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LETTER

2.1 μm four-mirror standing-wave optical parametric oscillator with high brightness and efficiency

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Abstract
We report a high-brightness and high-efficiency degenerate periodically poled MgO:$LiNbO_3$ (PPMgLN) optical parametric oscillator (OPO), configured with a four-mirror standing-wave cavity and pumped by a *Q*-switched Nd:YVO_4 laser. Attributed to the successful mode matching of four-mirror standing-wave cavity, we have obtained good beam qualities both in single-pass and double-pass geometry. The beam qualities of single-pass pump geometry are $M^2 \sim 1.6$ and 1.7 in the horizontal and vertical directions, and the beam qualities of double-pass pump geometry are $M^2 \sim 1.8$ and 1.9. Optical to optical conversion efficiencies of 38% and 55% are achieved, respectively. With a volume Bragg grating used as the output coupler, we achieved a narrow linewidth of less than 2 nm.

(Some figures may appear in colour only in the online journal)

1. Introduction

Laser sources operating in the 2.1 μm regime are of interest for several applications in remote sensing, air monitoring and medical applications. A large amount of studies are devoted to achieving such a laser source with high efficiency and good beam quality. An effective approach is to develop a degenerate OPO based on quasi-phase-matched (QPM) materials, pumped by a commercial 1.06 μm Nd laser [1–7]. These QPM crystals offer attractive alternatives to birefringent materials employing type-II phase matching. Quasi-phase matching in type-I configuration can utilize the largest nonlinear coefficient and overcome the problem of walk-off effect, resulting in high efficiency and good beam quality [3]. Hirano *et al* have achieved over 50 W output with a conversion efficiency of 71.4% in the 2 μm regime [4]. Bhushan *et al* have achieved a slope efficiency of 58% from the 1.064 to 2 μm region by using a 36 mm long PPMgLN in a single-pass pump configuration [5]. Elder *et al* have achieved efficiency of 56% and beam quality factor M^2 of less than 2 at 2.1 μm output from a PPLN OPO of double-pass pump geometry [6]. In our previous work, we have achieved 74% conversion efficiency of 1.06–2.1 μm from a compact PPMgLN OPO pumped by a Nd:YVO_4 laser—however the beam quality factor M^2 exceeds 5 [7].

In this letter, we report a high-brightness and high-efficiency degenerate PPMgLN OPO with a four-mirror standing-wave cavity. We have achieved an optical to optical conversion efficiency of 55% from 1.06 to 2.1 μm and output power of 3.8 W with $M^2 \sim 1.8$ and 1.9 in the horizontal and vertical directions by using a double-pass pump geometry.

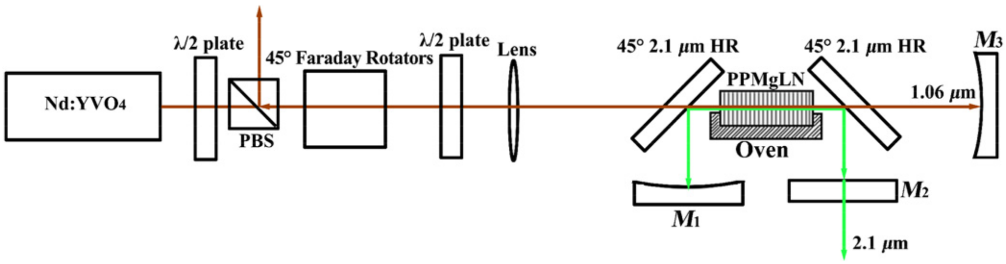

Figure 1. Layout of experimental setup.

2. Experiments and results

A four-mirror standing-wave cavity is applied to the PPMgLN OPO, as shown in figure 1. Optimum mode matching between pump and parametric laser can be achieved by adjusting the position of M_1 and M_2. The PPMgLN OPO consists of a curved mirror M_1, a pair of 45° dichroic mirrors, a flat output coupler M_2 and a 26 mm long PPMgLN crystal with a 3.4 mm × 1 mm aperture. The curved mirror M_1, whose radius of curvature is 225 mm, is coated to be highly reflective (>99.8%) at the output wavelength (2.1 μm). The PPMgLN is positioned between a pair of 45° dichroic mirrors which are highly reflecting (>99.7%) at the output wavelength and highly transmitting (>99%) at the pump wavelength (1.06 μm). 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 coated ($R < 1\%$) for both the pump and the output wavelengths, and it has a 32.1 μm grating period. The crystal is stabilized at 89.5 °C for maximum gain near degeneracy. The flat output coupler (OC) M_2 is coated to be highly reflective for pump wavelength, and reflectivity is 60% for 2.1 μm with a 100 nm bandwidth. Mirror M_3 with −150 mm radius of curvature is used for the 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 and high transmission (>99%) for the output wavelength.

The pump source is a multilongitudinal-mode *Q*-switched $Nd:YVO_4$ laser. It has a spectral bandwidth of ∼30 GHz at 1.06 μm and a beam quality factor M^2 of less than 1.2. The repetition rate is 20 kHz. The pump beam is sent through a half-wave plate (HWP), followed by a polarizing beam splitter (PBS) and a 45° Faraday rotator that together function as a variable attenuator, to prevent back reflections and dominate the pump power. The polarization of the pump beam is rotated by the second HWP to be vertical, aligned with the z axis of PPMgLN crystal. The pump beam is focused by an $f = 150$ mm lens to a beam radius of 150 μm inside the PPMgLN crystal. The pump power is adjusted by the first HWP. The maximum available pump power after the focusing lens is 6.9 W with pulse duration of 22 ns. This results in a maximum fluence of 1 J cm^{-2}, which does not exceed the damage fluence of ∼2 J cm^{-2}, at the surface.

We initially investigated the single-pass pump configuration (without M_3). In order to generate a high-beam-quality and high-efficiency 2.1 μm laser source, a number of different OPO cavity lengths were tested. 2.1 μm output with better beam quality and higher conversion efficiency is achieved with the cavity length of 215 mm. The OPO output power and conversion efficiency as function of incident pump power are shown in figure 2.

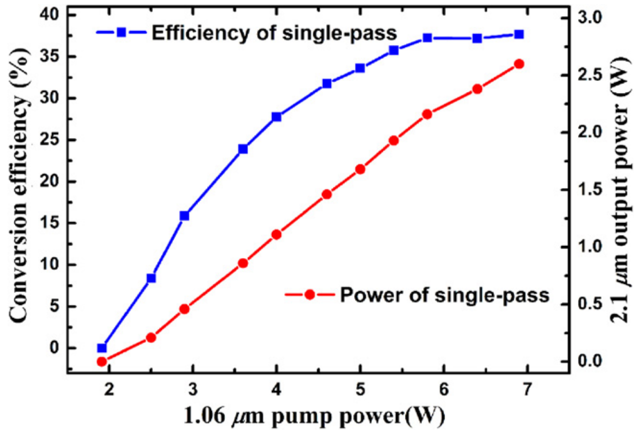

Figure 2. The output power and conversion efficiency of the PPMgLN OPO with single-pass pump geometry.

A maximum output power of 2.6 W with an optical to optical conversion efficiency of 38% and a slope efficiency of 46% is obtained; operating at 4 times the threshold of 1.71 W. The M^2 value of 2.1 μm output was measured by the knife-edge method, as shown in figure 3. The measured M^2 for the 2.1 μm beam is 1.6 and 1.7 in the horizontal and vertical directions, respectively, at the maximum output power. Compared with our previous work [8], the beam quality is found to be better. With the OPO cavity length increasing, the Fresnel number will decrease; thus, the beam quality can be improved. Attributed to the successful mode matching of four-mirror standing-wave cavity with the optimized curve mirror, good beam quality and high conversion efficiency have been achieved. This improved beam quality of the OPO output resulted from the fact that the lower-order transverse modes generating the OPO output efficiently with better beam quality are the main modes. A worse beam quality in the vertical direction might be attributed to a temperature gradient in the vertical plane. The lower surface of the PPMgLN crystal was attached to the copper block of the oven, heated to 89.5°C to optimize phase matching, and its upper surface is in contact with air; therefore, a vertical temperature gradient in the PPMgLN

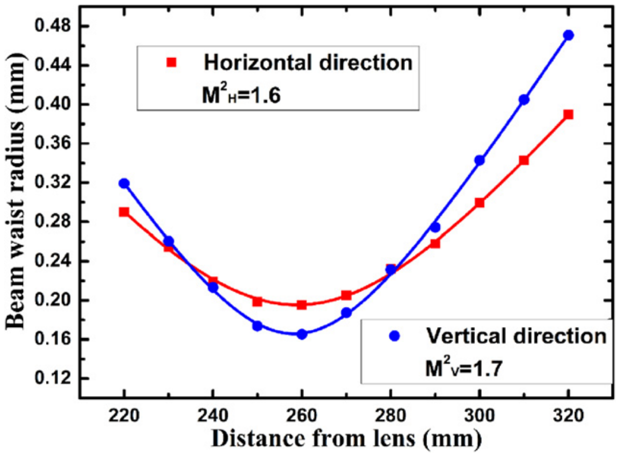

Figure 3. M^2 values of the horizontal and vertical directions of single-pass pump geometry.

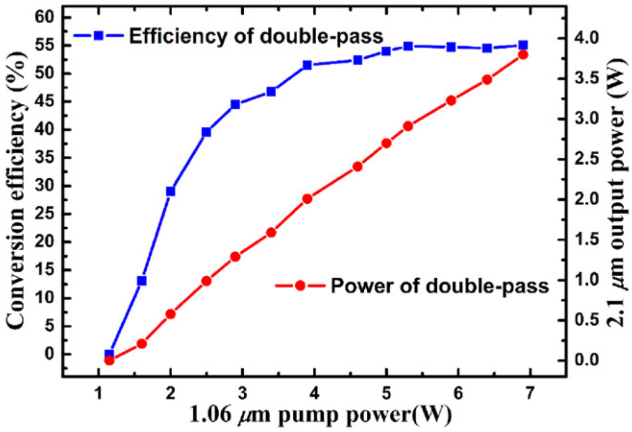

Figure 4. Output power and conversion efficiency of the PPMgLN OPO with double-pass pump geometry.

crystal was formed by the vertical heat flow from its lower surface to upper surface. The temperature gradient led to the phase-mismatch effect in the vertical plane, resulting in the slightly poor beam quality in this direction. Moreover, this effect might also result in a reduction of the efficiency of the PPMgLN OPO.

To improve the efficiency, the dichroic mirror (M_3) is used to retro-reflect the pump beam back through the crystal. No other changes are made to the experimental arrangement. A maximum output power of 3.8 W with an optical to optical conversion efficiency of 55% and a slope efficiency of 66% is obtained operating at 7 times the threshold of 1.05 W, as shown in figure 4. The beam quality can deteriorate quite drastically in a linear OPO cavity with large Fresnel number when the OPO is driven more than 2 times above the oscillation threshold [9]. The double-pass OPO was operated 7 times above threshold instead of 4 times as in the case of single-pass operation. Therefore, the beam quality became worse in the double-pass geometry. However, attributed to the optimum mode matching of the pump and the parametric beams, a good beam quality in double-pass geometry has been achieved, as shown in figure 5. The M^2 values of the horizontal and vertical directions increased to 1.8 and 1.9, respectively, at the maximum power. Compared to the single-pass geometry, there is only a little reduction in beam quality.

Note that on removing the 45° Faraday rotator, there is an output power increase due to multiple passes of the pump pulse between the output coupler of the pump laser and the OPO output coupler. The maximum output power increases to 4 W, corresponding to a conversion efficiency of 58%. The threshold decreases to lower than 1 W. In our experiments, all cases are obtained in a stable operation with a standard deviation of the power fluctuations less than 1% of the average power in an hour. There is no observable change to the pump laser power stability, or to the OPO output power stability (comparing single-pass with multi-pass geometry). We think that the residual pump power back into the pump laser is not high enough to lead to a big breach of the operating mode of the pump laser. The maximum efficiency can be achieved by using a higher pump power with the pump-to-threshold ratio of 10 [10]. With a high power Nd:YAG pump source of 18 W at 10 kHz repetition rate, we achieved 10.4 W at 9 times the threshold of 1.2 W with the double-pass configuration. This corresponds to a conversion efficiency of 60%.

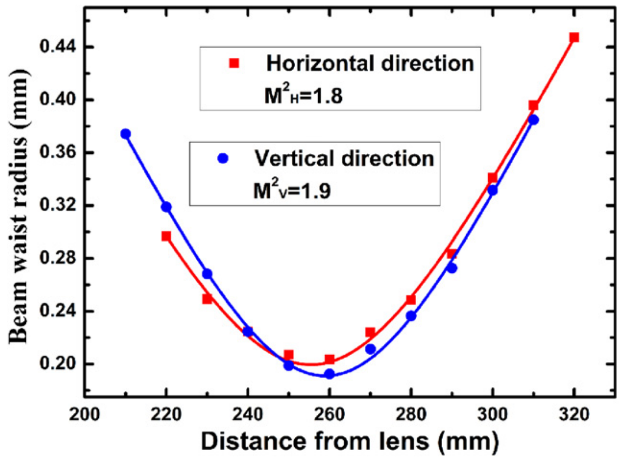

Figure 5. M^2 values of the horizontal and vertical directions of double-pass pump geometry.

The spectral bandwidth of our OPO is ~60 nm, as shown in figure 6. For some applications, such as mid-infrared region generation in $ZnGeP_2$ (ZGP) OPO, 2.1 μm lasers with narrow linewidth are needed. Therefore, the flat OC M_2 was replaced by a volume Bragg grating (VBG) OC. A narrow linewidth of less than 2 nm is obtained, which is narrower than the acceptance bandwidth of ZGP crystal, as marked with dash-dotted line in figure 6. The maximum power of 3.6 W is achieved, and the M^2 values for the maximum output are 2.2 and 2.3 in the horizontal and vertical directions, respectively. There is only a little reduction in the output power and beam quality, compared to the OPO with ordinary OC. Therefore, it is believed that a ZGP OPO pumped by our 2.1 μm laser with narrow linewidth can achieve an efficiency conversion.

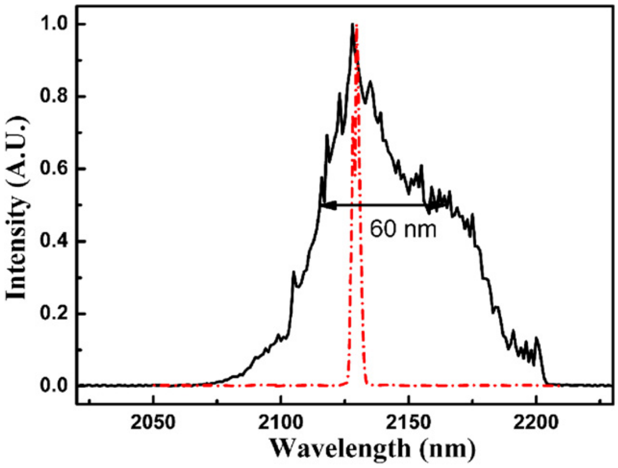

Figure 6. Output spectra from PPMgLN OPO with ordinary OC (solid line) and VBG OC (dash dot line).

3. Conclusion

In conclusion, we have demonstrated a high-brightness and high-efficiency degenerate PPMgLN OPO, pumped by a 1.06 μm Q-switched Nd:YVO_4 laser using a double-pass pump four-mirror standing-wave geometry. The output with a long-term stability can be obtained in this geometry. Maximum conversion efficiency of 55% and output power of 3.8 W with $M^2 \sim 1.8$ and 1.9 in the horizontal and vertical directions around the degenerate wavelength are achieved. The beam quality and conversion efficiency of the output are restricted by each other, but they can be controlled with the modulation of the cavity configuration in combination with focusing lens and pump source. In addition, we have also achieved a 2.1 μm output with narrow linewidth less than 2 nm by using a VBG OC. Future research will focus on a mid-infrared OPO with high power and high efficiency.

Acknowledgments

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