

Continuous-wave singly resonant optical parametric oscillator placed inside a ring laser

Haim Abitan and Preben Buchhave

A cw singly resonant optical parametric oscillator (SRO) was built and placed inside the cavity of a ring laser. The system consists of a diode-end-pumped Nd:YVO₄ ring laser with intracavity periodically poled lithium niobate as the nonlinear gain medium of the SRO. When the laser was operated in a unidirectional mode, we obtained more than 520 mW of signal power in one beam. When the laser was operated in a bidirectional mode, we obtained 600 mW of signal power (300 mW in two separate beams). The power and the spectral features of the laser in the unidirectional and bidirectional modes were measured while the laser was coupled with the SRO. The results show that it is preferable to couple a SRO with a unidirectional ring laser. © 2003 Optical Society of America

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1. Introduction

A tuneable cw coherent light source that has a single frequency, low rms power fluctuations, and a single TEM₀₀ spatial mode is a most desirable device for many spectroscopic applications. One possible method to obtain such a source is to construct an optical parametric oscillator (OPO).

In early research, the double-resonance OPO (DRO) was investigated. In this device, a second-order nonlinear crystal is placed inside an optical resonator. This crystal is designed so that two waves, a signal and an idler, could resonate in the cavity. The threshold of a cw DRO is relatively low. In 1993 Schiller and Byer¹ constructed a total-internal-reflection DRO with 0.4-mW pump threshold. However, early experiments with DRO showed that the simultaneous requirements for phase matching and energy conservation of the resonating signal and idler impose severe restrictions on the length of the optical cavity and on the spectral fluctuations of the pump. In effect, it is difficult to sustain stable operation in terms of frequency and power (owing to mode hopping). In a DRO one must use elaborate techniques to stabilize the laser frequency and the

DRO cavity length. Owing to these complications, the DRO could be used mainly in research laboratories.

On the other hand, in a singly resonant OPO (SRO), only one wave is in resonance at any time (the signal or the idler) within the optical cavity, and the constraint upon the cavity length is alleviated. It was predicted that the operation of the SRO would be stable without mode hopping at the cost of a high threshold, about 100 times larger than that of the DRO. Therefore it required a high pumping power that was accessible only from pulsed lasers. For that reason, pulsed SRO emerged as the first practical tuneable source to be commercially available (Chromatix, Spectra-Physics MOPO-700 series and a few others).

In the past few years, new laser techniques have been applied and solid-state diode-pumped lasers and high-gain nonlinear crystals, e.g., periodically poled crystals have been exploited, removing the high threshold hurdle of the SRO and allowing the cw SRO to become a reality.

In 1992 that Yang *et al.*² built and demonstrated the operation of the first external-cavity cw SRO. The researchers used a KTP crystal as the nonlinear gain medium and pumped it with a powerful single-frequency 532-nm second harmonic of a Nd:YAG laser. They obtained single frequency signal and idler outputs without mode hopping.

In 1996 Bosenberg *et al.*³ built the first external-cavity cw SRO with the novel gain medium (at that time) known as periodically poled lithium niobate (PPLN). The quasi-phase-matching method allows

The authors are with the Department of Physics, Denmark Technical University, DK-2800 Lyngby, Denmark. H. Abitan's e-mail address is abitan@fysik.dtu.dk.

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In 1997 Colville *et al.*⁴ built the first intracavity cw SRO. Originally, this configuration was proposed for use in a DRO in 1962 by Kroll⁵ and was analyzed by Oshman⁶ in 1968. In intracavity configuration, one places the SRO inside the laser cavity and takes advantage of the high field inside the laser resonator to attain the relatively high threshold power that is required for the SRO. Colville *et al.* used an argon-ion laser to pump a standing-wave Ti:sapphire laser. The Ti:sapphire cavity hosted an intracavity SRO, with KTP as the nonlinear gain medium. The researchers tuned the OPO by tuning the Ti:sapphire frequency with a birefringence filter. They successfully converted the whole available pump power (as if an optimum coupler were used) to an idler output power. In 1998 Stothard *et al.*⁷ reported on a standing-wave diode-pumped Nd:YVO₄ laser with intracavity SRO that hosts a PPLN. The threshold was relatively low (310 mW of the diode pump), and the researchers managed to extract 70-mW idler power. The same group reported on the operation of the same Ti:sapphire laser system, but instead of the KTP crystal they used other quasi-phase-matched crystals: PPLN,⁸ PPRTA,⁹ and PPKTA.¹⁰

Schneider *et al.*^{12,13} used a stabilized monolithic single-frequency Nd:YAG with 1-kHz linewidth to pump a pump-enhanced external-cavity SRO with PPLN. They observed single-frequency operation of the signal and the idler without mode hopping with a 5-MHz linewidth. The spectral characteristics of the signal and the idler showed a dependency on the temperature stability of the PPLN and on the spectral characteristics of the pump. Yang *et al.*^{2,14} reported on an external-cavity SRO with KTP as the nonlinear gain medium. The signal and idler outputs were made of a single frequency when the pump was made of a single frequency. Bosenberg *et al.*¹⁵ reported on a single-frequency SRO with PPLN as

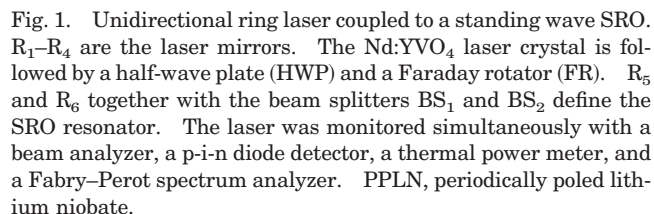


Fig. 1. Unidirectional ring laser coupled to a standing wave SRO. R_1 – R_4 are the laser mirrors. The Nd:YVO₄ laser crystal is followed by a half-wave plate (HWP) and a Faraday rotator (FR). R_5 and R_6 together with the beam splitters BS₁ and BS₂ define the SRO resonator. The laser was monitored simultaneously with a beam analyzer, a p-i-n diode detector, a thermal power meter, and a Fabry–Perot spectrum analyzer. PPLN, periodically poled lithium niobate.

In this paper we report on a system that consists of a SRO with PPLN as its nonlinear gain medium. The SRO is placed inside the cavity of a diode-pumped Nd:YVO₄ ring laser (lasing at 1064 nm). We operated the laser in a unidirectional mode and in a bidirectional mode and measured the output power of the SRO. In the unidirectional mode, the laser operated with a single axial mode, and we obtained 520 mW of signal power at a 6-W diode pump in a single-beam. When the laser was operated in the bidirectional mode (with multiaxial modes), we obtained 600 mW of signal power (two beams with 300 mW each) at the same diode-pump power. This is, to the best of our knowledge, the most powerful all solid-state intracavity cw SRO. In addition to being an efficient laser for generation of a powerful SRO, we find that the single-frequency operation and the low-power fluctuations of a unidirectional laser are preserved while it is coupled with the SRO.

Figure 1 illustrates the configuration of the SRO we built: a diode-pumped Nd:YVO₄ ring laser coupled to a SRO. The nonreciprocal Faraday rotator combined with the reciprocal half-wave plate and the polarized gain in the Nd:YVO₄ laser crystal act as an optical rectifier, thereby forcing the laser into unidirectional operation. We operated the laser in a unidirectional mode or a bidirectional mode by inserting or removing the Faraday rotator and the half-wave plate.

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ters BS₁ and BS₂ are made of a BK7 glass. They are coated for high transmission at the pump and signal ($T = 99.5\%$ at 1064 nm and $T \approx 95.4\%$ for 1.8–2 μm) and high reflectivity at the idler ($R = 99.9\%$ at 2.4–2.7 μm). Mirrors R₅ and R₆ of the SRO have –100 mm radius of curvature with the same coatings as the beam splitters.

The PPLN crystal (Deltronic, Santa Ana, Calif.) with dimensions of 30 mm $\times$ 10 mm $\times$ 0.5 mm has one poling period of 31 μm . The two end faces of the PPLN crystal were optically polished and had multi-layer antireflective coating: $R < 0.5\%$ at 1064 nm and $R < 0.5\%$ at 2200–2500 nm (the wavelength of the resonating idler). We operated the crystal at a temperature range of 160–177 °C. Operation at high temperatures is advantageous for the efficient annealing of the crystal from its photorefractive effect. The features of the laser beam were monitored by continuous and simultaneous measurements (see Fig. 1).

A beam analyzer (Version 6.4, Melles Griot) monitored the beam shape of the laser beam that is transmitted through mirror R₃. A p-i-n silicon (PDA50, Thorlabs) detector connected to an oscilloscope (Tetronix) monitored the dynamics of the power levels of the laser in short time scales (seconds to microseconds). The detector was placed so that it would capture the beam transmitted through mirror R₆ of the SRO. A thermal power meter (Melles Griot broadband power/energy meter calibrated to the range of 200–20000 nm) measured the signal power transmitted through BS₁ and mirror R₁. The thermal power meter could detect power fluctuations of the signal in a second time scale. A Fabry–Perot spectrum analyzer (Spectra-Physics model 470, 2-GHz free spectral range and 6.7-MHz bandwidth) monitored the axial modes of the laser. It was placed in front of mirror R₂.

First, the cw bidirectional laser was examined with mirrors R₁–R₄ positioned in bow-tie configuration, as seen in Fig. 1. We designed the resonator so that it would have a waist of 300 μm at the laser crystal (for optimal mode matching with the diode laser pump) and a 67- μm waist between mirrors R₁ and R₂ (where the PPLN would be placed). After aligning the laser we measured a total intracavity cw power of 120 W (60 W in each direction) at 6-W diode pumping. Then the two beam splitters BS₁ and BS₂ were inserted and aligned so that the angle of incidence of the laser beam to the plane of the beam splitters was 30°. At this configuration we measured 90-W intracavity power (45 W in each direction). The p-i-n silicon detector showed 10% rms power fluctuations in second and microsecond time-scales. The Fabry–Perot analyzer showed random hopping of several axial modes. The beam analyzer indicated a dominant TEM₀₀ competing with higher transverse modes.

We inserted the Faraday rotator and the half-wave plate. The laser operated in a unidirectional mode. It had 0.25% power fluctuations in microsecond and second time scales. The Fabry–Perot analyzer indi-

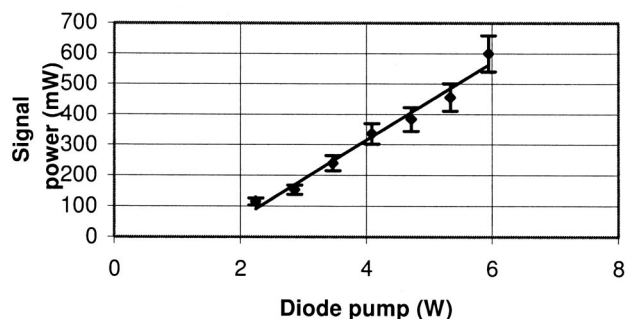


Fig. 2. Signal output versus diode pump power when the laser is bidirectional. The output power of the signal was measured with a thermal power meter. The power was emitted in two separate beams.

cated that the laser operated in a single axial frequency for typically 30 s before mode hopping appeared. The beam analyzer showed a stable TEM₀₀ transverse mode.

We removed the Faraday rotator and the half-wave plate, and the laser returned to being bidirectional. The PPLN was placed between the beam splitters along the path of the laser beam. The resonator was readjusted slightly (to compensate for the optical length of the PPLN and its thermal lens), and the maximum intracavity power that we could obtain at 6 W of diode pumping was 36 W (18 W in each direction).

We observed similar power and spectral characteristics as we had observed for a bidirectional laser without the PPLN. The beam analyzer showed slow modulation of the beam profile. This was caused by the annealing of the PPLN from its photorefractive effect.

We continued by aligning the mirrors of the SRO until we obtained the optimal signal output power of 600 mW (two separate beams of 300 mW). Considering the transmission loss of the signal from BS₁ (5%) and R₁ (29%), this power corresponds to generation of 900-mW signal and 678-mW idler with 26% optical-to-optical conversion efficiency.

We measured the characteristics of the bidirectional ring laser as it was coupled with the SRO. The power characteristics of the laser beam in time scales of seconds down to microseconds were examined with the p-i-n detector. The laser power had 10% rms power fluctuations in second and microsecond time scales. We noticed from the simultaneous measurements of the Fabry–Perot analyzer and the p-i-n detector that there was a level of correlation between the laser power fluctuations and the random competition between its axial modes. When a high level of power fluctuations were observed with the PIN detector, we noticed a simultaneous increase in the erratic hopping of the laser axial modes.

A thermal power meter measured the output power of the signal in the bidirectional mode. This measurement is given in Fig. 2. Around threshold (2-W diode pump) the SRO operated in bursts. The points of measurements in Fig. 2 are above threshold from

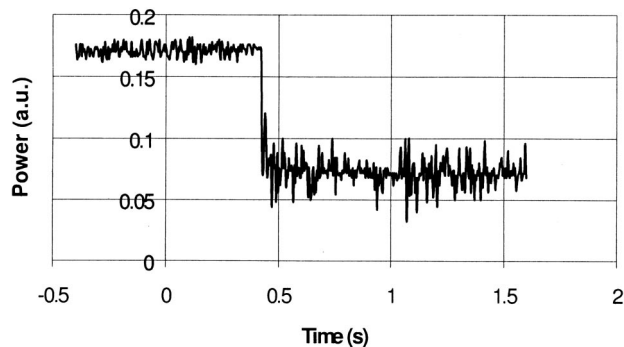


Fig. 3. Bidirectional laser power as monitored with a p-i-n detector. When the SRO was turned on, we observed a sharp drop in the laser power. The power fluctuations of the coupled-laser SRO are typical for every level of diode pump. High-power fluctuations were observed simultaneously with intense bursts of mode hopping of the axial modes of the laser.

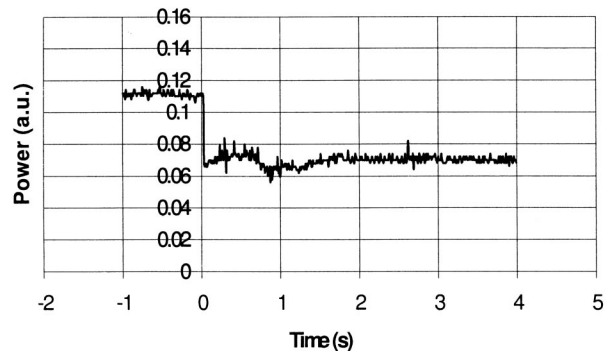


Fig. 5. Unidirectional laser power as monitored with a p-i-n detector. When the SRO was turned on we observed a drop in the laser power. The power fluctuations of the laser when it is coupled to the SRO are typical for every level of pumping. The slow power fluctuations are due to the photorefractive effect in the PPLN.

where we started to observe stable signal power with 10% rms power fluctuations. The power is the sum of the power that is emitted from two separate beams. Figure 3 shows the power of the laser when the SRO is off and on (by unblocking the path of the idler). The coupled operation of the two oscillators is erratic.

We inserted the Faraday rotator with the half-wave plate, and the laser was enforced to operate in a unidirectional mode while being coupled to the SRO. We obtained 520 mW of signal power in a single beam. Considering the transmission losses through BS₁ and R₁, this power corresponds to a generation of a 750-mW signal and a 565-mW idler that are generated in a single pass with 22% optical-to-optical conversion efficiency. Figure 4 shows the signal power versus the diode pump power. At threshold (around 2-W diode pump) the SRO operated in bursts. The given measurements are from the point where the SRO gave a stable output power.

The Fabry-Perot analyzer indicated that the laser operated with a single axial frequency for typically 30 s before mode hopping appeared. We observed that the power characteristics of the laser and the

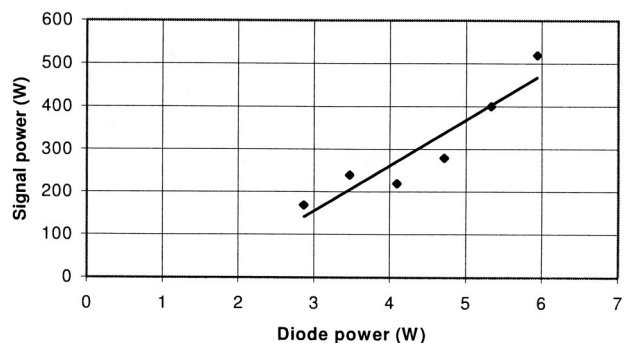


Fig. 4. Signal power versus the diode laser pump power when the Nd:YVO₄ laser is unidirectional. The power meter indicated that the signal power had 2.5% rms power fluctuations. In microsecond time scale the p-i-n detector indicated 0.25% rms power fluctuations.

signal improved significantly. In a time scale of seconds, we observed with the p-i-n detector about 2.5% rms power fluctuations of the laser power. Since we measured the same power fluctuations when the coupled SRO was turned off (by blocking the path of the idler) and only 0.25% of rms power fluctuation for the unidirectional laser without the PPLN, we deduce that the 2.5% slow fluctuations were caused by the PPLN. We observed with the beam analyzer that the profile of the TEM₀₀ laser beam was continuously developing unusual distortions in a time scale of seconds. The laser mode was a TEM₀₀ mode, but the intensity of its profile was slowly modulated with irregular shapes. These modulations were observed only when the PPLN was in the laser path. We suspect that the 2.5% rms power fluctuation and the modulation of the TEM₀₀ are related to the thermal annealing of the PPLN from the photorefractive effect. In a microsecond time scale, the silicon p-i-n detector indicated that the power of the laser was very stable with 0.25% rms power fluctuations. Figure 5 shows the power of the laser pump with the SRO off and on in a time scale of a second (We blocked and unblocked the SRO cavity). Comparing Fig. 5 with Fig. 3 one can appreciate the difference: The unidirectional laser couples with the SRO in a very stable manner. We could not detect a difference in the power fluctuations of the laser when the SRO was on or off. However, at the range of a 6-W diode pump, we could observe bursts of noisy power oscillations of the laser. These bursts appeared rarely and for short time intervals (a few seconds). They were similar to those in the bidirectional mode (as in Fig. 3). Whenever a burst appeared we observed with the Fabry-Perot simultaneous erratic hopping of the laser axial mode. The characteristics of the two modes of operation are summarized in Table 1.

The tuning characteristics of the SRO are shown in Fig. 6. We tuned the temperature in the range of 160–177 °C and used the Sellemier equations for PPLN as determined by Jundt¹⁶ to calculate the wavelength tuning. The Sellemier equations as

Table 1. Characteristics in the Three Modes of Operation

Feature	Bidirectional Laser ^a	Unidirectional Laser ^a
Power mode	cw	cw
Spatial mode	TEM ₀₀ with frequent competition from other modes	TEM ₀₀
Axial modes of the laser	>1	1
Signal output (net output) milliwatts	300 + 300	520
Power rms fluctuations	10% seconds to microsecond time scale	2.5% seconds time scale 0.25% microsecond
Beam analyzer	Distorted unstable TEM ₀₀ profile	Distorted stable TEM ₀₀ profile

^aCoupled to a SRO.

given by Jundt were generated especially for an IR OPO pumped by a 1064-nm laser. Their accuracy is highly reliable with uncertainty of 2.4×10^{-4} for the refractive index.

From the Sellemier equations and the temperature measurement for the PPLN (0.1 °C accuracy), the tuning range of the signal can be calculated with a reliable accuracy. It was calculated to be 75 nm. At 160 °C and 177 °C the signal wavelength was calculated to be 1870 and 1945 nm, respectively (Fig. 6).

We could not investigate thoroughly the spectral features of the signal and the idler owing to lack of appropriate instrumentation (Fabry-Perot and a spectrometer for the range 1870–1950 nm).

3. Discussions and Outlook

We built a cw SRO that is in an intracavity configuration to a diode-end-pumped Nd:YVO₄ ring laser. The laser was operated in a unidirectional mode with a single frequency and in a bidirectional mode with multiaxial modes. The measurements of the power fluctuations of the laser at microsecond and second time scales proved that a unidirectional laser with a coupled SRO is a very stable system. The coupling of the laser with the SRO is normally free of power oscillation between the two oscillators. We measured 2.5% rms power fluctuations of the signal in second time scale. Relying on the measured power fluctuations of the pump power in microsecond time scale, we assume that the signal had similar 0.25% rms power fluctuation. There was no trace for

power oscillations between the unidirectional laser power and the SRO power.

Another important point is that the 520-mW signal power is emitted in one beam. This is a very advantageous feature in intracavity configuration. In other intracavity SROs involving standing-wave lasers, half of the generated power is usually lost.

It appears from previous reports^{12,13,15} that when a single-frequency laser pumps a SRO with PPLN as the nonlinear gain medium the signal and the idler have a single axial mode. It seems likely that in the unidirectional mode of our laser (when the laser operated on a single axial frequency), the signal and the idler also operated with a single frequency. However, we could not verify this speculation.

It is feasible to generate more-powerful tunable systems such as the system described in this paper and with better performances. One should consider the use of more appropriate laser crystals (such as Nd:YLF) and better nonlinear crystals. The use of quasi-phase-matched KTA could eliminate the 2.5% rms power fluctuations caused by the photorefractive effect in PPLN. Further research will study the exact characterization of the spectral composition of the signal and the idler at each mode of the laser operation.

The QuantumProtein center at Denmark Technical University is planning to use this system for Raman spectroscopy to investigate the protein-folding problem. In such applications one wishes to have a single-mode powerful tuneable coherent source, and this system may be suitable.

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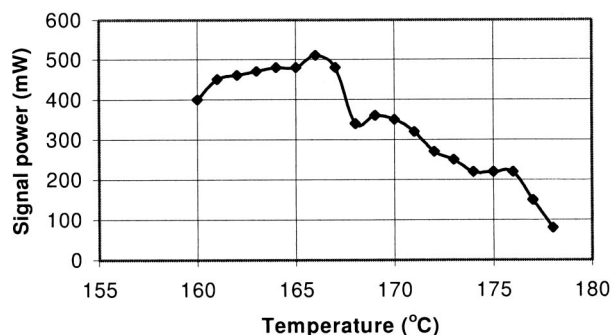


Fig. 6. Signal output power versus the temperature at the PPLN. At 160 °C the signal wavelength is 1870 nm; at 177 °C the signal wavelength is 1945 nm.

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