Q-switching Pulse Operation in 1.5-µm Region Using Copper Nanoparticles as Saturable Absorber

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We demonstrate a passively Q-switched erbium-doped fiber laser (EDFL) using a copper nanoparticle (CuNP) thin film as the saturable absorber in a ring cavity. A stable Q-switched pulse operation is observed as the CuNP saturable absorber (SA) is introduced in the cavity. The pulse repetition rate of the EDFL is observed to be proportional to the pump power, and is limited to 101.2 kHz by the maximum pump power of 113.7 mW. On the other hand, the pulse width reduces from 10.19 µs to 4.28 µs as the pump power is varied from 26.1 mW to 113.7 mW. The findings suggest that CuNP SA could be useful as a potential saturable absorber for the development of the robust, compact, efficient and low cost Q-switched fiber laser operating at 1.5-µm region.

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Q-switched pulsed lasers are widely employed in applications that require high pulse energy, such as micromachining, drilling, holography and dentistry.¹² Q-switched fiber lasers have gained a greater interest compared with the conventional solid state systems because of their advantages such as producing high beam quality, high output power and relatively compact in size. A Q-switching operation is typically obtained based on the modulation of the quality factor Q of a cavity, which can be realized by inserting a saturable absorber (SA) into the laser cavity. This passive modulating device (SA) operates according to Pauli’s blocking principle with a change in absorption prompted by the optical intensity.³⁴

Up to date, various passive SAs have been proposed and demonstrated for pulse generation. Semiconductor saturable absorber mirror (SESAM) is one of the most popular SA in solid state lasers.⁵ Although the device parameters such as saturation energy, absorption wavelength and recovery time can be accurately controlled with the modern semiconductor technology, SESAM requires complex and costly fabrication process. Therefore, many researchers have shifted their interest to carbon based materials such as single walled carbon nanotubes (CNTs) and graphene as new SAs for pulsed laser generation.⁶–⁹ For instance, Liu et al. reported a multi-wavelength mode-locked laser operation using a CNT SA. The laser achieved a multi-wavelength operation centered at three different wavelengths of 1540, 1550 and 1560 nm when the chirped fiber Bragg grating was utilized in the cavity.¹⁰ Recently, Liu et al. reported the potential of the CNT based mode-locked laser to generate bisoliton by incorporating the large anomalous dispersion FBG.¹¹ On the other hand, graphene has also gained a tremendous interest as an excellent SA since it has zero bandgap energy. However, its weak absorption results in a low modulation depth. In addition to graphene, more recently a new emerging and promising material, called black phosphorus (BP), is also discovered. It has a direct bandgap for all thickness, resulting in extraordinary light emission to complement graphene and topological insulator (TI).¹²–¹³ Delicate and careful attention is needed during the exploitation process to produce a single layer and defect free graphene, TI, and BP.

Despite exploring new methods and materials in developing SAs for Q-switching pulse generation, metal nanoparticles-based SAs especially transition metal elements are rarely being investigated. These elements pick up a great interest amongst scientific researchers as they hold a unique optical property such as ultrafast response time, broad saturable absorption band and large third-order nonlinearity.¹⁴–¹⁷ Very recently, Wu et al. reported a Q-switch pulse generation by using copper nanowires (CuNWs) as the saturable absorber in the visible range laser region (635 nm) with repetition rate of 239.8–312.4 kHz, pulse width of 0.685–0.394 µs and the maximum output power up to 9.6 mW.¹⁸ However, a literature review has indicated that no research has been carried out using copper as saturable absorbers in near infrared (NIR) regions.

In this Letter we propose and demonstrate a passively Q-switched fiber laser based on the CuNP thin-film SA in a 1550 nm region by using an EDFL cavity.
The laser generates Q-switching pulse train with pulse width of 4.28 µs, repetition rate of 101.2 kHz and output power of 1.860 mW at the maximum input power of 113.7 mW.

In this experiment, we used pure copper (Cu) pallets as our saturable absorber material. The watersoluble synthetic polymer, polivinyl-alcohol (PVA), was prepared in the form of thin film as a host material. Next, both the PVA thin film and Cu were placed inside a KENOSISTEC thermal evaporation chamber for the deposition process. During the process, Cu was intensely heated by the Joule effect until it evaporated, and nano sized particles of Cu were deposited into the surface of the PVA thin film with a pre-set layer of 16 nm in thickness. Fabricated copper nanoparticle saturable absorbers in thin-film PVA (CuNP-SA) were characterized by using the energy-dispersive x-ray (EDX) analysis to confirm the presence of the material as shown in Fig. 1(a). It was observed that about 50.09 Wt% of Cu element was traced in the surface of the thin film. High intensity of the carbon peak comes from the PVA film (C$_2$H$_2$O)$_2$.

The investigation towards the absorption property of the CuNP SA was performed by broadband absorption in the C-band region 1300–1600 nm with consideration of the measured 7 dB insertion loss, as illustrated in Fig. 1(b). Nonlinear transmission measurements for the SA were also performed by launching a mode-locked laser (wavelength of 1560 nm, pulse width of 3 ps, repetition rate of 1.0 MHz) into the SA sample. By performing a balance twin-detector measurement, the modulation depth of the CuNP film is measured to be around 36% as shown in Fig. 1(c). The measurement data was fitted by the formula of $T(I) = \alpha_{sat}/(1 + I/I_{sat}) + \alpha_{ns}$, where $T(I)$ is the transmission, $\alpha_{sat}$ is the modulation depth, $I$ is the input intensity, $I_{sat}$ is the saturation intensity, and $\alpha_{ns}$ is the non-saturable absorption. The mode-locked source here is a self-constructed passively mode-locked fiber laser. Figure 1(d) presents the typical FESEM image of CuNP showing a homogenous distribution of Cu particles with the thickness of 16 nm.

Figure 2 shows the experimental setup of the proposed Q-switched EDFL. The laser cavity consists of a 2.4 m erbium-doped fiber (EDF) as the gain medium, C1 and C2 output couplers, isolator, 980/1550 nm wavelength division multiplexer (WDM), and CuNP thin film as SA. The EDF used has an erbium ion concentration of 2000 ppm, and numerical aperture (NA) of 0.24. A single mode 980 nm pump laser was utilized to pump the EDF to generate a laser in the 1565 nm region. The output from the laser cavity was extracted by a C1 (90:10) optical coupler and further split by a C2 (50:50) optical coupler for the optical spectrum and pulse train measurement. An isolator was employed to enable unidirectional propagation of light inside the laser resonator thus avoiding any detrimental effects. Optical power meter was swapped with optical spectrum analyzer (OSA) for average output power measurement.

Figure 3(a) shows the output spectra of EDFL at their thresholds of 26.1 mW and 12.9 mW with and without the CuNP thin film SA, respectively. The Q-switched laser self-started as the operating pump power was raised to 26.1 mW and operated at wavelength of 1561 nm with peak power of $-13.66$ dBm and the optical bandwidth was measured to be 0.03 nm. Such a low threshold power for Q-switching operation resulted from the small intra-cavity loss performed by the CuNP SA as the high intensity at even low input power of 1550 nm were produced in the cavity. As seen in Fig. 3, the operating wavelength was shifted from 1565 to 1561 nm due to the insertion loss when CuNP SA is sandwiched between the fiber ferrules. In exchange for this loss, the EDFL operation occurs at a shorter wavelength where high gain was accumulated. Figures 3(b) and 3(c) illustrate the pulse train of Q-switched EDFL and single pulse envelop, respectively. Typical Q-switch pulse shape obtained and illustrated for 69.13 kHz corresponds to 14.465 µs of distance be-
between pulses when the input pump power was set into 69.9 mW. A single pulse profile at this pump power has full width half maximum (FWHM) of 5.42 µs. A single radio-frequency (RF) output spectrum with span resolution of 1.5 MHz was measured and illustrated in Fig. 3(d). The fundamental RF peaks at maximum output pulse of 101.2 kHz having a signal-to-noise ratio (SNR) of ~50.9 dB, which confirms the stability of the pulse.[19]

Figure 4(a) depicts the relationship between pulse repetition rate and pulse width with input pump power. A stable output pulse train with monotonic increment of repetition rate from 41.7 kHz to 101.2 kHz was observed with the 980-nm pump power increasing from 26.1 mW to 113.7 mW. This differs from the pulse duration measurement as it narrows and shortens from 10.19 µs to 4.28 µs, which is a typical characteristic of Q-switching operation. Unlike mode-locking operation, normally repetition rate will be fixed when we increase the input pump power. Recently, Liu et al. demonstrated that the repetition rate for mode locking operation can be tuned using linearly chirped fiber Bragg grating.[20]

As the pump power increases, more power circulates inside the laser cavity, thus hastening the saturation of the SA. From Fig. 4(a) it can be seen that small changes of pulse width from 80–113.7 µm indicates that the SA were almost saturated with continual increasing the light intensity (pump power). Furthermore, pulse operation is switched into the CW mode as the pump is increased above 113.7 mW.

In the experiment, we obtain that the pulse energy and output power increase with the pump power as shown in Fig. 4(b). Output with pulse energy of 18.377 nJ and average output power of 1.860 mW are achieved at the maximum pump power of 113.7 mW. This can be realized from the strong modulation of the net gain. The increase of the pump power leads to a rise of average output power and shortens the pulse width, and hence higher pulse energy is extracted in the Q-switching process. Based on the measurement as shown in Figs. 4(a) and 4(b), the peak power as a function of the pump power can be calculated, as shown in Fig. 4(c). The peak power increases gradually from 0.79 mW to 4.29 mW.

![Fig. 3](image1.png) **Fig. 3.** Typical Q-switch output performance. (a) Laser spectrum with and without the CuNP thin film SA at threshold powers of 26.1 mW and 12.9 mW, respectively. (b) Period of pulse train at 69.13 kHz. (c) Corresponding single pulse envelope at 69.13 kHz. (d) Radio Frequency spectrum at the maximum output pulse of 101.2 kHz.

![Fig. 4](image2.png) **Fig. 4.** Q-switching performance of the proposed Q-switched EDFL. (a) Repetition rate and pulse width against the pump power. (b) Average output power and pulse energy against the pump power. (c) Peak power as a function of the pump power.

Meanwhile, with current cavity, no mode-locking operation has been observed, we expect that this can be obtained by optimizing the dispersion and SPM parameters of the cavity. At this moment, we are working to demonstrate the mode-locking operation. The expected repetition rate for our cavity is about 22 MHz corresponding to the 9 m cavity length.

In summary, we have proposed and demonstrated a passively Q-switched EDFL operating at 1561 nm by using a first time developed pure metal silver nanoparticle thin film at a threshold input pump power of 26.1 mW. By increasing the input pump power up to the maximum pulse generated 113.7 mW, the pulse laser action is obtained with the maximum energy of 18.377 nJ, the output peak power up to 4.29 mW, a pulse width about 4.28 µs and the repetition rate in the range of 41.7–101.2 kHz. This study shows the potential of metal nanomaterial, specifically copper, as a great alternative for the Q-switching pulse generation.

### References