Passively Q-switched erbium fiber laser with a thin crystalline film of bismuth telluride used as a saturable absorber

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Abstract. Performance of a passively Q-switched erbium fiber laser with a narrow bandgap Bi₂Te₃ semiconductor thin film used as a saturable absorber was studied experimentally. In order to obtain repetitively-pulsed lasing, a Q-switcher was fabricated as a section of the standard SMF-28 optical fiber with a short (~4 mm in length) chemically etched out tapered section laterally covered with the bismuth telluride film. This Q-switcher was installed in a specially designed circuit of a ring-type erbium fiber laser pumped by a laser diode at 975 nm wavelength. The fiber diameter in the middle of the tapered section was 10-15 µm. Two types of taper coverage were studied: Bi₂Te₃ flakes suspended in isopropanol and a ZnTe/Bi₂Te₃ uniform polycrystalline thin-film heterostructure synthesized on a lateral surface of a tapered fiber section via MOCVD. In the first case, we observed laser oscillation at a wavelength of 1565 nm as a train of 7-26 µs pulses with a 86-50 µs repetition period at pump powers varying from 26 to 75 mW. In the second case, CW oscillation in the circuit appeared at a pump power of 30 mW while conversion to the repetitively-pulsed mode with a kilohertz repetition rate occurred at pump powers within the range of 34-40 mW. The results obtained indicate the feasibility of effective interaction of the evanescent field with a bismuth telluride film used as a saturable absorber. This interaction is sufficient to achieve a stable repetitively-pulsed lasing in the circuits of passively Q-switched fiber lasers.

1. Introduction

Saturable absorbers (SA) are used in laser systems for realizing passive Q-switching and mode-locking. They are relatively inexpensive, compact, and come with various structural designs [1]. Semiconductor saturable absorption mirrors (SESAMs) [2,3] and 2D materials (graphene [4,5] and carbon nanotubes [6]) are usually used in passively mode-locked laser systems. 2D materials form a separate group of SA, which has recently attracted great interest. Graphene has established itself primarily as a saturable absorber able to function in a wide spectral range of incident light. Nevertheless, this is not the only SA that has such an advantage. Quite recently, the group of 2D nanomaterials was appended with black phosphor [10] and topological insulators (TI), gaining an advantage in wide-band saturable absorption, as well as in fast backup. The known representatives of...
TI are bismuth telluride (Bi\textsubscript{2}Te\textsubscript{3}) [7], antimony telluride (Sb\textsubscript{2}Te\textsubscript{3}) [8], and bismuth selenide (Bi\textsubscript{2}Se\textsubscript{3}) [9,14].

In circuits of 2D pulsed fiber lasers, SA is usually deposited on the surface of a thinned fiber section. This section can be prepared by side polishing of a fiber [11-12], etching the reflecting cladding, or using other methods which would place an absorbing film in the vicinity of a light-guiding fiber core. This is necessary to achieve an effective interaction between the absorbing film and the evanescent mode field of light launched in a fiber core.

SA can be deposited on the surface of a taper as a mixture of 2D flakes mechanically exfoliated from a crystal and a binding agent [8]. Another way uses immersion of a taper in a bath filled with absorber solution or suspension [10]. There are also various known methods for film deposition on the surface of the taper from the gas phase. Pulsed laser deposition [13], magnetron sputtering [14], chemical vapor deposition [15] and metalorganic chemical vapor deposition (MOCVD) [16] are widely used for this purpose. They are distinguished by excellent versatility, which makes it possible to deal with various surfaces other than fibers and to carefully control the deposition process.

The current work is devoted to the investigation of oscillation modes intrinsic to a passively Q-switched erbium fiber laser with a fiber taper covered by a Bi\textsubscript{2}Te\textsubscript{3} film used as a Q-switching element. The goal of the research was to settle a range of the diameters for tapered fiber sections produced via etching of silica reflecting claddings that would be suitable to achieve nonlinear absorption in a bismuth telluride film deposited on the lateral surface of a taper as a saturable absorber. To accomplish this, we adapted the MOCVD technology for covering fiber tapers with crystalline Bi\textsubscript{2}Te\textsubscript{3} films, fabricated samples of passive tapered-fiber-based Q-switches, built an experimental pulsed fiber laser based on them, and studied its operation in the passively Q-switched repetitively-pulsed oscillation mode.

2. Experiment

We placed an uncoated section of a standard SMF28 single-mode silica fiber with diameters of the outer and light-guiding cores of 125 \(\mu\text{m}\) and 8 \(\mu\text{m}\), respectively, in a bath with an NH\textsubscript{4}F + (NH\textsubscript{4})\textsubscript{2}SO\textsubscript{4} etchant at a temperature of 30 °C, which provided an average etching rate of about 10 nm/s. As soon as the necessary value of a fiber diameter in a range of 10-15 \(\mu\text{m}\) was achieved, we stopped the etching process. Two tapers 4 mm long each were selected for further experiments. The tapers had outer diameters of 12.5 and 10.5 \(\mu\text{m}\).

![Figure 1](image)

**Figure 1.** The dependence of the tapered fiber transmission at a wavelength of 1565 nm on the duration of ZnTe/Bi\textsubscript{2}Te\textsubscript{3} heterostructure film deposition. The sharp drops in the plot correspond to the start of the film growth while the gradual rises following these drops are due to the temperature variation in the reactor.
We used two methods to apply SA on the taper. In the first method, we crushed a single crystal of Bi$_2$Te$_3$ to powder and mixed it with isopropanol in the ratio 1:100, thus obtaining a suspension. In the second method, we deposited SA in the form of a monolithic-type crystalline film from the gas phase immediately on the lateral surface of the taper using MOCVD. In this experiment, we recorded ‘in situ’ transmission spectra of the taper in the wavelength range of 1-1.6 $\mu$m with help of a NIRQuest 512 spectrometer.

We deposited a thin ZnTe buffer layer followed by a layer of Bi$_2$Te$_3$ on the taper placed within the reactor heated to a temperature of 390 °C. The deposition run consisted of two steps as shown in figure 1. The deposition ended on reaching ~60% transmission.

![Figure 2](image-url)

**Figure 2.** (a) A diagram of the erbium fiber laser used in the experiments. (b) Emission spectrum of the fiber laser with a taper covered with a Bi$_2$Te$_3$ film.

The prepared tapers served as a part of the ring cavity of the fiber laser as indicated in figure 2(a). The normalized emission spectrum of the laser with the SA installed in the ring cavity is depicted in figure 2(b). A fiber-coupled laser diode with a 975 nm wavelength and an output power of up to 300 mW was used as a pump source. In our experiments, stable fiber laser oscillation took place within a range of pump powers from 20 to 120 mW. An erbium-doped fiber section 120 cm long with an absorption coefficient as high as 23 dB/km at a 975 nm wavelength was used as an active medium in the laser. The full length of the ring cavity was 8 m.

### 3. Results

When using SA with Bi$_2$Te$_3$ suspension in isopropanol, CW laser oscillation appeared at a pump power of 26 mW, while the repetitively-pulsed oscillation mode came at pump powers ranging from 34 to 73 mW.

Over the course of time, the pump power threshold for CW lasing increased to 50 mW, while the passively Q-switched mode disappeared completely. The observed effects can be associated with two factors. The first one is the evaporation of isopropanol, which leads to an increase in the concentration of Bi$_2$Te$_3$ flakes in the suspension. The second factor is as follows: under the action of the evanescent field gradient, Bi$_2$Te$_3$ flakes are captured on the surface of the taper due to the effect of optical tweezing. Both factors contribute to an increase in light absorption in the coated taper and a decrease in the ring cavity Q-factor.

Figure 3 and figure 4 illustrate the dependence of the lasing mode on the pump power.
Figure 3. Lasing modes at different pump powers with the use of a fiber taper immersed in the Bi$_2$Te$_3$ suspension as a Q-switch. The pump power is 34 mW: (a) single impulse, (b) group impulse.

Figure 4. Lasing modes at different pump powers with the use of a fiber taper immersed in the Bi$_2$Te$_3$ suspension as a Q-switch. The pump power is 73 mW: (a) single impulse, (b) group impulse.

Figure 5. The pulsed oscillation mode of a ring fiber laser with Q-switching bismuth telluride used as a saturable absorber, obtained via MOCVD film deposition on a taper. The first picture shows the shape of a separate pulse.

Figure 5 illustrates the oscillation modes of a laser with a ring cavity containing a taper covered with a film deposited via MOCVD. This laser starts to operate in the CW mode at a pump power of 30 mW. At pump powers of 34 to 40 mW, the pulses with a kilohertz repetition rate appear, indicating the functioning of the deposited SA layer.
4. Conclusion
With the help of the ring-type erbium fiber laser, we experimentally compared the two techniques for tapered fiber coating with a bismuth telluride saturable absorber. Q-switches with a ZnTe/Bi$_2$Te$_3$ thin film heterostructure produced by MOCVD demonstrated better and more stable results. This technique does not require continuous replenishment of the suspension with isopropanol evaporating over time, and provides more stable and durable operation. This film nevertheless provides Q-switching in a narrower range of ring laser pump powers.

As the result of the experiments, we found that 10.5 $\mu$m is the maximum diameter for fiber tapers associated with the standard SMF28 fiber, where the nonlinear absorption of the deposited bismuth telluride film can transfer oscillation of an erbium fiber laser from CW to the Q-switching mode. The data obtained would help one to further optimize the fabrication technique for passive taper-type fiber optic Q-switches intended for operation in various configurations of pulsed fiber lasers.

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