Vol 18 No 10, October 2009
1674-1056/2009/18(10)/4314–05

Chinese Physics B

© 2009 Chin. Phys. Soc.
and IOP Publishing Ltd

High efficiency continuous-wave tunable signal output of an intracavity singly resonant optical parametric oscillator based on periodically poled lithium niobate*

Ding Xin(丁 欣)[a)b)†], Sheng Quan(盛 泉)[a)b)], Chen Na(陈 娜)[a)b)],
Yu Xuan-Yi(禹宣伊)[c)], Wang Rui(王 睿)[a)b)], Zhang Heng(张 衡)[a)b)],
Wen Wu-Qi(温午麒)[a)b)], Wang Peng(王 鹏)[a)b)], and Yao Jian-Quan(姚建铨)[a)b)]

[a)] *College of Precision Instrument and Opto-electronics Engineering, Institute of Laser and Opto-electronics, Tianjin University, Tianjin 300072, China*

[b)] *Key Laboratory of Opto-electronics Information Science and Technology, Ministry of Education, Tianjin 300072, China*

[c)] *College of Physics Science, Photonics Research Center, Nankai University, Tianjin 300071, China*

(Received 9 October 2008; revised manuscript received 12 January 2009)

In this paper we report on a continuous-wave (CW) intracavity singly resonant optical parametric oscillator (ICSRO) based on periodically poled $LiNbO_3$ (PPLN) pumped by a diode-end-pumped CW Nd:YVO_4 laser. Considering the thermal lens effects and diffraction loss, an optical ballast lens and a near-concentric cavity are adopted for better operation. Through varying the grating period and the temperature, the tunable signal output from 1406 nm to 1513 nm is obtained. At a PPLN grating period of 29 μm and a temperature of 413 K, a maximum signal output power of 820 mW at 1500 nm is achieved when the 808 nm pump power is 10.9 W, leading to an optical-to-optical conversion efficiency of 7.51%.

Keywords: continuous-wave, intracavity optical parametric oscillator, periodically poled lithium niobate crystal, tunable eye-safe laser

PACC: 4265K, 4265, 4260

1. Introduction

High-power eye-safe lasers in a range of 1.3–1.6 μm have several potential applications including instance remote sensing, optical spacial communication, medical treatment, pollution detection, Doppler lidar systems, etc. Recently, there are many approaches to obtaining 1.3–1.6 μm lasers, including quantum well lasers,[1,2] fiber lasers[3−5] and optical parametric oscillator (OPO)/optical parametric generator (OPG).[6−16] Seth Bank *et al* reported a 1.5-μm GaInNAs (Sb) quantum well laser with a pulse output of 70 mW peak power in 2003 and a CW output of 10 mW in 2005.[1,2] In 2005, Shen *et al*[4] reported a highly efficient Er, Yb-doped fiber laser from 1532 nm to 1568 nm with more than 100 W output power. The highest output power of 1565 nm was 188 W, with an optical conversion efficiency of 40.3%. A 500-mW Raman fiber laser in a range of 1406–1500 nm was reported by Mei *et al*[5] in 2003. In comparison with the quantum well lasers and the fiber lasers, when high power and wide tunable range are required simultaneously, OPO/OPG is regarded as a flexible solution. In 2001, Wu *et al*[6] reported a high-repetition-rate intracavity-pumped KTA OPO at 1.5 μm with an output power of 10.9 W, corresponding to an optical-to-optical conversion efficiency of 1.91%. In 2004, Lin *et al*[7] reported on an extracavity PPLN OPO with an output wavelength range of 1.44–1.74 μm pumped by a nanosecond Nd:YVO_4 laser. Ji *et al*[8] reported on a quasi-continuous-wave 1493–1538 nm signal output of intracavity PPLN OPG with an output power of 280 mW and an optical-to-optical conversion efficiency of 5.6% in 2006. In 2007, a Q-switched periodically poled $RbTiOAsO_4$ (PPRTA) intracavity optical parametric oscillator (ICOPO) in a range of 1.4-1.6 μm was reported by Bo Lin *et al*[9], the maximum output energy was 615 μJ at 1.558 μm. In the

*Project supported partly by the National Natural Science Foundation of China (Grant Nos 60637010 and 60671036), the National Basic Research Program of China (Grant No 2007CB310403), and the Tianjin Applied Fundamental Research Project, China (Grant No 07JCZDJC05900).

†Corresponding author. E-mail: dingxin@tju.edu.cn

same year, Henderson and Stafford[10] reported on a single-frequency CW extracavity MgO: PPLN OPO in a range of 1.6–1.9 μm, which reached a highest output power of 5.1 W at 1650 nm when the single-frequency 1064-nm pump power was 14.5 W. It can be seen from these reports that the main approaches to obtaining eye-safe range lasers in the OPO/OPG field focused on pulsed or quasi-continuous-waves pumping with high peak pump power, or single-frequency extracavity pumping. However, by exploiting the high circulating pump intensities, the intracavity pumping technique uniquely allows extension of the operation of CW OPO to low-threshold, high efficiency and no restriction of single-frequency pumping.

In this paper, we report on a continuous-wave signal output of a PPLN intracavity singly resonant optical parametric oscillator pumped by a diode-end-pumped CW Nd:YVO_4 laser. Through changing grating period and temperature, a tunable signal output from 1406 nm to 1513 nm is obtained. At a PPLN grating period of 29 μm and a temperature of 413 K, a maximum signal output power of 820 mW at 1500 nm is achieved when the 808-nm pump power is 10.9 W, leading to an optical-to-optical conversion efficiency of 7.51%.

2. Experimental setup and analysis

A schematic diagram of the ICSRO in the experiment is depicted in Fig.1. The pump source for the ICSRO is a diode-pumped CW Nd:YVO_4 laser consisting of a 0.4%-doped α-cut gain crystal Nd:YVO_4 with 3 mm×3 mm×8 mm in dimension. The laser diode (LD) is a high-brightness fiber-coupled diode-laser-array emitting at 808 nm with a 400-μm diameter fiber bundle end. The multi-lens optical couplers (L_1 and L_2) focus the diode laser beam into the Nd:YVO_4 crystal, forming a spot of 400 μm in diameter. The entrance surface of the Nd:YVO_4 crystal is coated for high reflection (HR) at 1064 nm and antireflection (AR) coated at 808 nm. The output surface of the Nd:YVO_4 is AR coated at 1064 nm. The Nd:YVO_4 crystal is cooled by refrigerant water at 15 °C.

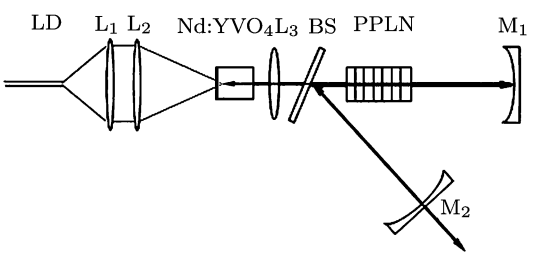


Fig.1. Schematic diagram of the all-solid-state CW ICSRO. (L_1 and L_2: coupling lenses, L_3: lens, BS: beam splitter, M_1 and M_2: cavity mirrors).

The SRO resonator consists of a concave high reflector M_1 ($R = 100$ mm) and an output coupler M_2 ($R = 90$ mm). M_1 is HR coated ($R > 99\%$) at both the pump and the resonant signal wavelengths (1400–1550 nm) on concave surface. M_2 is specified to be partially reflecting ($R = 95\%$) in the signal wavelength range (1400–1550 nm) only. The flat-flat beam splitter (BS) is AR coated at 1064 nm on both sides and HR at 1400–1550 nm on one side. An uncoated PPLN crystal with a size of 24 mm×8 mm×1 mm, which contains seven gratings, equally spaced in periods from 26 μm to 29 μm, is employed in experiment. To facilitate temperature tuning and to avoid photorefractive effects, the PPLN crystal is located in a servo-controlled oven.

The resonator of the 1064-nm laser is a flat-concave cavity. Taking the thermal-lens effect of the Nd:YVO_4 crystal into account, to obtain a higher power output and better beam quality, the Nd:YVO_4 laser should operate at the stable-power point of the U-shape curve indicating the change of spot radius versus thermal-lens focus length. At the same time, the larger oscillating mode volume and the pumping mode volume must be matched well in the Nd:YVO_4 crystal. Besides, in order to realize an efficient OPO operation, the pump intensities in the OPO resonator should be increased. A lens L_3, which has a focal length of 100 mm and is coated AR at 1064 nm on both sides, is inserted into the cavity as the optical ballast. As described in Ref.[11], the lens L_3 utilized as an optical ballast can make the pumping beam radius insensitive to thermal lens effects and focus the pump beam waist radius for the purpose of sufficient pump intensity.

According to calculations, the optical ballast L_3 is located close to Nd:YVO_4 crystal, the PPLN crystal is fixed at the beam waist of 1064 nm laser, which is 102 mm away from M_1 and 58 mm away from the HR face of the Nd:YVO_4 crystal. As a result, the TEM_{00} mode spot radius (ω_0=216 μm) of the 1064 nm laser is matched to the pump beam waist spot radius of 200 μm well in the Nd:YVO_4 crystal and the beam waist of 1064 nm laser (ω_1) is narrowed to 70 μm. Propagation of the laser is shown in Fig.2. With a

maximum LD power of 10.9 W, the intracavity power density in the PPLN crystal is about 0.4 MW/cm^2, so the OPO pump power is high enough but still far below PPLN damage threshold 0.2 GW/cm^2.[17] Meanwhile, the 1064-nm laser is operating at the stable-power point of the U-shape curve when the LD pump power is 10.9 W with an 80-mm thermal-lens focal length of the Nd:YVO_4 crystal as shown in Fig.3.

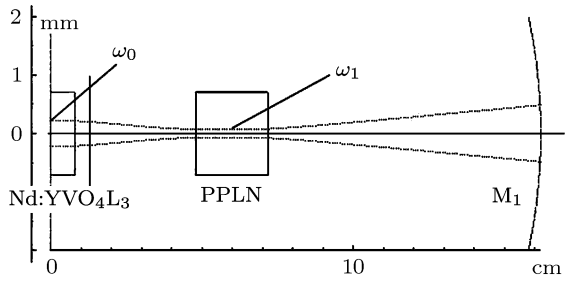


Fig.2. Optical transmission in resonator of 1064-nm laser.

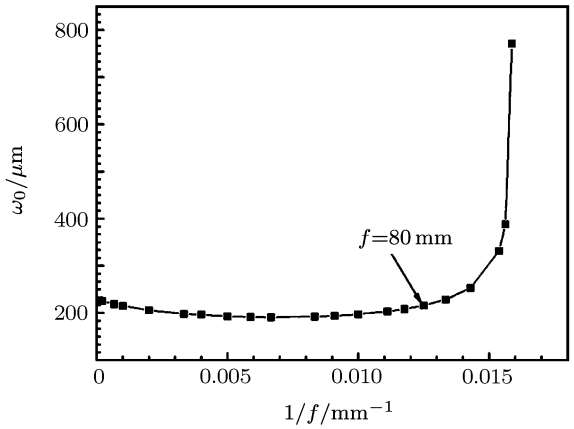


Fig.3. U-shape curve of the fundamental mode spot radius in the Nd:YVO_4 crystal as a function of the thermal-lens focal length.

By controlling the curvature radius of M_2 and the distance between M_2 and M_1, the well matched mode volume of the signal beam and 1064 nm beam can be obtained in the centre of PPLN crystal to reduce the diffraction loss. In the experiment, mirror M_2 with a curvature-radius of 90 mm and the near-concentric cavity are adopted for the PPLN–SRO. The distance between M_1 and M_2 is 185 mm. The TEM_{00} mode spot radius of signal (ω_2 = 76 μm) and the TEM_{00} mode spot radius of 1064 nm laser match well in the PPLN crystal as shown in Fig.4.

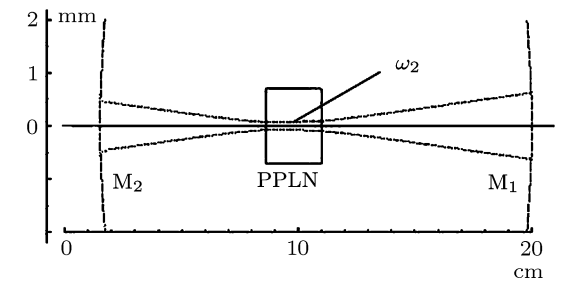


Fig.4. Optical transmission in the PPLN–SRO (equivalent straight-cavity).

3. Results

The tunable signal outputs under different temperatures and different grating periods are investigated in the experiment. When the temperature of PPLN crystal varies from 393 K to 453 K at a grating period of 29 μm, the signal wavelength ranging from 1495 nm to 1513 nm is obtained (measured by an optical spectrum analyzer: Agilent 86142B). The theoretical curve and the experiment data are shown in Fig.5. When the grating period of PPLN crystal varies from 27 μm to 29 μm at 413 K, the signal wavelength ranging from 1406 nm to 1500 nm is achieved as shown in Fig.6.

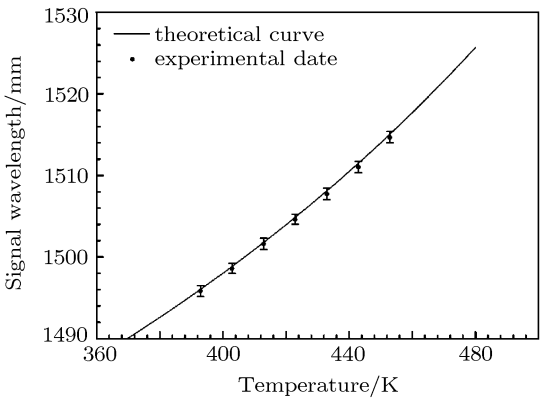


Fig.5. Signal wavelength as a function of temperature at a grating period of 29 μm.

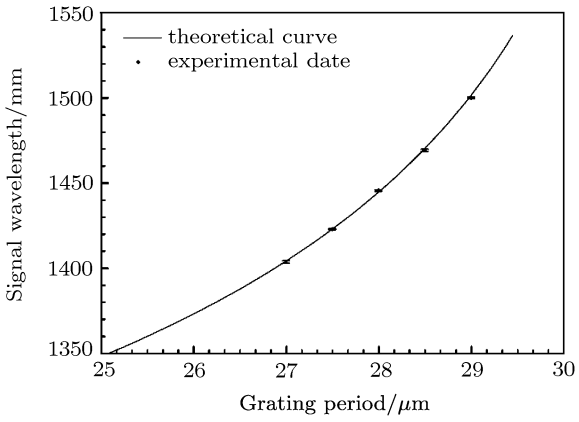


Fig.6. Signal wavelength as a function of grating period at 413 K.

Obviously, the experimental data at the different temperatures and the different grating periods fit to the theoretical curves well; errors of temperature tuning and grating period tuning are less than 0.7 nm and 0.5 nm as shown in the figures.

The signal output powers at different temperatures (393–453 K) for a grating period of 29 μm and at 413 K for different grating periods (27–29 μm) are measured by a power meter (Molectron EPM1000) separately when the pump power is 10.9 W. It can be seen from Figs.7 and 8 that the signal output powers at different temperatures (393–453 K) for a grating period of 29 μm vary in a range of 10 mW and the signal output powers at 413 K for different grating periods (27–29 μm) vary in a range of 30 mW. As shown in Fig.9, at the PPLN grating period of 29 μm and the temperature of 413 K, the SRO threshold is 2.5 W, and the maximum signal output power of 820 mW at 1500 nm is achieved when the LD power is 10.9 W, leading to an optical-to-optical conversion efficiency of 7.51%. Due to the Nd:YVO_4 crystal thermal lens effects and pump depletion in the nonlinear parametric process, the signal output power ripple is about ±1.2% observed in the experiment.

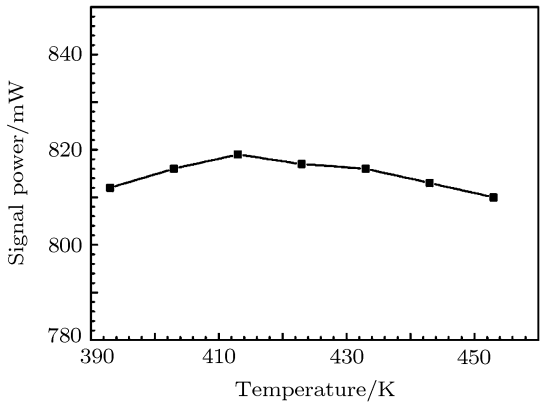


Fig.7. Signal output power as a function of tuning temperature at a grating period of 29 μm.

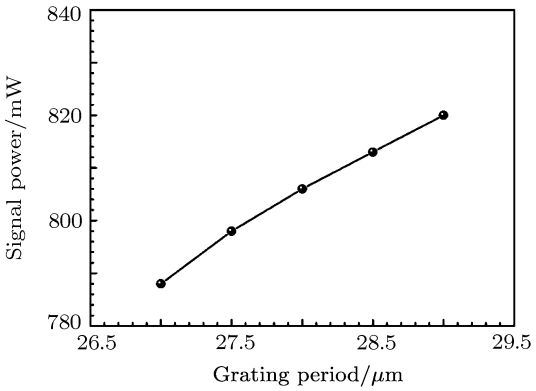


Fig.8. Signal output power as a function of grating period at 413 K.

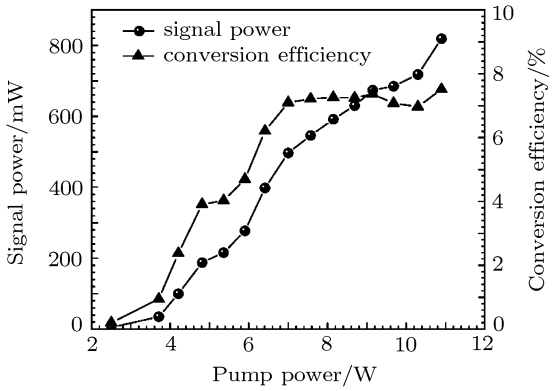


Fig.9. Output power and optical conversion efficiency at 1500 nm each as a function of 808-nm pump power.

4. Conclusion

In this paper, we demonstrate an intracavity CW PPLN–SRO pumped by a LD pumped Nd:YVO_4 laser which can generate CW near-infrared wave. An IC-SRO is carefully designed for high efficiency signal output, including an optical ballast lens and a near-concentric cavity, which are adopted for suppressing the diffraction loss and the thermal focal effect of the Nd:YVO_4 laser. Through changing the grating period and the temperature, a tunable signal output from 1406 nm to 1513 nm is obtained. At a PPLN's grating period of 29 μm and a temperature of 413 K, the SRO threshold is 2.5 W, and a maximum signal output power of 820 mW at 1500 nm is achieved when the LD power is 10.9 W, leading to an optical-to-optical conversion efficiency of 7.51%.

References

[1] Bank S, Ha W, Gambin V, Wistey M, Yune H, Goddard L, Kim S and Jr J S H 2003 *Journal of Crystal Growth* **251** 367

[2] Goddard L L, Bank S R, Wistey M A, Yuen H B, Rao Z and Jr J S H 2005 *J. Appl. Phys.* **97** 0831011

[3] Sahu J K, Jeong Y, Richardson D J and Nilsson J 2003 *Opt. Commun.* **227** 159

[4] Shen D Y, Sahu J K and Clarkson W A 2005 *Opt. Express*

13 4916

[5] Mei J J, Liu D M, Wang Y and Huang D X 2003 *Semiconductor Photonics and Technology* **9** 201

[6] Wu R F, Lai K S, Wong H F, Xie W J, Lim Y L and Lau E 2001 *Opt. Express* **8** 694

[7] Lin X C, Kong Y P, Zhang Y, Zhang J, Yao A Y, Bi Y, Sun Z P, Cui D F, Li R N, Wu L A and Xu Z Y 2004 *Chin. Phys.* **13** 1042

[8] Ji F, Zhang B G, Li E B, Zhou R, Zhang T L, Lu Y, Zhao P, Wang P and Yao J Q 2006 *Chin. Phys. Lett.* **23** 2113

[9] Lin B, Lee H S and Prasad C R 2007 *Opt. Express* **15** 4902

[10] Henderson A and Stafford R 2007 *Opt. Lett.* **32** 1281

[11] Zhang G Y, Song F, Feng Y and Xu J J 2000 *Acta Phys. Sin.* **49** 1495 (in Chinese)

[12] Lindsay L D, Stothard D J M, Rae C F and Dunn M H 2003 *Opt. Express* **11** 134

[13] Chen Y F, Chen S W, Tsai S W and Lan Y P 2003 *Appl. Phys.* B **77** 505

[14] Zendzian W, Jabczynski J K, Wachulak P and Kwiatkowski J 2005 *Appl. Phys.* B **80** 329

[15] Tsai L Y, Chen Y F, Lin S T, Lin Y Y and Huang Y C 2005 *Opt. Express* **13** 9543

[16] Turnbull G A, Dunn M H and Ebrahimzadeh M 1998 *Appl. Phys.* B **66** 701

[17] Koechner W 2002 *Solid-State Laser Engineering* (Beijing: Science Press) p555 (in Chinese)