Optik 127 (2016) 10223–10227

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

WS_2/fluorine mica (FM) saturable absorber for high power optical pulse formation

L. Li [a,b,*], Z.F. Wang [b], Y.G. Wang [b], X. Wang [b], G.W. Yang [b]

[a] School of Science, Xi'an University of Posts and Telecommunications, Xi'an 710121, China
[b] State Key Laboratory of Transient Optics and Photonics, Xi'an Institute of Optics and Precision Mechanics, Chinese Academy of Sciences, Xi'an 710119, China

ARTICLE INFO

Article history:
Received 25 June 2016
Received in revised form 12 August 2016
Accepted 17 August 2016

Keywords:
Fiber laser
Mode-locking
Saturable absorber

ABSTRACT

The report presents the high power mode-locking operation in an anomalous-dispersion fiber laser with a novel WS_2 saturable absorber (SA) based on fluorine mica (FM) substrate. Compared to organic host material such as polymer, FM has higher softening temperature, heat dissipation and laser damage threshold. By employing the SA, a stable mode-locked fiber laser is achieved. The duration of the pulse broadens from 2.816 ns to 3.654 ns almost linearly with increasing pump power. The average output power and single pulse energy can increase up to 33.5 mW and 4 nJ at the maximum pump power respectively. The results indicate that WS_2/FM material is an ideal SA for high power Er-doped fiber (EDF) lasers.

1. Introduction

High power pulse fiber laser oscillators are of great importance for a variety of applications such as material processing, remote sensing, and light detection systems [1–3]. In general, the high power optical pulses are generated from the master oscillator power amplifier (MOPA), in which the output power from master laser is in weak level. However, the multistage pulse formation scheme introduces additional complexity and noise to the MOPA system, which leads to the low power efficiency. These drawbacks can be overcome by employing a SA in the master oscillator, which can keep stable mode-locking operation even under high intra-cavity power. Thus, researchers are always interested in exploring high performance SAs to obtain high power pulses directly from the laser oscillator [4–6], which are with the characters of wavelength independent, high heat dissipation and high laser damage threshold [7–9]. Up till now, various kinds of SAs materials have attracted great attentions in recent years. Semiconductor saturable absorber mirrors (SESAMs) [10], carbon nanotubes [11,12], graphene [13,14], topological insulators (TIs) [15], semiconducting transition metal dichalcogenides (TMDs) [16] and black phosphorus (BP) [17] have been experimentally studied, which possess a high third-order nonlinear susceptibility and short recovery time. In particularly, 2D TMDs, such as MoS_2 [18], WS_2 [19], $MoSe_2$ [20] and $MoTe_2$ [21] have got a lot of attentions and are considered to be a kind of promising SAs materials. Depending on the coordination and oxidation states of transition metal atoms, TMDs can either be semiconducting or metallic in nature [22]. Unfortunately, most of these SAs suffer from optical power-induced thermal damage such that the SAs into polymer host materials are burned out with the optical power of 30 mW level [23]. So the previous commonly used SAs cannot endure high intra-cavity power for high power pulse formation.

* Corresponding author at: School of Science, Xi'an University of Posts and Telecommunications, Xi'an 710121, China.
E-mail address: lilu@opt.cn (L. Li).

http://dx.doi.org/10.1016/j.ijleo.2016.08.040
0030-4026/

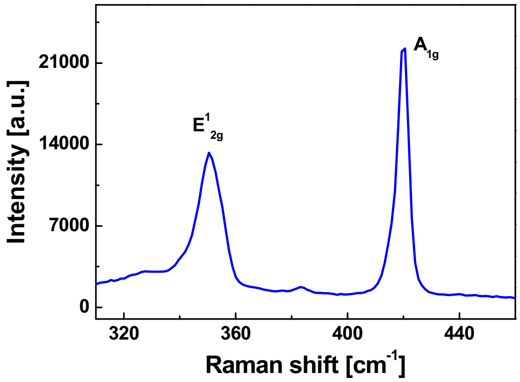

Fig. 1. Raman spectrum of WS_2 nanosheets excited by 633 nm laser.

Therefore, in order to keep these SAs operating for more efficient and robust pulse formation in the high power regime, a developed scheme of inorganic materials as substrate should be introduced. As everyone knows, inorganic materials have higher softening temperature, heat dissipation and laser damage threshold than those of organic materials. FM is a perfect inorganic material with the excellent virtues such as high temperature resistance, high elasticity, good transmission performance and non-absorbing impurities performance. The FM can be stripped into one layer with the thickness of 20 μm and is not easy to break off because of its high flexibility. Therefore, depositing TMD layers onto 20 μm thickness of one layer FM would be helpful for improving the performance of SA.

In this work, we have realized high power mode-locking operation in EDF laser with WS_2/FM SA. The WS_2/FM SA is fabricated by depositing WS_2 layers onto 20 μm thick one layer FM using a thermal decomposition method. By incorporating WS_2/FM slip into EDF laser cavity, the stable mode-locking operation is obtained at the fundamental repetition rate of 8.2 MHz. The pulse duration increases from 2.816 ns to 3.654 ns by simply increasing the pump power. The maximum average output power and single pulse energy are measured to be as high as 33.5 mW and 4 nJ, respectively. The experimental results show that the WS_2/FM SA has the potential to be used in high power mode-locked fiber lasers in practice.

2. Fabrication of WS_2/FM SA

The WS_2/FM SA is fabricated as reference [24] and the WS_2 layers are with average thickness of 4 nm. As a kind of inorganic material, the melting point and thermal conductivity of FM are 6 times and 10 times higher than those of polyvinyl alcohol (PVA) respectively, which indicate that WS_2/FM can operate in high power regime [24]. A Raman spectroscopy system with an excitation wavelength of 633 nm is utilized to confirm the existence of WS_2. Fig. 1 shows two typical bands which are identified as $E_{2g}{}^1$ at 350.5 cm^{-1} and A_{1g} at 420.7 cm^{-1}, where $E_{2g}{}^1$ is assigned to the in-plane mode and A_{1g} corresponds to the out-of-plane vibration mode of WS_2 [25]. The nonlinear saturable absorption of WS_2/FM SA is measured based on a balanced twin-detector measurement system. The modulation depth and non-saturable loss of are evaluated to be 3.1% and 15%, respectively. The insertion loss of the WS_2/FM is measured to be 0.87 dB with a continuous laser.

3. Experimental setup

The schematic diagram of EDF laser is depicted in Fig. 2. The ring laser oscillator cavity consists of a gain fiber, a wavelength division multiplexer (WDM), a polarization independent isolator (PI-ISO), optical coupler (OC), a polarization controller (PC) and a WS_2/FM SA. A 4 m long EDF with absorption coefficient of 3 dB/m at 976 nm is employed as the gain medium. The EDF is pumped by a 976 nm laser diode (LD). The PI-ISO is used to force the unidirectional operation in the fiber ring cavity. The PC is engaged in achieving different polarization sates. The optical coupler is used and 10% portion of the laser is coupled out from the laser cavity. The other fibers and pigtails of the optical components are single-mode fibers (SMFs) with a total length of 25.5 m. The dispersion parameters D at 1550 nm for EDF and SMF are −16 and 17 ps/(nm.km), respectively. The net cavity dispersion $_{\beta 2}$ is calculated to be −0.47 ps^2.

4. Experimental results and discussion

In the experiments, EDF laser starts the continuous wave (CW) at the pump power of 4 mW. Further increasing the pump power to 280 mW with slight adjusting the PC, the stable mode-locking operation is achieved. The mode-locking operation could be observed until the pump power rises to 650 mW. Fig. 3(a) shows the corresponding mode-locking spectrum. The central wavelength is 1561.6 nm. The central part of the spectrum in linear scale is illustrated in Fig. 3(b). It can be seen that the spectrum is slightly broaden as the pump power increases. Notably, the linear spectrum exhibit smooth profile with no obvious spikes. The pulse train is presented in Fig. 3(c). The time interval between two pulses is 121.95 ns, which