Graphene Q-switched, tunable fiber laser

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We demonstrate a wideband-tunable Q-switched fiber laser exploiting a graphene saturable absorber. We get∼2μs pulses, tunable between 1522 and 1555nm with up to∼40nJ energy. This is a simple and low-cost light source for metrology, environmental sensing and biomedical diagnostics.

Q-switching and mode-locking are the two main techniques enabling pulsed lasers[1]. In mode-locking, the random phase relation originating from the interference of cavity modes is fixed, resulting in a single pulse[1], with typical duration ranging from tens ps to sub-10 fs[2], and a repetition rate corresponding to the inverse of the cavity round-trip time[2]. In mode-locking, many aspects, including the dispersive and nonlinear proprieties of the intracavity components, need to be precisely balanced in order to achieve stable operation[1, 2]. Q-switching is a modulation of the quality factor, Q, of a laser cavity[1], Q being the ratio between the energy stored in the active medium and that lost per oscillation cycle[1] (thus, the lower the losses, the higher Q). In Q-switching, the active medium is pumped while lasing is initially prevented by a low Q factor[1]. The stored energy is then released in a pulse with duration ranging from μs to ns when lasing is allowed by a high Q factor[1]. The time needed to replenish the extracted energy between two consecutive pulses is related to the lifetime of the gain medium, which is typically∼ms for erbium-doped fibres[1]. Thus the repetition rate of Q-switched lasers is usually low (∼kHz[1]), much smaller than mode-locked lasers[1, 2]. On the other hand, Q-switching enables much higher pulse energies and durations than mode-locking[1]. Q-switching has advantages in terms of cost, efficient operation (i.e. input power/output pulse energy) and easy implementation, compared to mode-locking, which needs a careful design of the cavity parameters to achieve a balance of dispersion and nonlinearity[1, 2]. Q-switched lasers are ideal for applications where ultrafast pulses (<1ns) are not necessary, or long pulses are advantageous[3, 4], such as material processing, environmental sensing, range finding, medicine and long-pulse nonlinear experiments[3–5].

Q-switching can be active (exploiting, e.g., an acousto-optic or electro-optic modulator[1]), or passive (using, e.g., a saturable absorber (SA)[1]). Passive Q-switching features a more compact geometry and simpler setup compared to active, which requires additional switching electronics[1]. For Q-switching the SA recovery time does not need to be shorter than the cavity round-trip time, since the pulse duration mainly depends on the time needed to deplete the gain after the SA saturates[1, 2], unlike mode-locking[2]. Doped bulk crystals[5], and semiconductor saturable absorber mirrors (SESAMs)[3, 6] are the most common SAs in passive Q-switching[1]. However, the use of doped crystals as SAs requires extra elements (mirrors, lenses) to focus the fiber output into the crystal[5]. SESAMs have limited operation bandwidth, typically few tens nm[7], thus are not suitable for broad-band tunable pulse generation. Broadband SAs enabling easy integration into an optical fiber system are thus needed to create a compact Q-switched fibre laser.

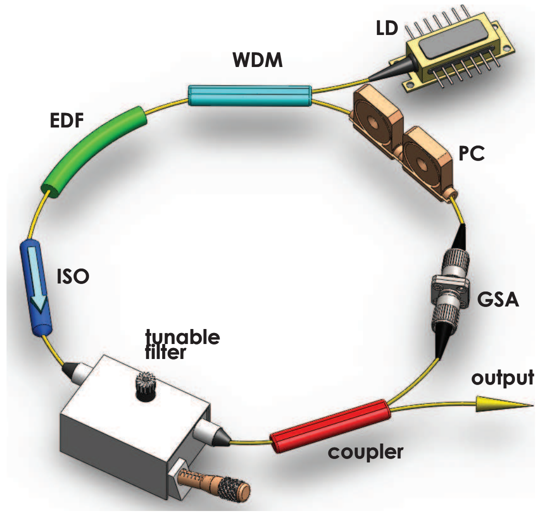

FIG. 1: Setup: laser diode (LD), wavelength division multiplexer (WDM), erbium-doped fiber (EDF), isolator (ISO), graphene SA (GSA), polarization controller (PC)

Single wall carbon nanotubes (SWNTs) and graphene are ideal SAs, due to their low saturation intensity, low cost and easy fabrication[8–22]. Broadband operation is achieved in SWNT using a distribution of tube diameters[8, 17], while this is an intrinsic property of graphene, due to the gapless linear dispersion of Dirac electrons[18–21, 23]. Q-Switching was reported using SWNTs: Ref.24 achieved 14.1nJ pulse energy and 7μs width, while Ref.25 13.3nJ and 700ns. After the demonstration of a graphene-based mode-locked laser[17], various group implemented graphene SA in a variety of mode-locked cavity designs[18–22, 26–28].

Here, we demonstrate a fiber laser Q-switched by a graphene saturable absorber (GSA). The broadband absorption of graphene enables Q-switching over a 32nm range, limited only by our tunable filter, not graphene itself. The pulse energy is∼40nJ, for∼2μs duration.

Graphite flakes are exfoliated by mild ultrasonication with sodium deoxycholate (SDC)[19, 21, 29]. A

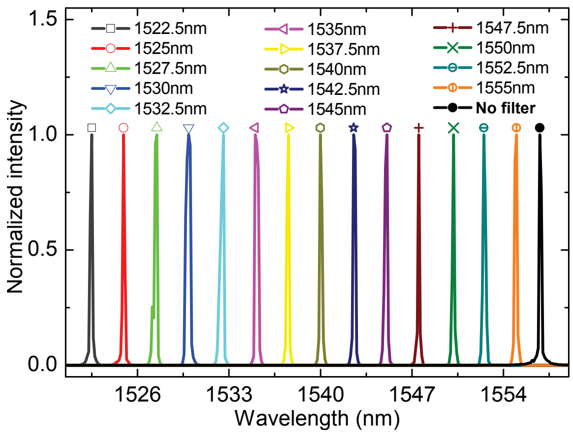

FIG. 2: Output spectra for 14 tuning wavelengths. The curve with a filled circle corresponds to Q-switching without filter.

dispersion enriched with single (SLG) and few layer graphene (FLG)[21] is then mixed with an aqueous solution of polyvinyl alcohol (PVA). After water evaporation, a$\sim$50μm thick graphene-PVA composite is obtained[17, 19]. This is then placed between two fiber connectors to form a fiber-compatible SA, then integrated into a laser cavity, Fig.1, with 1.25m erbium doped fiber (EDF) as gain medium, pumped with a 980nm laser diode (LD), coupled via a wavelength division multiplexer (WDM). An optical isolator (ISO) ensures unidirectional light propagation. An in-line tunable optical bandpass filter is inserted after the ISO. Our EDF can support lasing between 1520 and 1560nm[30]. The operation wavelength is selected rotating the dielectric interference filter. The 20% port of an optical coupler provides the laser output. The rest of the cavity consists of a combination of single mode fiber (SMF) Flexcor 1060 and SMF-28. All fibers used in our cavity are polarization-independent, i.e. they support any light polarization, even if this changes as a result of outside perturbations (e.g. mechanical stresses, bending, or temperature). Thus, to improve the output pulse stability, we place in the cavity a polarization controller (PC), consisting of 2 spools of SMF-28 fiber acting as retarders. The total retardation induced by the PC is a function of the fiber geometry in the spool[30]. This allows to maintain a polarization state after each round trip. The total cavity length is$\sim$10.4m. The operation is evaluated by a 14GHz bandwidth photo-detector and an oscilloscope. A spectrum analyzer with 0.07nm resolution measures the output spectrum.

Continuous wave (CW) operation starts at$\sim$43mW pump power; pulsed operation at$\sim$74mW. The repetition rate is pump-dependent up to$\sim$200mW (Fig.4b), a typical signature of Q-switching[1]. The output spectrum is tunable from$\sim$1522 to 1555nm. This is comparable to the 31nm range reported for doped crystal Q-switched tunable lasers[5], but much larger than the 5nm thus far achieved for SWNT Q-switched lasers[24, 25]. Our tun-

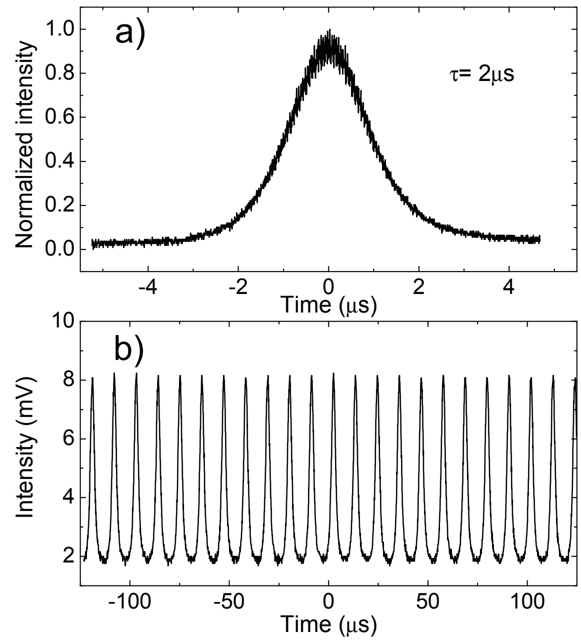

FIG. 3: a) Single pulse envelope. b) Typical pulse train for 2.8mW output power.

ing range is limited by the filter and by the EDF gain, not the GSA. Fig. 2 shows the output spectra for 14 wavelengths at$\sim$2.5mW output power. Without filter, the laser exhibits Q-switching at 1557nm. The full width at half maximum (FWHM) spectral width is 0.3$\pm$0.1nm over the whole tuning range, much shorter than thus far achieved for graphene mode-locked lasers[18–22, 26–28].

Fig.3a plots a typical pulse envelope, having FWHM$\sim$2μs, comparable to fiber lasers Q-switched with other SAs (e.g. SESAMs[3, 6], doped crystals[5], and SWNTs[24, 25]), but much longer than thus far achieved in graphene mode-locked fiber lasers[18–22, 26–28]. The output pulse duration has little dependence on wavelength, possibly due to the flat gain coefficient of our EDF[30]. Fig.3b shows the pulse train for a typical laser output at 158mW pump power.

The output power varies from 1 to 3.4mW as a function of pump power. The slope efficiency, i.e. the slope of the line obtained by plotting the laser output power against the input pump power[1], is$\sim$ 2%. The repetition rate as a function of pump power varies from 36 to 103KHz (Fig.4b), with a 67KHz change for a 2.4mW output power variation. Unlike mode-locked lasers, where the repetition rate is fixed by the cavity length[1], in Q-switched lasers this depends on pump power[1]. As this increases, more gain is provided to saturate the SA and, since pulse generation relies on saturation, the repetition rate increases with pump power[1]. The maximum output pulse energy is$\sim$40nJ for$\sim$60KHz repetition rate, similar to that achieved using other SAs[25]. Compared to graphene mode-locked fiber lasers[18–22, 26–

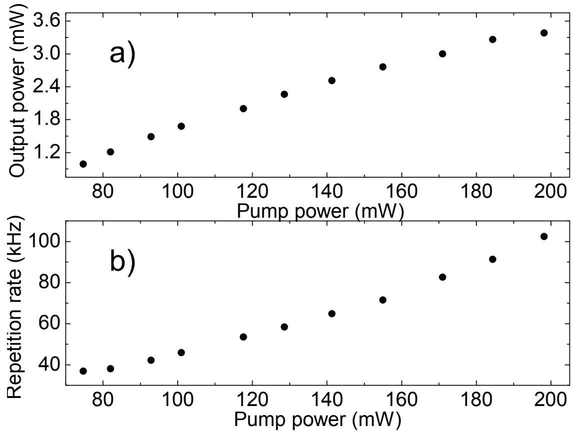

FIG. 4: (a)Output power and (b) repetition rate, as a function of input pump power at 1540nm

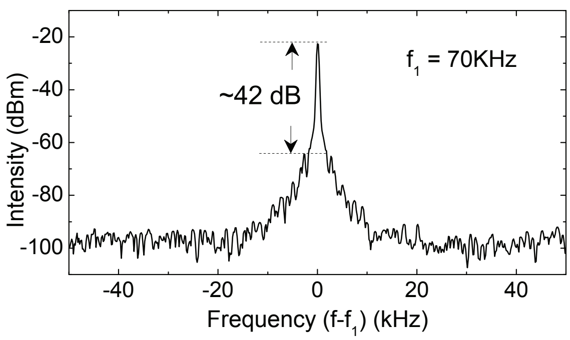

FIG. 5: RF spectrum measured around∼70KHz at 1540nm

28], our pulse energy is∼6 times larger, but with less peak power, due to the larger pulse duration. It is also much larger than thus far achieved in SWNT Q-switched lasers[24, 25]. Even higher energies, thus peak powers, could be enabled by evanescent field interaction with GSA[27] and high-gain fibers (e.g. cladding-pumped fibers[5] or large mode area fibers[3]).

The radio-frequency (RF) measurement of the output intensity at 70Hz, corresponding to a period of∼143μs, is shown in Fig.5. The peak to pedestal extinction is∼40dB (10^4 contrast), confirming pulse stability.

In conclusion, we achieved Q-switching exploiting a graphene-based saturable absorber, using standard, telecom grade, fibre components. The wideband operation of graphene enables broad band tunability. Such wideband Q-switched laser could provide a simple, low-cost, and convenient light source for metrology, environmental sensing and biomedical diagnostics.

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