Efficient continuous-wave eye-safe region signal output from intra-cavity singly resonant optical parametric oscillator*

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We report an efficient continuous-wave (CW) tunable intra-cavity singly resonant optical parametric oscillator based on the multi-period periodically poled lithium niobate and using a laser diode (LD) end-pumped CW 1064 nm Nd:YVO_4 laser as the pump source. A highly efficiency CW operation is realized through a careful cavity design for mode matching and thermal stability. The signal tuning range is 1401–1500 nm obtained by varying the domain period. The maximum output power of 2.2 W at 1500 nm is obtained with a 17.1 W 808 nm LD power and the corresponding conversion efficiency is 12.9%.

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

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1. Introduction

The coherent radiation at 1.3–1.6 μm near the infrared eye-safe region has important applications, such as instance remote sensing, optical spacial communication, pollution detection, and Doppler lidar systems.[1,2] The quasi-phase-matching (QPM) singly resonant optical parametric oscillators (SROs) have been established as an efficient method to generate tunable outputs in this region.[3] Though the QPM-SRO can take advantage of its very large nonlinear coefficient, the high threshold of the SRO hinders its continuous-wave (CW) operation. Bosenberg *et al.* firstly reported a CW broadly tunable near infrared QPM-SRO based on the periodically poled lithium niobate (PPLN) crystal with a single transverse-mode pump source and the extra-cavity pump scheme.[4] They also demonstrated that a very high pump depletion and conversion efficiency could be achieved with a fine pump source and a four-mirror ring cavity or a four-mirror linear cavity.[5] In recent years, with the improvement of the pump source and the nonlinear medium, several watts of CW near-infrared output can be easily obtained, and the average output power of a pulsed QPM-SRO can reach several tens of watts.[6,7] However, CW QPM-SRO research still relies on the single frequency pump source and the extra-cavity scheme.[8] Besides that method, Stothard *et al.* demonstrated an efficient CW intra-cavity PPLN-SRO.[9] By utilizing a high pump power intensity circling in the cavity, the intra-cavity SRO can realize a CW operation with a rather low pump threshold and reach a high conversion efficiency.

In this work, a high efficiency all-solid-state tunable intra-cavity SOR laser is demonstrated, a tunable laser from 1401 nm to 1500 nm is achieved, Under the

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absorbed pump power of 17.1 W, the maximum average output power at 1500 nm is 2.2 W, and the corresponding conversion efficiency is 12.9%. It has the merits of being compact and efficient with a low threshold and wide tunable range.

2. Experimental setup

Our experimental setup is sketched in Fig. 1. A laser diode (LD) end-pumped CW Nd:YVO_4 laser operating at 1064 nm was used as the pump source of the optical parametric oscillator. The pump source was an 808-nm fiber-coupled laser diode with a core diameter of 400 μm, a numerical aperture of 0.22. The multi-lens coupler reimaged the pump into an Nd:YVO_4 crystal with a ratio of 1:1. The 3 mm×3 mm ×8 mm Nd:YVO_4 crystal was 0.4%-doped and α-cut. The input face of the crystal (M_0) was coated with a high reflection (HR) film at 1064 nm and an antireflection (AR) film at 808 nm. The concave mirror M_1 (r = 100 mm) to compose the laser cavity was coated with an HR film at both 1064 nm and 1.4–1.55 μm signal region. A flat–flat beam splitter (BS) was coated with AR films at 1064 nm on both sides and an HR film at 1.4–1.55 μm on one side. A concave output coupler M_2 (r = 90 mm) was partially reflecting (r = 95%) at the signal wavelength range. The signal beam folded by the BS resonated between M_1 and M_2 and then output through M_2.

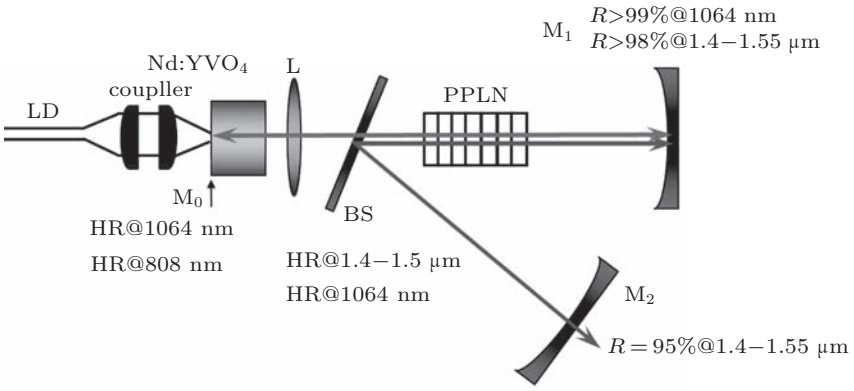


Fig. 1. Schematic diagram of tunable CW intra-cavity OPO.

An uncoated PPLN crystal with dimensions of 24 mm×8 mm×1 mm was used as the nonlinear crystal. It contained 5 gratings equally spaced in the domain periods from 27 μm to 29 μm. The L was a focal lens AR coated at 1064 nm on both sides. The lens, utilized as an optical ballast, made the radius and the location of the 1064 nm laser beam waist insensitive to the variation of the Nd:YVO_4 crystal's thermal focal length as the pump power changed.[10] It also focused the pump beam waist radius to provide a sufficient pump intensity. To facilitate temperature controlling and to avoid photorefractive damage, the PPLN crystal was placed in a servo-controlled oven with a control precision of 0.1 °C. The Nd:YVO_4 crystal was cooled by refrigerant water at 10 °C.

A well mode matching in the two conversion processes and the thermal stability are essential to realize a stable CW operation and a high conversion efficiency. The cavities were carefully designed to achieve these essentials.

When the LD reached the maximum power of 17.1 W, a thermal focal length of 75 mm of the Nd:YVO_4 crystal was measured. The focal length L was chosen to be 100 mm, and it was placed close to the crystal. The stable area distribution of the main cavity of the thermal focal length versus the distance from L to M_1 is shown in Fig. 2, where the black area is the stable area of the cavity. According to Fig. 2, when the thermal focal length of Nd:YVO_4 is varied from 80 mm to 1000 mm, the distance from L to M_1 should be 0–40 mm or 84–140 mm to ensure the cavity in the stable area. We chose the distances from L to M_1 to be 120 mm, 135 mm, and 140 mm respectively. The spot radius of the 1064 nm laser in the cavity is shown in Fig. 3. According to the mode match principle in Nd:YVO_4 and PPLN, we chose the distance from L to M_1 to be 135 mm. In this case, the laser beam radius in the Nd:YVO_4 crystal was

220 μm, which matched with the 250 μm LD spot radius very well. Meanwhile, the beam waist radius of the 1064 nm laser was narrowed to 67 μm and appeared at 101 mm from M_1. The distance from M_2 to M_1 was determined to be 187 mm, while the waist radius of the signal was 75 μm and appeared at 99 mm from M_1 (calculated at the wavelength of 1500 nm), which was close to the beam waist of the 1064 nm pump beam. So the distance from the center of the PPLN crystal to M_1 was determined to be 100 mm.

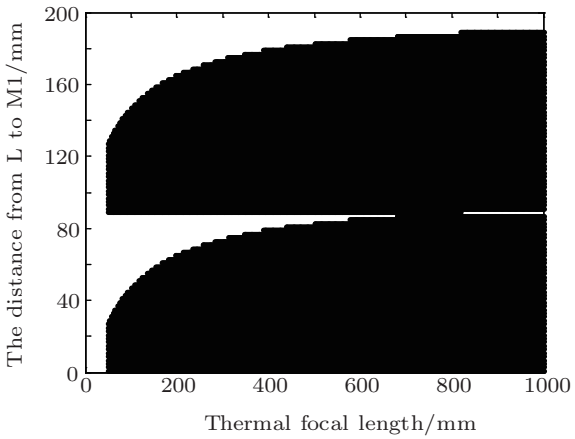


Fig. 2. Stability diagram for 1064 nm laser cavity.

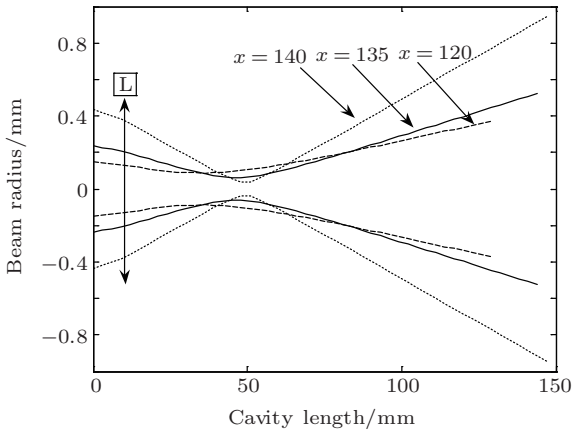


Fig. 3. Beam radius of 1064 nm laser versus cavity length.

A good spatial overlapping was achieved in both processes of laser and OPO, thus ensuring a high conversion efficiency. Meanwhile, the focusing parameters were $\xi_p = L/b_p = 0.41$ and $\xi_s = L/b_s = 0.46$, where L is the crystal length, b_p and b_s are the confocal parameters of the pump and the signal lasers, respectively. The confocal parameter is $b = 2\pi n\omega^2/\lambda$, where n is the refractive index of the PPLN, and λ is the wavelength of the laser. The performance of our SRO was limited by the crystal length to some extent.

3. Results and discussion

The tunable output was obtained by varying the grating period of the PPLN crystal. When the grating period of the PPLN was varied from 27 μm to 29 μm at the temperature of 140 °C, signal outputs from 1404 nm to 1500 nm were obtained (measured by an optical spectrum analyzer: Agilent 86142B). The measured wavelengths matched well with the theoretical curve, as shown in Fig. 4, where the solid lines represent the theoretical tuning curves calculated from the quasi-phase-matching condition.[11]

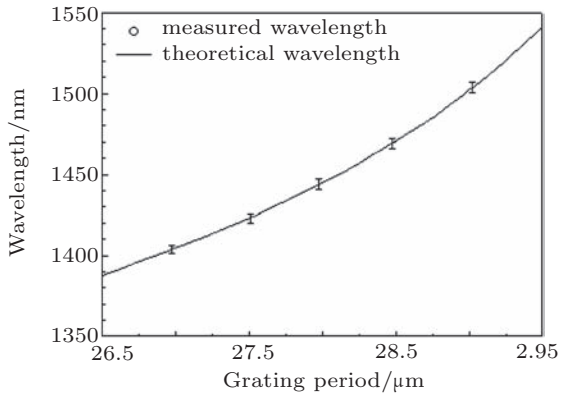


Fig. 4. Wavelength of the CW PPLN-ICSRO as a function of grating period at 140 °C

The wavelengths of the CW ICSRO at different temperatures at the grating period of 29 μm were shown in Fig. 5. The temperature of PPLN was varied from 373 K to 473 K in the experiment, the signal wavelength was 1.50–1.53 μm. The theoretical curve and the experimental data are shown in Fig. 6.

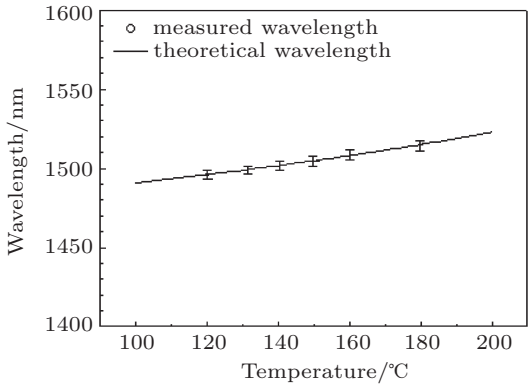


Fig. 5. Wavelength of the CW PPLN-ICSRO as a function of temperature at grating period of 29 μm.

Figure 6 shows the signal power (measured by a power meter: Molectron EPM10000) and the conversion efficiency at 1.5 μm as functions of the diode laser

power delivered to the Nd:YVO_4 crystal. For measuring the signal power precisely, a filter (HT at 1.5 μm, HR at 1064 nm) was placed behind output mirror M_2. The threshold of the ICSRO was 2.7 W at the diode pumping power. At the LD power of 17.1 W, the maximum signal output power of 2.2 W was achieved, which corresponded to an optical-to-optical conversion efficiency of 12.9%.

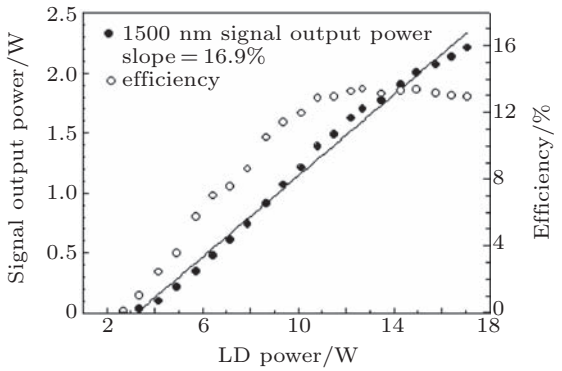


Fig. 6. Output power and conversion efficiency of the signal at 1.5 μm.

Due to the Nd:YVO_4 laser's thermal lens effects and pump depletion during the nonlinear parametric process, the instability of the signal output power was about ±8% in the experiment.

4. Conclusion

In this paper, we have demonstrated an intracavity CW PPLN-ICSRO pumped by an LD pumped Nd:YVO_4 laser. An optical ballast lens and a near-concentric cavity were adopted by considering the thermal focal length of the Nd:YVO_4 laser. At the PPLN grating period of 29 μm and the temperature of 413 K, the ICSRO threshold was 2.7W, and the maximum signal output power of 2.2 W at 1.5 μm was achieved at the LD power of 17.1W, which led to an optical-to-optical conversion efficiency of 12.9%.

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