Theoretical and experimental studies for high-repetition-rate disordered crystal lasers with harmonic self-mode locking

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Abstract: A harmonically self-mode-locked $Nd:Sr_3Y_2(BO_3)_4$ disordered crystal laser with subpicosecond pulse duration is demonstrated. We exploit the damped harmonic oscillator model to numerically verify that the mode spacing of the laser cavity can be modified to be the harmonics of the free spectral range of the Fabry-Perot cavity when the optical length of the laser cavity is close to a commensurate ratio of the optical length of the Fabry-Perot cavity. In experiment, the Fabry-Perot cavity can be formed by the pump facet of the disordered crystal and the front mirror. A 110 GHz single-pulse harmonically mode-locked pulse train with pulse duration of 857 fs is experimentally achieved under optical lengths of 27.19 and 4.08 mm for the laser cavity and Fabry-Perot cavity respectively, corresponding to a fractional number of 20/3. A maximum output power of 162 mW is obtained at an incident pump power of 3.1 W.

OCIS codes: (140.3480) Lasers, diode-pumped; (140.3580) Lasers, solid-state; (140.4050) Mode-locked lasers.

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1. Introduction

Light sources with high repetition rates are scientific interest for many potential applications, such as telecommunication, optical clocking, photonic switching, high signal-to-noise ratio measurements, and high capacity optical networks [1–7]. Many approaches have been developed to achieve high repetition rates, including harmonically mode-locked fiber lasers, quantum-well Fabry-Perot lasers, quantum-dash-based Fabry-Perot mode-locked lasers, and passively mode-locked solid-state lasers [8–11]. Among these methods, harmonic mode locking is a promising approach with the advantages of compactness and low cavity losses. In the past few years, harmonically mode-locked operation has been explored in numerous traditional solid-state lasers, such as $Nd:YVO_4$ lasers, Nd:YLF lasers, and Yb:YAG lasers [12–15].

Compared to conventional laser crystals, disordered crystals possess the random distribution of cations in the host material to lead to the large inhomogeneous spectral broadening [16]. The broader emission spectra are beneficial for generating shorter mode-locked pulse [17]. On the other hand, disordered crystals can be more insensitive to the pump wavelength than conventional laser crystals in the diode pumping scheme owing to the broad absorption spectra [18]. Furthermore, disordered crystals usually have the positive coefficient of the variation of thermal conductivity on temperature that is useful in balancing the thermal effects for power scale up [19]. Nowadays, various disordered crystals, such as Nd:GAGG, Nd:CLNGG, and Nd:GYSGG, have been employed to achieve passively mode-locked lasers with a semiconductor saturable absorber mirror [20–22]. Nevertheless, harmonically self-mode-locked lasers with disordered crystals as the gain medium are seldom explored [23].

$Nd:Sr_3Y_2(BO_3)_4$ disordered crystal belongs to the orthorhombic system [24] which possesses much broader emission spectrum than those belong to the cubic (Nd:GAGG, Nd:CLNGG, and Nd:GYSGG) or tetragonal (Nd:SGGM) system. In this work, we utilize a $Nd:Sr_3Y_2(BO_3)_4$ disordered crystal as the gain medium to generate a harmonically self-mode-

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locked laser at high repetition rate together with ultrashort pulse. First of all, we numerically show that when the ratio of the optical length of the laser cavity to the optical length of the Fabry-Perot cavity, denoted as q/p, is exactly close to a fraction number, the temporal trace will display single-pulse harmonic mode locking. In the experiment, we can realize the harmonically mode-locked lasing output once the optical cavity length L_{cav} and the separation d between the gain medium and the front mirror satisfy a commensurate ratio. A 110 GHz pulse train with pulse duration as short as 857 fs is obtained at an optical cavity length L_{cav} of 27.19 mm and a separation d of 4.08 mm, corresponding to a fractional number of 20/3. At an incident pump power of 3.1 W, an average output power of 162 mW is achieved, corresponding to a slope efficiency of 7.9%. To the best of our knowledge, it is the highest repetition rate ever obtained in disordered crystal lasers and the first report for $Nd:Sr_3Y_2(BO_3)_4$ disordered crystal laser manipulated in the harmonically self-mode-locked operation.

2. Theoretical analysis

The evolution of laser oscillation from the free-running state toward the steady-state mode-locked operation was firstly investigated by F. Krausz et al. [25]. The condition for self-starting mode locking can be expressed as

$$\kappa P_i > \frac{1}{\ln(m)}\frac{T_r}{T_c} \tag{1}$$

where κ is a characteristic of the Kerr nonlinearity, P_i is the circulating intracavity power in the free-running laser, T_r is the cavity round-trip time, and T_c is a finite correlation time concerning axial modes oscillating in the free-running laser. Referring to Eq. (1), a shorter T_r is more beneficial to the self-starting mode locking. The effective round-trip time for n-th order harmonic mode locking can be reduced n times. Therefore, high-order harmonic mode locking may be more useful for the self-starting mode locking. Next, we theoretically analyze the condition for achieving the harmonically mode-locked operation.

The frequency spectrum of the phase-locked longitudinal modes in the laser cavity can be described by the damped harmonic oscillator model and given by

$$I(f) = \sum_{m=-M}^{M} \frac{(f-f_0)^2\gamma_c}{\left[(f-f_0)^2-(m\Delta f_c)^2\right]^2+\left[(f-f_0)\gamma_c\right]^2} e^{-\frac{m^2}{(\Gamma/\Delta f_c)^2}} \tag{2}$$

where f_0 is the center frequency, Δf_c is the mode spacing of longitudinal modes, γ_c is the damping constant for the laser cavity, and Γ is the linewidth of the gain profile. Here, we presume the distribution of longitudinal modes to be Gaussian-shaped. Provided that the front mirror and the pump surface of the laser crystal form a Fabry-Perot cavity, the resultant frequency spectrum of the laser emission is modulated with an effective transmission function:

$$\begin{aligned} I(f) = &\sum_{m=-M}^{M} \frac{(f-f_0)^2\gamma_c}{\left[(f-f_0)^2-(m\Delta f_c)^2\right]^2+\left[(f-f_0)\gamma_c\right]^2} e^{-\frac{m^2}{(\Gamma/\Delta f_c)^2}} \\ &\times \sum_{n=-N}^{N} \frac{(f-f_0)^2\gamma_{FP}}{\left[(f-f_0)^2-(n\Delta f_{FP})^2\right]^2+\left[(f-f_0)\gamma_{FP}\right]^2} \end{aligned} \tag{3}$$

where γ_{FP} and Δf_{FP} are the damping constant and mode spacing for the Fabry-Perot cavity, respectively. Note that Δf_{FP} can be rewritten as $q\Delta f_c/p$, where q/p is the ratio of the optical length of the laser cavity to the optical length of the Fabry-Perot cavity. Figure 1(a)-1(c) demonstrate the frequency spectra of the laser output for q/p = 10/1, 10/1.015, and 10/1.075

with the following parameters: f_0 = 282.2 GHz, Δf_c = 7.3 GHz, γ_c = 0.01, γ_g = 0.1, Γ = 592.3 GHz, M = 100, N = 10. The temporal forms of the laser output corresponding to Fig. 1(a)-(c) can be obtained by Fourier transforming Eq. (3) as shown in Fig. 1(d)-1(f). When the ratio q/p is precisely close to the fractional number of 10/1, we can see it obviously that the frequency spectrum exhibits a well Gaussian profile as illustrated in Fig. 1(a). In the meanwhile, the laser output shows good harmonic mode locking with tenth order as demonstrated in Fig. 1(d). With slightly deviating the numerator p from 1 to 1.015, the profile of the frequency spectrum can still be Gaussian-shaped with center frequency shifted, as referring to Fig. 1(b). For the temporal structure shown in Fig. 1(e), the pulse train can still maintain to be 10-th harmonic mode locking except for some amplitude fluctuation. However, when the numerator p is much deviated from 1 to 1.075, no Gaussian shape is observed in the frequency spectrum and the temporal trace displays a multi-pulse mode-locked operation, as depicted in Fig. 1(c) and 1(f). According to the numerical results, we can find out that the optical length of the laser cavity must be very close to the commensurate ratio of the optical length of the Fabry-Perot cavity for achieving a good harmonically mode-locked pulse train.

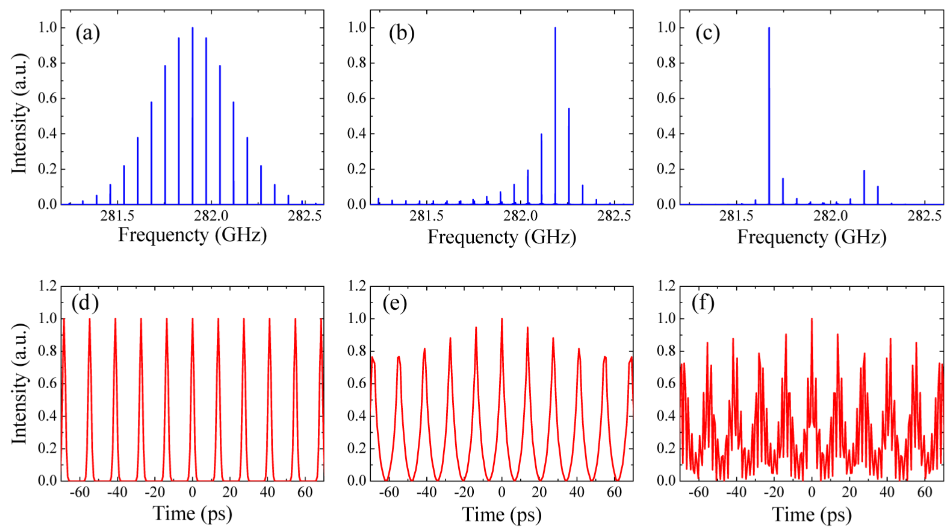

Fig. 1. (a)-(c) Numerical results for the frequency spectrum with three different fraction numbers q/p of 10/1, 10/1.015, and 10/1.075, respectively. (d)-(f) Temporal structures corresponding to the Fourier transformation of the frequency spectrum shown in (a)-(c), respectively.

3. Experimental setup

The experimental setup for the harmonically self-mode-locked $Nd:Sr_3Y_2(BO_3)_4$ disordered crystal laser with a concave-plano resonator is shown in Fig. 2(a). The $Nd:Sr_3Y_2(BO_3)_4$ disordered crystal was cut along the b axis with a Nd^{3+} concentration of 0.685 at.% and a dimension of 3 mm × 3 mm in cross section and 8 mm in length. Both end surfaces were coated for antireflection at the pump wavelength of 808 nm and the lasing wavelength of 1064 nm. Figure 2(b) shows the fluorescence spectrum of the $Nd:Sr_3Y_2(BO_3)_4$ disordered crystal in the $^4F_{3/2}\rightarrow{}^4I_{11/2}$ transition at room temperature. The luminescence bandwidth can be seen to be nearly 25 nm which is wider than those of Nd:GAGG (4 nm) [21], Nd:CLNGG (16.5 nm) [26], and Nd:GYSGG (4.95 nm) [22] disordered crystals. The luminescence lifetime is 75.8 μs at room temperature [27]. To ensure the laser working in the stable operation, the disordered crystal was wrapped with indium foil and mounted in a water-cooled copper block with circulating water maintained at 16 °C. The front mirror was an 100-mm-radius-of-curvature concave mirror with high-reflectance coating at 1064 nm (>99.8%). A flat wedged output coupler with 98% reflection at 1064 nm was utilized in the experiment.

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The pump source was a 3-W 808-nm fiber-coupled laser diode with a core diameter of 100 μm and a NA of 0.16. A pair of identical plano-convex focusing lenses with 25-mm focal length and 85% coupling efficiency was used to reimage the pump beam into the laser crystal. The average pump diameter was approximately 120 μm.

Since the pulse repetition rate in our experiment was higher than the bandwidth limit for both digital oscilloscope (20 GHz) and RF power spectrum analyzer (26 GHz), no peaks were observed in the digital oscilloscope or RF power spectrum analyzer. The temporal behavior of the laser output was studied with the help of the first- and second-order autocorrelations. The first-order autocorrelation trace was monitored by a Michelson interferometer (Advantest, Q8347). It was also capable of performing optical spectral analysis by Fourier transforming the first-order field autocorrelation with a resolution of 0.003 nm. The second-order autocorrelation trace was recorded with a commercial autocorrelator (APE pulse check, Angewandte Physic & Elektronik GmbH) for performing the profile of the single mode-locked pulse.

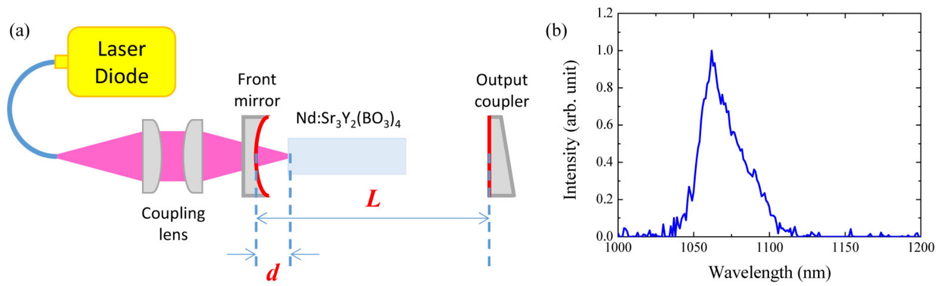

Fig. 2. (a) Experimental setup for a harmonically self-mode-locked $Nd:Sr_3Y_2(BO_3)_4$ disordered crystal laser. (b) Fluorescence spectrum of the $Nd:Sr_3Y_2(BO_3)_4$ disordered crystal at room temperature.

4. Experimental results and discussion

First of all, we measured the output performance of the laser system. The experimental result for the average output power as a function of the incident pump power is shown in Fig. 3. At an incident pump power of 3.1 W, an average output power of 162 mW was experimentally obtained, corresponding to a slope efficiency of approximately 7.9%. Next, we adjusted the ratio of the optical cavity length L_{cav} to the separation d between the front mirror and the laser crystal to investigate the temporal behavior under an incident pump power of 2.4 W. Experimental results reveal that when the pump power is slightly above the threshold (> 1 W), the self-mode-locked performance is almost the same for all the investigated pump powers. Only when the pump power is near to the threshold power (between 0.98 and 1 W), the harmonically self-mode-locking is difficult to obtain.

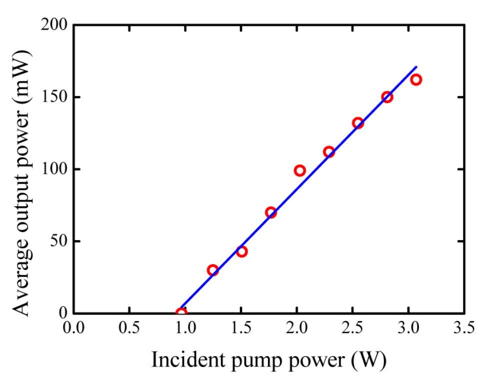

Fig. 3. Experimental results for the output power versus the incident pump power.

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At first, we set the optical cavity length L_{cav} and separation d to be 21.32 and 2.24 mm, respectively. Under this condition, the ratio L_{cav}/d can be calculated to be slightly deviated from a simple fractional number of 10/1. Therefore, the laser output displayed a multi-pulse mode-locked operation at repetition rate of approximately 70 GHz as revealed in Fig. 4(a). After finely adjusting the optical cavity length L_{cav} to be precisely close to the commensurate ratio of the separation d, the single-pulse mode locking with a pulse separation of 13.64 ps could be achieved as depicted in Fig. 4(b). In this case, the optical cavity length L_{cav} and separation d were 21.47 and 2.14 mm, respectively. We can find out that the ratio L_{cav}/d was quite close to the fractional number of 10/1. By scanning the optical cavity length from 20 to 30 mm while suitably tuning the separation d, single-pulse harmonic mode locking with different orders could be experimentally observed. Figure 4(c) and 4(d) demonstrate pulse trains of the single-pulse harmonic mode locking with pulse separation of 18.28 and 9.11 ps, corresponding to the repetition rate of 50 and 110 GHz respectively. The optical cavity length L_{cav} and separation d are 21.63 and 2.10 mm for Fig. 4(c), and 27.19 and 4.08 mm for Fig. 4(d), respectively. The ratio L_{cav}/d can be found to be close to fraction numbers of 8/1 and 20/3. The fluctuations of the measured harmonically mode-locked single-pulse train are all better than 5%.

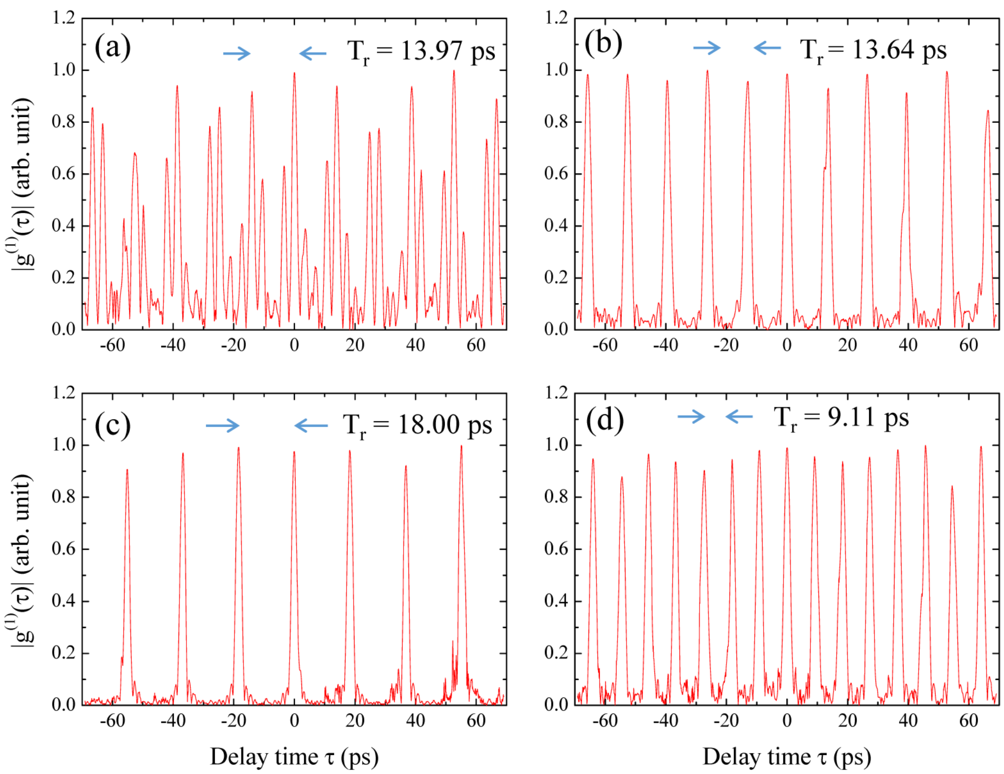

Fig. 4. Experimental traces of the first-order autocorrelations for the operation of three cases of harmonic mode locking: (a) the trace for the multiple-pulse mode locking with repetition rate of 70 GHz; (b) the trace for the single-pulse mode locking with repetition rate of 70 GHz; (c) the trace for the single-pulse mode locking with repetition rate of 55 GHz; (d) the trace for the single-pulse mode locking with repetition rate of 110 GHz.

The optical spectra corresponding to the single-pulse mode locking for the ratios L_{cav}/d = 10/1, 8/1, and 20/3 are shown in Fig. 5. The mode spacing was found to be approximately 0.286, 0.209, and 0.412 nm, which was consistent with the pulse repetition rate of 70, 55, and 110 GHz as shown in Fig. 4(b)-4(d), respectively. Additionally, we can see that the envelopes of the lasing spectrum display a Gaussian shape. These results reveal that the ratios L_{cav}/d are

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precisely close to a fractional number as we discussed in the section of the theoretical analysis. On the other hand, the second-order autocorrelation traces for L_{cav}/d = 10/1, 8/1, and 20/3 are demonstrated in Fig. 6. The full width at half maximum of a mod-locked pulse was approximately 1.54, 1.59, and 1.32 ps for L_{cav}/d = 10/1, 8/1, and 20/3, respectively. Assuming the temporal intensity to be the sech^2 profile, the pulse durations were found to be 0.998, 1.03, and, 0.857 ps, respectively. The time-bandwidth product was calculated to be 0.357, 0.332, and 0.419, which was 1.13, 1.05 and 1.33 times of the Fourier transform limit value for the sech^2-shaped pulses. The present results recommend the Nd:$Sr_3Y_2(BO_3)_4$ disordered crystal as a promising gain medium for generating high repetition rate with ultrashort pulse duration.

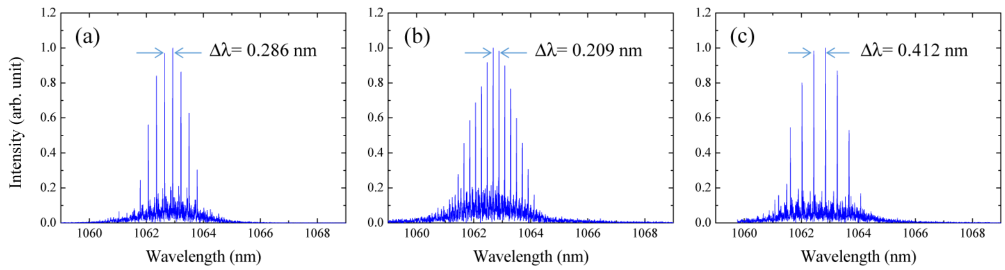

Fig. 5. (a)-(c) Optical spectra for single-pulse harmonic mode locking with ratio L_{cav}/d of 10/1, 8/1 and 20/3, respectively.

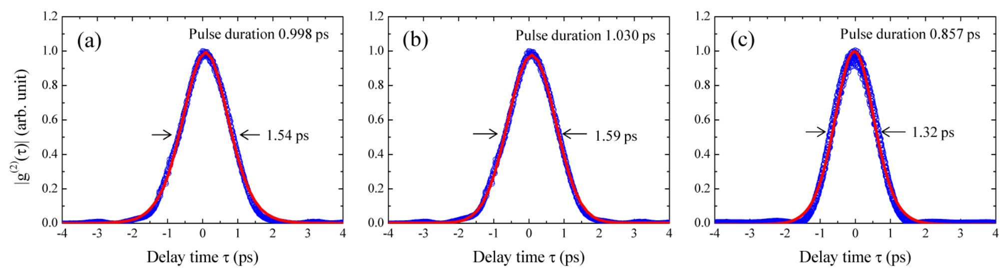

Fig. 6. (a)-(c) The second-order autocorrelation traces and sech^2 fitting curves for single-pulse mode-locked pulses with ratio L_{cav}/d of 10/1, 8/1, and 20/3, respectively.

5. Conclusion

In conclusion, we have successfully demonstrated a harmonically self-model-locked Nd:$Sr_3Y_2(BO_3)_4$ disordered crystal laser with subpicosecond pulse duration. It is theoretically and experimentally found that the single-pulse harmonic mode locking can be realized by adjusting the optical lengths of the laser cavity to be close to a commensurate ratio of the optical length of the Fabry-Perot cavity. At the optical cavity length L_{cav} of 27.19 mm and the separation d, which is the distance from the front mirror to the pump facet of the gain medium, of 4.08 mm, corresponding to the ratio L_{cav}/d of 20/3, the single-pulse mode locking with repetition rate of 110 GHz and pulse duration of 857 fs is obtained. At an incident pump power of 3.1 W, an output power of 162 mW is generated for the laser system.

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