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Green-pumped continuous-wave parametric oscillator based on fanout–grating MgO:PPLN

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We report the first green-pumped continuous-wave (cw) optical parametric oscillator (OPO) based on MgO:PPLN in a fanout grating design. Pumped by a single-frequency cw laser at 532 nm, the OPO provides tunable radiation across 813–1032 nm in the signal and 1098–1539 nm in the idler by simple mechanical translation at a fixed temperature of 55°C. By deploying a 25-mm-long crystal to minimize thermal effects and using output coupling for the signal wave, we generate a total output power of up to 714 mW at 30% extraction efficiency in excellent Gaussian beam quality with $M^2 < 1.1$ and high output stability. Simultaneous measurements of signal and idler power result in passive stability of 2.8% and 1.8% rms, respectively, over 1 h. Strong thermal effects contribute to the high stability and excellent beam quality, while linear and green-induced infrared absorption limit the power scaling capabilities of the OPO. The output signal is single-mode with an instantaneous linewidth of ∼3 MHz and frequency stability of ∼84 MHz over 72 s.

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Tunable continuous-wave (cw) single-frequency light sources are of interest for a diverse range of applications, from spectroscopy and trace gas sensing to biomedicine [1]. In particular, optical parametric oscillators pumped in the green represent an attractive approach for the generation of tunable visible and the near-infrared (near-IR) radiation. Because of the small parametric gain available under low pump intensities in the cw regime, practical operation of cw OPOs relies almost exclusively on quasi-phase-matched (QPM) nonlinear materials [2], exploiting the highest nonlinear tensor coefficients combined with long interaction lengths under noncritical phase matching. Such cw OPOs have been previously demonstrated using well-established oxide-based QPM nonlinear materials [3–5]. However, detrimental photorefractive effect and green-induced infrared absorption (GRIIRA) have hampered further development of green-pumped cw OPOs based on periodically poled $LiNbO_3$ (PPLN) and $LiTaO_3$ (PPLT), while strong thermal effects hinder the performance of green-pumped OPOs based on PPKTP. These deleterious effects have been significantly alleviated by doping with MgO in PPLN and PPLT, enabling development of cw green-pumped OPOs based on MgO-doped PPLN (MgO:PPLN) [6–10] and stoichiometric PPLT (MgO:sPPLT) [11–13]. The growth and fabrication of MgO:sPPLT, however, remains challenging, resulting in limited availability of this material. On the other hand, because of a mature growth and poling technology, together with high nonlinearity, MgO:PPLN can now be readily fabricated in multi-grating, as well as fanout grating designs for the development of near-IR to mid-IR cw OPOs pumped at ∼1.064 μm. Such OPOs are now well established, providing widely tunable radiation from ∼1.45 to ∼4 μm at Watt-level powers [14,15]. However, as a material with different linear and nonlinear optical properties compared to MgO:sPPLT and PPKTP, MgO:PPLN presents a different set of challenges for the development of green-pumped cw OPOs. Previous reports of cw green-pumped OPOs based on MgO:PPLN include singly resonant oscillators (SROs) for the signal [6–9] and idler [10] in linear [6,8,9], as well as ring [7,10] cavity configurations using uniform grating structures. Such OPOs deploy single- or multi-grating crystal designs, where wavelength tuning is typically achieved by changing the temperature of the nonlinear crystal. This significantly reduces the wavelength tuning rate in these crystals, particularly away from degeneracy, where material dispersion requires relatively large change in the phase-matching temperature for a small variation in the output wavelength. Under these circumstances, using fanout structures in which the grating period varies continuously across the lateral dimension of the crystal, provides continuous and rapid wavelength tuning at a fixed temperature. However, the development of green-pumped OPOs for the generation of visible to near-IR wavelengths requires short grating periods ($\Lambda < 10$ μm), which presents significant challenges in the fabrication of QPM structures in a fanout design with a large enough length and clear aperture. Nevertheless, with progress in QPM crystal growth and fabrication technology, the use of fanout grating designs has already been demonstrated in green-pumped cw OPOs based on MgO:sPPLT and PPKTP [16,17]. However, to the best of our knowledge, such OPOs based on fanout grating MgO:PPLN have not been demonstrated so far. In this Letter, we report the first green-pumped cw OPO

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based on fanout–grating MgO:PPLN, continuously tunable over 813–1032 nm in the signal and 1098–1539 nm in the idler at a fixed temperature, by simple mechanical translation of the crystal across its lateral dimension. Moreover, by deploying signal output coupling, we demonstrate simultaneous extraction of useful output in both parametric waves at a total external efficiency of 30%, with maximum signal powers up to 339 mW and idler powers up to 400 mW across the tuning range.

The schematic of the experimental setup for the green-pumped cw OPO based on fanout–grating MgO:PPLN is shown in Fig. 1. The pump source is a cw frequency-doubled $Nd:YVO_4$ laser (Coherent Verdi V10) delivering up to 10 W of output power at 532 nm in a single-frequency, linearly polarized beam with $M^2 < 1.1$. The nonlinear crystal for the OPO is 25-mm-long, 12-mm-wide, and 0.5-mm-thick 5 mol% MgO:PPLN, incorporating a fanout grating structure with a continuously varying period over $\Lambda = 6.9-8.1$ µm across its lateral dimension. Unlike previous reports on green-pumped cw OPOs which deployed 40–50 mm crystals [6–10], here we use a relatively short interaction length of 25 mm. Owing to the 15 times higher linear absorption coefficient of MgO:PPLN at 532 nm compared to 1064 nm [18], the use of shorter crystal minimizes thermal loading due to green pumping, thereby enabling stable long-term operation with excellent beam quality. The crystal faces are antireflection-coated at 532 nm ($R < 1\%$) and 750–1060 nm ($R < 1\%$), and over 1060–1850 nm ($R < 2\%$). The crystal is housed in an oven with temperature stability of $\pm$ 0.01°C and mounted on a motorized linear translation stage with a resolution of 0.1 µm to enable fine and continuous grating tuning across its lateral dimension. The OPO is configured in a compact ring cavity comprising two plano-concave mirrors, M_1 and M_2 ($r = 100$ mm), and two plane mirrors, M_3-M_4. The mirrors are all highly reflecting ($R > 99.8\%$) over 620–1030 nm for signal, and highly transmitting ($T > 97\%$) across 1078–3550 nm for the idler and at 532 nm for the pump, ensuring SRO operation in signal. For signal extraction and optimization of OPO performance, M_4 can also be replaced by a plane output coupler (OC) with variable transmission ($T = 1-2\%$) across 720–1000 nm. The idler output is separated from the transmitted pump using a dichroic mirror, M_5. The pump beam is focused to a waist radius of $w_0 \sim 45$ µm initially at the center of the MgO:PPLN crystal, with a corresponding focusing parameter of $\xi \sim 0.47$. Before implementation of the OPO, we measured the transmission of the MgO:PPLN crystal to be $T \sim 93\%$ at the pump wavelength for e-polarization corresponding to type-0 ($e \rightarrow ee$) QPM parametric interaction, as shown in the inset of Fig. 1. In order to avoid catastrophic damage to the crystal, we limited the pump power below 2.5 W for all measurements. This corresponds to a pump intensity of 39.3 kW/cm^2 in the MgO:PPLN crystal.

Wavelength tuning in our green-pumped cw OPO can be performed by temperature tuning for a fixed grating period or by continuously varying the fanout grating period of the MgO:PPLN crystal at a constant temperature. We first characterized the tuning capabilities of the OPO at a fixed crystal temperature of 55°C by varying the crystal position laterally across the pump beam to continuously change the QPM grating period. The results are shown in Fig. 2. The red data points represent the signal wavelengths, measured using a spectrometer (*Ocean Optics* HR4000), while the black dots represent the corresponding idler wavelengths, calculated from energy

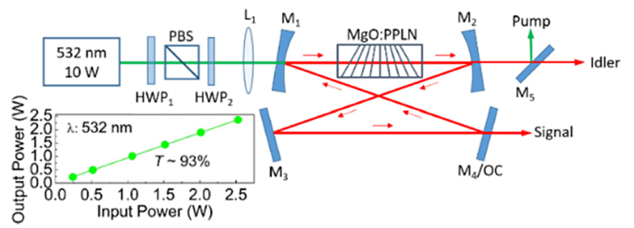

Fig. 1. Configuration of green-pumped fanout–grating MgO:PPLN cw OPO. HWP, half-wave-plate; PBS, polarizing beam-splitter; L, lens; M, mirrors; OC, output coupler. Inset: crystal transmission at 532 nm.

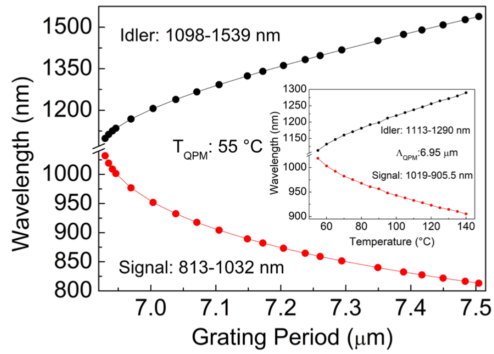

Fig. 2. Signal and idler wavelength tuning range of the green-pumped cw OPO as a function of the MgO:PPLN fanout grating period at a fixed temperature of 55°C. Inset: temperature tuning at a fixed grating period of $\Lambda = 6.95$ µm using all highly reflecting mirrors.

conservation. The grating periods were estimated from the measured wavelengths by using relevant Sellmeier equations [19]. By varying the lateral position of the fanout crystal to change the grating period over $\Lambda = 6.93-7.50$ µm, we were able to tune the OPO across 813–1032 nm in the signal and 1539–1098 nm in the corresponding idler, as shown in Fig. 2. We can also achieve wavelength tuning in the OPO by changing the crystal temperature while keeping the grating period fixed. Using all highly reflecting mirrors (M_1-M_4), at a fixed grating period of $\Lambda = 6.95$ µm, by varying the crystal temperature from 55 to 140°C, we were able to tune the OPO across 905.5–1019 nm in the signal and correspondingly 1290–1113 nm in the idler, as shown in the inset of Fig. 2. The temperature tuning rate of the OPO for the signal wavelength is ~1.3 nm/°C, which is relatively slow, compared to grating tuning, where a crystal translation by ~1.5 mm can provide identical wavelength coverage. On the other hand, tuning over the entire OPO operating range can be achieved by translating the crystal over ~5.15 mm. The OPO can be tuned across 813–1032 nm in ~2 s, while it requires >1 min for the output power to reach a steady state. Hence, the fanout grating design can provide rapid tuning at a fixed temperature compared to temperature tuning with a uniform grating period, which requires several minutes to cover the same wavelength range.

The simultaneously generated signal and idler powers across the OPO tuning range for a maximum input pump power of 2.4 W are shown in Fig. 3. The measurements were performed with an OPO cavity comprising three highly reflecting mirrors (M_1-M_3) and an OC for signal extraction.

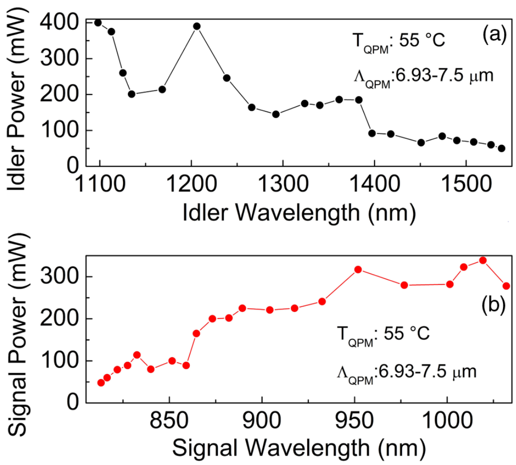

Fig. 3. (a) Idler, and (b) signal output powers across the tuning range of the green-pumped fanout-grating MgO:PPLN cw OPO.

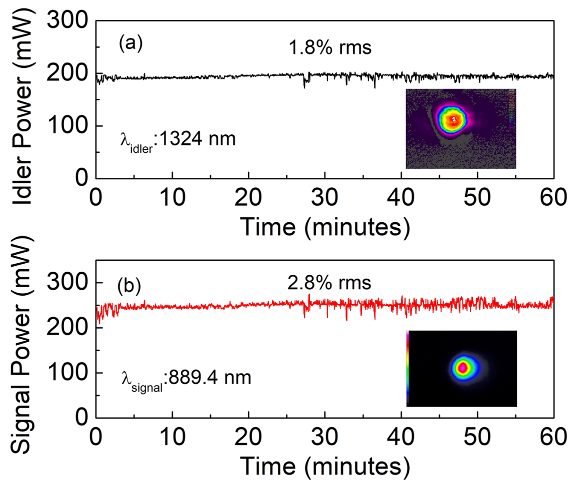

Fig. 4. Passive power stability of the (a) idler, and (b) extracted signal over 1 h. Inset: corresponding spatial beam profiles.

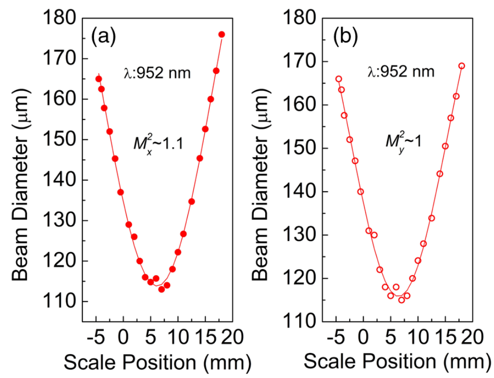

Fig. 5. Measured signal beam quality at 952 nm in the (a) horizontal and (b) vertical directions.

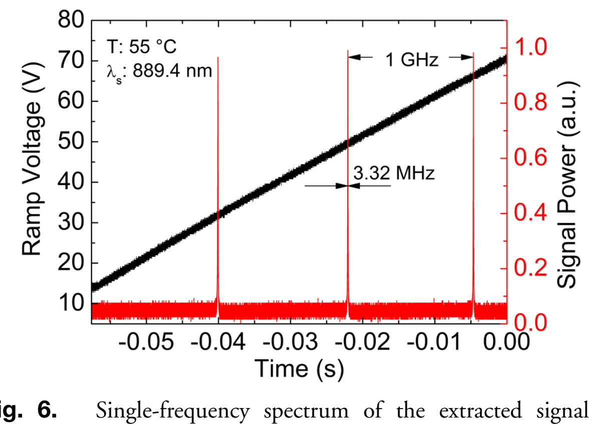

Fig. 6. Single-frequency spectrum of the extracted signal at 889.4 nm.

The signal power varies from 278 mW at 1032 nm to 48 mW at 813 nm, with a maximum of 339 mW at 1019 nm, while the idler power varies from a maximum of 400 mW at 1098 nm to 50 mW at 1539 nm. The maximum total simultaneously generated output power is 714 mW, measured at a signal wavelength of 1019 nm and the corresponding idler wavelength of 1113 nm, representing an overall OPO extraction efficiency of 30%. The minimum OPO threshold was recorded to be 2.04 W at an operating signal wavelength of 889 nm. This relatively higher threshold compared to previously reported green-pumped MgO:PPLN cw OPOs is attributed to the short interaction length of the crystal used here in combination with the output coupling. The decline in idler power at longer wavelengths and the corresponding drop in signal power at shorter wavelengths are attributed to the reduction in parametric gain further away from degeneracy. In spite of the short interaction length of the MgO:PPLN crystal compared to earlier reports [7–9], the performance of our green-pumped OPO in terms of output power and extraction efficiency is superior at identical pumping levels.

We carried out simultaneous long-term signal and idler power stability measurements at a signal wavelength of 889 nm and corresponding idler wavelength of 1324 nm for a pump power of 2.4 W, with the results shown in Fig. 4. The signal power exhibits a passive power stability better than 2.8% rms over 1 h, while the simultaneously recorded idler power displays a power stability of 1.8% rms. Similar power stabilities are also observed at other signal and idler wavelengths. The far-field spatial profile of the signal beam, measured at a distance of ∼25 cm from the OC, and the idler beam, measured at a distance of ∼30 cm from the output mirror, M_2, are shown in the insets of Figs. 4(a) and 4(b), respectively. As can be seen, both signal and idler beams have Gaussian profile, with circularity of 95% and 94%, respectively. We further characterized the beam quality of the signal extracted from the OPO, using a lens of focal length $f = 125$ mm and a scanning beam profiler, resulting in a measured value of $M^2 < 1.1$ at a signal wavelength of 952 nm, along both axes, as shown in Fig. 5.

Using a confocal Fabry–Perot interferometer, we recorded the output signal spectrum at 889.4 nm, with the result shown in Fig. 6. The measurement confirms a single-frequency spectrum with an instantaneous full-width at half-maximum (FWHM) linewidth of 3.3 MHz. Using a wave meter, we also recorded the frequency stability of the signal, resulting in a peak–peak deviation of 84.23 MHz over 72 seconds about the mean wavelength of ∼890.89 nm, as shown in Fig. 7.

Given the maximum input pump power limit of 2.4 W to avoid any damage to the crystal, the OPO operated <2 times

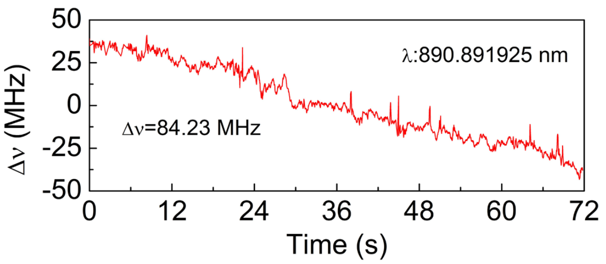

Fig. 7. Frequency stability of the extracted signal beam at 890 nm.

above threshold (2.04 W). However, we also observed severe thermal effects in the MgO:PPN crystal under green pumping. As described earlier, we measure the transmission of the MgO:PPLN crystal to be ∼93% at 532 nm. Considering the 1.5%/cm linear absorption, ∼4% of the 7% loss is attributed to the absorption at the pump wavelength, resulting in a significant thermal load in the nonlinear crystal. Moreover, considering a thermal conductivity of 4.6 W/m.K [20] and a thermo-optic coefficient of $6.5 \times 10^{-5}\ K^{-1}$, we estimate a thermal lens of focal length, $f_{th} = 20$ mm, which is of the same order as the 25 mm length of the MgO:PPLN crystal, implying a strong thermal lens in the material. We attribute the well-defined signal spatial beam profile with a tightly confined mode and the stable output performance of the OPO to the thermal lens in the MgO:PPLN crystal. At the same time, it should also be noted that MgO:PPLN is susceptible to GRIIRA, which is reported to be $1.1 \times 10^{-3}\ cm^{-1}$ at a green power density of $25\ kW/cm^2$ [21]. This value is significantly higher than that of MgO:sPPLT which exhibits no signature of GRIIRA at the same green power density [21]. While MgO doping is expected to alleviate photorefractive effect in PPLN and reduce GRIIRA, the relatively low thermal conductivity and significantly lower threshold for GRIIRA appear to be the limiting factors for power scaling the green-pumped MgO:PPLN cw OPO. However, at the current pumping levels below 2.5 W, we have found that our green-pumped cw OPO operates reliably over many hours without any damage to the MgO:PPLN crystal.

In conclusion, we have demonstrated the first green-pumped OPO based on fanned-grating MgO:PPLN. By exploiting the fanout grating structure, the OPO is continuously tunable across 813–1032 nm in the signal and 1098–1539 nm in the idler by lateral translation of the crystal at a fixed temperature. The OPO can deliver a total simultaneous output power of 714 mW at an extraction efficiency of 30%, with signal powers up to 339 mW at 1019 nm and idler powers up to 400 mW at 1098 nm. The signal and idler powers exhibit passive power stability of 2.8% and 1.8% rms, respectively, over 1 h, with excellent spatial beam quality, in a single-frequency signal spectrum with an FWHM linewidth of 3.3 MHz. The exploitation of a fanout grating design, together with signal output coupling result in not only wide, rapid and uninterrupted wavelength tuning, but also improved output powers and frequency stability. We have not observed any damage to the crystal after long-term operation at pump powers up to 2.5 W. The use of signal output coupling combined with a relatively short interaction length also reduces the thermal load in the MgO:PPN crystal, resulting in increased conversion efficiency, high spatial beam quality, and improved output stability. Strong thermal lensing contributes to the stability of the OPO, while linear absorption, together with GRIIRA, limit the power scalability of the OPO. Because of the mature growth technology and high nonlinearity of MgO:PPLN compared to MgOs:PPLT, it can be a viable material for development of green-pumped cw OPOs at moderate power levels.

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