High-power, Broadband, Continuous-wave, Mid-infrared Optical Parametric Oscillator based on MgO:PPLN

S. Chaitanya Kumar,[1,*] Ritwick Das,[1] G. K. Samanta,[1] and M. Ebrahim-Zadeh[1,2]
[1] *ICFO-Institut de Ciencies Fotoniques, Mediterranean Technology Park, 08860 Castelldefels, Barcelona, Spain*
[2] *Institucio Catalana de Recerca i Estudis Avancats (ICREA), Passeig Lluis Companys 23, Barcelona 08010, Spain*
[*] *corresponding author*: *chaitanya.suddapalli@icfo.es*

Abstract: We present a broadband, high-power, fiber-laser-pumped, continuous-wave optical parametric oscillator for mid-infrared by exploiting extended phase-matching properties of MgO:PPLN. Total powers of 11.3W, with 5.3W broadband mid-infrared idler in excellent beam quality are generated.

OCIS codes: 190.4970, 140.3510.

Optical sources capable of generating broadband, continuous-wave (cw) radiation at high power in the mid-infrared (IR) are of significant interest for a variety of applications including single-shot spectroscopy of large molecules [1], multi-component trace-gas detection [2], and as potential seeds for high-energy ultrafast lasers and amplifiers in the mid-IR. The conventional technique for broadband mid-IR generation is based on the exploitation of high-intensity, ultrafast laser sources in combination with short interaction lengths in nonlinear crystals to achieve single-pass parametric down-conversion [3]. However, the deployment of these schemes in the cw regime is a challenging proposition due to very low single-pass gain. In the present work, we report a cw singly-resonant optical parametric oscillator (SRO) that can provide broadband radiation in the mid-IR at multiwatt power level, with excellent beam quality, and in a compact and practical design using a fiber laser pump source.

In order illustrate the idea of extended phase-matching, we expand the phase-mismatch factor ($\Delta k = k_p - k_s - k_i$, where k_p, k_s, k_i are propagation constants at pump, signal and idler wavelengths, respectively) around the central pump wavelength, λ_0,

$$\Delta k = \left[\Delta k\right]_{\lambda=\lambda_0} + \left[\frac{\partial(\Delta k)}{\partial\lambda}\right]_{\lambda=\lambda_0} \Delta\lambda + \frac{1}{2}\left[\frac{\partial^2(\Delta k)}{\partial\lambda^2}\right]_{\lambda=\lambda_0} (\Delta\lambda)^2 + \frac{1}{6}\left[\frac{\partial^3(\Delta k)}{\partial\lambda^3}\right]_{\lambda=\lambda_0} (\Delta\lambda)^3 \ldots \qquad \ldots (1)$$

The first term in the expansion of Δk could be made zero by choosing an appropriate poling period for the nonlinear crystal (Λ), so as to achieve quasi-phase-matching (QPM) at λ_0. The extension in the phase-matching bandwidth (BW) is achieved when the higher-order terms in the expansion also vanish. In 5% MgO-doped periodically-poled $LiNbO_3$ (MgO:PPLN) crystal, the material dispersion is such that the first-order derivative term vanishes for a pump wavelength λ_0=1059 nm, crystal temperature T=100 °C and Λ=30 μm. This is evident in Fig. 1, where we have plotted Δk as a function of pump wavelength for Λ=30 μm and T=100 ºC. Due to the fact that $\partial(\Delta k)/\partial\lambda = 0$, the curve flattens close to λ_0 = 1059 nm and, hence, the pump acceptance BW is essentially determined by the second-order derivative term, as

$$\Delta\lambda_p = 2(5.57/l)^{1/2}\left[\partial^2(\Delta k)/\partial\lambda^2\Big|_{\lambda=\lambda_0}\right]^{-1/2} \qquad \ldots (2)$$

where l is the crystal length. This leads to the pump acceptance BW of ~104 cm^{-1} for a crystal length of 5 cm.

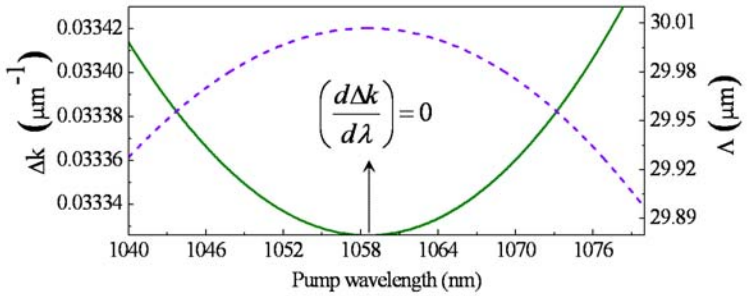

Fig. 1. Variation of phase-mismatch and corresponding QPM grating period (Λ) required as a function of pump wavelength at T=100 ˚C

For the implementation of broadband cw SRO, we deploy a broadband cw Yb-fiber pump laser (IPG Photonics, central wavelength ~1060 nm), delivering a maximum output of 28 W in a linearly polarized beam with good spatial quality (M^2<1.12). The schematic of the experimental setup and the SRO configuration are similar to our earlier report [4]. In order to exploit the broad phase-matching BW of MgO:PPLN, we choose a 50-mm-long crystal with Λ=30 μm and the crystal is kept at T=100±0.1°C. The signal beam waist of ~76 μm at 1523 nm results in optimum overlap with the pump. In Fig. 2(a), we show the measured spectrum of the fiber pump laser at the maximum available power relative to the parametric gain curve for the 50 mm MgO:PPLN crystal (T=100°C, Λ=30 μm). It could be seen that the laser exhibits a BW of ~73 cm^{-1} at a centre wavelength of 1060 nm, with a large fraction of the spectrum lying within the pump acceptance BW of the crystal. The measured spectrum of the depleted pump, shown in Fig. 2(b), confirms that ~63.5 cm^{-1} of the input pump spectrum undergoes discernable depletion in transmission through the SRO cavity. If it is assumed that the resonant signal (λ_s~1523 nm) exhibits a single-frequency, narrow linewidth due to high finesse of the SRO cavity ($\Delta\nu$~6 MHz), the reconstructed idler spectrum exhibits a BW of 63.7 cm^{-1} at the central idler wavelength of λ_i~3454 nm, as shown in Fig. 2(c).

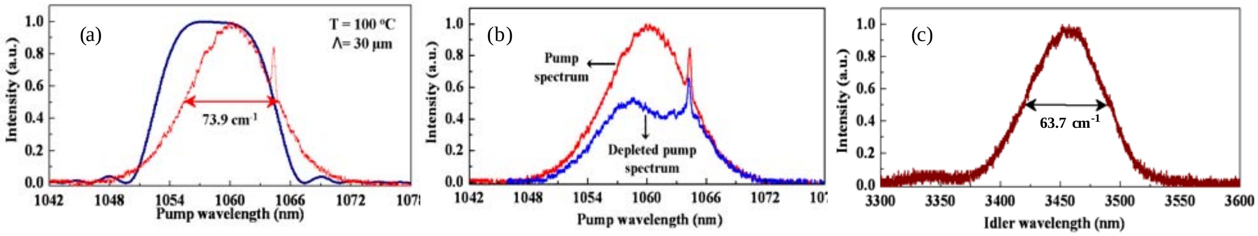

Fig.2. Recorded (a) Pump spectrum (red solid line) and the calculated pump acceptance BW (dark-blue solid line) for 50 mm long MgO:PPLN crystal, (b) Input (red) and depleted (blue) pump spectrum for the SRO, (c) Reconstructed idler spectrum of the SRO

From the power scaling measurements, we have found the threshold for broadband SRO to be ~5.8 W and for the maximum available pump power of 25.5 W, the SRO generates as much as 5.3 W of broadband mid-IR power at an extraction efficiency of 20.8%. The pump depletion was measured to be 80.6% at the maximum input pump power for the SRO configuration. In order to maximize the total power extraction and reduce thermal load on the MgO:PPLN crystal, we also employed partial out-coupling of the resonant signal wave [4] by replacing one of the plane mirrors of the ring cavity with an output coupler (OC) with ~3.5% transmission (un-optimized) at the signal wavelength (λ_s~1523 nm). It is evident from Fig. 4 that although the OC-SRO threshold increases to 12.1 W compared to the SRO, the maximum total (signal plus idler) power extracted from the device is now 11.2 W (7.2 W signal and 4.0 W idler) for a maximum available pump power of 25.5 W at an extraction efficiency of 44%. Under this condition, we recorded a pump depletion of 73.3% for the OC-SRO. We have also measured the far-field energy distribution of the signal and idler beams at the maximum input pump power, which are shown in the inset of Fig. 3. The M^2 measurements result in M^2<1.16 for the signal and M^2<1.50 for the idler.

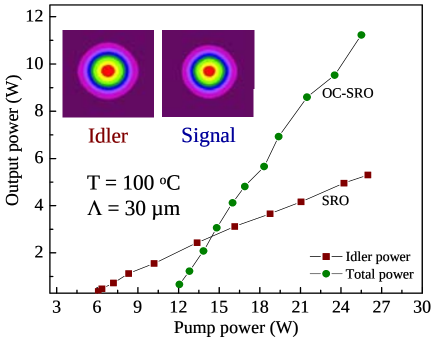

Fig. 3. Variation of total extracted power as a function of pump power for MgO:PPLN SRO and OC-SRO. Inset: Spatial beam profiles of the extracted signal and idler from the OC-SRO.

References:

[1] Ł.W. Kornaszewski *et al.*, Opt. Express, **15**, 11219-11224 (2007).

[2] T. Yanagawa *et al.*, Opt. Lett., **31**, 960-962 (2006).

[3] D. Brida *et al.*, Opt. Lett., **33**, 2901-2903 (2008).

[4] G. K. Samanta *et al.*, Opt. Lett., **34**, 2255-2257 (2009).