Q-switched erbium-doped fiber lasers based on copper nanoparticles saturable absorber

E I Ismail¹, F Ahmad¹, S Ambran¹, A A Latiff² and S W Harun³

¹Malaysia-Japan International Institute of Technology, Universiti Teknologi Malaysia, Jalan Sultan Yahya Petra, 54100 Kuala Lumpur, Malaysia
²Centre for Telecommunication Research & Innovation (CeTRI), Fakulti Kejuruteraan Elektronik & Kejuruteraan Komputer (FKEKK), Universiti Teknikal Malaysia Melaka (UTeM), 76100 Durian Tunggal, Melaka, Malaysia
³Photonics Engineering Laboratory, Department of Electrical Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia

ezzatulirradah5@gmail.com; fauzan.kl@utm.my

Abstract. We reported a generation of passively Q-switching pulses in an erbium-doped fiber laser by exploiting copper nanoparticles polyvinyl alcohol polymer composite (CuNP-PVA) based saturable absorber (SA). The modulation depth and the saturation power intensity of the CuNP-PVA film are calculated as 18 % and 0.021 kW/cm², respectively. A maximum repetition rate of 104.2 kHz, the shortest pulse width of 5.1 µs and pulse energy up to 20.4 nJ was observed at 1558 nm wavelength.

1. Introduction

The evolution of 1-, 2- and 3-Dimensional material in the field of material sciences has allowed the realization of a multitude of new devices, called saturable absorber (SAs). These SAs are the key to generate passively Q-switched fiber lasers. Passively Q-switched fiber lasers have been extensively used in optical communications, range finding and material processing due to its flexible and compact advantages [1,2]. Essentially, Q-switched laser has its convenience especially in terms of relatively high pulse energy and tunable repetition rate. Originally, saturable absorber begins with semiconductor saturable absorber mirrors (SESAMs) to generate pulsed outputs in laser cavities [3]. However, due to their complex procedure, limited bandwidth and expensive costs lead the researchers to explore material which acquires high laser damage threshold, good fiber compatibility and low optical saturable intensity [4-8]. Two-dimensional (2D) layered materials including graphene and transition metal dichalcogenides (TMDCs) have been employed as SA considering their simplicity of manufacture and inexpensive cost contrasting to SESAMs [9-12]. Graphene normally has a low optical saturation which is 2.3% per layer and TMDCs are progressively available in the visible region because of their substantial bandgaps. Still, 2D materials in specific, are acknowledged as a strong prospect for the cutting-edge photonics innovation in light of their ultrafast carrier elements and wideband responses [13,14]. Next, black phosphorus (BP) has been regained as one of the next SA for optoelectronic applications [15]. However, they are also vulnerable to high laser optical damage threshold and easily oxidized to oxygen and moisture environment.

Quite recently, metal nanomaterial such as silver and copper attract many researchers as the next generation of SAs as it has high potential in the optic application. Copper especially has broad saturable absorption, large third-order nonlinearity and ultrafast response time [16,17]. Muhammad et al. proposed a Q-switched fiber laser with copper-PVA at the 1.5 wavelength region. The laser operated at a repetition rate and pulse width of 101.2 kHz and 4.28 µs respectively, while the maximum average output power was obtained at 1.86 mW [18]. Sinan et al. reported Q-switch pulse using copper oxide-
PVA at 1560 nm with a repetition rate of 83 kHz, pulse width 2.6 µs of and the maximum pulse energy of 66 nJ [19].

In the present work, a passively Q-switched EDFL was successfully realized at C-band region by incorporating a copper nanoparticles polymer composite based SA into a ring fiber laser cavity. The modulation depth and the saturation power intensity of the CuNP-PVA film are 18% and 0.021 kW/cm² respectively. The laser generates a Q-switching pulse train with the shortest pulse width of 5.1 µs, a repetition rate of 104.2 kHz and an output power of 2.1 mW at the maximum input pump power of 198.0 mW.

2. Preparation and optical characterization of the CuNP-PVA based SA.

The copper nanoparticles PVA film fabricated in this work is utilized as SA to generate laser pulses in erbium-doped fiber laser (EDFL). Commercially available copper nanoparticle powder from Sigma Aldrich are used to fabricate the SA. The copper nanoparticles are obtained in a powder consist of an average of 25 nm particles size. The film based SA is prepared by first dissolving 25 mg of copper nanoparticles powder in tetrahydrofuran (THF) and undergone ultrasonic bath for 6h to ensure the dispersion of the copper nanoparticles. Apart from that, the polymer host is prepared by dissolving 1g of PVA powder into 120 ml DI water. The mixture is stirred for 6 hours to ensure the homogeneous solution at 500 rpm at 145 °C. Then, 10 ml of the dispersed copper nanoparticles in THF solution is added into approximately 10 ml of the dissolved PVA solution to form a CuNP-PVA composite solution with a composition ratio of 1:1. The prepared CuNP-PVA composite solution is stirred for another 1 hour at room temperature to ensure the good binding of the composite as well as to allow any excess solvent to evaporate. Finally, about 20% of the resulting CuNP-PVA composite solution is taken for analysis while the remainder is poured into a petri dish and dried in room temperature for 3 days to produce the desired free-standing film of CuNP-PVA film.

Figure 1(a) shows the transmission electron microscope (TEM) of copper nanoparticles a 50 nm scale bar. Figure 1(b) demonstrates the nonlinear transmission profile of twin detector measurement. According to data fitting as shown in the figure below, the modulation depth and the saturation power intensity of the CuNP-PVA film calculated as 18% and 0.021 kW/cm², respectively. The measured modulation depth of CuNP-PVA thin film is comparable to that of other materials such as Cu-PVA at 36 % [18], CuO-PVA at 3.5 % [19] and silver nanoparticles-PVA at 19% [20].

![Figure 1. Characteristics of CuNP-PVA film (a) TEM image (b) nonlinear transmission](image)

3. Experimental setup

Figure 2 illustrates the experimental set-up of the proposed passively Q-switched EDFL with the CuNP-PVA thin film. The cavity is composed of a 975 nm laser diode (LD) as the pump sources and is
associated with a 980/1550 nm wavelength division multiplexer (WDM) port. The normal port of the WDM is currently connected to a 3.0 m long erbium-doped fiber (EDF). The EDF has a numerical aperture (NA) of 0.16 and erbium ion absorption of 23 dB/m at 980 nm with a core and cladding diameters of 4 µm and 125 µm respectively. To secure unidirectional propagation of light in the ring cavity, a polarization-independent isolator was used. Then, the end of the isolator is associated with a fiber-based 90:10 optical coupler, which is utilized to remove roughly 90% of the proliferating signal for examination. The 90% port of the coupler then again is associated with an integration of the SA between the two fiber ferrules. At last, the end of the SA is connected back with the 1550 nm port of the WDM. The end coupler of 10% port is associated with another 3 dB optical coupler to monitor simultaneously the results of the Q-switching performance. With one end of 50%, the coupler is associated with a Yokogawa AQ6370B optical range analyzer (OSA) for optical spectrum range. The opposite end of the coupler is associated with an InGaAs photodetector (1.3 GHz Thorlabs DET10D/M) coupled with 350 MHz oscilloscope (OSC, GW Instek GDS-3352), and 7.8 GHz Radio Frequency spectrum analyzer (RFSA, Anritsu MS2683A) and a Thorlabs control power meter for the estimation of the output power.

Figure 2. Schematic of the Q-switched fiber laser utilizing CuNP-PVA SA.

4. Result and discussion
The laser operates within the continuous wave laser (CW) at 32.76 mW input pump power. After the integration of the SA in the cavity, Q-switched operation is realized at the increasing input pump power of 83.61 mW up to the maximum input pump power of 198.0 mW. The relatively high threshold for the CW operation indicated too high overall cavity loss and high insertion loss of the SA device. The SA presented intracavity loss modulation and transformed the working from CW to Q-switching operation. When the pump power is increasing to 83.61 mW, a self-starting stable Q-switch pulse is observed with a repetition rate of 52.74 kHz and a pulse-width of 9.44 µs. It remains noticeable until the pump power extent to 198.0 mW. The output spectrum of the Q-switched laser operates at a wavelength of 1558 nm is shown in Figure 3.
Figure 3. Output Spectrum of the Q-switched pulse at a maximum pump power of 198.0 mW.

Figure 4(a) indicates an oscilloscope trace of the Q-switched pulse at the maximum LD pump power. It can be seen that the pulses trains become narrower as the pump power increases. The time interval between the adjacent pulses was about 14.3 µs, which corresponds to 104.2 kHz pulse repetition rate. The pulse envelope full width at half-maximum (FWHM) value of 5.1 µs. It is also observed there is no trace of mode-locking operation during the Q-switching process.

The stability of the generated Q-switched output is confirmed by monitoring the pulse in the radio frequency spectrum analyser at the maximum LD pump power. Figure 4(b) shows the stability of the Q-switched pulse recorded in RFSA. The highest repetition rate of 104.2 kHz is measured with a high signal to noise ratio (SNR) of about 54 dB at the maximum input pump power of 198.0 mW. The RF spectrum also showed no frequency components other than the multiples of the fundamental frequency which indicates excellent stability of the oscillating Q-switched pulses in the laser cavity.

Figure 4. Typical output pulse characteristics (a) oscilloscope trace of the pulse train (b) radio frequency spectrum of the proposed Q-switched fiber laser at the maximum input pump power of 198.0 mW.

Figure 5(a) illustrates the Q-switching performance of calculated pulse energy and output power of the pulse against the input pump power. As expected, both pulse energy and output power show an increasing trend against the input pump power. Over the input pump power range of 83.61–198.0 mW, the output power of the Q-switched laser is seen to increase from 0.74 mW to 2.13 mW. Similarly, the pulse energy also increases from 14.12 nJ to 20.44 nJ over the same power range, although at a pump power above 153.53 mW, the pulse energy is seen to decrease slightly. This is attributed to insufficient
time for the CuNP based SA to fully recover from saturation at the high pump power. The highest pulse energy calculated was 20.44 nJ obtained at a maximum input pump power of 198.0 mW.

The relationship between the repetition rate and pulse width is shown in Figure 5(b). It can be seen the detailed evolution of the repetition rate increased steadily from 52.74 kHz to 104.2 kHz from input pump power of 83.61 mW to 198.0 mW, while the pulse width, on the other hand, decreases from 9.44 to 5.08 µs. This is the trendline behaviour for passively Q-switching operation where when the increasing input pump power is almost linearly with increasing repetition rate and decreasing the pulse width.

Figure 5. Q-switching performances (a) Average output power and output pulse energy against power (b) Repetition rate and pulse width against pump power

5. Conclusion
In this work, a passively Q-switched EDFL is proposed and demonstrated. The system employs a CuNP-PVA SA in the ring cavity and provides the desired pulse output. The system is capable of generating pulsed outputs with a maximum repetition rate of 104.2 kHz, the narrowest pulse width of 5.1 µs and pulse energy of 20.44 nJ at the maximum input pump power of 198.0 mW. The RF spectrum showed the signal noise to a ratio of about 54 dB.

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