High-power, continuous-wave, singly resonant optical parametric oscillator based on MgO:sPPLT

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We report a high-power, widely tunable, cw singly resonant optical parametric oscillator (OPO) based on MgO:sPPLT. The OPO is pumped in the green by a cw diode-pumped Nd:YVO$_4$ laser at 532 nm and can provide continuously tunable output across 848–1430 nm. Using a 30 mm crystal and double-pass pumping, an oscillation threshold of 2.88 W has been obtained, and single-pass idler powers in excess of 1.51 W have been generated over 1104–1430 nm for 6 W of pump power at an extraction efficiency of 25.2% and photon conversion efficiency of 56.7%. © 2007 Optical Society of America

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The advent of quasi-phase-matched (QPM) nonlinear materials has had a profound impact on cw optical parametric oscillators (OPOs). The vast majority of cw OPOs developed to date have been based on periodically poled LiNbO$_3$ (PPLN), providing spectral coverage from above $\sim$1 $\mu$m to the absorption edge of the material near $\sim$5 $\mu$m. For wavelength generation below $\sim$1 $\mu$m, the use of PPLN is precluded by photorefractive damage induced by the visible pump or signal radiation. As such, the development of practical cw OPOs for the visible to near infrared, particularly in high-power singly resonant oscillator (SRO) configurations, necessitates the search for alternative QPM materials.

Periodically poled LiTaO$_3$ (PPLT) is one such promising candidate, due to its transparency down to $\sim$280 nm, high optical nonlinearity ($d_{eff}$ $>$ 10 pm/V), and increased resistance to photorefractive damage. In stoichiometric growth, the coercive field for poling is reduced by 1 order of magnitude from congruent form, and the optical damage threshold is increased by up to 3 orders of magnitude. Doping with MgO also results in further reductions in photorefractive susceptibility to visible radiation. With the ongoing advances in poling technology, the fabrication of bulk MgO-doped stoichiometric PPLT (MgO:sPPLT) with shorter grating periods over long interaction lengths has also become possible, paving the way for the development of practical cw OPOs for the visible and near infrared based on MgO:sPPLT by using powerful laser pump sources in the visible.

Earlier demonstrations of OPO devices using PPLT and its related derivatives include a pulsed nanosecond SRO based on sPPLT and pumped by a Q-switched Nd:YAG laser at 1064 nm, providing an average power up to 300 mW at 1 kHz and tuning in the near to mid-infrared.$^1$ Subsequently, a nanosecond SRO based on sPPLT and pumped by a frequency-doubled Nd:YAG laser at 532 nm was demonstrated, delivering a total average power of 490 mW at 3.5 kHz in the visible and near infrared.$^2$ More recently, a quasi-cw SRO based on MgO:sPPLT was reportedly pumped by 170 $\mu$s pulses from a frequency-doubled Nd:YAG laser at 532 nm, producing 70 $\mu$s signal pulses at 635 and 640 nm at 40 Hz, with a peak pulse power of 1.2 W and an average power of $\sim$60 mW.$^3$ In an earlier report, a PPLT cw SRO pumped at 925 nm by an InGaAs diode laser was demonstrated, generating 244 mW of idler power with tuning over 1.55–2.3 $\mu$m in the mid-infrared.$^4$ Soon after, a pump-enhanced PPLT cw OPO using a frequency-doubled Nd:YAG laser at 532 nm was reported, providing 60 mW of output power and tuning in the near to mid-infrared.$^5$

Here we report a high-power cw SRO based on MgO:sPPLT, pumped in the green, which can provide more than 1.5 W of idler output at 25.2% external power efficiency and 56.7% photon conversion efficiency, with tuning across 848–1430 nm. A schematic of the experimental setup is shown in Fig. 1. The SRO is pumped by a frequency-doubled cw diode-pumped Nd:YVO$_4$ laser at 532 nm (Coherent, Verdi V-10), delivering up to 10 W of single-frequency output in a linearly polarized beam with a diameter of 2.25 mm and an $M^2$ factor $<1.1$. Using a confocal interferometer (FSR=1 GHz, finesse=400), we measured the instantaneous linewidth of the laser to be <25 MHz. The pump beam was directed to the SRO through an optical isolator and a power attenuator comprising a half-wave plate and polarizing beamsplitter cube. A second half-wave plate was used to yield the correct pump polarization for phase matching relative to the crystal orientation. The crystal is a

![Fig. 1. Schematic of the experimental design for the MgO:sPPLT cw SRO. HWP, half-wave plate; PBS, polarizing beam splitter; M, mirror.](Image)
oscillation. The input mirror over 1100–1500 nm, thus ensuring singly resonant for the pump, while the output mirror characteristics identical to M2, is used as a cutoff filter for pumping. A plane mirror, M3, with reflectivity determined from direct measurements to be 99% reflecting at 532 nm to allow double-pass transmission and efficiency roll-off, we performed independent measurements of single-pass crystal transmission at 1282 nm (signal at 910 nm), and represent the idler output only in the forward direction. They do not account for the idler power generated in the backward direction in the second pass of the pump through the crystal, but they have been corrected for ~25% idler loss due to residual reflectivity of mirror M2 and cut-off mirror M3. Because of the relatively high (~25%) reflection losses of the uncoated transmission optics between the pump laser and SRO, we could deliver a maximum pump power of 7.6 W, as evident in Fig. 3. The SRO operation threshold is reached at 2.88 W of pump power. Interestingly, the onset of oscillation is accompanied by the generation of 550 mW of idler power, while below threshold no output power is present. We believe this abrupt behavior may be due to thermal lensing effects. Above threshold, we observe a steady increase in the idler output with a slope efficiency of 26.5%, reaching a maximum single-pass power of 1.2 W at 5.47 W of pump power. This represents a maximum forward-pass idler power extraction efficiency of 21.9% and a corresponding external photon conversion efficiency of 52.8% from the pump to the idler. At pump powers above 5.47 W, there is a clear roll-off in idler power and efficiency. The behavior is broadly consistent with the prediction of the theoretical model for a double-pass-pumped SRO, attributed to the effects of pump back-generation. However, the roll-off occurs at a photon conversion efficiency of 52.8%, well below the 100% level predicted by theory.

To identify possible sources of thermal lensing and efficiency roll-off, we performed independent measurements of single-pass crystal transmission at

\[ \lambda_p = 532 \text{ nm} \]

\[ \Lambda = 7.97 \mu \text{m} \]

\[ \text{Wavelength (\text{nm})} \]

\[ \text{Temperature (°C)} \]

\[ \eta = 26.5\% \]

\[ \lambda_p = 1282 \text{ nm} \]

\[ \text{Input Pump Power (W)} \]

\[ \text{Idler Power (W)} \]

\[ \text{Photon Conversion Efficiency} \]

1 mol.% bulk MgO:sPPLT sample, 30.14 mm long, 1 mm thick, and 2.14 mm wide. The sample contains a single grating with period of \( \Lambda = 7.97 \mu \text{m} \) and is housed in an oven with a temperature stability of ±0.1 °C. The crystal faces are antireflection coated for a grating period of 7.97 mm, with 99% transmission at 532 nm. The residual reflectivity at the idler wavelength is 1% to 15% over 1000–1400 nm.

The SRO is configured in a linear standing-wave cavity comprising two concave mirrors, M1 and M2, of radius of curvature \( r = 50 \text{ mm} \). The cavity mirrors are >99% reflecting for signal wavelengths over 840–1000 nm and >85% transmitting for the idler over 1100–1500 nm, thus ensuring singly resonant oscillation. The input mirror (M1) has 94% transmission for the pump, while the output mirror (M2) is >99% reflecting at 532 nm to allow double-pass pumping. A plane mirror, M3, with reflectivity characteristics identical to M2, is used as a cutoff filter for the signal and any residual pump, to enable measurements of the idler output.

To optimize SRO operation, we used several focusing conditions, corresponding to different values of the focusing parameter \( \xi = \ell / b_p \). Here \( \ell = 30 \text{ mm} \) is the crystal length and \( b_p = k w_{ap} \) is the confocal parameter of the pump, with \( k = 2 m_p / \Lambda_p \), where \( n_p \), \( \Lambda_p \), and \( w_{ap} \) are the refractive index, wavelength, and waist radius of the pump beam inside the crystal, respectively. We used four different focusing conditions corresponding to \( \xi = 0.3, 0.8, 1.5, \) and 2. The optimum SRO operation with maximum idler output power was obtained with \( \xi = \ell / b_p = 2 \). The corresponding pump beam waist at the center of the SRO cavity was determined from direct measurements to be \( w_{ap} \approx 24 \mu \text{m} \). The signal spot size was adjusted by translation of the SRO cavity mirrors, M1 and M2, to yield a confocal parameter \( b_s = b_p \), resulting in a waist radius of \( w_{sp} \approx 32 \mu \text{m} \).

Figure 2 shows the SRO tuning range as a function of the crystal temperature. The solid curve is the tuning range predicted from the Sellmeier relations for stoichiometric LiTaO3, confirming reasonable agreement between experimental data and calculation. The SRO could be continuously tuned over 1026–848 nm in the signal and 1104–1430 nm in the idler by varying the crystal temperature from 51° to 248°C. Thus the tuning was continuous over 848–1430 nm, except for a small gap near degeneracy (1026–1104 nm) due to the reflectivity falloff of SRO mirrors to prevent doubly resonant oscillation. The limit to SRO tuning at the extremes of the signal and idler range was set by the maximum operating temperature of the oven at 248°C.

The idler output power and photon conversion efficiency as functions of pump power at the input to the crystal are shown in Fig. 3. The data were obtained at 139°C, corresponding to an idler wavelength of 1282 nm (signal at 910 nm), and represent the idler output only in the forward direction. They do not account for the idler power generated in the backward direction in the second pass of the pump through the crystal, but they have been corrected for ~25% idler loss due to residual reflectivity of mirror M2 and cut-off mirror M3. Because of the relatively high (~25%) reflection losses of the uncoated transmission optics between the pump laser and SRO, we could deliver a maximum pump power of 7.6 W, as evident in Fig. 3. The SRO operation threshold is reached at 2.88 W of pump power. Interestingly, the onset of oscillation is accompanied by the generation of 550 mW of idler power, while below threshold no output power is present. We believe this abrupt behavior may be due to thermal lensing effects. Above threshold, we observe a steady increase in the idler output with a slope efficiency of 26.5%, reaching a maximum single-pass power of 1.2 W at 5.47 W of pump power. This represents a maximum forward-pass idler power extraction efficiency of 21.9% and a corresponding external photon conversion efficiency of 52.8% from the pump to the idler. At pump powers above 5.47 W, there is a clear roll-off in idler power and efficiency. The behavior is broadly consistent with the prediction of the theoretical model for a double-pass-pumped SRO, attributed to the effects of pump back-generation. However, the roll-off occurs at a photon conversion efficiency of 52.8%, well below the 100% level predicted by theory.

To identify possible sources of thermal lensing and efficiency roll-off, we performed independent measurements of single-pass crystal transmission at
532 nm. In these experiments we could deliver up to 9 W at the input to the crystal. The pump was focused to the same waist radius of $w_{op}=24\ \mu m$ in the crystal, and the transmission loss was recorded as a function of input power. A plot of transmitted power against input power resulted in a straight line, confirming the absence of two-photon absorption up the maximum available input power of 9 W, corresponding to focused intensities of 0.49 MW/cm². Hence the role of two-photon absorption as a possible source of thermal lensing and efficiency roll-off could be discounted. From the slope of the graph, and after correcting for the residual reflectivity of the crystal faces from direct measurements, we determined the linear absorption of the crystal to be 10.14% for the 30.14 mm sample, representing a loss coefficient of 0.32% cm⁻¹.

From direct measurements, we determined the linear absorption of the crystal to be 10.14% for the 30.14 mm sample, representing a loss coefficient of 0.32% cm⁻¹. The absence of two-photon absorption, but the presence of significant linear absorption at 532 nm is consistent with earlier reports, confirming that single-photon absorption may in fact play a major role in thermal lensing and roll-off effects here. With proper thermal management, we expect to be able to control the detrimental effects of thermal lensing in the present device. Another significant factor may be pump-induced infrared absorption of the intracavity signal or the idler, but this has been reported to be reduced to nearly zero in MgO:sPPLT. Experimental determination of this parameter was, however, not possible with our present setup due to the lack of a suitable infrared source.

We also recorded the forward-pass idler power across the obtained tuning range of 1104–1430 nm, with the results shown in Fig. 4. The data were obtained near the peak of idler power (Fig. 3) at an input pump power of 6 W. The SRO could provide as much as 1.51 W of idler output near 1170 nm for 6 W of pump power at a conversion efficiency of 25.2%, and a corresponding photon conversion efficiency of 56.7%. Across ~55% of the total tuning range (1120–1295 nm), the idler power could be maintained above 1 W, with more than 700 mW available over ~80% of the total tuning range. At the extremes of the tuning range, the SRO could still deliver 500 mW of idler power. We also observed SRO operation at temperatures as low as 52°C without the onset of spatial instabilities due to photorefractive effects. We did not observe any distortions in the idler and pump beam spatial profiles when operating the SRO well above threshold at the highest input pump powers. These observations are consistent with previously measured photorefractive damage threshold of 2 MW/cm² in sPPLT when subjected to green radiation at 514.5 nm. In our SRO, the maximum power of 7.6 W at 532 nm in a beam waist radius of $w_{op}\sim24\ \mu m$ results in a local intensity of 0.84 MW/cm² in double-pass pumping, well below the reported photorefractive damage threshold.

We verified the spectral quality of the signal and idler output using a confocal interferometer (FSR = 1 GHz, finesse=400). Insofar as the free spectral range of the OPO cavity was 1.03 GHz (optical length 145.5 mm), we could just resolve the signal and idler mode structure by using the interferometer. In the absence of any frequency selection elements within the SRO cavity, we observed signal oscillation over more than one longitudinal mode, with frequent hops between two modes. The idler followed similar behavior, oscillating on more than one longitudinal mode, with regular hops between the modes. The use of a three-mirror or ring resonator with the inclusion of an intracavity etalon should readily allow the generation of single-frequency signal and idler radiation, making the SRO a promising source of high-power, narrow-linewidth cw radiation with wide and continuous tuning in the visible and near infrared.

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References

6. The MgO:sPPLT crystal was supplied by HC Photonics Corporation, Hsinchu, Taiwan.