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Generation of sub-100 fs pulses from mode-locked Nd,Y:SrF_2 laser with enhancing SPM

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Abstract

A mode-locked laser using Nd,Y:SrF_2 crystal as the gain medium is presented in this letter. By special design of the cavity for enhancing the self-phase modulation effect, femtosecond mode-locking with 97 fs pulse duration and 13.2 nm spectral width centered at 1061 nm is obtained at a repetition rate of 96 MHz. The average output power is 102 mW under 925 mW pump power, corresponding to the optical-to-optical efficiency of 11%. To the best of our knowledge, these are the first sub-100 fs pulses generated from a mode-locked Nd doped crystal laser.

Keywords: Nd,Y:SrF_2 crystal, femtosecond mode-locking, self-phase modulation

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

1. Introduction

Sub-100 fs pulsed lasers have extensive applications in ultrafast spectroscopy, optical frequency comb and optical coherent tomography, which continuously drive researches on such lasers [1–4]. Nowadays, sub-100 fs pulses have been successfully generated in many kinds of Yb-doped solid-state lasers [5–11]. However, it remains a challenge to generate sub-100 fs pulses from Nd doped crystals. Although Nd:glass can be used to generate pulses less than 100 fs, it is limited with disadvantages such as poor thermal conductivity.

In recent years, fluorides applied in lasers have attracted high attention for their simple cubic structures, good crystallographic properties and good thermal properties [12–14]. As laser host materials, they have been demonstrated to be excellent in Yb-doped femtosecond lasers [15, 16]. For the Nd doped fluorides, the Nd:SrF_2 crystal is found to be a potentially useful laser-pumped storage medium [17]. Continuous-wave (CW) lasers of 19% slope efficiency and 37% slope efficiency have been demonstrated for ceramic and crystal, respectively [18, 19]. Co-doping with non-active ions such as Y^{3+} or La^{3+} as buffers in Nd:SrF_2 can further restrain clustering effect thus improving the quantum efficiency of Nd^{3+}. This method has been demonstrated to be of use in Y^{3+} or Lu^{3+} co-doped Nd:CaF_2 lasers [20] and Y^{3+} co-doped Nd:SrF_2 lasers [21]. In the mode-locked operation, near-100 fs pulses with 89 mW output power and 264 fs pulses with 180 mW output power were obtained from diode-pumped Nd,Y:CaF_2 mode-locked lasers [22, 23]. We have realized an efficient femtosecond mode-locked Nd,Y:SrF_2 laser with 332 fs pulse duration and 395 mW average power [24]. Considering the over 15 nm emission spectral bandwidth, Nd,Y:SrF_2 has great potential

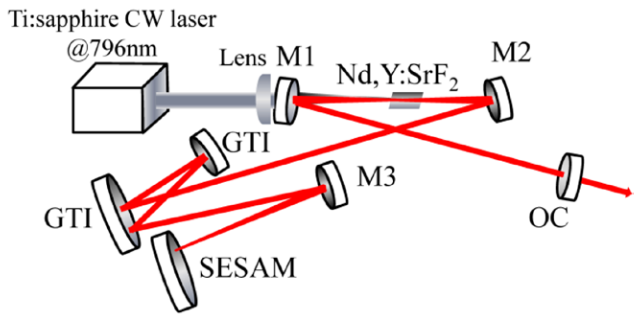


Figure 1. Schematic of the experimental setup for Nd,Y:SrF_2 mode-locked laser. Lens: focal length of 100 mm; M1: dichroic mirror with radius of curvature (ROC) of 200 mm, anti-reflected (AR) at 796 nm and high-reflected (HR) at 1000–1100 nm; M2, M3: plane-concave mirrors with ROC of 150 mm and 300 mm, respectively, HR at 900–1100 nm and 1020–1100 nm, respectively; GTI1, GTI2: Gires–Tournois interferometer mirrors with GDD of −250 fs^2; SESAM: semiconductor saturable absorber mirror; OC: output coupler.

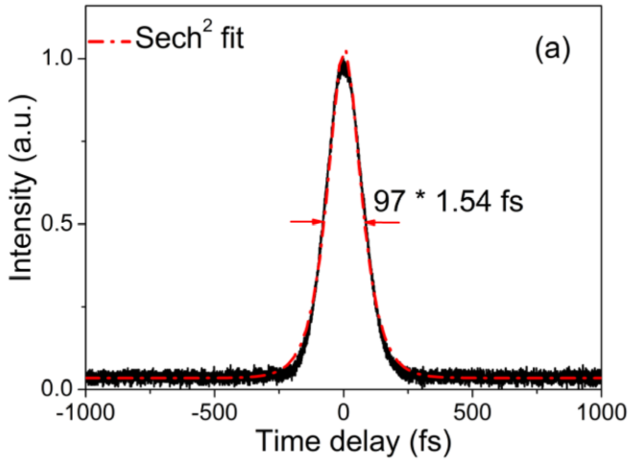
to achieve near Fourier transform limited 78 fs mode-locked pulses.

In this letter, a pulse of 97 fs is obtained from the mode-locked Nd,Y:SrF_2 laser at a repetition rate of 96 MHz. The average output power is 102 mW under 925 mW CW Ti:sapphire laser pump power, corresponding to the optical-to-optical efficiency of 11%. It shows the four-level Nd gain media has a special advantage over quasi-three level Yb media in an easily emitting laser with low pumping power. The mode-locked spectrum has a 13.2 nm bandwidth at the central wavelength of 1061 nm, slightly deviating from the peak fluorescence emission spectrum, which indicates that the spectrum is broadened by enhancing the self-phase modulation (SPM) effect.

2. Experiments

The gain medium was a Brewster-cut SrF_2 crystal co-doped with 0.4% at. Nd^{3+} and 10% at.Y^{3+}. The size of the crystal was $3 \times 3.8 \times 6\,mm^3$ with a gain length of 6 mm. The Nd,Y:SrF_2 had an absorption peak at 796 nm and an emission peak at 1057 nm with 15.5 nm bandwidth. The gain medium was wrapped with indium foil and mounted tightly on a water-cooled copper heat sink block, cooled by the flowing water. During the experiment, after trying different temperatures, the flowing water was finally set at 12 °C for best laser performance. To achieve the optimized results, a homemade 796 nm CW Ti:sapphire laser with 1 W output power was chosen as the pumping source rather than a laser diode (LD) at 796 nm.

The experimental setup is shown in figure 1. To achieve sub-100 fs mode-locking operation, we specially designed the resonator in the following aspects. Firstly, we employed a pair of GTI mirrors with group delay dispersion (GDD) of −250 fs^2 at 1020–1080 nm and finely adjusted the reflection-times per round-trip to precisely control the second-order dispersion in the cavity. Secondly, the transmittance of the broadband output coupler (OC) was chosen as 0.3%, keeping high laser intensity in the cavity to enhance the SPM. Thirdly, The SESAM used was designed for 0.4% modulation depth at 1064 nm, with non-saturable loss of 0.3%, saturation fluence of 90 μJ cm^{-2} and relaxation time of 500 fs, which brought in very low loss. According to the ABCD matrix calculation, the laser beam has a radius of about 60 μm in the crystal and 65 μm on the SESAM. In the practical experiment, we adjusted the focal spot of the pumping laser slightly deviating from the center of the crystal to match the beam waist, thus achieving the highest output power.



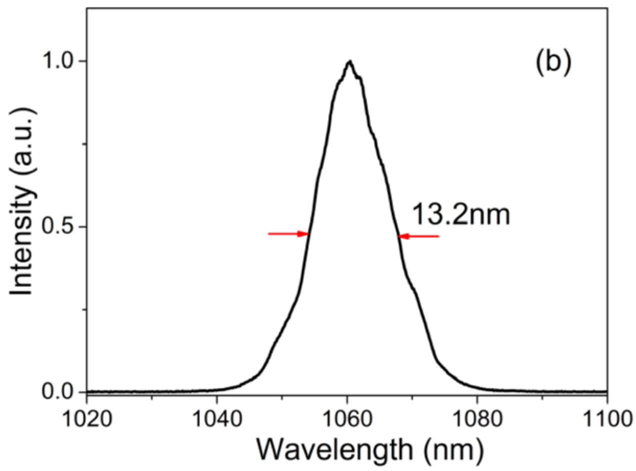


Figure 2. (a) Intensity autocorrelation trace and (b) laser spectrum of the mode-locking operation with 0.3% OC. The output power was 102 mW under 925 mW pump power.

3. Results and discussions

By continuously optimizing the mirrors, SESAM and the output power, sub-100 fs mode-locking operation was realized. The pulse duration was measured using a commercial intensity autocorrelator (FEMTOCHROME REASEARCH INC., FR-103MN), as shown in figure 2(a), the full width at half maximum (FWHM) pulse width was 97 fs assuming a $sech^2$ pulse shape. Figure 2(b) shows the corresponding spectrum with 13.2 nm spectral width centered at 1061 nm, recorded by an optical spectral analyzer (YOKOGAWA, AQ6370C). Long

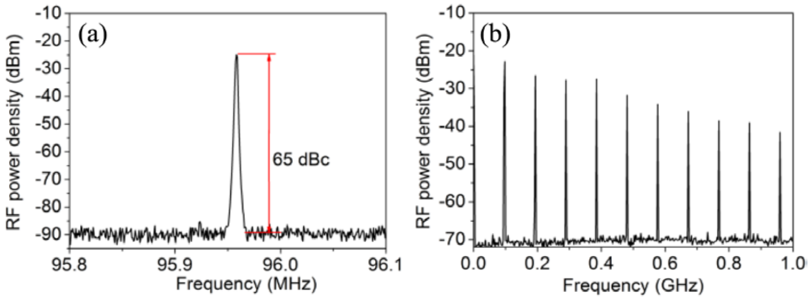


Figure 3. (a) RF spectrum at the fundamental beat note. (b) RF spectrum of 1 GHz wide-span range.

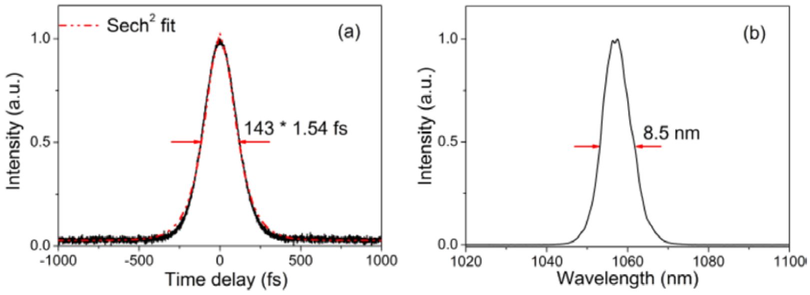


Figure 4. (a) Intensity autocorrelation trace of 143 fs pulses and (b) the corresponding laser spectrum with the 1.6% OC. The output power was 232 mW.

range scanning of the intensity autocorrelation and spectrum suggested the mode-locking was operated in single pulse chain without any modulation. The output power of the mode-locking was 102 mW under the pump power of 925 mW, corresponding to the optical-to-optical efficiency of 11%. The time-bandwidth product was 0.341, approaching the Fourier transform limit of 0.315 for sech^2 pulses.

We also measured the radio frequency (RF) spectra of the laser with a RF spectral analyzer (Agilent E4407B) and a fast detector of 1 GHz bandwidth. Figure 3(a) shows a 65 dBc fundamental beat note at 95.96 MHz with a resolution bandwidth of 1 kHz. Figure 3(b) shows the high harmonics of the fundamental beat note measured with a resolution bandwidth of 100 kHz and a span from 0 to 1 GHz. Both figures together illustrate the mode-locking is clean without obvious noise.

When we replaced the 0.3% OC with the one of 1.6% transmittance, another mode-locking regime was achieved. The highest mode-locked output power up to 232 mW was obtained with the same pump power. In this case, the pulse duration became longer to 143 fs, with an 8.5 nm spectral width centered at 1057 nm, as shown in figure 4.

As we know, the balance between the dispersion and SPM plays an important role for the pulse duration in the soliton mode-locked lasers. With the same dispersion configuration in the experiment, the higher intracavity power favors stronger SPM, thus broadening the mode-locking spectral bandwidth. When using the 0.3% OC, the intracavity power was calculated to be 34 W, while it is only 14.5 W for the 1.6% OC case. As a result, 97 fs pulses were obtained with 0.3% OC by enhancing the SPM effect. If we further increasing the intracavity power with 1.6% OC by increasing the pump power, a new sub-100 fs mode-locking with higher output power may be realized. Figure 5 shows the mode-locking spectra of the 97 fs pulses and 143 fs pulse as well as the fluorescence spectrum. As can be seen the spectrum for 97 fs was slightly red-shifted from the peak fluorescence.

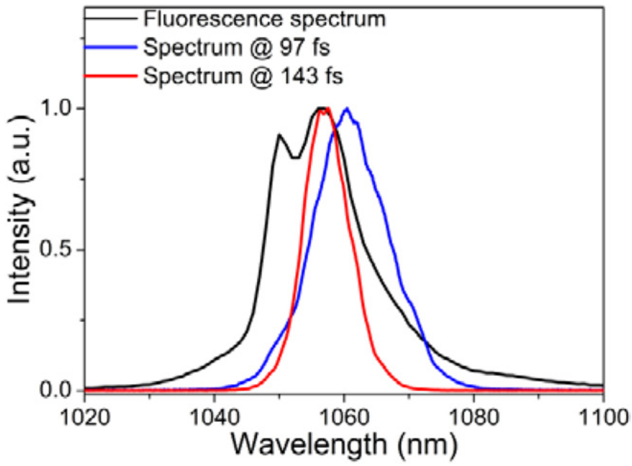


Figure 5. Comparison of the spectra with fluorescence emission spectrum of Nd,Y:SrF$_2$, 97 fs mode-locked spectrum and 143 fs mode-locked spectrum, respectively.

The round trip GDD around 1061 nm in the cavity was estimated to be −978 fs^2, resulting from 222 fs^2 in the Nd,Y:SrF$_2$, 300 fs^2 due to mirrors (M1,M2, M3 and OC), 0 fs^2 due to SESAM and −1500 fs^2 due to the GTI mirrors (6 times reflection in a round trip). We have tried just reflecting 4 times on the GTI mirrors in a round trip, which results in GDD of −478 fs^2 in the cavity. Although it could stimulate shorter pulse and broader spectrum, the mode-locking was rather unstable. Hence, it is reasonable to believe if we better manage the dispersion to fully utilize the gain bandwidth of the fluorescence spectrum, even shorter pulses may be obtained [8].

4. Conclusions

In conclusion, we have generated 97 fs pulses from a mode-locked Nd,Y:SrF_2 laser by enhancing the SPM effect in the cavity. The mode-locking spectral bandwidth of 13.2 nm was close to the fluorescence bandwidth of the Nd,Y:SrF_2 crystal. The average output power reached 102 mW at the pump power of 925 mW. Our results show Nd,Y:SrF_2 crystal is a promising alternative for generating sub-100 fs pulses and may find potential application in high repetition rate chirped pulse amplification system.

Acknowledgments

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References

[1] Keller U 2003 *Nature* **424** 831
[2] Tan W D, Tang D Y, Xu X D, Li D Z, Zhang J, Xu C W and Xu J 2011 *Opt. Lett.* **36** 259
[3] Holzwarth R, Zimmermann M, Udem Th, Hänsch T W, Russbüldt P, Gäbel K, Poprawe R, Knight J C, Wadsworth W J and Russell P St J 2001 *Opt. Lett.* **26** 1376
[4] Pekarek S, Südmeyer T, Lecomte S, Kundermann S, Dudley J M and Keller U 2011 *Opt. Express* **19** 16492
[5] Liu H, Nees J and Mourou G 2001 *Opt. Lett.* **26** 1723
[6] Zorn M, Weyers M, Zhang H, Wang J and Jiang M 2006 *Opt. Express* **14** 11668
[7] Zaouter Y, Didierjean J, Balembois F, Leclin G L, Druon F, Georges P, Petit J, Goldner P and Viana B 2006 *Opt. Lett.* **31** 119
[8] Tokurakawa M, Shirakawa A, Ueda K, Yagi H, Noriyuki M, Yanagitani T and Kaminskii A A 2009 *Opt. Express* **17** 3353
[9] Uemura S and Torizuka K 2011 *Japan. J. Appl. Phys.* **50** 010201
[10] Yoshida A, Schmidt A, Petrov V, Fiebig C, Erbert G, Liu J, Zhang H, Wang J and Griebner U 2011 *Opt. Lett.* **36** 4425
[11] Sévillano P, Georges P, Druon F, Descamps D and Cormier E 2014 *Opt. Lett.* **39** 6001
[12] Catlow C R A, Chadwick A V, Greaves G N and Moroney L M 1984 *Nature* **312** 601
[13] Camy P, Doualan J L, Benayad A, Edlinger M V, Ménard V and Moncorgé R 2007 *Appl. Phys.* B **89** 539
[14] Boudeile J, Didierjean J, Camy P, Doualan J L, Benayad A, Ménard V, Moncorgé R, Druon F, Balembois F and Georges P 2008 *Opt. Express* **16** 10098
[15] Machinet G *et al* 2013 *Opt. Lett.* **38** 4008
[16] Druon F, Papadopoulos D N, Boudeile J, Hanna M, Georges P, Benayad A, Camy P, Doualan J L, Ménard V and Moncorgé R 2009 *Opt. Lett.* **34** 2354
[17] Payne S A, Caird J A, Chase L L, Smith L K, Nielsen D N and Krupke W F 1991 *J. Opt. Soc. Am.* B **8** 726
[18] Basiev T T, Doroshenko M E, Konyushkin V A and Osiko V V 2010 *Opt. Lett.* **35** 4009
[19] Alimov O K, Basiev T T, Doroshenko M E, Fedorov P P, Konyushkin V A, Nakladov A N and Osiko V V 2012 *Opt. Mater.* **34** 799
[20] Doualan J L, Su L B, Brasse G, Benayad A, Ménard V, Zhan Y Y, Braud A, Camy P, Xu J and Moncorgé R 2013 *J. Opt. Soc. Am.* B **30** 3018
[21] Jelínek M, Kubeček V, Su L B, Jiang D, Ma F, Zhang Q, Cao Y and Xu J 2014 *Laser Phys. Lett.* **11** 055001
[22] Qin Z P *et al* 2014 *Opt. Lett.* **39** 1737
[23] Zhu J F, Zhang L J, Gao Z Y, Wang J L, Wang Z H, Su L B, Zheng L H, Wang J Y, Xu J and Wei Z Y 2015 *Laser Phys. Lett.* **12** 035801
[24] Wei L, Han H N, Tian W L, Liu J X, Wang Z H, Zhu Z, Jia Y L, Su L B, Xu J and Wei Z Y 2014 *Appl. Phys. Express* **7** 092704