High average power 2 μm generation using an intracavity PPMgLN optical parametric oscillator

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Received October 14, 2011; revised November 14, 2011; accepted November 15, 2011; posted November 17, 2011 (Doc. ID 156467); published December 24, 2011

An intracavity quasi-phase-matched optical parametric oscillator (OPO) has been developed for the purpose of generating radiation with high average power and high repetition rate in the 2 μm regime. The device is a degenerate OPO based on a 3 mm thick MgO-doped periodically poled $LiNbO_3$ (PPMgLN) crystal, which is pumped in turn within the cavity by a diode side-pumped, Q-switched 1 μm Nd:YAG laser operating at 10 kHz. Up to 20 W broadband 2 μm radiation can be generated with a compact configuration under the crystal temperature of 115 °C. The beam profile is close to circularly symmetric with $M^2 \sim 10$.

OCIS Codes: 190.4970, 190.4400.

Laser sources operating in the 2 μm regime are of interest for several applications in remote sensing and medical treatment. A convenient approach to produce such wavelengths is to wavelength double a mature solid-state 1 μm Nd laser with a degenerate optical parametric oscillator (OPO). In order to obtain high efficiency and high output power, a complex pump laser with high power and good beam quality is necessary for the external pumping scheme. Therefore, the intracavity scheme is a better choice for reducing the requirement and the total size of the pump laser. Compared to the external scheme, this configuration takes advantage of the intense fluence inside the cavity with its compactness. Moreover, it can increase the effective nonlinear interaction length due to multiple passes of the pump pulse through the intracavity OPO [1]. Intracavity degenerate OPOs, based on birefringent materials such as $KTiOPO_4$ (KTP) employing type II phase matching, have been investigated by Wu and coworkers. [2–4]. They achieved over 20 W output at 2 μm from a walk-off compensated intracavity KTP OPO. However, due to the unoptimized compensated walk-off of the KTP, the laser beam profile had a large degree of ellipticity, with M^2 values ~16 and ~8 in two orthogonal polarizations.

Quasi-phase-matched (QPM) materials, such as periodically poled $LiNbO_3$ (PPLN) and periodically poled KTP (PPKTP), offer attractive alternatives to birefringent materials employing type II phase matching. QPM can utilize the largest nonlinearity and avoid the walk-off effect, resulting in high efficiency and good beam quality [5]. These degenerate OPOs have been investigated by several researchers. Hirano *et al.* have achieved over 50 W output at 2 μm from an extracavity OPO based on MgO-doped PPLN (PPMgLN), which is well known as a strong material for photorefractive damage [6]. However, to date, the output power of intracavity QPM OPO is restricted below 10 W [7]. One of the dominant factors is the small thickness of the crystal, which limits the optical aperture for the intracavity OPO interaction. In this Letter, we present a compact intracavity degenerate OPO that is based on a 3 mm thick PPMgLN and can obtain an average output power of 20 W at 2 μm with a circularly symmetric beam profile. The OPO is pumped by a diode side-pumped, high repetition rate Q-switched Nd:YAG laser.

The experimental setup of our intracavity PPMgLN OPO is shown in Fig. 1. Pumped by an unpolarized Nd:YAG laser instead of a polarized laser, the OPO can avoid the problem of depolarization loss due to the thermally induced birefringence, which results in a distorted laser beam [3]. The pump cavity is formed by an Nd:YAG module, an acousto-optical Q switch, and two flat mirrors. The Nd:YAG pump module consists of a 4 mm diameter, 120 mm long, cw diode side-pumped Nd:YAG crystal. Both of its side faces are flat and antireflection coated at 1 μm. The laser cavity is only 30 cm in length. The output coupler (OC) M_0 has reflectivity $R =$ 96% at 1 μm. We do not use $R = 100\%$ for M_0 in order to avoid optical damage caused by fluctuations of high laser intensities when tuning the OPO. Mirror M_2 is highly reflective at 1 μm and $R = 60\%$ at 2.1 μm with a 100 nm bandwidth. The intracavity OPO consists of two flat mirrors M_1, M_2 and a 20 mm long PPMgLN crystal with a $3\ \text{mm} \times 3\ \text{mm}$ aperture. The OPO cavity length is ~60 mm due to mechanical constraints. The input coupler M_1 is highly transmissive (>98%) at 1 μm and highly reflective (>99.5%) at 2 μm with a 100 nm bandwidth. We have experimented with different OCs for the intracavity OPO, using $R = 50\%$, 60%, and 70% at 2 μm for mirror M_2, and have achieved the maximum output power with

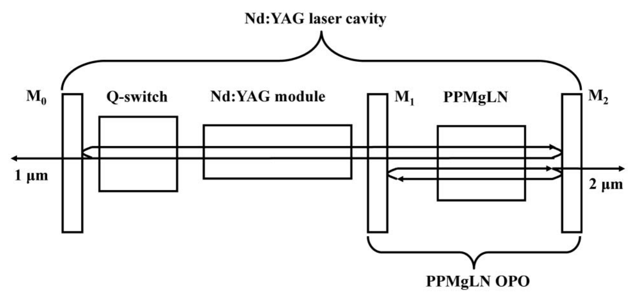

Fig. 1. Experimental setup of the intracavity PPMgLN OPO.

$R = 60\%$. The PPMgLN device is mounted in an oven with accuracy of 0.1 °C and temperature range up to 200 °C. Its input and output surfaces are antireflection coated for both the pump and the output wavelength. The crystal has a 32 μm grating period. This poling period results in degenerate wavelength of 2.1 μm under the crystal temperature of 115 °C. It is verified by an extracavity OPO experiment. We have produced idler radiation from 1.9 to 2.12 μm and signal radiation from 2.4 to 2.12 μm by changing the temperature from 70 °C to 115 °C.

The available maximum diode pump power is approximately 500 W at the diode current of 25 A. Without the intracavity OPO, the Nd:YAG laser can produce a 1 μm multimode radiation about 58 W at 10 kHz with the pulse width less than 70 ns when it is pumped at ~380 W (diode current = 20 A) with a 30% OC. When the OPO is placed inside the laser cavity, the output power drops to 40 W because of the loss introduced by the relatively smaller aperture of the PPMgLN compared to the laser crystal. One can highly decrease the loss of the laser, if using a Nd:YAG rod with less than 3 mm diameter. Figure 2 shows the calculated beam radius at the principle plane of the rod near the 1 μm OC M_0. In this calculation, the thermal focal length of the Nd:YAG rod varies from 100 to 20 cm (measured with an He–Ne laser), depending on the diode pumping power, and the thermal focal lens of PPMgLN is estimated according to the absorption factor and intracavity laser intensity. We can see that our laser is stable over a wide range of diode current from 12 to 21 A, corresponding to the diode pumping power from ~120 to 380 W.

We have achieved the maximum output power of 20 W at 2 μm with $R = 60\%$ for M_2 and at a repetition rate of 10 kHz. We have also obtained 7 W of 1 μm output from M_0 ($R = 96\%$ at 1 μm) at the diode current of 21 A. The 2 μm pulse duration is measured with an InGaAs detector (Thorlabs, DET10D). The pulse widths are approximately 60 ns. The 2.1 and 1 μm power are measured as a function of the diode pump current, and the results are plotted in Fig. 3. A ±0.5 W (~5%) oscillation is observed at the diode current of 20 A. The 1 μm output power drops and becomes unstable when increasing the diode current from 20 to 22 A. The 2 μm output power increases less than 1 W when increasing the diode current from 21

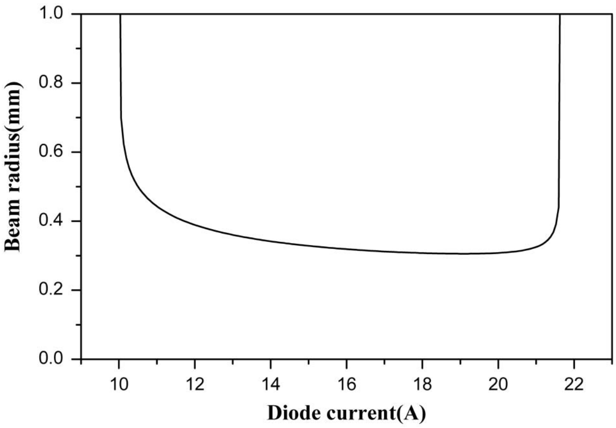

Fig. 2. Calculated beam radius at the principle plane of the rod near the 1 μm OC M_0.

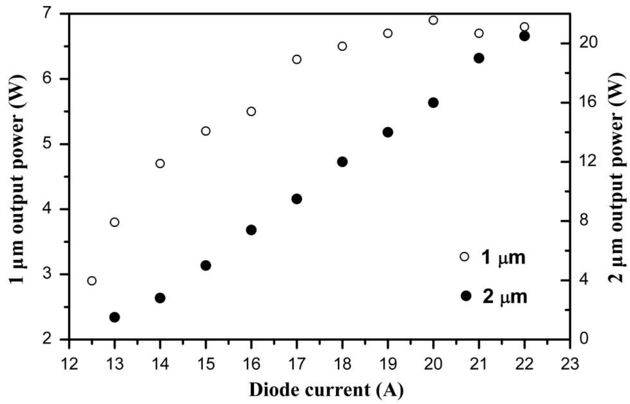

Fig. 3. Average output power of 2 μm (closed circles) and 1 μm (open circles) versus diode pump current.

to 22 A. The stability also becomes worse. This is caused by the splitting of the stability ranges, which induces significant high losses in the resonator. These results match well with the theoretical indications in Fig. 2. At the maximum output power, the efficiency of the power conversion of diode power to 2 μm power is about 5% for our intracavity PPMgLN OPO. It is larger by a factor of 1.3 than the intracavity KTP reported in [2]. However, obvious crystal temperature rising is found when the pump current is larger than 19 A. This is mainly caused by high intracavity power (>300 W). The final crystal temperature depends on the pump power. At the highest pump current (21 A), the rise is over 20 ° C. The slow rise of crystal temperature over 115 °C leads to a smooth power decrease due to the phase mismatch. In order to obtain a stable, high output power, the initial temperature should be adjusted lower than 115 °C according to the pump power.

As a result of the nature of degenerate QPM OPOs, a very broad (>80 nm) bandwidth is obtained, as shown in Fig. 4. The spectrum is measured using a 30 cm scanning monochromator containing a 300 line/mm grating blazed at 2 μm and a liquid-nitrogen-cooled InSb detector. The resolution of the monochromator is estimated to be 0.8 nm at around 2 μm. Spectral line narrowing by using passive elements such as diffraction gratings, etalons, and volume Bragg gratings has been reported [8–10]. This is also one of our future works. We have measured the

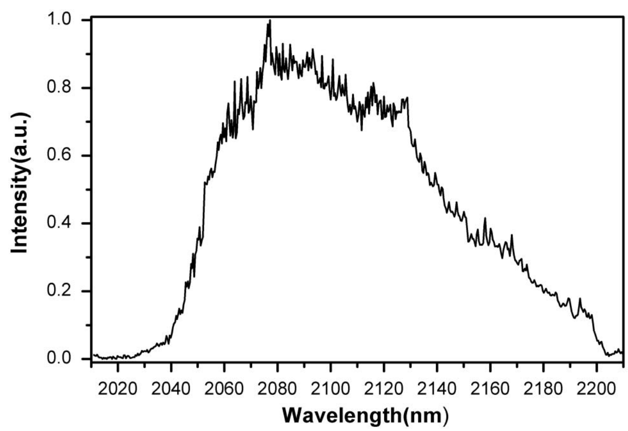

Fig. 4. Spectrum of the output from the PPMgLN OPO.

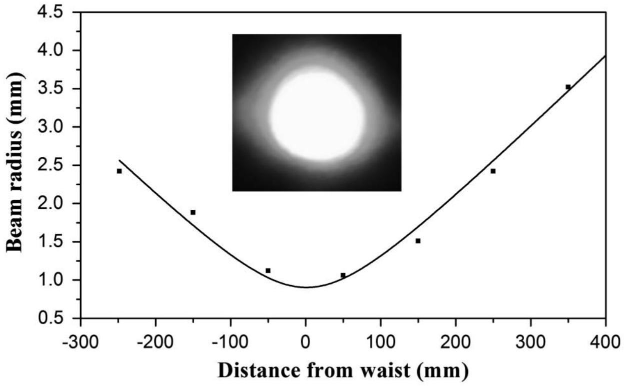

Fig. 5. Beam propagation behavior of OPO radiation. (Inset) Typical far-field photograph image of 2 μm profile on a screen at the maximum output power.

M^2 value of 2 μm output with 10 W power (at 17 A pump current) by the knife edge method; data are shown in Fig. 5. The measured M^2 is about 10 in the horizontal direction. The inset is a typical far-field photograph image of a 2 μm profile on a screen, which is nearly circularly symmetric at the maximum output of 20 W. The relatively poor beam quality is due to the fact that the thermal lensing effect in the Nd:YAG rod grows larger as the diode pump power increases. The beam quality becomes better as the 2 μm output power decreases.

In conclusion, we have demonstrated high average power operation of a degenerate intracavity PPMgLN OPO. The 2 μm radiation beam profile is circularly symmetric, which is a distinct advantage over that from an intracavity KTP OPO. Future improvements will focus on the linearly polarized pumped intracavity PPMgLN OPO based on birefringence compensation or the use of Nd:YVO_4 as the inherently birefringent polarized laser source, to obtain better beam quality and system stability.

This work was partially supported by the National Natural Science Foundation of China under grants 10732100, 11072271, 10972239, and 61008025, the Specialized Research Foundation for the Doctoral Program of Chinese Higher Education under grant 20100171120024, and the Fundamental Research Funds for the Central Universities of China under grant 11lgpy55.

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