IEEE Photonics Journal
An IEEE Photonics Society Publication

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Volume 6, Number 3, June 2014

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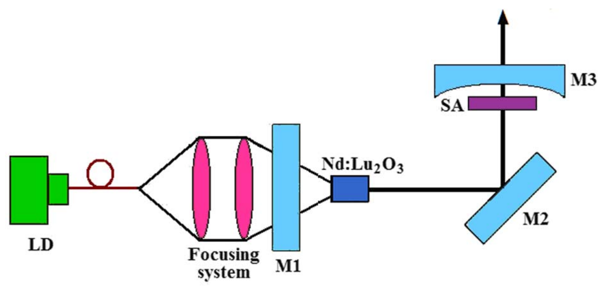

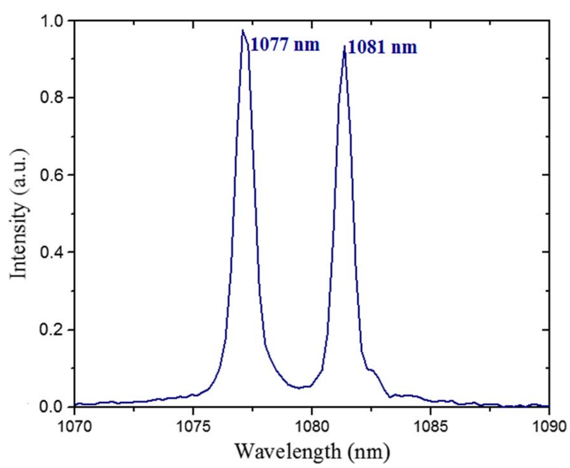

DOI: 10.1109/JPHOT.2014.2320734

Topological Insulator Simultaneously Q-Switched Dual-Wavelength $Nd:Lu_2O_3$ Laser

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DOI: 10.1109/JPHOT.2014.2320734

Manuscript received March 8, 2014; revised April 15, 2014; accepted April 22, 2014. Date of publication April 28, 2014; date of current version May 13, 2014. This work was supported in part by the National Natural Science Foundation of China under Grant 51025210, Grant 51102156, and Grant 51021062 and in part by the Shandong Province Young and Middle-Aged Scientists Research Awards Fund under Grant BS2011CL024. Corresponding authors: H. Yu and H. Zhang (e-mail: haohaiyu@sdu.edu.cn; huaijinzhang@sdu.edu.cn).

Abstract: We demonstrated the dual-wavelength simultaneously Q-switched $Nd:Lu_2O_3$ laser with a topological insulator Bi_2Se_3 as the Q-switcher. The continuous-wave $Nd:Lu_2O_3$ crystal laser with the slope efficiency of 31% was achieved, and the first $Nd:Lu_2O_3$ pulsed laser operation was reported, as far as we know. By using the wavelength-insensitive saturable absorption of topological insulators, the dual wavelength of the $Nd:Lu_2O_3$ crystal laser can be Q-switched simultaneously without the frequency selection of the saturable absorber, since the emission cross-sections of $Nd:Lu_2O_3$ at the wavelengths of 1077 and 1081 nm are comparable. The results indicate that the topological insulator is wavelength-insensitive and should be suitable for the dual-wavelength simultaneously Q-switched laser as a passive Q-switcher. It can be proposed that this work would provide an efficient technology for the dual-wavelength simultaneously Q-switched laser, which has promising applications in many regimes.

Index Terms: Topological insulator, Bi_2Se_3, $Nd:Lu_2O_3$ crystal, dual-wavelength laser.

1. Introduction

Dual-wavelength pulsed lasers have promising applications in the generation of coherent terahertz radiation, optical communications, pump-probe experiments, optical beating, etc. [1]–[11]. Passive Q-switching is a traditional technology for the generation of pulses. In the Q-switching process, the saturable absorber can also play the role of frequency selecting, since the absorption cross-sections of the traditional saturable absorbers and the emission cross-sections of the gain materials are different at different wavelengths [10], besides the dispersion of the laser cavity. Therefore, the ratio of oscillating modes at different wavelengths changes with the pump power, which indicates that the incident pump power and output power should be fixed during the applications such as in the generation of terahertz radiation by difference frequency generation and novel wavelength by the sum-frequency. Based on the Q-switched laser theory [12], [13], for the generation of

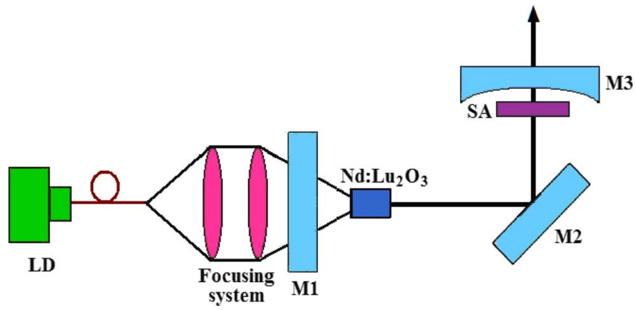

Fig. 1. Schematic arrangement of the passively Q-switched $Nd:Lu_2O_3$ laser.

dual-wavelength simultaneously Q-switched lasers with an unchanged ratio of oscillating modes, the saturable absorption of the Q-switcher should be wavelength-insensitive and the emission cross-sections of the gain material at different wavelengths should be comparable.

Topological insulator is a novel type of quantum matter. Recently, the quantum anomalous Hall Effect has been experimentally observed in a topological insulator [14]. Besides that shown above, it also has a narrow bulk gap (0.2–0.3 eV) and Dirac cone on the surface [15]–[18], which indicates that the topological insulator can be used as a wavelength-insensitive mode-locker and Q-switcher in the pulsed lasers [19], [20]. Recently, the saturable absorption of topological insulators with wavelength-insensitivity has been investigated, and their mode-locking and Q-switching performances have been studied at given wavelengths [19]–[22]. However, the dual-wavelength Q-switching of topological insulators has not been reported up to now. $Nd:Lu_2O_3$ as a gain material in the high-power solid-state lasers has more advantages, since it has high thermal conductivity, abundant emission peaks in the fluorescence spectra, low photon energy, etc. [23], [24]. Besides those shown above, its strongest emission peaks are located at the wavelengths of about 1077 and 1081 nm with the emission cross-sections of 8.52×10^{-20} cm^2 and 8.49×10^{-20} cm^2, respectively, corresponding to the transition from $^4F_{3/2}$ level to different terminal levels of $^4I_{11/2}$ generated by Stark splitting in the crystal-field. It can be proposed that the comparable emission cross-sections can generate dual-wavelength simultaneously Q-switched laser with the wavelength-insensitive topological insulator. Unfortunately, up to now, there have been no reports on the pulsed laser performances of $Nd:Lu_2O_3$ materials including ceramics and crystals [23]–[25]. In the investigation of $Nd:Lu_2O_3$ crystal, the high melting temperature (2530 °C) constrained achievement of high-quality crystals [23], [26]. Recently, we have reported the successful crystal growth with the optical floating zone method [23] and high-quality $Nd:Lu_2O_3$ crystals have been obtained. Here, we report the topological insulator Q-switched $Nd:Lu_2O_3$ lasers with simultaneous oscillating modes at the wavelengths of 1077 and 1081 nm.

2. Experimental Setup

The topological insulator Bi_2Se_3 sample was synthesized onto a 1-mm thick quartz plate with a diameter being about 25 mm by a polyol method [27], and then the plate with Bi_2Se_3 on it was used as the Q-switcher in our experiments. *The thickness of the Bi_2Se_3 was about 50 nm* [27]. The transmission spectrum of the plate was about 68% over the measured wavelength range from 900 to 2500 nm. Taking into account the reflectivity of the quartz substrate of 7%, the loss generated by the Bi_2Se_3 sample was nearly about 25% which showed its wavelength-insensitive absorption characteristic in a broadband range. The $Nd:Lu_2O_3$ crystal was grown by the optical floating zone method with a Nd^{3+} concentration of 1.0 at.% and dimensions of $2 \times 2 \times 4$ mm^3. Its end faces were polished and not coated.

The schematic arrangement of the passively Q-switched $Nd:Lu_2O_3$ laser was illustrated in Fig. 1. The pump source was a fiber-coupled 808 nm diode laser with a core diameter of 100 μm and numerical aperture of 0.22. The input mirror M1 was a plane mirror with antireflection (AR) coated at 808 nm and high-reflection (HR) coated at about 1080 nm. To avoid possible damage

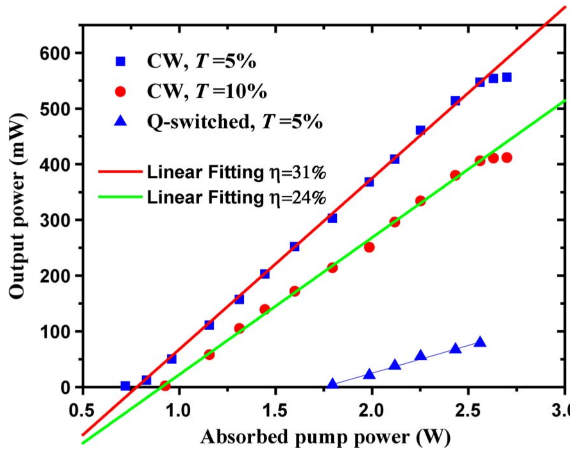

Fig. 2. Output power versus absorbed pump power for CW ($T = 5\%$ and 10%) and Q-switched ($T = 5\%$) laser operation.

and influence caused by the unabsorbed pump light on the Bi_2Se_3 sample, a three-mirror L-shape cavity was used with the total cavity length of 95 mm. The 45° folding mirror M2 was a plane mirror HR-coated at about 1080 nm. The length between M1 and M2 was about 40 mm. The output coupler (OC) M3 was a concave mirror with a curvature radius of 100 mm. The pump radiation was coupled into $Nd:Lu_2O_3$ crystal by a focusing system with the focusing ratio of 1:1. The $Nd:Lu_2O_3$ crystal was wrapped with indium foil and mounted in a copper block cooled by water at a temperature of 15 °C. The Bi_2Se_3 saturable absorber was placed between M2 and M3 to realize Q-switching operation eliminating the influence of the pump beam. The output power was measured with a Newport model 1916-R optical power meter. The temporal characteristics of the Q-switched pulse were studied by a Tektronix TDS3012C digital phosphor oscilloscope. The laser spectra were recorded with an Ocean Optics Inc. model HR4000CG-UV-NIR optical spectrum analyzer.

3. Results and Discussion

Removing the Bi_2Se_3 saturable absorber from the cavity, we firstly performed the continuous-wave (CW) operation of the $Nd:Lu_2O_3$ laser. In CW regime, two output couplers (OCs) with different transmissions (Ts) of 5% and 10% were employed. The variation of output power with absorbed pump power was given in Fig. 2. The thresholds absorbed pump power were 0.72 W and 0.93 W with the OCs of $T = 5\%$ and 10%, respectively. The higher maximum output power of 556 mW was obtained under the absorbed pump power of 2.7 W with the OC of $T = 5\%$ corresponding to the slope efficiency of 31% and optical-optical efficiency of 20.6%. With the OC of $T = 10\%$, the maximum output power of 412 mW was achieved, and the corresponding slope efficiency and optical-optical efficiency were 23.9% and 15.3%, respectively. With an OC with $T = 2\%$, the maximum output power was only 406 mW with the slope efficiency of 22%. Therefore, the OC with $T = 5\%$ should be the optimized one. It can also be observed that the output powers were saturated under the absorbed pump power of larger than 2.5 W, which should be attributed to the serious thermal induced lens which was induced by the small pump beam (diameter of 100 μm). From the spectra recorded by the optical spectrum analyzer, it could be found that the modes with wavelengths of about 1077 nm and 1081 nm oscillated with almost the same threshold due to the comparable emission cross-sections at the two wavelengths. The typical laser spectrum was presented in Fig. 3. By adjusting M3 to a tilt angle introducing the astigmatism into the cavity, the ratio of the two modes can be tuned, but it cannot be changed by the pump power. The CW results also indicated that by insetting a wavelength-insensitive Q-switcher, the dual-wavelength simultaneously Q-switched laser could be achieved.

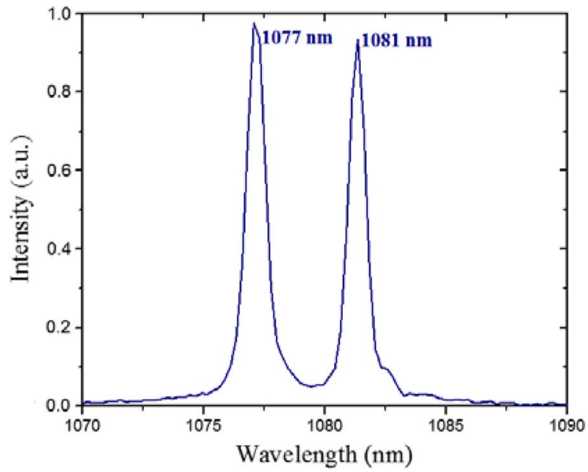

Fig. 3. CW laser and passively Q-switched laser spectrum of the dual-wavelength at 1077 and 1081 nm.

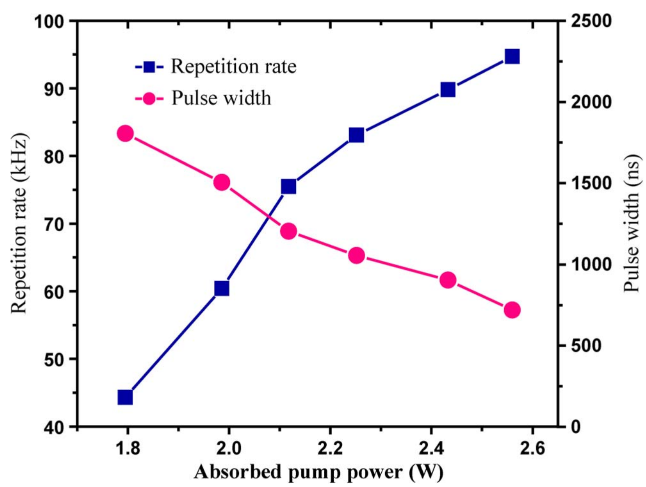

Fig. 4. Repetition rate and pulse width versus the absorbed pump power.

The threshold pump power for a four-level lasing system can be given by [28]

$$P_{th} = K(L - lnR) \quad (1)$$

where P_{th} is the threshold pump power, K is a constant for the crystal and cavity, L is the intracavity round-trip dissipative optical loss, and R *is the coupled reflectivity between the OC* and *the surface of the crystal*. Using the thresholds pump power measured with different OCs and *according to the multiple beam interference theory* [29], *L was calculated to be 3%, which indicated that the crystal quality should be improved.*

Since the OC of $T = 5\%$ could generate the highest output power and efficiency, and the saturable intensity of Bi_2Se_3 was high (4.3 GW/cm^2) which indicated the intracavity intensity should be high [19], the Q-switched laser performance was investigated with the OC of $T = 5\%$. By inserting the Bi_2Se_3 saturable absorber into the cavity and optimizing its position, we realized the passive Q-switching operation of the $Nd:Lu_2O_3$ laser. The dependence of the average output power on the absorbed pump power was also illustrated in Fig. 2. The threshold pump power was measured to be 1.80 W. When the pump power increased to 2.56 W, the maximum average output power of 79 mW was achieved. Augmenting the pump power, the output power was also saturated.

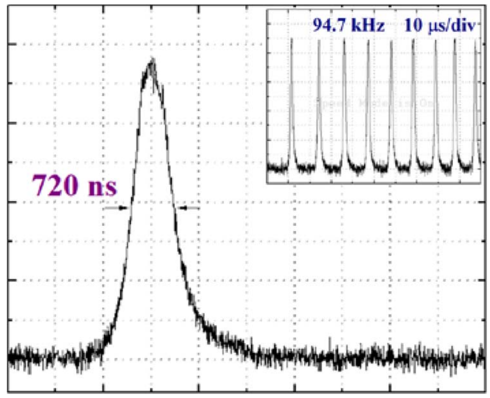

Fig. 5. Single pulse profile with duration of 720 ns (inset: corresponding pulse train with the repetition rate of 94.7 kHz).

The slope efficiency was 10.0% and optical-optical efficiency was 3.1%. The repetition rate increased from 44.3 to 94.7 kHz with the absorbed pump power rising from the threshold 1.80 to 2.56 W, while the pulse width decreased from 1.81 μs to 720 ns. The repetition rate and pulse width with the pump power were shown in Fig. 4. The large change of the pulse width indicated that the topological insulator saturable absorber was not fully saturated by the intracavity intensity at the pump power near threshold, although the OC with $T = 5\%$ was used. The pulse train with the repetition rate of 94.7 kHz and corresponding single pulse profile with duration of 720 ns were shown in Fig. 5. From this figure, it can be found that the pulse train was stable and no significant pulse jitter was observed on the oscilloscope, moreover, there was no satellite pulse before or after the pulse. *However, if the incident pump power increased further, the repetition rate rose* and *the Q-switching operation became unclear because the pulse width was large due to the low modulation depth of the Bi_2Se_3 sample* [19]. Based on the measured average output power and repetition rate, the pulse energy was calculated with the maximum pulse energy of 834.2 nJ. It should be noted that during all the experiments, no damage was observed on the Bi_2Se_3 sample, which indicates that Bi_2Se_3 could be employed for modulating large energy pulses, besides as a mode-locker with small pulse energy. *According to the passive Q-switching theory* [12], [13], *the pulse energy could be improved by using the topological insulator saturable absorber with larger modulation depth.*

With a spectrum analyzer, the Q-switched laser spectra under different absorbed pump power were recorded, which were almost unchanged with the CW laser spectra. The modes of 1077 and 1081 nm had almost the same thresholds. Furthermore, with the pump power increasing, the spectral intensity ratio of the two wavelengths remained unchanged, which indicated that the output power ratio of the two modes at different wavelength kept constant with the pump power and output energy. Combining the achieved stable pulse train, it can be concluded that the pulses of the modes at different wavelengths are time overlapped, and different with the traditional saturable absorber such as Cr:YAG [10], so the topological insulator is an ideal wavelength-insensitive saturable absorber for the generation of dual-wavelength laser pulses.

According to the analysis of the coupled rate equations [13], the initial population inversion density n_i at the start of Q-switching can be given by

$$\mathrm{n_i} = \frac{\ln\left(\frac{1}{\mathrm{R}}\right) + \ln\left(\frac{1}{\mathrm{T_0^2}}\right) + \mathrm{L}}{2\sigma l} \tag{2}$$

where $R = 95\%$ is the reflectivity of the OC at the laser wavelength; T_0 is the initial transmission of the Bi_2Se_3 saturable absorber; $l = 4$ mm is the length of the $Nd:Lu_2O_3$ crystal; and σ is the emission cross-section of $Nd:Lu_2O_3$ crystal at the laser wavelength, which is about 8.52×10^{-20} cm^2 at 1077 nm and 8.49×10^{-20} cm^2 at 1081 nm. From Eq. (2), n_i was calculated to be 1.251×10^{19} cm^{-3} and 1.255×10^{19} cm^{-3} for the modes at 1077 and 1081 nm, respectively, which were almost the same. As the pump power increases in the Q-switching operation, the population inversion density increases rapidly and reaches the threshold at 1077 and 1081 nm at the same time, so the modes at 1077 and 1081 nm should oscillate simultaneously, and the pulses should be synchronous and time overlapped. The results also identify that dual-wavelength simultaneously Q-switched lasers with an unchanged ratio of oscillating modes can be obtained by using a gain material with comparable emission cross-sections at different wavelengths and a Q-switcher with wavelength-insensitive saturable absorption. In addition, with a polarizer, the polarization of the dual-wavelength laser was investigated and found to be unpolarized due to the cubic symmetry of $Nd : Lu_2O^3$ crystal.

4. Conclusion

In conclusion, a dual-wavelength simultaneously Q-switched solid-state laser with a topological insulator Bi_2Se_3 as the Q-switcher was constructed. The CW $Nd : Lu_2O_3$ crystal laser with the slope efficiency of 31% was achieved and the dual-wavelength $Nd : Lu_2O_3$ crystal pulses at 1077 and 1081 nm were firstly achieved. The results indicated that topological insulator was suitable as a wavelength-insensitive passive Q-switcher, and the pulsed lasers should have promising applications in many regimes.

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