Passively Q-switched fibre laser based on interaction of evanescent field in optical microfibre with graphene-oxide saturable absorber

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Received: 07.03.2016

Abstract. We have developed and approved experimentally a passively Q-switched erbium-doped fibre laser. It is based on the saturable absorption of graphene oxide solution deposited around a microfibre waveguide. The microfibre is fabricated using a standard flame-brushing technique. By controlling the pump power in the cavity, the fibre laser can produce microsecond Q-switched pulses at 1529 nm with the maximum repetition rate 53.47 kHz. With a pumping power of 105.98 mW at 980 nm, each of the laser pulses has the energy about 0.78 nJ and the maximum output power is 42.15 μW.

Keywords: microfibre, saturable absorber, Q-switched, fibre laser

PACS: 42.55.Wd
UDC: 535.374:621.375.8

1. Introduction

Fibre lasers have enormous potential applications in spectroscopy, medical apparatus, optical communications and many other fields [1–3]. In general, fibre-laser pulses are subdivided into mode-locked and Q-switched ones. The mode-locked lasers are mostly used in the applications where ultra-fast pulses are required. Although Q-switched fibre lasers have lower frequencies in the kHz range than those of the mode-locked, their pulse energies are higher. There are two main techniques, active [4, 5] or passive [6], to generate Q-switched pulses. As compared to actively Q-switched fibre lasers, passive laser systems have a number of advantages, in particular a simpler setup and less bulkiness [7], which are suitable for small foot-print applications.

Most commonly, carbon-based structures are used as saturable absorbers (SAs) to achieve a passive Q-switching. So, in the case of evanescent-field interaction, a rolled carbon in the shape of carbon nanotubes has been deposited around a microfibre to achieve the pulse lasing mode [8]. Graphene is a two-dimensional carbon material which has attracted much attention of researchers and technologists in the fields of nanoelectronics and photonics in the last decades due to its unique properties, including low threshold levels of saturable absorption, ultrafast recovery times, and an ultra-broad wavelength-independent range of saturable absorption – from the visible region and down to the Terahertz one [9, 10]. Q-switched pulse lasers have been successfully developed basing on graphene (see Refs. [11–14]).

In the present study, we develop a Q-switched erbium-doped fibre laser based on the SA in graphene oxide (GO). Here the GO has been optically deposited around a tapered fibre in a very simple manner, namely by just dropping a few droplets of a GO solution on the waist region of a microfibre. Then the evanescent field of the light propagating in the tapered fibre waveguide interacts with the GO-solution droplets and forms the SA around the fibre waist. A stable pulse train has been obtained in this manner, with the repetition rate ranging from 37.06 to 53.45 kHz. As a result, our laser can generate the energy 0.78 nJ at 1529 nm, which corresponds to the maximum output power 42.18 µW.

2. Deposition of GO around a tapered fibre

A tapered optical fibre was fabricated with a heat-and-pull technique. A 1 cm long uncoated standard optical fibre was clamped on two optical-fibre holders. Then the fibre was heated using a movable butane-oxy flame for its softening. Finally, it was stretched to produce a microfibre with low losses (see Ref. [15]) and the waist 16 µm.

The evanescent optical field outside the microfibre can interact with the surrounding material when the cladding diameter of the fibre decreases to less than 30 µm [16]. By using a micropipette, a 0.5 µl of GO solution was dropped onto the waist of the microfibre where a laser light propagated. Due to the evanescent field in the microfibre and the mutual interaction between the microfibre and the GO solution, a nonlinear SA is formed around the microfibre [17]. Notice that interaction of the evanescent field in the microfibre with the SA at the lengths around the interaction length would increase the optical damage threshold, when compared with that typical for the direct interaction between the light and the SA [18]. Finally, the insertion loss of the GO-deposited microfibre was equal to 4.7 dBm.

Fig. 1a shows the Raman spectrum of the GO solution. The spectrum indicates two peaks, *D* and *G*. The *D* peak measured at 1355 cm^{-1} originates from a C–C bond, whereas that referred to as *G* is located at 1606 cm^{-1} and arises from the first scattering of E_{2g} phonon at SP^2 C atoms [19, 20]. Fig. 1b depicts an optical microscopic image of our tapered fibre deposited with the GO at the approximate length 20 µm.

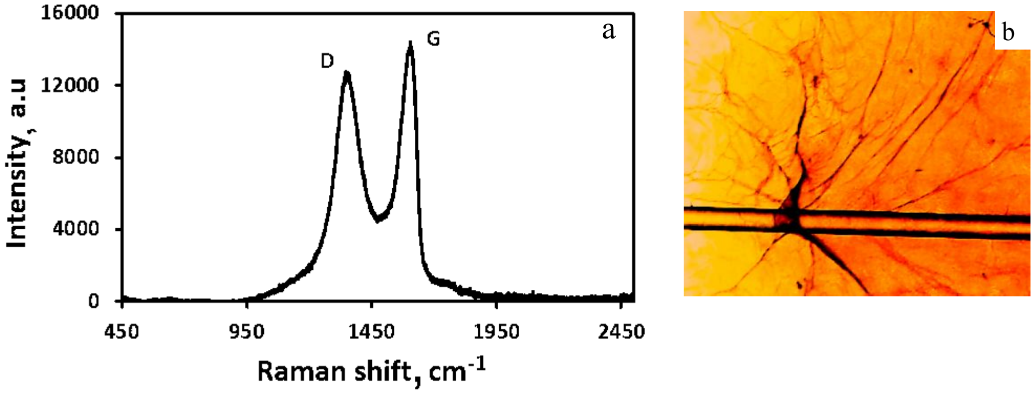

Fig. 1. (a) Raman spectrum of GO SA and (b) microscopic image illustrating deposition of GO SA on microfibre.

3. Experimental setup

Fig. 2 illustrates schematically a setup of our passively Q-switched fibre laser. A 980 nm laser diode is used for pumping a 3 m-long erbium-doped fibre (Fibre Core M12 Metro Gain) which acts as a gain medium connected to a 980/1550 wavelength division multiplexer. An optical isolator ensures unidirectional light propagation. There are also a 90/10 coupler, a GO-deposited microfibre, and a polarization controller for adjusting the polarization state. A 3 dB coupler is connected to the 10% output port to monitor simultaneously the output wavelength and the transient processe. The data is taken using an optical spectrum analyzer (Yokogawa AQ6370C) and a radio-frequency spectrum analyzer, whereas the Q-switched pulses are recorded with a digital oscilloscope (Yokogawa DLM 2054).

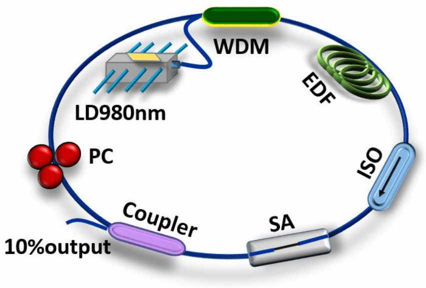

Fig. 2. Scheme of our passively Q-switched erbium-doped fibre laser: EDF denotes erbium-doped fibre, ISO optical isolator, LD980 laser diode emitting at 980 nm, PC polarization controller, and WDM wavelength division multiplexer.

4. Results and discussion

Once the Q-switched operation starts at the pump power of 56.17 mW, broadening of the output spectrum is clearly observed. At the 3 dB level, the bandwidth of the main peak centred at 1529 nm amounts to 2.12 nm (see Fig. 3). In addition, the gain related to this peak increases with increasing pump power and reaches its maximum at 105.98 mW, while the 3 dB bandwidth increases up to 2.44 nm. Broadening of the Q-switched output spectra is related to large third-order nonlinear parameters of the GO [21]. Once the threshold pump power (56.17 mW) is achieved, the laser starts to generate Q-switched pulses with the repetition rate 37.06 kHz and the pulse duration 26.97 μs. When the pump power increases to 105.98 mW, the repetition rate increases, too. Under the same conditions, the pulse duration drops somewhat. This phenomenon is illustrated in Fig. 4. In this case, the polarization controller is kept in the (unchanged) initial position while the pump power increases.

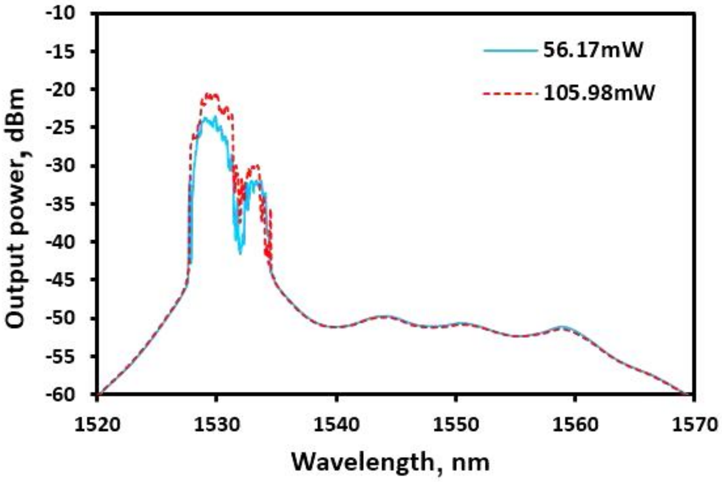

Fig. 3. Optical spectra of our fibre laser detected at two different pump powers.

Fig. 5 shows the output pulse train in the frequency domain obtained from the radio-frequency spectrum analyzer. The spectrum indicates that the fundamental frequency is equal to 43.57 kHz (see inset). There is a clearly defined pulse with the extinction ratio of ~ 38 dB of the fundamental frequency to the harmonics. Moreover, the broadband radio-frequency spectrum seen in Fig. 5 reveals no spectral modulation, thus indicating a stable repetition rate of the passive Q-switching observed at the pump power 88.36 mW.

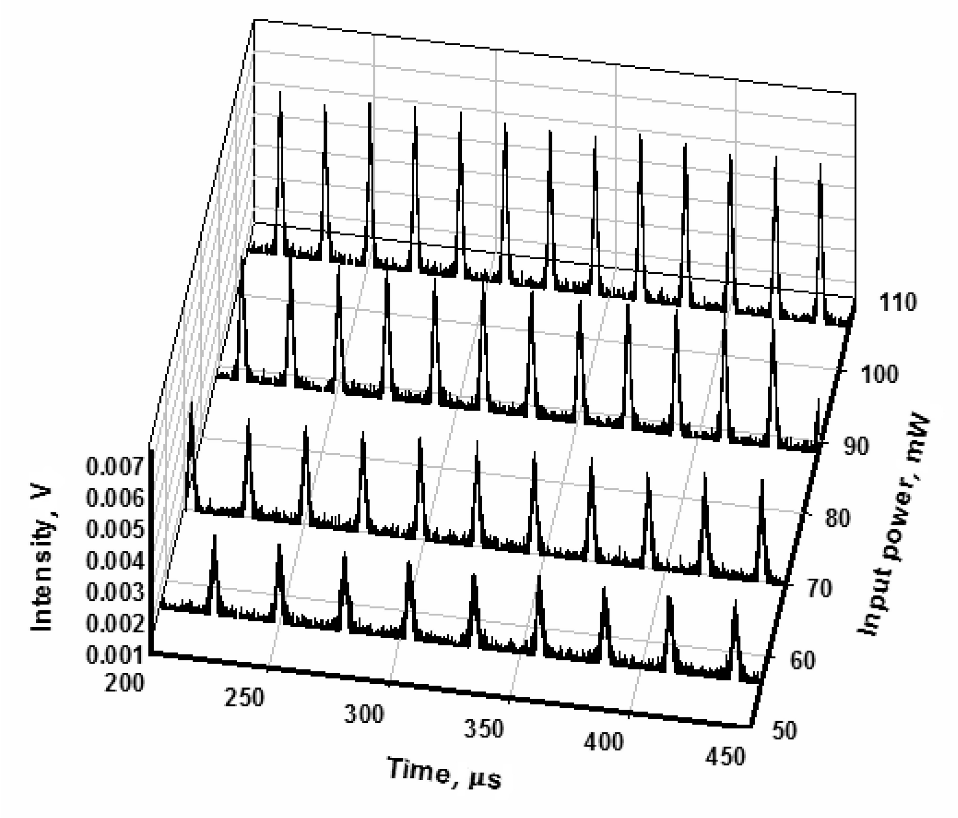

Fig. 4. Trains of Q-switched pulses detected at the pump powers 56.17, 69.85, 88.36 and 105.98 mW.

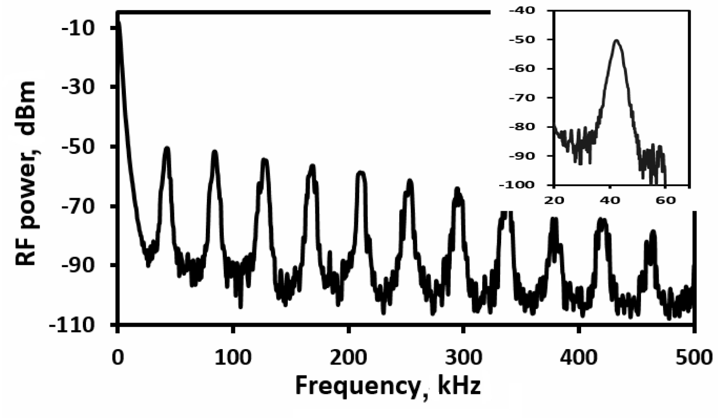

Fig. 5. Radio-frequency spectrum detected at the pump power 88.36 mW.

Similarly to the other passively Q-switched lasers, the repetition rate of our GO-based Q-switched fibre laser increases when the pump power does so. This is due to population inversion in the gain medium that requires short times to reach the threshold whenever the pump power increases (see Ref. [22]). The repetition rates from 37.06 to 53.45 kHz are observed when the input power increases from 56.17 up to 105.98 mW. This repetition rate is higher than that reported in Ref. [12] and comparable to the results of Ref. [23]. On the other hand, the pulse width for the same power region decreases from 3.67 down to 2.28 µs, as shown in Fig. 6.

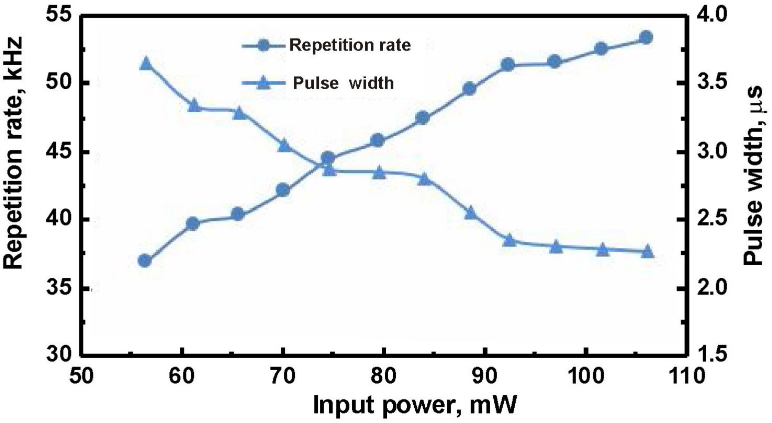

Fig. 6. Repetition rate and pulse width as functions of the pump power.

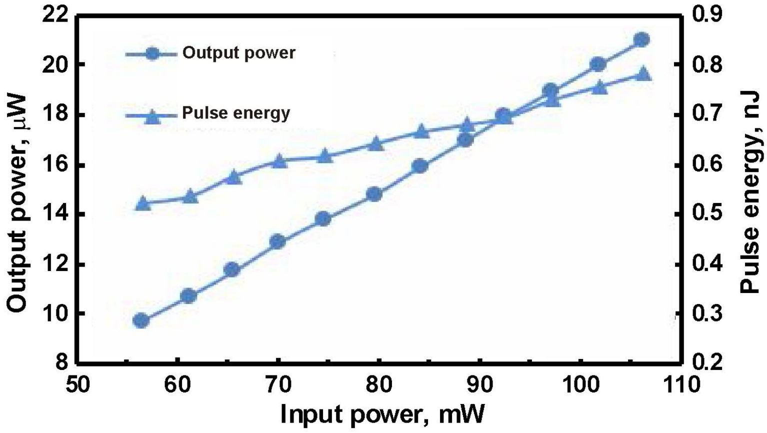

Fig. 7. Pulse energy and output power as functions of the pump power.

Fig. 7 shows the pulse energy and the output power of the pulsed laser as functions of the pump power. When the latter increases, more electrons fill up the energy state and so the SA saturates rapidly. Then both the pulse frequency and the pulse energy increase with increasing pump power. The pulse energy 0.78 nJ and the maximum output power 0.042 mW are achieved at the maximum input power 105.98 mW. However, the Q-switched pulses become unstable or even disappear with further increase in the pump power. We expect that the efficiency of the Q-switched pulsed laser can be further improved by optimization of the SA and the microfibre, as well as by a proper design of the laser cavity.

5. Conclusion

In summary, we have built the passively Q-switched erbium-doped fibre laser based on the GO SA, which is deposited around the microfibre waist, and experimentally demonstrated its successful operation. The SA was made by dropping the droplets of graphene solution on the microfibre with a micro-pipette. Q-switched pulses have been obtained above the threshold pump power of 56.17 mW. By adjusting the input power level, one can change the Q-switched pulse repetition rate from 37.06 to 53.45 kHz. The maximum pulse energy 0.78 nJ has been generated in this manner. The performance of the Q-switched erbium-doped fibre laser reported in this work can still be improved by optimizing the microfibre dimensions and the quality of the GO.

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Jaddoa M.F., Faruki M.J., Razak M.Z.A., Azzuhri S.R. and Ahmad H. 2016. Passively Q-switched fibre laser based on interaction of evanescent field in optical microfibre with graphene-oxide saturable absorber. Ukr.J.Phys.Opt. **17**: 58 – 64.

Анотація. *Запропоновано та апробовано лазер з пасивною модуляцією добротності на основі оптичного волокна, легованого ербієм. Робота лазера базується на насиченому поглинанні в оксиді графену, нанесеному навколо мікроволокна. Мікроволокно обробляли з використанням стандартної полум'яно-очищувальної технології. За умови контролю потужності нагнітання в резонаторі волоконний лазер може індукувати мікросекундні імпульси з модуляцією добротності на довжині хвилі 1529 нм з максимальною повторюваністю 53,47 кГц. Кожен імпульс мав енергію біля 0,78 нДж , а максимальна вихідна потужність становила 42.15 мкВт при нагнітанні лазерним діодом потужністю 105,98 мВт на довжині хвилі 980 нм.*