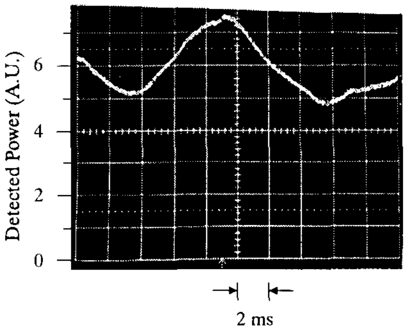


CThG1 Fig. 1 Interference between the YAG local oscillator (LO) and the self-phase-locked OPO outputs as the LO phase is scanned.

squeezed light generation. Self-phase locking is of particular interest because it suppresses the usual phase diffusion noise in the relative phase between the signal and idler without any external feedback control. It was first demonstrated in a type-I phase-matched MgO:LiNbO$_3$ OPO[1] in which the signal and idler waves were truly degenerate when their frequencies were equal. However, self-phase locking has not been observed in conventional type-II phase-matched OPOs because the orthogonally polarized signal and idler are always nondegenerate even at frequency degeneracy.

Self-injection locking can be induced in a type-II phase-matched OPO by use of an intracavity quarter-wave plate (QWP). In a linear cavity a double pass through a QWP is equivalent to rotating the angle of polarization by an amount that is determined by the relative angle between the QWP's fast (or slow) axis and the KTP's z axis. By setting this angle at a few degrees, part of the polarized signal wave (whose polarization is defined by the crystal's axes) is rotated by 90° and superimposed onto the orthogonally polarized idler wave, and vice versa. This polarization mixing provides the means for mutual injection locking when the OPO is tuned near frequency degeneracy within the capture range.

We have constructed a doubly resonant KTP OPO with an intracavity QWP. The angle between the QWP's fast axis and the KTP's z axis was set at $\rho = 5°$ and the QWP was aligned nearly perpendicular to the propagation axis. Pumped by the second harmonic of a 1064-nm YAG laser, the threshold was ~65 mW with or without the QWP. The OPO was operated at a pump power of 130 mW and was angle- and temperature-tuned to bring the OPO toward frequency degeneracy. We observed robust self-phase locking when the output frequencies came within the capture range of ~150 MHz from frequency degeneracy for a cavity-free spectral range (FSR) of 3 GHz. Figure 1 shows the interference signal between the self-phase locked OPO outputs and a local oscillator (LO) derived from the YAG laser as the LO phase was swept. In addition, we confirmed the self-phase locking condition by acousto-optically frequency shifting the LO by 80 MHz and observing the beat note between the LO and the OPO outputs.

We have also observed self-phase locking in a longer OPO cavity with a FSR of 1 GHz. While the finesse of the longer cavity was similar to that of the shorter cavity, its capture range was considerably smaller: ~25 MHz for $\rho = 7°$ and ~7.5 MHz for $\rho = 2.5°$. The smaller capture range is attributed to the smaller cavity linewidth and a reduction in the spatial overlap between the signal and idler beams which are their walkoff angle of 0.2°.

1. C. D. Nabors, S. T. Yang, T. Day, R. L. Byer, J. Opt. Soc. Am. **B7**, 815 (1990).

CThG2 10:45 am

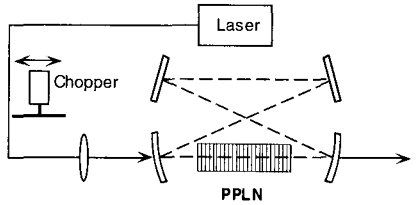
Continuous-wave 532-nm-pumped singly resonant optical parametric oscillation in periodically poled lithium niobate

Robert G. Batchko, Dennis Weise, Tomas Plettner, Gregory D. Miller, Martin M. Fejer, Robert L. Byer, *E. L. Ginzton Laboratory, Stanford University, California 94305-4085; E-mail: rgb@loki.stanford.edu*

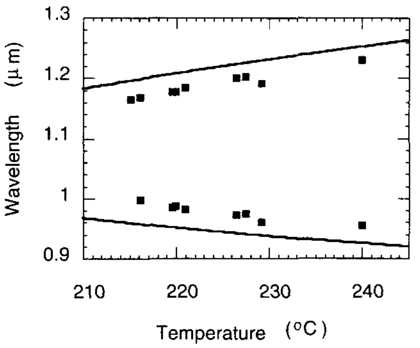
Continuous wave (cw) singly resonant optical parametric oscillators (SROs) have recently been shown to be highly efficient sources for broadly tunable radiation with threshold and output powers of several watts.[1] The performance demonstrated in these devices results from the high gain, low loss, and engineerability of periodically poled lithium niobate (PPLN).[2] In this work we extend the operation of PPLN-based cw SROs to sub-watt threshold utilizing a commercial 532-nm pump laser.

The experimental setup is shown in Fig. 1. The pump is a single-transverse-mode, multilongitudinal-mode intracavity-doubled diode-pumped Nd:YAG laser.[3] The laser has an output of ~5 W at 532 nm. The pump laser is mode-matched to the 64-μm waist (radius) of a "bow-tie" ring OPO cavity. The cavity has two 20-cm radius-of-curvature mirrors and two flat mirrors. The 5.3-cm-long, 0.5-mm-thick PPLN crystal has a 6.5-μm period for first order quasi-phase matching and is antireflection coated for the signal and idler waves from 0.8–1.1 μm. The round-trip cavity loss of the signal wave is ~6% and feedback for the idler wave is <5%.

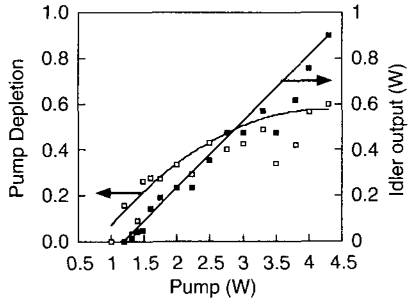
Figure 2 shows temperature tuning of the SRO. We heated the PPLN crystal from 215–242 °C obtaining continuous tuning from 953–1000 nm and 1160–1234 nm for the idler and signal wavelengths, respectively. The theoretical curve is derived from published Sellmeier coefficients for LiNbO$_3$.



CThG2 Fig. 1 Schematic of the SRO four mirror "bow-tie" ring cavity utilizing two 20 cm radius-of-curvature and two flat mirrors. The PPLN crystal is 5.3-cm long, 0.5-mm thick and has a grating period of 6.5 μm for first order quasi-phase-matching of the 532 nm pump at >200 °C.



CThG2 Fig. 2 Temperature tuning data for the SRO. The PPLN crystal was heated from 216–228 °C producing continuous tuning from 953–1000 nm and 1160–1233 nm for the signal and idler wavelengths, respectively. The theoretical curve is derived from published Sellmeier coefficients for LiNbO$_3$. The 15 °C offset between experiment and theory has also been observed in SHG with use of the same material.



CThG2 Fig. 3 Pump depletion and idler peak output power versus peak pump power incident on the curved input mirror. Idler quantum slope efficiency is 89%.

Thermal lensing in the PPLN, resulting from 532 nm absorption, increased cavity losses resulting in an oscillation threshold of ~2.2 W. Chopping the pump with a 50% duty cycle at 0.1–2 kHz reduced thermal focusing in the PPLN, resulting in a threshold peak power of 1.2 W at the input mirror and <1 W at the face of the PPLN crystal. Figure 3 shows pump depletion and idler peak output power as functions of peak pump power for chopped pump operation. The PPLN was heated to 220 °C to operate at signal and idler wavelengths of 960.6 nm and 1192 nm. At 4.3 W peak pump power at the input mirror, 0.9 W of idler peak output power was generated. At pump powers up to the available 3.6 times threshold, the idler quantum slope efficiency taken inside the PPLN crystal was 89%. At 3.6 times threshold, pump depletion was 60% and idler peak output was 0.9 W, achieving a quantum efficiency of 64%.

In summary, we demonstrated a low threshold cw SRO pumped by a commercial 532 nm multimode laser and obtained 0.9 W of idler peak output power and quantum efficiency of 64%. Thermal focusing effects in the PPLN were reduced but not completely eliminated by chopping the pump with a 50% duty cycle, so future work will focus on characterizing and reducing the thermal focusing in LiNbO$_3$.

1. W. R. Bosenberg, A. Drobshoff, J. I. Alexander, L. E. Myers, R. L. Byer, Opt. Lett. **21,** 17 (1996).
2. W. R. Bosenberg, A. Drobshoff, J. I. Alexander, L. E. Myers, R. L. Byer, Opt. Lett. **21,** 713 (1996).
3. Spectra Physics *Millennia.*

CThG3 11:00 am

Continuous-wave intracavity optical parametric oscillators

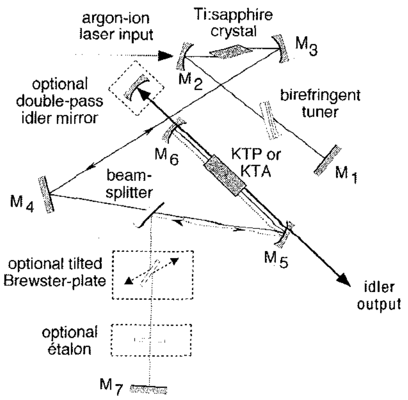
F. G. Colville, T. J. Edwards, G. A. Turnbull, M. H. Dunn, M. Ebrahimzadeh, *J. F. Allen Physics Research Laboratories, School of Physics & Astronomy, University of St Andrews, Fife KY16 9SS, Scotland; E-mail: fgc@st-and.ac.uk*

Continuous-wave (cw) singly resonant intracavity optical parametric oscillators (OPOs) are attractive sources for generating high-power, narrow-linewidth, stable radiation in the near-infrared.[1,2] Recent progress in this new field is outlined herein, including a comparison between KTP and KTA, étalons to stabilize the single-frequency output, and techniques for optimizing the output powers for the resonant or nonresonant OPO fields.

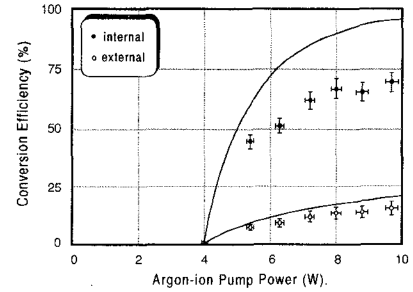
The Ti:sapphire (TIS) lasers are longitudinally pumped by low-power argon-ion lasers and configured to accommodate two intracavity tightly focused spots (Fig. 1). They operate with high intracavity powers by minimizing resonator loss and tuning around the peak of the gain profile. One-way circulating powers of 50 W are available to surpass singly resonant OPO thresholds. Spatial hole burning, characteristic of the standing-wave laser, results in a pump bandwidth of 20 GHz.

The OPO is formed by dual pump/signal high-reflectors as mirrors M_5 and M_6, and a dichroic-coated beamsplitter to discriminate the resonant pump and signal. An external mirror M_7 defines the OPO cavity. Mirrors M_5 and M_6 are antireflecting at the long-wavelength idler.

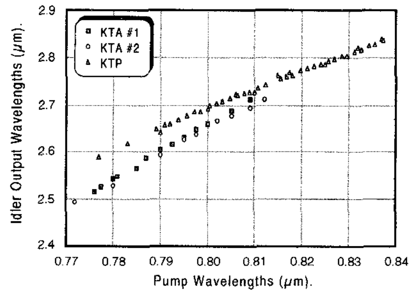
The idler output is optimized by maximizing the total downconverted power, achieved by carefully choosing the ratio of TIS to OPO thresholds.[2] At 9.7 W argon-ion input, the downconverted OPO power is 1.5 W; ≈70% of the maximum power provided by the TIS in the absence of nonlinear conversion. Of this downconverted power, 160 mW exits single-pass from mirror M_5 (and M_6) as the nonresonant idler wave. Figure 2 illustrates the OPO efficiency.



CThG3 Fig. 1 Schematic representation of the intracavity cw singly resonant optical parametric oscillator.



CThG3 Fig. 2 Intracavity OPO conversion efficiencies. The internal efficiency is defined as the ratio of the downconverted OPO power to the maximum Ti:sapphire power that can be generated in the absence of nonlinear conversion and with optimum output-coupling. The external efficiency is the ratio of the downconverted OPO power to the input argon-ion pump power. The points are experimental: the curves are from theory.



CThG3 Fig. 3 Idler tuning ranges by use of KTP and KTA nonlinear crystals.

Modifications to the OPO cavity (from beamsplitter to M_7) affect significantly the OPO performance. An uncoated plate rotated off Brewster's angle acts as a variable output-coupler for the resonant OPO wave, and can be optimized to extract the narrow-linewidth, single-frequency resonant wave. This optimization procedure is different than that above, resulting in higher threshold clamping levels and lower intracavity signal fields; power levels of ≈0.4 W for the resonant signal wave are expected when optimized. An alternative method is to replace the high-reflecting mirror M_7 with specific output-couplers. Both schemes will be discussed. Under free-running conditions, hopping between resonant cavity modes occurs typically on millisecond timescales.[2] However, the addition of an uncoated étalon is sufficient to sustain operation on the same single-axial-mode for periods in excess of ≈1 minute under free-running conditions. Absolute frequency stabilization and fine frequency tuning of the resonant wave are areas under investigation.

The OPO threshold can be halved by double-passing the idler field either at mirror M_6 or by an externally located piezomounted idler reflector. A comparison of these two techniques will be discussed. An additional benefit is that the idler output power is produced in one direction only.

The flexibility of the design permits coarse frequency tuning by incorporating different nonlinear materials within the laser cavity or by tuning the TIS laser. The use of KTP and KTA have resulted in signal (idler) outputs from 1.11 to 1.19 μm (2.5 to 2.8 μm); Fig. 3. The extension to longer wavelengths by use of new nonlinear crystals and solid-state pump sources will also be addressed.

1. F. G. Colville, M. H. Dunn, M. Ebrahimzadeh, CLEO/Europe 1996, paper CPD1.5.
2. F. G. Colville, M. H. Dunn, M. Ebrahimzadeh, to be published in Opt. Lett. **22** (1997).

CThG4 11:15 am

Focusing effects, conversion efficiency, and instabilities in singly resonant optical parametric oscillators

Shekhar Guha, L. E. Myers, R. C. Eckardt, *USAF Wright Laboratory, WPAFB, Ohio 45433*

The dependence of the oscillation threshold of a singly resonant optical parametric oscillator (SRO) on the focusing parameters of the pump and signal beams has long been determined,[1,2] but a similar study describing the focusing effects on the SRO conversion efficiency is not available in the literature for the general case of arbitrary focusing parameters. Recently, with the development of novel materials such as periodically poled $LiNbO_3$, high conversion efficiency has been demonstrated in cw SRO operation.[3] In some cases instability is observed a few times above threshold.[4] A theoretical analysis of the SRO efficiency is needed now not only to explain the observed SRO behavior but also to further improve the performance by optimization of the beam parameters.

We used a Green's function method[1] and a perturbation analysis of parametric interactions to derive closed-form expressions for the SRO conversion efficiency. The perturbation analysis consists of expressing the pump and the idler electric fields as series in powers of d, the nonlinear optical coefficient, and retaining terms in identical powers of d. For example, the pump and the idler fields are written as

$$E_p = E_p^{(0)} + d^2 E_p^{(2)} + d^4 E_p^{(4)} + \cdots,$$

$$E_i = d\, E_i^{(1)} + d^3 E_i^{(3)} + d^5 E_i^{(5)} + \cdots,$$

where $E_p^{(0)}$ is the incident pump beam. The resonating signal field is assumed to be constant in power, $E_s = E_s^{(0)}$, its beam shape determined by the resonator cavity and its power determined by the incident pump power.

The parametric interaction of $E_p^{(0)}$ and $E_s^{(0)}$ generate the first-order idler field $d\, E_i^{(1)}$. This idler field mixes with the signal field to generate the second-order pump field $d^2 E_p^{(2)}$, which in turn mixes with the signal field to generate the third-order idler field $d^3 E_i^{(3)}$, and so on. Knowing the focusing parameters of $E_p^{(0)}$ and $E_s^{(0)}$, all the terms in the series can be evaluated in terms of integrals. The gain in the signal