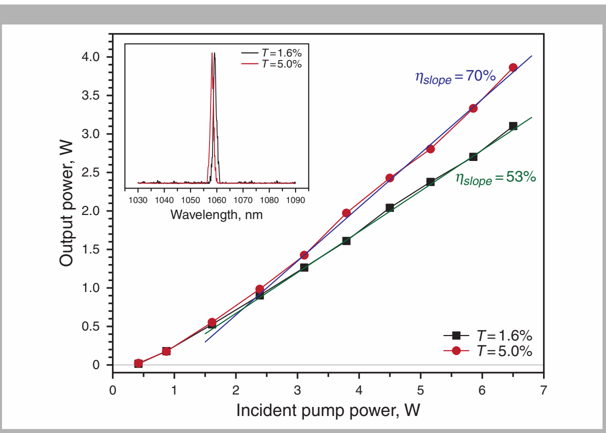
Abstract: A diode-pumped passively mode-locked Yb:$Lu_2Si_2O_7$ (Yb:LPS) laser is demonstrated for the first time, to our knowledge. Using a commercial semiconductor saturable absorber mirror (SESAM) as the mode locker and a pair of GiresTournois interferometer (GTI) mirrors for group-velocity dispersion (GVD) compensating, we have obtained stable femtosecond mode locked pulses. Two output couplers of transmission of 1.6% and 5% were used to exploit the mode locked laser performance. For the output coupler with $T = 1.6\%$, 195 fs pulses centered at 1042 nm were generated, and for the output coupler with $T = 5.0\%$, 450 fs pulses centered at 1058 nm were generated. The corresponding output power is 130 and 610 mW, respectively. Higher output could be obtained but the laser operated at multi pulse regime. In addition, a preliminary continuous wave (CW) laser performance test demonstrated a slope efficiency of up to 70% with respect to incident pump power, which is much higher than the previous value of 35% with respect to absorbed pump power.



The relationship between the incident pump power and laser output of Yb:LPS laser. The inset shows the corresponding laser wavelengths

Diode-pumped femtosecond passively mode-locked Yb:LPS laser

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1. Introduction

Diode pumped Yb^{3+}-doped ultrafast lasers have attracted considerable attention in the past two decades [1–3]. It is well known that the Yb^{3+}-doped lasers have a number of unique properties. Firstly, there are no undesirable effects, such as up-conversion, excited-state absorption and concentration quenching in the Yb^{3+}-doped lasers, as Yb^{3+} transitions involve only in two electronic manifolds $^2F_{7/2}$ and $^2F_{5/2}$. Secondly, the Yb^{3+}-doped gain media have low quantum defect, which results in much lower thermal loading in the gain media. Thirdly, Yb^{3+}-ions doped in most solid-state hosts have broad gain bandwidths, which is necessary for the generation of ultrashort mode locked pulses. In addition, the absorption band of Yb^{3+} ions well matches with the emission band of the InGaAs laser diodes, which allows that the lasers can be directly diode pumped.

Yb^{3+} ions doped in different hosts can exhibit diverse spectroscopic and laser characteristics. The demand for efficient, cost-effective and compact ultrashort pulse lasers has continuously driven the search for new Yb^{3+}-doped gain media. Up to now, various Yb^{3+}-doped crystals and their laser performances have been demonstrated. These

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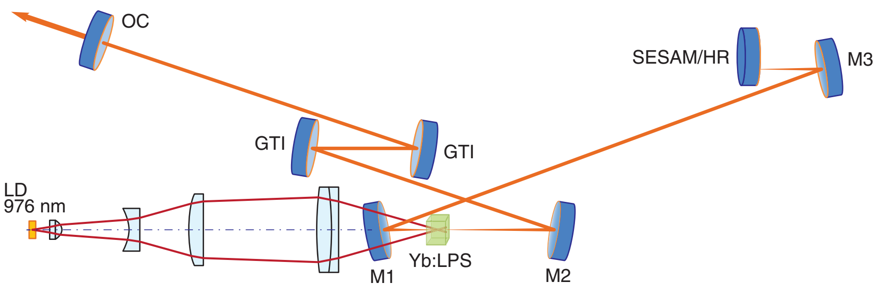

Figure 1 (online color at www.lasphys.com) Schematic of the mode-locked Yb:LPS laser setup. M1 – ROC = 100 mm HR@1000 – 1080 nm, M2 – ROC = 200 mm HR@1000 – 1080 nm, M3 – ROC = 200 mm HR@1000 – 1080 nm, and OC – plano output coupler

include garnets [4], vanadates [5], double tungstates [6,7], borates [8], apatites [9], sesquioxides [10], silicates [11], fluorides [12], and so on. Lutetium pyrosilicate crystal, $Lu_2Si_2O_7$ (LPS), belongs to the silicate family and has a low-symmetry monoclinic structure. Many other Yb^{3+}-doped silicate crystals, such as Yb:Gd_2SiO_5 (Yb:GSO) [13], Yb:Lu_2SiO_5 (Yb:LSO) [11], Yb:Y_2SiO_5 (Yb:YSO) [11], Yb:Sc_2SiO_5 (Yb:SSO) [14,15], Yb:GYSO [16], and Yb:LYSO [17,18] have shown attractive spectroscopic properties and laser performances. $Lu_2Si_2O_7$ is well known as phosphors and scintillators when doped with Ce^{3+} [19]. Zheng et al. firstly studied the spectroscopic properties of the Yb^{3+}-doped $Lu_2Si_2O_7$ (Yb:LPS) [20]. It was shown that Yb:LPS has three strong absorption bands around 905, 955, and 970 nm, respectively, each with a bandwidth of 21, 22, 29 nm and an absorption cross-section of 0.73×10^{-20}, 0.81×10^{-20}, and 1.33×10^{-20} cm^2. The fluorescence spectrum of the crystal extends from 950 to 1100 nm, structured with four peaks around 978, 996, 1032, and 1069 nm. The corresponding emission cross-sections are 0.18×10^{-20}, 0.31×10^{-20}, 0.34×10^{-20}, and 0.20×10^{-20} cm^2, respectively. For the 5 at.% doped Yb:LPS, the fluorescence lifetime was measured as ~1.88 ms [20]. The broad absorption bandwidth of the Yb:LPS crystal is beneficial for the direct diode pumping. However, up to now except continuous wave (CW) operation [21] no mode locking of the crystal is investigated. In this letter we report on the passive mode-locking operation of a diode pumped Yb:LPS laser. Mode locked with a commercial semiconductor saturable absorber mirror (SESAM) and dispersion compensated by a pair of GiresTournois interferometer (GTI) mirrors, stable pulses with 195 pulse duration centered at 1042 nm and 450 fs pulse centered at 1058 nm were achieved, respectively. Our results show that the Yb:LPS could be another promising gain medium for the direct diode pumped ultrafast lasers.

2. Experimental setup

Fig. 1 shows a schematic of our laser setup. The Yb:LPS crystal used was grown by the Czochraski method [14]. It has dimensions of $3\times3\times3$ mm^3 and an Yb^{3+} doping concentration of 5 at.%. The crystal was c-cut and antireflection coated from 970 to 1080 nm on both of its facets. Wrapped with indium foil, the crystal was mounted in a water-cooled copper heat sink whose temperature is kept at 17°C. A single emitter laser diode with central wavelength at 976 nm was used to pump the Yb:LPS crystal. The long strip shaped pump light emitted from the laser diode (LD) was firstly collected by an aspheric lens, and then reshaped into a collimated beam with near- square pattern by a telescope consisting of two cylindrical lenses, at last focused into the crystal by a doublet with focal length of 80 mm. The pump beam waist size in diameter was measured with knife-edge method to be about 55(fast axis)$\times$105(slow axis) μm^2. The slow axis of the laser diode was parallel to the tabletop. A SESAM (BATOP GmbH) was used as the mode locker. The SESAM was specified as having central wavelength at 1040 nm, a modulation depth of 0.4%, an absorbance of 0.7%, a saturation fluence of 90 μJ/cm^2 and a relaxation time of 1 ps. Based on ABCD calculations, the laser beam size in the crystal and on the SESAM was ~70 and ~40 μm in radius, respectively. To compensate the positive cavity dispersion, Two GTI mirror with group delay dispersion (GDD) of –500±100 fs^2 per bounce in the wavelength range from 1040 to 1090 nm was inserted into the cavity for the femtosecond pulse operation. The mode-locked pulse train was monitored with a low noise photodetector (New Focus, 1611-FC-AC) and displayed on a 1 GHz digital oscilloscope (Tektronix, DP0714). The optical spectrum was measured with a high-resolution optical spectrum analyzer (Ando, AQ-6315B). The pulse duration was measured with a commercial autocorrelator (APE, PulseCheck).

3. Results and discussion

The CW laser performance of Yb:LPS was tested preliminarily. For this purpose, a high reflection plane mirror was used as the end mirror. The Yb:LPS crystal absorbed about 70% of the incident pump power. As shown in Fig. 2 is the dependence of output power on incident pump power. Under the available maximum incident pump power of 6.5 W,

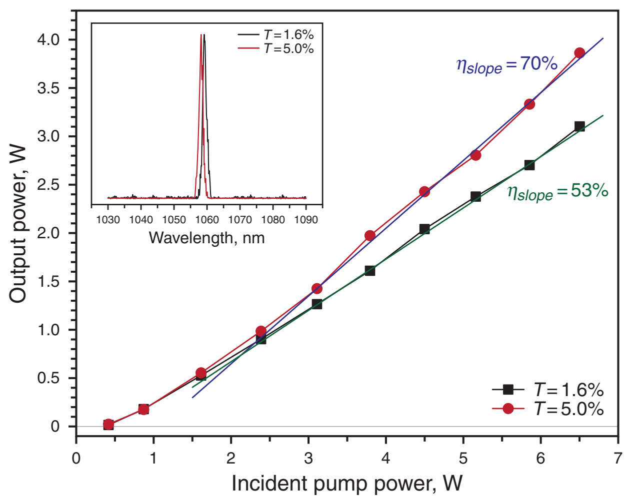

Figure 2 (online color at www.lasphys.com) The relationship between the incident pump power and laser output of Yb:LPS laser. The inset shows the corresponding laser wavelengths

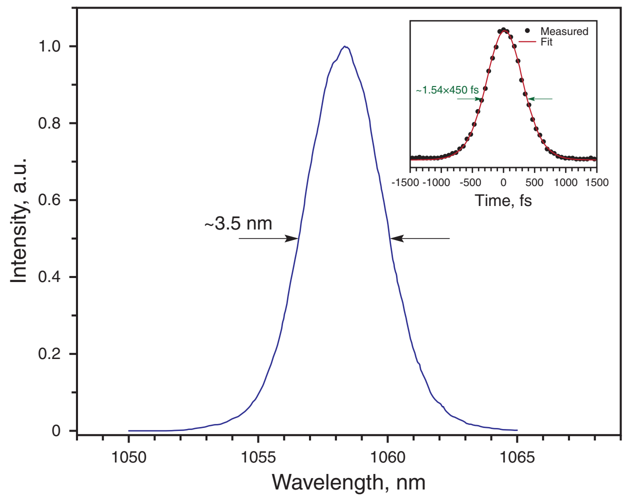

Figure 4 (online color at www.lasphys.com) Pulse duration (inset) and corresponding optical spectrum of the femtosecond mode-locked pulses for the case of $T = 5.0\%$

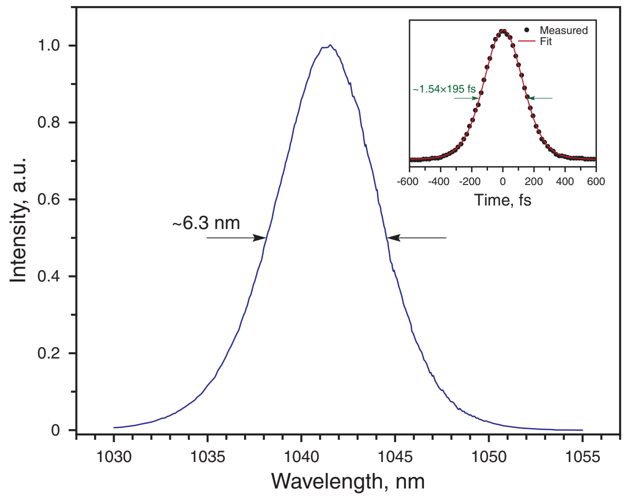

Figure 3 (online color at www.lasphys.com) Pulse duration (inset) and corresponding optical spectrum of the femtosecond mode-locked pulses for the case of $T = 1.6\%$

the generated laser output power reached 3.9 and 3.1 W for two output couplers with transmissions of 5.0% and 1.6%, respectively. The corresponding laser wavelengths are located around 1057 and 1059 nm, respectively, also shown in Fig. 2. The slope efficiencies with respect to the incident pump power were up to 70% and 53%, respectively, which indicated the good laser performance of Yb:LPS. Compared to 35% slope efficiency with respect to the absorbed pump power of Yb:LPS laser reported in [21], the laser performance was greatly enhanced in this work. The high efficiency is mainly contributed to the good mode matching in the crystal. The output beam was linear polarized and had a fundamental transverse mode under the maximum incident pump power for the two output couplers.

To initiate the mode-locking, The HR end mirror was replaced by the SESAM. The performance of the femtosecond laser was studied with two different output couplers of 1.6% and 5.0% transmission, respectively. Stable femtosecond mode-locked pulses were generated when the two GTI mirrors were used for compensating the positive dispersion introduced by the Yb:LPS crystal. The pulse repetition rate is around 90 MHz, which is in agreement with the cavity length of 166 cm. We found that the mode-locked laser operated at two different center wavelengths for the two output couplers.

When the output coupler with transmission of 1.6% was used, the stable CW mode-locking only occurred at 1042 nm, although around 1059 nm we could also observe Q-switched mode-locking through careful alignment. Fig. 3 shows the pulse duration and the corresponding spectrum for the case of $T = 1.6\%$, which were measured at the output power of 130 mW (the corresponding incident pump power is 2.55 W). If the incident pump power increased further, the mode locked single pulse would split into two pulses. Assuming a sech^2 pulse shape, the pulse duration is about 195 fs. The optical spectrum is centered at 1042 nm with a full width at half maximum (FWHM) bandwidth of 6.3 nm. The time bandwidth product (TBP) of the pulses is 0.34, close to that of the transformed-limited pulses.

However, the situation for the output coupler with transmission of 5% was quite different. The stable CW mode-locking was still obtained, but laser central wavelength shifted from 1042 to 1058 nm. And around 1042 nm could appear just the Q-switched mode-locking through careful alignment. Fig. 4 shows the pulse duration and the corresponding spectrum for the case of $T = 5.0\%$, which were measured at the output power of 610 mW (the corresponding incident pump power is 3.6 W). Similarly to the above case, further increasing pump power would cause double pulse or even multi-pulse operation regime. Assuming a sech^2 pulse shape, the pulse duration is about 450 fs. The optical spectrum is centered at 1058 nm with a FWHM bandwidth of 3.5 nm. The TBP of the pulses is 0.42. The larger TBP for 1058 nm pulses than for 1042 nm pulses indicated the more chirp for the former. The reason for this may be owing to the different group-velocity dispersion (GVD) amounts at the two wavelengths introduced by the SESAM and the output couplers.

For the both output couplers, when the laser operated in CW mode locking regime, the pulse duration decreased with the increasing pulse energy, while the corresponding spectral bandwidth broadened simultaneously. Once the pulse duration reaches a limit, the pulse then broke into two individual pulses. Accompanying the appearance of a new pulse, the pulse duration switched back to a longer value and the spectral bandwidth narrowed simultaneously. During the experiment, more than 1 W of output was obtained but the laser operated at multi pulse regime. We believe that through further improving the quality of the crystal and optimizing the cavity design (such as the dispersion compensation amount and spot sizes on SESAM and in crystal), much shorter pulses and more than 1 W laser output mode-locked in single pulse regime could be expected from the Yb:LPS laser.

4. Conclusion

In conclusion, we have first experimentally demonstrated the passive mode-locking of a diode pumped Yb:LPS laser. The preliminary CW laser performance test demonstrated a slope efficiency of up to 70% with respect to incident pump power. Using a commercial SESAM as the mode locker and a pair of GTI mirrors for GVD dispersion compensating, we have obtained stable femtosecond mode locked pulses. Two output couplers of transmission of 1.6% and 5% were used to exploit the mode locked laser performance. For the output coupler with $T = 1.6\%$, 195 fs pulses centered at 1042 nm were generated, and for the output coupler with $T = 5.0\%$, 450 fs pulses centered at 1058 nm were generated. The corresponding output power is 130 and 610 mW, respectively. Higher output could be obtained but the laser operated at multi pulse regime. Our results show that Yb:LPS crystal could be another promising gain medium for the diode pumped ultrashort pulse lasers.

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