Low-threshold picosecond optical parametric oscillation in quasi-phase-matched lithium niobate

V. Pruneri,[a)] S. D. Butterworth, and D. C. Hanna
Optoelectronics Research Centre, University of Southampton, Southampton SO17 1BJ, United Kingdom

(Received 22 April 1996; accepted for publication 11 June 1996)

We report a singly resonant optical parametric oscillator in periodically poled lithium niobate, synchronously pumped by the second harmonic of an amplified 10 μs pulse train from a continuous wave mode-locked Nd:YLF laser. Pulses of ~2 ps duration have been generated over the tuning range from 883 to 1285 nm with a typical threshold of 200 mW average power within the 10 μs envelope. The M^2 beam quality factor for the generated signal was ~1.1, indicating absence of any significant photorefractive damage. © *1996 American Institute of Physics.*
[S0003-6951(96)04034-X]

Periodically poled lithium niobate (PPLN) has become a reliable and efficient nonlinear material for quasi-phase-matched (QPM) second order nonlinear processes. By choosing the appropriate period of the domain reversal, a broad wavelength range (within the transparency of the material) can be accessed via processes such as second harmonic generation (SHG) and optical parametric oscillation. Thus, for example, blue and green light have been efficiently generated by continuous wave and Q-switched QPM–SHG in PPLN.[1-3] Tunable infrared QPM optical parametric oscillators (OPO) have also been demonstrated in PPLN, using a Q-switched, a quasi-cw, and a cw pump.[3,4]

For operation in the picosecond regime, the dispersion of PPLN causes a large group velocity mismatch (GVM) between interacting fields at different frequencies, thus, limiting the effective interaction length (l_{eff}). The GVM in PPLN is the same as for single domain lithium niobate since the periodic domain inversion produces a modulation only of the nonlinearity without altering the linear properties of the material. For frequency doubling of wavelengths around 1 μm, GVM is ~1 ps/mm. Despite this high dispersion, its large effective nonlinear coefficient (d_{eff}~20 pm/V) makes PPLN compare favorably with other nonlinear materials, such as $KTiOPO_4$ (KTP) (Ref. 5) and LiB_3O_5, (LBO)[6] in terms of the relevant figure of merit $(d_{eff}^2 l_{eff})/n^3$, where l_{eff} rather than l_{eff}^2 is used as tight focusing is assumed. In Table I we summarize this comparison that indicates around an order of magnitude advantage in favor of PPLN. Initial experimental results using picosecond pulses have begun to appear. Frequency doubling in PPLN of 25 ps pulses from a high power mode-locked semiconductor laser has produced 10 mW of blue light[7] with ~2.3% average conversion efficiency. We recently demonstrated the effectiveness of PPLN for frequency conversion of shorter duration pulses (2.6 ps) and higher power levels by performing SHG to the green (523 nm) with an average conversion efficiency of 65%.[8] Here, we report operation of a synchronously pumped OPO based on PPLN indicating the potential of PPLN for picosecond, and by implication, femtosecond OPOs. The pump consisted of the second harmonic of an amplified train (10 μs) of 2.6 ps pulses from an additive pulse mode-locked (APM) 1.047 μm Nd:YLF laser.

The PPLN sample with a domain reversal period (Λ) of 6.4 μm used in this experiment was 0.3 mm thick and was end-polished to a final length of 3.2 mm, suitable for ~2 ps pulses (l_{eff}~2mm). The fabrication by using electric field pulses has been extensively described,[1-3] and the optical assessment of this sample via SHG has been described in Ref. 8. The estimated $d_{eff}>15$ pm/V and the experimentally measured temperature bandwidth full width at half-maximum ~7 °C) of the phase matching curve (second harmonic power vs crystal temperature) were close to the theoretical limits for a perfect 3.2 mm grating. For the OPO experiment, the sample was antireflection (AR) coated with a single layer of MgF_2 for 930 nm. The coating should ideally provide a surface reflectivity loss <1% in the range 850–1050 nm and ~13% at the pump wavelength of 523.5 nm.

The threshold powers that we have demonstrated are well within the capabilities of a cw mode-locked source, such as the one we have used (with resonantly enhanced LBO frequency doubler)[6] for pumping a LBO OPO. However, since the resonant enhancement cavity was not available for this experiment, we chose instead to work in a quasi-cw scheme, with 10 μs pulses sliced from the cw mode-locked train, using an acousto-optic modulator, followed by amplification of the train in a diode-pumped Nd:YLF amplifier stage (see Fig. 1). In this way, after the amplifier, higher peak powers were achieved than were available in cw operation, thus, allowing efficient frequency doubling in the LBO without the need for a resonant enhancement cavity.[9] The pulse train length was enough, however, for a steady-state cw pumping condition to be accessed. This 523.5 nm pump source for the OPO could deliver up to

TABLE I. Comparison of PPLN with KTP and LBO for 2 ps pump pulse. $\lambda_p = 523.5$ nm, $\lambda_s = \lambda_i = 1047$ nm. If one starts to look at detailed comparisons, one would also have to consider damage thresholds, etc. The d_{eff} values for KTP and LBO are taken from Refs. 5 and 6.

	d_{eff} (pm/V)	l_{eff} (mm)	n	$d_{eff}^2 l_{eff}/n^3$
LBO	0.8	32	1.6	5
KTP	3.2	4.4	1.8	7.7
PPLN	20	1.8	2.2	68

[a)] Electronic mail: vp3@orc.soton.ac.uk

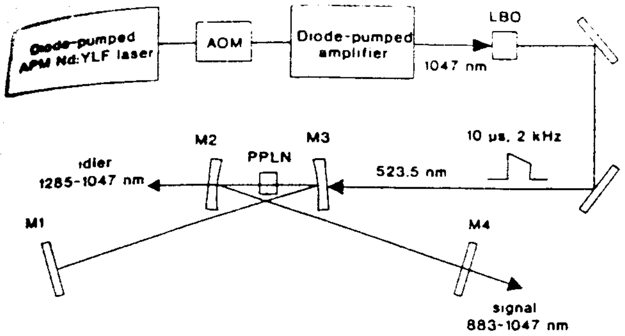

FIG. 1. Layout of the OPO and of the pump pulse source. M1:Hr plane mirror, M2 and M3: HR curved mirrors (ROC=100 mm), and M4 output coupler.

25 mW of average power (corresponding to 1.25 W "envelope-average" power within the 10 μs envelope at a repetition rate of 2 kHz). The duration of the pump pulses was ~2.3 ps (assuming sech^2 shape) while the bandwidth was ~205 GHz. The time–bandwidth product was thus ~0.47. The pump light was focused in the PPLN crystal to a spot size of 18 μm ($1/e^2$ intensity radius). The curved mirrors (M2 and M3, see Fig. 1) of radius of curvature (ROC)=10 cm were positioned to obtain an average spot size of ~26 μm (the beam was slightly elliptical because the non-normal incidence angle of ~5° on the curved mirrors produces astigmatism).

Initial results were obtained for a cw mode-locked doubly resonant OPO where the threshold was just 5 mW of average power incident on the crystal. Pump depletions up to 80% were observed at ten times above threshold.

The average green power in the cw case was limited to <80 mW and so the quasi-cw pulse trains (10 μs envelope at 2 kHz) were used to pump the singly resonant OPO (SRO). for the SRO the two curved mirrors (M2, M3) and one plane mirror (M1) were high reflectivity (HR) coated for 0.8–1.05 μm and with reflectivity <40% in the range 1.1–1.5 μm. The other mirror (M4) was the output coupler (O/C) with initial 3% transmittivity in the range 0.85–1.1 μm.

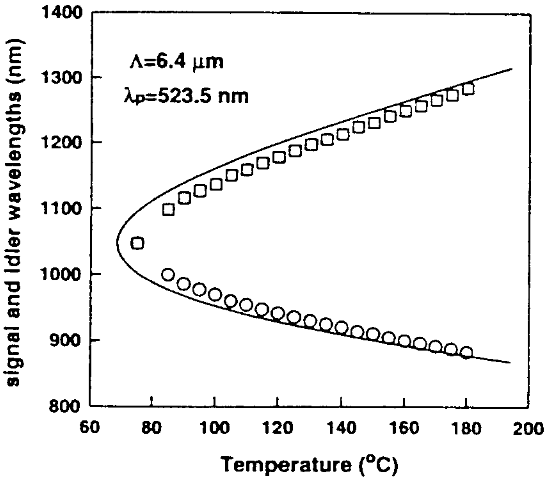

FIG. 2. Tuning curve for the singly resonant OPO. The degeneracy point has been found by SHG of 1.047 μm. The continuous line is a calculated trace.

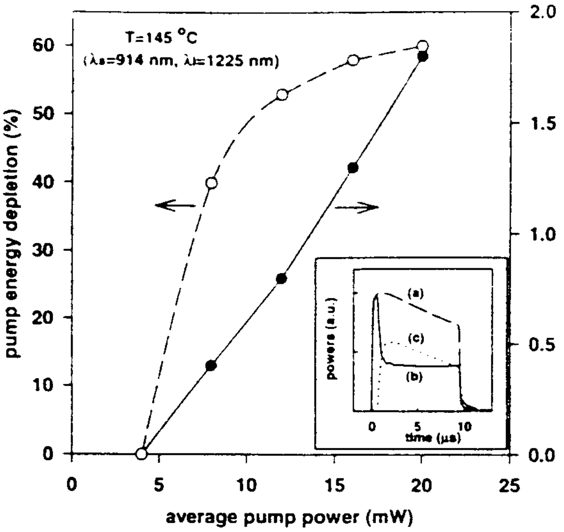

FIG. 3. Dependence of the average output signal power and of the pump energy depletion for the crystal at 145 °C (the corresponding envelope-average powers within the ⩽10 μs envelopes at 2 kHz are ⩾50 times the indicated powers). The inset shows the temporal behavior within the pulse envelope: (a) undepleted pump, (b) depleted pump, and (c) signal output.

The tuning of the SRO, from 883 to 1047 nm for the signal branch and corresponding from 1285 to 1047 nm for the idler branch, was achieved by changing the temperature of the crystal from ~75 to 180 °C (Fig. 2). Figure 3 shows the output average signal power P_s and the pump energy depletion as functions of the average pump power P_p with the crystal at ~145 °C, corresponding to signal (914 nm) and idler (1225 nm) wavelengths. The threshold of ~4 mW (~200 mW envelope average) corresponds to a peak pump power of ~780 W and to a peak pump intensity ~150 MW/cm^2. A typical time behavior of the SRO over the 10 μs envelope at ~50% pump depletion is shown in the inset of Fig. 3. Because of the rise time of this quasi-cw OPO, the actual duration for the signal envelope is slightly less than 10 μs, so the actual signal power within the envelope is slightly more than 50 times the signal power indicated in Fig. 3. The best average signal power output was 1.8 mW (~100 mW within the envelope) at five times above threshold while the corresponding pump energy depletion was ~60%. In fact, we observed pump energy depletions as high as 75% but the SRO in these conditions was not stable in the sense that broadening of the spectrum and instability in the shape of the pulses occurred, probably due to self-phase modulation.

The duration of the idler pulses was measured to be ~1.8 ps (assuming sech^2 shape) while the bandwidth of the corresponding spectrum was ~240 GHz giving a time–bandwidth product of ~0.43.

At five times above threshold (intracavity signal average power >3 W within the envelope and average pump power >1 W), we have not observed any significant photorefractive damage as confirmed by the absence of any roll off of the curve in Fig. 3, and by the measured M^2 beam quality factor of ~1.1 for the output signal in both vertical and horizontal planes.

Figure 4 shows the output of the SRO for two different

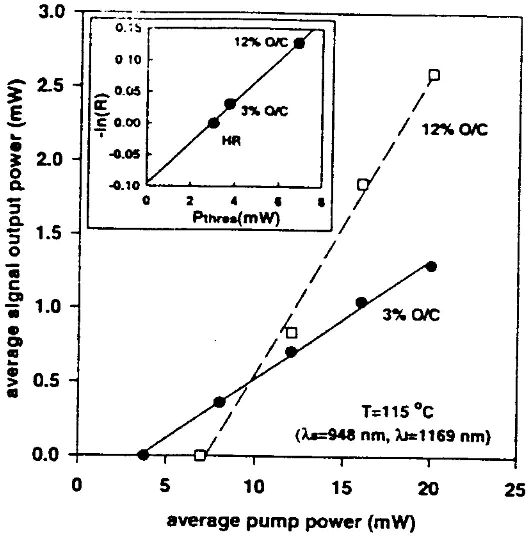

FIG. 4. Output of the SRO for two different output couplers. The inset shows the dependence of the threshold on the output coupling. From this dependence one can estimate the power loss per round trip to be 9%.

output couplers (3% and 12%) at a temperature of 115 °C ($\lambda_s = 948$ nm, $\lambda_i = 1169$ nm). With 12% output coupling, we improved the maximum output to 2.6 mW average signal power (~140 mW envelope average) corresponding to a slope efficiency of ~20%. The inset of Fig. 4 shows the dependence of the threshold on the transmittivity of the output coupler (HR, 3%, and 12% O/C). From this dependence the excess power loss per round trip (i.e., other than output transmission loss) can be estimated to be ~9%. This value agrees well with the estimate of signal output power from the corresponding depleted pump power (see Fig. 3). We believe that this single-pass loss of ~4.5% is mainly due to imperfect polishing and coating of the PPLN crystal. We separately measured a single-pass loss in the PPLN sample of ~4% at 1.047 μm. For a perfect single layer of MgF_2 AR coating for 930 nm, one would expect a single pass loss ~2% at 1.047 μm.

In conclusion, we have reported a picosecond optical parametric oscillator in PPLN, pumped at 523.5 nm by the second harmonic of an amplified APM Nd:YLF laser. Singly resonant quasi-cw operation has been achieved with low threshold as a result of the high parametric gain in the PPLN sample. By changing the temperature of the crystal, we have demonstrated tuning from 883 to 1285 nm. Average output signal powers up to ~140 mW (within the envelope at 2 kHz) have been produced with an efficiency of ~13%. Significant improvements are expected with better coatings on the crystal. These results and recent results that we have obtained[10] with PPLN directly pumped at 1.047 μm, using a cw-mode-locked train (to be reported in a separate publication), indicate that PPLN is an attractive nonlinear medium for picosecond, and probably also femtosecond OPOs.

[1] M. Yamada, N. Nada, M. Saitoh, and K. Watanabe, Appl. Phys. Lett. **62**, 435 (1993).

[2] V. Pruneri, R. Koch, P. G. Kazansky, W. A. Clarkson, P. St. J. Russell, and D. C. Hanna, Opt. Lett. **20**, 2375 (1995).

[3] V. Pruneri, J. Webjörn, P. St. J. Russell, and D. C. Hanna, Appl. Phys. Lett. **67**, 2126 (1995).

[4] L. E. Myers, R. C. Eckardt, M. M. Fejer, R. L. Byer, W. R. Bosenberg, and J. W. Pierce, J. Opt. Soc. Am. B **12**, 2102 (1995).

[5] See, for example, feature issues on OPO, J. Opt. Soc. Am. B **10**, (1993) and **12** (1995).

[6] S. D. Butterworth, S. Girard, and D. C. Hanna, J. Opt. Soc. Am. B **12**, 2158 (1995).

[7] L. Goldberg, R. W. McElhanon, and W. K. Burns, Electron. Lett. **31**, 1576 (1995).

[8] V. Pruneri, S. D. Butterworth, and D. C. Hanna, Opt. Lett. **21**, 390 (1995).

[9] S. D. Butterworth, W. A. Clarkson, N. Moore, G. J. Friel, and D. C. Hanna, Opt. Commun. (to be published).

[10] V. Pruneri, S. D. Butterworth, and D. C. Hanna, in *Trends in Optics and Photonics: Advanced Solid State Laser Proceedings* (Optical Society of America, 1996).