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Stable, 17.5 W, Optimally-output-coupled, Yb-fiber-pumped Mid-infrared Optical Parametric Oscillator

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Abstract: We report stable, continuous-wave, mid-infrared optical-parametric-oscillator based on MgO:PPLN, pumped by Yb-fiber-laser, generating total power of 17.5W at 61% extraction efficiency, in TEM_{00}(M^2_{Idler}<1.24,M^2_{Signal}<1.24) spatial mode with peak-peak idler power stability of 5% over 14 hours.

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High-power, continuous-wave (cw) mid-infrared optical parametric oscillators (OPOs) are unique sources of interest for variety of applications including photoacoustic spectroscopy and trace gas analysis, requiring wide tunability and narrow linewidth [1]. Such sources are also promising as first-stage pumps for cw OPOs in tandem, spanning the spectral coverage of these devices beyond the current practical limit of ~4 µm imposed by the onset of absorption of oxide-based nonlinear crystals. Singly-resonant OPOs (SROs) represent the most viable configuration for such applications, and using the widely established periodically-poled $LiNbO_3$ (PPLN), such devices have been extensively demonstrated previously. However, the generation of high mid-infrared optical powers in cw SROs is a challenging task, due to heavy thermal loading of the nonlinear crystal arising from the high intracavity signal intensities at increased pump powers. This can lead to saturation and subsequently a substantial drop in efficiency, thus limiting the available output power, as well as increased output instabilities. To date, the highest output power generated from a cw OPO is 10 W of idler at 3 µm for 50 W of pump at 20% efficiency using a SRO configuration [2]. Output coupling of SRO signal has enabled the generation of 8.6 W of total power (5.1 W signal, 3.5 W idler) for 15 W of pump, with improved extraction efficiency up to 59% [3].

Here we report the generation of 17.5 W of total power (9.8 W signal, 7.7 W idler) from an out-coupled cw SRO at 61% extraction efficiency. We also show that high output power stability and good beam quality can be maintained at such elevated output powers by careful control of crystal thermal loading effects through optimized signal out-coupling. To our knowledge, this is the highest output power and extraction efficiency reported from a cw OPO.

A schematic of the experimental setup is shown in Fig. 1. The OPO is pumped by a Yb-fiber laser, delivering up to 30 W of single-frequency output at 1064 nm in linear polarization, with M^2<1.01 and a nominal linewidth of 89 kHz. The fundamental beam is focused to a beam waist radius of 63 µm (ξ~1) at the centre of the crystal. The nonlinear crystal is a 50-mm-long, 5% MgO-doped periodically poled $LiNbO_3$ (MgO:PPLN), with five different grating periods ranging from 29.5 µm to 31.5 µm, in steps of 0.5 µm. The crystal is housed in an oven that can be temperature tuned from room temperature to 200 °C. The OPO is formed in a symmetric ring resonator that consists

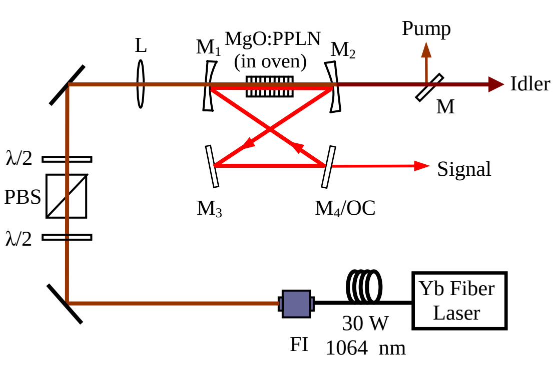

Fig. 1. Schematic of the Yb-fiber laser pumped MgO:PPLN OC-SRO.

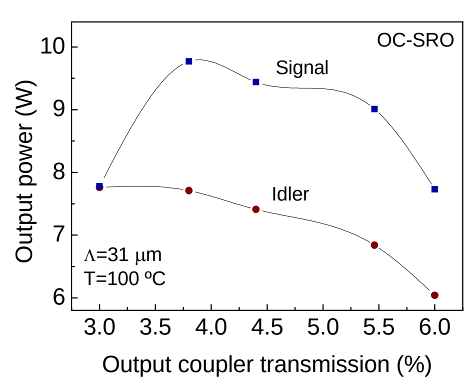

Fig. 2. Variation of the extracted signal and generated idler power with output coupler transmission.

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of two plano-concave mirrors, M_1 and M_2, and two plane mirrors, M_3 and M_4. All mirrors have R>99%@ 1.3-1.9 µm and T>90%@2.2-4 µm, thus ensuring SRO operation. The out-coupled SRO (OC-SRO) operation is achieved by replacing mirror M_4, which is high reflecting at the signal wavelength, by a suitable output coupler (OC) [4]. A proper cavity design ensures the pump and signal beam waists to be positioned at the center of the crystal. The total length of the cavity is 862 mm (FSR~348 MHz). A dichroic mirror, M, separates the generated idler from the pump.

In order to characterize the SRO, we performed power scaling at a temperature of 100 °C for a grating period of 31 µm, generating up to 8.6 W of idler power at 3061 nm for 28.6 W of pump at 30.1% efficiency. Temperature tuning the SRO from 50 °C to 200 °C resulted in the generation idler wavelengths from 2787 to 3147 nm which, towards the room temperature, is limited by the thermal loading of the nonlinear crystal due to high intracavity signal power. In order to efficiently manage the thermal load, thereby maximizing output power and efficiency, we performed signal out-coupling by deploying several OCs of transmission ranging from 3% to 6% in the signal wavelength range. Figure 2 shows the variation of extracted signal and idler power with OC transmission. As seen from the plot, with a 3.8% OC, we were able to generate 7.7 W of idler at 3070 nm together with 9.8 W of signal at 1627 nm, resulting in 17.5 of total power, at an overall extraction efficiency of 61%. The power scaling of the OC-SRO at the optimal output coupling of 3.8% along with that of SRO is shown in Fig. 3, clearly demonstrating >200% power enhancement over SRO. Further, the OC-SRO has enabled tuning down to room temperature, extending the tuning range from 1594-1714 nm (signal) along with 2803-3196 nm (idler). The inset of Fig. 3 shows the far field spatial beam profile of the idler at 3174 nm. The distortion in the beam profile from a perfect circular distribution is due to the tilt angle on the attenuation optics used in the measurements and is not an inherent property of the idler output beam. We also recorded the long-term idler power stability of the OC-SRO at 44 °C, where a peak-to-peak stability as high as 5% was obtained over 14 hrs at full idler power of >7 W (Fig. 4). Using a CaF_2 lens and a scanning beam profiler, we measured beam quality factors of M^2<1.24 and M^2<1.39 for the idler and signal, respectively, confirming the TEM_{00} spatial mode. To our knowledge, these are the first measurements of OPO idler power stability and spatial profile performed at these mid-IR wavelengths.

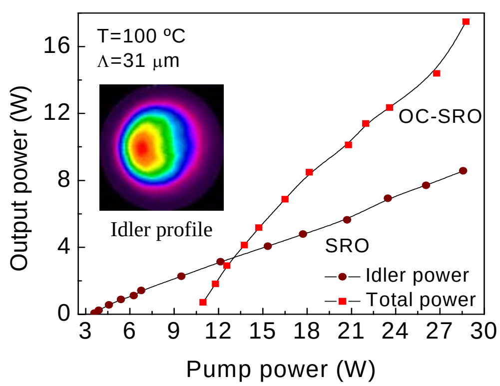

Fig. 3. Variation of the output power as a function of pump power in SRO and OC-SRO. Inset: Far-field spatial beam profile of the generated idler in SRO.

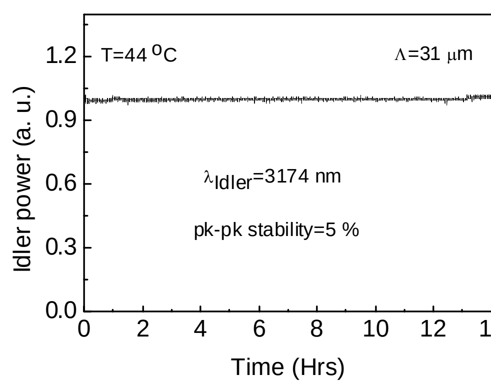

Fig. 4. Long term power stability of the idler at T=44ºC corresponding to an idler wavelength of 3174 nm.

In conclusion, we have generated 17.5 W of total infrared power at 61% extraction efficiency from a compact, fiber-pumped cw OPO by using optimized signal output coupling to control thermal loading of the nonlinear crystal. The exceptional power, high long-term stability and excellent beam quality make this cw OPO an attractive mid-infrared source for many applications. Full characterization of this system, including wavelength tuning, thermal issues and frequency stability have been performed and will be presented.

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