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Passive mode locking erbium-doped fiber laser using V_2O_5 polyethylene glycol saturable absorber

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ABSTRACT

An ultrashort pulse erbium-doped fiber laser (EDFL) in anomalous group delay dispersion (GDD) has been proven to produce a soliton wave production at 1596 nm. The mode-locking operation was generated by employing a vanadium pentoxide-polyethylene glycol (V_2O_5)-(PEG) film as absorber for all-fiber ring setup. Under anomalous dispersion, the soliton mode-locked laser produced a peak wavelength with 2.7 nm spectral bandwidth and Kelly sidebands. Under this condition, we obtained pulse energy of 210 nJ and pulse width of 1.40 ps. The maximum peak electrical power of 150 kW was calculated at the maximum pump power. These findings shows that the V_2O_5-PEG film can be a good saturable absorber (SA) device in generating stable mode-locking fiber laser at the 1.55- area.

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1. INTRODUCTION

Pulsed laser source in light detection and ranging (LiDAR) is one of the recent challenges that should be solved, especially in developing an autonomous vehicle. The commercial 980 nm laser diode (LD) used in the current LiDAR system of the current autonomous vehicle requires further improvement, such as replacing it with a safer laser wavelength. This is important since the system is used to determine the accurate distance for a moving vehicle even at a low speed. The 1.55-micron region is the most suitable wavelength to replace the existing pulsed laser source (980 nm LD), improving the resolution on time by flight. In fact, the fiber laser is recognized as a compact, stable, and practical laser under the field of lasers. High power in wideband operations comes from nonlinear fiber-based technology where ultrashort pulse fiber laser can fully enhance their performances [1]. The pulsed laser has good demand for industrial, military, and medical applications, such as for laser micromachining, surgery, terahertz-wave generation, optical imaging, or super-continuum generation [2]. The ultrahigh resolution of the optical fiber technology using a fiber super-continuum has been proven at various wavelength ranges via the passive and active techniques pulsed lasers [3]. Usually, external sources like electro and acoustic optic modulator are used in active techniques to perform the laser generation. However, it is too complex and bulky [4]. In contrast, a passive saturable absorber (SA) approach can give a more compact, flexible, and simple cavity resilience ability [5]. Semiconductor saturable absorber mirror (SESAM) has been reported to be quite expensive and requires post-growth ion in a demonstration [6]–[10].

Alternatively, nanomaterial SAs have tiny dimensionality that shows outstanding optoelectronic properties. Within these nanomaterials, graphene exhibits a nearly zero-energy bandgap that covers the wideband operation of the spectrum [11]–[14]. Another good SA to replace graphene is black phosphorus, but it lacks resilience ability due to air and oxygen [15], [16]. Besides, the revolution of SA in topological insulators (TIs) such as (Bi_2Te_3, Bi_2Se_3, Sb_2Te_3) in 2D materials and transition metal dichalcogenides (TMDCs), (MoS_2, WS_2, $MoSe_2$) are widely used in fiber laser. Complexity in handling dan fabricating these 2D materials often happens when dealing with two different material elements [17]–[20]. The topology insulator can have inherent problems affecting the technical and overall laser dirac surface process.

The evolution of SA in metal oxide materials has been rapidly explored, and among these materials are titanium dioxide (TiO_2), holmium oxide (H_2O_3) as a film SA. These SAs have different abilities where users can have multiple choices to decide the best SA in terms of stability, fabricating and cost [21]. Vanadium pentoxide (V_2O_5) is a stable and smart material, which can go through a reversible metal-insulator-transition, making this material a good candidate for SA. It exhibits highly anisotropic optoelectronic properties with a layered structure providing many interlayer spaces. This characteristic can facilitate faster mobility and better distribution during the charge-discharge processes [22]. In addition, the V_2O_5 bandgap, at ambient temperature, has been stated as from 0.6~2.3 eV, and from ~10-18s for the optical properties' lifetime [23], [24]. This paper introduces a new and rarely investigate V_2O_5 film SA using polyethylene glycol (PEG) thin film at erbium doped fiber. The bulk phase of 1.49 at a photon energy of 4.0 eV, which is interesting to investigate, particularly in the pulsed fiber laser application [25]. In this work, the V_2O_5 as film SA will be incorporated in the erbium-doped fiber laser (EDFL) cavity to promote a stable mode-locked laser.

2. LASER CONFIGURATION

The EDFL integrating V_2O_5 SA is shown in Figure 1. It comprises a laser diode pump with a central wavelength at 980 nm fusion spliced to erbium-doped fiber (EDF) via 980/1550 wavelength-division multiplexing (WDM). A fused isolator was applied to suppress back-scattering by forcing unidirectional propagation. 10% output of intra-cavity power was coupled out through a 10-dB optical coupler. Then, the obtained output laser was characterized. An optical spectrum analyzer (Yokogawa, AQ6370B) with a spectral resolution of 0.02 nm was used to observe the laser spectral. The temporal performance and radio frequency (RF) spectrum was measured via 1.2 GHz InGaAs photodetector (Thorlabs, DET01CFC) that connected to 350 MHz oscilloscope (GWINSTEK, GDS-3352) and 7.8 GHz RF spectrum analyzer (Anritsu, MS2683A). The actual pulse width was measured by using a femtosecond autocorrelator (Alnair Labs, HAC-200). The EDF that used as the gain medium has an ion concentration of 2000 ppm and a 24 dB/m absorption at 980 nm. The total cavity length is 21 m, including the additional 15 m long single mode fiber (SMF) and the 4 m long EDF gain medium. Both the EDF and SMF have a dispersion coefficient of 27.6 ps^2/km and -21.7 ps^2/km, respectively. The total cavity length is calculated to be 21 m with a net cavity dispersion of -1.004 ps^2.

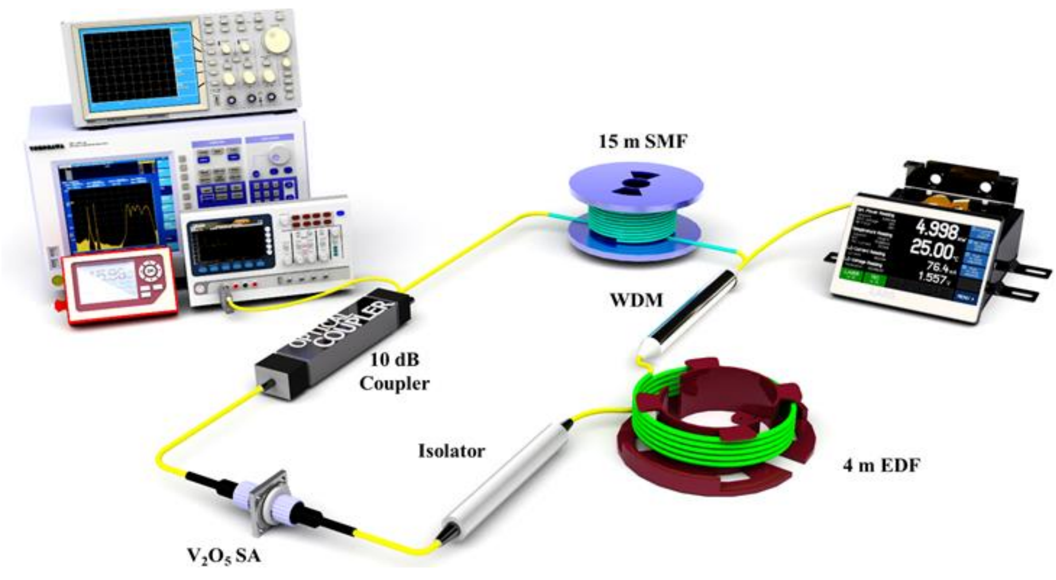


Figure 1. Mode-locked EDFL with V_2O_5 SA in ring setup

V_2O_5 thin film was prepared using simple solution mixture technique. Figure 2 shows some of the images related to the fabricated V_2O_5 film SA. The V_2O_5 film was fabricated by mixing and constant stirring the synthesized V_2O_5 with PEG solution for two hours. After that, both solutions, V_2O_5 and PEG, was cast on the petri dish and dried it in a vacuum oven to obtain a thin film SA, as shown in Figure 2(a). Figure 2(b) shows the field emission scanning electron microscope (FESEM) image of the V_2O_5 SA. The thin film was cut into 1mmx1mm before being placed onto the fiber end tip as shown in Figure 2(c). Figure 2(d) shows all type fiber connector used in the setup. Figure 3 depicts the nonlinear absorption profile of the V_2O_5 film. This nonlinear characteristic is used to ensure the ability of the optical SA in modulating high intensity pulsed laser. The saturation intensity and modulation depth are 90 MW/cm^2 and 7%, respectively, and was tested at 1.55-micron region.

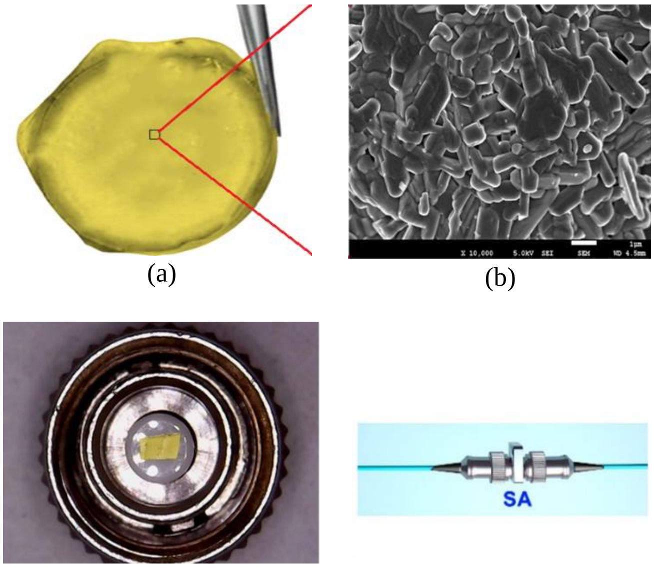


Figure 2. Fabrication process of V_2O_5 (a) thin film of V_2O_5 (b) FESEM image, (c) V_2O_5 onto a fiber end tip, and (d) all-fiber V_2O_5 SA expedient

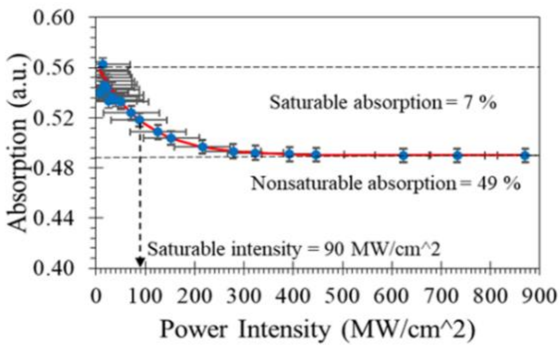
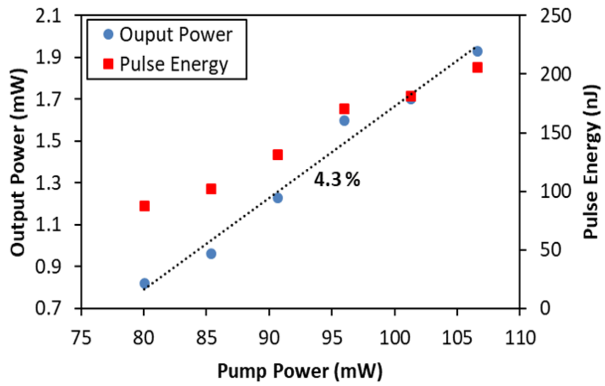


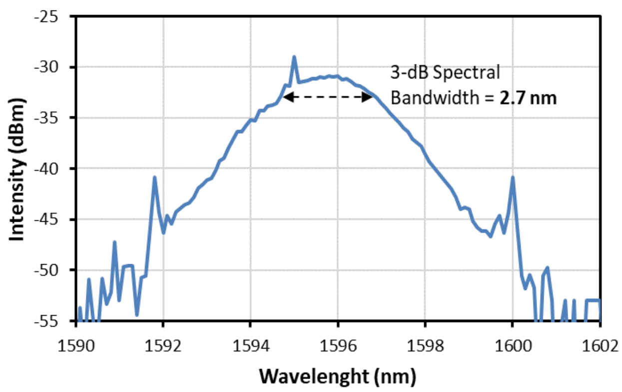
Figure 3. Nonlinear optical properties for V_2O_5 PEG SA

3. LASER PERFORMANCE

At first, we inserted a small piece of V_2O_5 film into the EDFL ring cavity. Then, we raised the input until a pulse generation was stably observed. Figure 4 displays the soliton EDFL performances. In particular, Figure 4(a) shows the overall output power and pulse energy of the mode-locking operation laser from the EDFL cavity. The self-started pulsing was induced at 80 mW and increase to 107 mW. The pulse train returned into a continuous wave, when it pushes higher from 107 mW. At the threshold pump, the mode-locked EDFL produced 0.82 mW output power with a pulse energy of 80 nJ. The maximum output power produced from this work was 1.93 mW, with each single-pulse train contain 210 nJ. At the maximum pump power, we obtained a 150 kW peak power. The slope efficiently plotted across the yield power describes the efficiency of 4.3%, which identifies the intra-cavity loss in our developed mode-locked EDFL is at an acceptable range. Figure 4(b) shows the obtained mode-locking operation has a consistent soliton spectral at 1596 nm with Kelly sidebands at both positive and negative sides. The mode-locked EDFL is observed to be operated under anomalous group delay dispersion of -0.26 ps2, which leads to the formation of soliton spectral with these Kelly sidebands. These sidebands are induced as soon the linear effect (anomalous group delay dispersion) and nonlinear effect (self-phase modulation) exist in a balanced state [2]. The figure also shows that the central peak wavelength has a 3-dB of 2.7 nm (317.77 GHz). The wavelength separation between central peak and sideband is 4.2 nm.



(a)



(b)

Figure 4. Performances of the soliton EDFL (a) the slope efficiency of mode-locking operation and (b) the optical spectrum of V2O5 SA

For temporal performances, the time-domain and frequency-domain were analyzed via a high-speed photodetector. Typically, a soliton laser generates a pulse width of less than a few picoseconds. Thus, it potentially enhanced the laser performance by developing a high peak power laser. Figure 5 depicts the mode-locked EDFL performances, when the laser cavity was incorporated with the V_2O_5 film SA. A pulse train of soliton EDFL is depicted in Figure 5(a). It shows two adjacent pulses separated by 105.8 ns, which corresponds to the round-trip time of total cavity length. The insert of Figure 5(a) shows the pulse train within the time of 5 µs, where the overall peak power of the pulse train is constant at 23 mV with a variant of ± 0.2. The full-wave half-maximum (FWHM) of single-pulse trace is measured at about 2 ns. Due to resolution limitations in the oscilloscope, this obtained FWHM is not the actual pulse width. We used the autocorrelator to measure the exact pulse width. Figure 5(b) shows the measured single-pulse trace with FWHM of 2.18 ps. Under sech2 fitting, the actual pulse width is relatively about 1.40 ps. The time-bandwidth product (TBP) is 0.445, showing a small pulse chirped. We expect the pulse width to lead to hundred femtoseconds with a further increase in the modulation depth and reduction in the non-saturable absorption. As confirmed through the RF spectrum analyzer given in Figure 5(c), the pulse train is considered stable. It shows the 1^{st} harmonic frequency (at 9.4 MHz), with a SNR of 40.66 dB. Under a 100 MHz span, the spectrum has a consistent harmonic frequency of about 94 MHz.

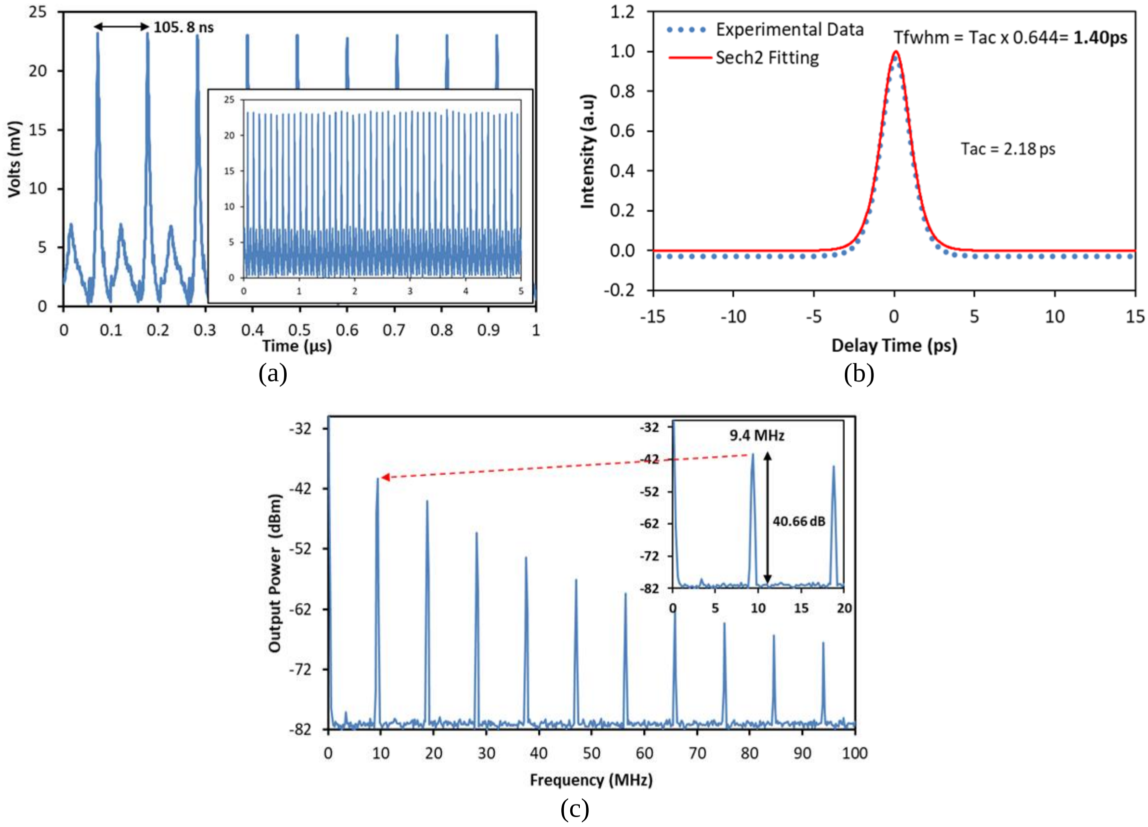


Figure 5. Mode-locked EDFL important performances (a) a pulse train at 107 mW, (b) $sech^2$ fitting curve, and (c) optical stabilty at 9.4 MHz based on the RF spectrum trace

4. CONCLUSIONS

V_2O_5 film with a modulation depth of 7% is integrated into EDFL to generate a soliton mode-locking operation. The film starts to saturate at 90 MW/cm^2, generating a repetition rate of 9.4 MHz, a pulse width of 1.40 ps, and the pulse stable at SNR of 40.66 dB. The mode-locked EDFL is operated under anomalous group delay dispersion of -0.26 ps^2, which leads to the formation of soliton spectral with Kelly sidebands. For power performance, the obtained laser has generated a significant peak power of 150 kW. This finding shows that the V^2O^5-PEG film can be a good alternative SA for inducing stable and high repetition rate pulsed fiber laser. Beside in future, PEG host material can be used for other transition metal oxides (TMO) materials which bring more robust and doable ability.

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