1.59 W, single-frequency, continuous-wave optical parametric oscillator based on MgO:sPPLT

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A watt-level, single-frequency, continuous-wave (cw) singly resonant optical parametric oscillator (OPO) based on MgO:sPPLT is described. Pumped in the green by a frequency-doubled cw diode-pumped $Nd:YVO_4$ laser at 532 nm, the OPO can provide up to 1.59 W of single-frequency idler output with a linewidth of ~7 MHz at pump depletions of as much as 67%. Using a compact ring resonator and optimized focusing in a 30 mm crystal, a singly resonant oscillation threshold of 2.84 W has been obtained under single-pass pumping. With a single grating period of 7.97 μm, continuous signal and idler coverage over 852–1417 nm is obtained by temperature tuning between 61°C and 236°C. The influence of thermal lensing on idler output power across the SRO tuning range is also verified. © 2007 Optical Society of America

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Periodically poled MgO-doped stoichiometric $LiTaO_3$ (MgO:sPPLT) is a promising nonlinear material for visible and near-IR cw OPOs because of increased resistance to the photorefractive effect, a transmission range down to ~280 nm, moderately large optical nonlinearity (d_{eff} > 10 pm/V), and high optical damage threshold. Advances in poling technology have also enabled the fabrication of bulk MgO:sPPLT crystals with shorter grating periods and improved optical quality over longer interaction lengths and wider apertures, opening up new possibilities for the development of practical cw OPOs for the visible and near-IR in high-power SRO configurations using powerful laser pump sources in the visible.

There have been earlier reports of OPOs based on periodically-poled $LiTaO_3$ (PPLT) or its related derivatives [1–5]. In a cw SRO configuration, we demonstrated a high-power OPO based on MgO:sPPLT pumped at 532 nm [6]. Using a two-mirror cavity design and double-pass pumping, we generated 1.51 W of cw idler power and tuning across 848–1430 nm in the near-IR. A similar device was also reported, providing 100 mW of single-frequency red radiation tunable over 619–640 nm [7]. Here, we report simultaneous single-frequency operation and high-power performance of cw SRO based on MgO:sPPLT pumped in the green. Using a compact ring resonator, tight focusing, and intracavity frequency selection, we have achieved a single-mode idler output of up to 1.59 W across 1140–1417 nm at pump depletions of up to 67% using single-pass pumping.

A schematic of the cw SRO is shown in Fig. 1. The SRO is configured in a compact ring cavity comprising two concave mirrors, M_1 and M_2, of radius of curvature r=50 mm, and two plane reflectors, M_3 and M_4. The mirrors all have >99.5% reflectivity over the signal wavelength range of 840–1000 nm and 85%–90% transmission for idler wavelengths over 1100–1500 nm, thus ensuring singly resonant oscillation. The angle of incidence on the concave mirrors, M_1 and M_2, is limited to <5° to minimize astigmatism. The nonlinear crystal is 1 mol.% bulk MgO:sPPLT, 1 mm thick, 2.14 mm wide, and 30.14 mm long, with a single grating period of Λ =7.97 μm [6]. The crystal temperature is controlled using an oven with a stability of ±0.1°C and maximum operating temperature of 250°C. The crystal faces are antireflection coated (R<1%) over 800–1100 nm, with high transmission (T>98%) at 532 nm. The residual reflectivity of the coating over the idler range of 1100–1400 nm is 1%–15%. For frequency selection, a 500-μm-thick uncoated fused silica etalon (free spectral range (FSR)=206 GHz, finesse ~0.6) is used at the second cavity waist between M_3 and M_4. The total optical length of the cavity including the crystal and etalon is 295 mm, corresponding to a FSR ~ 1.02 GHz. The pump source is a frequency-doubled cw diode-pumped $Nd:YVO_4$ laser at 532 nm, as described previously [6].

The optimum SRO operation was obtained with a relatively strong focusing parameter ξ=2, corresponding to a pump beam radius of w_{op}=24 μm inside the crystal [8]. The signal beam waist was w_{os} ~ 31 μm, resulting in optimum mode matching to the pump (b_s=b_p). To enable measurements of the idler beam, a mirror (M_5) with characteristics identical to the other cavity mirrors but >99% reflecting at 532 nm was used to filter out any residual pump and

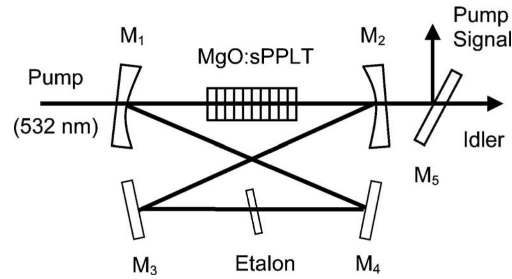

Fig. 1. Schematic of the high-power cw single-frequency SRO based on MgO:sPPLT.

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signal. In addition, unlike our earlier work with standing-wave cavities [6], here we employed single-pass pumping, with mirrors M_1 and M_2 both ~94% transmitting at 532 nm. Despite this, the combination of the compact ring resonator and tight focusing resulted in excellent overall SRO performance in terms of threshold, single-frequency operation at high output power and efficiency, and strong pump depletion, as we demonstrate here.

In Fig. 2 typical behavior of cw single-frequency idler power and corresponding pump depletion as functions of pump power at the input to the crystal are shown. The data were obtained at a temperature of 82°C, equivalent to an idler wavelength of 1187 nm (signal at 964 nm) and have been corrected for ~20% loss due to residual reflectivity of mirrors M_2 and M_5 at the idler. Due to a transmission loss of ~15% between the pump and the OPO, a maximum power of 8.46 W was available at the input to the crystal. As evident from the plot, the cw SRO reaches oscillation threshold at 2.84 W of input pump power. This value is close to, and in fact lower than, our previous result for a linear cavity with double-pass pumping [6]. Moreover, the present device does not exhibit the abrupt behavior of idler power and efficiency at threshold, observed with the standing-wave cavity under double-pass pumping, attributed to the effects of thermal lensing [6]. Here, the idler power rises smoothly from threshold and increases steadily to the maximum value of 1.55 W at 8.46 W of pump, confirming the superior performance of the ring cavity with single-pass pumping. The absence of significant thermal lensing at threshold may be attributed to the ~50% reduction in pump intensity within the crystal under single-pass pumping compared with double-pass pumping in a linear cavity [6]. At increased pump powers, there is evidence of saturation in the idler power and pump depletion, which is broadly consistent with the theoretical predictions for a single-pass-pumped SRO, where a maximum pump depletion of 71% is predicted for a Gaussian pump beam before the onset of backconversion [9]. However, the roll-off occurs at a pump power of ~7.8 W, which is ~2.75 times threshold compared with the value of 6.5 times predicted by theory.

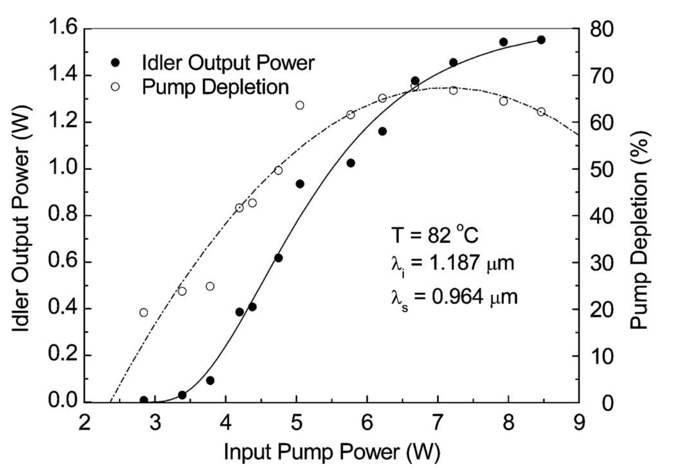

Fig. 2. Single-frequency cw idler power and corresponding pump depletion as functions of pump power.

In Fig. 3 the extracted single-frequency idler power and corresponding pump depletion are shown across the idler tuning range of 1.140–1.417 μm. The data were obtained near the peak of idler power and pump depletion at an input pump power of 7.8 W (Fig. 2). Across the entire tuning range, single-frequency operation could be maintained at the maximum power levels shown Fig. 3. The idler output power varied from 1.59 W at 1159 nm (70°C) to ~400 mW at the extreme of the tuning range near 1.417 nm. However, across 52% of the total tuning range, between 1140 and 1285 nm, single-frequency idler powers of >1 W could be obtained, with more than 400 mW available over the remainder of the tuning range. The pump depletion varied from 40% to 67% across the tuning range. The total signal and idler tuning range was 852–1417 nm, obtained by varying the crystal temperature between 61 and 236°C. The tuning was continuous, except for a small gap over 1026–1104 nm due to the reflectivity fall-off of SRO mirrors to avoid double resonance near degeneracy.

The fall in idler power and pump depletion towards the longer wavelengths are attributed to the increase in crystal coating losses and reduction in parametric gain further away from degeneracy. The crystal coating loss increases from 3% at the peak of idler power (1159 nm) to 16% at the 1417 nm, while the degeneracy factor accounts for a ~5% gain reduction between the two wavelengths. Another important contribution could be thermal lensing in the MgO:sPPLT crystal, as observed in our previous studies [6]. To ascertain the role of thermal lensing, we performed independent measurements of idler power with increasing pump power at different wavelengths and correspondingly different crystal temperatures. Figure 4(a) shows a comparison of cw idler power at 1254 nm (121°C) with that at 1187 nm (82°C) as a function of input pump power. Interestingly, the plots reveal that the cw idler power undergoes stronger saturation at the longer than at the shorter idler wavelength up to the maximum available pump power of 8.46 W. This implies that at pump powers above ~6 W, the SRO operation is substantially more efficient at lower crystal tempera-

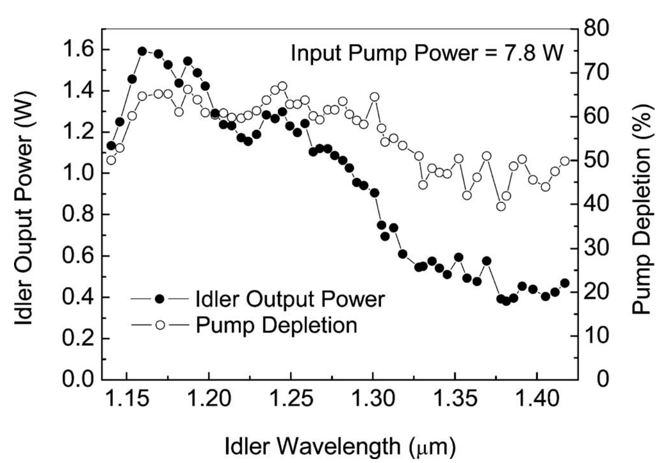

Fig. 3. Variation of cw single-frequency idler power and pump depletion across the idler tuning range.

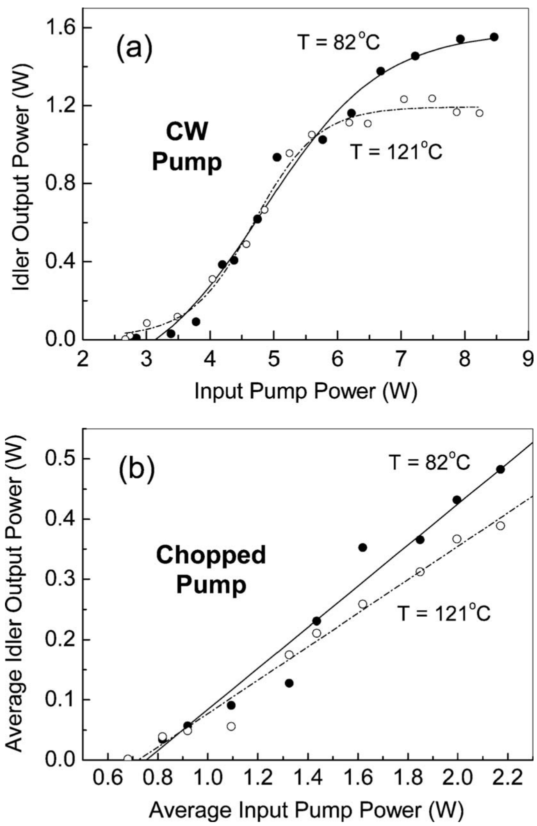

Fig. 4. Idler output power at 82°C (1187 nm) and 121°C (1254 nm) as functions of pump power for (a) cw pump beam and (b) chopped pump beam with a 25% duty cycle.

tures, confirming the drop in idler output power at longer wavelengths seen in Fig. 3.

To further verify thermal effects as the origin of the observed behavior, we repeated the same measurements using a chopped pump beam, with the results shown in Fig. 4(b). The pump was chopped at a duty cycle of 25%. As clearly evident form the plot, there is no saturation in idler power in this case, confirming thermal effects as origin of the saturation behavior in Fig. 4(a). The remaining difference in idler output power in Fig. 4(b) at the two different temperatures can be attributed to the difference in crystal coating loss (~5%) and parametric gain (1.2%) at the two idler wavelengths.

Based on a preliminary thermal lens model, we also calculate the magnitude of the thermal lens formed by the MgO:sPPLT crystal for different pump powers and temperatures. Using a measured linear absorption coefficient of 3.23% cm^{-1} for the crystal at 532 nm [6], we calculate the focal length of the thermal lens at 5 W of pump power as 15.6 cm at 82°C and 13.6 cm at 121°C, implying stronger lensing at higher temperatures. We also find that the focal length of the thermal lens decreases with increasing pump power, again implying stronger lensing at higher powers, as expected. At 8 W of pump power, for example, the focal length of the thermal lens reduces to ~9.4 cm at 82°C and ~8.5 cm at 121°C. The formation of the thermal lens can clearly lead to degradation in mode matching between the signal and pump from the optimum conditions, resulting in the

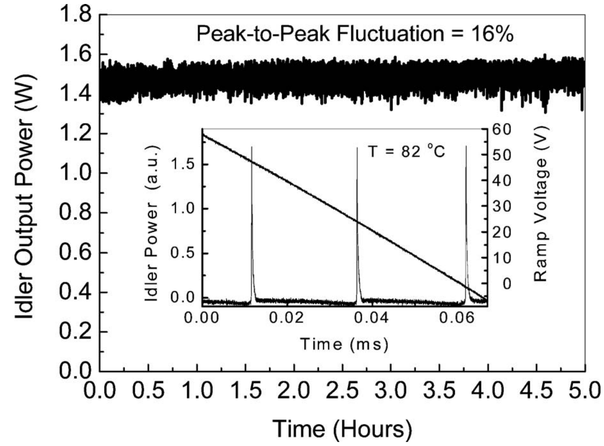

Fig. 5. Idler output power stability near 1.59 W over 5 h and the corresponding single-frequency spectrum (inset).

reduction in output power and efficiency. These calculations thus also confirm the role of thermal lensing in the reduction of idler power at longer wavelengths (higher temperatures), as evident in Fig. 3, as well as the stronger saturation of idler power in Fig. 4(a). Another contribution to thermal lensing may be the circulating signal intensity which, at the highest pump power of 8.46 W, can be >10 W. This can be verified using different levels of signal output coupling and is currently under investigation.

The SRO power stability and spectral output near the maximum of idler power at 1.59 W are shown in Fig. 5. Under free-running conditions and in the absence of thermal isolation, the idler power exhibits a peak-to-peak fluctuation of 16% over 5 h. The idler transmission spectrum through a confocal interferometer (FSR=1 GHz, finesse=400) confirms reliable single-frequency operation with an instantaneous linewidth of ~7 MHz at the maximum idler power. Similar behavior was observed at all other idler wavelengths and temperatures. With improved thermal isolation and active control, further improvements in SRO output stability are expected.

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