Compact Efficient 2.1-μm Intracavity MgO:PPLN OPO With a VBG Output Coupler

Jing Guo, Guangyuan He, Baofu Zhang, Xionghua Zheng, Zhongxing Jiao, and Biao Wang

***Abstract*— We present a compact efficient intracavity MgO:PPLN optical parametric oscillator (OPO) with a volume Bragg grating output coupler pumped by a Q-switched Nd:YVO$_4$ laser operating in 2.1-μm region. Narrowband 2.1-μm output power of 3.7 W is achieved with a pulse duration <2 ns at 15-kHz repetition rate. A maximum conversion efficiency of 19.5% from laser diode (LD) to 2.1 μm is obtained at 17.5-W LD pump power. The 2.1-μm beam quality factors M^2 of 1.85 and 2.37 in horizontal and vertical directions are obtained. To the best of our knowledge, the efficiency is the highest ever achieved from an intracavity OPO in 2-μm region.**

***Index Terms*— Solid state lasers, optical frequency conversion, cavity resonators, volume Bragg grating, compact, efficient.**

I. Introduction

EFFICIENT pulsed 2 μm laser sources with high beam quality are required for remote sensing and medical applications [1], [2]. In addition, narrow linewidth laser sources beyond 2 μm for pumping ZGP OPO [3]–[5] attract widespread application interests in defense and security. A convenient approach to produce such wavelengths is to wavelength-double a mature solid-state 1.064 μm Nd laser with a degenerate OPO. An attractive way to obtain high efficiency and high output power is to place the OPO inside the pump cavity. This configuration takes advantage of the intense fluence inside the cavity with its compactness, as well as increases the effective nonlinear interaction length due to the multiple passes of the pump beam through the OPO [6]. Wu and coworkers have investigated the intracavity degenerate OPOs based on birefringent materials such as KTiOPO$_4$ (KTP) employing type II phase matching [7]–[9]. With a walk-off compensated intracavity KTP OPO, they achieved over 20 W output power near 2.1 μm, corresponding to 3.9% of conversion efficiency from LD to 2.1 μm. Due to a thermally-induced birefringence and residual walk-off in the KTP crystals, their laser beam profile had a large degree of ellipticity, and the best value of M^2 factor was more than 8.

In order to improve the conversion efficiency and the beam quality, 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 [10]. Quasi phase matching can utilize the largest nonlinear coefficient and avoid the walk-off effect, resulting in high efficiency and high beam quality [11]. Cho et al. achieved 6 W output power at 2 μm from an intracavtiy OPO based on PPLN crystal, corresponding to 5.4% of conversion efficiency from the LD power of 110 W [12], and the M^2 value was measured to be 3.3. In a later experiment with a PPLT crystal, they improved the power to 9 W and the conversion efficiency from the 160 W LD power is 5.6% [13]. The M^2 value increased to 7 because the thermal lensing effect in the Nd:YAG rod becomes large as the LD power increases. In our previous work, we have obtained 20 W broadband (>80 nm) 2 μm laser from a compact intracavity PPMgLN OPO pumped by an unpolarized, diode side-pumped Nd:YAG laser [14]. The conversion efficiency is 5.3% and beam quality factor M^2 is about 10. Subsequently, we reported a narrowband (<2 nm) near-degenerate MgO:PPLN OPO based on a volume Bragg grating (VBG) output coupler (OC) pumped by a linearly polarized Q-switched Nd:YAG laser [15]. Maximum 2.1 μm power of 7.1 W is achieved with a conversion efficiency of 1.74% from the 408 W LD power. The dominant factor restricting the conversion efficiency is also the large depolarization loss in the diode side-pumped Nd:YAG laser rod due to the uncompensated thermally-induced birefringence.

In this letter, we use the inherently polarized a-cut Nd:YVO$_4$, a proved efficient gain medium amenable to end-pumping with high power fiber-coupled laser diodes, instead of the Nd:YAG as the pumping source. This change allows us to increase the pulse repetition rate from a few kilohertz to 15 kHz. With a compact intracavity PPLN OPO, we have achieved a conversion efficiency of 19.5% from LD to 2.1 μm and up to 3.7 W output power with the pulse duration of 1.8 ns at 15 kHz repetition rate. Beam quality factors M^2 of 1.85 and 2.37 in horizontal and vertical directions are obtained at the maximum power. The signal and idler radiations are confined within 2 nm linewidth at 2129 nm owing to the use of VBG as the output coupler.

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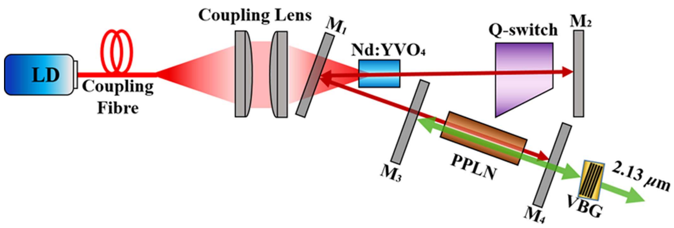

Fig. 1. Experiment setup of the intracavity MgO:PPLN OPO with a VBG OC.

II. Experiment Setup

The experimental schematic of our intracavity MgO:PPLN OPO is depicted in Fig. 1. The pump source is a 20 W fiber-coupled laser diode array at 808 nm; the coupling fiber pigtail has a core diameter of 400 μm and a numerical aperture of 0.22. The output beam from the optical fiber is imaged with 1:1 magnification into a 0.3 at. % doped a-cut $Nd:YVO_4$ crystal by a pair of aspherical plane-convex lenses with coupling losses about 2%. The 10-mm long $Nd:YVO_4$ crystal with a 4 mm $\times$ 4 mm aperture is wrapped with indium foil and mounted in a copper oven whose temperature is stabilized at 25 °C. Both ends of the crystal are flat and antireflection-coated at 1.064 μm and 808 nm with a reflectivity of 1.064 μm less than 0.1%. The laser cavity, formed by three flat mirrors M_1, M_2 and M_4, is a symmetric resonator. It is only 350 mm in length. Mirror M_1 is highly reflective (>99%) at 1.064 μm and highly transmissive (>98%) at 808 nm (at 15 degree angle of incidence). Mirror M_2 is highly reflective (>99.5%) at 1.064 μm. Mirror M_4 is highly reflective (>99.5%) at 1.064 μm and highly transmissive (>99%) at 2.1 μm. A 32-mm long acousto-optic Q-switch is used for intracavity Q-switching operation.

The intracavity OPO is formed by a mirror M_3, a MgO:PPLN crystal and a VBG OC. The OPO cavity length is 80 mm due to mechanical constrains. The input mirror M_3 is highly reflective (>99.5%) at 2.1 μm and highly transmissive (>98%) at 1.064 μm. The MgO:PPLN (HC Photonics, Corp.) with 20-mm length and 3 mm $\times$ 3 mm aperture is placed close to M_4, where the laser beam waist is 300 μm in radius, in order for the OPO to achieve high efficiency and high output power. The crystal has a single 32-μm grating period, with both ends antireflection-coated at 1.064 μm and 2.1 μm. The crystal is mounted in an oven with its temperature accuracy of 0.1 °C and a temperature range up to 200 °C; in our experiment, the oven is stabilized at 110.0 °C for achieving the maximum gain near degeneracy. The VBG (OptiGrate, Corp.) has a 5 mm $\times$ 6 mm aperture and 3.5-mm thickness. It is used not only as an output coupler but also as a spectrum filter of the degenerate OPO. The VBG has a reflective peak at 2129.6 nm with 70% diffraction efficiency and 0.8-nm bandwidth (FWHM). The surfaces of VBG are antireflection-coated for the oscillation wavelength (R<0.4%). They are also wedged ~5° relative to grating planes to minimize parasitic oscillations. The VBG follows closely after mirror M_4, which serves as the rear mirror of the laser and protects the VBG from being exposed to the intense fluence of the laser, resulting in a stable operation of the OPO.

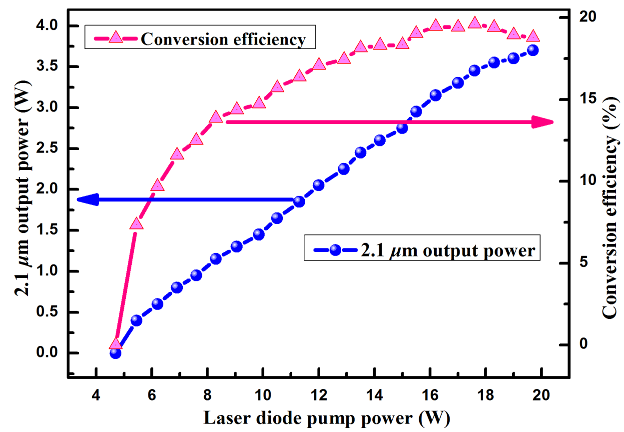

Fig. 2. 2.1 μm output power and conversion efficiency of the intracavity MgO:PPLN OPO versus LD power.

III. Results and Discussions

Without the intracavity OPO, the $Nd:YVO_4$ laser can produce 6.2 W output power with a 20% OC instead of mirror M_2 at 15 kHz repetition rate with the maximum available LD pump power of 20 W. The beam quality of 1.064 μm degenerated with the increase of the LD power. However, the M^2 values maintained less than 1.4 in both the horizontal and vertical directions. The 1.064-μm pulses were measured to be 20 ns long, with a Si transimpedance amplified detector (Thorlabs, PDA10A). With the intracavity OPO components, a narrow-bandwidth near-degenerate 2.1 μm operation is achieved. Figure 2 shows the 2.1 μm output power and conversion efficiency as a function of the LD power. A maximum output power of 3.7 W at 2.1 μm is achieved at 15 kHz, corresponding to a conversion efficiency of 18.5% from the LD power to 2.1 μm. A maximum conversion efficiency of 19.5% is obtained at the LD pump power of 17.5 W. To the best of our knowledge, it is the highest efficiency achieved from an intracavity OPO in 2 μm region. The conversion efficiency reduction is mainly attributed to that the beam quality of 1.064 μm is getting worse at higher LD power. Compared with the PPLN OPO intracavity pumped by a Nd:YAG laser [14], the conversion efficiency is improved by a factor of 3.7 with the use of a $Nd:YVO_4$ laser.

The 2.1 μm pulse duration is measured with an InGaAs detector (Thorlabs, DET08CFC). Figure 3 shows the pulse profile of the intracavity OPO output at the maximum power, and the inset graph shows the pulse train of the 2.1 μm. The pulse duration of 2.1 μm is 1.8 ns, which is much shorter than the 1.064 μm pulse width. For the intracavity OPO, the buildup time of the parametric pulse is determined by the parametric gain and the OPO photon lifetime [16], [17]. The OPO photon lifetime τ_{OPO} is given by the OPO photon losses and the round-trip time in the OPO cavity:

$$\tau_{OPO} \approx t_{ROPO}/(1-R), \quad (1)$$

where R is the reflectivity of the output coupler at the parametric wavelength, t_{ROPO} is the round-trip time of the OPO cavity. The photon lifetime in the 1.064 μm laser cavity is

$$\tau_P \approx t_{RP}/(1-\delta_P), \quad (2)$$

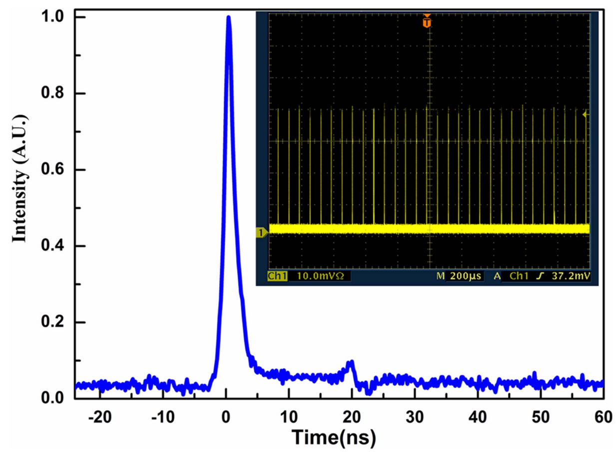

Fig. 3. Pulse shape of 2.1 μm at the maximum output power. Inset graph shows the pulse train of 2.1 μm.

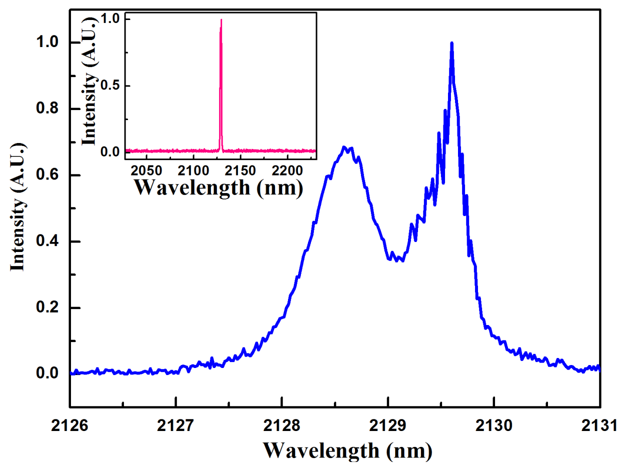

Fig. 4. Output spectrum from the 2.1 μm output with VBG OC. Inset graph shows the large scale scanning spectrum.

where δ_P is the round-trip fundamental wave intensity losses in the laser cavity and t_{RP} is the round-trip time of the laser cavity. In this case, the photon lifetime in the OPO cavity is much shorter than the photon lifetime in the laser cavity. Therefore, it is possible to store the energy for a long time in the pump cavity and have a short parametric pulse. This effect is different from what happens in the extracavity OPO, where the duration of the signal pulse is only a little shorter than the pump pulse [18]. A small sub-pulse after the principal pulse can be observed in Fig. 3. Such phenomenon is caused by the intense intracavity pump power and the low threshold of the intracavity OPO. When the Q-switch is on, the 1.064 μm oscillation occurs. The power of this fundamental wave exceeds the threshold of the OPO, resulting in the buildup of the first parametric pulse and the rising threshold of 1.064 μm laser. After the first OPO process ends, the threshold of the 1.064 μm laser decreases. The second 1.064 μm pulse is produced, and its energy is sufficient to permit the repetition of the OPO process, which leads to the creation of a second parametric pulse [17]. In our experiment, the weak additional pulse is negligible.

The 2.1 μm output spectrum, measured by a high resolution image spectrometer (HJY, iHR550), is shown in Fig. 4; the inset graph shows the large scale scanning spectrum. Apart

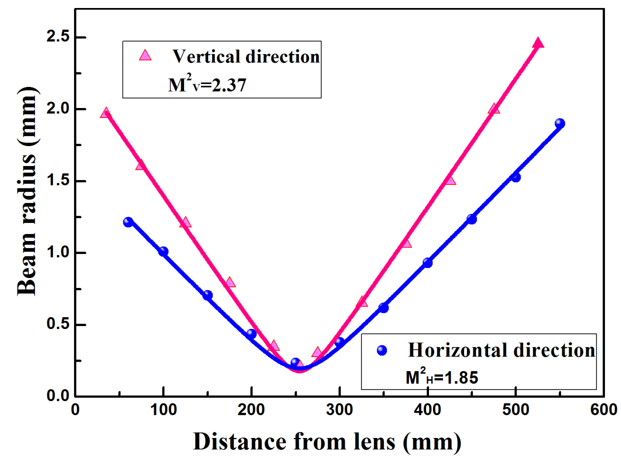

Fig. 5. M^2 measurements of the maximum 2.1 μm output by use of an $f = 200$ mm focusing lens.

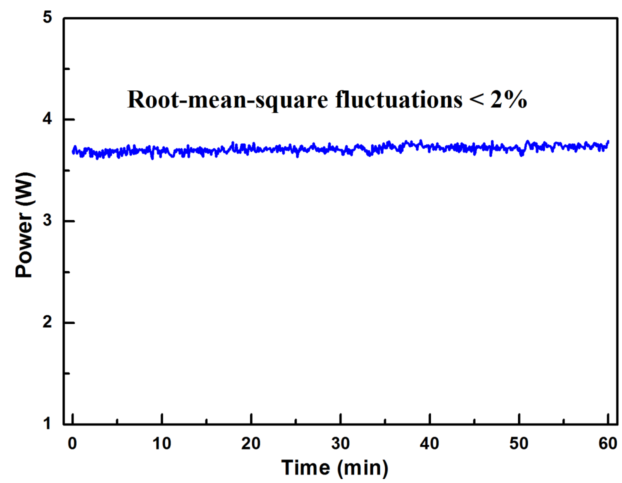

Fig. 6. Stability of the maximum 2.1 μm output power as a function of time.

from the signal and idler peaks, no other peaks can be found in the output spectrum. The signal and idler peaks are confined within 2 nm bandwidth at the degenerate wavelength of 2129 nm. The bandwidths of signal and idler wavelengths are both less than 1 nm. The idler wavelength, locked by the VBG, is 2129.6 nm, and it is not affected by the changing crystal temperature. Since the oscillator is singly resonant at the idler wavelength, it contributes to good beam quality and operation stability.

We have measured the M^2 values of the 2.1 μm at the maximum power, the result is shown in Fig. 5. The measured M^2 values for the 2.1 μm beam are 1.85 and 2.37 in the horizontal and vertical directions, respectively. Such a good beam quality at 2.1 μm is owing to the approximately TEM_{00} Gaussian profile of the 1.064 μm pump laser and the good mode matching between 1.064 μm and 2.1 μm. In our experiments, the 2.1 μm output power is always in a long term stability when ranged from 0.5 W to the maximum. The power stability at the maximum output power is shown in Fig. 6: the root-mean-square fluctuations is less than 2% of the average power in 1 h.

IV. CONCLUSION

In conclusion, we have demonstrated a compact intracavity narrowband near-degenerate MgO:PPLN OPO with high-efficiency and high-beam-quality, pumped by a Q-switched Nd:YVO_4 laser. Maximum conversion efficiency of 19.5% is obtained at the LD power of 17.5 W. The M^2 values for the 2.1 μm beam are 1.85 and 2.37 in the horizontal and vertical directions at the maximum output power of 3.7 W. Our future improvements will focus on the high-power 2 μm laser sources using laser diode with higher power or novel configurations.

REFERENCES

[1] S. W. Henderson *et al.*, "Coherent laser radar at 2 μm using solid-state lasers," *IEEE Trans. Geosci. Remote Sens.*, vol. 31, no. 1, pp. 4–15, Jan. 1993.

[2] T. Sumiyoshi, H. Sekita, T. Arai, S. Sato, M. Ishihara, and M. Kikuchi, "High-power continuous-wave 3- and 2-μm cascade Ho^{3+}:ZBLAN fiber laser and its medical applications," *IEEE J. Sel. Topics Quantum Electron.*, vol. 5, no. 4, pp. 936–943, Jul./Aug. 1999.

[3] M. Henriksson, M. Tiihonen, V. Pasiskevicius, and F. Laurell, "Mid-infrared ZGP OPO pumped by near-degenerate narrowband type-I PPKTP parametric oscillator," *Appl. Phys. B*, vol. 88, no. 1, pp. 37–41, 2007.

[4] M. Henriksson, L. Sjöqvist, G. Strömqvist, V. Pasiskevicius, and F. Laurell, "Tandem PPKTP and ZGP OPO for mid-infrared generation," *Proc. SPIE*, vol. 7115, pp. 71150O-1–71150O-10, Oct. 2008.

[5] M. Henriksson, L. Sjöqvist, M. Tiihonen, V. Pasiskevicius, and F. Laurell, "Tandem OPO systems for mid-infrared generation using quasi phase-matching and volume Bragg gratings," *Proc. SPIE*, vol. 6738, pp. 673805-1–673805-11, Oct. 2007.

[6] P. B. Phua, K. S. Lai, and R. Wu, "Multiwatt high-repetition-rate 2-μm output from an intracavity $KTiOPO_4$ optical parametric oscillator," *Appl. Opt.*, vol. 39, no. 9, pp. 1435–1439, 2000.

[7] R. F. Wu *et al.*, "Compact 21-W 2-μm intracavity optical parametric oscillator," *Opt. Lett.*, vol. 25, no. 19, pp. 1460–1462, 2000.

[8] R. F. Wu *et al.*, "Multi-watt ZGP OPO based on diffusion bonded walkoff compensated KTP OPO and Nd:YALO laser," in *Proc. Adv. Solid State Lasers*, vol. 68. 2002, pp. 194–197, paper TuA4.

[9] P. B. Phua, B. S. Tan, R. F. Wu, K. S. Lai, L. Chia, and E. Lau, "High-average-power mid-infrared $ZnGeP_2$ optical parametric oscillator with a wavelength-dependent polarization rotator," *Opt. Lett.*, vol. 31, no. 4, pp. 489–491, 2006.

[10] J. Guo, G. G. Lu, G. Y. He, Z. X. Jiao, and B. Wang, "2.1 μm four-mirror standing-wave optical parametric oscillator with high brightness and efficiency," *Laser Phys. Lett.*, vol. 10, no. 11, p. 115403, 2013.

[11] L. E. Myers, R. C. Eckardt, M. M. Fejer, R. L. Byer, W. R. Bosenberg, and J. W. Pierce, "Quasi-phase-matched optical parametric oscillators in bulk periodically poled $LiNbO_3$," *J. Opt. Soc. Amer. B*, vol. 12, no. 11, pp. 2102–2116, 1995.

[12] K.-H. Cho, B. K. Rhee, Y. Sasaki, and H. Ito, "Pulsed intracavity optical parametric oscillator with high average power based on periodically poled $LiNbO_3$," *J. Nonlinear Opt. Phys.*, vol. 14, no. 3, p. 383, 2005.

[13] K. H. Cho and B. K. Rhee, "Intracavity infrared OPO using periodically poled Mg-doped stoichiometric $LiTaO_3$ for generating high average power," *Proc. SPIE*, vol. 6875, pp. 68751A-1–68751A-8, Feb. 2008.

[14] Z. Jiao, G. He, J. Guo, and B. Wang, "High average power 2 μm generation using an intracavity PPMgLN optical parametric oscillator," *Opt. Lett.*, vol. 37, no. 1, pp. 64–66, 2012.

[15] Z. Jiao, J. Guo, G. He, G. Lu, and B. Wang, "Narrowband intracavity MgO:PPLN optical parametric oscillator near degeneracy with a volume Bragg grating," *Opt. Laser Technol.*, vol. 56, pp. 230–233, Mar. 2014.

[16] J. Falk, J. M. Yarborough, and E. O. Ammann, "Internal optical parametric oscillation," *IEEE J. Quantum Electron.*, vol. QE-7, no. 7, pp. 359–369, Jul. 1971.

[17] T. Debuisschert, J. Raffy, J.-P. Pocholle, and M. Papuchon, "Intracavity optical parametric oscillator: Study of the dynamics in pulsed regime," *J. Opt. Soc. Amer. B*, vol. 13, no. 7, pp. 1569–1587, 1996.

[18] G. He, J. Guo, Z. Jiao, and B. Wang, "High-efficiency near-degenerate PPMgLN optical parametric oscillator with a volume Bragg grating," *Opt. Lett.*, vol. 37, no. 8, pp. 1364–1366, 2012.