# ADVANCES IN CONTINUOUS-WAVE OPTICAL PARAMETRIC OSCILLATORS

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**Abstract:** We describe recent advances in continuous-wave (cw) optical parametric oscillators (OPOs) for the generation of tunable coherent radiation from the visible to mid-infrared. By deploying novel design concepts and exploiting new nonlinear materials and laser pump sources, spectral coverage from ~400 nm to ~4 μm at power levels >17 W are achieved using diode-pumped solid-state lasers, fiber lasers, and optically-pumped semiconductor laser pump sources.

## 1. INTRODUCTION

Coherent continuous-wave (cw) laser sources in different regions of the optical spectrum are of great interest for many applications, including spectroscopy, quantum information, and biomedicine, amongst many. Optical parametric oscillators (OPOs) are attractive sources of tunable cw radiation across the visible and the near- to mid-infrared [1]. In singly-resonant oscillator (SRO) format, they are capable of high optical powers, wide spectral coverage, and simplified coarse and fine tuning. The advent of quasi-phase-matched (QPM) ferroelectric nonlinear crystals, such as periodically-poled $LiNbO_3$ (PPLN) and $LiTaO_3$ (PPLT), has had an unparalleled impact on cw SRO technology. The flexibility offered by QPM grating engineering, which allows access to the highest nonlinear coefficients, together with long interaction lengths (80 mm in PPLN) and noncritical phase-mathcing, can enable the development of practical cw SROs with unmatched performance capabilities. Combined with the recent advances in solid-state, fiber, and semiconductor disk laser technology, compact, portable, robust, and viable sources of tunable cw radiation, capable of providing watt-level optical powers over expansive spectral regions from the visible to the near- and mid-infrared can be realized, as we describe here.

## 2. CW SRO FOR THE BLUE

We have developed a novel and practical source of cw radiation in the blue, which offers the advantages of wide tuning range, practical output power, single-frequency performance, and simple, compact, solid-state design, using cw SRO technology. The approach exploits internal second harmonic generation (SHG) of a cw SRO [2]. The configuration of the SRO is shown in Fig. 1. The cavity is formed in a ring, comprising two concave reflectors, $M_1$ and $M_2$ ($r$=50 mm), and two plane mirrors, $M_3$ and $M_4$. The nonlinear crystal is MgO:sPPLT ($d_{\mathrm{eff}}$~10 pm/V). It is 30-mm long, contains a single grating ($\Lambda$=7.97 μm) The pump source is a frequency-doubled, cw, single-frequency $Nd:YVO_4$ laser at 532 nm.

For internal SHG, we used $BiB_3O_6$ as the nonlinear crystal. The crystal was 5 mm in length long and 4×8 mm in aperture. It was cut for type I phase matching ($ee \rightarrow o$) in the optical $yz$-plane ($\varphi$=90°) at an internal angle $\theta$=160° at normal incidence ($d_{\mathrm{eff}}$~3.4 pm/V). The crystal end faces were AR-coated for the resonant signal ($R$<0.5% over 850-1000 nm) and for the SHG wavelengths ($R$<0.8% over 425-500 nm).

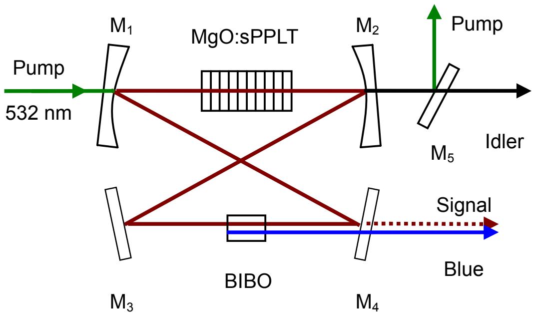

Fig. 1. Schematic of the cw SRO for the blue.

Figure 2 shows the extracted SH blue power across the tuning range. The measured power varies from 45 mW at 425 nm to 300 mW at 489 nm, with as much 448 mW available at 459 nm. We extracted >300 mW of blue power over 53% of the tuning range and >100 mW over 90% of the tuning range.

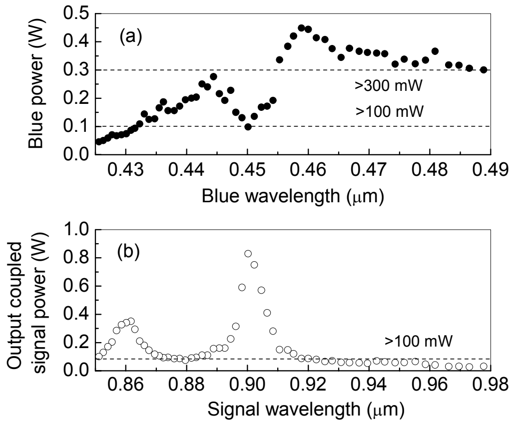

Fig. 2. (a) Extracted blue power, and (b) Output-coupled signal power across the tuning range.

The power scalability of the SRO near the maximum SHG power (at 460 nm) is shown in Fig. 3. At the maximum input pump power of 8.9 W, we obtained 432 mW of blue, 97 mW of out-coupled signal, and ~1.98 W of idler power, with a pump depletion of ~73%.

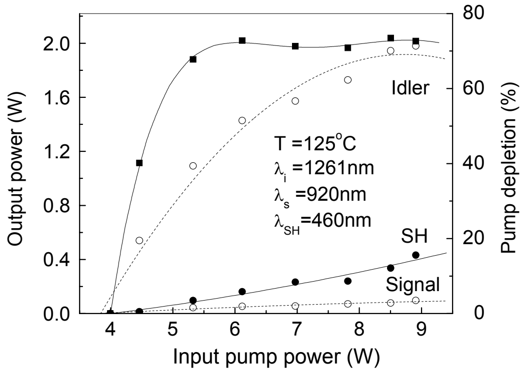

Fig. 3. Single-frequency blue, signal, idler power, and pump depletion versus input pump power.

## 3. FIBER-LASER-PUMPED CW SRO FOR THE NEAR- AND MID-INFRARED

We have also developed stable and high-power cw SROs for the near- to mid-IR using the rapidly advancing fiber technology [3]. A schematic of the experimental setup is shown in Fig. 4. The pump source is a cw, single-frequency Yb fiber laser delivering up to 30 W at 1064 nm in a linearly polarized beam of 4 mm diameter in $TEM_{00}$ spatial mode ($M^2$<1.01), with a nominal linewidth of 89 kHz. The nonlinear crystal is a 50-mm-long, 1-mm-thick, 5% MgO:PPLN, with five grating periods ranging from 29.5 µm to 31.5 µm. The SRO cavity is a symmetric ring, comprising two concave mirrors, $M_1$ and $M_2$ ($r$=150 mm), and two plane mirrors, $M_3$ and $M_4$. The pump beam is confocally focused to a beam radius of 63 µm at the centre of the crystal. The mirror reflectivities ensure SRO operation.

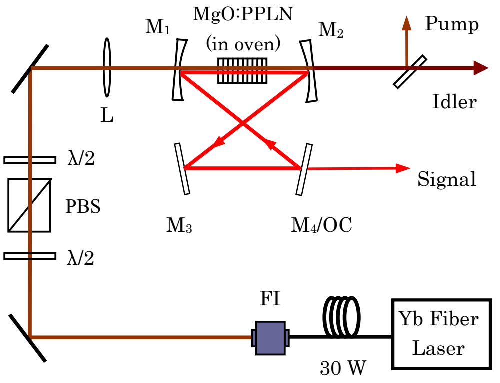

Fig. 4. Experimental setup of Yb-fiber-laser-pumped, high-power cw SRO based on MgO:PPLN crystal.

Power scaling of output-coupled SRO (OC-SRO) with optimum output coupling ($T$~3.8%), and comparison with the SRO, is shown in Fig. 5. In the SRO, an idler power up to 8.6 W was obtained at 3061 nm for 28.6 W of pump at 30% extraction efficiency, with a threshold power of 3.6 W and a pump depletion of 79%. No saturation of idler power was observed at this power level. With the optimal OC-SRO, we generated a total power of 17.5 W (9.8 W signal at 1627 nm, 7.7 W idler at 3070 nm) at an overall extraction efficiency of 61%. We also measured the quality factors of the output beam from the OC-SRO, where we obtained $M_x^2$~1.28 and $M_y^2$~1.22 for the idler at 3070 nm and $M_x^2$~1.29 and $M_y^2$~1.37 for the signal at 1627 nm. For the SRO, we obtained $M_x^2$~1.3 and $M_y^2$~1.22 for idler at 3061 nm.

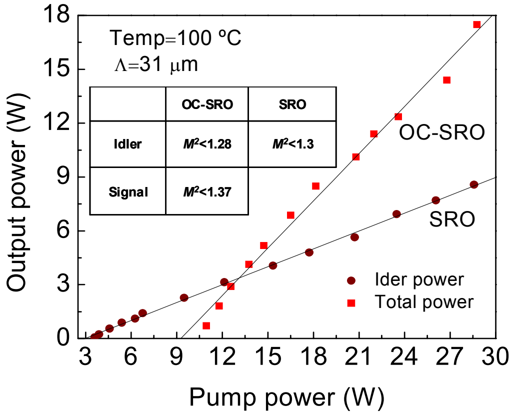

Fig. 5. Total extracted output power as a function of pump power from cw SRO and OC-SRO.

We characterized the cw SRO and OC-SRO output power across the tuning range by varying the MgO:PPLN crystal temperature. In the SRO, we were able to generate idler across 3147–2787 nm, providing a total tuning of 360 nm. For 28.6 W of pump, idler powers >7 W and pump depletions >65% were recorded over the entire tuning range. In the OC-SRO, by using a ~3–5% output coupler in 1.6–1.7 µm range, idler tuning over 3196–2803 nm together with signal tuning across 1594–1714 nm was achieved, extending the total coverage to 513 nm, and enabling room-temperature operation at 31°C with a total power of 15.7 W (9.1 W of signal at 1594 nm, 6.6 W of idler at 3196 nm).

We also investigated the output power stability in the two configurations at the maximum idler power. For the SRO, at 100 ºC, we measured a stability of 17.4 % over 1 hour. For the OC-SRO, at 100 ºC, we recorded a pk-pk stability of 13.6 % over 1 hour. However, in the OC-SRO, at the lowest operating temperature of 44 ºC, we measured a long-term peak-to-peak stability of 5% over 14 hours at 7 W of idler power, as shown in Fig. 6. Also shown in the inset of Fig. 6 is the spatial profile of the idler beam from the OC-SRO at 7 W, confirming a $TEM_{00}$ spatial mode.

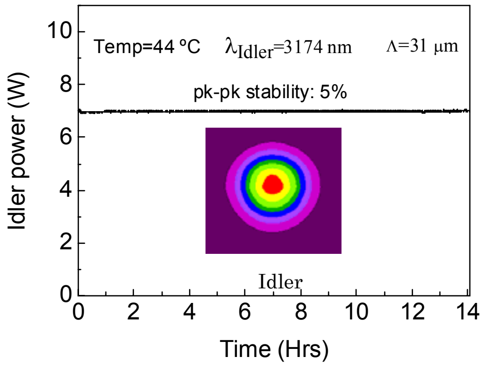

Fig. 6. Long-term power stability and far-field spatial profile of the idler beam from OC-SRO.

## 4. FIBER-LASER-GREEN-PUMPED CW SRO FOR THE NEAR-INFRARED

We have extended fiber laser pumping to the green, permitting the realization of cw SROs at wavelengths <1 µm [4]. The fiber green laser pump source is realized by efficient single-pass SHG of a cw Yb fiber laser in MgO:sPPLT [5]. The schematic of the experimental setup is shown in Fig. 7. The primary pump source is the same cw Yb fiber laser described in Section 3. The laser is frequency-doubled in a single-pass in a 30 mm MgO:sPPLT crystal with a single grating (Λ=7.97 µm), providing up to 9.64 W of cw green power at 532 nm [5]. The SRO is based on an identical MgO:sPPLT crystal and is configured in a compact ring cavity with two concave mirrors, $M_1$ and $M_2$ ($r$=100 mm), and two plane reflectors, $M_3$ and $M_4$. All mirrors have $R$>99% over 840-1000 nm and $T$>85% over 1100-1500 nm, except for $M_4$ (output coupler, $T$=0.71%-1.1% @840-1000 nm), thus ensuring SRO operation. A 500-µm fused silica etalon (FSR=206GHz, finesse~0.6) is used for frequency control. The total optical length of the cavity is 711 mm (FSR~422 MHz).

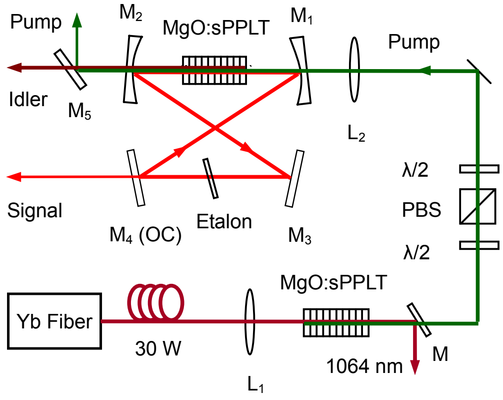

Fig. 7. Schematic of experimental design for the fiber-laser-pumped MgO:sPPLT cw SRO.

The extracted signal and idler output power across the tuning range of the OC-SRO is shown in Fig. 8, where useful signal and idler power over a total tuning range of ~550 nm is available. The signal power, Fig. 8(a), varies from 725 mW at 1000 to 277 mW at 855 nm at the extreme of the tuning range, with a maximum of 800 mW at 927 nm at the maximum available output coupling of 1.04%. The idler power, Fig. 8(b), varies from 1.9 W at 1136 nm to 745 mW at 1408 nm, with a maximum power of 2.1 W at 1168 nm. As evident in Fig. 8(b), the idler power is nearly constant at ~1.8 W over1136-1252 nm, which is 42% of the total idler tuning range.

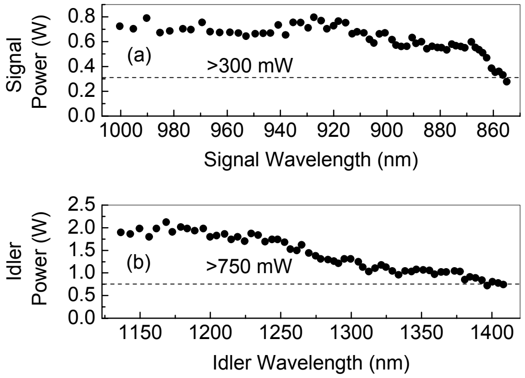

Fig. 8. (a) Extracted signal power, and (b) idler power, across the cw OC-SRO tuning range.

## 5. CW SRO PUMPED BY AN OPTICALLY PUMPED SEMICONDUCTOR LASER

Advances in optically-pumped semiconductor laser (OPSL) technology, providing power levels of up to several watts in good spatial beam quality and over a range of wavelengths, has presented new potential for the realization of a novel class of cw SROs in compact, practical, and portable design. By taking advantage of this development, we have been able to achieve practical watt-level operation of a cw SRO pumped by an OPSL [6]. The SRO cavity design and the MgO:sPPLT crystal are similar to that used in Sections 3 and 4, and are described in detail in [6]. The pump source is a 6-W, cw, OPSL at 532 nm, providing linearly polarized beam with $M^2$<1.1 and a measured linewidth of ~30 MHz.

Figure 9 shows the simultaneously extracted idler and signal power and the corresponding pump depletion for the OC-SRO, with finite signal coupling of 0.98%, versus pump power. The idler power reaches a maximum of 1.78 W and a signal power of 900 mW at the highest available pump power of 5.5 W. The maximum total extraction efficiency of the device is thus 48.7% and threshold is reached at 2.6 W of pump power. The pump depletion rises rapidly to a ~81% at 4.6 W of pump, and almost remain constant up to the maximum available power of 5.5 W.

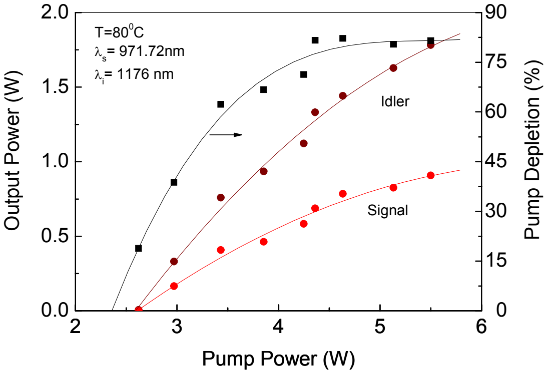

Fig. 9. Signal power, idler power, and pump depletion for the cw OC-SRO versus pump power.

We recorded the frequency stability of the signal at 971 nm. The results are shown in Fig. 10. Without frequency stabilization, the signal frequency exhibits a passive peak-to-peak stability better than 60 MHz over 60 seconds. We also confirmed single-frequency nature of the generated signal using a confocal interferometer (FSR=1 GHz, finesse~400), as shown in the inset of Fig. 10, where an instantaneous linewidth of 15 MHz was deduced.

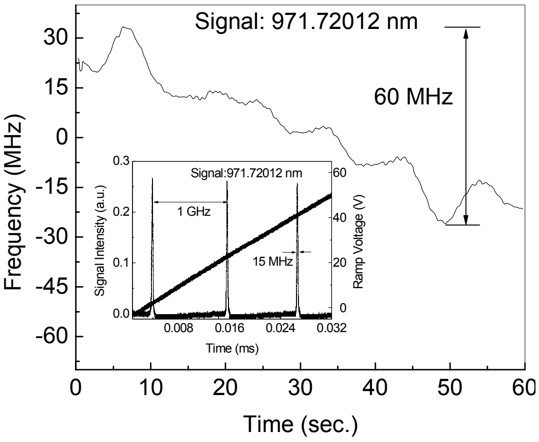

Fig. 10. Frequency stability of the cw OC-SRO. Inset: Single-frequency signal spectrum.

We also verified the output beam quality of the output signal beam from the OC-SRO, with the results shown in Fig. 11. The inset of Fig. 11 shows the far-field energy distribution of the signal, together with the intensity profiles and the Gaussian fits, indicating a $TEM_{00}$ beam with circularity >97%. We confirmed the $TEM_{00}$ beam quality by measurements of $M^2$ values, resulting in $M_x^2$~1.16 and $M_y^2$~1.28.

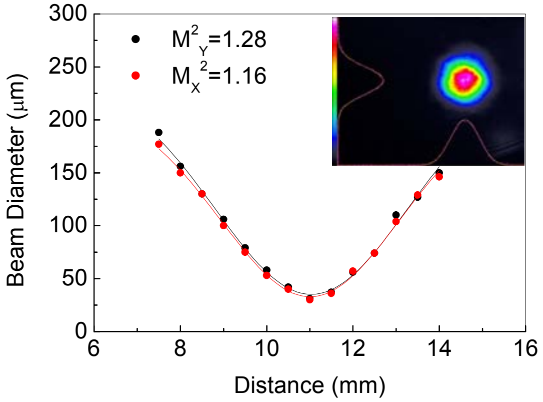

Fig. 11. Variation of signal beam diameter at 971 nm. Inset: Far-field $TEM_{00}$ energy distribution and intensity profiles.

## ACKNOWLEDGEMENTs

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