Optical parametric oscillation in periodically poled lithium niobate based on continuous-wave synchronous pumping at 1.047 μm

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A singly resonant optical parametric oscillator is reported that uses a periodically poled $LiNbO_3$ crystal and is synchronously pumped by a cw mode-locked 1.047-μm Nd:YLF laser. Picosecond pulses were tunable from 1.67 to 2.806 μm. Mean output powers of 120 mW (90 mW) were obtained for the signal (idler) wave with an overall slope efficiency of 61% at a pump depletion of 75% when the oscillator was operating at three times above threshold. © 1996 Optical Society of America

Periodically poled lithium niobate (PPLN) has a significantly larger figure of merit than KTP and LiB_3O_5 even after length limitations imposed by group-velocity dispersion are allowed for, thus suggesting its suitability for use with short pulses. We recently achieved operation of a synchronously pumped singly resonant optical parametric oscillator (OPO) in PPLN, using the second harmonic of a mode-locked Nd:YLF laser as the pump.[1] By going to a PPLN crystal having an appropriate (longer) period we were able to demonstrate synchronously pumped parametric oscillation, using cw mode-locked Nd:YLF laser output as the pump.[2] Temperature tuning of a single grating has permitted coverage of the tuning range 1.67–2.806 μm. With new grating periods and appropriate mirror coatings, cw synchronously pumped operation with tuning out to ~4.8 μm should be feasible, as already demonstrated for a Q-switched device.[3]

Using the fundamental Nd:YLF wavelength rather than its harmonic as the pump has a number of benefits in addition to the obvious ones of system simplification and improved overall efficiency. By operating the OPO at longer wavelengths we significantly reduce the group-velocity mismatch among the pump, signal, and idler waves, permitting the use of longer crystals or shorter pulses. In these experiments we use a 6-mm-long sample. However, in principle, for our 2.8-ps-duration pump pulses the lengths could be advantageously increased to ~20 mm, corresponding to a group-velocity mismatch of ~114 fs/mm between the pump and the signal/idler for degenerate operation, with the signal and the idler at 2.094 μm. The fact that the material dispersion is negative for operation at these longer wavelengths has the beneficial effect that the use of prisms for intracavity group-velocity dispersion compensation can be avoided.[4] Because of this a simpler resonator design can be used, and, in fact, we use a three-mirror resonator, as shown in Fig. 1. The longer grating period required in PPLN for quasi-phase-matched operation also makes the grating fabrication easier, permitting preparation of thicker samples, as is required for the larger beam sizes associated with longer samples and longer wavelengths.

Operation at longer wavelengths also reduces the degree of photorefraction, as indicated by Myers *et al.*,[5] so that greater average powers should be possible before photorefractive damage is experienced. This, together with the large nonlinearity of PPLN (we have estimated an effective nonlinear coefficient $d_{eff} > 16$ pm/V for our sample) and noncritical phase matching, makes it an interesting alternative to other nonlinear materials such as $KTiOA_5O_4$, $C_5TiOA_5O_4$, $RbTiOA_5O_4$, and $KNbO_3$ (Ref. 6) for the 1–5-μm range.

The experimental layout is shown in Fig. 1. The output from the additive-pulse mode-locked Nd:YLF laser (2.4-ps pulses, 105-MHz pulse repetition rate, 360-mW average power) passes through a Nd:YLF double-pass amplifier stage pumped by a 3-W diode laser, permitting amplification of the average power to as high as 940 mW when required, with a slight increase in pulse duration to 2.8 ps.[4] The OPO crystal was an antireflection-coated (single-layer MgF_2 centered at 1.9 μm), 6-mm-long, 0.5-mm-thick sample of PPLN with a 30.5-μm period and was produced by electric-field poling.[7,8] The crystal was mounted in

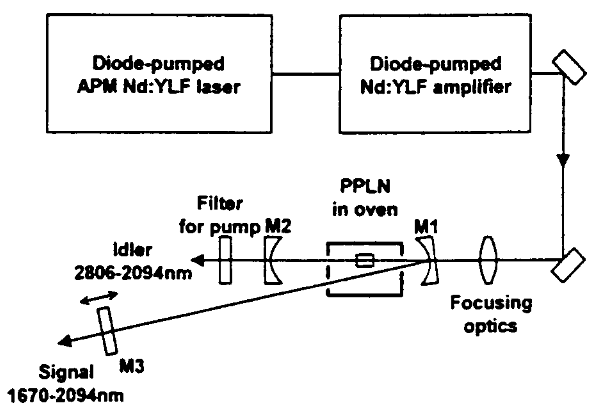

Fig. 1. Experimental layout: M1, high reflector with 100-mm radius of curvature; M2, high reflector with 150-mm radius of curvature; M3, high reflector or output coupler for the signal wave; APM, additive-pulse mode-locked.

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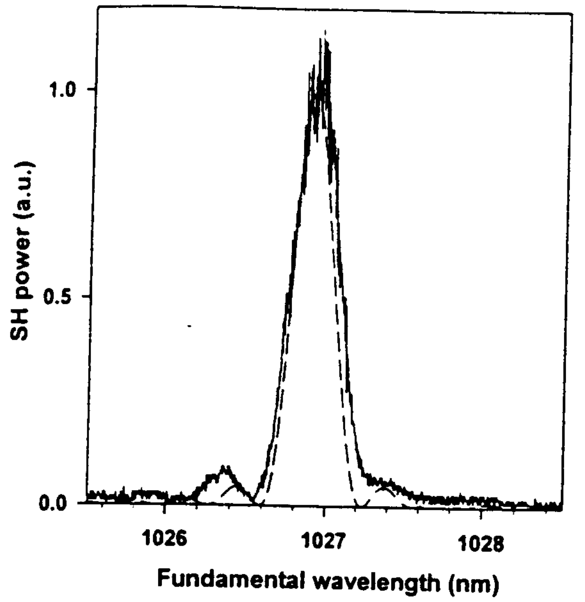

Fig. 2. Second-harmonic (SH) versus fundamental wavelength for 5th-order QPM. The dashed curve is a theoretical curve. For 6th-order QPM the curve has a similar shape and is centered around 971 nm with a bandwidth of 0.22 nm.

an oven that permitted the PPLN crystal to be uniformly heated to as high as 200 °C with a stability of ±0.1 °C. Preliminary optical assessment of the quality of the grating was made in fifth- and sixth-order quasi-phase matching (QPM) by frequency doubling of the output from a Ti:sapphire laser. The good agreement between experimental and theoretical phase-matching curves (Fig. 2) confirmed the excellent uniformity of the grating over the full length of the sample. From a comparison between experimental and theoretical d_{eff} for the fifth- and sixth-order QPM we estimated an average mark-to-space ratio of 43/57, which should provide a d_{eff} in first-order QPM greater than 95% of the theoretical value. This duty cycle is consistent with the estimate obtained by visual assessment of the grating.

The three-mirror resonator consisted of a tightly focused region formed by mirrors M1 and M2, yielding a waist size for the signal beam of 39 μm. We minimized the astigmatism by keeping the angle of incidence on M1 small (<3°). The resonator was completed by M3, a plane mirror that was either a high reflector or an output coupler for the signal wavelength and was mounted upon a linear translation stage, permitting the fine-length tuning necessary for pulse sychronization. The mirrors were coated to be highly reflecting in the range 1.65–2.1 μm but provided 84% transmission at 1.047 μm. To ensure singly resonant oscillation, the mirrors had >70% transmission in the range 2.2–2.7 μm, thus providing <0.8% round-trip feedback for the idler in this range. The amplified additive-pulse mode-locked output was focused within the PPLN sample to a spot size of 33 μm. With the crystal temperature at 170 °C and all three mirrors highly reflecting, the incident power threshold (in the crystal) was 54 mW. This increased to 140 mW for an output coupling of 8% at 1920 nm. From these measurements we deduce an excess round-trip loss (i.e., other than output coupler transmission) of 5.4% at this wavelength, which increased to 8.3% for a signal wavelength of 1804 nm. These values show good consistency with the estimate of expected signal/idler output powers based on the corresponding observed pump depletion and the partition of this energy between transmission loss and excess loss. The excess round-trip loss is attributed mainly to polishing imperfections and imperfection coatings on the crystal (a perfect single-layer MgF_2 coating would have 0.3% loss per surface). Actual threshold powers agree well with numerical calculations based on these known losses and the value of d_{eff} = 16 pm/V.

We tuned the OPO from 1.67 to 1.96 μm for the signal wave and from 2.24 to 2.8 μm for the corresponding idler wave by changing the crystal temperature from 60 to 190 °C. Operation at shorter signal wavelengths was limited by the bandwidth of the mirrors, as shown in Fig. 3. At a crystal temperature of 170 °C (λ_s = 1920 nm) the slope efficiencies for the signal and idler outputs were 35% and 26%, respectively. Signal output power of as high as 123 mW was measured at an incident pump power (in the crystal) of 500 mW. The corresponding idler power was 92 mW. The pump depletion (~70%) began to saturate when the OPO was operating at 3.3 times above threshold, as shown in Fig. 4. In addition to the signal output, there was also ~2 mW of 677-nm light output from sum-frequency mixing of the pump and signal waves and ~5 mW of 523.5-nm output from non-phase-matched harmonic generation of the pump.

We measured the temporal characteristics of the signal pulses by non-background-free autocorrelation, using a 1.3-mm-thick critically phase-matched $LiNbO_3$ crystal cut at θ = 47°. The signal pulse duration (τ_{ps}) fitted well to a sech^2 profile of duration 2.65 ps, as shown in Fig. 5. From a measurement of the signal

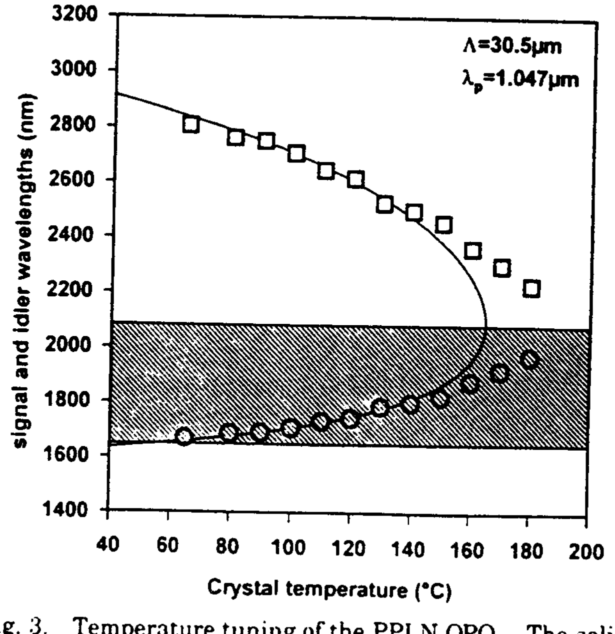

Fig. 3. Temperature tuning of the PPLN OPO. The solid curve is calculated with the Sellmeier equations of Edwards and Lawrence.[6] The shaded area is the mirror bandwidth.

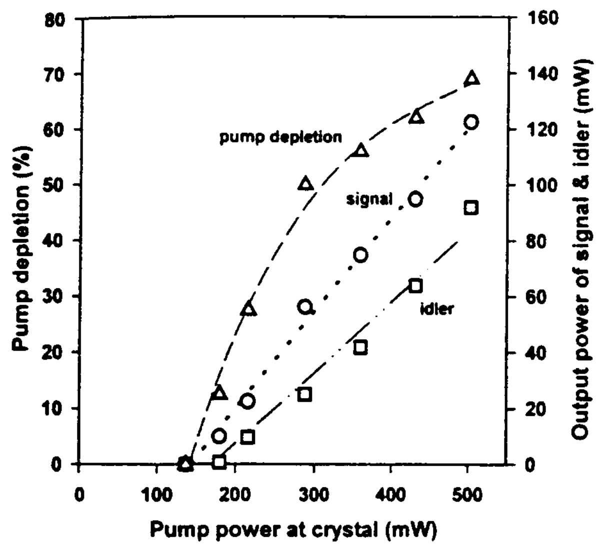

Fig. 4. Output power and depletion versus crystal pump power.

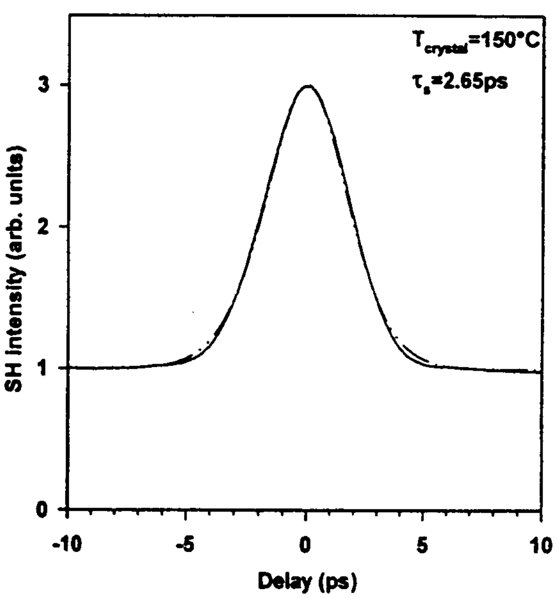

Fig. 5. Autocorrelation of signal pulses at 1824 nm. The dotted–dashed curve is a fit with a 2.65-ps sech^2 pulse shape.

bandwidth ($\Delta\nu_s$) we calculate the product $\Delta\nu_s \times \tau_{ps}$ to be 0.39, close to the transform-limited value of 0.32 for sech^2 pulses.

The beam quality (M^2) of the signal output was calculated from a series of measured spot sizes at various distances from the focal plane of a lens (f = 75 mm) by use of slits and a PbS detector. The results yield a value for M^2 of 1.18, which indicates the lack of any significant photorefractive damage. It should be noted that operation of the PPLN at elevated temperatures ($T_{crystal} > 60$ °C) seems to alleviate photorefractive damage, as noted by Myers *et al.*[5] The output power stability of the OPO was excellent, with a peak-to-peak noise of <5% (rms <3%), as measured from dc to 2 kHz with a PbS detector over a 5-s time scale. The low noise level can be attributed both to the low noise of the diode-pumped laser source and to the large tolerance to cavity-length detuning (Δl_{cav}) of the PPLN OPO, viz. Δl_{cav} = 170 μm at 3.3 times threshold and 1920 nm and Δl_{cav} = 90 μm at two times threshold and 1804 nm.

In conclusion, we have demonstrated a highly efficient picosecond OPO based on PPLN and pumping at 1.047 μm. Singly resonant operation has been achieved with low threshold as a result of the high parametric gain of the PPLN crystal. These results show that PPLN is already a serious candidate for use with picosecond OPO's working in the near-infrared range. We can expect improvements in the performance of the OPO by lowering the threshold through the use of longer samples (as long as 20 mm) and by reducing the excess cavity loss through better coatings on the crystal or by using a crystal with Brewster surfaces. The latter has the advantage of minimal loss for all three waves ($e \rightarrow e + e$ interaction) but has the slight disadvantage of reduced parametric gain as a result of an elliptical spot in the sample. By fabrication of gratings with different periods of domain reversal, e.g., from 30.5 to 25 μm, it will be possible to extend our demonstrated wavelength tuning range, potentially to cover 1.33–4.8 μm. Furthermore, the pump power requirements of such OPO's should be accessible by use of diode-pumped mode-locked erbium-doped fibers as the pump source,[10] thus promising a compact and low-cost route to broadly tunable subpicosecond pulses.

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