High-efficiency near-degenerate PPMgLN optical parametric oscillator with a volume Bragg grating

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We demonstrate a high-efficiency near-degenerate periodically poled $MgO:LiNbO_3$ (PPMgLN) optical parametric oscillator (OPO) using a volume Bragg grating (VBG) output coupler (OC) pumped by a multilongitudinal Q-switched $Nd:YVO_4$ laser at 20 kHz repetition rate. A total parametric power of 4.3 W with a conversion efficiency of 60% is achieved in a double-pass pump configuration. The output power improvement over the case of a single-pass pump is nearly 60%. Both the signal and the idler bandwidths are less than 40 GHz and are confined within 170 GHz bandwidth at 2128.8 nm. Such efficiency is, to our knowledge, the highest ever achieved from a degenerate OPO using a VBG OC. © 2012 Optical Society of America

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Efficient and tunable laser sources in the 3–5 μm region are required for medical and military applications. $ZnGeP_2$ (ZGP)-based optical parametric oscillators (OPOs) are currently the most attractive choice. However, owing to their large absorption (around 1 μm), they require pump sources with wavelengths longer than 2 μm. Apart from a Q-switched Ho laser [1,2], a convenient approach to produce such wavelengths is to wavelength double a 1 μm laser with a degenerate OPO [3–11]. This tandem OPO system benefits from the maturity and availability of the 1 μm Nd laser technology, but its effectiveness depends on the efficiency of the wavelength doubling stage. A Type II ($o \rightarrow e + o$) OPO based on birefringent materials, such as $KTiOPO_4$ (KTP), can act as a wavelength doubler with the advantage of its intrinsically narrow output bandwidth (<150 GHz) even close to or at degeneracy [3–6]. It is suitable for pumping a second-stage ZGP OPO, which has a pump acceptance bandwidth of ~500 GHz cm at 2.1 μm. However, the polarization of the signal and the idler beams from such an OPO are orthogonally polarized. Thus, special configurations, such as two separate ZGP OPOs, a wavelength-dependent polarization rotator, or a ZGP OPO followed by a ZGP optical parametric amplifier, are used to fully utilize the output beams from the KTP OPOs [4–6]. These methods involve complicated cavity designs, which require additional cavity components, alignment, and space. Among them, quasi-phase-matched (QPM) OPOs generate radiation with single polarization and wavelength at degeneracy that can be treated as single pump beams [7–11]. Moreover, they utilize the largest nonlinearity and avoid the walk-off effect, resulting in high efficiency and good beam quality [12]. However, due to the nature of a degenerate Type I QPM OPO, a very broad bandwidth (>4 THz) is generated [7,8]. Recently, volume Bragg gratings (VBGs) have been successfully used in high power or high energy 2 μm QPM OPOs for efficient spectral narrowing [8–11]. Henriksson *et al.* first demonstrated such a setup, obtaining a total output power of 1.56 W with 47% slope efficiency from 1.064 to 2.008 and 2.264 μm [8]. In a later experiment with a periodically poled potassium titanyl phosphate (PPKTP) crystal, the authors improved the output power to 7.9 W with 30% conversion efficiency near degeneracy [9]. Koch *et al.* demonstrated an output power of 1.7 W with a conversion efficiency of 21.3% and a spectral width of less than 0.7 nm (~45 GHz) at degeneracy [10]. When operating off degeneracy, a maximum output power of 2.15 W was obtained with a conversion efficiency of 26.8%. Saikawa *et al.* obtained over 55 mJ of the output energy with a conversion efficiency of 35% and a spectral bandwidth of less than 1.4 nm (100 GHz) [11]. Owing to double-pass pumping, the conversion efficiency was increased to 41%.

In this Letter, we demonstrate a high-efficiency near-degenerate PPMgLN OPO using a VBG OC. By using a double-pass pump configuration, we have achieved a conversion efficiency of 60% from 1.064 to 2.1 μm and up to 4.3 W output power with the pulse duration less than 22 ns at 20 kHz repetition rate. The power improvement over the case of a single-pass pump is nearly 60%. Both the signal and the idler bandwidths are less than 0.6 nm (40 GHz) and are confined within 2.5 nm (170 GHz), which is narrower than the ZGP acceptance bandwidths.

The experimental setup of our PPMgLN OPO is shown in Fig. 1. It consists of an input coupler M_1, a VBG OC, and a 30 mm long PPMgLN crystal with a 3.4 mm × 1 mm aperture. The flat mirror M_2 is used for second pass of the pump beam through the crystal in a double-pass pump geometry, and it has high reflection (>99.8%) for the pump wavelength (1.06 μm) and high transmission (>99%) for the output wavelength (2.0–2.2 μm). The

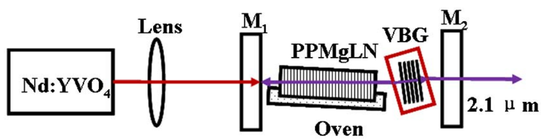

Fig. 1. (Color online) Layout of the experimental setup.

input coupler M_1 is coated highly transmissive (>98%) at pump wavelength and highly reflective (>99.8%) at the output wavelength. It is slightly tilted to the pump beam to prevent the formation of a parametric cavity with M_2 (perpendicular to the pump beam). This alignment will result in a weak noncollinear phase matching in the crystal. 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 antireflection (AR) coated ($R < 1\%$) for both the pump and the output wavelengths, and it has a 32.1 μm grating period. The crystal is tilted (~1°) to avoid parasitic broadband oscillation and is stabilized at 89 °C for maximum gain near degeneracy. The VBG OC has a reflectance peak at 2129.6 nm with 70% diffraction efficiency and 0.8 nm bandwidth. It has a 5 mm × 6 mm aperture and 3.5 mm thickness. The surfaces are AR coated for the pump and the oscillation waves ($R < 0.4\%$). They are also wedged ~5° relative to grating planes to further minimize parasitic oscillations.

The pump source is a multilongitudinal Q-switched Nd:YVO_4 laser. It has a spectral bandwidth of ~30 GHz at 1064.4 nm and a beam quality factor M^2 of less than 1.2. The repetition rate we used in this experiment is 20 kHz, and the pump power is adjusted by varying the diode current. The pulse duration decreases from 35 to 23 ns when increasing the diode current from 17 to 22 A, corresponding to 1 μm output power from 0.85 to 2 W. There are only small variations (20 ± 2 ns) in the pulse duration when increasing the diode current from 23 to 34 A, corresponding to 1 μm output power from ~2.2 to 7.25 W. The maximum available pump power after the focusing lens is 7.2 W with pulse duration of 22 ns, and the pump beam is focused to an ~300 μm diameter in the crystal. This resulted in a maximum fluence at the crystal surface of 1 J/cm^2 (~50 MW/cm^2), which is below the surface damage fluence of ~2 J/cm^2. The cavity length is ~50 mm due to mechanical constraints from the commercial oven. We initially investigated the single-pass pump configuration. The OPO output power as a function of incident pump power is shown in Fig. 2. A maximum output power of 2.7 W with a conversion efficiency of 37% and a slope efficiency of 45% is obtained operating at 5 times the threshold of 1.75 W. The beam quality of the output is measured using the knife edge method, with a result of $M^2 \sim 2.3$ and 2.4 in the horizontal and vertical directions, respectively.

To lower the threshold and improve the efficiency, the dichroic mirror (M_2) is placed after the VBG to retroreflect the pump beam back through the crystal. A maximum output power of 4.3 W with a conversion efficiency of 60% and a slope efficiency of 64.5% is achieved at 9 times the threshold of 0.8 W, as shown in Fig. 2. The maximum efficiency can be achieved if using a higher pump power with the pump-to-threshold ratio of 10 [13]. The threshold of the double-pass pump configuration is more than 2 times lower than that of the single pass, and the output power improvement is nearly 60%. The output spectrum is shown in Fig. 3, and the inset is a large scale scanning spectrum with a 0.3 nm step. Apart from the signal and idler peaks, no other peaks can be seen in the output spectrum. These spectra are measured by a 30 cm scanning monochromator containing a 300 lines/mm grating blazed at 2 μm and a liquid-nitrogen-cooled InSb detector. The signal and idler peaks are separated by 1.6 nm and confined within 2.5 nm bandwidth at the degenerate wavelength of 2128.8 nm. The spectral bandwidths are 0.43 nm (27 GHz) and 0.55 nm (40 GHz), respectively, for signal and idler waves. There is only a little overlap between them, so the oscillator should be singly resonant on the idler wave. The idler wavelength is locked by the VBG and does not change with the crystal temperature. A 0.2 W variation is observed when the temperature is 0.5 °C away from the optimum temperature of 89 °C. As has been pointed out by Koch *et al.*, by using a multilongitudinal mode laser, the phase fluctuations of the signal and idler waves are averaged across the longitudinal pump modes; therefore, stable operation on degeneracy can be obtained [10]. In our experiments, the single resonance and multilongitudinal oscillation resulted in a very stable operation near degeneracy, and the standard deviation of the power fluctuations is less than 0.8% of the average power. It should be noted that an optical isolator to prevent pump light being fed back into the pump laser is not used in the double-pass geometry. The absence of the isolator does not have significant impact on the stability of the pump

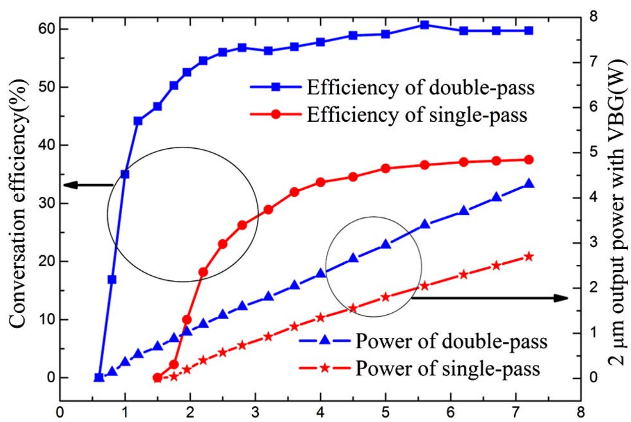

Fig. 2. (Color online) Total output power and conversion efficiency of the PPMgLN OPOs.

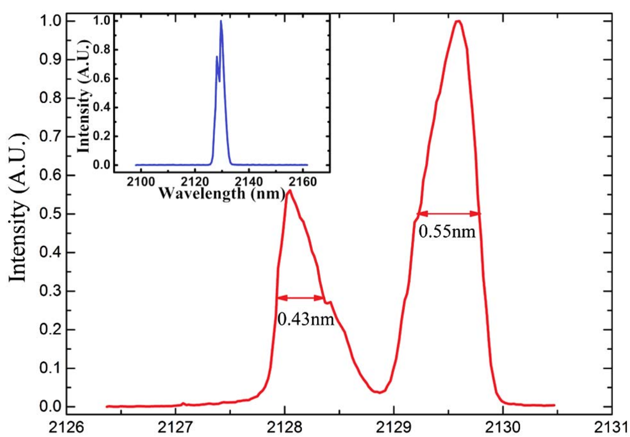

Fig. 3. (Color online) Output spectra from the PPMgLN OPO. Inset graph shows the large scale scanning spectrum.

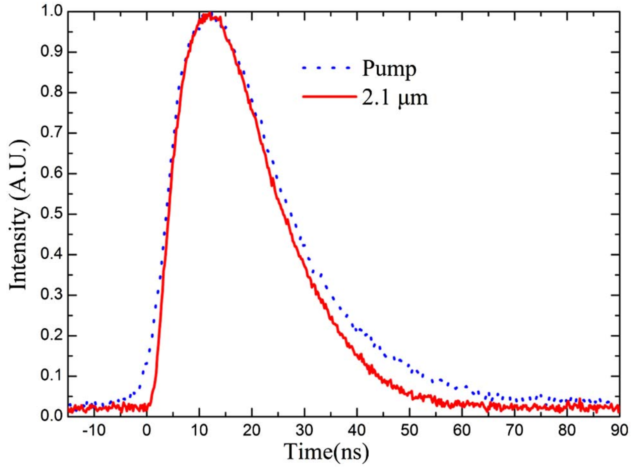

Fig. 4. (Color online) Pulse shapes of pump (dotted curve) and 2.1 μm (solid curve) at the maximum output power.

power or the OPO output power at low power level [14], and we think that this is especially suitable for multilongitudinal oscillation. In our experiments, the output power stability of the OPO is not measurably different with the presence of the double-pass pump. Further, due to the absence of the isolator, the depleted pump beam after double passing the OPO is partially reflected by the output coupler of the pump laser, which leads to multiple passes of the pump pulse through the OPO. This results in an output power improvement of about 20% compared with the value (3.6 W) of a pure double-pass pump calculated using SNLO [15]. The 2.1 μm pulse duration is measured with an InGaAs detector (Thorlabs, DET10D). The pulse width is approximately 19 ns, which is ~2 ns shorter than the pump laser pulse, as shown in Fig. 4. There is no long tail in the pulse shape, and this will improve the efficiency of the second conversion stage. There is a beam quality reduction when changing from single- to double-pass pumping [16]. In the double-pass configuration, M^2 values of the horizontal and vertical directions increase to 3.2 and 4.2, respectively, at the full power.

In conclusion, we have demonstrated a high-efficiency, narrowband near-degenerate PPMgLN OPO by using a double-pass pump configuration. Maximum conversion efficiency of 60% and output power of 4.3 W with spectral bandwidth of less than 170 GHz around the degenerate wavelength is achieved. The multilongitudinal pump and single resonance condition provide a low power fluctuation of 0.8%. The pulse widths are less than 20 ns without long tails at 20 kHz repetition rate. These experimental results indicate that the device will be useful for the development of an efficient compact mid-infrared laser system.

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