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Observation of self-Q-switching in bulk Yb:GdYSiO laser*

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We report the first self-Q-switched Yb-doped $GdYSiO_5$ (Yb:GYSO) laser operating at 1080 nm. Stable Q-switched pulses with a repetition rate of 18.1 kHz and pulse duration of 9.45 μs are obtained. A maximum average output power of 452.6 mW is achieved with a 1% transmission output coupler. With a 3% transmission output coupler, the shortest pulse width of 6.6 μs is obtained. It demonstrates that Yb:GYSO crystal can be simultaneously employed as a saturable absorber and a gain medium to generate microsecond Q-switched pulses in the near infrared region.

Keywords: self-Q-switching, Yb:GYSO, saturable absorber

PACS: 42.60.Gd, 42.55.Tv, 42.70.–a **DOI:** 10.1088/1674-1056/27/4/044202

1. Introduction

Pulsed lasers have been widely used in the fields of material processing, remote sensing, laser radar, laser ignition, optical communication, nonlinear optics, etc.[1,2] For many practical applications, a pulsed laser source with relatively high peak power, large pulse energy and tunable pulse repetition rate is favorable, which can be realized by the Q-switching technique. The Q-switched pulsed laser typically can be obtained by active modulators or saturable absorbers.[3,4] The complex structure and insertion loss of Q-switchers restricts the development of pulsed laser. Another method of generating the Q-switched pulsed laser is self-Q-switching. There are multiple mechanisms of the self-Q-switching formation, such as Kerr lensing,[5] Brillouin scattering,[6] re-absorption of gain medium,[7] nonlinear loss,[8] and stimulated scattering.[9] There are some reports about self-Q-switched Yb^{3+} crystal laser. Low-threshold diode-pumped Yb^{3+}, Na^{+}:CaF_2 self-Q-switched laser was demonstrated in 2005.[10] A self-Q-switched and orthogonally polarized dual-wavelength laser was investigated with Yb:CGB crystals in 2014.[11] Self-Q-switching was observed in a bulk Yb:KGW oscillator in 2015.[12] No additional modulation elements are required in the self-Q-switched laser cavity, which reduces the laser volume and cost considerably.

The alloyed Yb:GYSO crystal was grown by the Czochraski method from a 50/50 solution of GSO and YSO,[13] which exhibits the C2/c structure. The Yb:GYSO has the advantages of a low pump threshold, excellent laser performance, desirable mechanical properties and long fluorescence lifetime. The absorption and emission spectra of Yb:GYSO crystal are shown in Fig. 1,[13] which indicates that Yb:GYSO has a broad emission spectrum spanning from 960 nm to 1100 nm, including several emission peaks near 1004 nm, 1039 nm, 1056 nm, and 1080 nm respectively. Pulsed Yb:GYSO lasers with active modulators or saturable absorbers have been reported. Zhou *et al.*[14] realized the generation of 210-fs laser pulses at 1093 nm by a self-starting mode-locked Yb:GYSO laser in 2009. He *et al.*[15] demonstrated diode-pumped soliton and non-soliton mode-locked Yb:GYSO lasers in 2011. Zhu *et al.*[16] reported a passively mode-locked Yb:GYSO laser generating 324 fs at 1091 nm. Tian *et al.*[17] demonstrated the dissipative soliton mode locking in a diode pumped $Yb:GdYSiO_5$ (Yb:GYSO) laser operating in the positive dispersion regime. However, self-Q-switched Yb:GYSO laser has not been reported to date.

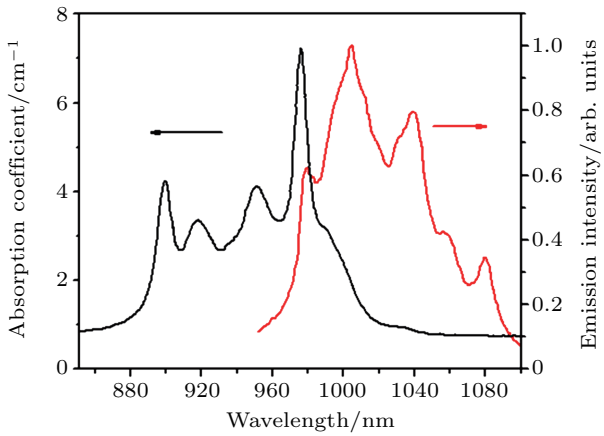


Fig. 1. (color online) Absorption and emission spectra of Yb:GYSO laser crystal at room-temperature.[13]

In this paper, we use a bulk Yb:GYSO crystal as a gain medium without any saturable absorbers in the cavity, realize the stable self-Q-switching operating near 1080 nm, and obtain pulses with a wavelength as short as 6.6 μs, a maximum

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average output power of 452.6 mW and the largest single pulse energy of 47.9 μJ. The experimental results are briefly explained by the re-absorption loss effect of the Yb:GYSO crystal with long excited-state lifetime. To the best of our knowledge, this is the first report on a self-Q-switched Yb:GYSO laser.

2. Experimental setup

The experimental setup of the self-Q-switched Yb:GYSO laser is shown in Fig. 2. The pump source was a high power fiber coupled diode laser operating at 976 nm with a maximum output power of 25 W. Two coupling lenses (L_1 and L_2) were used to focus the pump beam from the fiber bundle (with 105-μm core in diameter and 0.2 NA) into the laser crystal. The spot size of the pump beam radius on the laser crystal facet was calculated to be about 106.9 μm. The gain medium was a cut with a length of 5 mm and a cross section of 6 mm×3 mm Yb:GYSO crystal with a doping concentration of 5 at.%. The crystal length was 5 mm in the direction of the laser and orientation is random. The laser crystal was water-cooled down to a temperature of 15 °C. The input mirror M1 was a dichromic plane mirror high-transimissive at 976 nm and high-reflective from 1020 nm to 1100 nm. Two concave mirrors with transmissions of 1%, 3% at 1030 nm were used as the output couplers (OC) alternatively, and their curvature radii were both 100 mm. After fine tuning, a stable passively Q-switched operation could be achieved with a cavity length around 67 mm.

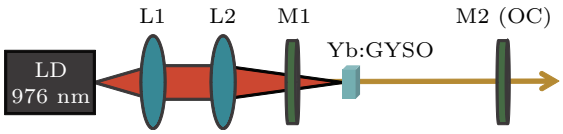


Fig. 2. (color online) Schematic diagram of the self-Q-switched Yb:GYSO laser.

3. Results and discussion

In experiment, the laser oscillates in a cw mode after fine collimation and the pump threshold is measured to be 3.4 W and 4.6 W with different output transmission values of 1% and 3% respectively. The threshold of cw laser in our experiment is higher than those of similar Yb^{3+}-doped solid lasers,[13,18] which is due to the fact that the cavity is designed for self-Q-switching, and the mode matching between pump laser and oscillating laser is not optimum. After we finely tune the tilt angle of the OC, the laser is turned to the pulsed state when the pump power exceeds 6 W in the two cases. The relationship between the output power and the pump power is shown in Fig. 2. To protect the crystal from being destroyed by the thermal effect, the maximum incident pump power is limited to 11.2 W. In the Q-switching regime, a maximum output power of 452.6 mW is achieved with an output transmission of 1% at a pump power of 10 W, corresponding to an optical-to-optical conversion efficiency of 4.2% and a slope efficiency of 8.6%. With an output transmission of 3%, we obtain a highest output power (309.2 mW) in the Q-switching operation. When the pump power reaches 11 W, the Q-switched pulses become unstable in both cases. Figure 3 indicates that the efficiency of self-Q-switched laser is lower than the counterpart cw laser with output coupler of 1% and 3% transmission, which is mainly due to the misalignment of the cavity mirrors. Because the crystal orientation is random, the output laser is circularly polarized instead of linearly polarized. The inset in Fig. 3 shows the long-term pulse trains at a pump power of 10 W, which demonstrates that the Q-switching is very stable.

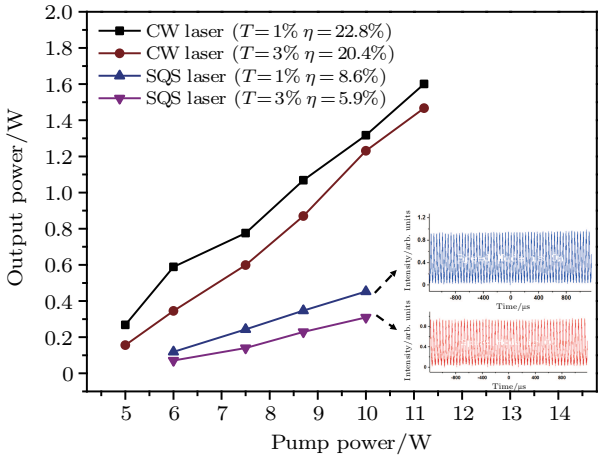


Fig. 3. (color online) Plots of output power in the cw mode and self-Q-switched state versus pump power under different transmission values of OC.

The pulse duration and the repetition rate of the self-Q-switched pulses versus pump power are shown in Fig. 4(a). With the increase of pump power, the pulse duration decreases gradually while the repetition rate increases, which are the typical characteristics of the passive Q-switching behavior, apparently different from those for the mode-locked lasers.[15] The single pulse energy and peak power of the self-Q-switched pulses versus the pump power are shown in Fig. 4(b). For the 1% OC, as the pump power increases from 6.26 W to 10 W, the pulse duration decreases monotonically from 16.96 μs to 9.45 μs while the pulse repetition rate increases from 9.2 kHz to 18.1 kHz, corresponding to 12.9 μJ to 47.89 μJ of the single pulse energy and 2.06 W–4.78 W of the peak power. For the 3% OC, while the pump power increases from 6.26 W to 10 W, the pulse duration decreases monotonically from 12 μs to 6.6 μs while the pulse repetition rate increases from 7.8 kHz to 13.5 kHz, corresponding to a pulse energy of 9.08 μJ–22.89 μJ and a peak power of 0.75 W–3.46 W. At the pump power of 10 W, the shortest pulse duration of 6.6 μs is achieved with a 3% transmission output coupler, and the highest output power of 452.6 mW is delivered for 1% transmission output coupler which is larger than the reported self-Q-switched Yb:KGW laser.[12]

In Fig. 5, we present a temporal pulse profile and a typical oscilloscopic trace under different output couplers. The pulse trains are recorded by a digital oscilloscope (54866A, Agilent

Technologies) when a small portion of the output laser is injected into a photodiode. Minimum pulse durations are obtained to be 9.45 μs and 6.6 μs for 1% and 3% output couplers, respectively.

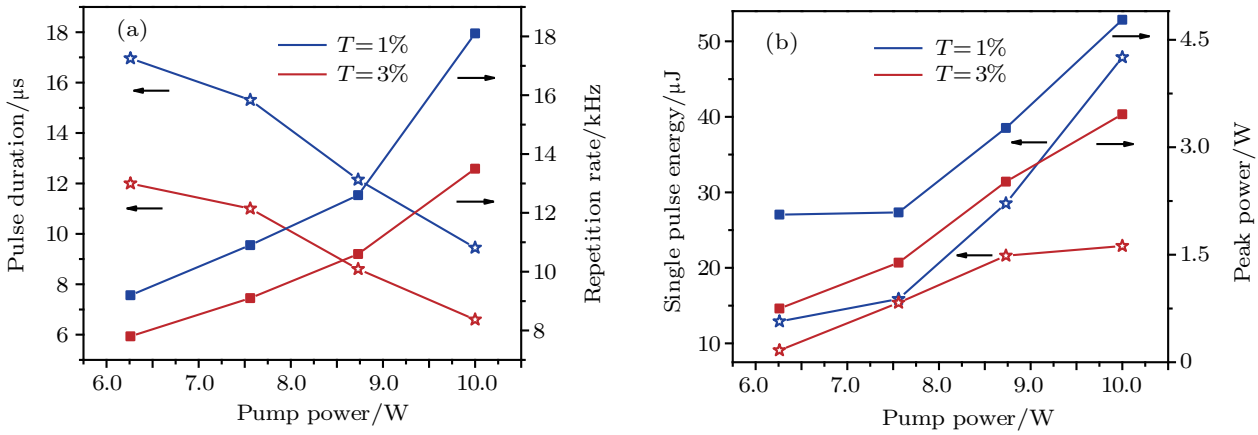


Fig. 4. (color online) (a) Pulse duration and pulse repetition rate versus the absorbed pump power. (b) Single-pulse energy and peak power versus absorbed pump power.

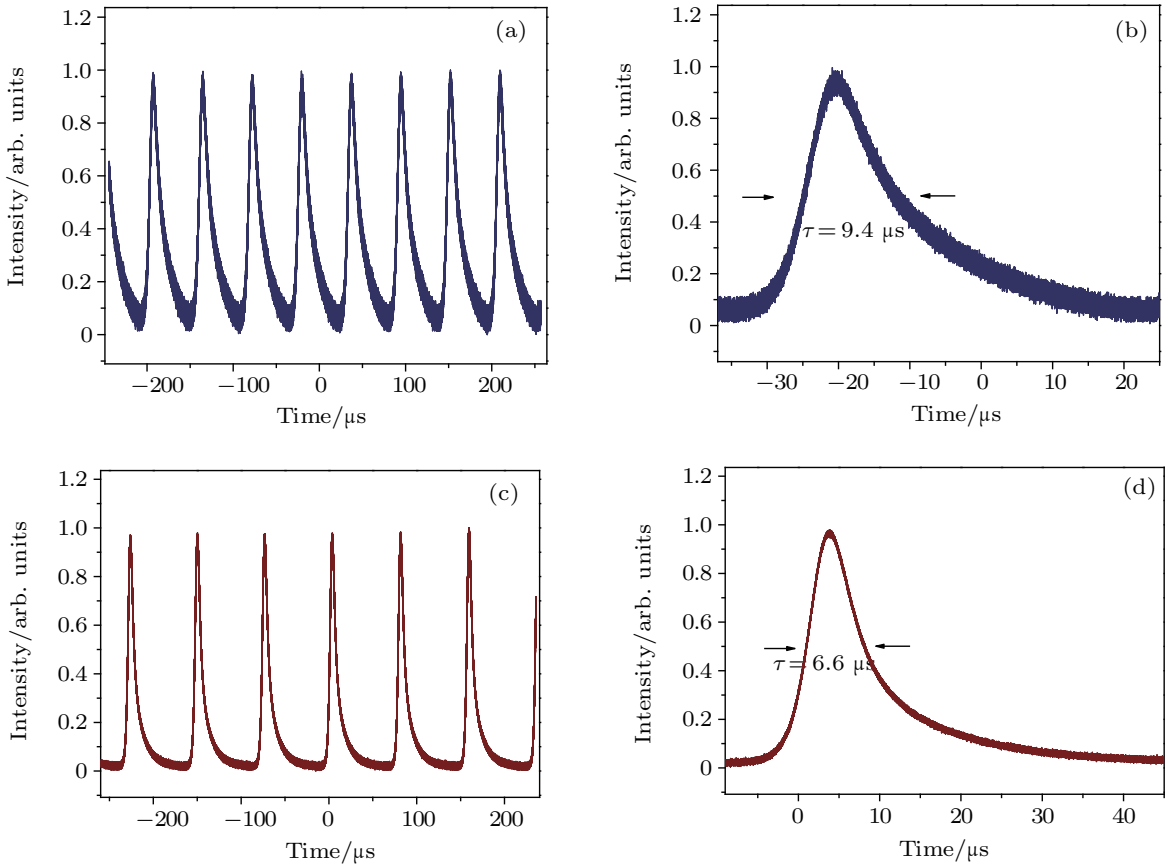


Fig. 5. (color online) Pulse trains of Q-switched pulses and temporal profile of the shortest pulse at the pump power of 10 W, showing (a) Q-switched pulse trains with $T = 1\%$, (b) temporal profile of shortest pulse with $T = 1\%$, (c) Q-switched pulse trains with $T = 3\%$, and (d) temporal profile of shortest pulse with $T = 3\%$;

The spectra of the cw laser and self-Q-switched pulses are detected by a spectrometer (S2000, Ocean Optics) with a resolution of 0.8 nm, and the results are shown in Fig. 6, demonstrating that the pulsed laser operates, separately, at 1080.8 nm and 1081.5 nm, which correspond to transmission values of 1% and 3%, respectively. The drift of central wavelength may possibly be attributed to the mode competition between the oscillating modes.

As to the mechanism of formation, we note that the self-Q-switching is observed in Yb:CGB crystal, which is attributed to the re-absorption effect for the long-lifetime Yb^{3+} crystal.[11] The Yb:GYSO crystal also exhibits a comparatively large excited-state lifetime, which is as high as 1.92 ms. The long excited-state lifetime ensures the considerable accumulation of inversion population during re-absorption. When the population of ground state is minimized and the ex-

cited state is fully populated, the re-absorption loss decreases rapidly, which acts as a saturable absorber, and thus resulting in the formation of Q-switching. After that, the saturated absorber recovers from saturated state to unsaturated state. With the continuous pumping, the gain population is reversed, rebooting the re-absorption for the next Q-switched pulse. When the gain is far above the re-absorption loss with the pump increasing, the re-absorption keeps up full bleach and the gain medium stores low energy. As a result, the Q-switching tends to be unstable and the laser finally would turn into cw operation, which is consistent with our experimental result. So, we believe that the self-Q-switching can be attributed to the reabsorption effect of the Yb:GYSO crystal with long excited-state lifetime. In our experiment, the reabsorption effect can be improved by modulating the Fresnel loss of OC and the cavity loss, meanwhile, the output power is reduced because of the misalignment of the OC. However, the laser cannot oscillate when the loss is too large. Therefore, for the self-Q-switched laser, the Fresnel loss and the cavity loss must be properly controlled to start self Q-switching while sustaining laser oscillation, which entails much experimental research. The different reabsorption effect results in different repetition rates and pulse durations. In the next work, we can adjust the re-absorption effect by changing the cavity structure and output transmission to shorten pulse duration and increase peak power.

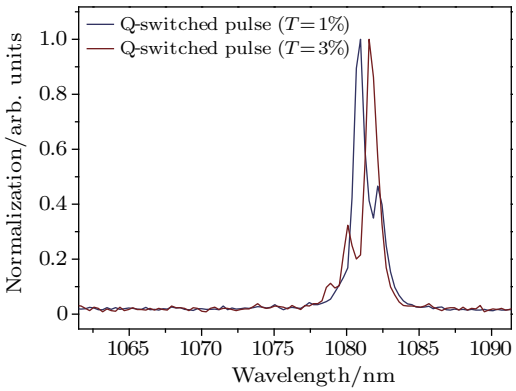


Fig. 6. (color online) Typical spectra for self-Q-switched pulses with OC of $T = 1\%$ and 3%, respectively.

4. Conclusions

In this work, we demonstrate the first self-Q-switched Yb:GYSO laser operating at 1.08 μm with a compact linear cavity. Under a pump power of 10 W, a maximum average output power of 452.6 mW and the largest single pulse energy of 47.9 μJ with a pulse duration of 9.45 μs and a pulse repetition rate of 18.1 kHz are obtained by a 1% transmission output coupler. The shortest pulse duration of 6.6 μs with an output power of 309.2 mW is achieved by a 3% transmission output coupler. Our experiment is the first observation of self-Q-switched Yb:GYSO laser and shows that Yb:GYSO crystal is also a self-Q-switched crystal for compact all-solid-state lasers.

References

[1] Zayhowski and J 1999 *Laser Focus Word* **35** 129
[2] Paschotta R 2008 *Wiley-VCH* **15** 16
[3] Liu J H, Tian J R, Guoyu H Y, Xu R Q, Li K X, Song Y R, Zhang X P and Su L B and Xu J 2016 *Chin. Phys. B* **25** 034207
[4] Wang X, Li L, Li J P and Wang Y G 2017 *Chin. Phys. B* **26** 044203
[5] Weber B C and Hirth A 1996 *Opt. Commun.* **128** 158
[6] Freund I 1968 *Appl. Phys. Lett.* **12** 388
[7] Liu J J, Fan X W, Liu J, Ma W W, Wang J Y and Su L B 2016 *Opt. Lett.* **41** 4660
[8] Cai W, Liu J, Li C, Zhu H T, Ge P G, Zheng L H, Su L B and Xu J 2015 *Opt. Commun.* **334** 287
[9] Fotiadi A A, Mégret P and Blondel M 2004 *Opt. Lett.* **29** 1078
[10] Su L B, Xu J, Xue Y H, Wang C Y, Chai L, Xu, X D and and Zhao G J 2005 *Opt. Express* **13** 15
[11] Xu J L, Ji Y X, Wang Y Q, You Z Y, Wang H Y and Tu C Y 2014 *Opt. Express* **22** 6577
[12] Liu J H, Tian J R, Dou Z Y, Hu M T and Song Y R 2015 *Chin. Opt. Lett.* **13** 061407
[13] Du J, Liang X Y, Xu Y, Li R X, Xu Z Z, Yan C F, Zhao G J, Su L B and Xu J 2006 *Opt. Express* **14** 3333
[14] Zhou B B, Wei Z Y, Zhang Y D, Zhong X, Teng H, Zheng L H, Su L B and and Xu J 2009 *Opt. Lett.* **34** 31
[15] He J P, Liang X Y, Li J F, Zheng L H, Su L B and Xu J 2011 *Chin. Phys. Lett.* **28** 084204
[16] Zhu J F, Tian W L, Wang J L, Wang Z H, Wei Z Y, Zheng L H, Su L B and and Xu J 2012 *Opt. Lett.* **37** 5190.
[17] Tian W L, Zhu J F, Wang Z H, Wang J L and and Wei Z Y 2014 *Chin. Opt. Lett.* **12** 031401.
[18] Li W X, Hao Qiang, Ding L E, Zhao G J, Zheng L H, Xu J and and Zeng H P 2008 *IEEE J. Quantum Electron.* **44** 567