Ti_3AlC_2 coated D-shaped fiber saturable absorber for Q-switched pulse generation*

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In this letter, a titanium aluminum carbide (Ti_3AlC_2) coated D-shaped fiber is proposed and demonstrated as a new saturable absorber (SA) for Q-switched laser pulse generation. In preparing the SA, the Ti_3AlC_2 powder is dispersed in liquid polyvinyl alcohol (PVA) before the solution is dropped and left to dry onto a polished surface of D-shape fiber. The SA is added to an erbium-doped fiber laser (EDFL) cavity to modulate the cavity loss for Q-switching. The Q-switched laser is obtained at 1 561 nm. The pulse width of the pulses can be varied between 7.4 μs and 5.1 μs with a corresponding repetition rate range from 41.26 kHz to 54.35 kHz, when the pump power is increased from 42.2 mW to 71.5 mW. At 71.5 mW pump, the pulse energy is obtained at 70.3 nJ. The signal-to-noise ratio (*SNR*) of the fundamental frequency is recorded at 67 dB, which indicates the stability of the laser.

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Q-switched pulsed laser generation can be achieved in fiber laser configuration by either active or passive technique[1,2]. In the former, external modulators, such as electro-optic and acousto-optic modulators, were used in the laser cavity to modulate the Q-factor and produce short pulses with high output energy. In the latter, the Q-factor modulation can be produced using a saturable absorber (SA) device incorporated in the laser cavity. Compared to the bulky active system, the passive approach is preferable due to its compactness and more versatile system. Up to now, a variety of materials have been proposed and employed as SA, namely carbon nanotubes[3], graphene[4], black phosphorus[5], topological insulators[6], and transition metal dichalcogenides (TMDs)[7]. These materials exhibit intensity-dependent transmission.

Recently, MXenes, a new type of material, has also gained tremendous interests for various optoelectronic applications[8]. They have unique optical properties, which are also suitable for SA application. These materials are typically produced from their precursor, the MAX phases. Compared to MXenes, MAX phases do not require strong etching solutions, such as ammonium bifuoride (NH_4HF_2), hydrofuoric acid (HF), or a mixture of hydrochloric acid (HCl) and lithium fuoride (LiF), thus minimizing the fabrication process and cost[9]. Titanium aluminum carbide (Ti_3AlC_2) is one of the materials which belong to the MAX phases group. It has gained attention in recent years, thanks to its resistance to high temperature and containing good oxidation[10].

Previously, Ti_3AlC_2 SA was incorporated to erbium-doped fiber laser (EDFL) cavity based on conventional way by directly sandwiching it between two fiber ferrules[11]. The propagating photons in fiber's core interact with Ti_3AlC_2 at the insertion point. Thus, it creates some undesirable loss at the connector. The SA could also be damaged during the insertion and alignment of the SA inside the laser cavity. Thus, in this work, Ti_3AlC_2 is coated over the side-polished or D-shape fiber to function as an SA in the EDFL cavity. This technique allows light-matter interaction at the side-polished area while improving the damage threshold of any SA material[12]. The Q-switched operation has been reported in recent years based on D-shape fibers coated with the cadmium selenide[13] and molybdenum disulfide[14] SA materials.

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The setup of Q-switched fiber laser utilizing a Ti_3AlC_2 coated D-shape fiber is illustrated in Fig.1(a). At first, we obtained the Ti_3AlC_2 solution by mixing Ti_3AlC_2 powder and liquid polyvinyl alcohol (PVA) after stirring and sonication of about 24 h and 2 h, respectively. The prepared solution was then dropped over the polished region of the fiber and left to dry for a few hours to form an SA device. Fig.1(b) shows the nonlinear absorption curve of the Ti_3AlC_2 coated D-shaped fiber SA, which was obtained by utilizing a balanced twin detector approach. It indicates a saturable absorption of 0.6% for the Ti_3AlC_2 SA. The saturable intensity and non-saturable absorption are 250 MW/cm^2 and 72.8%, respectively. It is also worthy to note that no obvious polarization-induced loss can be observed for D-shaped fiber in our experiments.

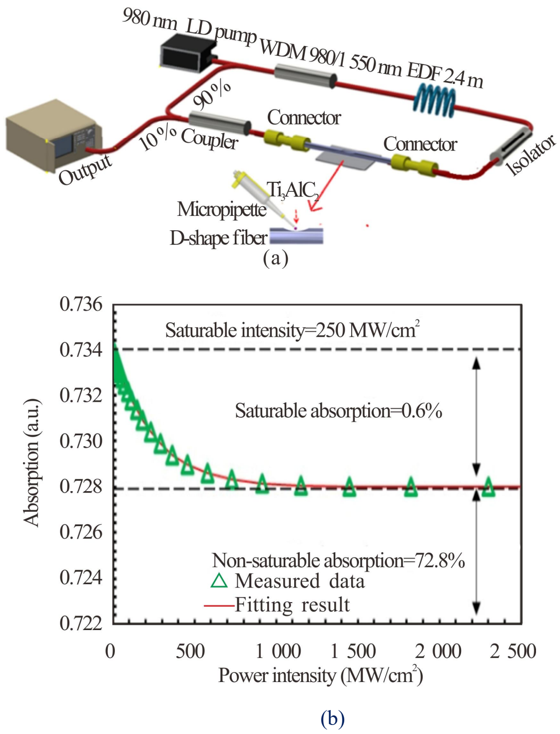


Fig.1 (a) The EDFL cavity setup for generating Q-switched pulses with D-shaped fiber coated with Ti_3AlC_2 as SA; (b) Nonlinear absorption profile of the SA

The wavelength division multiplexing (WDM) is connected to a 2.4-m-long erbium-doped fiber (EDF) to allow the pump photons to be injected into the gain medium and provides lasing in 1.5 μm region. The erbium ions with concentration of 1 500 ppm are doped in the core of EDF, and they provide absorption of 90 dB/m at 980 nm. The EDF has a numerical aperture of 0.20 and core diameter of 4 μm. It is forward pumped by a laser diode (LD) operating at 980 nm via a WDM. The isolator and 10 dB output coupler are used to prevent light reflection within the cavity and to output half of the power from the cavity, respectively. Assuming the group velocity dispersion (GVD) values of EDF and undoped single mode fiber (SMF) are ~27.6 ps^2/km and ~−21.7ps^2/km, respectively, the net cavity dispersion is calculated approximately at ~0.010 ps^2. The total cavity length is about 5 m.

The passive Q-switching is achieved due to the cavity loss modulation by the SA device. The Ti_3AlC_2 SA saturated before the saturation of the gain medium and thus it allows the gain medium energy to reach a sufficient level for generating pulses via Q-switching. The temporal characteristics of the Q-switched pulses are analysed using a 12 GHz photodetector, a 350 MHz oscilloscope, and a 7.8 GHz radio frequency spectrum analyzer (RFSA). The laser output power is checked by utilizing an optical power meter (OPM) while the laser spectrum is measured by an optical spectrum analyzer (OSA). In this experiment, we investigated the performance of the cavity in two cases. Firstly, no SA was used into the cavity, and secondly the Ti_3AlC_2 coated D-shape fiber was inserted into the cavity. No pulsing was detected on the oscilloscope in the first case (without SA). As the SA was incorporated into the setup, a pulsing operation was observed as the 980 nm pump power was set from 42.2 mW to 71.5 mW. The experiment was also repeated by replacing the SA with an uncoated D-shaped fiber. It is observed that the proposed fiber laser fails to initiate the Q-switching operation without Ti_3AlC_2. This verifies that the generation of pulses is due to the light interaction with Ti_3AlC_2 in D-shape fiber.

The performance of the Q-switched laser is shown in Fig.2. The pulse width and repetition as a function of pump power are presented in Fig.2(a). When the launch power is raised from 42.2 mW to 71.5 mW, the pulse repetition rate varies from 41.26 kHz to 54.35 kHz. The produced pulse was inversely correlated with the LD power. It was shortened from 7.4 μs to 5.1 μs. In principle of laser, the Q-switched pulse width is strongly dependent on the population inversion density. The larger pump power enhances the population inversion and thus reduces the pulse width, as shown in Fig.2(a). The Q-switched pulse width can be further shortened by reducing the cavity loss and lengthening the gain fiber.

Fig.2(b) displays the output power and pulse energy versus the LD launch power. Both output power and pulse energy are raised with increasing LD power from 2.75 mW to 3.82 mW and from 66.6 nJ to 70.3 nJ, respectively. The population inversion depletes rapidly owing to the bleached Ti_3AlC_2 at high pump power. Therefore, the pulse width is reduced, and higher pulse energy is obtained from the Q-switching process. The slope efficiency of the laser is obtained at 3.4%. These behaviors of pulse width, repetition rate, output power and pulse energy with the pump power are typical characteristics for a Q-switched laser. The more power delivered by the laser diode pump, the quicker the SA is saturated. This would lead to the reduction of the rising and falling time of the pulses, and hence reducing the pulse width and increasing the repetition rate. The almost-linear output power and pulse energy relations with the LD power prove a stable performance. When the pump power is between 72—250 mW, the pulse trains are distorted and then dispersed, which indicates that the SA is bleached. When the LD power is set in the range of 42.2-71.5 mW, the pulse trains are restored again. This indicates that the optical damage threshold is above 250 mW. The optical spectrum has a peak centered at ~1 561 nm, as shown in Fig.3. It shows the output spectrum at 71.5 mW launch power. The laser maintained the shape of the output spectrum throughout the experiment (~3 h), where no distortion or shifting to higher or lower frequencies was observed. It is also worthy to note that the measurement was repeated three times in the experiment to ensure the repeatability of the laser.

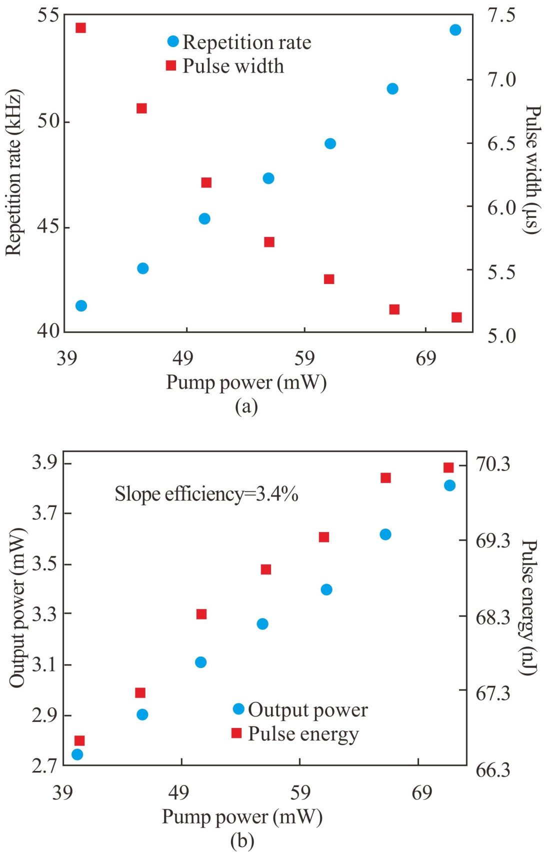


Fig.2 Performance of the Q-switched laser with Ti_3AlC_2 coated D-shape fiber inside the cavity: (a) Pulse rate and width versus pump power; (b) Output power and pulse energy versus pump power

Fig.4 shows the typical pulse trains produced by the laser at pump power of 42.2 mW, 55.9 mW and 71.5 mW, respectively. The corresponding repetition rates and pulse widths are 41.3 kHz and 7.4 μs, 47.3 kHz and 5.72 μs, 54.4 kHz and 5.12 μs, respectively. The pulse trains are recorded for 500 μs and no distortion or modulation is observed. The pulse trains are uniform, which shows the stable laser operation. The pulse periods are illustrated in the inset of figures, which show the given pulse trains at shorter time spans. At 42.2 mW, 55.9 mW and 71.5 mW, the pulse period is 24.24 μs, 21.14 μs and 18.4 μs, respectively. The radio frequency spectrum is given in Fig.5, where the signal-to-noise ratio (*SNR*) at fundamental frequency of 64.4 kHz is recorded as 67 dB. This high *SNR* reflects stable and good Q-switched laser pulses. The mode-locked pulses could also be produced by inserting additional SMF inside the cavity to ensure large anomalous dispersion, so that the net cavity dispersion is in the anomalous regime. The SMF can also balance the dispersion within the cavity with nonlinearity, thereby triggering a self-started mode-locked pulse.

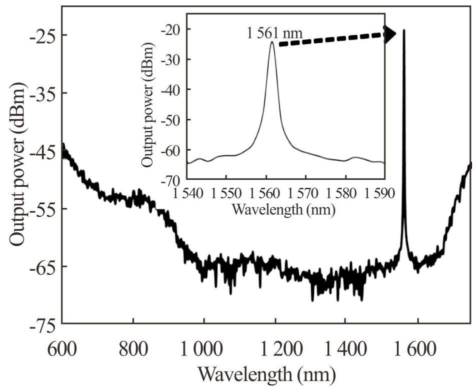
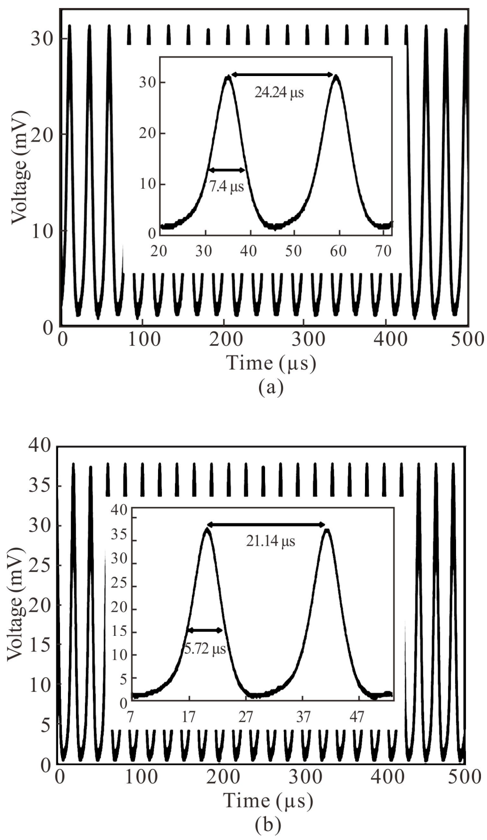
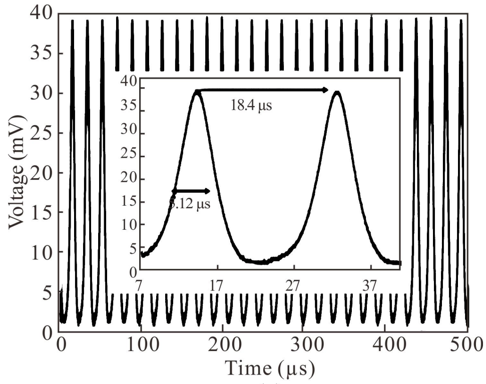


Fig.3 Output spectrum with Ti_3AlC_2 coated D-shape fiber inside the cavity (Inset shows the enlarged spectrum at 1 561 nm region)





(c)

Fig.4 Output pulse trains for 500 μs at (a) 42.2 mW, (b) 55.9 mW and (c) 71.5 mW, respectively (The inset shows the enlarged pulse trains with two pulse envelopes)

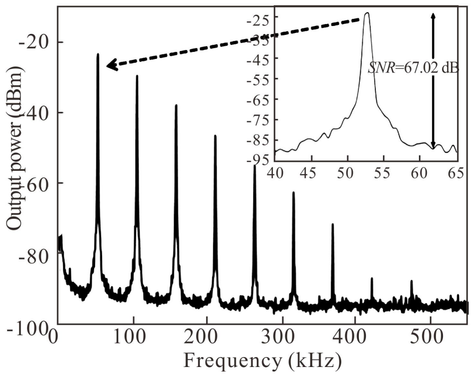


Fig.5 RF spectrum with 500 kHz span

In conclusion, a Q-switched pulse generation was successfully demonstrated in an EDFL cavity using the newly developed Ti_3AlC_2 based SA. This SA was successfully capable to generate Q-switched pulses operating at 1 561 nm. When the launch power was raised from 42.2 mW to 71.5 mW, the pulse repetition rate varied from 41.26 kHz to 54.35 kHz, while the produced pulse width was shortened from 7.4 μs to 5.1 μs. At 71.5 mW pump power, the maximum output power and pulse energy were obtained at 3.82 mW and 70.3 nJ, respectively. The laser performance was very stable, in which an *SNR* of 67 dB was recorded. These results demonstrate that the proposed Ti_3AlC_2 material has a promising potential to be used as a kind of SA for pulse generation or other nonlinear optical devices.

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Statements and Declarations

The authors declare that there are no conflicts of interest related to this article.

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