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Continuous-wave singly resonant optical parametric oscillator based on periodically poled $LiNbO_3$

Walter R. Bosenberg, Alexander Drobshoff, and Jason I. Alexander

Lightwave Electronics Corporation, Mountain View, California 94043

Lawrence E. Myers and Robert L. Byer

E. L. Ginzton Laboratory, Stanford University, Stanford, California 94305

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We report a continuous-wave singly resonant optical parametric oscillator (OPO) based on periodically poled lithium niobate. The simple, two-mirror OPO, pumped by a 1.064-μm Nd:YAG laser, had a 2.6–4.5-W threshold and an output of >1.2 W at 3.3 μm and was tuned over 1.45–1.62 μm (signal) and 3.98–3.11 μm (idler). The noise characteristics and the spectral properties of the device are described. © 1996 Optical Society of America

The relative merits of singly resonant optical parametric oscillators (SRO's) and doubly resonant optical parametric oscillators (DRO's) have been understood for many years.[1] SRO's, in which only the signal wave is resonated, offer superior amplitude and spectral stability at the cost of higher oscillation thresholds.[2] DRO's, in which the signal and the idler waves are both resonated, offer >100 times lower oscillation thresholds but generally have much lower spectral and amplitude stability.[3,4] For pulsed optical parametric oscillators (OPO's), pump intensities are typically ample to drive a SRO. Thus, in the pulsed regime, SRO's are nearly universally used because of their better stability. For cw OPO's, SRO thresholds are typically higher than practical pump lasers can provide. Because of the high SRO oscillation threshold, a significant amount of effort has gone into taming cw DRO's for use in applications. With stable pump lasers, carefully engineered OPO cavities, and multiple control loops, highly stable and coherent DRO's have been demonstrated.[5] However, even in these advanced DRO's, tuning of the OPO output requires complex, simultaneous adjustment of multiple parameters for continuous tuning ranges of <10 GHz to be achieved.[6]

In 1993 Yang *et al.* demonstrated the first cw SRO, using a custom-built, resonantly doubled, single-frequency Nd:YAG laser to pump an OPO based on $KTiOPO_4$.[7,8] They recorded an oscillation threshold of 4.3 W and an output of 1.9 W at 1.039 μm but could not significantly tune the device. A key result from Yang's research was the demonstration of stable SRO behavior from a cw OPO device, providing motivation for making cw SRO's based on simpler pump lasers.

In this Letter we report the demonstration of a broadly tunable cw SRO device that uses a simple experimental configuration. The key to our research is the recently developed nonlinear material, periodically poled lithium niobate (PPLN). The high gain and low loss of PPLN[9] make it possible to attain oscillation thresholds of a few watts when pumping with the 1.064-μm line of the Nd:YAG laser. The quasi-phase matching used with PPLN allows the OPO to be tuned anywhere within the transparency range of the crystal (a tuning range of 1.35–~5 μm for pumping at 1.064 μm).[10] We achieved cw SRO oscillation thresholds of 2.6–4.5 W, outputs of >1.2 W at 3.3 μm, and significant tuning in two important spectral regions. The OPO ran robustly at 2 to 3 times threshold over a period of several weeks with no optical damage to any crystal or optic. Without the complexity associated with DRO's, we have realized the stable, tunable outputs that early researchers in the field had predicted for SRO's.

The experimental configuration is shown in Fig. 1. The pump laser is a single-transverse-mode multiple-longitudinal-mode diode-pumped Nd:YAG laser. The laser has an output of ~17 W with nearly diffraction-limited beam quality ($M^2 \approx 1.1$). The output of the pump laser is passed through a variable attenuator and an optical isolator, providing 13 W of power for pumping the OPO. The pump beam is mode matched to the OPO cavity with a single 200-mm

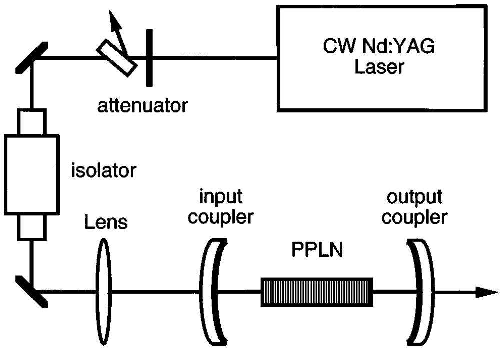

Fig. 1. Schematic of the experimental configuration. The diode-pumped Nd:YAG laser produces 17 W of polarized TEM$_{00}$ output. The PPLN is 50 mm long and has a grating period of 29.75 μm for first-order quasi-phase matching of 1.064-μm pump photons to 1.57-μm signal and 3.25-μm idler photons (at a crystal temperature of 175 °C). Not shown is the crystal oven. The crystal temperature was kept in the range of 110–220 °C.

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focal-length lens, producing a 97-μm beam waist (radius) inside the crystal. We used a 50-mm-long PPLN crystal with a grating period of 29.75 μm for first-order quasi-phase matching, resulting in signal and idler wavelengths of 1.57 and 3.25 μm, respectively, at crystal temperatures of ~175 °C. The fabrication techniques described elsewhere[9] were used with full 7.62-cm-diameter, 0.5-mm-thick LiNbO$_3$ wafers to produce the long PPLN crystals used here. The two end faces of the crystal had antireflection coatings with power reflectivities of 6%, 0.3%, and 7% for each surface, at the pump, signal, and idler wavelengths, respectively. The crystal was placed in an oven and operated at temperatures of $>120\,°\mathrm{C}$ to avoid the effects of photorefraction.[9] The symmetric OPO resonator had cavity mirrors with 50-mm radii of curvature, which were separated by 104 mm. The input coupler of the OPO cavity had reflectivities of 2%, 99.7%, and ~3% at the pump, signal, and idler wavelengths, respectively. The output coupler was a coated CaF$_2$ substrate with reflectivities of 14%, 99.5%, and ~11% at the pump, signal, and idler wavelengths, respectively. For the two-mirror linear OPO cavity the round-trip cavity loss for the signal wave was ~2% at the signal wavelength and >99% at the idler wavelength, satisfying the condition for singly resonant operation when the laser was pumped several times above the oscillation threshold.[11]

In Fig. 2 we show the OPO output versus pump input. The threshold of 4.5 W (~30 kW/cm^2) is in reasonable agreement with a calculated value of 3.7 W for a single-frequency pump laser,[12] indicating that, as predicted for SRO's,[1] all the axial modes of the pump laser participate in driving the OPO above threshold. For pumping at 13 W (2.9 times threshold), 1.24 W of unresonated 3.3-μm idler and 0.36 W of resonated 1.57-μm radiation were generated. The low signal output power (compared with the idler output power) is due to the low value of output coupling used.

The crystal length of 50 mm and the pump beam waist of 97 μm yield a focusing parameter $\xi = 0.42$, where $\xi = L/b$, L is the crystal length, and b is the confocal parameter of the pump (or signal) beam inside the crystal. Reference 12 shows that minimum threshold is attained for $1 \le \xi \le 7$. By focusing the pump more tightly to yield ξ values of 0.62, 1.0, and 1.6, we observed oscillation thresholds of 4.2, 2.9, and 2.6 W, respectively.[13] However, along with decreasing the threshold, the higher ξ values produced a sudden increase in the noise of the OPO output when the OPO was pumped more than 1.7 times above threshold. The sudden increase in noise (the amplitude noise would jump from 1% to 17% rms) was highly reproducible and coincided with a reduction in the conversion efficiency as well as with a change in the spectral properties of the OPO. The cause of this effect is currently being investigated; however, by simply increasing the spot size of the pump we achieved low-noise operation even when pumping ~3 times above threshold.

We observed the spectral qualities of the OPO's signal output, using solid étalons coated for $R = 95\%$ at 1.55 μm. Nine étalons were used, ranging in thickness over 0.1–15 mm, corresponding to free spectral ranges of 33–0.2 cm^{-1}. Inasmuch as the OPO cavity free spectral range is 0.03 cm^{-1}, individual cavity modes could be resolved with the étalons. Despite a pump laser linewidth of ~2.2 GHz FWHM corresponding to ~9 longitudinal modes, we observed that the resonated signal wave operated on a single longitudinal mode of the OPO resonator with a linewidth of <0.02 cm^{-1} (0.5 GHz). The free-running OPO stayed on one longitudinal mode for 10–20 s until cavity length, crystal temperature drift, or both caused the OPO to hop to a nearby longitudinal mode. The OPO crystal oven had open loop temperature control (i.e., a Variac transformer driving the heater), and the cavity was open to air. We expect that with minimal attention to mechanical and thermal design we will be able to operate the OPO on a single-longitudinal mode indefinitely.

To verify the amplitude stability of the SRO we measured the signal output with a fast photodiode. The data were taken with $\xi = 0.42$. During 1-s intervals (Fig. 3a) the OPO ran on one longitudinal mode, and we measured ~1% noise (rms). Over a 30-min interval (Fig. 3b), with the OPO mode hopping every 10–20 s, the noise increased to 4.7% (rms). In Fig. 3c we show the OPO output when the cavity length is varied with a piezoelectric transducer. Mode hops occur only at cavity length changes that are a large fraction of the free spectral range of the OPO cavity (790 nm), which is consistent with SRO operation. For a similarly constructed DRO, mode hops occur for every 2-nm change in cavity length and every 3-MHz shift in pump frequency.[14] Our device operates without mode hops over ranges more than 2 orders of magnitude greater than these values, demonstrating the broad cavity length and pump frequency tolerances associated with SRO operation.

We tuned the output wavelengths of the cw OPO by both temperature tuning and domain-period tuning. Varying the temperature of the crystal over 110–220 °C tuned the output over 1.54–1.61 μm (signal) and 3.41–3.14 μm (idler). Operation below 110 °C was prevented by photorefractive distortion of the beams in the crystal, and operation above 220 °C was limited by the losses of the cavity mirrors as the OPO tuned to longer signal wavelengths. We achieved broader tuning by varying the quasi-phase-matching period of the domain grating in the PPLN crystal. We used a 25-mm-long PPLN crystal that had

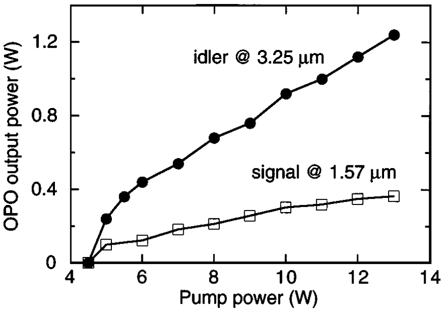

Fig. 2. Output versus input of the cw PPLN OPO. The oscillation threshold is 4.5 W. The maximum output is 1.25 W at 3.25 μm and 0.36 W at 1.57 μm with 13 W of pump.

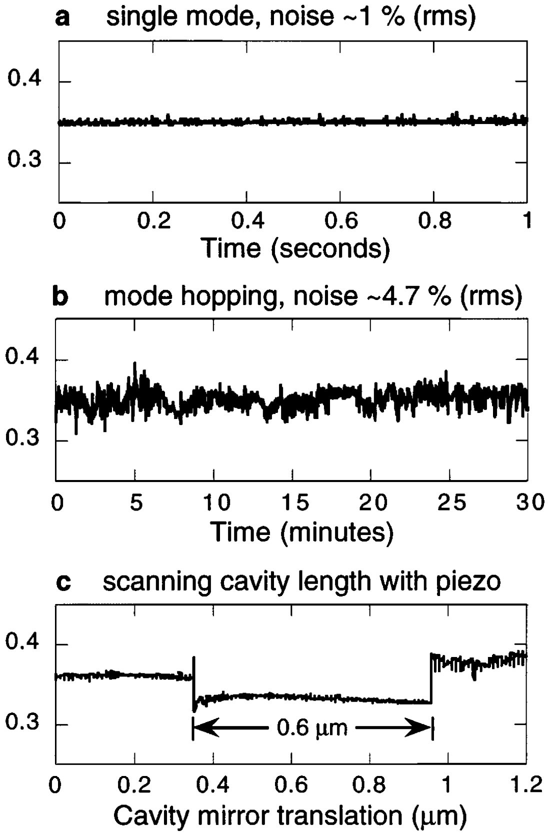

Fig. 3. Amplitude noise characteristics of the cw SRO. The Y axis of each graph is signal power in watts. Note that the bottom of the Y axis is not zero; therefore the fluctuations appear enlarged. a, Output of the free-running OPO over a 1-s interval with single-longitudinal-mode operation. b, Output of the free-running OPO over a 30-min interval with longitudinal mode hopping causing the increased noise. c, OPO output when the cavity length is swept with a piezoelectric transducer. The well-defined mode hops occur at a large fraction of the free spectral range of the signal (0.79 μm) and indicate the singly resonant nature of the device.

multiple grating structures similar to those reported in Ref. 10. By translating the crystal to allow the pump to pass through regions having domain periods of 28–30 μm we produced cw radiation over 3.98–3.11 μm (idler) and 1.45–1.62 μm (signal) with the crystal temperature at 175 °C. This tuning range was again limited by the reflectivities of the OPO cavity mirrors.

In summary, we have demonstrated a versatile midinfrared cw singly resonant optical parametric oscillator. The OPO had a few-watt threshold, produced >1.2 W of midinfrared radiation, and was tuned through technologically important spectral regions. The OPO operated on a single longitudinal mode of its resonator when pumped by a multilongitudinal mode pump. Without any system complexity the OPO output had low noise ($\sim$1% rms), and at no time did we observe optical damage to any crystal or optic. Future studies will be directed at optimizing this device and developing an understanding of its behavior above threshold.

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References

1. S. E. Harris, Proc. IEEE **57,** 2096 (1969).
2. J. E. Bjorkholm, Appl. Phys. Lett. **13,** 399 (1968).
3. R. G. Smith, IEEE J. Quantum Electron. **QE-9,** 530 (1973).
4. R. C. Eckardt, C. D. Nabors, W. J. Kozlovsky, and R. L. Byer, J. Opt. Soc. Am. B **8,** 646 (1991).
5. D. Lee and N. C. Wong, J. Opt. Soc. Am. B **10,** 1659 (1993).
6. F. G. Colville, M. J. Padgett, and M. H. Dunn, Appl. Phys. Lett. **64,** 1490 (1994).
7. S. T. Yang, R. C. Eckardt, and R. L. Byer, Opt. Lett. **18,** 971 (1993).
8. S. T. Yang, R. C. Echardt, and R. L. Byer, Opt. Lett. **18,** 475 (1993).
9. 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).
10. L. E. Myers, R. C. Eckardt, M. M. Fejer, R. L. Byer, and W. R. Bosenberg, Opt. Lett. **21,** 594 (1996).
11. S. T. Yang, R. C. Eckardt, and R. L. Byer, J. Opt. Soc. Am. B **10,** 1684 (1993).
12. S. Guha, F. J. Wu, and J. Falk, IEEE J. Quantum Electron. **QE-18,** 907 (1982).
13. In focusing the pump more tightly, we changed the focal length of the lens (see Fig. 1), moved the crystal to the new focus location, and adjusted the curvature and spacing of the OPO cavity mirrors to maintain the same mode matching between the pump and the OPO resonator.
14. A. J. Henderson, M. J. Padgett, F. G. Colville, J. Zhang, and M. H. Dunn, Opt. Commun. **119,** 256 (1995).