ALL-FIBER YTTERBIUM DOPED Q-SWITCHED FIBER LASER BASED ON COPPER NANOPARTICLES SATURABLE ABSORBER

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The Q-switching pulses generation in an Ytterbium-doped fiber laser (YDFL) passively Q-switched by a copper nanoparticles (CuNP) based saturable absorber (SA) was experimentally demonstrated. The high-quality SA with a modulation depth of 36% was fabricated by depositing nano-sized particles of Cu layer onto the surface of polyvinyl alcohol (PVA) film through the thermal evaporation process. By inserting the SA into a YDFL cavity, stable Q-switched operation was achieved with the maximum pulse energy up to 7.48 nJ, the shortest pulse width of 3.89 μs and pulse repetition rates varying from 41 to 104 kHz. These results suggested that CuNP could be developed as an effective SA for pulsed laser operation at 1 μm.

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1. Introduction

Q-switched fiber lasers have obtained intense research interests in recent years for their potential applications in micromachining, drilling, holography and dentistry [1,2]. Compared to conventional solid-state lasers, they are of great interest due to their advantages of high output power, excellent beam quality and relatively compact in size. Passive techniques are preferable compared to the conventional active methods because of their capability of compactness, and simplicity in design[3,4]. A Q-switching pulses train can be typically obtained by modulating the quality factor, Q of a cavity, using a saturable absorber (SA) device. Up to date, several kinds of SAs have been proposed and demonstrated in the literature review such as semiconductor saturable absorber mirrors (SESAMs)[5,6], carbon nanotubes (CNTs) [7], and 2D type nanomaterial including graphene, topological insulator, transition metal dichalcogenide [8-10].However, in order to obtain ideal SAs with the characters of wavelength independent, high damage threshold and simple fabrication, exploration of new materials still remains as an on-going issue.

Recently, metal nanoparticles-based materials especially transition metal elements have revealed a high potential in electronic and optic applications. This is attributed to their unique optical properties such as ultrafast response time, broad saturable absorption band and large third-order nonlinearity[11,12].For instance, Wu et. al. has demonstrated a Q-switched laser with a copper nanowires saturable absorber. The laser operated at visible wavelength region of 635 nm with repetition rate and pulse width were tunable in a range of 239.8 – 312.4 kHz and 0.685 - 0.394 μs, respectively while the maximum output power was obtained at 9.6 mW [13].

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In this letter, we demonstrate a passively Q-switched Ytterbium-doped fiber laser (YDFL) based on copper nanoparticles (CuNP) polymer film SA. The high quality CuNP SA with a modulation depth of ~36% was obtained by depositing nano-sized particles of Cu onto the surface of polyvinyl alcohol (PVA) film through the thermal evaporation process. By incorporating the SA into an YDFL cavity, it emits stable Q-switching pulses train operating at wavelength of 1040.6 nm with pulse duration in a range from 9.46 μs to 3.89 μs, and repetition rates from 41 kHz to 104 kHz. The experimental results further demonstrated the broadband nonlinear saturable absorption potential of CuNP for generating stable pulse laser.

2. Fabrication and characterization of SA

In the experiment, pure copper (Cu) pallets were used as the SA material while the water-soluble synthetic polymer, PVA was prepared in the form of thin film as a host material. Cu was deposited onto the surface PVA thin film inside thermal evaporation chamber of KENOSISTEC E-beam with pre-set layer of 16 nm thickness. During the deposition process, Cu were intensely heated by Joule effect until it evaporated to produce nanoparticles of Cu, which were deposited into the film surface. Fig. 1 shows the energy dispersive X-ray (EDX) graph of the fabricated CuNP PVA film. It consists of 50.09 Wt% of Cu element and 30.64 Wt% of carbon from PVA (C2H4O)x. The transmission loss of the film is measured to be around 7dB. Fig. 2 illustrates the Field Emission Scanning Electron Microscopy (FESEM) image of the CuNP PVA film. It indicates a thin layer of Cu was homogenously distributed onto the polymer film.

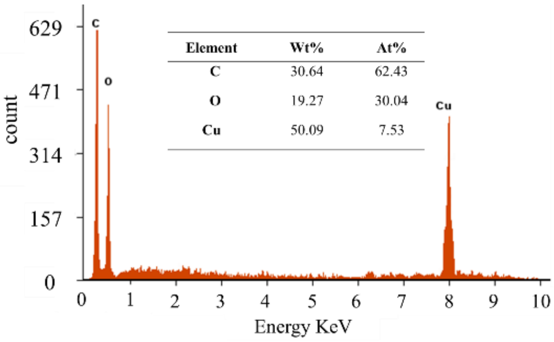


Fig. 1. EDX spectrum of CuNP PVA film

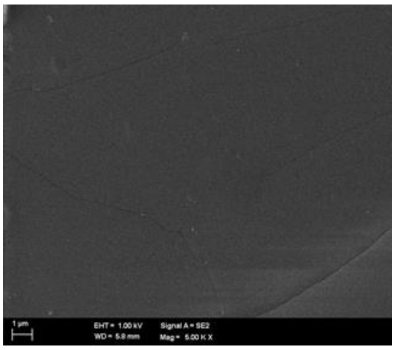


Fig. 2. FESEM image of CuNP PVA film

A balanced twin detector measurement system was used to measure the nonlinear transmission property of the CuNP PVA film. A self-constructed passively mode-locked fiber laser (with a central wavelength of 1560 nm, repetition rate of 1.0 MHz and pulse width of 3 ps) was used as a laser source in the measurement system. By gradually increasing the input power of the laser, the optical transmittance with respect to different input optical power was recorded. Fig. 3 shows the measurement data, which was fitted by the formula of $T(I)=\alpha sat/(1+I/Isat)+\alpha ns$. Here, T(I) is the transmission, αsat is the modulation depth, I is the input intensity, Isat is the saturation intensity, and αns is the non-saturable absorption. From the analysed data, the modulation depth measured was 36 %, significantly higher than other SA material that have been previously reported. The saturation intensity was measured at 20 MW/cm2, also relatively high due to CuNP high resistance to photo-bleaching. The non-saturable losses of the SA were 14%. Based on these data, the CuNP PVA film has met necessary requirement to be a good SA for pulsed laser generation

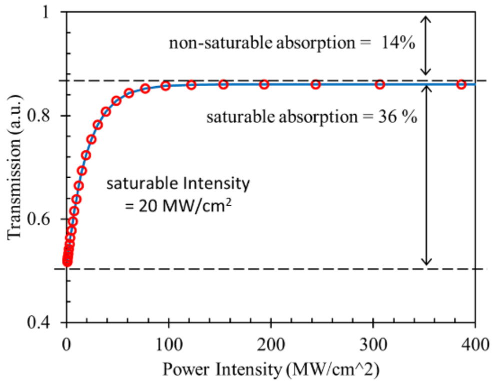


Fig. 3. Nonlinear optical absorption profile of CuNP PVA film

3. Results and discussion

Fig. 4 shows the schematic diagram of the proposed Q-switched YDFL. The laser cavity consists of a 2m long Ytterbium-doped fiber (YDF) as the gain medium, a 95/5 output coupler, an isolator, a 980/1050 nm wavelength division multiplexer (WDM), and a newly developed CuNP thin film based SA. The YDF used has Ytterbium ions absorption of 23 dB/m at 1020 nm. It was forward pumped by a 980-nm pump via the WDM. The isolator was incorporated inside the laser cavity to ensure unidirectional propagation of light and thus preventing any detrimental effects inside the laser resonator. The prepared CuNP PVA film was sandwiched between two fiber ferrules via a fiber adapter to form a fiber-compatible SA device. The insertion loss of the SA device was recorded as 1.5 dB at 1020 nm. The output coupler was used to tap out 5% of output for observation and retains 95% to oscillate in the cavity. An optical spectrum analyzer (OSA) with spectral resolution of 0.05 nm was used to observe the optical spectrum of the Q-switched YDFL, while the oscilloscope was used to analyze the output pulse train via a photodetector. Optical power meter was swapped with OSA to measure the average output power of the laser output.

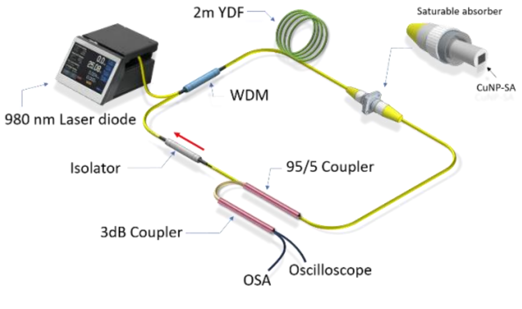
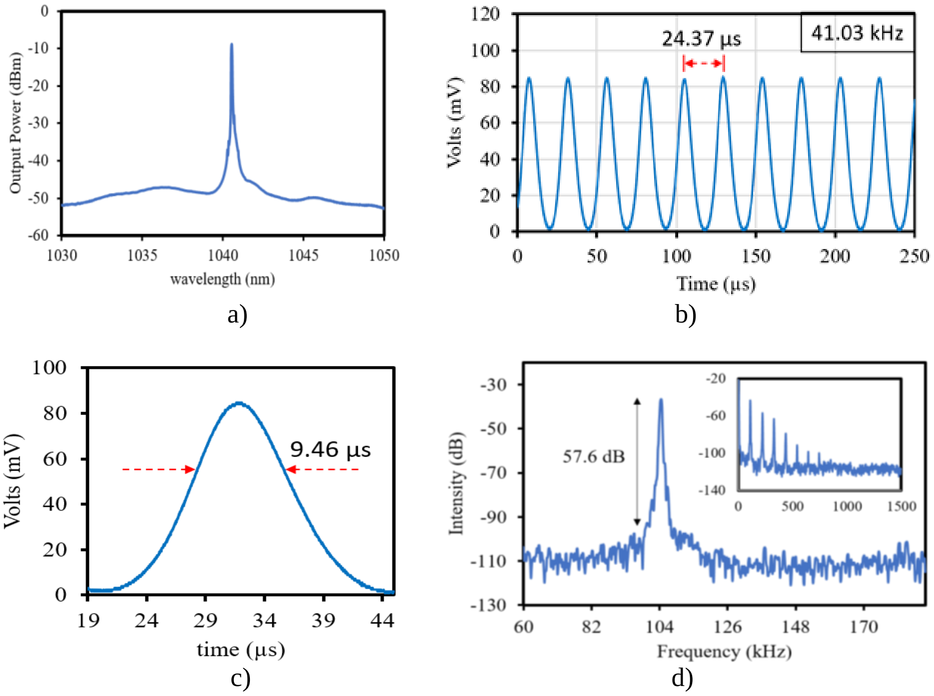


Fig. 4. Schematic diagram of the Q-switched YDFL configuration

The self-started Q-switching pulse train was obtained as the 980-nm pump power was raised to 157 mW and its operation was maintained up to the maximum pump power of 229 mW. Fig. 5 (a) shows the output spectrum at its threshold pump power of 157 mW. It operates at 1040.6 nm wavelength with peak power of -8.83 dBm. Figs. 5 (b) and (c) illustrates the oscillation trace of Q-switched YDFL and single pulse envelop respectively at the threshold pump power of 157 mW. It indicates a typical Q-switching pulse shape with 24.37 µs of distance between pulses, which corresponds to a repetition rate of 41.03 kHz. A single pulse profile at thispump power has full width half maximum (FWHM) of 9.46 µs. To investigate the laser stability, the RF spectrum was investigated. Fig. 5(d) shows the spectrum with a span resolution bandwidth of 190KHz and 1.5 MHz. As shown in the figure, the signal-to-noise (SNR) of the spectrum is over 57 dB, which indicates that the Q-switched pulses operated in a relatively stable regime. The broadband RF spectrum in the inset of Fig. 5(d) further confirms the stability of the Q-switched laser operation.



a) b)

c) d)

Fig. 5. Typical Q-switching output performance:(a) Laser spectrum at threshold power of 157 mW (b) Period of pulse train at 41.03 kHz (c) Corresponding single pulse envelope at 41.03 kHz (d)RF spectrum.

Fig. 6 shows the relationship between repetition rate and pulse width of the Q-switched laser with different input pump power. It is observed that the repetition rate is monotonically increased from 41.03 kHz to 104.3 kHz as the 980-nm pump power was increased from 157 mW to 229 mW. On the other hand, the pulse duration was narrowed or shortened from 9.46 to 3.89 µs with the increment of pump power. The result is a typical characteristic of Q-switching operation. The average output power and pulse energy of the Q-switched laser were also measured as a function of the input pump power. The result is shown in Fig. 7, indicating the increase of pulse energy and output power with the increment of pump power. Both trends are realized from the strong modulation of the net gain. The increment of pump power leads to a raise of average output power and shorten the pulse width and hence higher pulse energy is extracted in the Q-switching process. However, the pulse energy saturated at pump power of 177 mW where the maximum value of 7.48 nJ. An average output power of 0.78 mW was achieved at the maximum pump power of 229 mW. The performance of Q-switched pulses is expected to be further improved by optimization of both SA parameter and the laser cavity design.

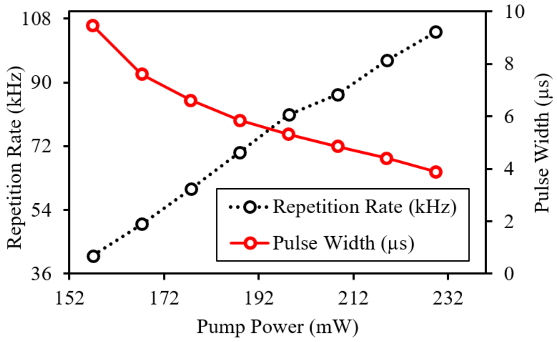


Fig. 6. The repetition rate and pulse duration as a function of pump power

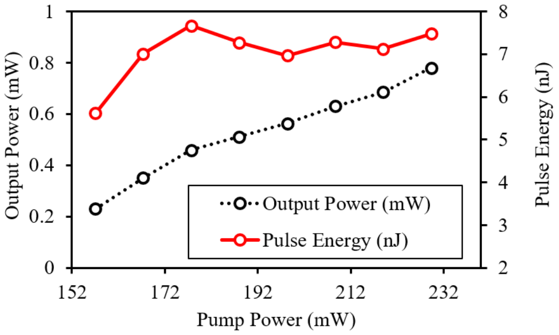


Fig. 7. Average output power and pulse energy against pump power

4. Conclusions

In summary, a stable all-fiber passively Q-switched fiber laser operating at 1040.6 nm was successfully demonstrated based on the CuNP PVA SA and YDFL cavity. The SA used in our experiment was prepared by depositing Nano-sized particles of Cu onto the surface of PVA film through the thermal evaporation process. By incorporating the SA into the laser cavity, Q-switching pulses train was generated at the threshold pump power of 157 mW. By adjusting the pump power level, the Q-switched laser produced a range of pulse repetition frequency from 41 to 104 kHz with a minimal pulse width is 3.89 µs. These experimental results clearly indicated that the CuNP can be considered as a great alternative SA material for the Q-switching pulse generation.

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References

[1] S.T. Hendow, S.A. Shakir, Opt Express **18**, 10188 (2010).

[2] J.P. Wood, M. Plunkett, V. Previn, G. Chidlow, R. J. Casson, Lasers Surg Med, **43**, 499 (2011).

[3] Q. Bao, H. Zhang, Y. Wang, Z. Ni, Y. Yan, Z.X. Shen, K.P. Loh, D.Y. Tang, Advanced Functional Materials **19,** 3077 (2009).

[4] A.R. Muhammad, M.T. Ahmad, R. Zakaria, H.R.A. Rahim, S.F.A.Z. Yusoff, K.S. Hamdan, H. H. M. Yusof, H. Arof, S.W. Harun, Chinese Physics Letters **34**, 034205 (2017).

[5] Y. Bai, W. Xiang, P. Zu, G. Zhang, Chin. Opt. Lett. **10**, 111405 (2012).

[6] X. Yin, J. Meng, J. Zu, W. Chen, Chin. Opt. Lett. **11**, 081402 (2013).

[7] M.T. Ahmad, A.A. Latiff, Z. Zakaria, D.I.M. Zen, N. Saidin, H. Haris, H. Ahmad, S.W. Harun, Microwave and Optical Technology Letters **56**, 2817 (2014).

[8] Z. Sun, T. Hasan, F. Torrisi, D. Popa, G. Privitera, F. Wang, F. Bonaccorso, D.M. Basko, A.C. Ferrari, ACS Nano **4**, 803 (2010).

[9] C. Zhao, H. Zhang, X. Qi, Y. Chen, Z. Wang, S. Wen, D. Tang, S.D. A., D.A. J., Applied Physics Letters **101**, 211106 (2012).

[10] L. Zhang, Z. Zhuo, R. Wei, Y. Wang, X. Chen, X. Xu, Chin. Opt. Lett. **12,** 021405 (2014).

[11] H. Guo, M. Feng, F. Song, H. Li, A. Ren, X. Wei, Y. Li, X. Xu, J. Tian, IEEE Photonics Technology Letters **28,** 135 (2016).

[12] D.A. Glubokov, V.V. Sychev, A.S. Mikhailov, A.E. Korolkov, D.A. Chubich, B.I. Shapiro, A.G. Vitukhnovskii, Quantum Electronics **44**, 314 (2014).

[13] D. Wu, J. Peng, Z. Cai, J. Weng, Z. Luo, N. Chen, H. Xu, Optics Express **23**, 24071 (2015).