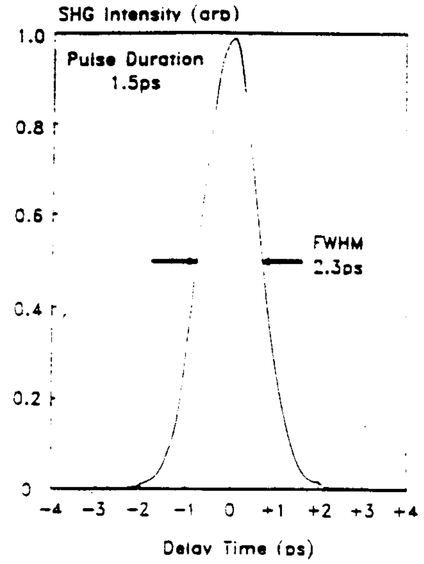

Fig. 3. OPO signal autocorrelation at a pump power of 100 mW. The FWHM is 1.5 ps if a sech^2 pulse shape is assumed. SHG, second-harmonic generation.

upon the OPO cavity. This represents an external conversion efficiency of ~16% of the 523-nm pump into tunable signal output. The OPO signal output was in a clean, circular TEM$_{00}$ beam. A further ~27 mW of average output power of the nonresonated idler was obtained from the Brewster plate. At this pumping level, the pump depletion was ~79%.

The OPO was angle tuned in the crystallographic *xy* plane by rotating the KTP crystal in the horizontal plane about the vertical *z* axis. The tuning range, shown in Fig. 2, was measured with a grating optical spectrum analyzer with a resolution of 0.1 nm. The combined tuning range of the signal and idler of ~94 nm was limited by the fall in reflectivity of the output coupler when it was tuned to shorter signal wavelengths. None of the high-reflectivity mirrors had been specified to be wideband (range 960–1040 nm), and the output coupler was operating near the edge of its reflectivity range, e.g., the transmission had increased to 10% at 1005 nm.

The OPO output power and pulse duration were both extremely sensitive to the precise length of the OPO cavity. With the OPO cavity length adjusted for maximum output power, operation was quite stable with ~4% amplitude noise (rms from dc to 5 kHz) on the output. This level of performance was achieved without any active cavity-length stabilization.

At this length setting, the OPO pulse duration was measured by means of second-harmonic autocorrelation to be ~2.2 ps FWHM if a sech^2 pulse shape is assumed, with a smooth corresponding spectrum of ~0.56 nm FWHM. This was measured at a pump power of ~200 mW. When the pump power was reduced to ~100 mW, the OPO pulse duration was reduced to ~1.5 ps, with an oscillating bandwidth of ~0.77 nm, as shown in Fig. 3. By lengthening the cavity by ~8 μm from this position, the pulse duration could be reduced to ~920 fs, with an oscillating bandwidth of ~1.24 nm. However, operation at this point corresponded to a region of sharply varying output power with cavity-length variation and thus was extremely sensitive to cavity-length fluctuations in the absence of active stabilization. For the various pulse durations, the time–bandwidth products were in the range of ~0.32–0.34, close to that for bandwidth-limited sech^2 pulses.

The stable-amplitude temporal and spectral output of the OPO and the large ratio of resonated to nonresonated circulating intensities in the OPO cavity (~35 times) are all indicative of singly resonant operation.

In conclusion, we have demonstrated what we believe to be the first operation of a cw mode-locked singly resonant optical parametric oscillator in an extracavity configuration synchronously pumped by a diode-laser-pumped source. This device has exhibited high conversion efficiency with useful output powers and good stability with bandwidth-limited and diffraction-limited performance. With properly designed mirror sets, and appropriately cut and coated KTP crystals, a much broader tuning range than that demonstrated should be possible. These qualities make this device a promising source for general use in the study of ultrafast phenomena.

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