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High-power 3.8 μm tunable optical parametric oscillator based on PPMgO:CLN

Yuefeng Peng *, Xingbin Wei, Weimin Wang, Deming Li

Institute of Applied Electronics, China Academy of Engineering Physics, P. O. Box 919-1013, Mianyang Sichuan, 621900, China

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The experimental results of a high-power 3.8 μm tunable laser are presented on a quasi-phase-matched single-resonated optical parametric oscillator in PPMgO:CLN pumped by a 1064 nm laser of an elliptical beam. Theoretical analyses of the PPMgO:CLN wavelength tuning are presented. The pump source was an acousto-optical Q-switched cw-diode-side-pumped Nd:YAG laser. The beam polarization matched the e–ee interaction in PPMgO:CLN. When the crystal was operated at 90 °C and the pump power was 150 W with a repetition rate of 10 kHz, average output power of 22.6 W at 3.86 μm and 63 W at 1.47 μm was obtained. The slope efficiency of the 3.86 μm laser with respect to the pump laser was 17.8%. The M^2 factors of the 3.86 μm laser were 1.74 and 4.86 in the parallel and perpendicular directions, respectively. The mid-IR wavelength tunability of 3.7–3.9 μm can be achieved by adjusting the temperature of a 29.2 μm period PPMgO:CLN crystal from 200 °C to 30 °C, which basically is accorded with the theoretic calculation.

1. Introduction

Mid-IR lasers in the 3–5 μm wavelength region have many applications, such as military countermeasures, remote monitoring of the special environment, and so on [1,2]. Because of their high repetition rate, high stability and compact configuration, the mid-IR solid-state lasers play an important role in the field of mid-IR countermeasures. Northrop Grumman's Viper laser is a small, lightweight multi-band laser for infrared countermeasure (IRCM) applications which covers the wavelength range of 1–3 μm, 3–5 μm and 8–12 μm [3]. OPOs can offer a unique combination of high peak power, good beam quality, wide wavelength tunability and power scalability. With the development of good quality and large size periodically poled nonlinear crystal technology, a high average power or high energy tunable laser would be obtained by a quasi-phase-matched (QPM) optical parametric oscillator (OPO) [4–12]. Periodically poled MgO-doped $LiNbO_3$ crystal (PPMgO:LN) is the most universally used ferroelectric material for quasi-phase matching an OPO, since the doping MgO can significantly enhance PPLN crystal's photorefractive damage threshold and effectively reduce its coercive field. Peng et al. achieved 16.7 W output power at 3.8 μm from a PPMgO:CLN-OPO pumped by a 1064 nm Nd:YAG laser [4]. Recently this team has achieved about 40 W output power at 2.9 μm by PPMgO:CLN-OPO. Hirano et al. reported a high-average-power OPO based on a 1 mm thickness MgO-doped PPLN; the total output power was 57 W for both 2.02 μm and 2.25 μm laser with a slope efficiency of 82.2% [7]. Sumiyoshi et al. achieved 270 mJ output energy from a PPLN-OPO pumped by a pulsed LD-pumped Nd:YAG laser [8].

In this paper, an average output power of 85.6 W was obtained on quasi-phase-matched single-resonated optical parametric oscillator in PPMgO:CLN (periodically poled 5 mol% MgO-doped congruent $LiNbO_3$ crystal) pumped by a 1064 nm laser, with 22.6 W at the mid-infrared wavelength of 3.86 μm and 63 W at the near-infrared wavelength of 1.47 μm.

2. Analysis of QPM wavelength tuning by adjusting PPMgO:CLN crystal temperature

The quasi-phase-matching (QPM) can utilize the largest non-linear coefficient of crystals. In theory, QPM is able to achieve phase matching in the entire transmission range of crystals. $LiNbO_3$ is a typical negative uniaxial crystal with the transmission range of 330–5000 nm. Of all its second-order non-linear polarization tensor, d_{33} has the largest non-linear optical coefficient of 27.4 pm/V, which is 7.5 times larger than d_{31} of the birefringent phase matching (BPM) commonly used. The d_{33} of periodically poled lithium niobate (PPLN) is utilized along with advantages of high gain, low threshold, and high efficiency. In QPM based on PPMgO:CLN, the crystal is generally periodically poled along the crystal's z-axis and all interacting waves are polarized parallel to the z-axis. In nonlinear interactions that involve frequency conversion, two basic conditions must be satisfied. The first condition is energy conservation of the participating wavelengths, the second condition is phase matching between the propagating waves. In the case of periodically poled crystals with a

* Corresponding author.
E-mail address: qiaopyf@yahoo.com.cn (Y. Peng).

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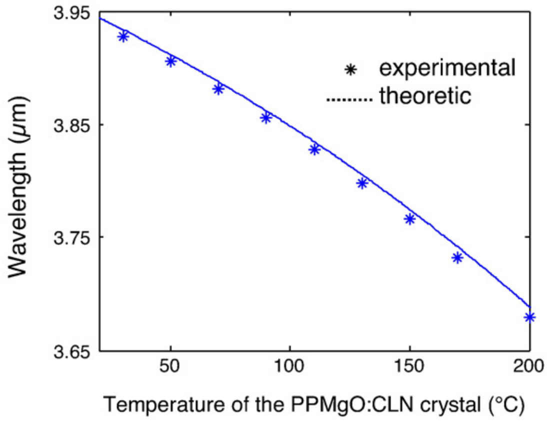

Fig. 1. Laser output wavelength versus temperature of PPMgO:CLN pumped by a 1064 nm laser.

period of $\Lambda(t)$, the energy conservation and the optimal collinear first-order QPM interaction for extraordinary polarized waves are achieved by satisfying Eq. (1):

$$\begin{cases} 1/\lambda_p = 1/\lambda_s + 1/\lambda_i \\ n_{ep}/\lambda_p = n_{es}/\lambda_s + n_{ei}/\lambda_i + 1/\Lambda(t) \end{cases}, \quad (1)$$

where λ_p, λ_s, and λ_i are the pump, the signal and the idler vacuum wavelength, respectively. n_{ep} is the extraordinary refractive index at the pump wavelength, n_{es} and n_{ei} are the corresponding qualities for the signal and the idler waves, respectively. $\Lambda(t)$ is the actual poling period of PPMgO:CLN, taking account of the thermal expansion.

The crystal poling period $\Lambda(t)$ at temperature t is normalized to the poling period $\Lambda(t_0)$ at t_0 according with the following formula

$$\Lambda(t) = \Lambda(t_0)[1 + a(t-t_0)], \quad (2)$$

where a is the crystal thermal expansion coefficient, $a = 1/l \cdot \partial l/\partial T$. l represents the length of crystal.

The extraordinary refractive index of PPMgO:CLN(5 mol% MgO doping) is given as [13]

$$n_e^2(\lambda, t) = 5.756 + 2.86\times10^{-6}f(t) + \frac{0.0983 + 4.7\times10^{-8}f(t)}{\lambda^2-[0.202 + 6.113\times10^{-8}f(t)]^2} + \frac{189.32 + 1.516\times10^{-4}f(t)}{\lambda^2-12.52^2} - 1.32\times10^{-2}\lambda^2, \quad (3)$$

For temperatures t expressed in degrees Centigrade, $f(t)$ is given as:

$$f(t) = (t-24.5)(t + 570.82), \quad (4)$$

In QPM OPO, the wavelength tuning methods used are commonly temperature tuning, period tuning, and angle tuning. The fine precision and continuousness of wavelength tuning can be achieved by temperature tuning. The combination of grating period tuning and temperature tuning can construct widely and continuously wavelength tunable laser sources. By Eqs. (1)–(4), laser output wavelength versus the temperature of PPMgO:CLN is shown in Fig. 1 with a 29.2 μm grating period at 25 °C and a 1064 nm pump laser. In theory, the mid-IR wavelength tuning ranges of 3.7–3.9 μm for the idler laser can be achieved by adjusting the PPMgO:CLN crystal's temperature from 200 °C to 30 °C.

3. Experimental setup

The experimental setup is a single-resonated optical parametric oscillator (SROPO), pumped by a Nd:YAG 1064 nm laser of an elliptical beam, shown in Fig. 2. The 1064 nm laser cavity was formed by flat mirror M_1($R>99.5\%$@1064 nm), output coupler flat mirror M_2 ($R = 50\%$@1064 nm), two cw-diode-side-pumped Nd:YAG modules, two acousto-optical Q-switches, a 90° rotator of quartz, and a 1064 nm laser polarizer. The 1064 nm laser with high power and good beam quality was obtained by optimizing the laser parameters. The beam polarization matched the e–ee interaction in PPMgO:CLN, thus the maximal nonlinear coefficient d_{33}(27.4 pm/V) is available and walk-off of the beams can be avoided. The PPMgO:CLN-OPO was formed by a 1 mm × 5 mm × 45 mm PPMgO:CLN, together with flat mirrors M_3 and M_4. Mirror M_3 was antireflection (AR) coated with AR@1064 nm, $R\approx90\%$@1.4–1.6 μm, and high-reflection (HR) coated HR@3.6–4.0 μm, while M_4 was coated with HR@1064 nm, AR@1.4–1.6 μm and $R = 70\%$@3.6–4.0 μm. The PPMgO:CLN crystal had a grating period of 29.2 μm@25 °C. Both end faces of the PPMgO:CLN were AR coated with AR@1064 nm, 1.4–1.6 μm and 3.6–4.0 μm. The PPMgO:CLN was staged in an oven with the temperature range up to 200 °C, which is conveniently used to adjust and control the crystal operating temperature. The temperature of the oven can be controlled with the precision of 0.1 °C. The coupled system was formed by two cylindrical lenses and a spherical lens. The size and shape of the pump beam can be adjusted by the coupled system to match the profile of PPMgO:CLN. The spot size of the elliptical pump beam is about 0.8 mm × 3.5 mm at the center of the crystal. Limited by the thickness of the crystal and low damage threshold of mid-IR OPO, high-power mid-IR laser can be hardly achieved with a round pump beam; however an elliptical pump beam covers more area of the incident surface, which efficiently elevates the output power and reduces the danger of optics damage. With the increase of the crystal's thickness (3 mm in commerce and 5 mm in laboratory [10]), even higher power mid-IR laser would be obtained by PPMgO:CLN-OPO.

4. Results and discussion

When the crystal was operated at 90 °C and the pump power was 150 W with the repetition rate of 10 kHz, average output power of 22.6 W at 3.86 μm and 63 W at 1.47 μm was obtained. The slope efficiency of 3.86 μm laser with respect to the pump laser was 17.8%. Laser output power versus pump power is shown in Fig. 3. The output power saturation of 3.86 μm laser does not appear, so it is possible to obtain higher output power with higher pump power. The main problem encountered during the experiment is the damage of optical coat. In the early times of the experiments, the damage threshold of

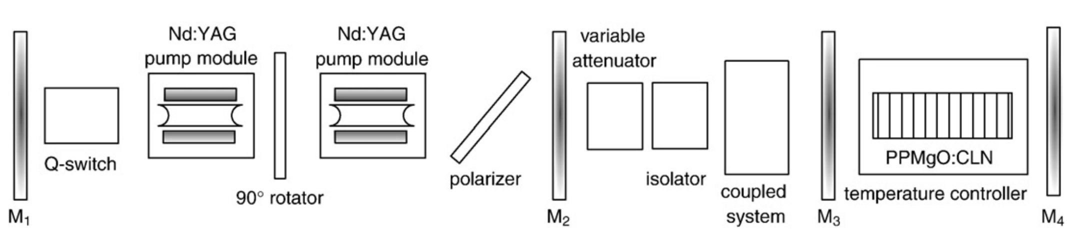

Fig. 2. Schematic of the experimental setup.