Samarium oxide film for picosecond mode-locked erbium-doped fiber laser

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Abstract
The saturable absorber device based on the samarium oxide film (Sm_2O_3) was employed inside the erbium-doped fiber laser (EDFL) cavity to initiate mode-locked at 1562 nm. A Sm_2O_3-PVA had generated mode-locked laser with a pulse width of as short as 3.4 ps, corresponds to a repetition rate of 1.88 MHz. The EDFL cavity initiated stable mode-locked pulses within the pump power of 91 to 142 mW. At a maximum attainable pump power of 142 mW, a laser cavity consumed maximum output power of 22.6 mW, corresponds to pulse energy of 12 nJ. Mode-locked EDFL generated was stable as it exhibits SNR of 68 dB and pumps efficiency of 15%. Our laser cavity was optimum as we captured stable mode-locked within a 1.55 µm region, thus open the potential for laser commercialization in the industry of micromachining and laser cutting technology. This demonstration shows the potential of samarium oxide as a saturable absorber in an all fiber-based laser cavity.

Keywords
Laser, Erbium doped fiber, Saturable absorber

1. Introduction

Emerging technology in short-pulse laser within the duration of a microsecond to femtosecond had attracted tremendous research attention in a few decades, thanks to its ability to construct a laser system with low cost and high efficiency. Vast applications had utilized pulsed laser for industrial purposes including micromachining, metal cutting, and corrective eye surgery [1-3]. For instance, 3D microfabrication of material utilized pulsed laser as a favorable approach in comparison to a continuous-wave laser. This is due to minimal chemical postprocessing and no special chamber or vacuum condition required for the process, thus it is cheaper and consumed less energy than other approaches [4]. Conventionally, the pulsed laser was initiated using electrically driven devices incorporated inside the laser system, acousto-optic and electro-optic modulator. Those techniques possess few limitations owning to their unsynchronized electrical signal and complex laser configuration, making them detrimental for commercial purposes.

In 1996, Keller et al. had introduced semiconductor saturable absorber mirrors (SESAM's) for the generation of a nanosecond to femtosecond pulse in a solid-state laser cavity [5]. Nonetheless, SESAM's has a narrow optical bandwidth and complex preparation method, making them less attractive in the laser pulsing method. Therefore, many all-fiberized lasers were introduced thus attracted much research interest, specifically the one which utilizes a material as a saturable absorber (SA) inside a laser cavity. An SA is a nonlinear material incorporated inside a laser cavity that modulate light to product almost uniform high intensity pulses. Many materials were utilized as SA in near-infrared (1-2 µm) laser cavity such as graphene [6], transition metal dichalcogenides (TMDCs) [7], topological insulators (TIs) [8] and black phosphorus (BP) [9]. Among all, two-dimensional (2D) allotropes are the most interesting one, graphene (the "godfather" of 2D material) had open deep yet remarkable research interest in the material world. Since then, tremendous findings on the peculiar optical characteristics of 2D materials had been widespread. Some of the other material utilized as SA inside a fiber laser cavity was metal oxide, metal nanoparticles, rare-earth oxide, ternary metal carbides/nitrides (MXene/MAX phase), antimonene, and bismuthene [10-15].

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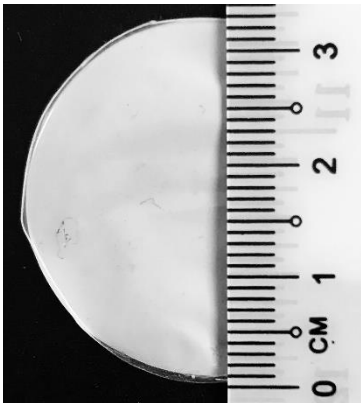
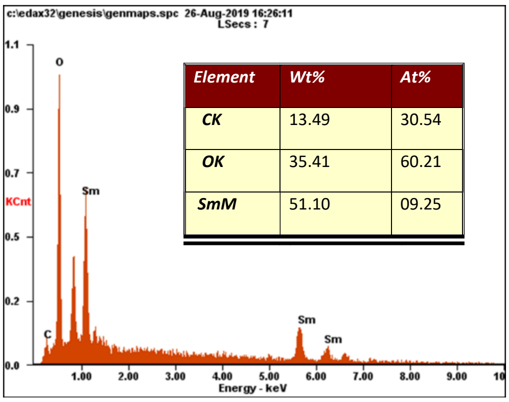
In the authors' knowledge, up till now, only a few works demonstrated mode-locked (ML) erbium-doped fiber laser (EDFL) using rare-earth oxide as SA [16, 17]. Herein, we proposed a mode-locking generation in an EDFL cavity by utilizing a samarium oxide film as saturable absorber. The optical properties of Sm_2O_3 was also excellent with a modulation depth of 30%. Thus, our SA device is efficient for the ultrashort pulse generation in the 1.55-µm laser cavity. This approach focused on the SA with ease of preparation procedure, making Sm_2O_3 one of the options for a pulsed laser generation in the near-infrared region.

2. Preparation, and characterization of Sm_2O_3 SA

The Sm_2O_3-PVA was prepared by using stirring and ultrasonication of Sm_2O_3 powder with polyvinyl alcohol (PVA). The process starts with the preparation of the PVA solution. Initially, a 1g of PVA powder (MFCD00081922, Sigma Aldrich) was dissolves in 120 mL of deionized water by stirring at room temperature. Next, a 50 mg of Sm_2O_3 was stirred with the prepared PVA solution. The mixture was stirred for 24 hrs using a magnetically actuated stirrer. Then, the solution undergoes ultrasonication for 2 hrs to ensure all the powder was dissolved. The heterogeneous mixture of the stirred solution was poured into a petri dish and left to dry for two days at room temperature. A Sm_2O_3-PVA was then peeled from the petri dish, the image of the Sm_2O_3 film was depicted in Figure 1 (a). The developed Sm_2O_3 film has a diameter of ~3.3 cm (based on the petri dish diameter) and a thickness of ~50 µm. The confirmation of the elemental composition was captured with an energy dispersive x-ray spectroscopy (EDS). Figure 4 (b) depicted the obtained EDS spectrum, which unraveled three main elements in the Sm_2O_3 film. The constituent of carbon is 13.49 in weight% and 30.54 in atomic% from the whole thin film SA. While the oxygen contributed to 35.41 in weight% and 60.21 in atomic% of the structure. The measurement proved samarium as the major element that makes up the film, with 51.10 in weight% and 9.25 in atomic%. Figure 4 (c) shows a linear absorption spectrum of the SA device, at the working wavelength of 1.56-µm, the absorption was 3.8 dB. Finally, the nonlinear absorption measurement with a twin-balanced detector technique revealed the graph in Figure 4 (d). The developed Sm_2O_3 SA has a saturable absorption of 30%, which is higher than the previous works [18, 19]. The prepared SA has a non-saturable absorption of 66% and a saturable intensity of 90 MW/cm^2.



(a)



(b)

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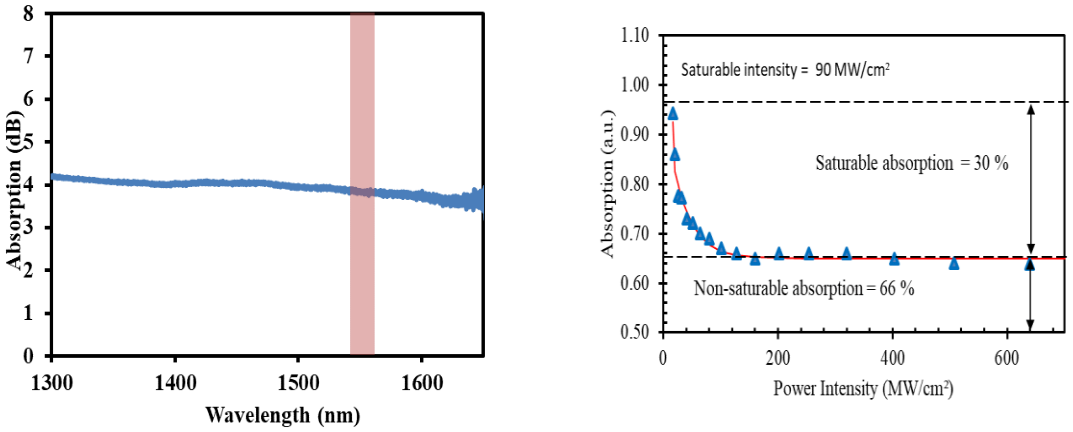


(c) (d)

Figure 1. (a) The image of thin film with approximately 3.3 cm diameter, (b) EDS spectrum, (c) linear absorption spectrum, and (d) nonlinear absorption spectrum of Sm_2O_3.

3. Experimental setup for a mode-locking generation in an EDFL cavity

The mode-locked laser was initiated using a developed EDFL cavity, as shown in Figure 2. A 980 nm laser diode pump connects to wavelength division multiplexer (WDM) with 980/1550 nm input ports. An output port of WDM links to the erbium-doped fiber (EDF) as a signal amplifier. EDF has a length of 2.4 m, a core diameter of 4 µm, a cladding diameter of 125 µm, an absorption coefficient of 23 dB/m, and a numerical aperture (NA) 0.16. Next, the light passes through an isolator that ensure unidirectional light source propagation. Unilateral light was then connected to the optical coupler, with 20% expelled from the cavity for analysis purposes. Later, 80% of light converged to the Sm_2O_3-PVA, which was sandwiched in between two fiber-ferrule. Next, the light was permitted to propagate through a 100 m single-mode fiber (SMF-28). The addditional length of SMF-28, provides nonlinearity in the laser cavity, which may enhance the development of mode-locked laser. The train of ultrashort pulses will continue as the light cycles back inside the EDFL cavity. Temporal characteristics of mode-locked EDFL was captured using a 350 MHz digital oscilloscope (GWINSTEK, GDS-3352) and 7.8 GHz ANRITSU, MS2683A radio frequency spectrum analyzer (RFSA) connected via a 7-GHz InGaAs photodetector. The pulsed laser's output performance was monitored using a digital power meter and a YOKOGAWA, AQ6370D optical spectrum analyzer (OSA) with a resolution of 0.02 nm. The autocorrelator (ALNAIR LABS, HAC200) was used to capture a fast-moving photon inside the laser cavity.

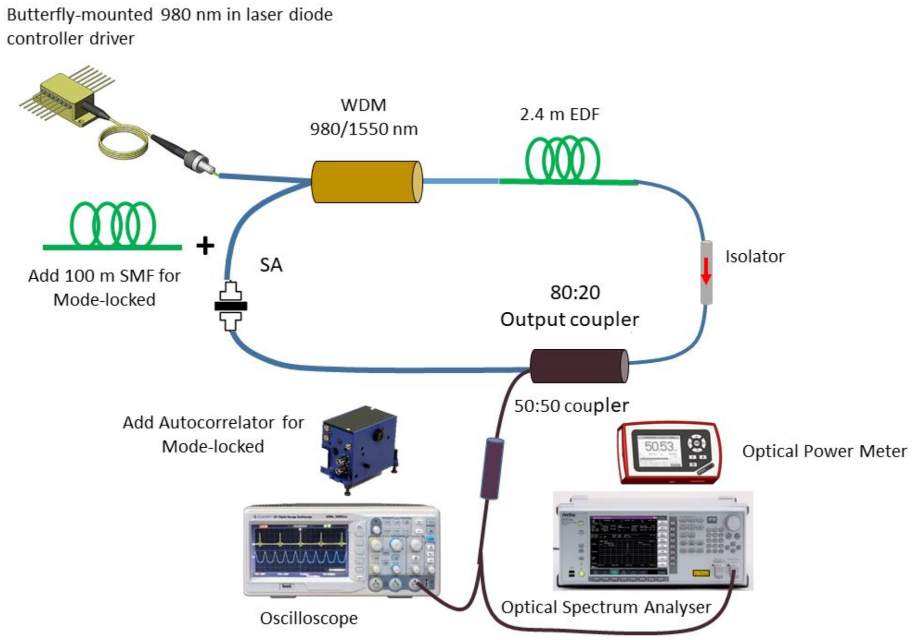
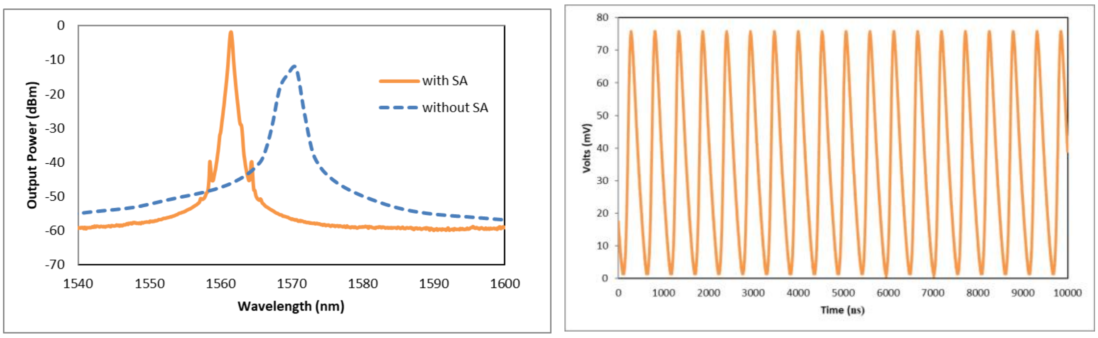


Figure 2. Experimental setup for picosecond mode-locking generation in an EDFL cavity.

4. Results and discussion

Self-started mode-locked appear at the pump power of 91 mW, stable until the pump power of 142 mW. Figure 3 (a) depicts an optical spectrum of continuous-wave and mode-locked captured at the maximum attainable pump power of 142 mW. Without SA, the laser operates at a center wavelength of 1570 nm, while the incorporation of Sm_2O_3 causes the peak to blueshift. The mode-locked generated own a center wavelength of 1562 nm. The OSA's trace of mode-locked laser indicates the EDFL is in the soliton regime, proven by the existence of a pair of Kelly sidebands in the spectrum. The anomalous cavity dispersion has triggered the soliton shape of mode-locked laser. By referring to Figure 3 (b), consistent pulses were observed on the oscilloscope, captured within 10000 ns duration. The peak-to-peak distance between two pulses indicate a cavity round-trip time of 531 ns, and it matches the cavity length of 113.4 m. Figure 3 (c) shows the RF spectrum obtained at a pump power of 142 mW. The RF signal captured at the fundamental frequency of 1.88 MHz revealed the signal-to-noise ratio (SNR) of 68 dB. Finally, the autocorrelator trace depicts a full-width half minimum (T_{fwhm}) of 3.4 ps, which was calculated based on the T_{ac} of 5.26 ps. The 3dB spectral bandwidth of laser (with SA included) is about 0.3 nm. As shown in Figure 3 (d), the trace's theoretical and experimental line fits perfectly.



(a) (b)

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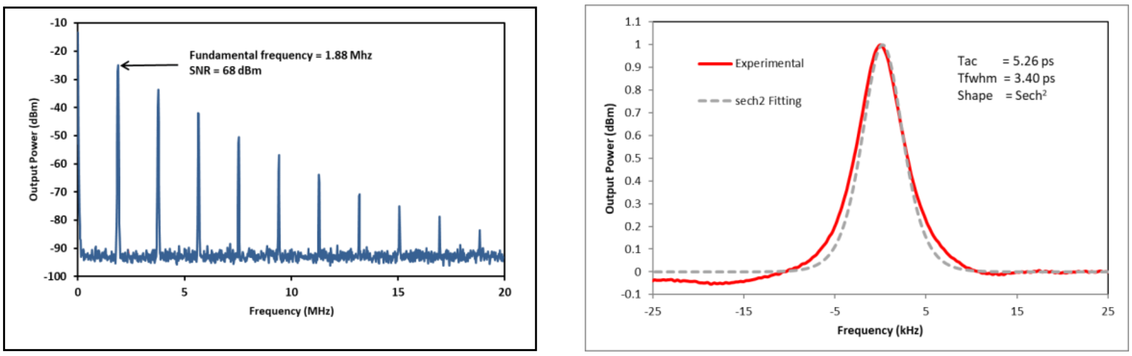
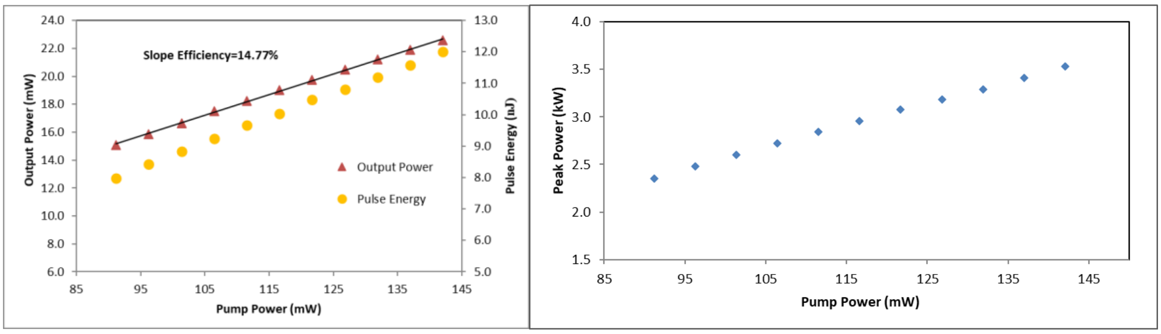


(c) (d)

Figure 3. Spectral and temporal performances of the generated mode-locked laser; (a) OSA spectrum, (b) oscilloscope spectrum, (c) radio frequency spectrum, and (d) autocorrelator trace.

The performance of mode-locked was investigated over a variation of pump power. The graph of pulse width and repetition rate against the pump power was shown in Figure 4 (a). As the pump power varied within 91 to 142 mW, the pulse width fluctuates between 3.4 to 3.8 ps. Simultaneously, the repetition rate is nearly consistent from 1.84 to 1.88 MHz with the same pump power variation. The maximum attainable pump power of 142 mW generates mode-locked with the pulse width and repetition rate of 3.4 ps and 1.88 MHz, respectively. However, pulse width and repetition rate might be enhanced via the construction of shorter cavity length and deployment of highly doped EDF; thus, introduced better mode-locked performance. When the pump power increased from 91 to 142 mW, the peak power also increased from 2.35 to 3.53 kW in Figure 4 (b).



(a) (b)

Figure 4. Mode-locked performances within the pump power of 91-142 mW; (a) The graph of repetition rate and pulse width as a function of pump power, and (b) the graph of peak power as a function of pump power.

5. Conclusion

Sm_2O_3 was successfully incorporated inside the EDFL cavity for pulse generation at 1562 nm. Sm_2O_3 was embedded into PVA to construct a free-standing thin film for easy incorporation of SA inside the EDFL cavity. Mode-locked generated attained pulse width of 3.4 ps and a repetition rate of 1.88 MHz, within the pump power of 91 to 142 mW. The output power of mode-locked EDFL measured within the same range of pump power was 15.1 to 22.3 mW, corresponds to the pulse energy of 8 to 12 nJ. Sm_2O_3-PVA shows excellent laser parameters, SNR of 68 dB, pump efficiency of 15% and a stable mode-locked behavior across the variations of 91-142 mW pump power.

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