CHIN. PHYS. LETT. Vol. 35, No. 4 (2018) 044204

Mode-Locked Erbium-Doped Fiber Laser Using Vanadium Oxide as Saturable Absorber

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(Received 18 February 2018)

A mode-locked erbium doped fiber laser (EDFL) is demonstrated using the vanadium oxide (V_2O_5) material as a saturable absorber (SA). The V_2O_5 based SA is hosted into poly ethylene oxide film and attached on fiber ferule in the laser cavity. It shows 7% modulation depth with 71 MW/cm^2 saturation intensity. By incorporating the SA inside the EDFL cavity with managed intra-cavity dispersion, ultrashort soliton pulses are successfully generated with a full width at half maximum of 3.14 ps. The laser operated at central wavelength of 1559.25 nm and repetition frequency of 1 MHz.

PACS: 42.55.Wd, 42.60.Gd, 42.70.Nq DOI: 10.1088/0256-307X/35/4/044204

Passively mode-locked fiber lasers represent the state of the art in laser technology, which carry great promise for portable and powerful pulsed light sources. They have practical advantages over other types of lasers such as very high efficiency, superior waveguide characteristics, reduced thermal effects, and excellent beam quality. They offer a wide variety of potential applications including optical communication, frequency metrology, micromachining, and biomedical and military applications.[1−3] Unlike the active mode locking technique realized by inserting an electrical signal-driven active modulator into the laser cavity,[4,5] the passive mode-locking technique does not require an external signal for pulse generation creation. The generation of pulses is realized passively through the internal structure of the laser cavity that gives more advantages to the output pulsed laser. The commonly used method is to insert a saturable absorber (SA) material into the laser cavity. The SA is a nonlinear optical modulator whose modulation depth is controlled by the pulse itself, in which the absorption coefficient decreases as the light intensity increases. Hence, the pulse train with high peak intensity passes through the SA with much less loss as compared with that in a continuous wave laser with several modes as the energy available is concentrated in the periodic pulses, thus a stable pulse train can be generated in the cavity.

Among the materials that can be used as SAs, we find dyes, semiconductor saturable absorber mirrors (SESAMs),[6] graphene,[7] and carbon nanotubes (CNTs).[8−11] Lately, transition metal dichalcogenides (TMDs) such as molybdenum disulfide (MoS_2) and tungsten disulfide (WS_2), topological insulators (TIs), and black phosphorous (BP) have also shown good potential as SAs for pulse laser applications.[12−16] Very recently in 2016, transition metal oxide nanoparticles such as cobalt oxide (Co_3O_4), zinc oxide (ZnO), titanium dioxide (TiO_2), and nickel oxide (NiO[17−21] have been established as SAs in Q-switched fiber lasers. Transition metal oxides represent a class of materials that show promising nonlinear optical properties. Over the past few decades, transition metal oxides have been intensively studied not only due to optical nonlinearity, but also their mechanical strength and thermal and chemical stability. For example, several metal oxide films exhibit a large nonlinear optical response with a third-order nonlinear susceptibility.

Vanadium oxides are one of the most important transition metal oxides. Vanadium can exist in several forms of oxides, which are commonly available as VO, V_2O_3, VO_2 and vanadium oxide (V_2O_5). V_2O_5 is the most important and the most stable member of the oxide series.[22] The nonlinear optical absorption characteristics of V_2O_5 have been studied in Ref. [23]. In this Letter, we present a mode-locked erbium-doped fiber laser (EDFL) using a V_2O_5 film as SA. The V_2O_5 based SA is hosted into a polyethylene oxide (PEO) film, which is then sandwiched between two fiber ferrules and incorporated into the laser cavity.

V_2O_5 was synthesized by the chemical reaction reported in Ref. [24]. In a typical synthesis, 20 g of NH_4VO_3 (Sigma Aldrich, Malaysia) was dissolved in 500 mL of deionized water. Then, 0.1 g of Triton X-100 surfactant was added in the above solution under constant stirring at 90℃ for 60 min to complete the emulsification. To acidify the solution, concentrated HNO_3 (35% Merck) was added dropwise in the above mixture. The dark brown precipitates were formed overnight, which were collected and washed with deionized water to removed acid and traces of surfactant. After that, the collected precipitates were dried in a hot air oven at 90℃ for 12 h. Finally, the dried powder was crushed and calcined at 500℃ for

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5 h in a box furnace at a heating and cooling rate of 25℃/min to obtain yellowish-brown V_2O_5.

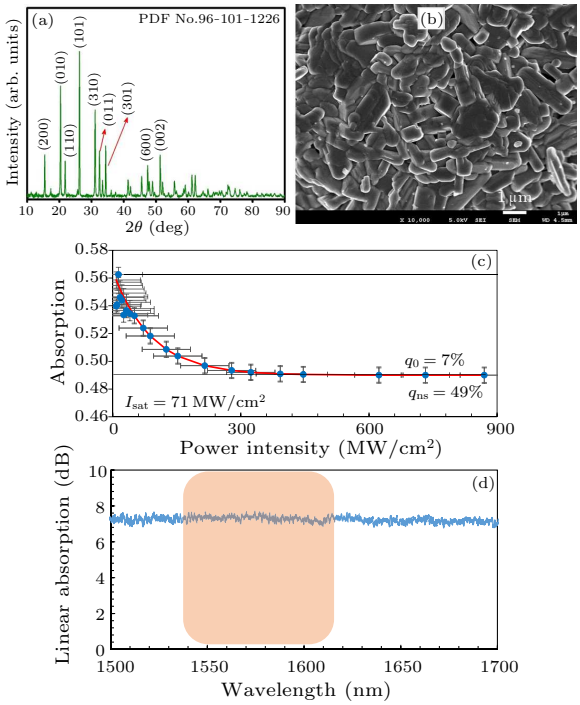

Fig. 1. (a) XRD pattern of synthesized V_2O_5, (b) FE-SEM image, and (c) nonlinear saturable absorption of the V_2O_5-SA film (d) linear absorption spectrum.

The structural crystallinity and phase purity of V_2O_5 have been investigated by x-ray diffraction (XRD) as shown in Fig. 1(a). As shown in the figure, V_2O_5 displays sharp peaks at 2θ values of 15.4, 20.3, 21.7, 26.2, 31, 32.4, 34.4, 47.4 and 51.3, which correspond to the lattice planes of (200), (010), (110), (101), (310), (011), (301), (600) and (002), respectively. All diffraction peaks for V_2O_5 can be indexed as an orthorhombic crystal phase (space group $Pmn21$, PDF 96-101-1226) without showing any impurity. Field emission scanning electron microscopy (FESEM) was performed to investigate the surface morphology of the prepared V_2O_5. Figure 1(b) is the FESEM image of V_2O_5 showing the tubular shape of V_2O_5.

To fabricate the V_2O_5 SA thin film, the synthesized V_2O_5 was integrated with a polymer. Here 1.0 g of poly ethylene glycol (PEO) was dissolved in 120 mL deionized water and the PEO solution was stirred for 2 h at a constant temperature of 50℃ to obtain a uniform transparent solution. Subsequently, an appropriate amount of V_2O_5 was added in the PEO solution and was kept under constant stirring for another 2 h to obtain a homogenous slurry. Finally, the solution mixture containing the V_2O_5-PEO composite was cast onto the teflon petri and dried in a vacuum oven at 60℃ for 24 h to obtained a light yellow solid thin film. The film was sandwiched between two fiber ferrules via a fiber connector with the help of an index matching gel to construct a fiber compatible SA device. The insertion loss of the device is estimated to be less than 1 dB.

The nonlinear saturable absorption of the V_2O_5-SA film was then determined using the twin-detector technique with a homemade mode-locked fiber laser as an illumination source with a repetition rate of 15 MHz and pulse width of 0.9 ps centered at 1554 nm. The absorption for different input intensities was recorded, as plotted in Fig. 1(c), after fitting using the saturation model[25]

$$T(I) = 1 - q_0 \exp\left(-\frac{I}{I_{sat}}\right) - q_{ns},$$

where $T(I)$ is the transmission, q_0 denotes the modulation depth of SA which represents the maximum change in absorption, I is the input intensity, I_{sat} represents the SA saturation intensity, and q_{ns} is the non-saturable absorption. The saturation intensity and modulation depth of the V_2O_5-SA were determined to be around 71 MW/cm^2 and $7 \pm 0.5\%$, respectively. Figure 1(d) shows the linear absorption characteristic of the V_2O_5-SA film, which has an absorption loss of about 7.2 dB at the 1550 nm region and thus is capable functioning as an SA in the wavelength region.

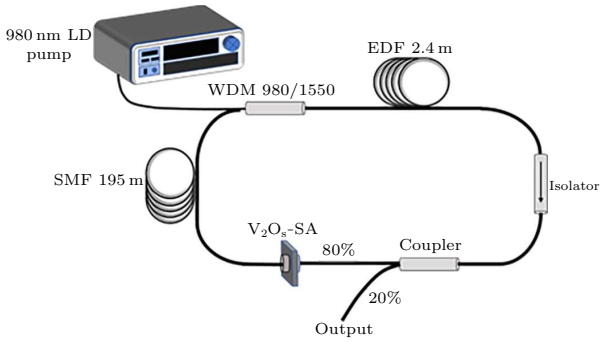

Fig. 2. Schematic diagram of the experimental setup.

The experimental setup of the EDFL system with V_2O_5 SA is illustrated in Fig. 2. The erbium-doped fiber (EDF) was core-pumped by a 980 nm laser diode (LD) through a wavelength division multiplexer (WDM). A 2.4-m-long EDF was used as an active medium with an erbium ions concentration of 2000 ppm, an absorption coefficient of 24 dB/m at 980 nm, and the numerical aperture of 0.4. An isolator was used to ensure unidirectional propagation of light inside the ring cavity. A 20/80 output coupler was used for laser extraction. The total cavity length is around 201 m after adding 195 m standard single mode fiber (SMF). The group velocity dispersions of the EDF and SMF at 1550 nm are approximately 27.6 ps^2/km and -21.7 ps^2/km, respectively. In addition, the 0.5 m HI 1060 WDM used has -48.5 ps^2/km group velocity dispersion. The estimated net cavity dispersion is about -4.25 ps^2. The output laser performance has been detected using an OSA (Yokogawa, AQ6370B) with a spectral resolution of 0.02 nm and a 350 MHz digital oscilloscope (GWINSTEK: GDS-3352) through a 1.3 GHz photodetector (Thorlabs, DET10D/M). To measure the pulse width a femtosecond Autocorrelator (Alnair Labs, HAC-200) was used.

Mode-locking operation of the laser was started at 81 mW pump power. Figure 3(a) shows the typical optical spectrum of the generated mode-locked pulses centered at a wavelength of 1559.25 nm and in a soliton regime due to the anomalous dispersion in the cavity as the estimated net cavity dispersion was around $-4.25\,\mathrm{ps}^2$. An oscilloscope and an auto-correlator were then used to study the temporal profile of the mode-locked EDFL. Figure 3(b) shows the oscilloscope trace with a stable pulse train showing two adjacent pulses separated by around 1 μs, which corresponds to a 1 MHz repetition rate. The obtained pulse duration on the oscilloscope is not the actual value, due to the resolution limitation in the oscilloscope. Therefore, an optical auto-correlator was used to measure the pulse duration. Figure 3(c) indicates that the measured auto-correlator pulse trace has a sech^2 pulse profile with 3.14 ps at full width of half maximum (FWHM).

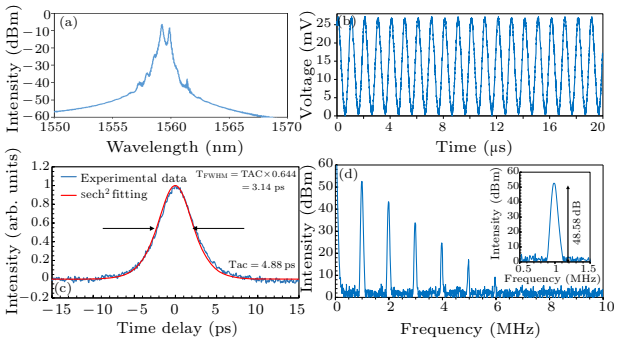

Fig. 3. Spectral and temporal characteristic of the mode-locking pulses: (a) output spectrum, (b) typical pulse train, (c) auto-correlator trace, and (d) RF spectrum with 10 MHz span. The inset in (d) is the enlarged spectrum for the fundamental mode showing a signal-to-noise ratio of 48.58 dB.

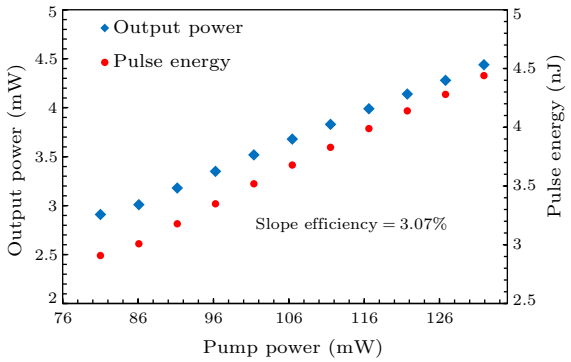

Fig. 4. Output power and pulse energy versus pump power.

The degree of suppression of the adjacent harmonics has been measured to investigate the stability of the pulse via RF spectrum as shown in Fig. 3(d). It shows that the fundamental frequency of the cavity is around 1.01 MHz and the adjacent harmonics are suppressed by 48.6 dB, which confirms the stability of the pulse. In addition to presenting the signal-to-noise ratio of the generated pulse, the RF spectrum could also be used to indicate the pulse width size based on the Fourier transfer analysis. Normally, fs and few-ps pulse width have an infinite order number of repetition rate with constant amplitude (SNR). However, we observe that the repetition rate amplitude rapidly decreases until 6 harmonics. This is most probably due to the limitation of our photo-detector bandwidth. Therefore, the actual pulse width was measured using an auto-correlator in this work. The output power and pulse energy of the generated mode-locked laser versus pump power have been investigated as shown in Fig. 4. The output power increases from 2.91 mW to 4.72 mW as the pump power is increased from 81 mW to 132 mW, and so does the pulse energy. The maximum pulse energy of 4.44 nJ was obtained at the maximum pump power of 132 mW.

In conclusion, we have successfully demonstrated a mode-locked EDFL in a ring cavity using V_2O_5 SA. The modulation depth and saturation intensity of the proposed V_2O_5-SA are determined to be 7% and $71\,\mathrm{MW/cm}^2$, respectively. The generated optical pulses are centered at 1559.25 nm and have a duration of 3.14 ps with a repetition frequency of 1 MHz. The results show that V_2O_5 can be used as an effective SA in generating the mode-locked fiber laser.

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