Q-switched in-band pumped erbium doped fiber laser operating at L-band region

Z. JUSOH[a,b], S. W. HARUN[a,c], N. S. SHAHABUDDIN[a,c], H. AROF[a], H. AHMAD[b]
[a]*Department of Electrical Engineering, Faculty of Engineering, University of Malaya 50603 Kuala Lumpur Malaysia*
[b]*Faculty of Electrical Engineering, Universiti Teknologi MARA (UiTM), 40450 Shah Alam, Malaysia*
[c]*Photonics Research Centre, University of Malaya 50603 Kuala Lumpur, Malaysia*

A Q-switched Erbium-doped fiber laser (EDFL) operating in L-band region is demonstrated using an in-band pumping scheme in conjunction with a single-walled carbon nanotubes (SWCNT) based saturable absorber (SA). The performance of the conventional EDFL in a ring cavity without the SA is also investigated for various Erbium-doped fiber (EDF) lengths. It is found that the EDFL lasing wavelength shifts from 1601 nm to 1572 nm as the EDF length is increased from 4 m to 10 m. At EDF length of 4.5 m, the slope efficiency and pump power threshold of the laser are approximately 6.7 % and 42 mW. By incorporating a newly developed SWCNT based SA in the laser cavity, a Q-switched pulse train is successfully generated with a repetition rate of 6.7 kHz and a pulse width of 30.9 µs. The center wavelength of the Q-switched EDFL is 1598nm and it operates with an average output power of 0.3 mW.

(Received May 2, 2014; accepted May 15, 2014)

Keywords: In-band pumping, Erbium doped fiber, L-band fiber laser, Q-switched fiber laser, Single-walled carbon nanotubes saturable absorber

1. Introduction

Short-pulse fiber lasers operating near 1.6 µm or in long wavelength band (L-band) region are important for many applications in remote sensing, range finding, medicine, material processing, and telecommunications [1-3]. In this spectral region, lasers are found to be safer to the eyes and have lower transmission loss. L-band amplifier and laser can be realised using an Erbium-doped fiber (EDF) as a gain medium in conjunction with 980 nm or 1480 nm pumping. The L-band emission is achieved via quasi-two-level system whereby 1550 nm photons are generated by pumping a relatively longer EDF and absorbed to emit photons in L-band region [4]. Emission at wavelength 1.6 µm can also be achieved using in-band pumped EDF [5] involving the transition of $^4I_{13/2}$ manifold to the ground-state manifold $^4I_{15/2}$. The laser operation is possible even with only two manifolds due to the energy variations within each manifold. Ions are pumped from the lower manifold (usually the ground-state) to some higher manifold, and the laser transition ensues directly from there back to the lower manifold, without any intermediate manifolds.

Q-switched fiber lasers are generally used for generating high-energy pulses at relatively low repetition rates [6]. They can be constructed by active [7] or passive techniques [8]. Compared to those fabricated using the active technique, passively Q-switched fiber lasers are advantageous in terms of compactness, simplicity, and flexibility in design. They have been intensively investigated using different kinds of saturable absorbers (SAs) such as transition metal doped crystals [9] and semiconductor saturable absorber mirrors (SESAMs) [10]. However, these SAs are complex and expensive to fabricate. Furthermore, their incompatibility with many optical fibers limits their widespread application. Recently, single-walled carbon nanotubes (SWCNTs) have been discovered to show promising potential in mode locked fiber laser systems due to its intrinsic saturable absorption properties, ultrafast recovery time and wide absorption wavelength bandwidth [11-12]. In this paper, we demonstrate a simple and compact Q-switched in-band pumped Erbium-doped fiber laser (EDFL) using SWCNT-based saturable absorber (SA). The SA is constructed using homemade SWCNT-PEO composite film, which is sandwiched between two fiber connectors. The SA is then integrated in an EDFL cavity to generate a self-starting, stable Q-switched pulses operating in L-band region using an in-band pump of 1550 nm.

2. Experimental setup

A homogeneous suspension is prepared by mixing 250 mg SWCNTs (99% pure, diameter of 1-2 nm and length of 3-30 µm) with 400 ml 1% sodium dedocyl sulfate (SDS) solution in deionized water and then ultrasonicating it for 30 minutes at 50 W. Dispersion of SWCNT throughout the mixture is achieved via the ultrasonification with the aid of sodium dedocyl sulfate (SDS) solution. Then the solution is centrifuged at 1000 rpm to remove large particles of undispersed CNT to obtain dispersed suspension that is stable for weeks. SWCNT-PEO composite is fabricated by adding 1.8 ml of dispersed SWCNT suspension containing 1.125 mg of solid SWCNT into a solution of 1 g PEO (average molecular weight of 1×10^6 g/mol) in deionized water and thoroughly mixing them. The SWCNT-PEO composite is casted onto a glass petri dish and kept in a vacuum oven at 60°C for 48 hours to form a thin film. The free standing film has peak absorption at 1.5 µm with thickness of around 50µm and used as saturable absorber for ultrafast pulse generation. An SWCNT based SA is finally constructed by cutting a small part of the homemade SWCNT-PEO composite film (~2×2 mm²) and sandwiching it in between two FC/PC fiber connectors, after depositing index-matching gel onto the fiber ends. The SA plays the key role of a passive Q-switcher in this work.

The configuration of the proposed Q-switched in-band pumped EDFL using the fabricated SWCNT-based SA is shown in Fig. 1. The resonator consists of a piece of 4.5 m long Erbium-doped fiber (EDF), a WDM coupler, an SWCNT-based SA, an output coupler and an isolator. The total length of the cavity of the resonator is 18 m. The EDF used has an Erbium ion concentration of 2000 ppm. An external tunable light source, which is amplified by a high-power amplifier (HPA) is launched into the EDF via a WDM coupler for in-band pumping. Two isolators are used in this setup; one is after the HPA to avoid back reflection to HPA and the other is incorporated in the ring resonator to allow unidirectional operation of the laser in clock-wise direction. The Q-switched laser output is tapped from the 3dB output coupler, measured by a power meter and monitored with a photo-detector, which is attached to an oscilloscope. The experiment is also carried out without the SA, where the laser performance is investigated for various EDF lengths. An optical spectrum analyzer (OSA) is used to measure the output spectrum of both lasers configured with and without SA.

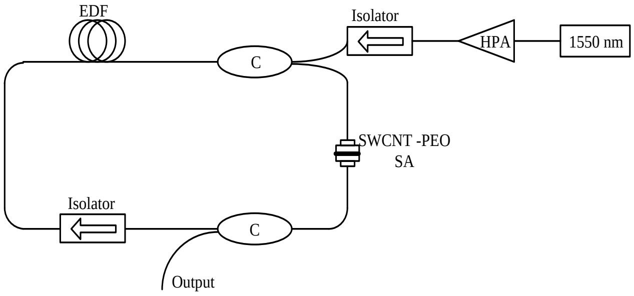

Fig. 1. Configuration of the proposed Q-switched in-band pumped EDFL.

3. Result and discussion

The performance of the EDFL configured without the SA was first investigated for various EDF lengths. In this work, the EDF was in-band-pumped at 1550 nm using the lowest two levels ($^4I_{15/2}$ and $^4I_{13/2}$) while amplifying at 1580 nm region. Fig. 2 shows the ASE spectrum obtained by pumping the EDF with 100 mW of 1550 nm laser for three different EDF lengths of 4 m, 4.5m and 10 m. As shown in the figure, the spectrum peaks at 1565 nm for the longest EDF length of 10 m. The peak shifts to a shorter wavelength of 1562 nm as the EDF length is reduced to 4 m. This shift is caused by the decrease in the amount of Erbium ions (since the fiber used is shorter) that reduces population inversion and consequently emits less photon at longer wavelengths. This shows that both spontaneous and stimulated emissions are more pronounced in longer wavelength region as the EDF length increases.

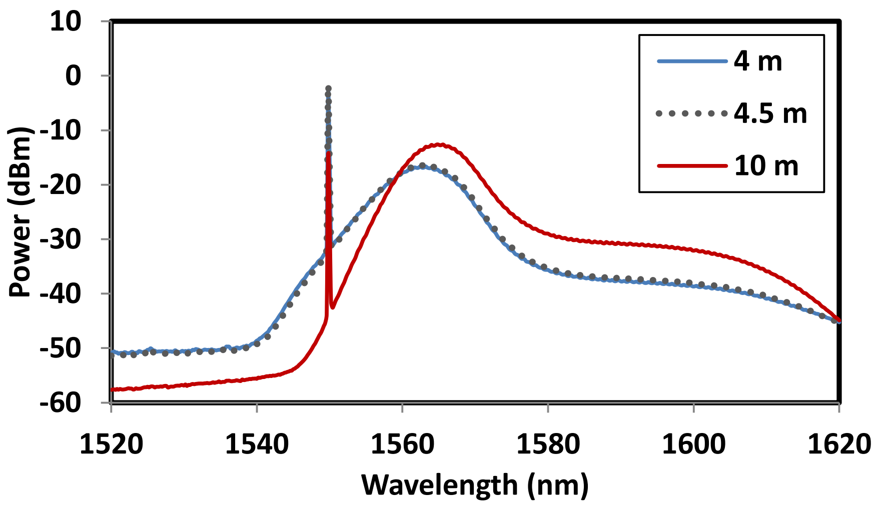

Fig. 2. ASE spectrum from the in-band pumped EDF at three different lengths of EDF used.

Fig. 3 shows the output spectra of in-band pumped EDFL at three different lengths of EDF with the 1550 nm pump power fixed at 156 mW. As seen, the lasing wavelength peaks at 1601 nm, 1593 nm and 1572 nm as the EDFL is configured with EDF length of 10 m, 4.5 m and 4 m respectively. This shows that longer EDF allows the EDFL to lase at longer wavelength as the ASE spectrum shifts to longer wavelength when EDF length increases. In the proposed EDFL, a backward pumping scheme was utilized to discriminate the pump light from the oscillating laser. However, the residual pump laser can still be observed at the output spectrum due to Rayleigh scattering as evident in both Figs. 2 and 3. The peak power of the residual pump is about -38 dBm, which is approximately 35 dB lower than that of the laser. Fig. 4 shows the relationship between the output power and the pump power of the EDFL at three lengths. The slope efficiencies with respect to the incident pump power are obtained at around 6.7 %, and 5.8 % and 5.3 % for the EDF lengths of 4.5 m, 10 and 4 m, respectively. The efficiency of the laser is relatively low due to a strong unabsorbed pump power. The lowest threshold pump power of 42 mW achieved by the EDF length of 4.5 m.

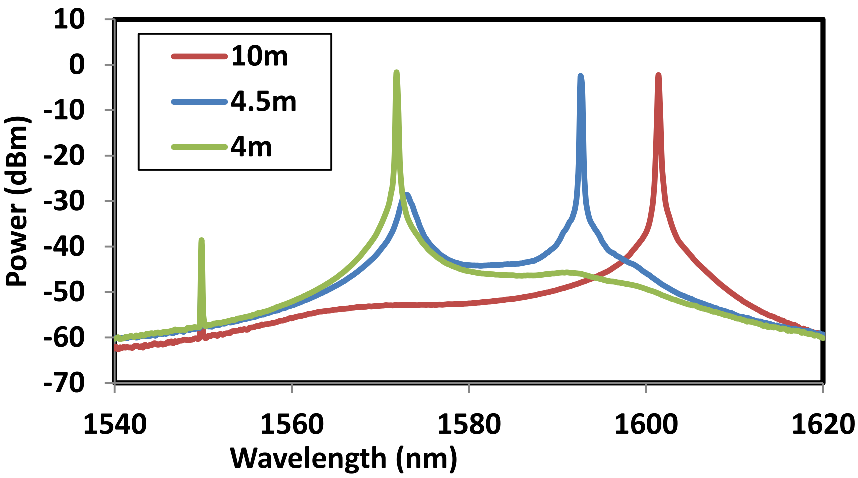

Fig. 3. Output spectrum of the EDFL configured without the SA when the 1550 nm pump power is fixed at 156 mW.

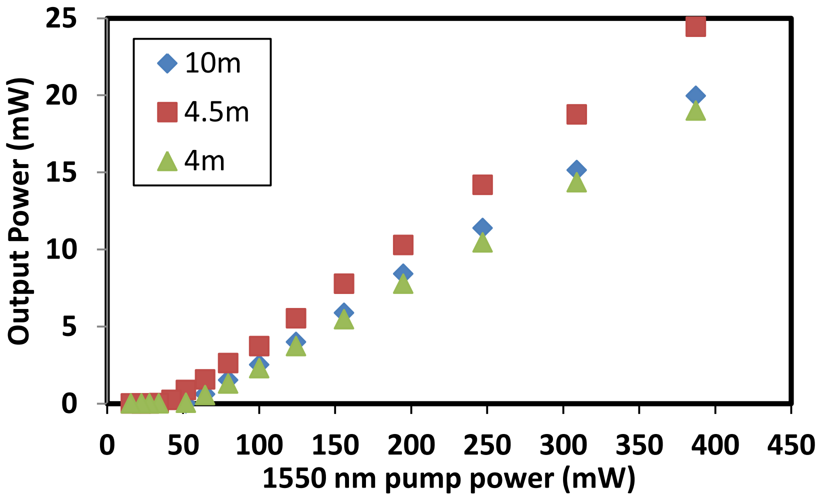

Fig. 4. Output power characteristic of the non Q-switched EDFL against the 1550 nm pump power at different EDF lengths.

When the SWCNT based SA was added to the ring cavity, a stable self-started Q-switched pulse train was observed for the EDFL configured with 4.5 m long EDF. The pulses formed by the Q-switching process in the resonator were detected using a 6-GHz photodetector and a 500-MHz digital phosphor oscilloscope. Fig. 5 shows a typical oscilloscope trace of the pulse train at the pump power of 80 mW. The Q-switched laser produces a pulse train with a repetition rate of 6.7 kHz, pulse width of 30.9 μs and average output power of 0.3 mW. It is also experimentally observed that both the repetition rate and output power of the generated Q-switched laser have a monotonically increasing trend with the pump power level. The inset of Fig. 5 shows the output spectrum of the laser as measured by an OSA with a resolution of 0.1 nm. As seen, the laser operates at 1598 nm with a slight spectral broadening as the pump power increases above the threshold. This is most probably due to self-phase modulation effect (SPM), where the optical Kerr effect induces a phase shift in the pulse that leads to change in the frequency spectrum. The FWHM of the spectrum was 2.0 nm. The output power of the laser could be improved by reducing the insertion loss of the SA and optimizing the laser cavity.

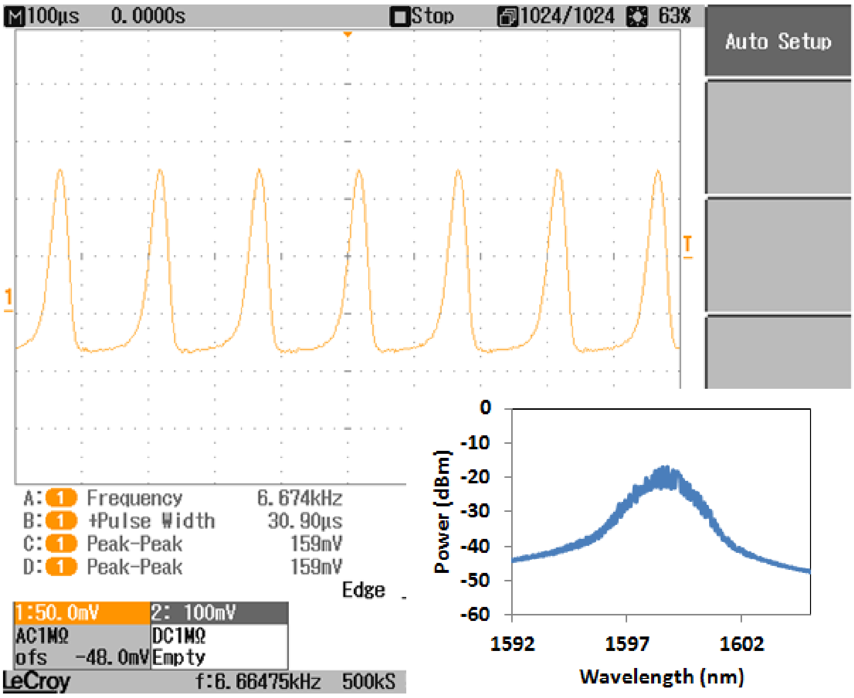

Fig. 5. Typical pulse train of the proposed Q-switched in-band pumped EDFL. Inset shows the output spectrum of the laser.

4. Conclusion

Q-switching pulse train operating at L-band region is successfully demonstrated using an in-band pumped EDFL configured with SWCNT-based SA. The SA is constructed by using homemade SWCNT-PEO composite film, which is sandwiched between two fiber connectors. Without the SA, the EDFL operates in CW mode with the lasing wavelength shifting from 1601 nm to 1572 nm as the EDF length used is increased from 4 m to 10 m. At EDF length of 4.5 m, the slope efficiency and pump power threshold of the laser are obtained at 6.7 % and 42 mW. By integrating the SA in the laser cavity, a self-starting Q-switched pulse train operating at 1598 nm is successfully generated. The proposed laser has a repetition rate of 6.7 kHz, pulse width of 30.9 µs and average output power of 0.3 mW when the EDF length and 1550 nm pump power are fixed at 4.5 m and 80 mW.

Acknowledgement

This project was funded by the Ministry of Higher Education under ERGS (Grant No. ER012-2012A) and University of Malaya (Grant No. PG068-2013B).

References

[1] F. Rotermund, W. B. Cho, S. Y. Choi, I. H. Baek, J. H. Yim, S. Lee, A. Schmidt, G. Steinmeyer, U. Griebner, D. I. Yeom, K. Kim, V. Petrov, Quantum Electron., **42,** 663 (2012).

[2] Z. Sun, A. G. Rozhin, F. Wang, V. Scardaci, W. I. Milne, I. H. White, F. Hennrich, A. C. Ferrari, Appl. Phys. Lett. **93**, 061114 (2008).

[3] Z. G. Lu, J. R. Liu, P. J. Poole, S. Raymond, P. J. Barrios, D. Poitras, G. Pakulski, P. Grant, D. Roy-Guay, Optics Express, **17**(16), 13609 (2009).

[4] S. W. Harun, N. Tamchek, P. Poopalan, H. Ahmad, IEEE Photon. Technol. Letts., **15**, 1055 (2003).

[5] E. L. Lim, S. Alam, D. J. Richardson, Optics Express, **20**(17), 18803 (2012).

[6] O. Svelin, Principles of Lasers, 4th Ed. (Plenum, New York, 1998).

[7] T. Y. Tsai, Y. C. Fang, Opt. Express **17**, 1429 (2009).

[8] Y. K. Yap, Richard M. De La Rue, C. H. Pua, S. W. Harun, H. Ahmad, Chin. Opt. Lett. **10**, 041405 (2012).

[9] L. Pan, I. Utkin, R. Fedosejevs, IEEE Photon. Technol. Lett., **19**, 1979 (2007).

[10] J. Y. Huang, W. C. Huang, W. Z. Zhuang, K. W. Su, Y. F. Chen, K. F. Huang, Opt. Lett., **34**, 2360 (2009).

[11] Z. Sun, A. G. Rozhin, F. Wang, T. Hasan, D. Popa, W. O'Neill, A. C. Ferrari, Appl. Phys. Lett. **95**, 253102 (2009).

[12] X. Q. Wang, M. Wang, Z. H. Li, Z. Y. Liu, Acta Phys. Sin. **53**, 2254 (2004).

*Corresponding author: swharun@um.edu.my