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1500-nm *Q*-switched fibre laser with carbon nanotubes

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Abstract. **A *Q*-switched fibre laser operating at 1500 nm is proposed and demonstrated. The laser uses a saturable absorber (SA) based on carbon nanotubes (CNTs) to generate *Q*-switched pulses, while a 30-m-long depressed-cladding erbium-doped fibre (DC-EDF) provides the necessary gain in the desired wavelength region. The proposed laser has lasing and pulsed thresholds of 30 mW and 50 mW respectively, along with a maximum output power, pulse energy and peak power of 0.5 mW, 7.6 nJ and 2.2 mW. Additionally, the output of the system also has a maximum repetition rate of 59.4 kHz with the shortest pulse duration measured at 3.4 μs. The output pulses are smooth and uniform, with no indication of self mode-locking.**

Keywords: *Q-switching, fibre laser, carbon nanotubes, S-band.*

1. Introduction

Compact and stable pulsed lasers have found interesting applications in optical communications, imaging and even materials processing due to their small size and low manufacturing costs. Generally, pulsed lasers can be classified as either mode-locked lasers or *Q*-switched lasers, which in turn can be achieved either through active or passive means. Of particular interest are passively pulsed fibre lasers, which have a relatively simple configuration, but still able to generate pulses in femto-, pico- and nanosecond ranges [1 – 6]. Although many passively mode-locked fibre lasers have been proposed to date, the approach to their implementation can be quite challenging because it requires careful adjustment of the group velocity dispersion (GVD) in order to generate a stable output pulse. On the other hand, *Q*-switched pulses are not wholly dependent on the GVD, and as such are easier to generate, although at the cost of lower repetition rates and wider pulse durations. Nevertheless, *Q*-switched pulses have an advantage of larger pulse energies and higher average output powers [7], thereby finding tremendous use in applications that do not require very high repetition rate pulses such as laser rangefinders, materials processing application and also optical time domain reflectometry [8].

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In order to achieve passive *Q*-switching in fibre lasers, early approaches used semiconductor saturable absorber mirrors (SESAMs) [9 – 11]. However, a far much simpler approach has been recently demonstrated, using carbon nanotubes (CNTs) [12 – 14] and later layers of graphene [15 – 17] to act as saturable absorbers (SAs). While graphene is a better candidate for SA applications due to its ultrabroad saturation range, covering visible to mid-infrared (IR) regions, as well as being wavelength independent, CNTs still have a high potential as an SA in fibre laser applications. This is because of its ease of fabrication, requiring only deposition CNTs in a host material (usually available commercially) with a generally stable output in the *Q*-switched region.

There have been reports of the use of CNTs as SAs for *Q*-switched operation in the C- and L-bands [13, 14, 18], as well as in the 2-μm region [12]. However, as increasing demands for bandwidth have now pushed the envelope into the 1500-nm (S-band) region, applications for *Q*-switched fibre lasers operating in this region would be of great importance.

Thus, we have proposed and demonstrated a *Q*-switched fibre laser using a CNT-based SA for operation in the 1500-nm region. The system uses a 30-m-long depressed-cladding erbium-doped fibre (DC-EDF) as a gain medium, while a thin CNT film is sandwiched between two connectors to function as an SA for the generation of the desired *Q*-switched pulses. This is the first time, to our knowledge, that *Q*-switched pulses have been passively generated in this region using CNT-based SAs.

2. Experimental setup

Figure 1 shows the setup of the proposed *Q*-switched fibre laser using a CNT-based SA. The setup utilises a 30-m-long depressed-cladding erbium-doped fibre as a linear gain medium for the laser cavity. The DC-EDF has an absorption coefficient of approximately 6.2 dB m^{-1} at a wavelength of 1530 nm, as well as absorption peaks of 7.6 and 1.2 dB m^{-1}, respectively, at 980 and 1500 nm. For operation in the desired region of 1500 nm, the DC-EDF is wound on a spool with a diameter of about 9 cm so as to suppress lasing at wavelengths of more than 1530 nm [19].

The DC-EDF is pumped by a 980-nm laser diode (LD) with a varied pump power, which is connected to the 980-nm port of the 980/1550 nm wavelength division multiplexer (WDM). The common port of the WDM is in turn connected to the DC-EDF, whose output is connected to a polarisation insensitive 1550-nm optical isolator, which ensures the anticlockwise propagation of the waves in the cavity. The output

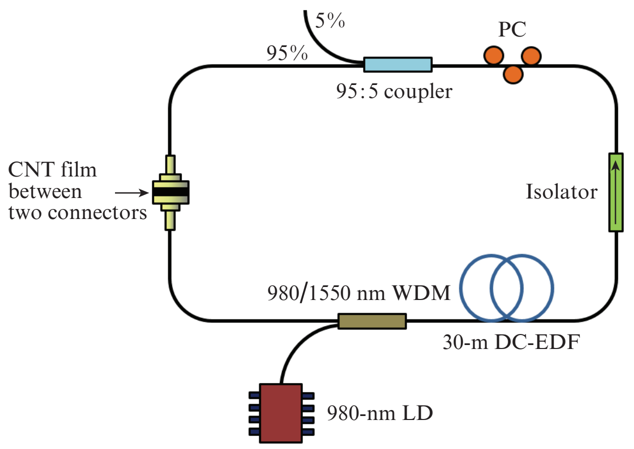

Figure 1. Experimental setup of the proposed CNT-based *Q*-switched S-band fibre laser.

port of the isolator is connected to a polarisation controller (PC), with the other end being joined to the input port of a 95:5 fused tap coupler. The 95% port of the coupler is connected to the CNT-based SA, whereby the CNT thin film is sandwiched between two fibre connectors which are clasped by an FC/PC adaptor. The SA acts a passive *Q*-switching element. The other end of the SA is connected to the 1550-nm port of the WDM, thus completing the ring cavity. The portion of the signal extracted by the 5% port of the tap coupler is first made to propagate through a 1 × 2 (3 dB) coupler, with one port connected to a Yokogawa AQ6317 optical spectrum analyser (OSA) with a resolution of 0.02 nm and is used to analyse the spectral properties of the generated signal. The other port is connected to a 20-GHz photodetector (Agilent 83440C) that is in turn connected to a LeCroy 352A oscilloscope, and is used to analyse the temporal behaviour of the extracted signal.

3. Results and discussion

The dependence of the average output power on the 980-nm pump power for this CNT-based *Q*-switched S-band fibre laser is shown in Fig. 2. The measurements were performed with the CNT-based SA placed in the optical circuit. The threshold for continuous wave (cw) operation in this S-band fibre laser is approximately 30 mW, whereby below this value, lasing is absent. A further increase in the pump power will still result in cw operation, until a pump power of about 50 mW is reached, when a *Q*-switched pulse with an average output power of about 0.1 mW is first observed. The average power is measured using an ILX ILX OMM-6810B Lightwave integrating sphere, which provides the total measured power. A further increase in the pump power results in the average output power increasing linearly, and at a maximum pump power of 155 mW, an average output power equals 0.5 mW. The slope efficiency, which is determined by the slope of the line obtained when plotting the output power of the proposed laser against the pump power, is approximately 0.4%.

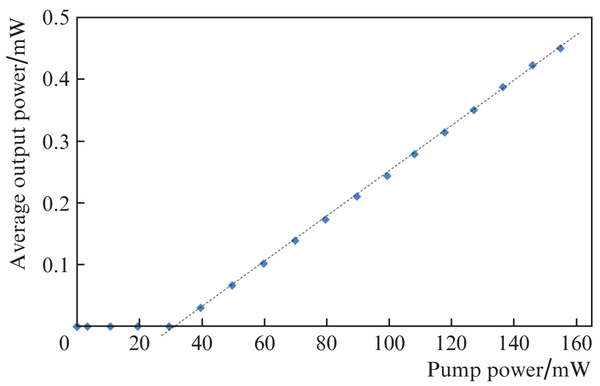

Figure 2. Average output power as a function of the pump power.

Figure 3 shows the output spectra of the CNT-based *Q*-switched S-band fibre laser taken from the OSA with a spectral resolution of 0.02 nm at four different pump powers of ~90, ~108, ~127 and ~155 mW. One can see that both the laser bandwidth and the peak amplitude of the laser output spectrum increases with increasing pump power. The increase of the laser bandwidth spectrum with respect to the pump power is analysed by taking the output power reference level at –45 dBm. At this output power, the wavelength spans from 1495.5 nm to 1499.7 nm at a pump power of 90 mW, giving the bandwidth of about 4.2 nm. As the pump power is increased to 108 mW, the wavelength span increases to 4.6 nm, from 1495.3 nm to 1499.9 nm. At a maximum pump power of 155 mW, the wavelength obtained has a bandwidth of 5.9 nm, spanning from 1495.1 nm to 1501.0 nm, which is the largest obtained for this system. In the case of the peak power, the values obtained are –22.3 dBm at 1498.3 nm (for a pump power of 90 mW), increasing to –20.9 dBm at 1498.3 nm (at a pump power of 108 mW), –19.6 dBm at 1498.4 nm (at a pump power of 127 mW) and finally –19.6 dBm at 1498.3 nm (at the maximum pump power).

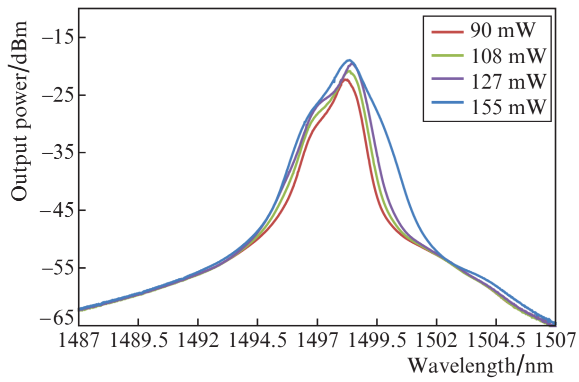

Figure 3. (Colour online) Laser output spectra at different pump powers.

The repetition rate and pulse duration of the generated *Q*-switched pulses at different pump powers are given in Fig. 4. As was mentioned above (see also Fig. 4), *Q*-switched operation only begins at a pump power of approximately 50 mW, with an initial repetition rate of 26.6 kHz. One can see from Fig. 4 that the repetition rate is linearly dependent on the pump power. At the highest pump power of ~155 mW, the fastest repetition rate of 59.4 kHz is obtained. The pulse duration on the other hand has two slopes, with a slope initially decreasing steeply at 10.3%, obtained at pump powers of between 50 to 80 mW, and a subsequently more gradual decrease at pump powers of 80 to 155 mW, with a slope coefficient of 2.3%. At the lowest pump power of 50 mW, a pulse duration of 8.2 μs is obtained, and quickly narrows to about 5.1 μs at the pump power of around 80 mW. This gives a reduction of about 0.1 μs for every increase of 1 mW in the pump power. However, a subsequent increase in the pump power above 80 mW does not narrow the pulse duration as drastically as before, with the narrowest pulse duration of 3.4 μs obtained at the maximum pump power of 155 mW, giving a reduction of about 0.02 μs mW^{-1}. This behaviour is similar to that observed in paper [20].

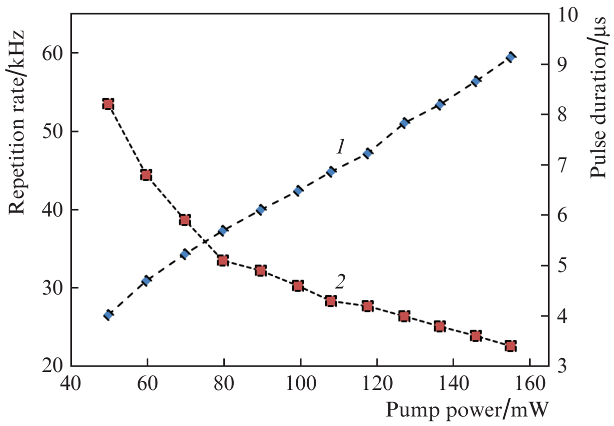

Figure 4. (*1*) Pulse repetition rate and (*2*) pulse duration as functions of the pump power.

The behaviour of the dependence of the repetition rate on the pump power of the fibre laser with CNT layers indicates that a further increase in the pump power, if possible, will yield faster repetition rates. However, from the plot of the pulse duration, it can be seen that the CNT layers have begun to show the onset of saturation, and thus a further increase in the pump power will significantly not change the pulse duration.

Figure 5 shows the pulse energy and peak power of the generated Q-switched pulses as functions of the pump power. It can be seen that both the pulse energy and the peak power increase linearly with increasing pump power. At a minimum pump power of 50 mW, which is also a threshold for Q-switching to occur, a pulse energy of about 2.5 nJ is obtained, with a corresponding peak power of 0.3 mW. At the maximum pump power, a pulse energy of 7.6 nJ is obtained, along with a corresponding peak power of 2.2 mW. On average, the plot of the pulse energy has a slope efficiency of about 4.8%, which gives an average rate of increase of 0.04 nJ for every 1 mW.

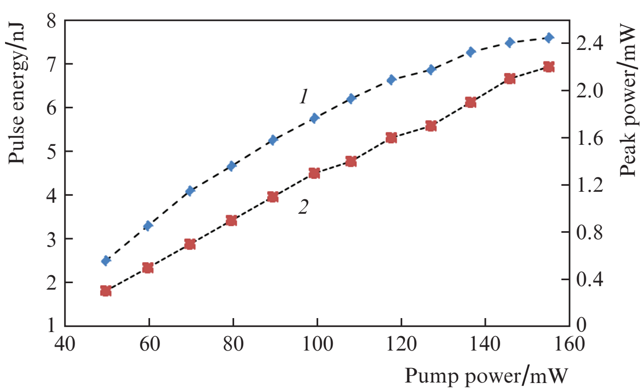

Figure 5. (*1*) Pulse energy and (*2*) peak power of Q-switched pulses as functions of the pump power.

In the case of the peak power, the plot obtained in Fig. 5 has a slope efficiency of about 1.8%, which corresponds to an increase in the peak power of about 0.02 mW per 1-mW increase in the pump power. It is interesting to note that at higher pump powers, above 140 mW, the pulse energy tends to indicate that saturation is beginning to take place. This can also be deduced from Fig. 4, which shows the pulse duration decreases slightly at higher pump powers.

Figures 6a and 6b show the trace variation of the Q-switched output pulse train measured by the oscilloscope via the 6-GHz photodetector at two different pump powers, ~70 and ~155 mW, respectively. As shown in Fig. 6a, at a pump power of ~70 mW, the pulse train has a repetition rate of 34.3 kHz at a pulse duration of 5.9 μs. Increasing the pump power to a maximum value of ~155 mW yields the highest

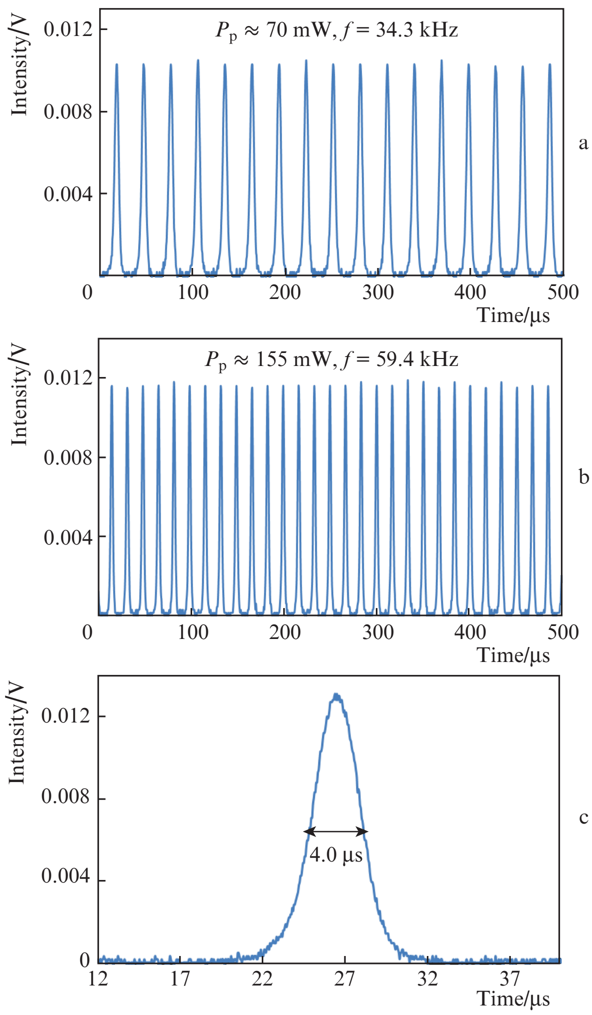

Figure 6. Q-switched pulse trains at a pump power of (a) ~70 mW (a repetition rate, f = 34.3 kHz) and (b) ~155 mW (a repetition rate, f = 59.4 kHz), as well as (c) profile of a single 4.0-μs pulse at a pump power of ~127 mW.

repetition rate of 59.4 kHz as well as the shortest pulse duration of 3.4 μs in the system (Fig. 6b).

The example of a single pulse envelop of the pulse train with a pulse duration of 4.0 μs at a pump power of ~ 127 mW is illustrated in Fig. 6c. It can be seen that all the generated pulse trains are smooth and uniform. This confirms that the proposed fibre laser is free from any self-mode locking, and to the best of our knowledge, this is the first successful demonstration of a *Q*-switched S-band fibre laser with a CNT-based passive SA.

4. Conclusions

A *Q*-switched S-band fibre laser incorporating a CNT-based SA is proposed and demonstrated for operation in the 1500 nm region. The proposed laser uses a 30-m long DC-EDF as a linear gain medium, while the SA is used as a *Q*-switch. The proposed fibre laser has cw and *Q*-switched pulse thresholds of about 30 and 50 mW respectively. The *Q*-switched laser has a slope efficiency of 0.4%, as well as an output power, repetition rate and pulse duration of 0.5 mW, 59.4 kHz and 3.4 μs at the maximum pump power of 155 mW. At this pump power, a maximum pulse energy and a maximum peak power of 7.6 nJ and 2.2 mW are obtained. The generated pulses are smooth and uniform, thereby indicating that the output is not self mode-locked. This is, to our knowledge, the first report of the use of CNTs as a *Q*-switching mechanism at this wavelength range.

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References

1. Liu J., Wu S., Yang Q.H., Wang H. *Opt. Lett.*, **36**, 4008 (2006).
2. Chong A., Buckley J., Renninger W., et al. *Opt. Express*, **14**, 10095 (2006).
3. Pierrot S., Saby J., Bertrand A., Liegeois F., Duterte C., Coquelin B., Hernandez Y., Salin F., Giannone D. *IEEE Lasers and Electro-Optics (CLEO) and Quantum Electronics and Laser Science Conf.* (San Jose, USA, 2010) paper CFD3.
4. Kelleher E.J.R., Travers J.C., Sun Z., Rozhin A.G., Ferrari A.C., Popov S.V., Taylor J.R. *Appl. Phys. Lett.*, **95**, 111108 (2009).
5. Sun Z., Rozhin A.G., Wang F., Hasan T., Popa D., O'Neill W., Ferrari A.C. *Appl. Phys. Lett.*, **95**, 253102 (2009).
6. Yap Y.K., De La Rue R., Pua C.H., Harun S.W., Ahmad H. *Chin. Opt. Lett.*, **10**, 041405 (2012).
7. Svelto O. *Principles of Lasers* (New York: Plenum, 1998).
8. Ahmad H., Muhammad F.D., Zulkifli M.Z., Harun S.W. *IEEE Photon. J.*, **4**, 2205 (2012).
9. Paschotta R., Haring R., Gini E., Melchior H., Keller U., Offerhaus H.L., Richardson D.J. *Opt. Lett.*, **24**, 388 (1999).
10. Kivistö S., Hakulinen T., Guina M., Rößner K., Forchel A., Okhotnikov O. *Proc. SPIE*, **6998**, 69980Q-8 (2008).
11. Spühler G.J., Paschotta R., Fluck R., Braun B., Moser M., Zhang G., Gini E., Keller U. *J. Opt. Soc. Am. B*, **16**, 376 (1999).
12. Jung M., Koo J., Chang Y.M., Debnath P., Song Y.W., Lee J.H. *Laser Phys. Lett.*, **9**, 669 (2012).
13. Dong B., Hao J., Hu J., Liaw C.Y. *Opt. Fiber Technol.*, **17**, 105 (2011).
14. Dong B., Hu J., Liaw C.Y., Hao J., Yu C. *Appl. Opt.*, **50**, 1442 (2011).
15. Ahmad H., Zulkifli M.Z., Muhammad F.D., Jemangin M.H., Dimyati K., Pal B.P., Harun S.W. *IEEE Photon. J.*, **4**, 2050 (2012).
16. Popa D., Sun Z., Hasan T., Torrisi F., Wang F., Ferrari A.C. *Appl. Phys. Lett.*, **98**, 073106 (2011).
17. Cao W.J., Wang H.Y., Luo A.P., Luo Z.C., Xu W.C. *Laser Phys. Lett.*, **9**, 54 (2011).
18. Song Y.W. *Appl. Opt.*, **51**, 290 (2012).
19. Ahmad H., Saat N.K., Harun S.W. *Laser Phys. Lett.*, **2**, 369 (2005).
20. Wei L., Zhou D.P., Fen H.Y., Liu W.K. *IEEE Photon. Technol. Lett.*, **24**, 309 (2012).