Nanosecond-pulse fiber lasers mode-locked with nanotubes

E. J. R. Kelleher,[1,a)] J. C. Travers,[1] Z. Sun,[2] A. G. Rozhin,[2] A. C. Ferrari,[2] S. V. Popov,[1]
and J. R. Taylor[1]
[1]*Femtosecond Optics Group, Department of Physics, Imperial College, Prince Consort Road, SW7 2AZ, United Kingdom*
[2]*Department of Engineering, University of Cambridge, Cambridge CB3 0FA, United Kingdom*

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We demonstrate that mode-locking of ytterbium fiber lasers with a carbon nanotube saturable absorber can produce pulses ranging from 20 ps to 2 ns at repetition rates between 21 MHz and 177 kHz, respectively, depending on cavity length. Nonlinear polarization evolution is not responsible for mode-locking. Even in the nanosecond regime, clean single pulses are observed and the pulse train exhibits low jitter. Combined with extremely large chirp, these properties are suited for chirped-pulse amplification systems. © *2009 American Institute of Physics*. [doi:10.1063/1.3207828]

Picosecond and subpicosecond mode-locking of fiber lasers using single wall nanotubes (SWNTs) has been demonstrated at a range of wavelengths, employing various configurations.[1–11] Passively mode-locked fiber lasers with all-normal dispersion cavities have been widely investigated as a means of obtaining high pulse energies.[12] Recently, elongating the cavity was proposed to provide a source of low repetition rate, long duration, and high energy pulses suitable for a range of applications.[13,14] Long-pulse mode-locking based on nonlinear polarization evolution (NPE) can result in noiselike high energy pulses, stabilized by a positive group dispersion fiber added to the cavity.[15] The low coherence of such systems limits their application. A regime of long-pulse passive mode-locking was recently identified by employing a saturable absorber.[12–14] In this case, the mode-locking dynamics can be well described by the classic mode-locking theory of Haus *et al.*[16]

Here we demonstrate that by using a SWNT saturable absorber, stable long-pulse mode-locking can also be obtained in an all-normal dispersion regime. The pulse duration varies (from 20 ps to 2 ns) with cavity length. The linear dispersion associated with the long fiber cavity on its own does not explain the extreme pulse broadening. The extra nonlinearity of the fiber is required for giant-pulse dynamics. Reference 13 attributed giant-pulse mode-locking to NPE, while in Ref. 14 additional normally dispersive fiber was required for pulse shaping. We show that despite some dependence of pulse duration on polarization, NPE and large normal dispersion are not essential for initiation of stable mode-locking with SWNTs. Absence of intentional spectral filtering gives extremely chirped pulses, ~750 times the transform limited duration. These can be suitable for compression, provided the duration is chosen to match external compressor configurations. SWNT-based devices are cheaper compared to other passive mode-lockers, such as semiconductor saturable absorber mirrors, and easier to integrate into all-fiber geometries.[1–11,17,18]

Our all-fiber mode-locked ring laser setups are shown in Fig. 1. The primary configuration [Fig. 1(a)], used for most of our studies, consists of a 2 m Yb-doped fiber amplifier, followed by a SWNT-polyvinyl alcohol (PVA) saturable absorber, a polarization controller, a fused fiber coupler with 15% output, an inline optical isolator, and a single-mode optical fiber with a length (varied using cut-back and fusion splices) between 1 and 1200 m. All of the cavity fiber has a dispersion coefficient of $\sim -30\ \mathrm{ps\ nm^{-1}\ km^{-1}}$ and a nonlinearity of $3\ \mathrm{W^{-1}\ km^{-1}}$ at 1.06 μm. In contrast to Ref. 12, neither inline spectral filters nor polarization selective components are used. The lasing wavelength selection results from the overlap of gain and spectral loss profiles of the laser components and dynamic filtering effect of the saturable absorber. An all-single-mode fiber format prevents higher-order modal effects contributing to the broadening mechanism. This could not be ruled out in Ref. 13.

We analyze the mode-locking dependence on distributed fiber dispersion and nonlinearity, comparing the performance of the primary cavity [Fig. 1(a)] with a configuration including a lumped dispersive element [Fig. 1(b)]. In this case, the extra dispersive fiber is replaced with a fiber integrated circulator and chirped Bragg grating, providing a dispersion of 35.7 or $-35.7\ \mathrm{ps\ nm^{-1}}$ depending on orientation, a spectral bandwidth of 3.36 nm and a transmission of -27.7 dB.

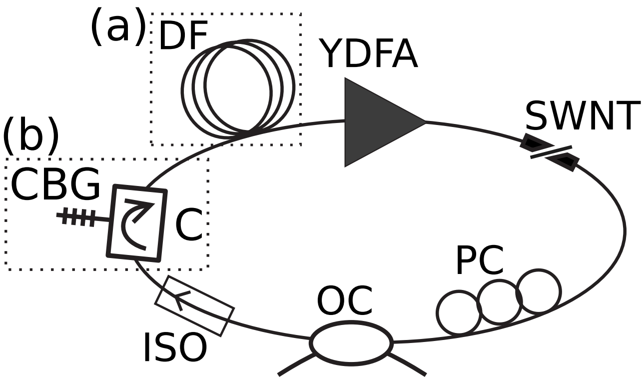

FIG. 1. (a,b) Laser setups. Common to both: YDFA: Yb-doped fiber amplifier; SWNT: nanotube based saturable absorber; PC: polarization controller; OC: fused fiber output coupler; ISO: isolator. Setup (a) has also a dispersive fiber (DF). In setup (b), the DF is removed and a circular (C) and a chirped Bragg grating (CBG) are included.

[a)] Electronic mail: edmund.kelleher08@imperial.ac.uk. URL: www.femto.ph.ic.ac.uk.

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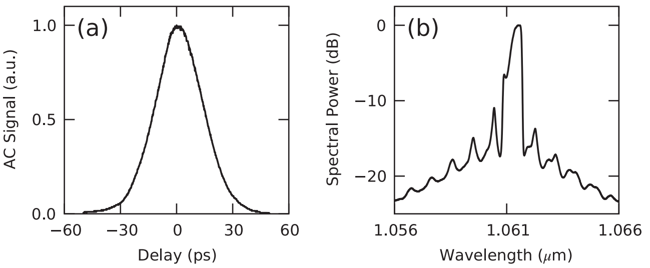

FIG. 2. Intensity autocorrelation (a) and spectrum (b) for the 10 m cavity.

Mode-locking is achieved with a saturable absorber prepared using CoMoCat SWNTs,[19] dispersed in a PVA film.[6,7] The SWNT film is integrated into the cavity by clamping it between two angled physical contact fiber connectors.[6,7] The linear transmission of the SWNT film at the operating wavelength is ~51%. The PVA film with no SWNTs has high transparency between 400 and 1300 nm and does not contribute to the saturable absorption properties of the composite. Typical recovery time is subpicosecond,[20] significantly shorter than the observed mode-locked pulse duration. The absorber has a damage threshold of ~0.16 mW μm^{-2} at 1.06 μm. The total loss of the primary ring cavity is in excess of 11 dB, not including the loss introduced into the cavity by the addition of the dispersive fiber.

The autocorrelation full-width at half-maximum (FWHM) of the 10 m cavity is 30 ps [Fig. 2(a)], corresponding to a ~20 ps pulse. The spectral FWHM of 0.47 nm is centered at 1.062 μm [Fig. 2(b)]. The output pulses are considerably chirped as the transform limit of such spectral bandwidth is ~2.5 ps, assuming a sech^2 profile. Mode-locking is self-starting with a small dependence on the polarization controller. However, the output pulse shape does not depend on polarization, with approximately equal power in each axis. Mode-locking cannot be initiated without the SWNT element. The repetition rate is 21 MHz and pulse energy ~1.75 pJ.

Figure 3 shows comparative results for the 1200 m cavity. The pulse intensity profile and sech^2 fit agree with the analytical mode-locking theory.[16] 1.7 ns pulses at 177 kHz repetition rate with energy of up to 0.18 nJ are produced. The spectral FWHM of 0.52 nm, centered at 1.059 μm, indicates strong chirp with a time-bandwidth product of 236. This is ~750 times the transform limit. The linear chirp, with a magnitude 0.14 nm ns^{-1}, is measured using a 1 m monochromator and sampling oscilloscope, indicating compressibility down to a near bandwidth limited duration of 2–3 ps. Such large chirp naturally arises in this mode-locking regime due to the balance of nonlinearity, dispersion, and saturable absorption.[12,16]

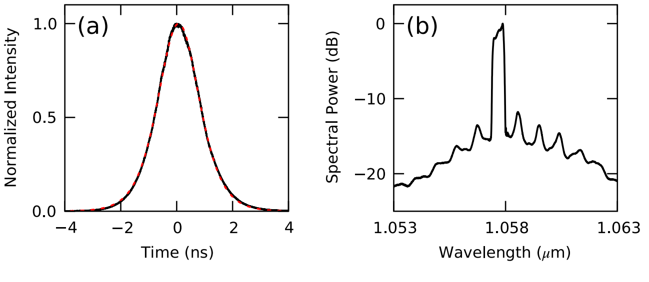

FIG. 3. (Color online) Pulse shape (a), with sech^2 fit (red dashes). Corresponding spectra (b) for the 1200 m cavity.

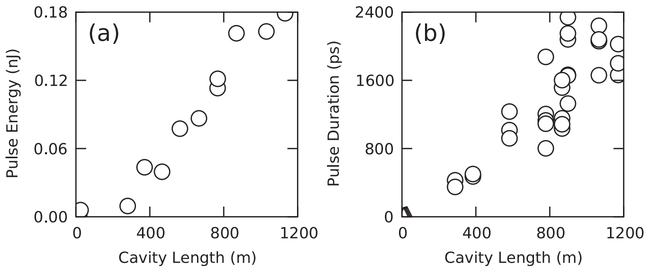

FIG. 4. Pulse energy (a) and pulse duration (b) as a function of cavity length. Pulse duration measured using an autocorrelator (triangles) or a fast photodiode and sampling oscilloscope (circles).

Figure 4 shows how the output pulse energy and pulse duration increase with cavity length. The variation in pulse duration corresponds to different states of the polarization controller and pump power. This demonstrates the possibility of obtaining any pulse duration in the range from 20 ps to 2 ns by cavity length tuning. The output peak power is ~70 mW and constant with increasing length, corresponding to an intracavity peak power of ~0.5 W. Despite the long length of fiber in the cavity and nanosecond pulse durations, the peak power is below the stimulated Raman threshold. The lack of Raman scattering was confirmed through observation of the spectrum. We note that Ref. 13 did not state whether Raman scattering was present in their ultralow rep-rate system, where peak power exceeded 1 kW.

The radio frequency (rf) spectrum of the mode-locked pulse train from the 1200 m cavity has a peak to pedestal extinction ~50 dB at a resolution of 30 Hz [Fig. 5(a)]. Measurements on a 400 MHz analog oscilloscope also confirms clean and stable mode-locking with no transient effects nor signs of Q-switched behavior [Fig. 5(b)]. Stability of mode-locking was proven on timescales of at least 1 h. We also measured the temporal profile with a 15 ps photodiode and 50 GHz sampling scope and confirmed that the pulses do not consist of noiselike structures, characteristic of similar systems based on NPE. The higher coherence of SWNT-based long-pulse mode-locking suggests the usefulness of such a source for chirped pulse amplification schemes, where the need for a stretcher, pulse-picker, and preamplifier could be eliminated.

To determine if a lumped dispersion equivalent to that of the 1200 m single mode fiber used in the cavity could cause similar mode-locking behavior, the fiber is replaced with a circulator and chirped fiber Bragg grating (CBG) [Fig. 1(b)]. With the grating orientated to provide a normal dispersion, no mode-locking can be obtained, only Q-switched output. This confirms that the self-phase modulation introduced by the long fiber provides the necessary spectral bandwidth for

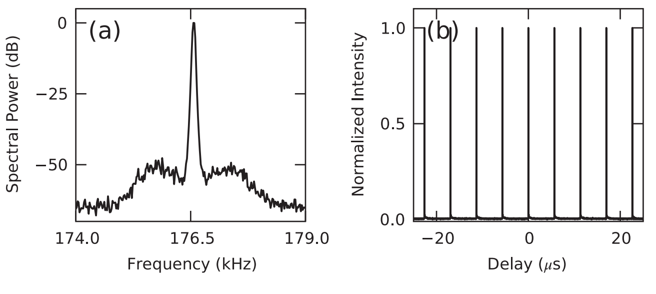

FIG. 5. RF spectrum (a) and pulse train (b) of the 1200 m laser.

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the pulse shaping action of the SWNT saturable absorber. In the steady-state mode-locking regime, this balances the dispersion of the pulse.[16,21] With the grating providing net anomalous dispersion, mode-locked operation, with an autocorrelation FWHM of 10.9 ps, is observed, as might reasonably be expected in the soliton regime.[17]

In conclusion, we demonstrated an all-normally dispersive Yb fiber ring laser mode-locked with a nanotube-PVA saturable absorber. Preselectable low-intensity noise pulses ranging from 20 ps to 2 ns with energies of up to 0.18 nJ, chosen by the laser cavity length, were generated. Stable mode-locking was achieved without any intentional spectral filters in the presence of strong normal dispersion, requiring no polarization evolution contribution. The mode-locked pulses were up to 750 times their transform limited duration, indicating an extreme chirp. The increased linear dispersion introduced into the cavity by the extra fiber is itself insufficient to explain the extreme pulse broadening, the additional nonlinearity of the extra fiber being required to maintain the giant-pulse mode-locking. Dechirping such giant-pulses requires a suitable means of compression. For shorter cavity lengths, producing subnanosecond mode-locked pulses, standard compression formats, such as photonic crystal fibers or bulk gratings, could be employed.

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