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Continuous-wave 532-nm-pumped singly resonant optical parametric oscillator based on periodically poled lithium niobate

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We report a continuous-wave (cw) 532-nm-pumped singly resonant optical parametric oscillator (SRO) based on periodically poled lithium niobate. The pump source is a commercial 5-W cw diode-pumped, multilongitudinal-mode, intracavity-doubled Nd:YVO$_4$ laser. Using a four-mirror ring SRO cavity and single-pass pumping, we achieved subwatt internal oscillation threshold, 56% quantum efficiency, and output tuning from 917 to 1266 nm. © 1998 Optical Society of America

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Recent advances in engineerable nonlinear optical materials have permitted the development of a wide range of tunable coherent light sources based on quasi-phase matching (QPM). One such material, lithium niobate (LiNbO$_3$), has gained importance in QPM applications because it can readily be periodically poled and has a large nonlinear coefficient, transparency from the near ultraviolet through the mid infrared, and low cost. Among the numerous nonlinear optics applications of periodically poled LiNbO$_3$ (PPLN) now being explored, optical parametric oscillators are of increasing interest.[1–3]

The first cw singly resonant optical parametric oscillators (SRO's) were introduced by Yang *et al.* in 1992 and utilized KTiOPO$_4$ (KTP) as the nonlinear medium.[4,5] At the time, KTP offered the best available combination of material properties, such as high gain, low absorption loss, suitable temperature-acceptance bandwidth, and high damage threshold. By pumping at 532 nm with a resonantly doubled, single-frequency cw lamp-pumped Nd:YAG laser, an oscillation threshold of 4.3 W was achieved. This research demonstrated the high spectral purity, narrow linewidth, and high efficiency of cw SRO's as well as their greater stability compared with doubly resonant optical parametric oscillators with respect to pump-frequency and cavity-length fluctuations. However, because of to the limitations of type II noncritical phase matching, the KTP SRO could not be significantly tuned.

In 1996 Bosenberg *et al.* demonstrated the first cw quasi-phase-matched SRO.[6,7] This device was based on bulk PPLN as the nonlinear medium. With a quasi-phase-matched nonlinear coefficient of $d_Q \approx 14.4$ pm/V, substantially larger than that of type II noncritically phase-matched KTP ($d_{32} = 3.6$ pm/V),[1] the PPLN SRO reached an oscillation threshold of 3.6 W. The pump source for this device was a 1064-nm Nd:YAG laser, which required PPLN with a 29.75-μm domain period. With this period PPLN the idler was tuned from 3 to 4 μm, a significant improvement over that of the KTP SRO's. The milestones of their research were 80% conversion efficiency and maintaining single-longitudinal-mode oscillation in a ring SRO when it is pumped with a multilongitudinal-mode laser. At that time, fabrication of long samples of PPLN was not practical for domain periods shorter than ~20 μm, so efficient cw QPM was therefore limited to the mid-infrared spectrum.

Recently Miller *et al.* reported the fabrication of high-quality 0.5-mm-thick, 6.5-μm-domain-period PPLN over full 76-mm-diameter wafers of LiNbO$_3$.[8,9] The demonstration of 42%-efficient cw second-harmonic generation of 2.7 W of 532-nm radiation opened the visible spectral region to efficient cw single-pass interactions. In this Letter we report a cw 532-nm-pumped PPLN-based SRO with ~1-W threshold and output wavelengths in the near infrared.

The experimental setup is shown in Fig. 1. The pump laser was a Spectra-Physics Millennia, a 5-W cm 532-nm single-transverse-mode multilongitudinal-mode intracavity-doubled diode-pumped Nd:YVO$_4$ laser. The pump beam was mode matched into a four-mirror bow-tie ring cavity that formed the SRO resonator. The cavity comprised two 20-cm radius-of-curvature mirrors and two flat mirrors. The total empty-cavity optical path length was 116.6 cm.

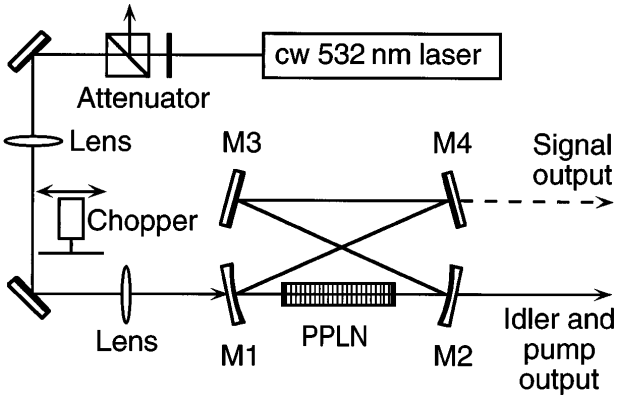

Fig. 1. Schematic diagram of the four-mirror bow-tie ring SRO. The pump was a cw 532-nm 5-W frequency-doubled Nd:YVO$_4$ laser. The cavity utilized two 20-cm radius-of-curvature mirrors (M1, M2) and two planar mirrors (M3, M4). All mirrors were highly reflecting at 900–1000 nm. The PPLN crystal was 53 mm long and 0.5 mm thick and had a grating period of 6.5 μm.

All four mirrors were highly reflecting from 900 to 1000 nm, and the combined mirror transmission at 1100–1200 nm was approximately 90%, thus making the cavity resonant at the signal wavelengths. The PPLN crystal was 53 mm long, 3 mm wide, and 0.5 mm thick, with a 6.5-μm domain period. The 6.5-μm domain period of the PPLN was chosen for phase matching at temperatures above ∼200 °C, thereby eliminating the effects of photorefraction.[1] In Ref. 9 we give a detailed description of the fabrication process for the PPLN. Both end faces of the PPLN crystal were antireflection- (AR-) coated to 800–1100 nm. The coatings were evaporation deposited at a 100 °C substrate temperature to ensure good adhesion when the crystal was heated during operation. The PPLN crystal was mounted in an oven located at the waist of the SRO cavity. The SRO cavity mode had a 64-μm waist and was thus confocally focused in the PPLN crystal. The SRO optics were not optimized for transmission at 532 nm, with each mirror and AR-coated crystal surface having a pump transmission of ∼88%. The combined pump power loss from the SRO input mirror and the AR-coated PPLN input face was 22.6%.

Absorption of 532-nm pump radiation in the PPLN crystal caused thermal lensing and beam pointing instability of the transmitted pump and the idler beams. With increasing 532-nm power these effects intensified, and oscillation became unstable. We reduced these losses by modulating the pump with a 50%-duty-cycle mechanical chopper at 2 kHz. With lower average 532-nm power in the PPLN, lower threshold, stable oscillation, and fixed spot sizes of the transmitted pump and idler were observed. Figure 2 is a plot showing 1192-nm internal idler power (squares) and pump depletion (circles) versus internal pump power. Because the SRO mirrors and the PPLN AR coatings were not optimized for transmission at 532 nm, the pump power levels are presented in terms of power internal to the PPLN crystal. Internal idler power is determined as the idler power measured at the output of mirror M2 (see Fig. 1) adjusted by a factor of 4.3 to account for Fresnel and mirror losses. The data in Fig. 2 were taken with the pump modulated as described above. Both pump and idler power levels represent peak power during the approximately square-wave chopper cycle. The oscillation threshold was 0.93 W internal to the PPLN crystal, 1.06 W at the input face of the PPLN crystal, and 1.2 W at the SRO input mirror. With 3.3 W of internal pump power the internal idler power was 0.82 W, giving a 78% idler quantum slope efficiency internal to the PPLN crystal. Residual loss limited pump depletion to 60% and internal quantum efficiency to 56% for 3.3 W of internal pump power. Despite this loss, the PPLN's large parametric gain of ∼8.5%/W (Ref. 10) allowed us to maintain cw SRO operation by using two other cw 532-nm pump lasers; a 2-W Spectra-Physics Millennia II and a 9-W Nd:YAG Lightwave Series 220, which we single-pass frequency doubled in PPLN.

We extracted signal power from the SRO by replacing mirror M4 with a planar 96% reflector at the 961-nm signal wavelength. Figure 3 shows plots of output power for both the 961-nm signal and the 1192-nm idler versus pump power internal to the PPLN in this output-coupled cavity. The signal power and the idler power were measured at the outputs of mirrors M4 and M2, respectively. The pump was again modulated at 2 kHz with a 50% duty cycle, and pump, signal, and idler power levels represent peak power during the chopper cycle. With the added mirror loss the oscillation threshold increased to ∼1.8 W internal to the PPLN. No significant beam-steering or thermal lensing effects were observed in the output beams for internal peak pump powers up to the available 3 W.

Figure 4 shows the SRO output wavelengths as a function of the temperature of the PPLN crystal. Using the mirror set described in Fig. 1, we heated the crystal from 212 to 260 °C, achieving signal tuning from 988 to 917 nm and idler tuning from 1151 to

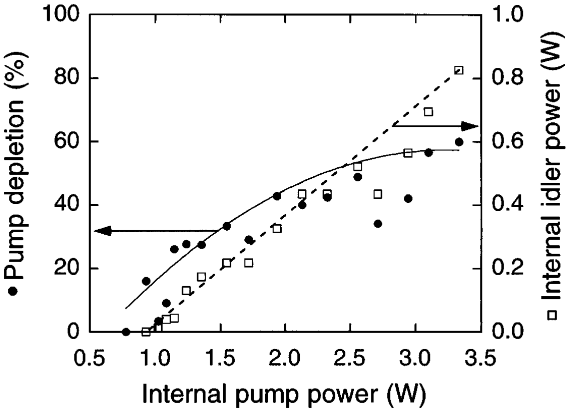

Fig. 2. Pump depletion and idler power internal to the PPLN crystal versus pump power internal to the PPLN crystal. To reduce thermal loading of the PPLN at 532 nm, a 50%-duty-cycle mechanical chopper was used to modulate the pump. Pump and idler power levels represent peak power during the chopper cycle.

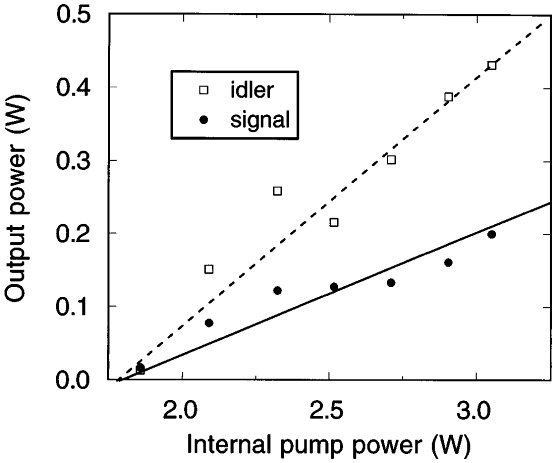

Fig. 3. Output power of the 961-nm signal and the 1192-nm idler versus pump power internal to the PPLN crystal for the output-coupled cavity. A planar $R = 96\%$ at 961-nm reflector was used as an output coupler for the resonated signal. The pump was modulated with a 50%-duty-cycle chopper, and power levels represent peak power during the chopper cycle.

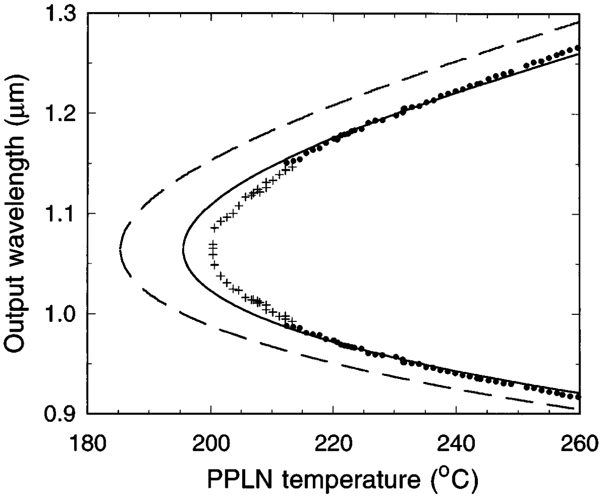

Fig. 4. Wavelength tuning versus temperature for the SRO. The 6.5-μm-domain-period PPLN was heated from 200 to 260 °C, tuning the output from 917 to 1266 nm. Two mirror sets were utilized, one set optimized for off-degenerate tuning (circles) and a second set optimized for near-degenerate tuning (crosses). Double resonance was observed at phase matching very near degeneracy. Two theoretical tuning curves are calculated from the temperature-dependent Sellmeier equations for the index n_e in congruent $LiNbO_3$ of Edwards and Lawrence[11] (dashed curve) and Jundt[12] (solid curve).

1267 nm (circles). We achieved near-degenerate oscillation, with signal tuning from 1059 to 992 nm and idler tuning from 1065 to 1147 nm, by replacing both flat cavity mirrors with flat 1064-nm high-reflector mirrors and heating the crystal from 200 to 213 °C (crosses). We noted the turning on of double resonance at phase matching very near degeneracy with signal and idler mode hopping. Two theoretical tuning curves are also shown in Fig. 4. These curves were calculated from the temperature-dependent Sellmeier equations for the index n_e in congruent $LiNbO_3$ as published by Edwards and Lawrence[11] (dashed curve) and recently by Jundt[12] (solid curve). Good agreement was observed with the Sellmeier equation of Jundt, whereas, as has been reported elsewhere, the actual phase-matching temperature for SRO degeneracy is approximately 15 °C higher than that calculated by Edwards and Lawrence.[1,2,8,9]

We characterized the loss mechanism in PPLN by examining 532-nm-induced IR absorption in the crystal. We focused 180 mW of 1064-nm radiation from a cw single-frequency Nd:YAG laser to a 64-μm waist in the PPLN crystal. This IR beam was aligned collinearly with the cw 532-nm pump beam. Both beams were unchopped, and the crystal was heated to a non-phase-matching temperature of 216 °C. The total insertion loss of the PPLN at 1064 nm, without 532-nm light present, was ~0.5%. With 532-nm power levels of ~1 W present internal to the PPLN the transmitted IR power was reduced by approximately 4%. This transmission loss scaled approximately with the square of the pump power for internal pump powers of 0–1 W. When the 532-nm beam was blocked the IR transmission recovered to the original 0.5% loss with a time constant of ~20 s. This 4% green-induced IR loss is consistent with the SRO threshold measurements introduced above, assuming a quadratic dependence of IR absorption of 532-nm intensity. A more detailed study is necessary to elucidate this green-induced IR absorption in PPLN.

To summarize, we have demonstrated a cw PPLN-based SRO pumped by a 532-nm multilongitudinal-mode diode-pumped frequency-doubled Nd:YVO_4 laser. Because of the large effective nonlinear coefficient and the long interaction length of the PPLN, subwatt internal threshold, 56% conversion efficiency, and output tuning from 917 to 1267 nm were achieved. Although device performance was limited by 532-nm-induced IR absorption and thermal lensing in PPLN, the crystal's large parametric gain permitted simple and reliable SRO operation with a variety of commercial pump lasers. Future research will focus on reducing these losses and on improving material yield at domain periods under 6 μm for further visible light interactions.

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