Laser Phys. Lett. **13** (2016) 105003 (5pp) doi:10.1088/1612-2011/13/10/105003

Letter

Passive mode locking of a Nd:KGW laser with hot-band diode pumping

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Received 21 June 2016, revised 5 August 2016
Accepted for publication 15 August 2016
Published 2 September 2016

Abstract

Passive mode locking of a Nd:KGW laser with hot-band diode pumping at 910 nm was demonstrated. A semiconductor saturable absorber mirror was used as a mode locking mechanism. The laser generated 2.4 ps pulses at a repetition rate of ~83.8 MHz. An average output power of 87 mW was obtained at 1067 nm. To the best of our knowledge, this is the first report on passive mode locking of a Nd:KGW laser with low quantum defect pumping which holds great promise for further output power scaling.

Keywords: diode-pumped lasers, passive mode locking, Nd-ion lasers

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

1. Introduction

Over the last decade the number of applications of ultrashort light pulses have skyrocketed and include such different areas as nonlinear frequency conversion [1–5], nonlinear microscopy [6], nonlinear [7] and time-resolved [8] spectroscopy. Neodymium-doped crystals are famous for efficiently producing short pulses with excellent beam quality. Among the various Nd-doped crystals, the crystal of Nd-doped potassium gadolinium tungstate (Nd:KGd$(WO_4)_2$, Nd:KGW) is well-known for continuous-wave (CW) [9, 10], Q-switched [10] and mode-locked operation [11, 12]. This laser crystal has strong polarized emission lines at 1067 nm (corresponds to $^4F_{3/2} \rightarrow {}^4I_{11/2}$; $\sigma_{em} = 3.4 \times 10^{-19}$ cm^2) and 1350 nm (corresponds to $^4F_{3/2} \rightarrow {}^4I_{13/2}$; $\sigma_{em} = 0.82 \times 10^{-19}$ cm^2) [13]. High third-order nonlinearity of the host [14] along with high Raman gain coefficient [15] make this crystal attractive as Raman converter to realize eye-safe spectral range at 1537 nm [16]. Moreover, when doped with Yb-ion it also allows generation of powerful ultrashort pulses [17–20].

In comparison with other popular gain media Nd:KGW offers higher stimulated emission cross-section than Nd:YAG and broader gain bandwidth than Nd-doped YLF or YVO_4. This makes it particularly suitable for generation of ultrashort pulses. Its relatively short upper-state lifetime (110 μs at 3% doping) results in reduced tendency towards self-Q-switching dynamics [21]. The first passively mode-locked operation of a Nd:KGW laser diode-pumped at 808 nm was demonstrated by Major *et al* utilizing a saturable Bragg reflector. The laser produced 6.3 ps pulses with 1 W of average output power [11]. In another work, self-starting additive-pulse mode locking in a diode-pumped Nd:KGW laser produced 2.3 ps pulses at 0.85 W of output power with the shortest recorded pulse duration of 1.9 ps [12]. Kerr-lens mode locking of a flashlamp pumped laser was demonstrated by Lettenberger *et al* to produce the shortest reported to date pulses of 1.7 ps from Nd:KGW crystal [22].

At the same time this monoclinic biaxial crystal exhibits strong anisotropy in its optical and thermal characteristics. Its thermal conductivity (2.6, 3.8 and 3.4 W m^{-1} K^{-1} along the [1 0 0], [0 1 0] and [0 0 1] crystallographic axes, respectively [23]) is in between the Nd:glass and Nd:YVO_4 hosts. Unfortunately, large quantum defect resulting from the commonly used diode pumping around 810 nm and moderate thermal conductivity prevents this crystal to be operated at high pump powers [9, 11].

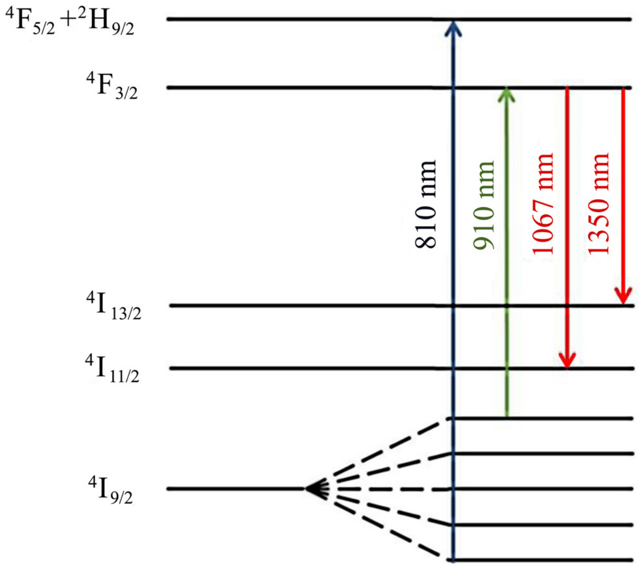

Figure 1. Energy level diagram of Nd:KGW crystal.

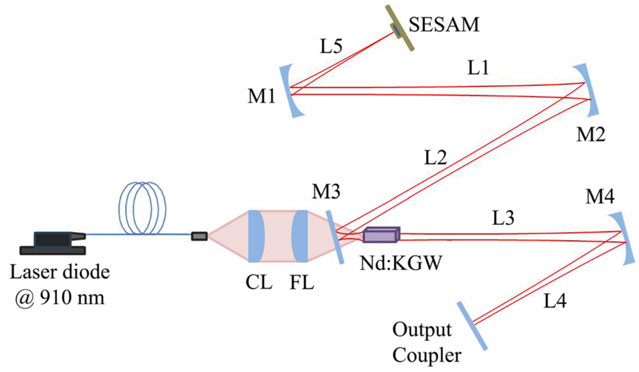

Figure 2. Experimental setup of mode-locked Nd:KGW laser.

Recently it was shown that quantum defect in Nd:KGW can be significantly reduced (>45%) by using a hot-band pumping technique at ~910 nm [24]. In this case the electrons are excited from the thermally populated highest sublevel (i.e. hot band) of the ground state manifold directly into the emitting laser level. When previously used with Nd:YVO_4 laser crystal, such a dramatic reduction in quantum defect enabled slope efficiencies up to 81% and 77% in the continuous wave [25] and mode-locked [26] regimes, respectively. Moreover, the effect of thermal lensing was reduced by more than a factor of two [27].

In this work we explored the possibility of extending this promising approach from the CW to mode-locked regime in a Nd:KGW laser. We demonstrate passive mode locking of a hot-band diode-pumped Nd:KGW laser with semiconductor saturable absorber mirror (SESAM). The laser produced 2.4 ps long pulses at 1067 nm with 87 mW of average output power. To the best of our knowledge, this is the first report of a mode-locked Nd:KGW laser with low quantum defect pumping. The generated pulses are also the shortest reported so far for the mode-locked Nd:KGW lasers based on SESAM. Our results open the way for further power scaling of ultrashort pulse Nd:KGW lasers.

2. Experimental set-up

One of the key features of this work is hot-band pumping with low quantum defect. This concept is illustrated in figure 1 showing the energy levels of Nd-ion in KGW matrix. Traditional pumping scheme around 810 nm as well as lasing transitions at 1067 nm and 1350 nm are shown along with the implemented low quantum defect hot-band pumping transition around 910 nm [13]. This excitation scheme has the lowest possible quantum defect in this particular system. Another possibility of low quantum defect pumping would be a direct in-band transition around 880 nm [13, 28] corresponding to the excitation of an electron from the ground state to the emitting laser level $^4F_{3/2}$. In this case, however, quantum defect will be larger than for the pumping wavelength around 910 nm.

A simple 5-mirror cavity shown in figure 2 was designed to study the mode-locked operation. A 20 mm long N_g-cut Nd:KGW slab crystal with dimensions of $1.6 \times 6 \times 20$ mm was used for this experiment. It had 3 at.% doping concentration (Altechna). The N_g-cut of the crystal was selected because it provides positive thermal lensing with low astigmatism [29]. The crystal had flat end-faces which were antireflection coated at oscillating wavelength of 1067 nm. Cavity mirrors were highly reflective at the same wavelength. Mirrors M1, M2 and M4 were curved folding mirrors with radii of curvature 50, 400 and 500 mm, respectively. The flat mirror M3 was a dichroic mirror used for introducing the pump and folding of the cavity. The employed output coupler had 1.6% transmission. The distances between these components $L1$–$L5$ were selected using ABCD matrix formalism to be 314, 455, 481, 462 and 37 mm, respectively, in order to provide a mode size diameter of ~600 μm in the crystal. A thermal lens of ~100 mm, which was determined from the CW measurements [24, 30], was taken into account.

A high power fiber-coupled laser diode (110 μm core, NA = 0.12) operating around 910 nm (~5 nm at half maximum) was used as a pump source. The pump imaging setup consisted of collimating (CL, $f = 40$ mm) and focusing (FL, $f = 200$ mm) lenses, producing a pump spot diameter of ~550 μm in the crystal. The laser crystal was wrapped in indium foil and sandwiched in an aluminum heat sink for better heat dissipation. Both the laser diode and the crystal were water-cooled at 16 °C.

As a mode locking element a semiconductor saturable absorber mirror was chosen for its ease of use as compared to Kerr-lens [22] or additive-pulse [12] mode locking techniques. On the other hand, as can be seen from the previous results, the fast non-resonant Kerr nonlinearity employed in these mode locking mechanisms and their higher modulation depth resulted in much shorter pulses than from a semiconductor saturable absorber in [11] which had a modulation depth of ~1%. Taking into account these points we selected a SESAM that had a relaxation time of 1 ps and 6% modulation depth (Batop GmbH). Unfortunately, such combination of parameters comes at the price of higher non-saturable losses that were at the same level as modulation depth. High intracavity

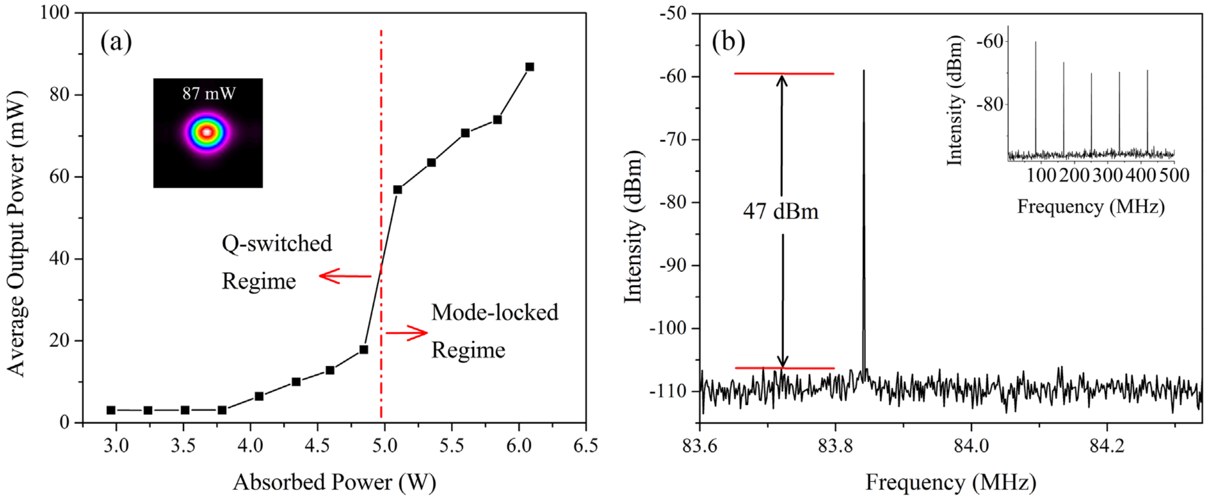

Figure 3. (a) The measured output power. Inset: transverse beam intensity profile at the full output power; (b) RF spectrum of the fundamental mode at ~83.8 MHz. Inset: wide span RF spectrum.

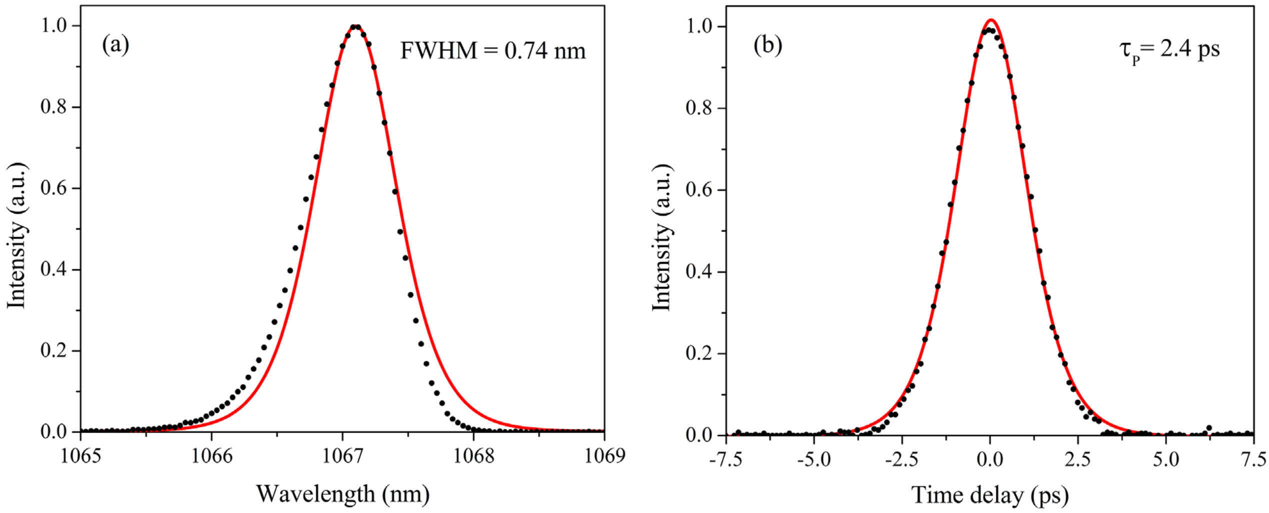

Figure 4. The spectrum (a) and the intensity autocorrelation (b) of the generated pulses. Red solid lines indicate corresponding sech^2 shape fits.

losses have a negative impact on output power. Thus, there is a trade-off between short pulse duration and high output power.

In the cavity the SESAM was used as one of the end mirrors. It had a saturation fluence of 70 μJ cm^{-2}. The beam spot size diameter on SESAM was about ~130 μm.

3. Results and discussion

Although absorption cross-section of hot-band pump transition employed in this work is in general fairly weak, the pump absorption in the relatively long used Nd:KGW crystal at 910 nm pump wavelength was measured to be up to 70% at the highest pump power level, corresponding to the absorption coefficient of 0.6 cm^{-1}. The pump power intensity at the crystal end-face was calculated to be 3.6 kW cm^{-2} and no crystal fracture was observed.

In the initial CW experiments (SESAM was replaced by a highly reflecting mirror) the laser could produce ~1 W of output power at full pump power. With the SESAM in the cavity the input–output power performance of the designed laser is displayed in figure 3(a). The laser exhibited two separate regimes of operation. Below 5 W of absorbed pump power the Q-switched mode-locked regime was observed. Above that point, stable mode-locked pulse train was routinely generated with a period of 11.8 ns (cavity round-trip time). At the onset of the mode-locked regime a sudden jump in the output power was observed as shown in figure 3(a). This can be interpreted as a full saturation of the SESAM by the generated pulses, which bleached its saturable losses (i.e. modulation depth) of 6%. For 6.08 W of absorbed pump power, 2.4 ps long pulses were obtained at 87 mW of average output power. The high level of intracavity loss (~6%) introduced by the SESAM contributed to the moderate output power.

The radio frequency (RF) spectral power of the mode-locked laser is shown in figure 3(b). The spectral power of the fundamental mode was 47 dBm above the noise level. In a wide-range RF scan measurement (inset in figure 3(b)), no additional peaks between the higher order modes were observed indicating stable single-pulse mode locking.

Spectral and temporal profiles of the generated pulses are presented in figure 4. The time-bandwidth product was calculated to be 0.44 and deviates from the transform-limited one (0.315 for $sech^2$) as expected in the positive dispersion mode locking regime. The peak power of the pulses was >0.4 kW and energy of each pulse was >1 nJ. The output beam was nearly diffraction limited and the beam quality factor M^2 was found to be less than 1.18.

Typical pulse durations produced by the SESAM mode-locked diode-pumped Nd:YAG, Nd:YLF and Nd:YVO lasers are in the 5–10 ps range [31]. In these cases the modulation depth of the absorbers was ~0.5–1% and the crystals were no longer than ~5 mm. The latter is important because this reduces the amount of positive intracavity dispersion which stretches the circulating pulses. For example, a longer (20 mm) Nd:YVO crystal used in [26] produced 16 ps pulses when used with SESAM which had 1.2% modulation depth. Therefore, despite the 20 mm long crystal used in our work the generated pulses are significantly shorter than can be expected. This can be mainly explained by the much higher modulation depth (6%) of the used SESAM.

4. Conclusion

In conclusion, we have demonstrated passive mode locking of a Nd:KGW laser hot-band-pumped at 910 nm. A SESAM was used to generate 2.4 ps pulses at a repetition rate of ~83.8 MHz. An output power of 87 mW was obtained at 1067 nm. This is the first report of mode locking performance observed with hot-band pumping in Nd:KGW laser. At the same time the generated pulses are the shortest reported to date for SESAM mode-locked Nd:KGW lasers. Low quantum defect pumping at 910 nm opens the way for further output power scaling due to the reduced influence of thermal effects. Powerful sources of picosecond pulses or their harmonics are attractive for applications in spectroscopy [7], nonlinear frequency conversion [1–3] or synchronous pumping of Ti:sapphire and other lasers [32, 33].

Acknowledgments

This work was supported by the Natural Sciences and Engineering Research Council of Canada, University of Manitoba, and Western Economic Diversification Canada.

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