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~ 2μ s 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 μ s 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 \sim ms for erbium-doped fibres[1]. Thus the repetition rate of Q-switched lasers is usually low ($\sim kHz[1]$), 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 acoustooptic 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 el-

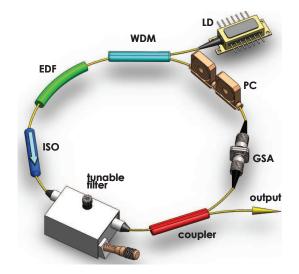


FIG. 1: Setup: laser diode (LD), wavelength division multiplexer (WDM), erbium-doped fiber (EDF), isolator (ISO), graphene SA (GSA), polarization controller (PC)

ements (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.

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 7μ s 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 modelocked 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~2 μ s duration.

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

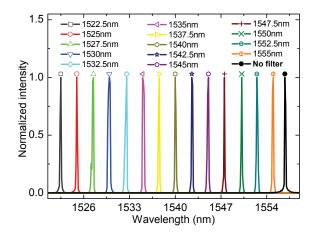


FIG. 2: Output spectra for 14 tuning wavelengths. The curve with a filled circle corresponds to Q-switching without filter.

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, $a \sim 50 \mu m$ 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 1560 nm[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 ~ 10.4 m. 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~43mW pump power; pulsed operation at~74mW. The repetition rate is pump-dependent up to~200mW (Fig.4b), a typical signature of Q-switching[1]. The output spectrum is tunable from~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-

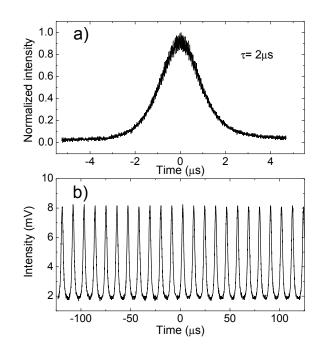


FIG. 3: a) Single pulse envelope. b) Typical pulse train for $2.8 \mathrm{mW}$ output power.

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~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±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 $\sim 2\mu$ s, 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~ 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~40nJ for~60KHz repetition rate, similar to that achieved using other SAs[25]. Compared to graphene mode-locked fiber lasers[18–22, 26–

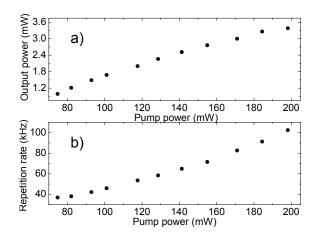


FIG. 4: (a)Output power and (b) repetition rate, as a function of input pump power at 1540nm

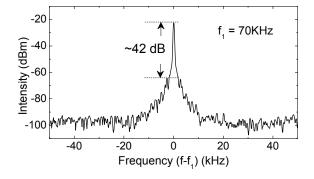


FIG. 5: RF spectrum measured around~70KHz at 1540nm

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 Qswitched 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~ 143μ s, 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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