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Diode-pumped femtosecond mode-locked Nd, Y-codoped CaF_2 laser

Jiangfeng Zhu[1], Lijuan Zhang[1], Ziye Gao[1], Junli Wang[1], Zhaohua Wang[2], Liangbi Su[3], Lihe Zheng[3], Jingya Wang[3], Jun Xu[3] and Zhiyi Wei[2]

[1] School of Physics and Optoelectronic Engineering, Xidian University, Xi'an 710071, People's Republic of China
[2] Beijing National Laboratory for Condensed Matter Physics, Institute of Physics, Chinese Academy of Sciences, Beijing 100190, People's Republic of China
[3] Key Laboratory of Transparent and Opto-Functional Advanced Inorganic Materials, Shanghai Institute of Ceramics, Chinese Academy of Sciences, Shanghai 201800, People's Republic of China

E-mail: zywei@iphy.ac.cn

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Abstract

A passively mode-locked femtosecond laser based on an Nd, Y-codoped CaF_2 disordered crystal was demonstrated. The Y^{3+}-codoping in $Nd:CaF_2$ markedly suppressed the quenching effect and improved the fluorescence quantum efficiency and emission spectra. With a fiber-coupled laser diode as the pump source, the continuous wave tuning range covering from 1042 to 1076 nm was realized, while the mode-locked operation generated 264 fs pulses with an average output power of 180 mW at a repetition rate of 85 MHz. The experimental results show that the Nd, Y-codoped CaF_2 disordered crystal has potential in a new generation diode-pumped high repetition rate chirped pulse amplifier.

Keywords: solid-state lasers, mode-locked lasers, diode-pump, ultrafast lasers

(Some figures may appear in colour only in the online journal)

1. Introduction

With the rapid development of chirped pulse amplification (CPA) technology, it is very desirable to generate a high energy ultrahigh peak power petawatt-level laser at a relatively high repetition rate for the study of high field light–matter interactions. However, most of the petawatt CPA laser facilities in the world, either Ti : sapphire-based or Nd : glass-based, are operated in single-shot [1–3] or very low repetition rate [4]. A repetitive petawatt CPA laser system relies on large-size and good thermal conductivity laser gain media. Calcium fluoride-based laser crystals have long been recognized as important laser gain media for high energy lasers since they have high thermal conductivity (9.7 W mK^{-1} for undoped CaF_2) and low nonlinear refractive index (n_2 = 0.43 × 10^{-13} esu) [5]. Meanwhile, large single crystals can be grown with high optical quality. In recent years, extensive research on femtosecond mode-locking and terawatt CPA lasers based on Yb^{3+}-doped CaF_2 crystal has been reported [6–11], which shows great potential for high energy petawatt laser systems. Nd^{3+}-doped CaF_2 crystal is another promising laser gain medium for its four-level nature. However, there is a strong quenching effect in $Nd:CaF_2$ single crystal. When the doping concentration of Nd^{3+} is up to 0.05%, Nd^{3+} clusters come into $Nd:CaF_2$ crystal, forming fluorescence quenching centers. In addition, $Nd:CaF_2$ has a relatively low emission cross section of less than 2.0 × 10^{-20} cm^2 at 1.06 μm, meaning a high saturation energy density and low energy extracting efficiency when used as an amplifying medium. As a matter of fact, $Nd:CaF^2$ as a laser system has been abandoned for a long time. Recently, Y^{3+} and Nd^{3+} codoping in CaF_2 to form Nd, $Y:CaF_2$ disordered crystal was extensively studied to solve the problems above [12, 13]. Co-doping with Y^{3+} buffer ions in $Nd:CaF_2$ can vary the local coordination structure of Nd^{3+} ions and break the Nd^{3+} clusters, which markedly suppressed the quenching effect and improved the fluorescence quantum efficiency. By varying the Y^{3+} concentration, the emission spectra of Nd, $Y:CaF_2$ crystal can be more concentrated and smooth, which could support short femtosecond pulse duration similar to the $Yb:CaF_2$ lasers. Su *et al* studied

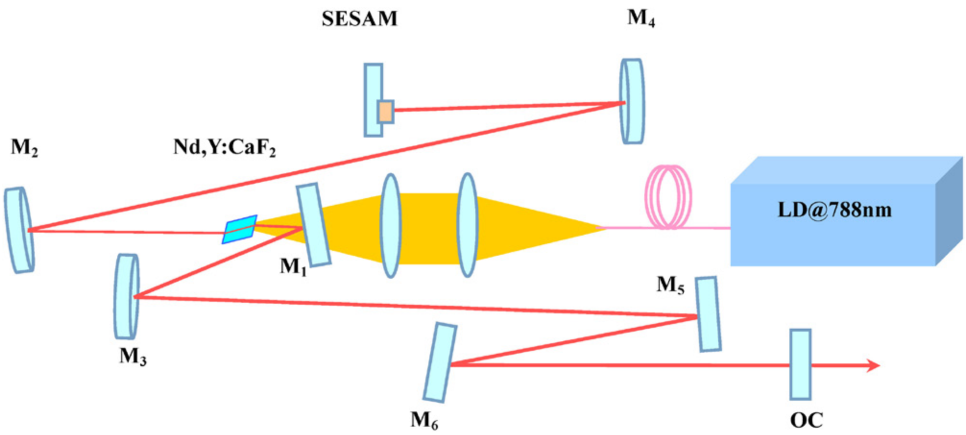

Figure 1. Schematic of the experimental setup. LD: laser diode; M_1: plane dichroic mirror; M_2 and M_3: concave mirrors with ROC of 200 mm; M_4: concave mirror with ROC of 300 mm; HR: high reflective mirror; M_5 and M_6: GTI mirrors; SESAM: semiconductor saturable absorber mirror; OC: output coupler.

the emission bandwidth, cross section and lifetime characteristics of 2.0% Nd : CaF_2, 2 : 0% Nd; 2 : 0% Y : CaF_2 and 2 : 0% Nd; 6 : 0% Y : CaF_2 [14]. They got a preliminary continuous wave (CW) laser operation with a 2 : 0% Nd; 2 : 0% Y : CaF_2 crystal resulting in 25 mW output power. Most recently, Qin *et al* realized a diode-pumped femtosecond mode-locked Nd, Y-codoped CaF_2 laser generating a pulse duration as short as 103 fs and an average output power of 89 mW [15]. In order to get such short pulses, they inserted a knife edge into the cavity to maintain a fundamental mode while the output power decreased significantly.

In this letter, we report on a diode-pumped passively mode-locked femtosecond Nd, Y : CaF_2 laser with a maximum output power of 180 mW. A fiber-coupled diode laser emitting at 788 nm was used as the pump source. Under the pump power of 5.2 W, the maximum output power of the CW laser was as high as 410 mW. Next, by using a pair of Gires–Tournois interferometer (GTI) mirrors to compensate for the intracavity dispersion and a semiconductor saturable absorber mirror (SESAM) for passive mode locking, a stable femtosecond mode locking was achieved with an output power of 180 mW and a pulse duration of 264 fs. We believe, to the best of our knowledge, both the CW and the mode-locked output power, are the highest ever reported from an Nd,Y-codoped fluoride crystal laser.

2. Experimental layout

The experimental setup used for the generation of CW and a mode-locked femtosecond laser with the Nd, Y : CaF_2 crystal was presented in figure 1. The pump laser (GKD-30FMS, Beijing GK Laser Technology Co. Ltd) was a high-brightness fiber-coupled laser diode (LD) with a 200 μm fiber core diameter and a numerical aperture of 0.22. The output wavelength of the LD could be varied from 786 to 790 nm by adjusting its working temperature. For matching the absorption peak of the Nd, Y : CaF_2 crystal, the LD temperature was adjusted to 25 °C. In this case, the emitting wavelength was at 788 nm with 4 nm spectral width. We did not try to move the wavelength to 790 nm by increasing the LD temperature for fear of damaging the power supply. The pump beam from the fiber was collimated and focused into the active crystal with a refocusing lens set with a magnification of 1 : 0.8. The calculated beam waist diameter in the crystal was about 160 μm. The Nd, Y : CaF_2 crystal used in our experiment is optimized with 0.5 at.% Nd-doping and 10 at.% Y-doping, which exhibited two absorption peaks at 790 and 797 nm and a fluorescence bandwidth of larger than 20 nm around 1054 nm. These features guarantee highly efficient commercial LD pumping and sub-100 fs ultrashort pulse generation. The Brewster angle-cut crystal had an optical pass length of 6.0 mm and 3 × 3 mm^2 cross section. The crystal was wrapped with indium foil and placed in contact with a water-cooled copper heat sink mount at the set temperature of 10 °C. A modified confocal folding cavity was designed to realize highly efficient pump absorption and femtosecond mode-locking operation. The folding section was formed by three mirrors (M_1–M_3). The input mirror M_1 was a plane dichroic mirror coated with high transmission from 800 to 1000 nm and high reflection from 1020 to 1200 nm. M_2 and M_3 were concave mirrors with a radius of curvature (ROC) of 200 mm. In order to initiate passive mode-locking, the laser beam was focused on a SESAM by a concave mirror with ROC of 300 mm. The SESAM was designed with a modulation depth of 0.7%, a non-saturable loss of ~0.4% measured at 1064 nm and a saturation fluence of 90 μJ cm^{-2}. The recovery time was about 500 fs. Two GTI mirrors (M_5 and M_6) were used for dispersion compensation in the resonator. In the experiment, three output couplers (OCs) with transmission of 0.8, 1.6 and 2.5%, respectively, in the range of 1020–1200 nm were used to investigate the output characteristics.

3. Results and discussion

CW performance of the Nd, Y : CaF_2 laser was tested by replacing the SESAM with a plane high reflection mirror and without two GTI mirrors. Under the maximum pump power of 5.2 W, the CW output power with three different OCs was shown in figure 2(*a*). The single pass absorption of the pump power for the 6 mm crystal is about 50%. A maximum output power of 410 mW was achieved with a 2.5% OC, corresponding to a slope efficiency of 9.56%. By inserting a SF6

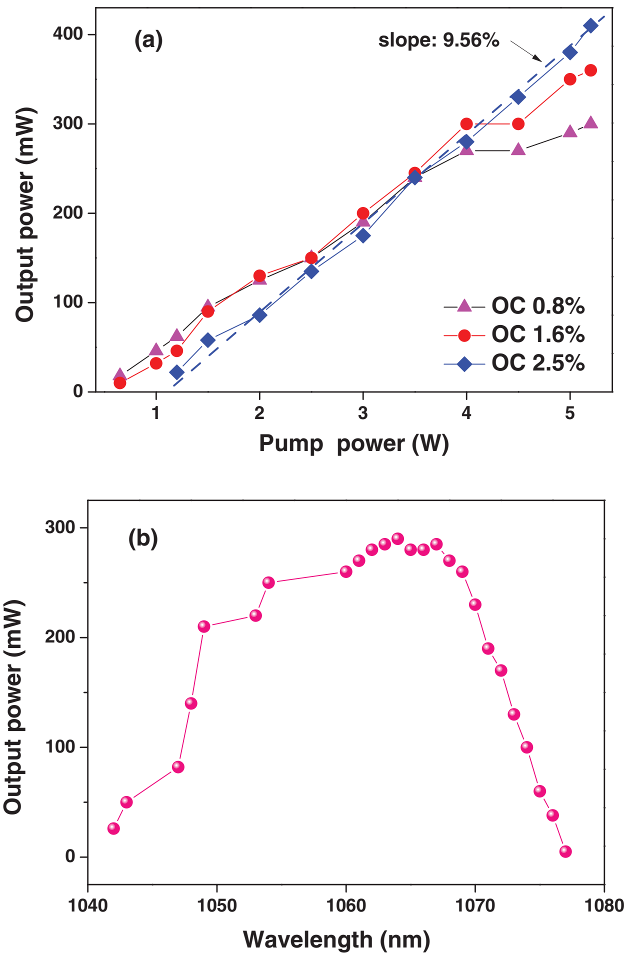

Figure 2. (*a*) CW output power versus the pump power for three OCs of 0.8, 1.6 and 2.5% transmission, respectively. (*b*) Wavelength tuning curve with an SF6 prism and a 2.5% OC.

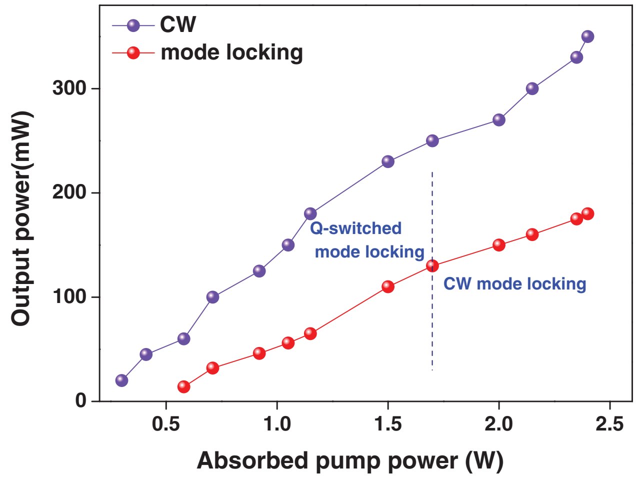

Figure 3. CW and passive mode-locked output power versus the absorbed pump power with a 0.8% OC.

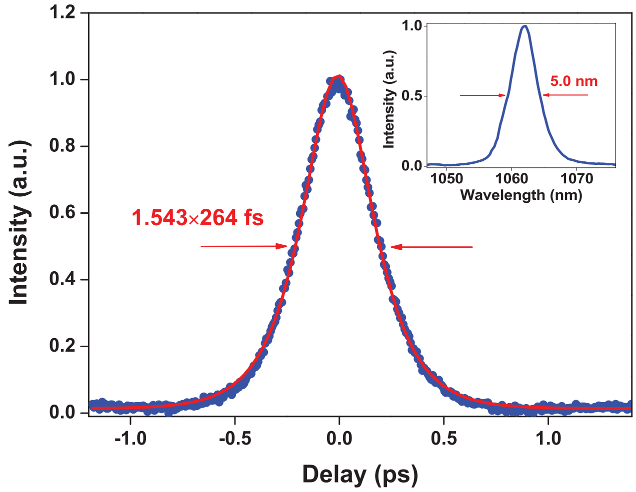

Figure 4. Measured intensity autocorrelation trace of the mode-locked pulses (blue dotted) with a sech2 fitting (red solid). Inset shows the corresponding spectrum.

prism into the other arm, we got the CW wavelength tuning range extended from 1042 to 1076 nm for the 2.5% OC and the pump power of 4.5 W, as shown in figure 2(*b*). The smooth and broad spectral tuning range further proved the possibility to generate sub-100 fs pulses by mode-locking.

For femtosecond operation, the 0.8% OC was used for short pulse generation. Two GTI mirrors instead of the prism pair were employed for dispersion compensation in order to minimize the intracavity loss. A total group delay dispersion (GDD) of –1450 fs^2 was introduced to balance the positive dispersion by the laser crystal and the cavity mirrors. By carefully aligning the cavity, we obtained stable CW mode-locking when the absorbed pump power exceeded 1.7 W. The mode-locked output power depending on the absorbed pump power was depicted in figure 3. For comparison, the CW output power was also shown by just replacing the SESAM with a plane high reflection mirror. The highest output power for stable mode-locking reached 180 mW for an absorbed pump power of 2.5 W. Higher pump power would cause multi-pulse instability and damage to the SESAM, so we kept the absorbed pump power of 2.5 W for pulse measurement. The mode-locked laser spectrum and the pulse duration are shown in figure 4. The laser had a central wavelength at 1061 nm with a full width at half maximum (FWHM) bandwidth of 5.0 nm.

The pulse duration was measured by a commercial intensity autocorrelator (APE: pulseCheck USB). The intensity-autocorrelation trace suggested a pulse duration of 264 fs assuming a sech^2-pusle shape. The corresponding time-bandwidth-product was 0.35 which was close to the Fourier-transform limit of 0.315 for the sech^2 pulses. The mode-locked pulse train was monitored by a 1 GHz fast diode and a 500 MHz bandwidth oscilloscope (Tektronix, DPO3052). The pulse train had a repetition rate of 85 MHz, corresponding to the cavity length of 1.76 m. The smooth pulse train indicated stable CW mode-locking without Q-switching. Long time mode-locking was tested for several hours with the laser uncovered. The output power had a rms fluctuation of about 5%. We believe if the laser was sealed in a box, the output power would be more stable and the mode-locking would last much longer.

4. Conclusion

In conclusion, we have demonstrated an efficient diode-pumped femtosecond passively mode-locked Nd, Y-codoped

CaF2 laser. CW mode-locked output power as high as 180 mW was achieved for an absorbed pump power of 2.5 W. The laser centered at 1061 nm had a pulse duration of 264 fs. The broad tunability of the Nd, Y-codoped CaF2 crystal makes it superior for generating ultrashort pulses down to sub-100 fs by means of Kerr-lens mode-locking technique. The high power mode-locking performance in this experiment suggests Nd, Y : CaF2 has bright potential in a high-energy repetitive CPA system.

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