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Passively Mode-Locked Femtosecond Laser with Disordered Crystal Nd:CGA as Gain Medium *

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We present a laser-diode-pumped passively mode-locked femtosecond disordered crystal laser by using Nd:$CaGdAlO_4$ (Nd:CGA) as the gain medium. With a pair of SF6 prisms to control the dispersion compensation, laser pulses as short as 850 fs at 1079 nm are obtained with a repetition rate of 124.6 MHz. The measured threshold pump power is 1.45 W. A maximum average output power of 122 mW is obtained under the pump power of 5.9 W. These results show that Nd:CGA could be a promising laser medium for generating femtosecond ultrashort pulse at about 1 μm.

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Ultrashort pulses around 1 μm have widespread applications in fields such as spectroscopy, fiber communication and medicine. As is well known, laser material plays an important role in ultrashort lasers due to the fact that their properties such as spectral bandwidth and thermal conductivity influence the performances of the ultrashort laser directly. Recently, Nd-doped disordered crystals such as Nd:CLNGG,[1] Nd:SLG,[2] Nd, Y:CaF_2,[3] Nd:LGS[4] and Nd, Y:SrF_2[5] have drawn wide attention since they possess the advantages of both Nd-doped glasses and ordered crystals, that is, broad emission spectra and good thermal properties. Their broad emission spectra make subpicosecond pulse width feasible, while good thermal properties facilitate heat diffusivity and stabilization of the ultrashort lasers based on them. Unfortunately, not all Nd-doped disordered crystals can be used to generate femtosecond pulses, even though their emission spectra bandwidths are theoretically broad enough to support femtosecond laser operation.[6,7]

Nd:$CaGdAlO_4$ (Nd:CGA) possesses the disordered crystal structure. It can be grown with high Nd^{3+} concentration.[8] Its emission spectral bandwidth near 1080 nm is 8 nm[8] for 2 at.% Nd^{3+} concentration and 12 nm[9] for 1 at.% Nd^{3+} concentration. In addition to the broad emission spectrum, it also has broad absorption spectrum. Its absorption spectral bandwidth near 806.5 nm is 3.3 nm,[8] which is beneficial for efficient diode pumping. Its laser operation wavelength around 1 μm is at 1079 nm,[9] which results in a green output at about 540 nm, which is closer to the maximum visibility at 555 nm in comparison to the frequency doubled 1.064 μm material.

However, not many reports of Nd:CGA were published. In 1997, the spectroscopic characteristics and cw laser performance of Nd:CGA were first reported.[8] Recently, with a 2 W pump source, our research group realized picosecond passively mode-locking operation without dispersion compensation as well as cw tuning operation of the Nd:CGA laser.[9] In this Letter, based on previous works, taking a pair of SF6 prisms as dispersion compensation elements, we report a diode-pumped femtosecond mode-locked Nd:CGA laser for the first time to our knowledge. The 122 mW average output power with 850 fs pulse width and the repetition rate of 124.6 MHz at 1079 nm are obtained.

Figure 1 presents the layout of the mode-locked Nd:CGA laser, consisting of a fiber-coupled cw laser diode with a fiber core diameter of 100 μm and a central wavelength of 806 nm, a 1:1 coupling system, a c-

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cut Nd:CGA crystal with dimensions of $3\times3\times6\,\mathrm{mm}^3$ and Nd^{3+} concentration of 1 at.%, four cavity mirrors (M1, M2, M3 and M4), a semiconductor saturable absorber mirror (SESAM) and a pair of SF6 prisms. In the experiment, the Nd:CGA crystal was end-pumped by a laser diode through a 1:1 coupling system. The pump laser spot radius in the Nd:CGA crystal was about 50 µm. A piece of commercial SESAM was employed to start and sustain the mode-locking, which was specified for a $90\,\mathrm{\mu J/cm^2}$ saturation fluence, 0.4% modulation depth and a less than 500 fs recovery time at 1.06 µm. To achieve an optimum mode matching between the pump and the oscillating lasers in the Nd:CGA crystal and a suitable spot size on the SESAM, an X-type folded resonator was employed in the experiment. The length of the whole X-type cavity is 1.2 m. In Fig. 1, L_1 is the distance between M1 and the left side of Nd:CGA crystal; L_2 is the distance from right side of Nd:CGA crystal to M2; L_3 is the distance between M2 and M3; L_4 is the distance between M1 and M4, and L_5 is the distance between M3 and SESAM. Specifically, L_1, L_2, L_3, L_4 and L_5 are 39, 34, 298, 776 and 43 mm, respectively. According to the ABCD propagation matrix method, the laser mode sizes in the Nd:CGA crystal and on the SESAM are about 100 µm and 70 µm in diameter, respectively. Plane-concave M1 in the cavity serves as an input coupler. M2 and M3 are both folding mirrors. The curvature radii of M1, M2 and M3 are 75 mm, 75 mm and 100 mm, respectively. Plane mirror M4 with low-transmission ($T = 0.8\%$) around laser wavelength was used as the output coupler to reduce the critical pulse energy required to stabilize cw mode-locking.[10] To keep efficient and stable laser operation, the front and rear surfaces of the Nd:CGA crystal were both high transmission (HT) coated at pump and laser wavelengths. In addition, the Nd:CGA crystal was wrapped with thin indium foil and mounted within a copper heat sink which was cooled by 11℃ water. M1 was HT coated at pump wavelength and high reflection (HR) coated around laser wavelength. Both M2 and M3 were HR coated around laser wavelength. When constructing the cavity, we set the fold angle as small as possible to minimize the influence of astigmatism. To compensate for the intra-cavity dispersion, a pair of SF6 prisms were employed. In the experiment, we can control the negative GDD induced by the prism pair by adjusting the insertion of prisms and the distance between the two prisms.

Compared with the ps mode-locked Nd:CGA laser we reported in Ref. [9], the Nd:CGA laser in Fig. 1 was improved in two aspects to guarantee fs laser operation: (1) we adopted dispersion compensation with prism pair which was absent in the ps mode-locked Nd:CGA laser. (2) Since the fiber core diameter used in the fs Nd:CGA laser was different from that used in the ps Nd:CGA laser, we re-designed the cavity parameters to guarantee a good mode matching and a suitable spot size on SESAM.

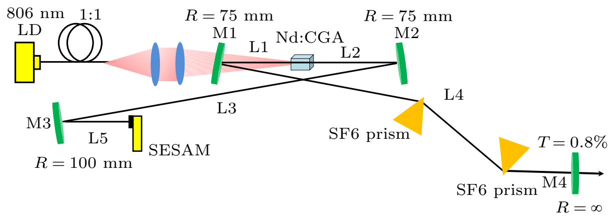

Fig. 1. Experimental setup of the mode-locked Nd:CGA laser.

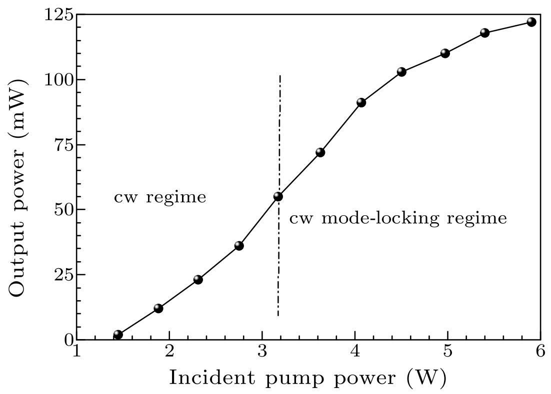

Fig. 2. The dependence of output power on the incident pump power in the Nd:CGA laser.

With careful optimization of the cavity alignment especially the position of the SESAM and the pair of SF6 prisms, perfect cw femtosecond mode-locking operation was achieved in the Nd:CGA laser. The distance between the SF6 prisms was finally set at 49 cm, and the amount of GDD introduced by the prism pair was about $-2550\,\mathrm{fs}^2$. The dependence of output power on the incident pump power in the Nd:CGA laser is depicted in Fig. 2. It can be seen that the threshold pump power was about 1.45 W. With the increase of the pump power while below 3.2 W, the laser was operating in a cw regime. Once the incident pump power increases to 3.2 W, the laser would switch to stable self-starting cw mode-locking operation. In the experiment, we observed that there is no Q-switched mode-locking operation between cw regime and cw mode-locking regime, just like that occurring in Refs. [9,11]. Under stable mode-locking state, the maximum average output power of 122 mW was obtained at an incident pump power of 5.9 W, corresponding to the optical–optical conversion efficiency of 2%. To avoid destruction of the Nd:CGA, in the experiment, we did not increase the pump power higher than 5.9 W.

Figures 3(a) and 3(b) show the temporal traces of the mode-locked pulse train measured in different time scales 20 ns/div and 1 ms/div, respectively. The pulse repetition rate was 124.6 MHz, just corresponding to the cavity round trip time. Once the mode-locking started, its stable operation could be sustained for several hours. In the experiment, the rf of the mode-locked laser pulses was measured with an rf spectrum analyzer. The results are shown in Fig. 4 on a span of 2 MHz with a resolution bandwidth (RBW) of 1 kHz. The fundamental beat note was 124.6 MHz with a high extinction down to 60 dB. The inset of Fig. 4 exhibits the high harmonics of the fundamental beat note on a span of 1.5 GHz with 100 kHz RBW. It is obviously seen from the rf spectrum that the cw mode-locking was under a very stable condition and no spurious modulations were observed.

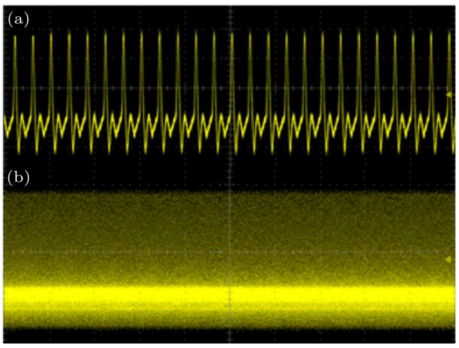

Fig. 3. Temporal traces of the cw mode-locked pulse train measured in different time scales (a) 20 ns/div and (b) 1 ms/div.

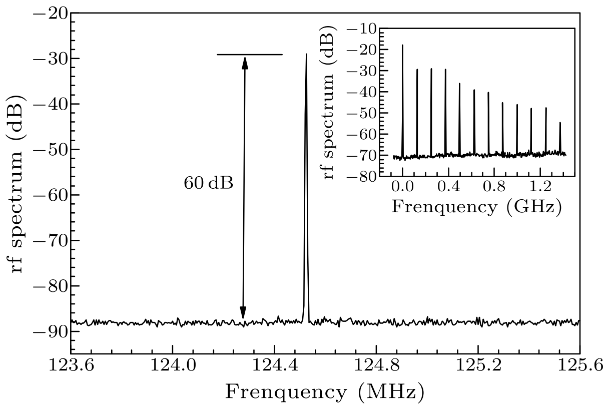

Fig. 4. The rf spectrum on a span of 2 kHz with an RBW of 1 kHz. Inset: rf spectrum on a span of 1.5 GHz with an RBW of 100 kHz.

The intensity autocorrelation trace displayed in Fig. 5 was measured with a commercial autocorrelator. From Fig. 5, we can see that the full width at half maximum (FWHM) of the clean autocorrelation signal was about 1.3 ps. Assuming a sech^2-shaped pulse profile, the pulse duration of the mode-locked pulses was estimated to be 850 fs. The inset of Fig. 5 is the corresponding optical spectrum measured with an optical spectrum analyzer when the Nd:CGA was under stable cw mode-locking operation. The FWHM of the spectrum was 1.8 nm at a central wavelength of 1079 nm. Therefore, the time-bandwidth product (TBP) of the mode-locked laser pulses was about 0.39, closer to the Fourier transform limit value (0.315) of a sech^2-shaped pulse.

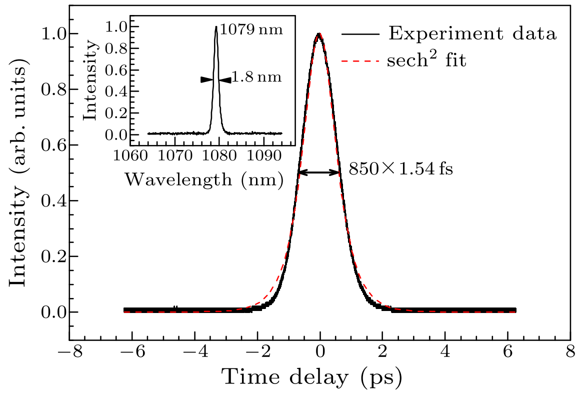

Fig. 5. Intensity autocorrelation trace of the mode-locked Nd:CGA laser. Inset: spectrum of the output laser centered at 1079 nm with a spectrum FWHM of 1.8 nm.

In our experiment, although the maximum mode-locking output power and optical–optical conversion efficiency were higher than the corresponding results obtained in some femtosecond disordered crystal lasers,[4,12,13] there was still plenty of room for improvement. For example, neither the SF6 prism pair nor the SESAM used in our experiment were specially designed for 1079 nm wavelength, which increased the cavity loss and to some extent decreased the output power as well as the optical–optical conversion efficiency. To obtain higher output power and higher efficiency, a more appropriate SESAM or prism pair will be used in future works.

In conclusion, we have successfully realized the operation of a diode-pumped femtosecond passively mode-locked Nd:CGA laser with SESAM as the mode-locker for the first time. The 850 fs pulses with repetition rate of 124.6 MHz were obtained. The pump power threshold was 1.45 W. A maximum average output power of 122 mW was obtained under the pump power of 5.9 W. It is believed that Nd:CGA is a promising gain medium for generating femtosecond ultrashort pulse at about 1 μm.

References

[1] Xie G Q, Tang D Y, Tan W D, Luo H, Zhang H J, Yu H H and Wang J Y 2009 *Opt. Lett.* **34** 103
[2] Agnesi A, Pirzio F, Tartara L, Ugolotti E, Zhang H, Wang J, Yu H and Petrov V 2013 *Laser Phys. Lett.* **10** 105815
[3] Qin Z P, Xie G Q, Ma J, Ge W Y, Yuan P, Qian L J, Su L B, Jiang D P, Ma F K, Zhang Q, Cao Y X and Xu J 2014 *Opt. Lett.* **39** 1737
[4] Liu J X, Wang Z H, He K N, Wei L, Zhang Z G, Wei Z Y, Yu H H, Zhang H J and Wang J Y 2014 *Opt. Express* **22** 26933
[5] Zhu J F, Wei L, Tian W L, Liu J X, Wang Z H, Su L B,

Xu J and Wei Z Y 2016 *Laser Phys. Lett.* **13** 055804
[6] Cong Z H, Tang D Y, Tan W D, Zhang J, Luo D W, Xu C W, Xu X D, Li D Z, Xu J, Zhang X Y and Wang Q P 2011 *Opt. Commun.* **284** 1967
[7] Xie G Q, Qian L J, Xu X D, Cheng Y, Zhao Z W, Tang D Y, Zhang J, Tan W D and Xu J 2010 *Laser Phys.* **20** 1331
[8] Lagatskii A A, Kuleshov N V, Shcherbitskii V G, Kleptsyn V F, Mikhailov V P, Ostroumov V G and Huber G 1997 *Quantum Electron.* **27** 15
[9] He K N, Liu J X, Wei L, Xu X D, Wang Z H, Tian W L, Zhang Z H, Xu J, Di J Q, Xia C T and Wei Z Y 2016 *Chin. Phys. Lett.* **33** 014203
[10] Hönninger C, Paschotta R, Morier-Genoud F, Moser M and Keller U 1999 *J. Opt. Soc. Am.* B **16** 46
[11] Schlatter A, Krainer L, Golling M and Paschotta R 2005 *Opt. Lett.* **30** 44
[12] Wang Q, Wei Z Y, Liu J X, Wang Z H, Zhang Z G, Zhang H J and Wang J Y 2013 *The 9th Conference on Lasers and Electro-Optics Pacific Rim* (Kyoto Japan, 30 June–5 July)
[13] Xie G Q, Qian L J, Yuan P, Tang D Y, Tan W D, Yu H H, Zhang H J and Wang J Y 2010 *Laser Phys. Lett.* **7** 483