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Narrowband intracavity MgO:PPLN optical parametric oscillator near degeneracy with a volume Bragg grating

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ABSTRACT

We report a narrow-bandwidth near-degenerate MgO:PPLN optical parametric oscillator (OPO) based on a volume Bragg grating (VBG) output coupler (OC) intracavity pumped by a linearly polarized Q-switched Nd:YAG laser. Maximum 2.1 μm output power of 7.1 W with beam quality factor M^2 of 2.0 and 2.3 in horizontal and vertical directions is achieved. 23.5 W of 1 μm radiation with fundamental mode is obtained simultaneously.

1. Introduction

High-beam-quality pulsed 2 μm laser sources are required for remote sensing and medical applications [1–3]. A convenient approach to produce such wavelengths is to wavelength-double a mature solid-state 1.064 μm Nd laser with a degenerate OPO. This tandem OPO system benefits from the maturity and availability of the 1.064 μm Nd laser technology, but its effectiveness depends on the efficiency of the wavelength doubling stage. A way to obtain high efficiency and high power output is to place the OPO inside the cavity of the Nd laser. It takes advantage of the intense fluence inside the cavity, as well as increases the effective nonlinear interaction length due to the multiple passes of the pump beam through the OPO [4]. Intracavity degenerate OPOs, based on birefringent materials such as $KTiOPO_4$ (KTP) employing type II phase matching, have been investigated by Wu and coworkers [5–7]. They achieved over 20 W output near 2.1 μm from a walk-off compensated intracavity KTP OPO. However, due to the unoptimized compensated walk-off of the KTP, the laser beam profile has a large degree of ellipticity, and the best value of M^2 factor is more than 8. To circumvent this problem, quasi-phase-matched (QPM) materials, such as periodically poled $LiNbO_3$ (PPLN), periodically poled $LiTaO_3$ (PPLT) and periodically poled KTP (PPKTP), offer attractive alternatives to birefringent materials employing type II phase matching [8]. Quasi phase matching can utilize the largest nonlinear coefficient and avoid the walk-off effect due to $e \rightarrow e+e$ interaction in the QPM crystals, resulting in high efficiency and good beam quality [9]. These intracavity QPM OPOs have been investigated by several researchers [10–12]. Cho et al. achieved 6 W output at 2 μm from an intracavity OPO based on PPLN crystal, and the M^2 was measured to be 3.3 [10]. In a later experiment with a PPLT crystal, they improved the output power to 9 W [11]. The M^2 value increased to 7 due to the fact that the thermal lensing effect in Nd:YAG rod becomes large as the diode pumping power increases. In our previous work [12], we have obtained 20 W broadband (>80 nm) 2 μm radiation from a compact intracavity PPMgLN OPO, which is pumped by an unpolarized Nd:YAG laser. The beam profile is approximate to circularly symmetric with $M^2 \sim 10$.

In this paper, we demonstrate a high-beam-quality and narrow-linewidth intracavity near-degenerate MgO:PPLN OPO using a VBG OC pumped by a linearly polarized Q-switched Nd:YAG laser. We have achieved a maximum 2.1 μm output of 7.1 W at 10 kHz repetition rate. Good beam quality factor M^2 of 2.0 and 2.3 in horizontal and vertical directions are obtained at the maximum output. The signal and idler radiations are spectrally confined within 2 nm bandwidth at 2129 nm. Besides the parametric radiation, 23.5 W of 1 μm radiation were obtained simultaneously.

2. Experimental design

The experimental setup of our intracavity PPMgLN OPO is depicted in Fig. 1(a). The laser cavity is formed by two flat mirrors M_1, M_3. Mirror M_1 is highly reflective ($R>99.9\%$) at 1.064 μm. Mirror M_3 is highly reflective ($R>99.5\%$) for 1.064 μm and $R=60\%$ for 2.1 μm with a 100 nm bandwidth. It serves as both the rear mirror of the laser and

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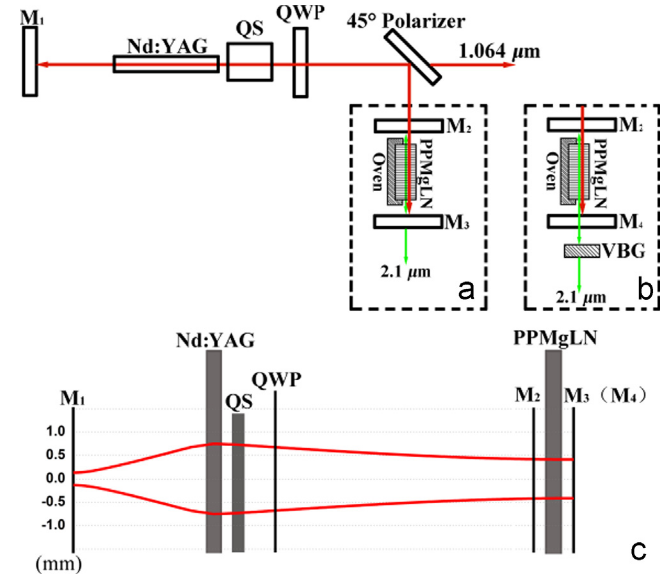

Fig. 1. Experimental setup of the intracavity PPMgLN OPO with (a) flat OC, (b) VBG OC and (c) the calculated 1.064 μm laser profile in the laser cavity. QS: acousto-optic Q-switch.

the output coupler for the OPO. The Nd:YAG pump module consists of a 110-mm long, 4 mm in diameter, water-cooled Nd:YAG rod side pumped by five cw diode arrays. The maximum diode pump power is approximately 500 W at the diode current of 25 A. Both ends of the rod are flat and antireflection-coated (AR-coated) at 1.064 μm. The 45° thin-film polarizer is inserted in the laser cavity to polarize the laser beam. It has high reflection ($R>99.8\%$) for the *s*-polarization (perpendicular to the optical table) and low reflection ($R<1\%$) for the p-polarization. As shown in Fig. 1(a), the *s*-polarization light oscillates in the laser cavity between M_1 and M_3, and a horizontal polarized 1.064 μm output is produced after the polarizer due to the depolarization, which is caused by the thermal-induced birefringence in the Nd:YAG rod [13]. The quarter-wave plate (QWP) is inserted into the laser cavity to partially compensate the depolarization loss [14]. Using the design criteria developed by Magni et al. [15]. and the thermal model for a working cavity described in Ref. [16], we have developed a large-volume fundamental mode and low-sensitivity laser cavity at the diode current of 21 A. The calculated fundamental mode profile in the laser cavity is shown in Fig. 1(c). The mode radius is ~0.75 mm in the middle of the rod.

The intracavity OPO, ~60 mm in length, is formed by two flat mirrors M_2, M_3 and a 20-mm long PPMgLN crystal (HC Photonics, Corp.) with a 3 mm × 3 mm aperture. The crystal is placed close to M_3, which is the place of the laser beam waist with 0.3 mm radius. The input coupler M_2 is highly transmissive (> 98%) at 1.064 μm and highly reflective (> 99.5%) at 2.1 μm. A number of OPO output couplers (M_3) with different reflectivities are tested in the experiment. The maximum conversion efficiency is achieved when using M_3 with $R=60\%$. The crystal is mounted in an oven with an accuracy of 0.1 °C and a temperature range up to 200 °C. Its input and output surfaces are AR-coated ($R<0.5\%$) for both the pump and the output wavelengths. It has a 32 μm grating period and is stabilized at 111.5 °C for achieving the maximum gain near degeneracy.

3. Experimental results

In this section, we present the experimental results of the laser and the intracavity OPO. Without the intracavity OPO, the Nd:YAG laser can produce 14.5 W output at 10 kHz repetition rate with the pulse width of 185 ns when it is pumped at 414 W (diode current = 22 A). This is obtained with a 20% OC instead of the highly reflective mirror M_1. The beam quality of the output is measured using the knife edge method, with a result of $M^2\sim1.3$ and 1.4 in the horizontal and vertical directions, confirming a nearly TEM_{00} Gaussian profile. We have also measured the M^2 values of the laser beam at different diode pump powers. We find that the laser mode is quite stable and there is only a slight degradation over the range of diode current from 21 A to 22 A, corresponding to the diode pump power from 386 W to 414 W. The beam quality factor will exceed 2 when the diode current is out of this range; and the stability of the laser becomes worse.

When the PPMgLN crystal and OPO mirror M_2 are placed inside the laser cavity, we have achieved the maximum output power of 8 W at 2.1 μm with $R=60\%$ for M_3 after careful alignment of the OPO cavity. At the same time, we have also obtained 27 W of 1.064 μm horizontal polarization output after the 45° polarizer. All these are obtained at a diode pump power of 408 W (diode current = 21.8 A). This corresponds to 1.96% conversion efficiency to 2.1 μm. The conversion efficiency to the total output laser (2.1 μm and 1.064 μm) is 8.58%. We have also measured the M^2 values of 2.1 μm output at the maximum output power to be 3.2 and 3.3 in the horizontal and vertical directions, respectively. The spectrum is measured using a 30 cm scanning monochromator which contains a 300 line/mm grating blazed at 2.1 μm and a liquid-nitrogen-cooled InSb detector. As a result of the nature of degenerate QPM OPOs, a broad spectral bandwidth (~80 nm) is obtained.

Currently, VBGs have been successfully used in degenerate QPM OPOs for efficient spectral narrowing [17–19], owing to excellent spectral selectivity together with low losses and high damage threshold. As shown in Fig. 1(b), a VBG is used as not only an output coupler but also a filter of the intracavity PPMgLN OPO in order to narrow linewidth of 2.1 μm output. The VBG (OptiGrate, Corp.) has a reflectance peak at 2129.6 nm with 70% diffraction efficiency and a 0.8 nm bandwidth. It has a 5 mm × 6 mm aperture and 3.5-mm thickness. The surfaces are AR-coated for the oscillation wavelength ($R<0.4\%$). They are also wedged ~5° relative to grating planes to minimize parasitic oscillations. Mirror M_4 is used in this experiment instead of Mirror M_3. It is highly reflective at 1.064 μm and highly transmissive at 2.1 μm with a bandwidth larger than 100 nm. It serves as the rear mirror of the laser and protects the VBG from being exposed to the intense fluence of the laser, enabling a stable operation. The length of the OPO cavity (formed by mirror M_2 and the VBG) increases to 105 mm due to the mechanical constraints. Except these, no other changes are made to the experimental arrangement.

A maximum output power of 7.1 W at 2.1 μm is achieved at 10 kHz repetition rate with the VBG configuration. We have also obtained 23.5 W of 1.064 μm horizontal polarization output after the 45° polarizer. All these are obtained at a diode pump power of 408 W. The optical-to-optical conversion efficiency of diode to 2.1 μm is 1.74%, and the total conversion efficiency is 7.5%. The output performance is shown in Fig. 2. The 2.1 μm and 1.064 μm output powers are extremely stable when increasing the diode pump power from 392 W to 408 W. The stability of 2.1 μm output is better than the ordinary mirror output coupler configuration; the standard deviation of the power fluctuations is less than 1% of the average power in 1 h.

The output spectra are shown in Fig. 3(a) and the inset is a large scale scanning spectrum with a 0.05 nm step. Apart from the signal and idler peaks, there is no other peak in the output spectrum. The signal and idler peaks are separated by 1.2 nm and confined within 2 nm bandwidth at the degenerate wavelength of 2129 nm. The spectral bandwidths are 0.34 nm and 0.61 nm, respectively, for the signal and idler waves. There is only a little overlap between them. The oscillator should be singly resonant on the idler wave, resulting in a beam quality improvement combined with a longer OPO cavity than the ordinary OC configuration. The measured M^2 values of the horizontal and vertical directions are 2.0 and 2.3; data are shown in Fig. 3(b).

The 2.1 μm pulse duration is measured with an InGaAs detector (Thorlabs, DET10D). Fig. 4 shows the pulse profiles of the OPO output with different OCs at different pump power. A temporal profile of multiple pulses is obtained with the 40% ordinary OC at the power of 408 W, as shown in Fig. 4(a). These relaxation oscillation type multiple pulses are caused by the interaction between the parametric process that generates the signal and idler from the 1.064 μm pump laser and the back conversion process in the OPO resonator with high intracavity power [20]. Depending on the intracavity power level of the laser and the OPO, the OPO can produce one signal pulse or multiple pulses. The intracavity power of the OPO cavity is 32 W (greater by a factor of $(1+R)/(1-R)$, where R is the reflectivity of the OC) at the pump power of 408 W. When a lower pump power of 392 W was used, we achieved 6 W output at 2.1 μm, corresponding to an intracavity power of 24 W. In this case, a single pulse is obtained, as shown in Fig. 4(b). We also measured the pulse profile from the setup with VBG OC at the pump power of 408 W, as shown in Fig. 4(c). The temporal profile is approximately a single pulse, which is different from the OPO with the ordinary OC at the same pump power. Such phenomenon is owing to that the OPO with VBG OC operates at a singly resonant configuration with low intracavity power [20]. Assuming the power of the signal is equal to the idler, we estimate the intracavity power of the idler is ~20 W, which is less than 32 W of the doubly resonant OPO with the ordinary OC.

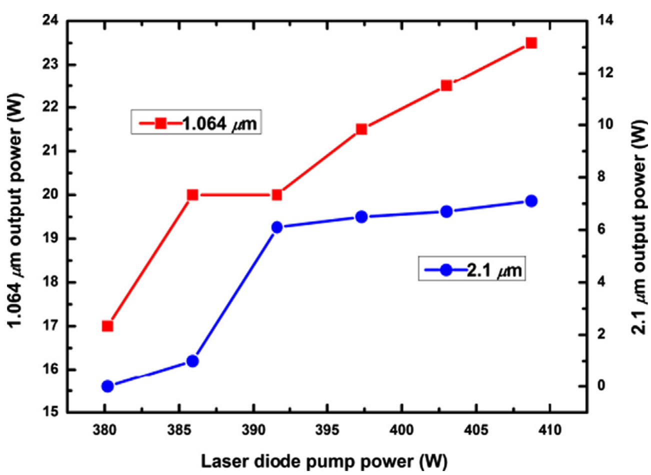

Fig. 2. Average output power of the 2.1 μm VBG OPO and the 1.064 μm laser versus diode pump power.

4. Conclusion

In conclusion, we have demonstrated a high-average-power and high-beam-quality, narrow-linewidth near-degenerate intracavity PPMgLN OPO pumped by a linearly polarized Q-switched Nd:YAG laser with a large-volume fundamental mode at high repetition rate. The parametric radiations are confined within 2 nm bandwidth at 2129 nm. The oscillator based on VBG is singly resonant on the idler wave, resulting in a beam quality improvement combined with the longer OPO cavity than the ordinary OC configuration. Maximum average output power of 7.1 W with good beam quality factor M^2 of 2.0 and 2.3 in horizontal and vertical directions is achieved. An output power of 23.5 W at 1.064 μm is produced after the 45° polarizer due to the depolarization, which is caused by the thermal-induced birefringence in the laser rod. The diode-to-laser conversion efficiency is 7.5%. Future improvements will focus on the linearly polarized pumped intracavity PPMgLN OPO based on birefringence compensation or the use of Nd:YLF as the inherently birefringent polarized laser source with which better efficiency can be obtained.

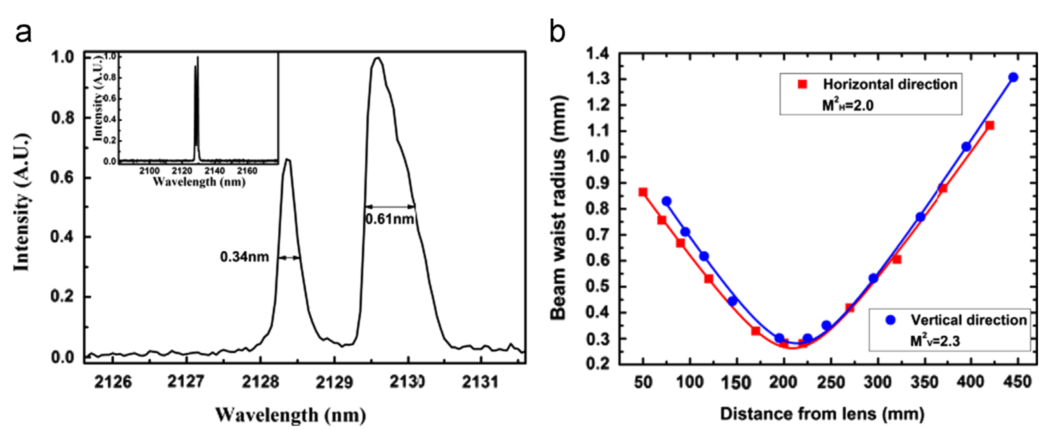

Fig. 3. (a) Output spectra from the PPMgLN OPO, inset graph shows the large scale scanning spectrum, and (b) M^2 measurements of the 2.1 μm OPO output by using an $f=150$ mm focusing lens.

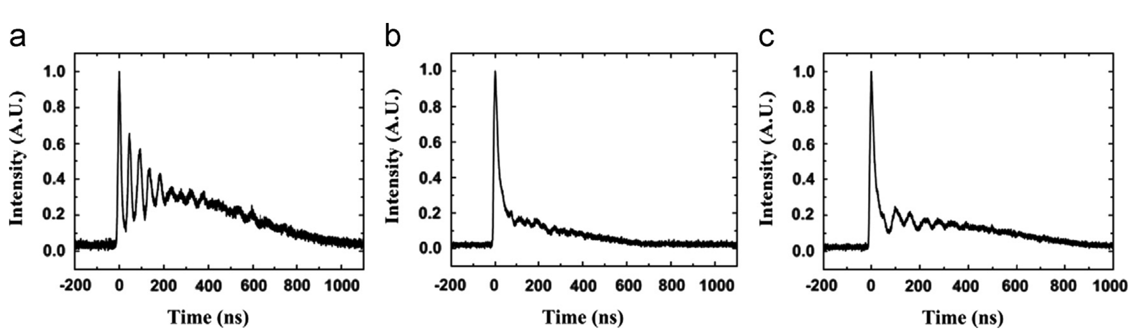

Fig. 4. The Q-switched pulses of the OPO output (a) with flat OC at a pump power of 408 W, (b) with flat OC at a pump power of 392 W, (c) with VBG OC at a pump power of 408 W.

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