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CW Singly-resonant Optical Parametric Oscillators Based on 1.064-μm-pumped Periodically Poled $LiNbO_3$

Lawrence E. Myers
USAF Wright Laboratory, WL/AAJL, Wright-Patterson AFB OH 45433

Walter R. Bosenberg, Jason I. Alexander
Lightwave Electronics Corp., Mountain View CA 98019

Mark A. Arbore, Martin M. Fejer, Robert L. Byer
Stanford University, Ginzton Laboratory, Stanford CA 94305

Abstract

We report cw singly resonant optical parametric oscillators with thresholds <3 W, output powers >2.5 W at 3.3 μm, and tunable over 1.4-1.6 μm and 3.1-4.0 μm.

Key Words

Nonlinear optics-parametric processes, Parametric oscillators and amplifiers, Nonlinear optical materials, Nonlinear optical devices.

The better stability of singly resonant optical parametric oscillators (SROs) compared with doubly resonant optical parametric oscillators (DROs) is well known.[1] Equally well known is the 100x higher threshold of a SRO vs. that of a DRO. In the cw regime, much work has gone into stabilizing DROs; however, even with complex control loops and careful cavity design, continuous tuning is limited to <10 GHz.[2] The first cw SRO was demonstrated in 1993 using a custom-built resonantly-doubled single-frequency Nd:YAG pump laser with KTP, but significant tuning was not possible.[3, 4] Despite the limited utility of this device, it demonstrated the important result of stable SRO behavior from a cw OPO.

In this paper, we present cw SROs based on the recently-developed nonlinear optical material periodically poled $LiNbO_3$ (PPLN). The high gain, low loss, and widely-tunable noncritical quasi-phasematching of PPLN have been shown to be useful for OPOs pumped by low peak power lasers, e.g. high-repetition-rate Q-switched solid-state lasers, long-pulse Nd:YAG lasers, and commercial cw diode lasers.[5] These attributes have now enabled us to demonstrate practical cw SROs with stable, efficient, single-frequency output using simple cavities and commercially-available pump laser powers. Low threshold and adjustable quasi-phasematching of a PPLN SRO permit direct pumping with 1.064 μm for a useful source of coherent cw radiation tunable over the spectrally important mid-IR range from 1.3 μm to ~5 μm.[6]

The PPLN used in this work was fabricated with the same electric-field poling methods reported elsewhere.[5] Since the first QPM OPO was demonstrated with 5-mm-long PPLN in 1994, the length of available crystals has grown dramatically. The poling methods are now successfully applied to full 3"-diameter 0.5-mm-thick $LiNbO_3$ wafers. The crystals for this cw SRO were 50-mm long with 29.75 μm period, which quasi-phasematched at 1.57-μm signal and 3.45-μm idler with 1.064-μm pumping at 175 °C.

The experimental set-up is shown in Fig. 1. The pump laser is diode-pumped Nd:YAG producing 17 W cw of polarized multi-longitudinal-mode output at 1.064 μm. 13 W is available to pump the OPO. The pump beam is focused to a 97-μm waist radius in the crystal. The OPO resonator is a simple two-mirror symmetric linear cavity with round trip signal loss of ~2% and round-trip idler loss of >99%.

Fig. 2 shows the OPO output vs. pump input. The threshold of 4.5 W agrees reasonably well with a calculated value of 3.7 W for a single-frequency pump laser,[7] indicating that all the laser modes pump a single mode of the resonant wave in an SRO.[1] The focusing parameter for this measurement is $\xi = L/b = 0.42$ where L is the crystal length and b is the confocal parameter of the pump (or signal) in the crystal. By

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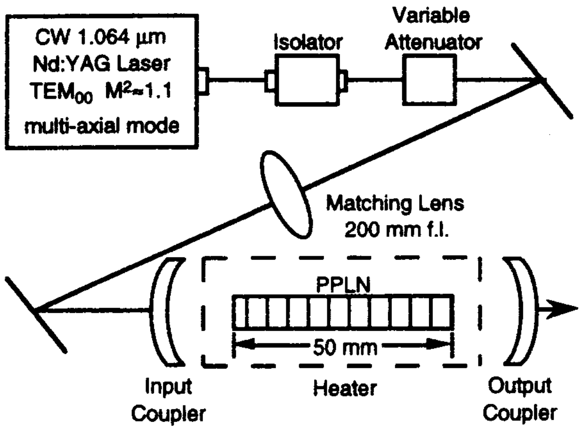

Figure 1. Experimental set up of cw SRO in PPLN. Mirrors have 50-mm radii of curvature and are separated by 104 mm. Reflectivities of the pump, signal, and idler are 2%, 99.7%, 3% for the input coupler, 14%, 99.5%, 11% for the output coupler, and 6%, 0.3%, 7% for each surface of the PPLN crystal.

focusing more tightly to give ξ = 0.62, 1.0, and 1.6, we lowered the oscillation threshold to 4.2 W, 2.9 W, and 2.6 W respectively. However, tighter focusing caused a sudden increase in amplitude noise of the OPO output when the pump power was raised above 1.7x threshold. This sudden increase in noise was very repeatable. It is not yet clear if this behavior is intrinsic to a cw SRO with tight focusing or an experimental effect (e.g. thermal). With loose focusing, low-noise operation was obtained even pumping 3x above threshold.

The spectral qualities of the OPO signal output were observed using solid etalons. Despite a pump laser linewidth of ~2.2 GHz FWHM corresponding to ~9 longitudinal modes, the resonated signal wave operated on a single longitudinal mode with linewidth <0.02 cm^{-1} (0.5 GHz). As shown in Fig. 3, the free-running OPO stayed on one longitudinal mode for 10-20 sec until drift of cavity length or temperature caused a mode hop. When the cavity length was scanned, the OPO stayed on a single cavity mode over >75% of the free spectral range, indicating the singly-resonant nature. For a comparable DRO, mode hops occur for 2-nm cavity length change or 3-MHz pump frequency shift, over two orders of magnitude more stringent than the tolerances of the SRO.[8, 9]

While this device can be temperature tuned, operation <110 °C is limited by photorefractive damage as shown in Fig. 4. Tuning by changing the quasi-phasematching period provides wide tunability at fixed temperature. Using a 25-mm long PPLN crystal with multiple grating sections[6] we tuned the output from 1.62-1.46 μm (signal) and 3.11-3.95 μm (idler), limited by losses of the optical coatings. With the right optics, this cw SRO can tune across the entire mid-IR transparency range of $LiNbO_3$ 1.3 μm to >4 μm.

We also operated the PPLN cw SRO using a four-mirror ring cavity in a bow-tie configuration. The threshold of this OPO was higher because of the additional optics, but it could be tightly focused without the increased noise seen in the linear cavity. The conversion efficiency was also much higher as shown in

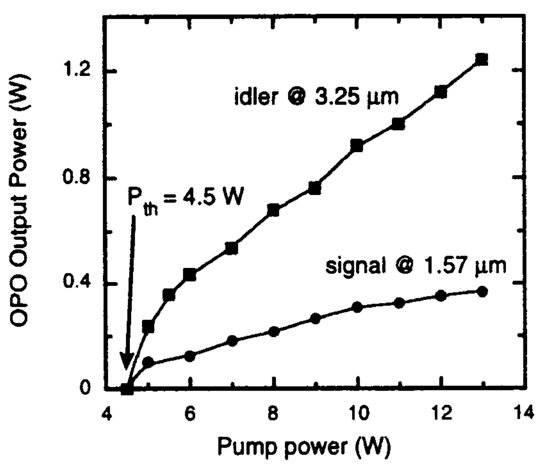

Figure 2. OPO output vs. pump input power for 29.75 μm period PPLN at 175 °C. The maximum output is 1.25 W at 3.25 μm pumping with 13 W at 3x above threshold. Signal power is low because of the low output coupling used. With tighter focusing, thresholds <2.6 W were obtained.

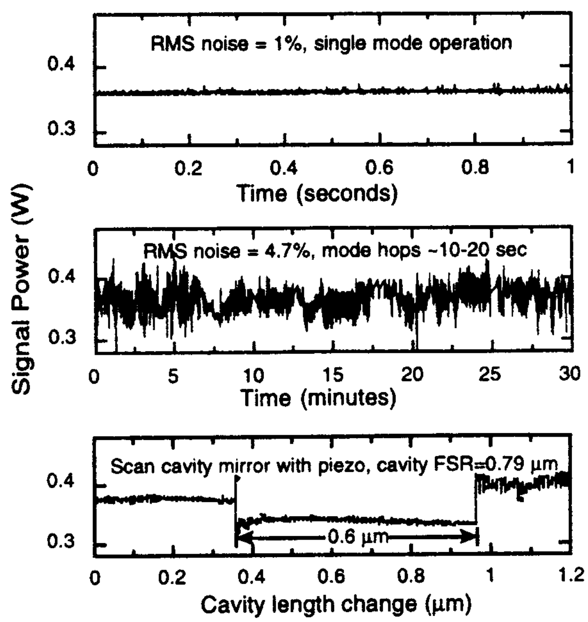

Figure 3. Stability of OPO signal power in PPLN cw SRO, with 6.7 W pump (2x threshold).

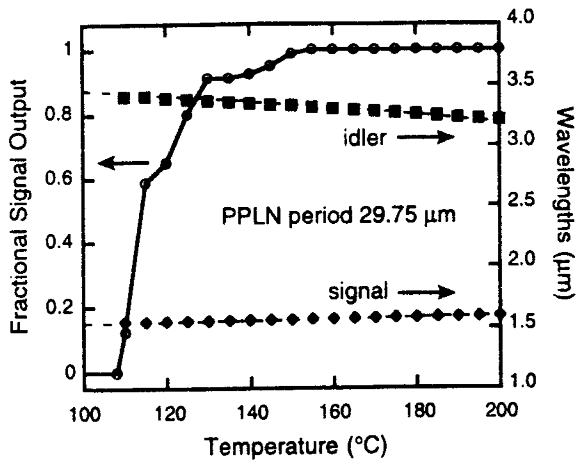

Figure 4. Heating the crystal eliminates photorefractive damage during OPO operation. Temperature tuning is possible as shown, but adjusting the quasi-phasematching period with a multi-grating PPLN chip gave broader tuning over 1.62-1.46 µm (signal) and 3.11-3.95 µm (idler) at 175 °C for PPLN periods 30-28 µm.

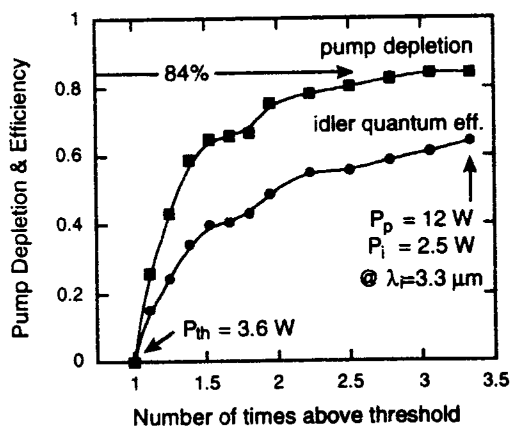

Figure 5. Pump depletion and idler quantum efficiency in the 4-mirror ring-cavity cw SRO. Pump depletion was 84% at 3x above threshold. Extracting this converted pump as idler was 76% efficient due to losses in the optical coatings. Idler power was 2.5 W with 12 W of pump for optical power conversion efficiency of 21%.

Fig. 5. Using the multi-grating piece described above, we obtained >1 W idler power over the tuning range 3-3.8 µm, and 0.6 W at 4 µm. The above-threshold behavior of cw SROs will be investigated in future experiments and theoretical modeling.

In conclusion, we have demonstrated practical implementations of cw SROs using PPLN. With simple OPO resonator designs, the threshold as low as 2.6 W is compatible with pumping with commercially available multi-longitudinal-mode cw-diode-pumped 1-µm lasers. The stability (~1 % rms), high conversion (>84 %), high power (2.5 W at 3.3 µm), and single-frequency output (<0.02 cm^{-1} linewidth) make these devices promising sources of coherent radiation tunable across the important mid-IR region.

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