Observation of Self-Frequency Doubling in Diode-Pumped Mode-Locked Nd-Doped $La_3Ga_5SiO_{14}$ Laser *

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A diode-pumped passively mode-locked Nd-doped $La_3Ga_5SiO_{14}$ (Nd:LGS) laser is realized by using a semiconductor saturable absorber mirror. With the pump power of 2 W, we obtain a 532 nm self-frequency doubling (SFD) laser together with a 10.9 ps fundamental laser at the repetition rate of 173.7 MHz. To the best of our knowledge, it is the first time for self-frequency doubling in the diode-pumped mode-locked Nd:LGS laser. Benefited from the diode lasers and its self-frequency doubling property, Nd:LGS could be a potential candidate for compact, stable and cheap ultrafast green laser sources.

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The $La_3Ga_5SiO_{14}$ (LGS) crystal has attracted widespread attention due to its multifunctional properties such as piezoelectric, electro-optic and dielectric properties, especially as a piezoelectric material.[1,2] With these excellent properties, more and more researches using LGS have been reported in recent years.[3,4] Doping with rare-earth ion, LGS can also be used as a laser material. In 1983, Kaminskii *et al.* reported laser operations with Nd-doped LGS crystal as a gain medium, for the first time.[5] Then the electrooptic coefficients of LGS were explored and were used to realize Q switch.[6] So far, continuous wave (cw) and Q-switched laser around 1 μm were demonstrated with Nd:LGS.[7,8] At quasi-three-level, tunable cw laser around 904 nm and its intracavity frequency doubling using a LBO crystal were also reported.[9,10] More significantly, due to the disordered structure of Nd:LGS, large inhomogeneous spectral broadening is obtained and will benefit the generation of ultrafast pulses. Recently we had obtained its femtosecond laser pumped by a Ti:sapphire laser.[11]

Based on the measurement of refractive indexes and the analysis of the nonlinear properties,[5] LGS crystal could not be used to obtain phase-matched second harmonic generation (SHG) of Nd^{3+} ion laser emission at the wavelengths of 1.06 μm and 1.37 μm. The phase-matching condition $n_e^{\omega} \geq n_o^{2\omega}$, cannot be fulfilled ($n_e^{1.06} = 1.89$ and $n_o^{0.532} = 1.91$).[5] Thus there was no SHG when Nd:LGS was used in cw and Q-switched laser.[8,10] However, it does not mean that it is impossible to obtain SHG for Nd:LGS or similar materials. When some nonlinear materials were used in the Maker–Fringe technique, one of the methods widely used to measure nonlinear properties of crystals, SHG could be observed.[12−17] The non-phase-matched SHG is closely related with the intensity of fundamental laser and nonlinear property of the crystal. Nd:LGS has been proved to be a good nonlinear crystal.[6] It is very possible to obtain SHG if the ultrafast Nd:LGS laser is achieved. Combining the merits of diode pump sources and self-frequency doubling property, Nd:LGS could be a potential candidate for compact, stable and cheap ultrafast green laser sources.

In this Letter, we report a diode-pumped mode-locked picosecond Nd:LGS laser at 1.06 μm using a semiconductor saturable absorber mirror (SESAM) and simultaneous generation of self-frequency doubling (SFD). An x-cut 1%-doped Nd:LGS crystal with dimensions of $3 \times 3 \times 8\,mm^3$ was employed as a gain medium, both facets of the crystal were polished and antireflection coated at 808 nm and around 1 μm. For heat dissipation, the crystal was wrapped with indium foil and mounted tightly on a water-cooled copper heat sink. The water temperature was maintained at 17℃ during the experiment. With broad fluorescence spectrum around 1.06 μm, Nd:LGS is potentially a good crystal for ultrafast pulse generation.[8] Figure 1 is the schematic layout of the experiment. A 2 W fiber-coupled diode laser (BWT, Beijing) was used to pump

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the crystal. The pump laser beam from the fiber with 50 µm core diameter was coupled into the crystal by a coupling system (the magnification is 1:1). In our experiment, the pump laser worked at 807 nm and the maximum power was 2 W.

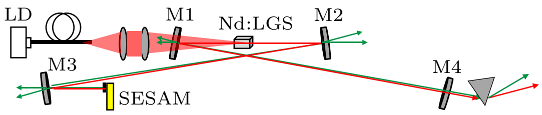

Fig. 1. The x-folded resonator used to realize the passively mode-locked Nd:LGS laser. LD: an 808 nm laser diode; M1 and M2: pump mirrors with curvature radius of 75 mm; M3: concave mirror with radius of 100 mm; M4: output coupler with a transmission of 0.5% around 1 µm.

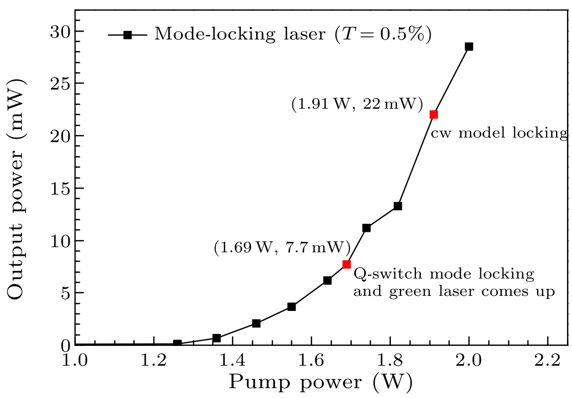

Fig. 2. The output power curve of the mode-locked fundamental laser with a 0.5% output coupler.

The laser cavity was an x-folded resonator. Both M1 and M2 were pump mirrors with curvature radius of 75 mm. M4 was the output coupler with a transmission of 0.5% from 1000 nm to 1100 nm. The SESAM was used as an end mirror, which had a modulation depth of 0.4%, a saturation fluence of 90 $\mu J/cm^2$ and a recovery time less than 500 fs at the central wavelength of 1064 nm (BATOP, Inc.). To start passively mode-locking, a curved highly reflected mirror M3 with radius of 100 mm was employed to focus the beam on the SESAM. The total cavity length was 0.864 m, corresponding to a repetition rate of 173.7 MHz. A prism was used to separate the fundamental and SFD laser beams on the right side of the output coupler M4. Due to the limitation of experimental conditions, mirrors used in the resonator were not reflected at 532 nm, thus the SFD laser could transmit through M1 to M4 and the output power we detected must be lower than that actually generated.

The measured output power of the mode-locked fundamental laser is shown in Fig. 2. At the threshold power of 1.26 W, cw laser was observed. With the increase of the pump power the output power of cw laser kept increasing and then ran into Q-switch. When the pump power increased to 1.69 W, the laser turned into Q-switched mode locking suddenly with the output power of 7.7 mW, and the SFD laser at 532 nm was observed. By further increasing the pump power, the power of SFD increased. The cw mode-locking was easily achieved at 1063 nm with the pump power of 1.91 W. Finally with the maximum pump power of 2 W, the output power of the fundamental laser and SFD laser were achieved with 28.5 mW and 40 µW, respectively. We could find that the output power of the SFD laser was strongly dependent on the pulse energy intensity of the fundamental laser.

The intensity autocorrelation trace of the fundamental laser measured by a commercial intensity autocorrelator (Femtochrome, FR-103MN) is shown in Fig. 3. Assuming a sech^2 pulse shape, the pulse width of 10.9 ps was obtained. Limited by the pump power, the output power of the SFD was very weak so that we could not measure its pulse width directly. The mode-locked pulse train measured by a photoelectric detector shows a result of 10 ns and 10 µs with a long-term stability.

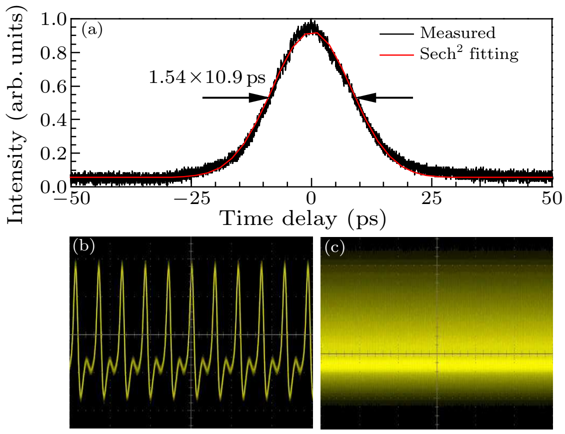

Fig. 3. Intensity autocorrelation trace and mode-locked trains of the fundamental laser. The measured data are described by the black curve and the sech^2 fitting shown as the red curve.

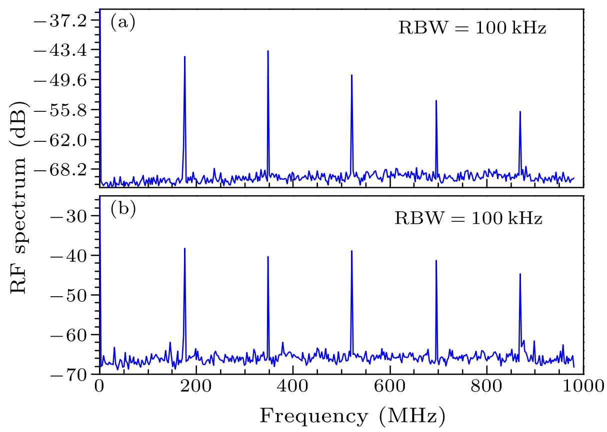

Fig. 4. The rf spectra of the repetition rate of the fundamental and SFD pulses with a resolution bandwidth (RBW) of 100 kHz and in the range of 1 GHz: (a) the fundamental pulse rf spectrum, (b) the SFD pulse rf spectrum.

A photoelectric detector and an rf spectrum analyzer (Agilent, E4402B) were used to measure the rf spectra of the repetition rate of the fundamental and SFD laser pulses. The results shown in Fig. 4 indicate a repetition rate of 173.7 MHz.

Figure 5 shows the spectra of the fundamental and SFD laser measured by an optical spectrum analyzer (AQ6315A, Ando Inc.). The fundamental pulse spectrum had an FWHM of 3.2 nm at the central wavelength of 1063 nm and narrowed to an FWHM of 1 nm centered at 532 nm as a result of the nonlinear interaction during the self-frequency doubling process.

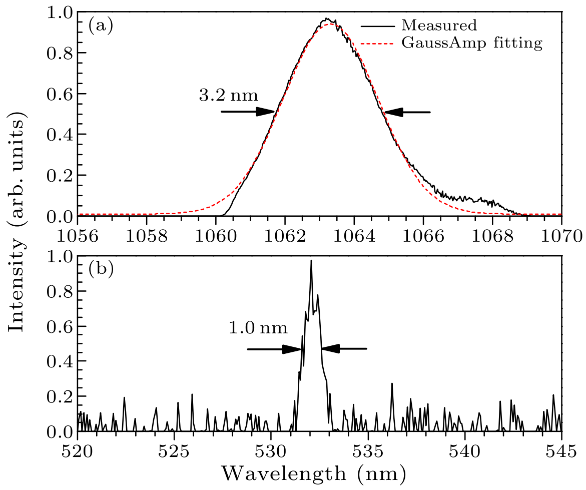

Fig. 5. Spectra measured by an optical spectrum analyzer: (a) the fundamental laser spectrum, (b) the SFD spectrum.

To this point, the experiment was performed for the Nd:LGS crystal at normal incidence. To obtain a better understanding, we changed the incident angle within a range of $\pm 1^\circ$. The SFD was always generated. Due to the limitation of the pump power, we could not obtain a quantitative measurement to the curve of SFD light power. Considering the non-phase-matched SHG is closely related with the intensity of the focused laser,[12–17] it should be the cause of the SFD laser with Nd:LGS. When the laser operated in cw and Q-switching regime, there was no SFD generation since the phase-matching condition could not be fulfilled in Nd:LGS. With the achieving of mode-locking, the intensity of the fundamental laser in the crystal increased in order of magnitude and the non-phase-matching SFD was obtained. However, there is no SHG in most of the ultrafast lasers with even higher pulse energy while SHG is just obtained in a few SFD lasers.[18–22] What we are interested in is the frequency doubling property of Nd:LGS, which does not consider a phase-matching SFD crystal.[5] To further investigate and obtain more details of the SFD generation in ultrafast Nd:LGS laser, we need a high power pump laser to improve the output power of the SFD laser, which will be our next work.

In conclusion, we have realized a diode-pumped mode-locked Nd:LGS laser. With the pump power of 2 W, a 532 nm SFD laser and a 10.9 ps fundamental laser at repetition rate of 173.7 MHz are simultaneously obtained. Thanks to its self-frequency doubling property and broad inhomogeneous spectra, Nd:LGS could be a potential candidate for compact, stable and cheap ultrafast green laser sources.

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