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Letters

Soliton compression of the erbium-doped fiber laser weakly started mode-locking by nanoscale p-type Bi$_2$Te$_3$ topological insulator particles

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Abstract

We demonstrate the nanoscale p-type Bi$_2$Te$_3$ powder-based saturable absorber-induced passive mode-locking of the erbium-doped fiber laser (EDFL) with sub-picosecond pulsewidth. Such a nanoscale topological insulator powder is obtained by polishing the bulk p-type Bi$_2$Te$_3$ in a commercial thermoelectric cooler (TE cooler). This is then directly brushed onto the end-face of a single-mode fiber patchcord, to avoid any mis-connecting loss caused by laser beam divergence, which can result in a mode-locked pulsewidth of 436 fs in the self-amplitude modulation mode of a TE cooler. To further shorten the pulse, the soliton compression is operated by well-controlling the group delay dispersion and self-phase modulation, providing the passively mode-locked EDFL with a pulsewidth as short as 403 fs.

Keywords: Bi$_2$Te$_3$, topological insulator, nano-particle, mode-locking, soliton, compression, fiber laser

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

1. Introduction

The three-dimensional topological insulator (TI) is also a Dirac material which has been comprehensively investigated due to its unique properties as quantum matter [1–3], such as an insulating bandgap for the bulk state but with an odd number of gapless Dirac cones on its surface [4]. The large bandgap of the bulk state is suitable for high-temperature spintronics applications. On the other hand, its topological surface state makes it a good candidate in applications of low-power spintronics devices [2]. The carrier behavior on the TI surface phenomenon is similar to that of a single-layer graphene. In addition, the bandgap of TI can be easily engineered by detuning the doping condition [1, 5], which could modify the effect of the saturable absorption in TI materials for photonic applications [6]. Recently, versatile TI saturable absorbers, including bismuth telluride (Bi$_2$Te$_3$) and bismuth selenide (Bi$_2$Se$_3$), have been employed to passively mode-lock the fiber lasers at telecommunication wavelength regime [7, 8]. These investigations have shown the potential of TI materials as
nonlinear saturable absorbers. In comparison with graphene [9, 10] or graphite [11, 12] saturable absorbers, the passively mode-locked laser pulsewidth generated by using TI saturable absorbers were limited at ps-degree in previous works. The improvement on the pulse shortening force in the passively mode-locked laser needs to be studied.

In this work, the p-type Bi$_2$Te$_3$ nanoparticle is obtained by mechanically polishing its bulk cube, taken apart by a TE cooler, which serves as the saturable absorber for the passively mode-locked EDFL. The Fermi level (EF) of the nanoscale p-type Bi$_2$Te$_3$ insulator powders is near the conduction band where we might expect a lower mode-locking threshold. These Bi$_2$Te$_3$ nanoparticles are directly brushed on the end-face of a single-mode fiber to shrink the absorber thickness and to reduce the loss induced by the beam divergence between two single-mode fiber (SMF) patchcords. With a precise cavity design on gain and dispersion, the passively mode-locked EDFL pulse, generated through the SAM of Bi$_2$Te$_3$ nanoparticles at the initial stage, which can be further compressed via the intra-cavity soliton compression to obtain a pulsewidth as short as 400 fs.

2. Experimental setup

In experiment, the bulk Bi$_2$Te$_3$ cube is obtained from a commercial TE cooler module which consists of n-type and p-type Bi$_2$Te$_3$ cubes in series connection to transfer the heat by Peltier effect. After removing the gold film coated on both sides of the bulk Bi$_2$Te$_3$ topological insulators, the p-type Bi$_2$Te$_3$ cube is polished to obtain the nanoparticles with average sizes of ~500 nm. Figure 1 shows the photographs of the TE cooler, the bulk p-type Bi$_2$Te$_3$ cube detached from the TE cooler, and the p-type Bi$_2$Te$_3$ powders mechanically polished with a commercial triturator. The lower left photograph shows the scanning electron microscopy (SEM) image of the triturated p-type Bi$_2$Te$_3$ nanoparticles.

The tetradymite-type crystal structure and the energy band diagram of the Bi$_2$Te$_3$ are also illustrated in the lower right part of figure 1. For the p-type Bi$_2$Te$_3$, the acceptor-type doping with hole as the majority carrier pulls down its EF from the bulk conduction band (BCB) to the bulk valence band (BVB), whereas the Dirac point (DP) moves upward to be closer to the BCB accordingly [2, 13]. This results in a higher density of states and leads to a larger linear absorption. To build up the high-gain EDFL cavity, a 2 m-long high-gain EDF (nLIGHT Liekki Er80-8/125) is employed as the gain medium, and the other fiber-optic components, including WDM couplers, isolators, output coupler and a polarization controller, contribute to a total SMF length of 5.8 m. Two high-power laser diodes (LDs), at wavelengths of 980 and 1480 nm, provide the forward and backward pumping via the corresponding wavelength-division multiplexing (WDM) couplers. A polarization independent optical isolator is inserted to determine the light circulation in the EDFL cavity, and a polarization controller (PC) is used to detune the circular polarization. With the output optical coupler, 5% output and 95% feedback are provided to construct the EDFL cavity. To insert the topological insulator-based saturable absorbers into the EDFL cavity, the p-type Bi$_2$Te$_3$ nanoparticles are directly brushed onto the connector end-face of the SMF patchcord, which is then connected with another patchcord. This direct brush method can effectively shorten the spacing between two patchcords, which aims to greatly reduce the loss caused by laser beam divergence when propagating in the space between two connectors. Figure 2 shows the passively mode-locked EDFL system, and the microscopic image illustrates the distribution of the Bi$_2$Te$_3$ nanoparticles on the end-face of the SMF patchcord.
3. Results and discussions

The composition and chemical bond states of the Bi$_2$Te$_3$ nanoparticles are probed by x-ray photoelectron spectroscopy (XPS). Figure 3(a) demonstrates the full-band XPS spectrum of the Bi$_2$Te$_3$ nanoparticle with contributed photoelectrons from the 4f and 3d orbits of Bi and Te atoms, respectively. Figure 3(b) depicts the zoom-in XPS spectra related to the Bi 4f-orbit photoelectrons, in which the photoelectrons contribute to two peaks at binding energies of 157.8 eV and 163.2 eV, corresponding to

![Figure 3](image)
the Bi 4f_{5/2} and 4f_{7/2} spin states [14–16]. Similarly, the figure 3(c) reveals two Te 3d-orbit photoelectron related spectral peaks, corresponding to the spin states of Te 3d_{3/2} and 3d_{5/2} at binding energies of 575.5 eV and 585.8 eV [14–16], respectively. The atomic composition ratio (Bi/Te) of the Bi_{2}Te_{3} nanoparticle characterized by the XPS analysis is about 0.68, which is in good agreement with the value given by the manufacturer. When the mode-locking mechanism is operated under self-amplitude modulation regime, the loss reduction helps to enhance the intra-cavity gain of the EDFL, which is an important factor to shorten the modulation regime, the loss reduction helps to enhance the intra-cavity gain of the EDFL.

The linear transmittance of the connected SMF patchcords with inserted Bi_{2}Te_{3} nanoparticles is about 0.87. To check the modulation depth, the nonlinear saturable absorbance of the Bi_{2}Te_{3} nanoparticle on the end-face of SMF patchcords is measured under high-peak-power femtosecond laser pulse illumination. When illuminating at high peak powers, the carrier transition is forbidden to reduce the optical absorption of the Bi_{2}Te_{3} nanoparticle due to the Pauli blocking effect. Typically, the total transmittance (T) is contributed by linear absorbance (q_{lin}) and nonlinear absorbance (q_{non}) given as:

\[ T = \exp(-\alpha L) = \exp(-q_{lin} + q_{non}(1 + I_{in}/I_{sat})) \]  

where \( I_{in} \) denotes the input power and \( I_{sat} \) the saturation power of the Bi_{2}Te_{3} nanoparticle. Figure 4 demonstrates the nonlinear transmittance and the normalized absorbance of the Bi_{2}Te_{3} nanoparticle. The Bi_{2}Te_{3} nanoparticle nonlinearly increases its transmittance, from 0.87 to 0.9, with a corresponding modulation depth of 27%, by enlarging pumping power to 290 kW cm^{-2}. The simulated parameters of \( q_{non}, q_{lin} \) and \( P_{sat} \) are -0.045, 0.1 and 581 kW cm^{-2}, respectively. The cavity gain enhancement effectively contributes to shortening the passively mode-locked EDFL pulselength when operated at SAM regime. Under the control of SAM, the enlarged gain increases the strength of each oscillating mode to be phase-locked for narrowing the EDFL pulselength. Successively, the self-phase modulation (SPM) effect in the EDFL cavity is induced with the enlarged pulse intensity caused by strengthened gain, which cooperates with the cavity group delay dispersion (GDD) to further compress the EDFL pulselength.

The relationships between output power \( P_{out} \) and input power \( P_{in} \) of the high-gain EDFA used in this experiment are demonstrated in figures 5(a) and (b). By driving the pumping LDs at maximal currents of 900 mA, the 980 nm LD and 1480 nm LD deliver the forward and backward pumping powers of 290 mW and 200 mW, respectively. The power gain of the EDFA in logarithm scale is measured as high as 21 dB with the incident power \( P_{in} \) of \(-15 \) dBm, which turns to linearly decrease with enlarging the input power up to \(-10 \) dBm or larger. The equation \( G = g_{0}(1 + P_{sat}/P_{in}) \) is utilized to numerically simulate the power gain of the EDFA under saturation condition, where \( g_{0} \) is the small-signal power gain and \( P_{sat} \) is the saturation power of the EDFA. In our case, the \( G \) in logarithm scale and \( P_{sat} \) of the high-gain EDFA are approximately 21.2 (or linear gain coefficient \( g_{lin} \) of 8.62) and 0.65 at pumping currents of 900 mA, respectively. The passively mode-locked EDFL pulse-train generated by the p-type Bi_{2}Te_{3} nanoparticles is demonstrated in figure 5(c).

The pulse-train shows a temporal spacing of 35 ns with corresponding repetition rate of 28.5 MHz due to the EDFL cavity length of 7.8 m. The stabilization quality of the EDFL pulse-train passively mode-locked by the p-type Bi_{2}Te_{3} nanoparticles is quantified by calculating the value of carrier amplitude jitter (CAJ), CAJ = (\sigma/I_{ave}) \times 100\% , in which \( \sigma \) is the standard deviation of peak pulse intensity and \( I_{ave} \) is the average pulse intensity [19, 20]. The calculated CAJ value is only 1.62%. Figures 6(a) and (b) provide the autocorrelation traces and the optical spectra of the p-type Bi_{2}Te_{3} nanoparticle-based passively mode-locked EDFL under different pumping conditions. The power gain \( G \) in logarithm scale raises from 19.7 to 21.2 (with \( g_{lin} \) increasing from 8.32 to 8.62) by increasing the driving currents of two pumping LDs from 600 to 900 mA. As a result, the passively mode-locked EDFL pulselength is narrowed from 436 to 403 fs, and the spectral full-width at half maximum (FWHM) is simultaneously broadened from 5.88 to 6.66 nm. The time-bandwidth products (TBPs) of the passively mode-locked EDFLs with different pumping currents remain around 0.315, to ensure the fundamental soliton with a hyperbolic secant pulse operated at nearly transform-limited condition. With the p-type Bi_{2}Te_{3} nanoparticle-based saturable absorber, the passively mode-locked EDFL is operated in the soliton mode-locking region with the Kelly sidebands observed on the shoulders of the optical spectra, under mutual perturbation from GDD and SPM [12]. The first-order Kelly sidebands can be observed on the EDFL spectrum at a pumping current of larger than 600 mA. By increasing the pumping current from 700 to 900 mA, the second order Kelly sidebands present.

Once the mode-locking pulse is started by the saturable absorber, the SAM, accompanied by the enhanced gain, dominates the pulse formation at the initial stage [21]. However, the SAM is limited by the gain and group velocity dispersion at linear regime, and the saturable absorption at nonlinear regime. In the optimized GDD case, the gain enhancement (or loss reduction) becomes even more important for pulselength narrowing. By directly brushing the polished p-type Bi_{2}Te_{3} nanoparticles onto the SMF end-face, which can effectively shorten the spacing between two patchcords to reduce the linear coupling losses caused by the laser divergence. In particular, the coverage area

![Figure 4](image-url). Nonlinear transmittance and normalized absorbance of the p-type Bi_{2}Te_{3} nanoparticle.
Figure 5. (a) The output power $P_{\text{out}}$ (dBm) and (b) the power gain (dB) of the established EDFA versus input power $P_{\text{in}}$. (c) The passively mode-locked EDFL pulse-train.

Figure 6. Experimental results of (a) autocorrelation traces and (b) optical spectra of the passively mode-locked EDFLs with the p-type Bi$_2$Te$_3$ nanoparticle-based saturable absorber.
ratio of the p-type Bi$_2$Te$_3$ nanoparticles on the connector end-face can be optimized to further reduce the linear insertion loss without sacrificing the nonlinear saturable loss too much. This helps to obtain the narrow pulse at first stage. When the circulated laser intensity is gradually enlarged to enhance the intracavity SPM effect, mutual perturbation of GDD and SPM takes place of the SAM to reshape the pulse at the second stage. That is, the saturable absorber only functions as a mode-locker to start the pulse formation. The SPM induced soliton compression becomes the key factor to compress the passively mode-locked EDFL pulsewidth into sub-500 fs degree. To induce the soliton mode-locking and optimize the pulse compression, the SPM ($\delta$) needs to be strong, and the effective GDD ($D$) in the EDFL cavity should be nearly, but not completely, compensated [20–22]. In our case, both the dispersion coefficients of 2 m EDF $\beta_{2,EDF}$ and 5.8 m SMF $\beta_{2,SMF}$ are about $-20$ ps$^2$ km$^{-1}$, thereby giving the cavity GDD of $-0.156$ ps$^2$. On the other hand, the SPM coefficient $\delta$ is approximately $0.01$ W$^{-1}$. The simulated pulsewidth and optical spectra by Haus master equation are shown in figure 7. When increasing the $g_0$ from 8.42 to 8.62 by enlarging the pumping currents of two LDs from 600 to 900 mA, the pulsewidth shortens from 430 to 405 fs and the spectral FHWM broadens from 5.9 to 6.8 nm; this is well correlated with experimental results. The simulated results also show the gradually enlarged Kelly sidebands on the shoulder of optical spectra, corroborating that the EDFL is in the operation of soliton mode-locking.

4. Conclusion

In conclusion, the 400 fs passively mode-locked EDFL with TI saturable absorber is here demonstrated for the first time. The p-type Bi$_2$Te$_3$ nanoparticles which serve as the saturable absorber are obtained by polishing the bulk from a TE cooler. The p-type TI is chosen due to the lower Fermi level, which is expected to reduce the mode-locking threshold. Under the high intensity illumination, the p-type Bi$_2$Te$_3$ nanoparticle shows the phenomenon of saturable absorption. The intensity-dependent optical transmittance of the Bi$_2$Te$_3$ nanoparticle increases from 0.87 to 0.9 by enlarging the illuminating peak intensity to 290 kW cm$^{-2}$, with a corresponding modulation depth of 27%. When the SAM dominates the pulse formation, the direct brush of p-type Bi$_2$Te$_3$ nanoparticles on the SMF end-face can effectively shorten the spacing of two patchcords, to reduce the loss caused by laser beam divergence. Therefore, the gain enhancement can be optimized to obtain the shortest pulse in the first stage. Under high intracavity intensity circulation, the passively mode-locked EDFL pulsewidth is further compressed by soliton compression in the second stage. To optimize the soliton compression, the cavity GDD ($-0.156$ ps$^2$) and the SPM ($0.01$ W$^{-1}$) are well-controlled to mutually compensate. When enlarging the power gain up to 21.2 dB by increasing the pumping currents of two LDs to 900 mA, the passively mode-locked EDFL with pulsewidth of 403 fs and optical FHWM of 6.86 nm is obtained.

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Figure 7. (a) Simulated autocorrelation traces and (b) optical spectra of the passively mode-locked EDFLs.
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