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Wavelength-Tunable Nonlinear Mirror Mode-Locked Laser Based on MgO-Doped Lithium Niobate

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Abstract: We present a high-power, wavelength-tunable picosecond Yb$^{3+}$: CaGdAlO$_4$ (Yb:CALGO) laser based on MgO-doped lithium niobate (MgO:LN) nonlinear mirror mode locking. The output wavelength in the continuous wave (CW) regime is tunable over a 45 nm broad range. Mode locking with a MgO:LN nonlinear mirror, the picosecond laser is tunable over 23 nm from 1039 to 1062 nm. The maximum output power of the mode-locked laser reaches 1.46 W, and the slope efficiency is 18.6%. The output pulse duration at 1049 nm is 8 ps. The laser repetition rate and bandwidth are 115.5 MHz and 1.7 nm, respectively.

Keywords: mode-locked laser; nonlinear mirror mode locking; lithium niobate

1. Introduction

Diode-pumped all-solid-state ultrafast lasers have received wide attention due to their broad applications in nonlinear frequency conversion, micro-machining, and medicine, since they have the advantages of simplicity, compactness, and variable wavelength [1–5]. The commonly used technology is passive mode locking based on a semiconductor saturable absorber mirror (SESAM), graphene, and a carbon nanotube (CNT) saturable absorber [6–8]. However, a SESAM requires complex fabrication and works under a lower damage threshold. For graphene and CNT saturable absorber mode locking, the power is constricted at the milliwatt level [7,8]. Nonlinear mirror mode locking (NLM) is an alternate passive mode locking technique to obtain ultrafast lasers with higher than average power. A nonlinear mirror consists of a frequency doubling crystal and a dichroic mirror [9]. The dichroic mirror partially reflects the fundamental wavelength (FW) and highly reflects a second harmonic wavelength (SH). In the intracavity, the partial FW is converted into an SH when it first passes the nonlinear crystal, and the SH is totally reflected by the dichroic mirror (DM) while the unconverted FW is partially reflected by the DM. For the backward passing, the SH is back-converted into the FW, due to the different phases of the FW and SH introduced by the air between the nonlinear crystal and the dichroic mirror. For the whole process, the different reflectivity between the FW and the SH leads to a nonlinear positive feedback. The intensity-dependent nonlinear reflectivity results in passive mode locking, thus it acts like a fast saturable absorber with a negative equivalent Im($\chi^3$). NLM is advantageous with its high damage threshold, large nonlinear loss modulation, and the capability of being able to work at any wavelength for which phase matching is satisfied in the nonlinear crystal’s transparent range, thus ensuring a wavelength-tunable laser with high power. The nonlinear crystals for NLM are generally divided into two types: birefringence phase-matching (BPM) crystals (BBO, BiBO, LBO, KTP) [10–16] and quasi-phase-matching (QPM) crystals (periodically poled LN, LT, KTP) [17–22]. The peak power of the output laser is commonly at the kilowatt level while a bulk laser crystal is utilized, as shown in Figure 1. Combined with a thin-disk (TD) laser crystal, NLM
could generate ultrafast lasers within several hundreds of femtoseconds and with peak powers up to 10 MW [23,24].

**Figure 1.** Peak power and pulse duration of NLM lasers around 1 μm. Black dots are NLM lasers based on BPM, red squares are NLM lasers based on QPM, green dot is our work. Dashed oval is thin-disk laser, dashed rectangle is bulk laser.

To date, most of the studies on NLM have focused on a particular wavelength, such as laser sources around 1, 1.3, and 2 μm [10–24]. However, tunable picosecond lasers with output powers at the watt level are also of interest. In this study, we demonstrate a picosecond-tunable Yb:CALGO laser which is achieved by MgO:LN nonlinear mirror mode locking. The wavelength tuning range is 23 nm from 1039 to 1062 nm. The pulse duration is 8 ps at 1049 nm. The average output power reaches 1.46 W, with a slope efficiency of 18.6%. The laser repetition rate and bandwidth are 115.5 MHz and 1.7 nm, respectively.

**2. Materials and Methods**

The schematic experimental setup of the tunable nonlinear mirror mode-locked Yb:CALGO laser is shown in Figure 2. The gain medium is an a-cut, 3 at.% Yb:CALGO crystal with dimensions of 4 mm × 4 mm × 8 mm, and both end faces are antireflection coated (R<1%) at the wavelengths of 976 nm and 1030–1080 nm. The pump light is a laser diode (LD) array operating at 976 nm. The maximum output power of the pump light is 30 W. The LD has a fiber with a core diameter of 105 μm and a numerical aperture of 0.22. A 1:1 optical coupling system is used to project the pump light onto Yb:CALGO. M1 is an input mirror with a transmissivity of 98% at 976 nm and a reflectivity of 99.5% at 1030–1080 nm on the left side. Two concave mirrors, M2 and M3, are folding mirrors, with radii of 500 and 200 mm, respectively. M4 is highly reflected at the SH and partially reflected at the FW. M4 and MgO:LN form a nonlinear mirror. A birefringent plate (BF) is used to constrain the laser wavelength within the phase-matching bandwidth of the second harmonic generation process. M1, M2, M3, and M4 form a z-type cavity and the length of the resonant cavity is 1.3 m. The size of MgO:LN is 5 mm × 5 mm × 5 mm (w × h × l), and the phase-matching angle of MgO:LN is cut to be θ = 79.2°, φ = 90°.
Figure 2. Schematic diagram of the experimental device of Yb:CALGO tunable mode-locked laser. M1 is plane input mirror, M2 and M3 are folding mirrors, M4 is output coupler, LN and M4 form a nonlinear mirror. BF is the birefringent filter.

3. Results

In the experiment, we tested four output couplers (OCs) at the FW (T= 1%, 2%, 5%, 9%). The maximum output power was achieved with the T = 9% OC, thus, subsequent experiments were measured based on the T = 9% OC. The birefringent filter was placed at the Brewster angle and its orientation was then tuned to select the FW. The wavelength-tunable operation of the CW laser was firstly tested under a pump power of 5.8 W. The wavelength was tunable over 45 nm from 1022 nm to 1067 nm, as shown in Figure 3a. The output power achieved its maximum when the wavelength was around 1049 nm, and it decreased when the wavelength was away from 1049 nm on both sides. The wavelength was then fixed at 1049 nm. The oscillation started at a threshold of about 1.8 W, and the maximum output power exceeded 1.7 W under a pump power of 9.8 W, with a slope efficiency of 22.2%. The output power increased linearly as the pumping power increased, as shown in Figure 3b.

Figure 3. (a) Tuning wavelength under CW and CWML operation. (b) Output power dependence on absorption pump power during CW and mode-locking operation.

The MgO:LN crystal was then inserted into the cavity and the position of MgO:LN was located near to M4. When MgO:LN was adjusted to the phase-matching angle, a green light transmitted through M3 could be observed. Besides, the relative phase shift between the FW and SH could be adjusted by moving the MgO:LN crystal along the transverse direction to ensure that the SH had the correct phase and efficient back conversion. The lasing threshold was 1.7 W and Q-switch mode locking was observed by the InGaAs detector (EOT, ET-3000, Traverse City, MI, USA) and digital oscilloscope (LeCroy, HDO4104A, New York, NY, USA). When the distance between MgO:LN and the OC was less than 5 mm and the pump power reached 3.6 W, CW mode locking (CWML) was realized. The pulse sequence was stable when the pump power was under 10 W. However, if the pump power exceeded 10 W, the thermal lens effect caused an unstable CWML output. We measured the
CWML output power as the pump power increased from 3.6 to 9.8 W, and the highest output power at 1049 nm was 1.46 W, with a slope efficiency of 18.6%, as shown in Figure 3b.

The tunable wavelength of the mode-locked laser was achieved according to the following procedures: (i) tuning orientation of the birefringent filter (selecting the FW), (ii) adjusting the phase-matching angle of the nonlinear crystal (satisfying the phase-matching condition of SH generation) and transverse position of the nonlinear crystal in millimeters (relative backward phase shift). The mode-locked laser wavelength was tunable over 23 nm from 1039 to 1062 nm (Figure 3a). For a wavelength that was shorter than 1039 nm or longer than 1062 nm, the obvious work-off effect made the mode locking extremely unstable. To obtain a mode-locked laser covering the entire CW range (45 nm), using MgO:LN with another appropriate phase-matching angle is recommended.

The pulse train at the timescale of 40 ns is shown in Figure 4a. The nearby pulse interval was 8.6 ns, which was consistent with the roundtrip time of the 1.3 m cavity length. The pulse train was also traced over 10 ms (Figure 4b), which showed that a pulse-to-pulse amplitude fluctuation was less than 2% at this timescale. The radio frequency (RF) waveform was detected by the spectrum analyzing function of the oscilloscope. As shown in Figure 4c, the fundamental frequency was 115.5 MHz when a resolution bandwidth (RBW) was set to be 5 kHz. According to the resonant cavity length, the frequency was calculated to be 115.38 MHz. The signal-to-noise ratio was 60 dB. Figure 4d shows an RF waveform in the range of 750 MHz with an RBW of 1 MHz.

![Figure 4](image_url)

**Figure 4.** (a) The pulse train at a timescale of 40 ns. (b) The pulse train at a timescale of 10 ms. (c) The RF spectrum of a CWML laser with an RBW of 5 kHz. (d) RF spectrum with a span of 750 MHz and an RBW of 1 MHz.

The spectrum property of the CWML operation was measured by a spectrum analyzer (AVASPEC-3648, Apeldoorn, The Netherlands). Figure 5a shows that the output tunable laser wavelength was from 1039 to 1062 nm. The full width at half maximum (FWHM) spectral bandwidth at a representative output wavelength (1049 nm) was ~1.7 nm. The autocorrelation trace was measured using an autocorrelator (APE pulseCheck USB IR, Berlin, Germany), as shown in Figure 5b. Assuming a Gaussian pulse shape, the pulse duration was about 8 ps. The peak power was about 1.58 kW at the maximum output power and the pulse energy was 12.6 nJ, accordingly. As the FW and SH have different group velocities in MgO:LN, the group velocity mismatch (GVM) is the major limiting effect for pulse shortening. Considering the time delay from the GVM between the FW and the SH in MgO:LN, the SH pulse after double passing through MgO:LN (length \( L_c \)) is delayed by approximately \( \tau_c = 2 \delta_t L_c \), where \( \delta_t = 1/v_{g2ω} - 1/v_{gω} = 0.6 \) ps/mm is the GVM parameter of MgO:LN. For the 5 mm long crystal used, the SH was relatively delayed by 6 ps to the FW. According to the Fourier
transform limit, the pulse duration should be 0.95 ps if the spectral bandwidth is 1.7 nm. Taking GVM into account, the final pulse duration was calculated to be 6.95 ps, which was consistent with our experiment result.

![Figure 5. (a) The wavelength-tunable mode-locked pulse spectrum. (b) Autocorrelation trace of the mode-locked pulses.](image)

4. Discussion

It is worth noting that, firstly, benefiting from its high damage threshold, the output power of NLM could reach the watt level. It is higher than mode locking using graphene and a CNT absorber, whose output power is commonly limited to the milliwatt level. Secondly, previous works around 1 μm on the NLM technique mostly focused on a particular wavelength (Table 1). However, the capability of being able to work at any wavelength in the nonlinear crystal’s transparent range was not fully utilized. Here, Yb:CALGO is utilized as a gain medium, since compared with other laser crystals in Table 1, it has a broad emission spectrum from 990 to 1050 nm [25]. In our experiment, the wavelength for CW operation could be extended to 1067 nm. Moreover, the BF is tuned to select the FW. MgO:LN is used as a nonlinear crystal. The phase-matching angle of MgO:LN could be adjusted to realize high nonlinear conversion efficiency. Therefore, Yb:CALGO combined with a MgO:LN-based NLM technique is an efficient method to obtain a high-power, wavelength-tunable picosecond laser.

| Nonlinear Crystal | Phase Matching Method | Laser Crystal | Wavelength (nm) | Pulse Width (ps) | Repetition Rate (MHz) | Power (W) | Peak Power (kW) | Reference Year |
|------------------|----------------------|--------------|----------------|-----------------|---------------------|----------|----------------|----------------|
| LBO              | BPM                  | Nd:YAG       | 1064           | 10              | 100                 | 0.7      | 0.7            | [10] 1994      |
| KTP              | BPM                  | Nd:YVO₄      | 1064           | 7.9             | 150                 | 1.35     | 1.14           | [11] 1997      |
| LBO              | BPM                  | Nd:YVO₄      | 1064           | 6               | 200                 | 2.5      | 2.08           | [12] 2001      |
| LBO              | BPM                  | Yb:YAG       | 1031           | 9               | 82                  | 0.9      | 1.2            | [13] 2003      |
| KTP              | BPM                  | Nd:GdVO₄     | 1063           | 57              | 137                 | 11.3     | 1.4            | [14] 2010      |
| BiBO             | BPM                  | Nd:GdVO₄     | 1063           | 5.7             | 144                 | 7.1      | 8.6            | [14] 2010      |
| BiBO             | BPM                  | Nd:YVO₄      | 1064           | 14              | 110                 | 12.5     | 7.7            | [15] 2010      |
| BiBO             | BPM                  | Nd:GdVO₄     | 1063           | 12.7            | 100                 | 16.8     | 13             | [16] 2012      |
| BBO              | BPM                  | TD:Yb:YAG    | 1030           | 0.323           | 17.8                | 21       | 3.6            | [22] 2017      |
| PPKTP            | QPM                  | Nd:YVO₄      | 1064           | 2.9             | 117                 | 0.5      | 1.3            | [17] 2010      |
| PPMgSLT          | QPM                  | Nd:GdVO₄     | 1064           | 3.2             | 107                 | 1.4      | 4.0            | [18] 2010      |
| PPLN             | QPM                  | Nd:YVO₄      | 1342           | 9.5             | 101                 | 1.52     | 1.5            | [19] 2011      |
| PPLN             | QPM                  | Nd:YVO₄      | 1064           | 2.8             | 186                 | 1.3      | 2.49           | [21] 2011      |
| MgO:LN           | BPM                  | Yb:CALGO     | 1039–1062      | 8               | 115.5               | 1.46     | 1.58           | Our work       |

Table 1. Passively mode-locked solid-state 1 μm lasers based on NLM.
As mentioned above, GVM is the major factor that limits pulse shortening. In MgO:LN, the nonlinear process is $o + o \rightarrow e$, where the FW is ordinary polarization and the SH is extraordinary polarization. After first passing MgO:LN, the FW goes faster than the SH due to GVM. If another birefringence crystal is inserted between MgO:LN and M4, and the polarization of the FW is parallel to the slow axis and SH polarization is parallel to the fast axis, the FW will goes slower than the SH. Therefore, the pulses of the FW and SH will overlap again and GVM is compensated [26].

5. Conclusions

In conclusion, we report a MgO:LN nonlinear mirror mode-locked picosecond Yb:CALGO laser. The mode-locked laser wavelength is tunable from 1039 to 1062 nm. The maximum output power of the mode-locked laser reaches 1.46 W at 1049 nm, and the slope efficiency is 18.6%. The output pulse duration is ~8 ps. The repetition rate is 115.5 MHz and the bandwidth of the mode-locked laser is 1.7 nm.

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