

Communication

# Yttrium Oxide ( $Y_2O_3$ ) as a Pulse Initiator in a Mode-Locking Erbium-Doped Fiber Laser

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**Abstract:** Mode-locking is an ultra-short pulse laser generation technique. The range of pulse duration may vary from picoseconds to femtoseconds. Yttrium Oxide ( $Y_2O_3$ ) based saturable absorber (SA) was appropriately revealed in the mode-locked method within the 1.55-micron regime.  $Y_2O_3$  is perfect for strength, melting point, and chemical stability and can be used as a laminated insulator due to its properties. Moreover,  $Y_2O_3$  also owns broadband service, switching speed, and engineering features. The  $Y_2O_3$ -PVA film was produced by combining the 50 mg  $Y_2O_3$  powder into a 50 mL polyvinyl alcohol (PVA) solution and stirring it at room temperature for about 24 h. A mode-locked pulse was recorded with the integrated  $Y_2O_3$ -PVA SA in the erbium-doped fiber laser (EDFL) cavity, and the output spectrum optical spectrum analyzer displayed was around 1560.66 nm. In addition to the sustained mode-locked pulse, a nearly constant repetition rate of 1.01 MHz at a specific pump power begins from 175.87 mW to 228.04 mW while the pulse duration is 4.15 ps. Lastly, the mode-locked pulse had been evaluated, which showed the peak power started from 4.94 kW to 6.07 kW.

**Keywords:** yttrium oxide; fiber laser; mode-locked method; saturable absorber



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## 1. Introduction

The pulsed fiber lasers are designed based on passive fiber oscillators, occupying both the industrial and scientific worlds. They were then amplified to reach the desired output pulse energies in several stages. Mode-locking is an ultra-short pulse laser generation technique. The range of pulse duration may vary from picoseconds to femtoseconds [1–5]. Fix-phase coordination is accomplished using passive mode-locking and no external pulse triggering. The mode-locked pulses are actively formed through the laser's internal structure, which provides the signal with more advantages (less loss and high gain) if it travels in the form of a pulse instead of a continuous wave mode. The simplest method is to use an SA inside the cavity. This SA has a nonlinear optical response, the absorption coefficient of which decreases with increasing light intensity. An ultrashort pulse may develop if the loss is modulated once every cavity round trip by SA and all longitudinal modes have a fixed phase relationship. As a result of the oscillating laser's mode-locking, an ultrashort pulse train (varying from ns to fs in duration) is produced at a set repetition rate in MHz, which corresponds to the laser cavity's free spectra range or the number of acquired pulses per second [6–8]. Specifically, saturable absorber mirrors (SESAM) are

commonly used for passive mode-locking and Q-switching [9]. When ideal for broadband lasers, these absorbers may exhibit very broad absorption characteristics. The nanotube absorber's recovery time is relatively short, but significant non-saturable losses can be an issue for some applications. Bismuthene [10] and MXene [11] have recently been identified as versatile SA for pulse generation in the 1.55-micron region. Bismuthene is known to possess a robust electronic transport network and improve long-term reliability, resulting in a marked increase in BPs. This allotrope's non-trivial bandgap (~0.55 eV) makes it effective for photonic and optoelectronic applications across a broad electromagnetic spectrum from ultraviolet to near-infrared [12]. Rather, a few studies have used MXene as an SA in a broad near-infrared range from 1 to 2  $\mu\text{m}$  [13]. Two-dimensional (2D) metal carbides or nitrides are favorable because they have a wide optical response, high electron mobility, and high optical transparency [14]. Moreover, their optical properties were incredible, including high optical damage tolerance, powerful switching capability, and an effective ultra-fast laser absorption coefficient [15]. Because of their outstanding optical and physical features, these 2D materials required detailed preparation methods to be implemented as an SA device in a near-infrared laser cavity. Moreover, the transition metal dichalcogenides (TMDCs) and transition metal chalcogenides (TMCs) have become more attractive. This is because the addition of the third element owing to their unique structure and remarkable physical and chemical properties endow these materials with considerable potential for applications in nanoscale devices.  $\text{Re}_x\text{Nb}_{(1-x)}\text{S}_2$ -based saturable absorber (SA) and  $\text{Nb}_x\text{Re}_{(1-x)}\text{S}_2$  nanosheets are the examples that have been used for SA in the generation of ultrashort pulses in EDF laser cavity [16,17]. Recently, Liu et al. demonstrated the soliton mode-locked using a tapered fiber based saturable absorber as an enhancement to nonlinearity with different thickness of  $\text{Y}_2\text{O}_3$  layer, namely 5 nm, 8 nm, and 20 nm acting as a material for an ultrafast laser generation [18].

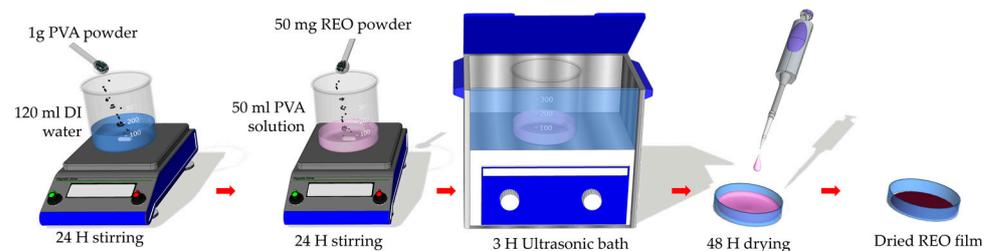
The rare earth oxide films analyzed can be useful for interference optics implementations in the 0.3–2.5- $\mu\text{m}$  spectral range because they follow the requirements described. In addition, they have very good stability over time when evaporated properly. When held at a constant level, conventional evaporation parameters allow films with reproducible properties to be generated. Moreover, standard evaporation parameters, if maintained at a constant level, enable the development of films whose refractive indices are included in the short range of 1.8–1.95, have good clarity across a broad spectral region, and are characterized by high mechanical and chemical resistance with reproducible properties [19]. It is a thermally stable white material used in the manufacture of special glass, crystal, and ceramics [20]. Limited work has been performed to demonstrate the ability of rare earth oxide to act as an SA for Q-switched and mode-locked generation in erbium-doped fiber lasers (EDFL) (1.55  $\mu\text{m}$ ). The mode-locked EDFL was achieved efficiently by incorporating the  $\text{Ho}_2\text{O}_3$  film SA with a 3 m single-mode fiber (SMF-28) in the cavity. The mode-locked laser created a stable repetition rate of 17.1 MHz and a pulse width as narrow as 650 fs between 62 mW and 180 mW of the pump power range [21].  $\text{Y}_2\text{O}_3$  is perfect for strength, melting point, and chemical stability. Yttrium oxide can also be used as a laminated insulator due to its properties. The main element of rare earth in xenotime is yttrium. This represents approximately 60% of the TRE [22].  $\text{Y}_2\text{O}_3$  is the most stable compound in the group of oxides. It is resistant to many metals, such as titanium or uranium, that are reactive molten.  $\text{Y}_2\text{O}_3$  is still a relatively new material in its industrial application as a pure ceramic. Other uses of  $\text{Y}_2\text{O}_3$  are as a raw material for high-temperature superconductors, in the manufacture of yttrium and other yttrium compounds, in the manufacture of red luminophores for CRT displays, in the manufacture of transparent IR and UV glass, in insulators, in glass, in ceramics, in refractories and stains, and in optical coatings. Yttrium Aluminum Garnet (YAG), a television red phosphorus host for europium, uses Yttrium Vanadate ( $\text{YVO}_4$ ), superconductors of high-temperature YBCO, Yttria-Stabilized Zirconia (YSZ), Yttria Iron Garnet (YIG) microwave filters, and energy-saving light bulbs. (It is part of triphosphor white phosphor coating in fluorescent tubes, CFLs and [23], spark plugs, gas mantles, steel additives, and cancer treatments. In this experiment, we focus only on real

SAs because they have many strengths, such as broadband service, switching speed, and engineering features [24,25]. An ideal SA should have a high threshold for damage, but it should also be efficient in cost and time. Saturable absorbers are majorly implemented in the generation of short optical pulses in both methods, passive Q-switching, and mode-locking lasers. Saturable absorbers are also particularly helpful for nonlinear filtration of external laser resonators, for example for pulse-cleaning and optical signal processing [26]. In addition, we focused on the development of the mode-locked EDFL using the recent growth of  $Y_2O_3$  thin film as an SA as it has an excellent optical nonlinearity for pulsed laser generation.

## 2. Synthesis and Characterization of Yttrium Oxide for Pulse Enabler

The SA's film in this experiment in generating robust mode-locked pulse generation from an EDFL cavity has been reported. Commercial Yttrium Oxide ( $Y_2O_3$ ) (Shanghai Xinglu Chemical Technology Co., Ltd., Shanghai, China) powder particles with 99% purity are dissolved in polyvinyl alcohol (PVA) solution to form the SA film. This is performed to allow for better integration of the  $Y_2O_3$  into an EDFL setup. We made the polymer film  $Y_2O_3$  by mixing the solution  $Y_2O_3$  powder with polyvinyl alcohol (PVA). For this procedure, 1 g of PVA powder was applied to the PVA solution in 120 mL of deionized (DI) water. The solution was added and mixed at room temperature for nearly 24 h using a magnetic stirrer.

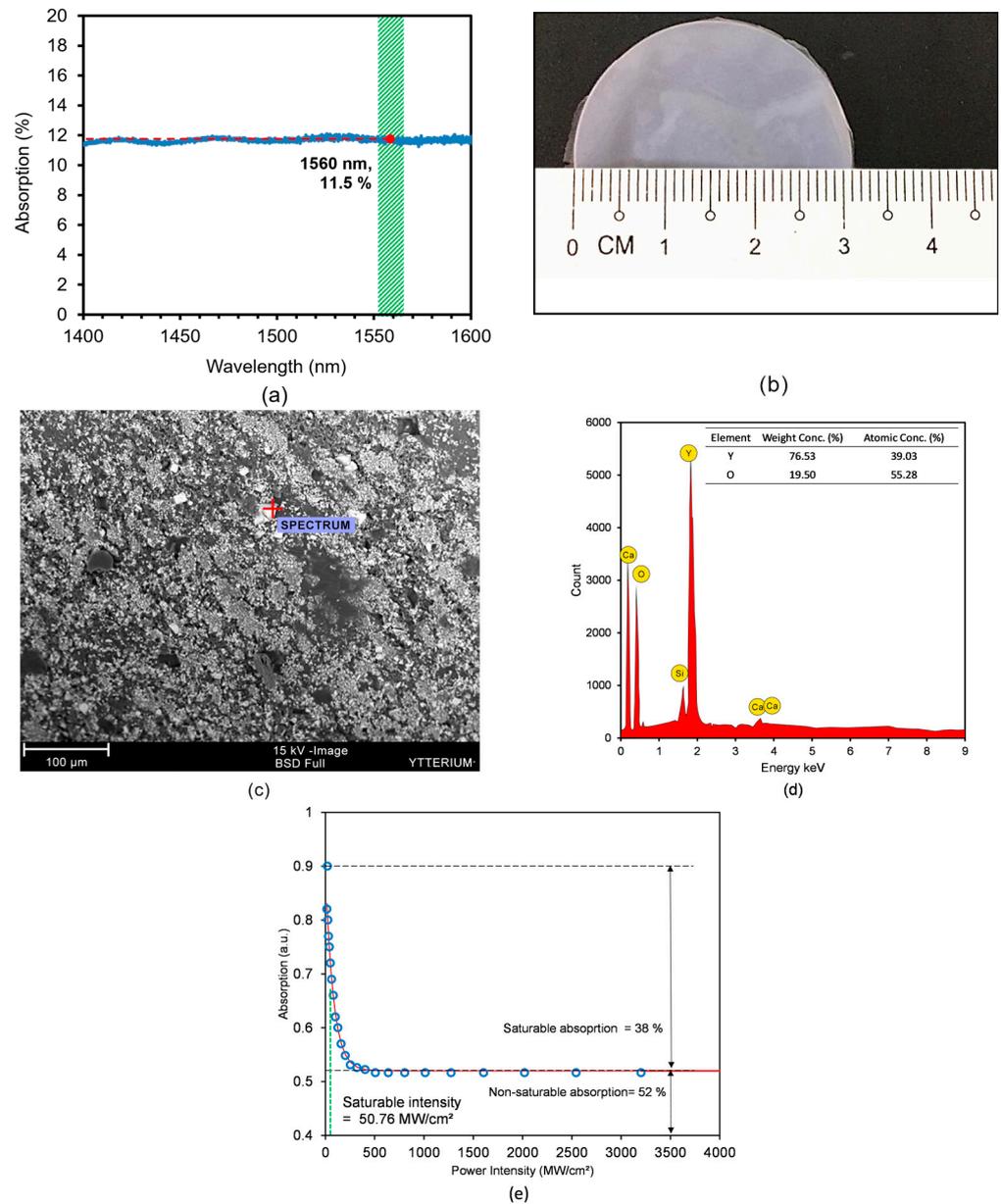
50 mg of  $Y_2O_3$  powder was reportedly mixed into 50 mL of prepared PVA solution. The  $Y_2O_3$ -PVA SA suspension was further stirred with a magnetic stirrer (Corning Digital Stirring Hot Plates, PC-420D, Reynosa, Mexico) for a minimum of 24 h. The mixture was then sonicated in an ultrasonic bath (Ultrasonic Cleaner, GT Sonic-P2, Guangdong, China) for at least 3 h. The most important issue in this procedure to remove the compound's substance is to break the bond between the molecules attached as per Van der Waals force. The homogeneous suspension sampled at the end of the process was put into a tiny glass petri dish. To develop a film, it was required to dry at room temperature for about 48 h, or 2 days. Figure 1 indicates  $Y_2O_3$ -PVA SA is produced utilizing a casting form.



**Figure 1.** The fabrication of  $Y_2O_3$ -PVA film.

It clearly shows detailed implementations for  $Y_2O_3$ -PVA characterization. The proposed study used Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray Spectroscopy (EDX) to investigate the surface structure of  $Y_2O_3$ -PVA compounds. Moreover, the film structure and surface morphology were observed using both SEM and EDX procedures. Most of the elements on the periodic table are easily recognizable and detectable in the electron scanning fields, except H, He, and Li. Figure 2a depicts the absorption profile of  $Y_2O_3$ -PVA film measured in a spectral range from 1400 nm to 1600 nm. A relatively flat line of approximately 11.5% absorption is observed near 1560 nm marked with red-dotted. The  $Y_2O_3$ -PVA film selectively absorbs low-intensity light and transmits light that is of sufficiently high intensity and is in accordance with the basic feature of SA for passive mode-locking. In addition, Figure 2b represents the physical image of the film  $Y_2O_3$ -PVA. Figure 2c shows an amplified picture of the film particles observed through SEM. The  $Y_2O_3$ -PVA compound is also investigated as being equally dispersed across the film. Figure 2d is the film EDX, which indicates the presence of Yttrium (Y) and Oxygen (O) elements in the film at about 76.53% and 19.50%, respectively. The nonlinear absorp-

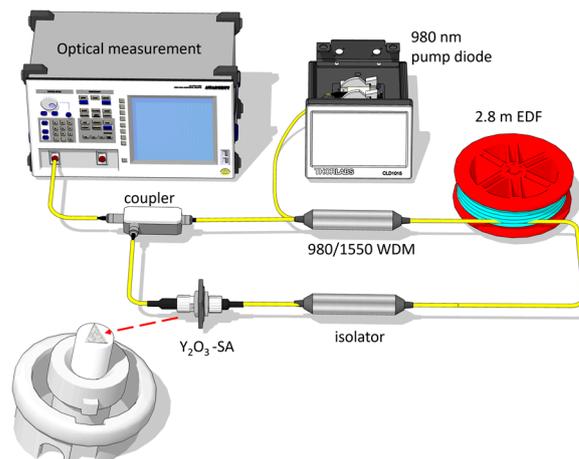
tion of the  $Y_2O_3$ -PVA was obtained by using a twin balance detection technique using a homemade mode-locked fiber laser as a seed pulsed light source. The laser operated at the center wavelength of 1560 nm with a repetition rate of 1 MHz and pulse width of 4.14 ps. The seed pulse train was amplified by an Erbium-doped fiber amplifier while the output power was controlled by an optical attenuator. The measured nonlinear optical profile was fitted into a simple saturation,  $\alpha(I) = \alpha_s / (1 + I/I_{sat}) + \alpha_{ns}$ , where the  $\alpha_s$  is the saturable absorption,  $I$  is the intensity,  $I_{sat}$  is the saturation intensity, and  $\alpha_{ns}$  is the non-saturable absorption. The saturable absorption is shown to be 38.0% while non-saturable absorption is shown to be approximately 52.0% in Figure 2e. The graph shows 50.76 MW/cm<sup>2</sup> for saturable intensity. Such a large non-saturable absorption was due to the low frequency of the mode-locked source used during the measurement. The non-saturable loss will be decreased as the frequency is high or vice versa [27].



**Figure 2.** (a) linear absorption profile of  $Y_2O_3$ -PVA, (b) physical image of  $Y_2O_3$ -PVA film, (c) surface morphology analysis of  $Y_2O_3$ -PVA using SEM with red cross mark showing the position of EDX analysis, (d) elemental analysis using EDX, and (e) modulation depth of  $Y_2O_3$ -PVA film with green and red dotted lines shows the saturable intensity and saturable absorption percentage respectively.

### 3. Experimental Setup

An approach focused on  $Y_2O_3$ -PVA SA is proposed, which is based on a mode-locked EDFL as shown in Figure 3. The Erbium-doped Fiber (EDF), 2.8 m long, with 90 dB/m 980 nm absorption, acts as a gain medium. Then a pump of 980 nm laser diode goes through a Wavelength Division Multiplexer (WDM) 980/1550 nm. A 90/10 coupler is then used to produce laser emissions for further use or data collection. To achieve unidirectional propagation of the oscillating laser in a ring configuration, an isolator is spliced between the two ferrules after the isolator. Laser spectrum properties were tracked and evaluated using an optical spectrum analyzer collected from a 90:10 optical coupler. A strong speed photodetector was attached to a GWINSTEK 500 MHz specification oscilloscope model and monitored the output pulse train. A 7.8 GHz type Radio Frequency (RF) spectrum analyzer (Anritsu MS2683A) is used to check the frequency and stability of the mode-locked laser. The overall output power of the pulse laser is determined by a power meter (ILX Lightwave OMM-6810B) coupled to its powerhead (ILX Lightwave). To achieve mode-locking, a piece of SMF-28 fiber (200 m long) is inserted into the cavity to modify the dispersion characteristic and improve its nonlinearity. As a result, the cavity's overall length is 113.5 m. The group speed dispersion (GVD) of the SMF, WDM fiber, and EDF is 21.7 ps<sup>2</sup>/km, 38 ps<sup>2</sup>/km, and 21.6 ps<sup>2</sup>/km, respectively. The anomalous dispersion system allows mode-locked laser operation.



**Figure 3.** The configuration of the mode-locked Erbium-doped Fiber Laser (EDFL) utilizing  $Y_2O_3$ -PVA SA.

### 4. Results and Discussion

To the best of the authors' knowledge, a new framework for a passively satisfactory and compact mode-locked EDFL by integrating  $Y_2O_3$ -PVA composite film into the ring cavity to function as a pulse initiator has been proposed. At a pump power range of 175.87 mW to 228.04 mW, a reliable mode-locked EDFL working at 1560.66 nm with a generated frequency in the range of 1.01 MHz and a pulse duration of 4.15 ps was achieved. The mode-locked laser remained stable at up to 228.04 mW of pump power.  $Y_2O_3$ -PVA SA is being used in the mode-locking process, and the film tends to create some loss inside that cavity, which is significantly larger for low intensity but small for a high-intensity short pulse.

Figure 4a illustrates the optical spectrum of the mode-locked EDFL. The laser has a center wavelength of 1560.66 nm and a peak power intensity of  $-11.9$  dBm. The 3 dB spectral bandwidth is approximately 0.85 nm. Two weak Kelly sidebands were also observed, which indicates the mode-locking pulses operate in a soliton regime. These pairs of Kelly sidebands are located almost symmetrically from the center wavelength of the spectrum and are usually observed on the soliton spectrum when constructive interference took place between the soliton pulse and dispersive waves. Figure 4b illustrates a typical

oscilloscope trace and a bigger trace of both the pulse period and pulse width of the mode-locked pulse train at a pumping power of 228.04 mW at a repetition rate of 1.01 MHz. The pulses locked in the phase train, as shown in Figure 4c, have an almost constant repetition rate of 1.01 MHz and a relatively small amplitude fluctuation (less than 5%). The  $Y_2O_3$ -PVA film was replaced with a pristine PVA film to substantiate that the laser’s mode-locking pulse generation was due to the  $Y_2O_3$ -PVA. For this configuration, no pulse was noticeable at any pump power on the oscilloscope. The pulses collected were very steady without any amplitude variations and had a standardized distribution. The EDFL cavity was noted to continue operating with a group velocity dispersion (GVD) of about  $21.90 \text{ ps}^2/\text{km}$  in the anomalous dispersion regime. The total net dispersion was estimated to be around  $-4.46 \text{ ps}^2/\text{km}$ . Based on the RF spectrum obtained at 228.04 mW pump power as provided in Figure 4d, the stability of the pulsed laser was further investigated. The fundamental frequency is found to be 1.01 MHz with 4 harmonics. This finding is very much in line with the pulse period obtained through the trace of the oscilloscope. It can also be shown from the RF range that the SNR is strong at 56.71 dB, which proves the stability of the mode-locked pulses. The SNR value was 56.71 dB, noting the steadiness of the mode-locking performances since the value exceeded 30 dB.

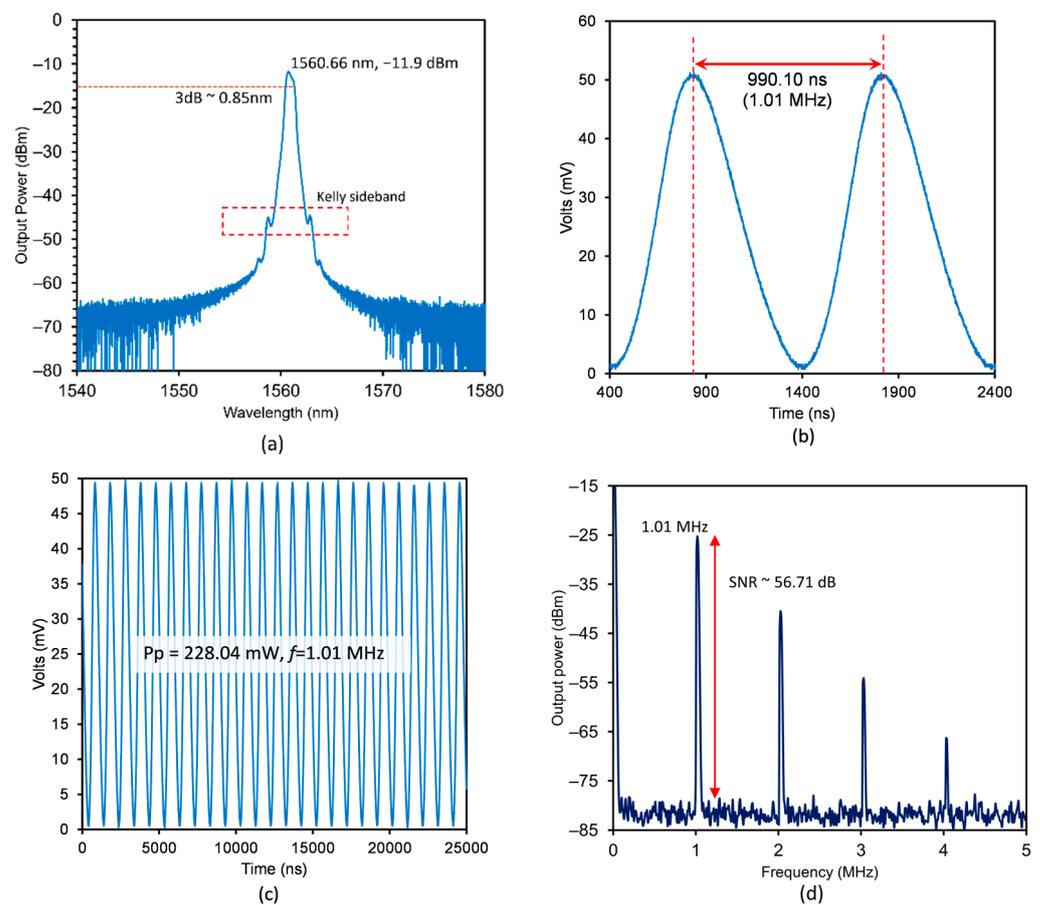
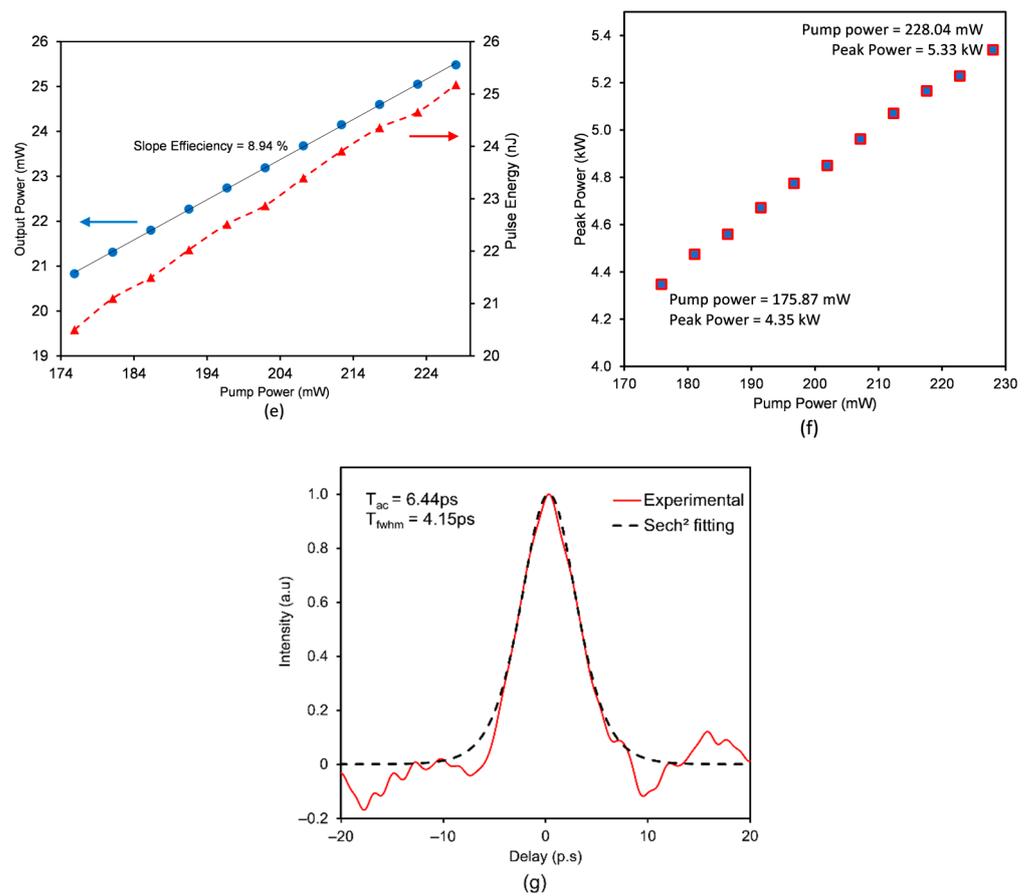


Figure 4. Cont.



**Figure 4.** Mode-locked pulse performances: (a) the Y<sub>2</sub>O<sub>3</sub>-PVA SA output spectrum at a pump power of 228.04 mW, (b) the enlarge of peak-to-peak with the constant frequency, (c) pulse train of the oscilloscope, (d) the RF spectrum at the pump power 228.04 mW, (e) the output power and pulse energy as a function of pump power, (f) peak power against pump power from 4.35 kW to 5.33 kW, and (g) the intensity against delay with 4.15 ps FWHM.

The mode-locked EDFL performances are shown in Figure 4e. As the pump power rises from 175.87 mW to 228.04 mW, the output power increases linearly from 20.83 mW to the maximum of 25.48 mW. At 8.94%, the appropriate slope efficiency can be determined. The pulse energy rises in perfect sync with the pump power, reaching a maximum of 25.80 nJ. At room temperature, the mode-locked operation was investigated for at least 1 h and observed no degradation on the output performances. The peak power was increased from 4.35 kW to 5.33 kW, as shown in Figure 4f. The pump power has increased from 175.87 mW to 228.04 mW. The optical range and strength of the pulse reveal zero noticeable fluctuations in laser performance measurement, indicating the designed system’s long-term stability. It also implies that the SA is in good physical condition, with a thermal damage threshold larger than the laser power. In addition, with the sech<sup>2</sup> fitting, Figure 4g shows the conventional autocorrelator trace of the mode-locking pulses. At a maximum pump power of 228.04 mW, the pulse used to have a full width at half maximum (FWHM) of 4.15 ps. 0.664 was found to be the Time Bandwidth Product (TBP). The TBP attained is slightly higher than the sech<sup>2</sup> transform’s minimum TBP of 0.315, indicating that the output pulses are chirped.

Table 1 compares the performance of several SAs with the Y<sub>2</sub>O<sub>3</sub> film utilized in this study to generate mode-locked fiber lasers, notably in the 1.55 m wavelength region. As demonstrated, the resulting pulse width and pulse energy are comparable to those reported in the literature [28–31].

**Table 1.** Performance comparison of mode-locked fiber lasers with various transition metal oxides (TMOs) saturable absorbers (SAs).

SA Materials	Operating Wavelength (nm)	Pulsewidth (ps)	Repetition Rate (MHz)	SNR (dB)	Maximum Pulse Energy	References
CO <sub>3</sub> O <sub>4</sub>	1558.86	1.25	5.68	72.37	1.99	[28]
MgO	1569	5.6	3.5	50	2.17	[29]
Sm <sub>2</sub> O <sub>3</sub>	1562	3.4	1.88	68	12	[30]
V <sub>2</sub> O <sub>5</sub>	1559.25	3.14	1	48.6	4.44	[31]
Y <sub>2</sub> O <sub>3</sub>	1560.66	4.15	1.01	56.71	25.80	This work

## 5. Conclusions

In summary, a configuration of the mode-locked approach has been successfully designed, and it has been noticed that the newly produced Y<sub>2</sub>O<sub>3</sub>-PVA SA has provided good performance for the mode-locking technique. The mode-locked EDFL based Y<sub>2</sub>O<sub>3</sub>-PVA produced maximum pulse energy and peak power at 25.80 nJ and 5.33 kW, respectively, and the developed stabilized mode-locked pulses have a 1.01 MHz constant repetition rate, a 4.15 ps pulse duration, a 25.48 mW maximum output power, and a 25.18 nJ maximum pulse power. The mode-locked pulse peak-to-peak is 990.10 ns. The hardness and effective Y<sub>2</sub>O<sub>3</sub>-PVA chemical stability contribute to increased laser stability, even at high power. Our findings proved that the Y<sub>2</sub>O<sub>3</sub>-PVA SA not only has powerful nonlinearity and potential benefits in achieving ultrashort pulse width but also has performed consistently in high-power operations. The Y<sub>2</sub>O<sub>3</sub>-PVA SA can thus gain attraction to the market opportunity for optical modulation and optoelectronic operating systems.

**Author Contributions:** Conceptualization, N.F.Z. and A.H.A.R.; methodology, N.F.Z.; validation, N.F.Z., S.W.H. and A.H.A.R.; formal analysis, N.F.Z.; investigation, N.F.Z.; resources, S.W.H. and M.B.; writing—original draft preparation, N.F.Z.; writing—review and editing, N.F.Z., A.R.M., M.F.M. and M.B.; visualization, A.R.M.; supervision, S.W.H., A.A. and F.E.D.; funding acquisition, A.R.M. All authors have read and agreed to the published version of the manuscript.

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**Conflicts of Interest:** The authors declare no conflict of interest.

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