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Femtosecond Pulses Generation From a Diode-Pumped Yb:$CaNb_2O_6$ Disordered Crystal Laser

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ABSTRACT We experimentally demonstrated a diode-pumped femtosecond Yb:$CaNb_2O_6$ disordered crystal laser. Pumping by a 978-nm fiber coupled laser diode and assisting by a semiconductor saturable absorber mirror, stable continuous-wave mode-locked laser pulses with a width of 170 fs at the central wavelength of about 1038 nm were obtained. The laser pulses had an average output power and a repetition rate of 135 mW and 80 MHz, respectively. To the best of our knowledge, this is the shortest laser pulses generated from Yb:$CaNb_2O_6$ disordered crystal lasers.

INDEX TERMS Yb:$CaNb_2O_6$ disordered crystal, SESAM, mode-locking, femtosecond laser, laser diode.

I. INTRODUCTION

In recent years, the compact, efficient and reliable all-solid-state ultrafast laser sources have attracted wide attentions for numerous applications in science and technology, such as ultrafast nonlinear spectroscopy, femtosecond optical coherent tomography, and superfine material processing. With the rapid development of highly efficient laser diodes, ultrafast lasers based on rare-earth doped materials operating in the near-infrared spectral region have been widely developed. Up to now, benefiting from mode-locking techniques (passively mode-locking assisted by semiconductor saturable absorber mirrors (SESAMs) [1] or Kerr-lens mode-locking [2]), there have been numerous studies on the generation of femtosecond pulses based on Nd^{3+}, Yb^{3+}, Tm^{3+}, Er^{3+}, etc doped materials, such as Nd:glass [3], Er:Yb:glass [4], Yb:glass [5], Yb:YAG [6]–[8], Tm:Lu_2O_3 [9], Yb:$CaGdAlO_4$ [10], Yb:KGW [11] and so on, including three different categories (glass, crystal, and ceramic).

As we know, broad emission spectral band and high thermal conductivity of these laser materials are important requirements to generate femtosecond laser pulses with high average power. Generally, the emission spectral band of glasses is much broader than crystals and ceramics. However, the thermal conductivity of glasses is much poorer than crystals and ceramics. Therefore, a new category gain material occupying these advantages is always pursued. Between glass and crystal, there exists a unique sort structure, the so-called disordered crystals, which possess the advantages of both crystals and glasses. Usually, their absorption and emission spectra were widened due to the inhomogeneous spectrum broadening and splitting effects, which make them a promising candidate of a laser gain medium for the generation of femtosecond pulses. Recently, femtosecond laser pulses were generated from a serials of disordered crystals, such as Nd,Y:CaF_2-103 fs [12], Nd,Y:SrF_2-97 fs [13], Nd,La:CaF_2-633 fs [14], Nd:$La_3Ga_5SiO_{14}$-381 fs [15], Nd:$Ca_3La_2(BO_3)_4$-79 fs [16], Tm:CLNGG-479 fs [17], Yb:$LuScO_3$-74 fs [18]. Also, the laser properties of another disordered crystal Yb:$CaNb_2O_6$ (Yb:CN) were also reported, and the CW laser operating at both single and double wavelengths was obtained [19], [20]. The Yb:CN disordered crystal possesses an emission spectrum bandwidth of 68 nm, which is larger than that of Yb:YAG and Yb-doped glasses, and provides the possibility of generating femtosecond laser pulses [19]. Besides, the relatively high thermal conductivity of 6.05 $Wm^{-1}K^{-1}$ for Yb:CN disordered crystal along c-axis supports the generation of high power laser [19]. In 2012, Li *et al.* firstly reported a diode-pumped passively mode-locked femtosecond Yb:CN disordered crystal laser, where laser pulses with a width of 251 fs and an average output power of 44 mW were generated [21].

In this work, we demonstrated a diode-pumped passively mode-locked Yb:CN disordered crystal femtosecond laser. In [21], two curved mirrors with radius of curvature (ROC) of 300 mm and 500 mm, respectively, were used to focus laser into crystal, and the laser beam size in the crystal was about 85 μm. Generally, the smaller ROC of curved mirrors introduces smaller focusing laser beam size and higher laser intensity. The higher laser intensity in the crystal enhances the self-phase modulation effect and the spectral width, which supports the generation of shorter laser pulses. Based on above considerations, in this experiment, we chose two curved mirrors with smaller ROCs to focus laser into crystal to strengthen the laser intensity in crystal for getting shorter laser pulses. In addition, we make the pump and laser match well in the crystal to obtain laser pulses with larger output power in our experiment. As a result, 170 fs laser pulses with an average output power of 135 mW have been generated. The central wavelength and repetition of laser pulses were at 1038 nm and 80 MHz, repetitively. To the best of our knowledge, this is the shortest pulses generated from a Yb:CN disordered crystal laser.

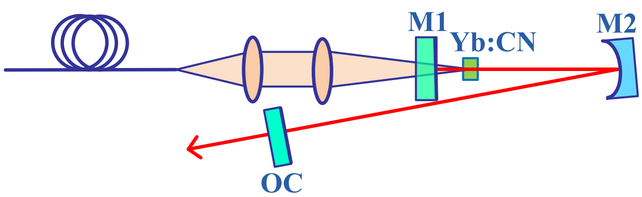

FIGURE 1. Experimental setups used to study the CW Yb:CN laser. M1: dichroic mirror; M2: concave mirror with ROC of 200 mm; OC: plane output coupler with transmissions of 0.6%, 1.5%, 5%, and 7.5%, respectively.

II. Experimental Setup

Fig. 1 shows the schematic of the CW Yb:CN laser. In our experiment, the Yb:CN disordered crystal was grown by the Czochralski method, with ytterbium concentration of 1.5 at.%, a dimension of 4×4×3 mm^3 and no anti-reflection coating. The Yb:CN disordered crystal can be efficiently pumped at a local absorption peak at 978 nm, and its important emission spectrum peak was around 1038 nm with a full width at half maximum (FWHM) of 14.5 nm, supporting the generation of sub-100 fs laser pulses [21]. Therefore, a fiber-coupled laser diode (Jenoptik, JOLD-7.5-BAFC-105) emitting at 978 nm with a core-diameter of 50 μm and a numerical aperture of 0.22 was used as a pump source. By using a series of lens with a magnification ratio of 1:1, the pump laser from the fiber output was focused into the Yb:CN disordered crystal. To effectively reduce the thermal load occurring inside the Yb:CN disordered crystal during laser action, the sample was wrapped with indium foil and then mounted in a water cooled copper block, which was maintained at about 14° C. The focusing pump laser was measured into the crystal with spot size of ~50 μm. The dichroic plane mirror (M1) was coated with antireflection at 980±10 nm and high reflection at 1020-1200 nm. The curved folding mirror with a radius of curvature (ROC) of 200 mm (M2) was coated for high reflection at 1000-1100 nm. The Yb:CN disordered crystal was placed between M1 and M2, and positioned close to M1. In the case of the CW laser experiment, the output couplers (OCs) had transmissions of 0.6%, 1.5%, 5% and 7.5% at 1040±50 nm. The end-pumped Yb:CN laser was optimized by adjusting the cavity length to yield maximum output power for a given pump level. The total cavity length was found to be 467 mm, corresponding to a nearly hemispherical configuration, which held for the entire pump power range.

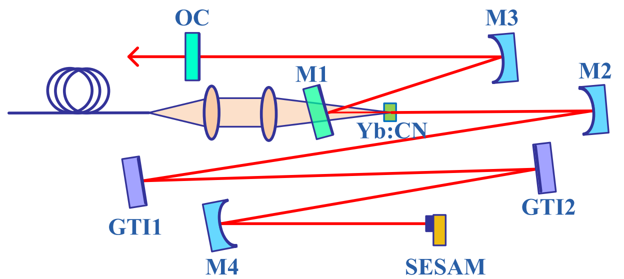

FIGURE 2. Experimental setup used to study the Yb:CN laser. M1: dichroic mirror; M2, M3, M4: concave mirrors (M2, M3 with ROC of 200 mm; M4 with ROC of 300 mm); GTI1, GTI2: −300 fs^2, and −100 fs^2; OC: plane output coupler with transmission T=1.5%; SESAM: semiconductor saturable absorber mirror.

The diode-pumped passively mode-locked Yb:CN laser setup used for the experimental investigations is schematically shown in Fig. 2. As we known, high pump power intensity is required for efficient laser operation, in particular when operating at a small spot size, like in femtosecond bulk lasers. Therefore, a coupling system with a magnification of 1:0.8 was used to focus the pump beam into the crystal. In this configuration, the diameter of pump laser beam was about 40 μm. An asymmetric, astigmatically compensated Z fold resonator was used, in which cavity the Yb:CN was positioned in the central folding. M1 was a plane dichroic-coated mirror for high transmission at 980±10 nm and high reflection (HR) at 1020-1200 nm, which folds one arm of the cavity to fit the short focus length (about 55 mm) of the coupling system. M2, M3, and M4 were concave mirrors with ROC of 200, 200, and 300 mm, respectively, HR-coated at 1000-1100 nm. M4 focused the laser beam on the SESAM, which terminated the resonator. A plane mirror with a transmission of 1.5% in the range of 1020-1200 nm was used as the output coupling. Two Gires–Tournois interferometers (GTI1 and GTI2) were inserted inside the cavity to introduce a negative group delay dispersion (GDD) of about −300 fs^2 at 1010-1080 nm and −100 fs^2 at 980-1130 nm, respectively, compensating the GDD introduced by the Yb:CN.

The dispersion of the Yb:CN was calculated to be about 810 fs^2. Furthermore, a SESAM designed to operate at the wavelength of 1040 nm with 0.4% modulation depth and saturation fluence of 120 μJ/cm^2 was used to initiate and stabilize the passive mode-locked regime. Its nonsaturable loss was specified to be 0.3%, and the relaxation time was less than 500 fs. Based on above design and the ABCD matrix formalism, the laser beam diameters in the crystal and on the SESAM were calculated to be near 46 μm and 90 μm, respectively. The laser beam matched well with the pump laser beam in the crystal. The total cavity length was about 1.875 m, corresponding to a repetition rate of about 80 MHz.

III. Results and Discussion

First, we tested the absorption efficiency of the Yb:CN disordered crystal for the pump laser at room temperature. Fig. 3(a) shows the absorbed pump power as a function of the incident pump power for the Yb:CN disordered crystal under nonlasing operation. The absorption coefficient was measured to be about 17.5%. The maximum absorbed pump power was about 1.23 W, limited by the maximum incident pump power of 7 W. The low ytterbium doping concentration and uncoated antireflective film of the Yb:CN disordered crystal result in a relatively low absorption efficiency. Then, we tested the continuous-wave (CW) laser performance of the Yb:CN disordered crystal with a three-mirror folded cavity shown as Fig. 1. The CW laser characteristics of Yb:CN disordered crystal under different OCs are given in Fig. 3(b). As shown in this diagram, with different transmissions output couplers, the average output power and the absorbed pump power nearly were a linear function. The laser pump threshold power were measured to be about 0.140 W, 0.140 W, 0.263 W, and 0.333 W for OCs with different transmissions of 0.6%, 1.5%, 5%, and 7.5%, respectively. Under the different OCs, the maximum average output power were about 416 mW, 538 mW, 545 mW, and 430 mW with the corresponding slope efficiencies of 46.5%, 64.3%, 75.2%, 63.0% and the corresponding light-light conversion efficiencies of 36.6%, 47.4%, 48.0%, 37.9%, respectively. The emission laser wavelength was measured to be always around 1038 nm for all OCs. In our experiment, no signs of roll-over were observed, hence, further power scaling is expected to be easily possible with higher pumping powers and larger pump spot diameters.

Next, the mode-locking performance of Yb:CN disordered crystal was investigated by using a Z cavity shown as Fig. 2. In the mode-locked experiment, we firstly adjusted the cavity alignment to generate CW laser. The laser pump threshold power of was about 0.30 W. Along with the increase of the absorbed pump power up to about 0.75 W, the stable Q-switched mode locking (QSML) laser was exhibited firstly. The low power density incavity resulted in the generation of QSML during the build process of mode-locking [22]. Therefore, the pump power was continued to increase. When the pump power was exceeded to 0.98 W, the stable continuous mode-locking (CML) operation was self-starting.

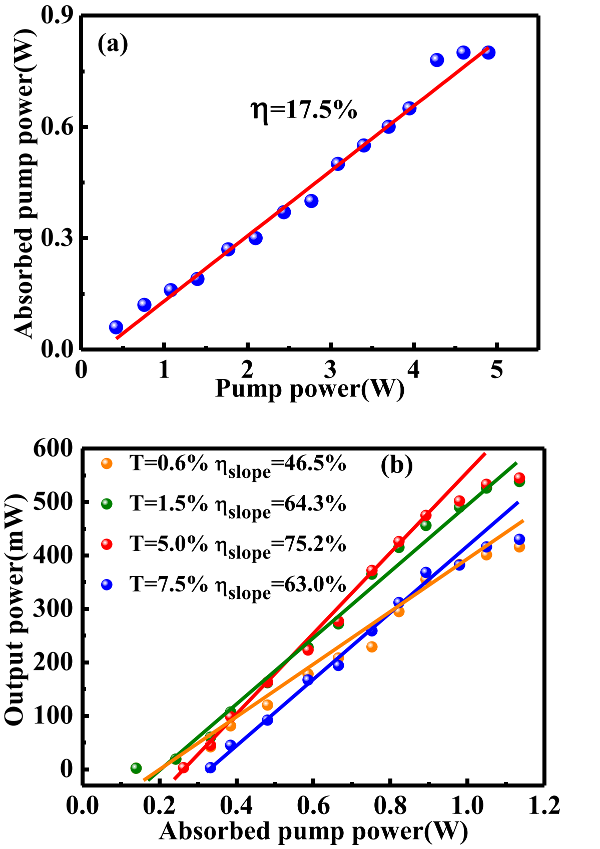

FIGURE 3. (a) The absorbed pump power as a function of the incident pump power for the Yb:CN crystal. (b) The CW laser characteristics of the Yb:CN disordered crystal under different OCs.

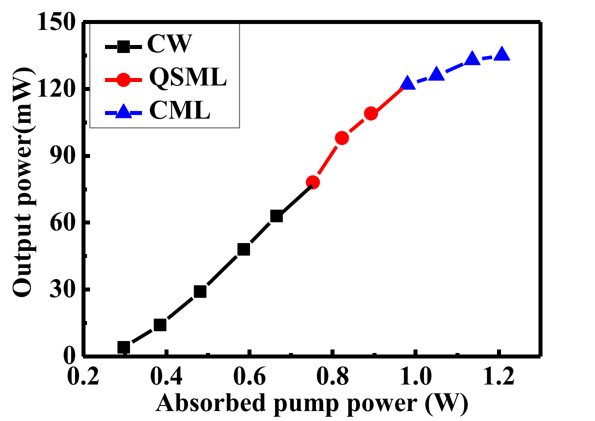

FIGURE 4. Average output power versus absorbed pump power of the Yb:CN laser under CW, QSML, and CML operations.

Under CW, QSML, and CML operations, the laser always worked with a single-mode output. Fig. 4 shows the dependence of the average output power on the absorbed pump power under CW, QSML, and CML operations. The maximum output power was 135 mW under the absorbed pump power of 1.20 W, corresponding to a light-light conversion efficiency of 11.3%. The QSML and CML pulse trains were detected by a fast photodiode (THORLABS DETA10A/M)

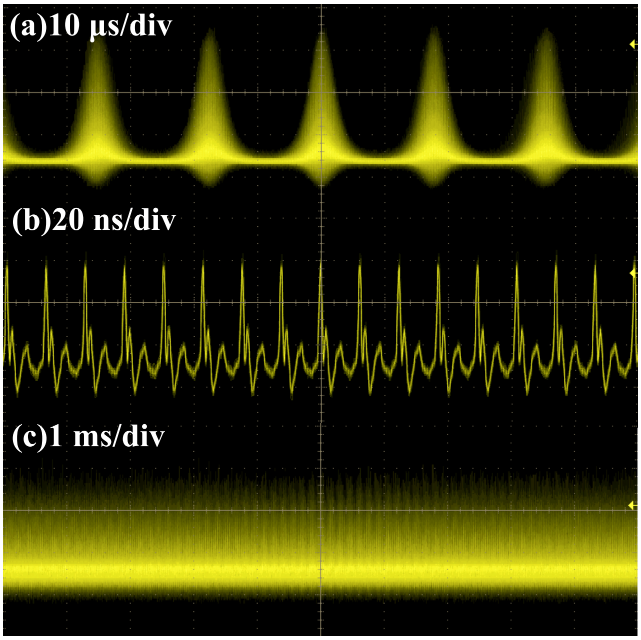

FIGURE 5. The QSML and CML pulse trains at (a) 10 μs/div, (b) 20 ns/div, and (c) 1 ms/div.

with a rising time of 1 ns and recorded with a digital phosphor oscilloscope (Tektronix DPO 3052) with a 500 MHz bandwidth. Fig. 5(a) shows the QSML pulse train at 10 μs/div, and Figs. 5(b) and (c) show the CML pulse trains at 20 ns/div and 1 ms/div, respectively. The repetition frequency of mode-locked laser pulses was about 80 MHz.

As we know, the GDD in the oscillator is an important issue to obtain very short pulses. In our experiment, three GTIs providing a negative dispersion of −100, −300, and −800 fs^2, respectively, were used in combination. When GTIs with a GDD of −100 and −300 fs^2 were used, the shortest pulses were generated. Fig. 6 shows the autocorrelation trace and spectrum of the mode-locked pulses. The pulse duration was measured by a commercial autocorrelator (APE, Pulse Check). Assuming a sech^2 pulse shape, the pulse duration is 170 fs. The corresponding pulse spectrum had a full width at half maximum (FWHM) bandwidth of 7.5 nm recorded by the spectrometer (Ocean Optics, USB4000). The time-bandwidth product of the mode-locked pulses was calculated to be about 0.355, which was close to Fourier transform limit value for the sech^2-shaped pulses. The beam profiles of CML laser pulses were measured in the near field by a commercial beam profiler (BeamAnalyzer USB), which as shown in Fig. 6(c) and (d). From Fig. 6(c) and (d), we can see that the CML laser pulses run in the fundamental mode with near diffraction-limited beam quality.

It should be pointed out that the total GDD in cavity is an important issue for the mode-locking. Generally, the total GDD in cavity was mainly introduced by Yb:CN crystal and GTI mirrors. For the case of the shortest pulse generation, the net GDD in the cavity was about 410 fs^2. In theory,

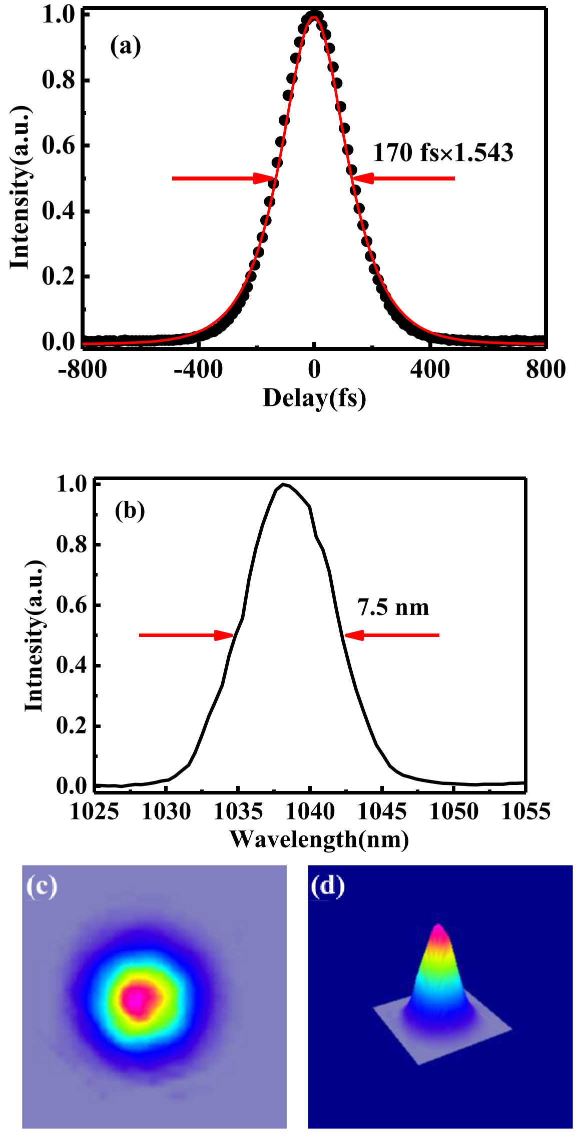

FIGURE 6. (a) Autocorrelation trace of the CML laser pulses (dotted-curve) with a sech^2 fitting (solid curve). (b) Spectrum of the CML laser pulses. (c) and (d) Beam profiles of the CML laser pulses.

GTI mirror with −800 fs^2 used to compensate for crystal dispersion would introduce about 10fs^2 cavity GDD, which supports shorter laser pulses. However, shorter laser pulses were not observed in our experiment. We think the reason may be that the GTI mirror with −800 fs^2 is around 1045 nm, which could not provide enough negative GDD at 1038 nm. Additionally, in order to obtain even shorter laser pulses, we also tried a pair of SF6 prism to compensate for the positive GDD of crystal. The laser pulses with a similar duration were generated, but the laser power was only several tens of milliwatts due to the introducing loss of the prisms.

IV. Conclusion

In conclusion, both CW and ML operations of a diode-pumped Yb:CN disordered crystal laser have been demonstrated. The CW laser characteristics under OCs with different transmissions were studied, and the highest slope efficiency was up to 75.2%. Under ML operation, laser pulses with pulse duration of 170 fs, average output power of 135 mW and repetition rate of 80 MHz at the centre wavelength of 1038 nm were generated. To the best of our knowledge, this is the shortest laser pulses from Yb:CN lasers. Through further optimizing the intracavity dispersion and by means of kerr-lens mode-locking, we believe that sub-100 fs mode-locked pulses could be possible.

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