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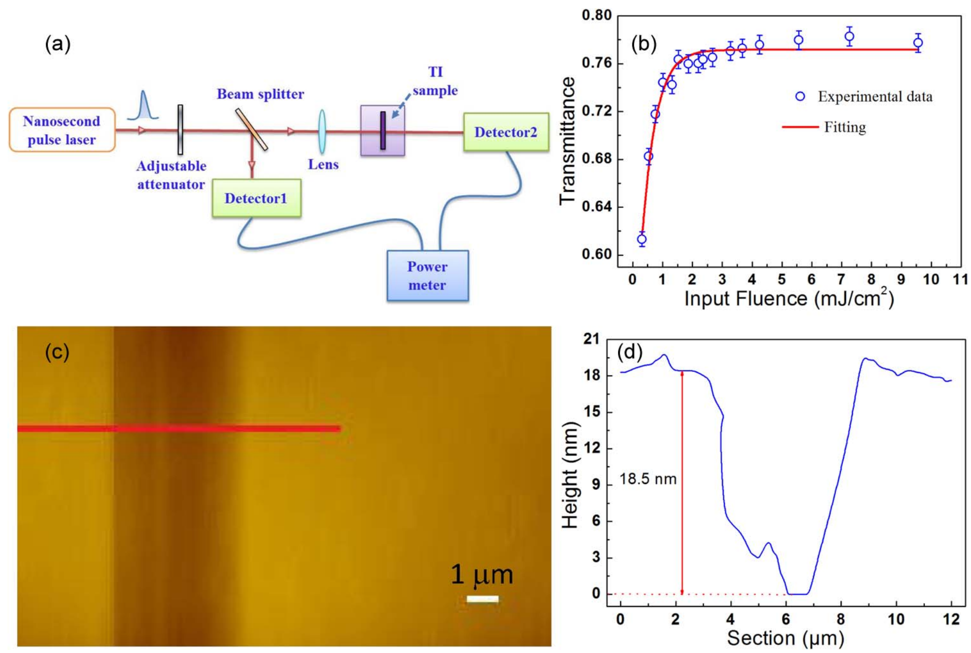
Pinghua Tang
Xiaoqi Zhang
Chujun Zhao
Yong Wang
Han Zhang
Deyuan Shen
Shuangchun Wen
Dingyuan Tang
Dianyuan Fan



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Topological Insulator: Bi_2Te_3 Saturable Absorber for the Passive Q-Switching Operation of an in-Band Pumped 1645-nm Er:YAG Ceramic Laser

Pinghua Tang,[1] Xiaoqi Zhang,[2] Chujun Zhao,[1] Yong Wang,[3] Han Zhang,[1] Deyuan Shen,[4] Shuangchun Wen,[1] Dingyuan Tang,[3] and Dianyuan Fan[2]

[1]Key Laboratory for Micro-/Nano-Optoelectronic Devices of Ministry of Education, College of Physics and Microelectronic Science, Hunan University, Changsha 410082, China
[2]Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai 201800, China
[3]School of Physics and Electronic Engineering, Jiangsu Normal University, Xuzhou 221116, China
[4]Key laboratory of Micro and Nano Photonic Structures (Ministry of Education), Department of Optical Science and Engineering, Fudan University, Shanghai 200433, China
P. Tang and X. Zhang contributed equally to this work.

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Abstract: An in-band pumped 1.645-μm Er:YAG ceramic laser passively Q-switched by a topological insulator: Bi_2Te_3 saturable absorber is reported. The average output power could reach up to 210 mW, corresponding to a pulsewidth, a pulse repetition rate, and a per-pulse energy of 6.3 μs, 40.7 kHz, and 5.3 μJ, respectively. This result indicates that the topological insulator: Bi_2Te_3 could be a promising saturable absorber such as graphene, with potential applications for solid-state lasers.

Index Terms: Topological insulator, Q-switching (Q-S), Er:YAG, ceramic laser.

1. Introduction

Lasers operated in the eye-safe wavelength regime around 1.645 μm are of great importance for various applications, such as remote monitoring, ranging, and optical communication [1]–[3]. In order to realize the laser emission at this interested wavelength, the in-band pumping of Er:YAG crystal bulk lasers by direct diode at 1470 or 1532 nm, or, alternatively, a hybrid fiber-bulk laser configuration were commonly employed [4]. To establish the Q-switching (Q-S) operation at 1.645 μm, the laser cavity must be incorporated with an intensity modulation component, namely, an electrooptic or an acoustic-optical switcher by Shen *et al.* [5], Wang *et al.* [6], and Moskalev *et al.* [7], in which, however, the intensity modulation component shows the disadvantage of being expensive, lossy, and bulky. To overcome those drawbacks from those crystal-based modulators, Gao *et al.* reported the first passive Q-S operation at 1.645 μm with a single pulse energy of 7.05 μJ by a graphene saturable absorber [8]. Since the first demonstration of passive mode locking by a graphene saturable absorber [9], graphene had already been widely recognized as a passive Q-switcher and a mode locker for various wavelengths in either fiber lasers [10]–[12] or solid-state lasers [8], [13]–[19]. Due to the linear energy band structure in graphene, it could absorb a wide spectrum of photons, and, therefore, operate as a broad-band saturable absorber, which accounts for the passive Q-S operation at 1.645 μm. However, in addition to graphene, saturable absorbers operating at 1.645 μm are still hardly available, and correspondingly, the search for new types of saturable absorbers, operating at this particular wavelength, is highly encouraged. Herein, we employed another effective saturable absorber: the topological insulator (TI): Bi_2Te_3 for the passive Q-switching in an in-band pumped 1.645-μm Er:YAG ceramic laser, with a maximum average output power up to 210 mW.

2. Experimental Setup and TISA

TI is a new type of Dirac material in which its bulk state behaves as an ordinary band insulator, with the Fermi Level sitting between the conduction and valence bands, and on its surface, a metallic conduction state is permitted [20], [21]. Its surface state shows a graphene-like band structure, that is, Dirac-like linear band dispersion [20], [21]. Although its unique electronic properties had been intensively investigated, its nonlinear optics property is relatively less studied. Recently, Bernard *et al.* has experimentally found that the TI: Bi_2Te_3 has showed saturable absorption behavior at telecommunication wavelength [22] and has acted as an efficient mode locker [23]. Herein, we experimentally found that the Bi_2Te_3, a TI saturable absorber (TISA) device, could work as a passive Q-switcher for solid-state laser operation at 1.645 μm. This also indicates that, like graphene, TI: Bi_2Te_3 could be another broad-band saturable absorber for laser photonics applications.

Currently, MBE growth [24], vapor–liquid–solid growth [25], and mechanical exfoliation of thin sheets from bulk crystals [26] can be used to prepare the high-quality topological insulator samples. However, the samples fabricated by these methods are expensive in cost or relatively small in size. In this letter, a hydrothermal intercalation/exfoliation method as a low-cost and convenient approach was adopted to synthesize the Bi_2Te_3 nanosheets [27], and the TISA component was prepared in [23] and [28] that could be also incorporated into the solid-state laser cavity. Based on a balanced twin-detector measurement technique, we performed the saturable absorption measurement of the TISA component using the experimental setup in Fig. 1(a). The laser source is an acousto-optic Q-switched solid-state laser with a center wavelength, a pulsewidth, and a repetition rate of 1645 nm, 350 ns, and 2 kHz, respectively. The laser source was split into two beams by a beam splitter (splitting ratio is 61.4%: 39.6%), namely, one as a reference beam used to characterize the power before the sample is monitored by detector 1, the other was focused on the sample by lens, and the laser intensity after TISA was monitored by detector 2. By continuously tuning the incident laser power through adjusting the optical attenuator, one can record the output power change with respect to different input powers. The nonlinear transmission curve is shown in Fig. 1(b). By fitting the measured data, one can find that the saturable energy density of the TISA component used for the passive Q-switching laser is about 0.45 mJ/cm^2. In order to verify whether the saturable absorption dynamics originates from the optical damage, we control the optical power at very low intensity and gradually increase the laser intensity from sufficiently low-power to high-power regime and then decrease the laser intensity from high-power to low-power regime. Almost the same nonlinear transmission curve can be still observed, no matter whether the laser power is increased from low intensity or decreased from high intensity. An atomic force microscopy (AFM) image was used to determine the thickness of the TI sample, as shown in Fig. 1(c). The corresponding height profile [see Fig. 1(d)] suggests that the average sample thickness is about 18.5 nm.

Fig. 2(a) shows the experimental setup of the passively Q-switched Er:YAG ceramic bulk solid-state laser, in which a Z-shaped cavity was designed. It consists of a plane input mirror (M1) with high reflectivity ($>$ 99%) from 1600 to 1700 nm and high transmittance ($>$ 97%) at 1532 nm. Both the concave mirrors (M2 and M3) are highly reflective ($>$ 99%) at the wavelength of 1500 to 1700 nm, with the curvature radius of 200 mm (M2) and 100 mm (M3), respectively. The plane output coupler (M4) has a transmittance of 5% at the lasing wavelength of 1.645 μm and a high reflectivity ($>$ 99%) at the pump wavelength of 1532 nm. The TISA component was placed close to the output coupler (M4). The total length of the resonator was approximately 754 mm. The Er:YAG ceramic pumped by an Er,Yb fiber laser under the current investigation had a length of 28.4 mm and a cross section of

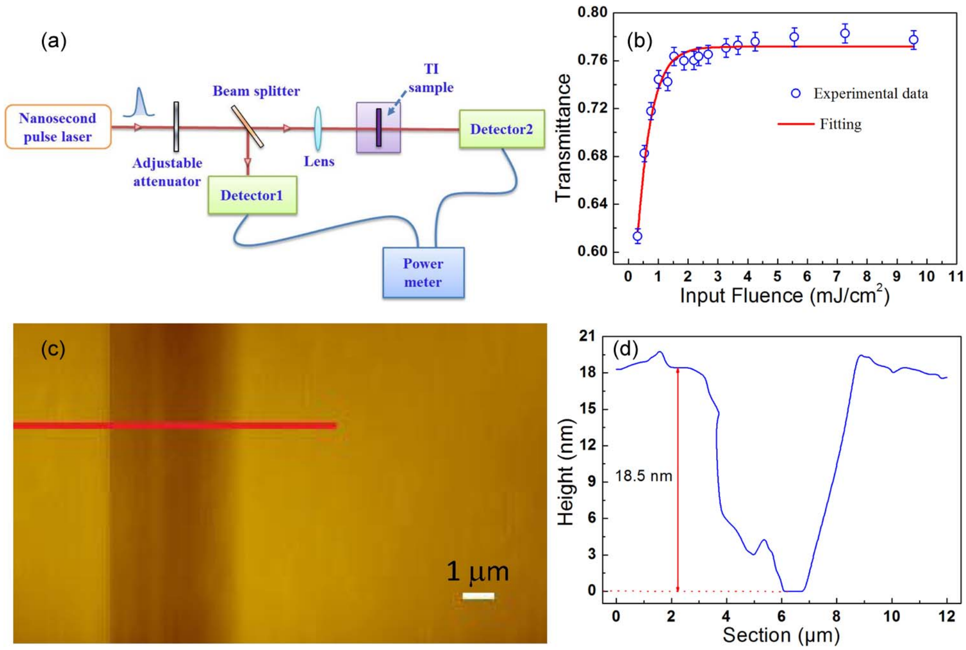

Fig. 1. (a) Experimental setup for saturable absorption measurement of TISA. (b) Nonlinear transmission curve of TISA. (c) AFM image of the TI sample and (d) its corresponding height profile.

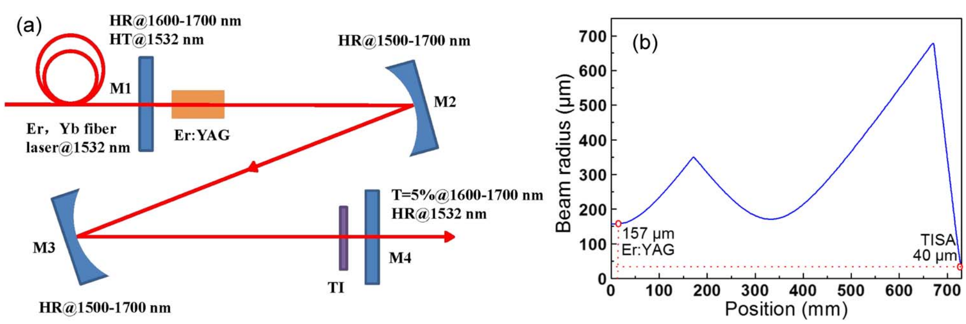

Fig. 2. (a) Experimental setup of the TI Q-switched Er:YAG ceramic laser. (b) Calculated beam radii of the Q-switched Er:YAG ceramic laser inside the cavity.

2×3.5 mm^2. The erbium-ion-doped concentration was 0.5 at.%. Both surfaces of the Er:YAG ceramic were antireflection coated for the 1500- to 1700-nm wavelength regime. The as-used hybrid fiber-bulk laser configuration with an Er,Yb fiber laser at the wavelength of 1532 nm as a pump source possesses several advantages. First, it can avoid the drawback of low pump-to-signal conversion efficiency from the current available diode pump laser because it has a relatively broad linewidth and poor beam quality [4]. Second, the thermal effect can be significantly suppressed in that most of the heat generated from quantum defect heating is deposited in the optical fiber [5]. Third, energy-transfer up-conversion effect can be greatly reduced for relatively low active ion concentrations used in the bulk ceramic (since good beam quality of the fiber pump source), which offers the potentials for increasing the pulse energy [5]. The Er,Yb fiber laser output was collimated and then focused onto the Er:YAG ceramic. The calculated radius of the oscillating mode in the middle of the Er:YAG ceramic was about 157 μm and about 40 μm on the TISA [see Fig. 2(b)]. The Er:YAG ceramic was wrapped with indium foil and mounted in a copper heat sink in order to maintain its temperature constant at 15.5 °C by the water cooler.

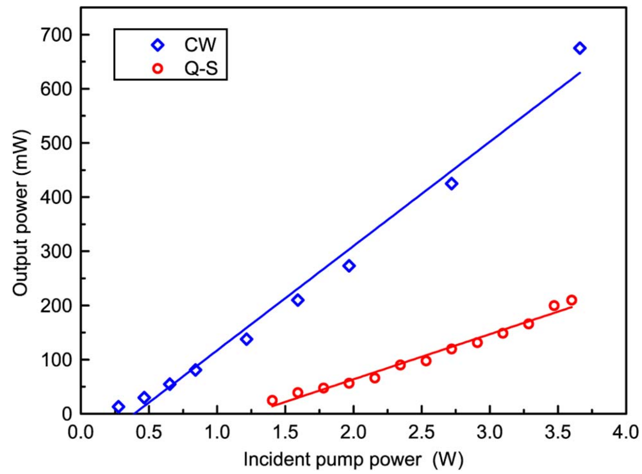

Fig. 3. Output power versus incident pump power for CW and Q-S operation.

3. Experimental Results and Discussion

Experimentally, we first examined the performance of the continuous-wave (CW) operation of the 1.645 μm Er:YAG ceramic laser without the TISA component. In this regime, the lasing threshold pump power was 323 mW. The output power quasi-linearly increases up to 675 mW, with the incident pump power increased to 3.6 W. The slope efficiency was about 19.2% with respect to the incident pump power. No self-Q-switching was observed during the process of increasing the pumping strength. Once the TISA component was placed inside the cavity after finely tuning the resonator and optimizing the position of the TISA component, a stable Q-switched laser operation could be readily obtained. In the Q-switched mode, the threshold pump power increased to 1.4 W. At a pump power of 3.6 W, the output power could reach to 210 mW, and the corresponding slope efficiency was about 8.4%. The output power versus the incident pump power for CW and Q-switched mode were both shown in Fig. 3. The lower output power and the slope efficiency of the Q-switched mode could be attributed to the large loss induced by the quartz substrate and TI sample in view that the quartz substrate was not antireflection coated, and the sample was not very uniform in large scale.

Fig. 4 shows the optical spectrum of the Q-S operation measured by a monochromator with the resolution of 0.2 nm; the central wavelength was located at 1.645 μm. The optical trace of the Q-switched pulse was recorded by a digital oscilloscope. Fig. 5 shows a typical Q-switched pulse train [see Fig. 5(a)] and the single pulse profile [see Fig. 5(b)] at the highest pump power of 3.6 W. The repetition rate and the pulsewidth were measured to be 40.7 kHz and 6.3 μs, respectively. During the experiments, we observed that the Q-switched pulses showed small intensity fluctuation.

The relation between the temporal pulsewidth, the repetition rate, and the pump power was plotted in Fig. 6. The pulsewidth decreased from 15.7 μs at the threshold pump power of 1.4 W to 6.3 μs at the pump power of 3.6 W, in parallel with the increase in the repetition rate with the pump power. The maximum single pulse energy could reach up to 5.3 μJ, corresponding to a shortest pulse of 6.3 μs and a repetition rate of 40.7 kHz. At this high power pumping, we did not observe either the laser damage of the TISA or the obvious degradation of its Q-switching performance.

4. Conclusion

We have demonstrated an Er:YAG ceramic laser Q-switched by TISA. In spite of the large loss due to the quartz substrate and the TI sample, laser output power up to 210 mW could be still achieved, indicating that TISA could be also effective for high power operation. By future antireflection coatings upon the quartz substrate and fabricating uniform sample, shorter pulses with higher single

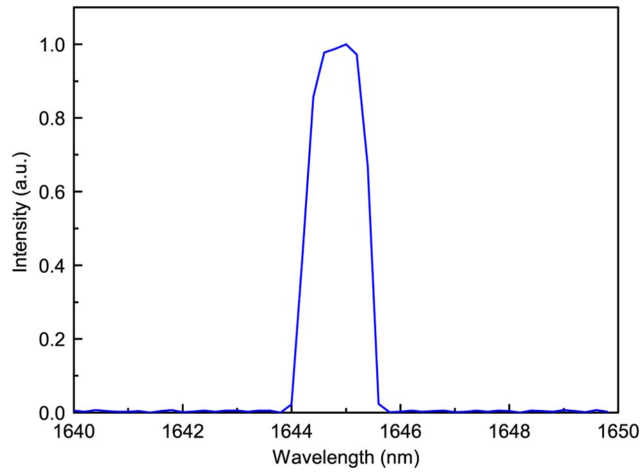

Fig. 4. Output spectrum of the Q-switched ceramic Er:YAG laser.

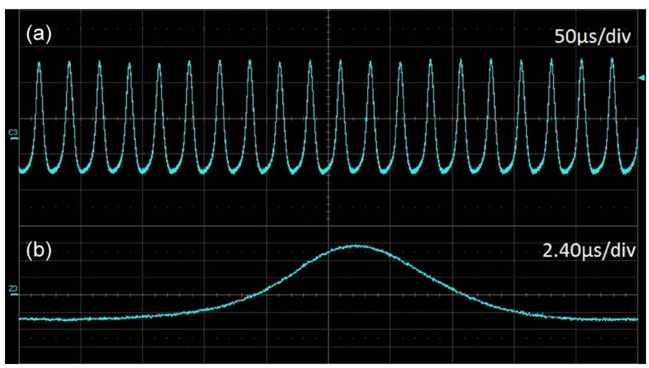

Fig. 5. (a) Pulse trains and (b) single pulse profile of the Q-switched Er:YAG ceramic laser when the pulse repetition rate and pulsewidth are 40.7 kHz and 6.3 μs, respectively.

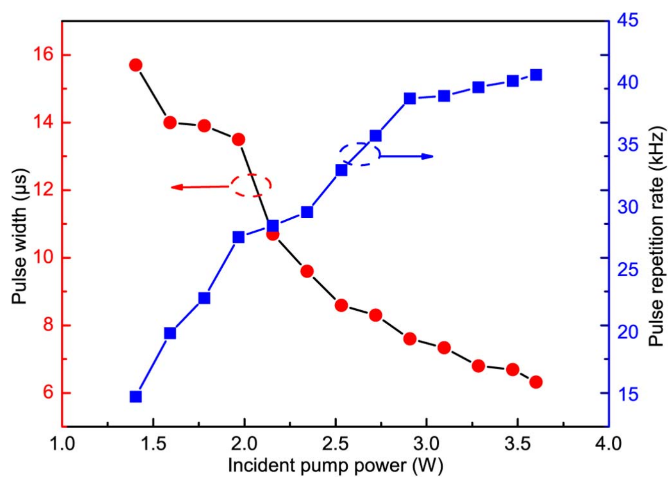

Fig. 6. Pulse width and repetition rate versus incident pump power for Q-S operation.

pulse energy could be potentially realized. Our finding indicates that TI may be an interesting nonlinear optics material for lasers.

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