Diode-pumped passively mode-locked Nd:YVO_4 laser at 1342 nm with periodically poled $LiNbO_3$

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Received October 6, 2010; revised January 11, 2011; accepted January 19, 2011; posted February 3, 2011 (Doc. ID 136188); published February 24, 2011

In this Letter, we demonstrate a nonlinear-mirror (NLM) mode-locked diode-pumped solid-state Nd:YVO_4 laser operating at 1342 nm, in which the NLM comprises a periodically poled $LiNbO_3$ crystal and a dichroic mirror. The self-starting threshold for cw mode locking is 1.5 W, which is significantly lower than that of saturable absorber mode locking. An average power of 1.52 W at 1342 nm is obtained under diode pump power of 10 W at 808 nm, with the slope efficiency being up to 16.8%. The pulse width and the repetition rate of the mode-locked laser output are about 9.5 ps and 101 MHz, respectively.

OCIS codes: 140.4050, 140.3480, 160.4330.

Mode-locked picosecond diode-pumped solid-state lasers have received considerable attention recently, for their wide applications such as in efficient nonlinear frequency conversion, material processing, and ultrafast spectroscopy. Usually, a passive mode-locking scheme is efficient and convenient for generating ultrafast oscillation, where a semiconductor saturable absorber mirror (SESAM) is frequently used [1,2]. However, the low damage threshold of the SESAM has limited its applications at high power levels [3,4]. In addition, owing to limitations of the semiconductor materials and the growth of technology, it is difficult and costly to manufacture a SESAM to work at an arbitrary wavelength to meet the needs of different applications. An alternate approach for passive mode locking is nonlinear-mirror (NLM) mode locking, which was proposed by Stankov and Jethwa [5]. The NLM mode lock consists of a frequency doubling crystal placed near a dichroic output coupler with high reflectivity at the second harmonic (SH) wavelength, and it partially reflects the fundamental lasing wavelength (FW). In the intracavity recirculation of the FW light, the FW is first converted into SH in forward propagation, and then the SH is backconverted to the FW. Because of the different reflectivity of the SH and FW, a nonlinear positive feedback is established. NLM mode locking is superior to SESAM mode locking for its higher damage threshold, faster response time, and the advantage of being able to work at any wavelength in the nonlinear crystal's transparent range. In the early days, NLM mode-locked lasers were demonstrated using birefringence-phase-matching crystals [6–9], and later the quasi-phase-matching (QPM) technique was applied to NLM, which showed higher efficiency and, consequently, a lower mode-locking threshold [10–13]. Up to now, most of the studies have focused on 1064 nm laser systems; however, picosecond lasers operating at other wavelengths are also of interest. For example, laser sources around 1.3 and 1.5 μm are important for telecommunication systems and may be used for fiber sensing and ranging [14–16].

In this Letter, we demonstrate for the first time to our knowledge, a cw, diode-pumped Nd:YVO_4 laser working at 1342 nm, using periodically poled $LiNbO_3$ (PPLN) as the NLM. QPM-based PPLN optical superlattice has a large nonlinear coefficient and is free of the spatial walk-off effect, which leads to a high nonlinear cavity loss modulation parameter, even with a short crystal. As a result, mode locking can be achieved with a low threshold and high stability against the Q-switched mode locking.

As is well known, the nonlinear cavity loss parameter κ is usually used to characterize NLM mode locking, which is defined as [8]

$$\kappa = -(dL/dP)_{P=0}, \tag{1}$$

where L is the round-trip loss and P is the instantaneous power of the fundamental wave. For a given laser cavity with the dichroic mirror's reflectance R at 1342 nm, κ can be written in the following form:

$$\kappa = -\gamma \mathrm{sinc}^2(\Delta k l_c/2) R[R + 1 + 2\cos(\Delta k l_c - \Delta\phi)], \tag{2}$$

where γ is the coupling coefficient without phase mismatch, l_c is the length of the nonlinear crystal, and $\Delta\phi = \phi_{\mathrm{SH}} - 2\phi_{\mathrm{FW}}$ is a phase shift between the FW and the SH at the backward propagation process due to the dispersion of air and the crystal. The PPLN can provide a reciprocal vector $\vec{G}$ to compensate for the phase mismatch, and, therefore, the momentum mismatch can be written as

$$\Delta\vec{k} = \vec{k}_{\mathrm{SH}} - \vec{k}_{\mathrm{FW}} - \vec{G} = \vec{k}_{\mathrm{SH}} - \vec{k}_{\mathrm{FW}} - \frac{2\pi}{\Lambda}, \tag{3}$$

where $\vec{k}_{\mathrm{FW}}$ and $\vec{k}_{\mathrm{SH}}$ are the wave vectors of the FW and the SH, respectively; Λ is the period; and we have $\vec{k}_{\mathrm{FW,SH}} = 2\pi n_{\mathrm{FW,SH}}/\lambda_{\mathrm{FW,SH}}$, where n_{FW} and n_{SH} are the refractive indices of the FW and the SH, respectively. In consideration of the large effective nonlinearity coefficient of PPLN, which is about 12.4 pm/V [17], we used a 2.5 mm long PPLN crystal to provide sufficient nonlinear loss modulation for the mode locking [18]. Considering the temperature coefficient $\partial \Delta k l_c/\partial T = 0.38\,\mathrm{rad}/°\mathrm{C}$ for

PPLN [19], the temperature bandwidth of κ exceeds 0.9 °C according to Eq. (2), which is 1 order higher than that reported by Cerullo *et al.* using a 15 mm long LBO [8]. The large bandwidth helps to stabilize the mode locking in the experiment.

The schematic experimental setup of the NLM mode-locked 1342 nm laser is shown in Fig. 1. The gain medium is an a-cut, 0.5 at.%, 2.0° wedged Nd:YVO_4 crystal with dimensions of 8 mm × 4 mm × 4 mm, and the two end faces are antireflection coated ($R < 1\%$) at wavelengths of 808 and 1342 nm. The laser crystal is mounted in a water-cooled copper holder and end pumped through M1 by a 20 W fiber-coupled diode-laser array at 808 nm. An optical coupling system is used to image the diode pump beam onto the laser crystal, resulting in a 390 μm beam diameter. M1 is coated for antireflection at 808 nm ($R > 98\%$) on both surfaces and high reflection ($R > 98\%$) at 1342 nm on the right side. Two concave mirrors M2 and M3 with radii of curvature of 500 and 200 mm, respectively, both with high reflection ($R > 99\%$) at 1342 nm, are arranged with an incidence angle below 5.0° in order to minimize astigmatism. M4 is a dichroic output coupler, which is 2° wedged with 91% reflectivity at 1342 nm and 99.9% reflectivity at 671 nm. The entire length of the laser cavity is about 1.5 m. The configuration described above provides a beam diameter of 100 μm in the PPLN crystal.

The PPLN was fabricated using the electrical poling technique at room temperature [20] being 2.5 mm × 3 mm × 0.5 mm in size with a poling period of 12.74 μm. The crystal was 1.0° wedged on one face to reduce the undesired reflection, which may interrupt the mode locking. Besides, we can adjust the relative phase shift between the FW and SH beam by moving the PPLN crystal along the transverse direction to ensure that the SH has the correct phase to reconvert to FW during the backpropagation through the crystal. Both end faces of the crystal were antireflection coated for 1342 and 671 nm ($R < 2\%$). The PPLN crystal was put in a temperature-controllable oven with an accuracy of ±0.1 °C.

In the experiment, we set the PPLN temperature at 160 °C, far from the phase-matching point (203.2 °C) and studied the cw operation of the laser system. We measured the output power with different output coupler reflectivities of 95%, 91%, and 87% at 1342 nm, respectively, to find that the maximum output power was achieved with reflectivity of 91%. The oscillation started with a threshold of about 1.0 W, and the maximum output power exceeded 2.3 W at a pump power of 10 W, with the slope efficiency being 25.4%. When we changed the temperature of the PPLN to the phase-matching point (203.2 °C), we observed Q-switched mode locking around the lasing threshold. However, the cw mode-locking operation occurred when the pump power reached 1 W. The self-starting threshold was measured to be around 1.5 W, corresponding to the intracavity pulse energy of ~20 nJ. The low continuous mode-locking (CML) and self-starting threshold was mainly attributed to the large effective nonlinearity coefficient of the PPLN [21,22]. We measured the CML output power as the pump power ranging from 1.2 to 10 W, and the highest output power at 1342 nm was 1.52 W with a slope efficiency of 16.8%. In that region, the M^2 factor of the laser varies from 1.2 to 2.3. However, when the pump power exceeded 10 W, the thermal lens effect would cause an unstable CML output with amplitude waving. The relations of the output power vary with the pump power in cw and CML operation, as is shown in Fig. 2. In both cases, the output power increased linearly with the pump power; however, the CML output power is slightly

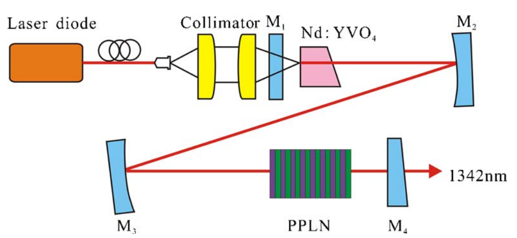

Fig. 1. (Color online) Schematic of NLM mode-locked 1342 nm laser.

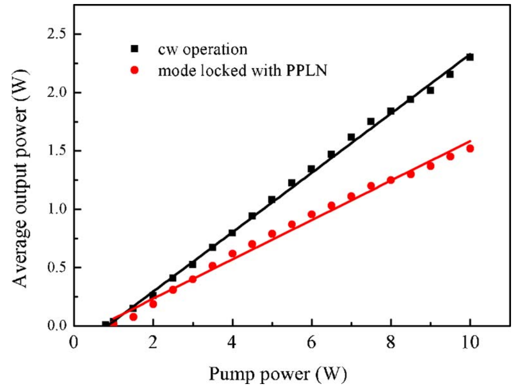

Fig. 2. (Color online) Measured average output power as a function of the incident pumping power in the cw and mode-locked regime.

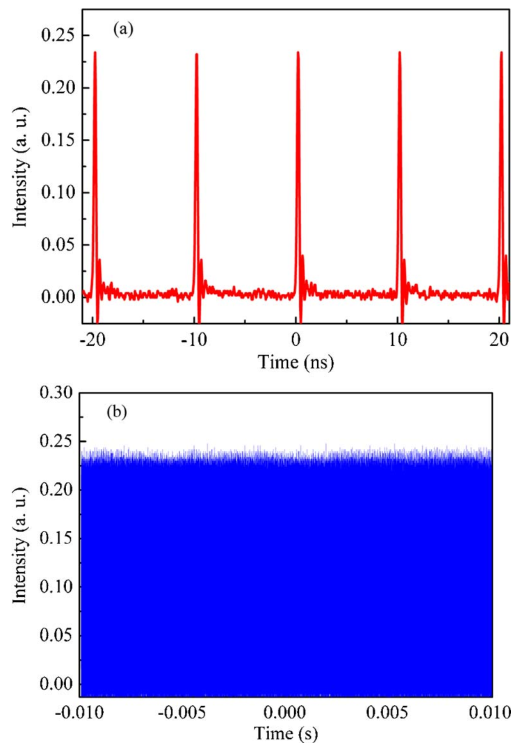

Fig. 3. (Color online) Captured waveform of the pulse train: (a) in nanosecond scale and (b) long-term recording of a cw mode-locked pulse train in millisecond scale.

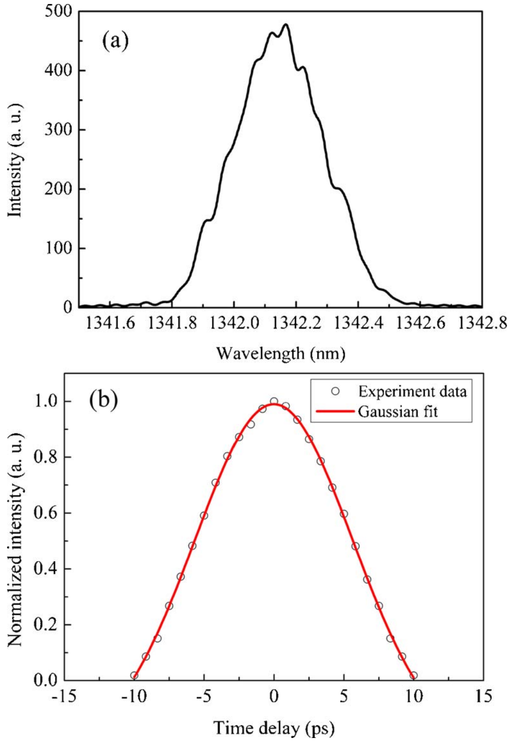

Fig. 4. (Color online) (a) Spectrum of cw mode-locked output and (b) autocorrelation trace of $Nd:YVO_4$ laser.

lower than that of the cw operation. And we can obtain a continuous tunable output power.

The waveform of the output lasing was detected with a high-speed InGaAs detector. Once the lasing threshold was reached, we could observe the mode-locked pulse train, as shown in Fig. 3(a). The repetition rate was measured to be 101 MHz, which was consistent with the round-trip time of the cavity length of 1.5 m. The measured pulse width was limited by the response speed of the InGaAs detector. We also traced over 20 ms, which is longer than the Q-switched or relaxation timescale [Fig. 3(b)], which depicts a pulse-to-pulse amplitude fluctuation of less than 3% during this timescale. The long-term power fluctuation was measured to be within $\pm 2\%$ in 2 h, according to the analysis of the temperature bandwidth of κ, which exceeds 0.9 °C, so a long-term stability CML train can be sustained with most commercially available ovens.

The spectral properties were measured by an optical spectrum analyzer (ANDO AQ-6315A) with a resolution of 0.05 nm. As shown in Fig. 4(a), the spectral FWHM was approximately 0.34 nm at the central wavelength of 1342.1 nm. The pulse duration measured using a homemade autocorrelator was about 9.5 ps, assuming a Gaussian pulse shape [see Fig. 4(b)]. The time–bandwidth product of the pulse was 0.54, which was 1.3 times the Fourier transform limit. Considering the dispersion of the PPLN, the time delays from the group velocity mismatch (GVM) between the FW and the SH in it is 4.5 ps/cm. For the 2.5 mm long PPLN used, the SH was relatively delayed by 2.2 ps to FW. Therefore, the GVM is the major limiting effect for the transform-limited performance, which can be improved by using a shorter PPLN or exploiting group-delay-compensation techniques [22].

In conclusion, we successfully constructed a picosecond 1342 nm laser based on the NLM method. By using a wedged 2.5 mm long PPLN, stable cw mode locking was achieved. The output CML pulse had a repetition rate of 101 MHz and duration of 9.5 ps. A maximum average output power of 1.52 W was achieved at the pump power of 10 W, with the slope efficiency up to 16.8%. Employing a double end-pumping scheme and cascading multigain mediums inside the cavity, the PPLN-NLM technique can be readily scaled to higher power picosecond lasing output.

This work was supported by the National Natural Science Foundation of China (NSFC) (11021403, 10904066, and NSAF10776011) and the State Key Program for Basic Research of China (2011CBA00205 and 2010CB630703).

References

1. U. Keller, D. A. B. Miller, G. D. Boyd, T. H. Chiu, J. F. Ferguson, and M. T. Asom, Opt. Lett. **17**, 505 (1992).
2. J. L. He, Y. X. Fan, J. Du, Y. G. Wang, S. Liu, H. T. Wang, L. H. Zhang, and Y. Hang, Opt. Lett. **29**, 2803 (2004).
3. L. R. Brovelli, U. Keller, and T. H. Chiu, J. Opt. Soc. Am. B **12**, 311 (1995).
4. N. Coluccelli, G. Calzerano, L. Bonelli, A. D. Lieto, M. Tonelli, and P. Laporta, Opt. Express **16**, 2922 (2008).
5. K. A. Stankov and J. Jethwa, Opt. Commun. **66**, 41 (1988).
6. A. Agnesi, C. Pennacchio, G. C. Reali, and V. Kubecek, Opt. Lett. **22**, 1645 (1997).
7. P. K. Datta, Shivanand, S. Mukhopadhyay, A. Agnesi, and A. Lucca, Appl. Opt. **43**, 2347 (2004).
8. G. Cerullo, M. B. Danailov, S. De Silvestri, P. Laporta, V. Magni, D. Segala, and S. Taccheo, Appl. Phys. Lett. **65**, 2392 (1994).
9. M. B. Danailov, G. Cerullo, V. Magin, D. Segala, and S. De Silvestri, Opt. Lett. **19**, 792 (1994).
10. Y. F. Chen, S. W. Tsai, and S. C. Wang, Appl. Phys. B **72**, 395 (2001).
11. S. J. Holmgren, V. Pasiskevicius, and F. Laurell, Opt. Express **13**, 5270 (2005).
12. H. Iliev, I. Buchvarov, S. Kurimura, and V. Petrov, Opt. Lett. **35**, 1016 (2010).
13. S. J. Holmgren, A. Fragemann, V. Pasiskevicius, and F. Laurell, Opt. Express **14**, 6675 (2006).
14. K. A. Stankov, V. Kubecek, and K. Hamal, Opt. Lett. **16**, 505 (1991).
15. R. Fluck, G. Zhang, U. Keller, K. J. Weingarten, and M. Moser, Opt. Lett. **21**, 1378 (1996).
16. S. C. Huang, H. L. Cheng, Y. F. Chen, K. W. Su, Y. F. Chen, and K. F. Huang, Opt. Lett. **34**, 2348 (2009).
17. I. Shoji, T. Kondo, A. Kitamoto, M. Shirane, and R. Ito, J. Opt. Soc. Am. B **14**, 2268 (1997).
18. K. A. Stankov, Appl. Phys. B **45**, 191 (1988).
19. D. H. Jundt, Opt. Lett. **22**, 1553 (1997).
20. S. N. Zhu, Y. Y. Zhu, Z. Y. Zhang, H. Shu, H. F. Wang, J. F. Hong, C. G. Ge, and N. B. Ming, J. Appl. Phys. **77**, 5481 (1995).
21. J. H. Lin, W. H. Yang, W. F. Hsieh, and K. H. Lin, Opt. Express **13**, 6323 (2005).
22. P. K. Datta, S. Mukhopadhyay, G. K. Samanta, S. K. Das, and A. Agnesi, Appl. Phys. Lett. **86**, 151105 (2005).