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500 fs wideband tunable fiber laser mode-locked by nanotubes

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ABSTRACT

Sub-picosecond tunable ultrafast lasers are important tools for many applications. Here we present an ultrafast tunable fiber laser mode-locked by a nanotube based saturable absorber. The laser outputs ~500 fs pulses over a 33 nm range at 1.5 μm. This outperforms the current achievable pulse duration from tunable nanotube mode-locked lasers.

1. Introduction

Ultrafast lasers are increasingly used in a wide range of applications, such as high speed telecommunications, ultrafast spectroscopy, laser surgery, and biomedical diagnostics [1–4]. Sub-ps lasers are especially crucial for applications requiring high temporal resolution, such as ultrafast spectroscopy to study excitation and relaxation processes and chemical reactions [2,3]. A sub-ps laser with wavelength tuning capability allows spectral-resolved investigation and is especially important for applications requiring resonant excitation [3], such as ultrafast photoluminescence [3]. Their advantages over free-space lasers, including compact and flexible geometry, high reliability and relaxed cooling requirements make mode-locked fiber lasers the focus of research in ultrafast pulse generation [5,6].

Semiconductor saturable absorber mirrors (SESAMs) have traditionally been used as saturable absorber (SA). However, SESAMs typically consist of a multiple quantum well structure grown by molecular beam epitaxy and require complex packaging [7–11]. Furthermore, SESAMs generally have a limited bandwidth (few tens of nm [7,11,12]), further limited by the need of distributed Bragg reflectors [11]. Single wall carbon nanotubes (SWNTs) [6,13–43] and graphene [6,44–50] have emerged as promising SAs, having fast recovery time [6,45], low saturation intensity [6,41–45], low cost and easy fabrication [6,44]. On the one hand, broadband operation can be achieved using a distribution of tube diameters [42]. On the other hand, this is an intrinsic property of graphene, due to the gapless linear dispersion of Dirac electrons [44–46,51,52].

Ref. [42] first demonstrated a tunable fiber laser mode-locked with SWNTs. However, the achieved output pulse duration, constrained by a 3 nm band-pass filter, was >2 ps [42]. Ref. [53] reported sub-ps pulses using an all-polarization maintaining fiber laser mode-locked by nanotubes. This approach requires a complex fabrication procedure [54], and has higher loss than traditional single mode fibers [54,55]. Here we report a 500 fs fiber laser mode-locked with SWNTs across a 33 nm range, using standard single mode fiber.

2. Experimental

The operation wavelength of SWNT-based saturable absorbers (SWNT-SA) is determined by the SWNT band-gap [6,42]. To match the operation wavelength of Erbium doped fibers (~1530–1560 nm), ~1.2 nm diameter SWNTs are required [56]. Therefore, we use SWNTs grown by laser ablation [57]. The SWNT-SA is fabricated as follows [6]: 2.7 mg SWNTs are ultrasonicated in 70 mg polymer in 10 ml de-ionized water using a tip sonicator (Branson 450A, 20 kHz) with ~50 W power for an hour in an ice bath. The dispersion is then centrifuged in a swing bucket rotor at 30,000 rpm (~72,000 g_{avg}) using a Beckman–Coulter Optima Max E centrifuge for 1 h. The top 60% dispersion is then decanted and drop cast in a Petri dish. Slow evaporation in a desiccator at room temperature and pressure results in a 30 μm thick SWNT–polymer composite film.

The laser (Fig. 1) consists of a cavity with 1.25 m highly doped Er-doped fiber (EDF), having a group delay dispersion (GDD) ~0.06 ps^2. This is pumped with a 980 nm laser diode coupled to the cavity with a wavelength division multiplexer (WDM), made of 1.8 m single mode fiber (Flexcor-1060) with GDD ~−0.013 ps^2. An isolator (ISO) ensures unidirectional operation. A tunable filter (TECOS, TFM) with a 12 nm passband is placed before the 20/80 output coupler, with the 20% port as the laser output. Following the output coupler is the SWNT-SA, and

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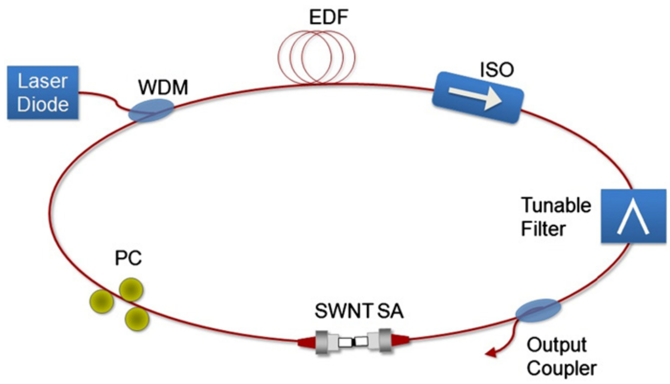

Fig. 1. Laser cavity layout, showing laser diode pump, erbium doped fiber (EDF), isolator (ISO), tunable filter, SWNT-saturable absorber (SWNT-SA), wavelength division multiplexer (WDM), polarization controller (PC).

a polarization controller (PC). The rest of the cavity is composed of single mode fiber (SMF-28) with GDD ~ -0.052 ps^2.

The laser is tuned by the bandpass filter, and the output is coupled to an optical spectrum analyzer (Anritsu, MS9710B) and a second harmonic generation (SHG) autocorrelator (APE, Pulse Check 50). To obtain information on the pulse train, the output is also coupled to a photodetector, an oscilloscope and radio frequency (RF) spectrum analyzer (Anritsu, MS2719B). Power dependent transmittance measurements are performed with a nanotube mode-locked $\sim$2 ps fiber source [42], tuned with a 3 nm bandpass filter amplified with an EDF amplifier.

3. Results and discussion

The tube diameter ranges from 1 to 1.4 nm, as determined by Raman spectroscopy [6], transmission electron microscopy (TEM) [57] and photoluminescence [6]. The corresponding band-gap is $\sim 0.7-1$ eV [56]. The absorption spectrum of the SWNT–polymer composite in Fig. 2 shows a peak $\sim$1568 nm, very close to the desired operation wavelength, in correspondence to the first transition of semiconducting SWNTs [56]. Another band $\sim$900 nm is seen, mainly due to the second and higher transitions [56]. The broad absorption, facilitating wide tunability, is due to the composite having a distribution of diameters.

From the power dependent transmission data (Fig. 3) the maximum transmittance at $\sim$400 MW cm^{-2} peak power is 56%. The modulation depth is 9–10%. Note that high modulation depth ($>10\%$) is typically requested for stable fiber laser mode-locking [13,58]. Higher SWNT concentrations are used to increase the modulation depth, but this also increases insertion losses. For example, the linear absorption at our designed operation wavelengths is $\sim$0.6 (Fig. 2), higher than the 0.2–0.5 previously reported for SWNT-SAs [6]. However, for fiber lasers the round trip gain is relatively high compared to bulk lasers, therefore higher insertion losses can be tolerated [6,39]. Fig. 3 shows that, although there is small variability in transmittance and modulation depth with wavelength, the SA properties remain similar across the tuning range. This contributes to the stability of mode-locking at all wavelengths.

Continuous-wave lasing starts at $\sim$4.6 mW pump power. The laser is self-starting for pump power $\geq$15.4 mW. At the edges of the filter (i.e. 1530 and 1563 nm), we need around 20 mW pump power to self-start mode-locking. This is because the filter has much higher insertion loss near the edges of its operation range. Also, our Er doped gain fiber has much less gain when operating out of its typical operation range (1530–1560 nm [55]).

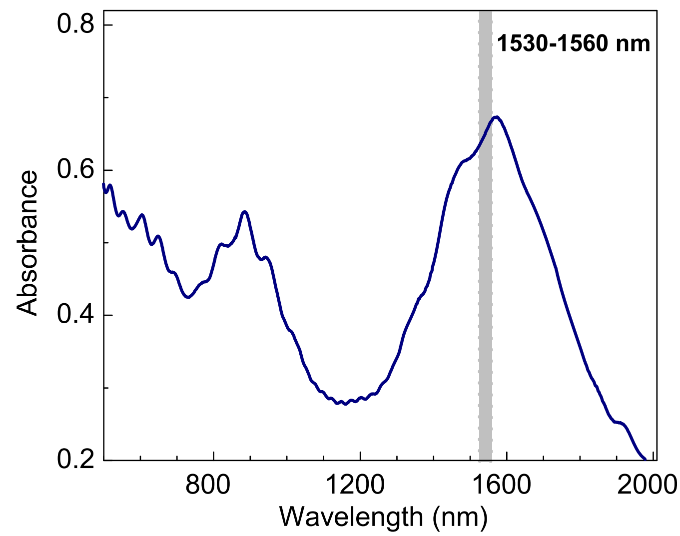

Fig. 2. Absorption spectrum of the SWNT composite. The desired operation wavelength range is marked.

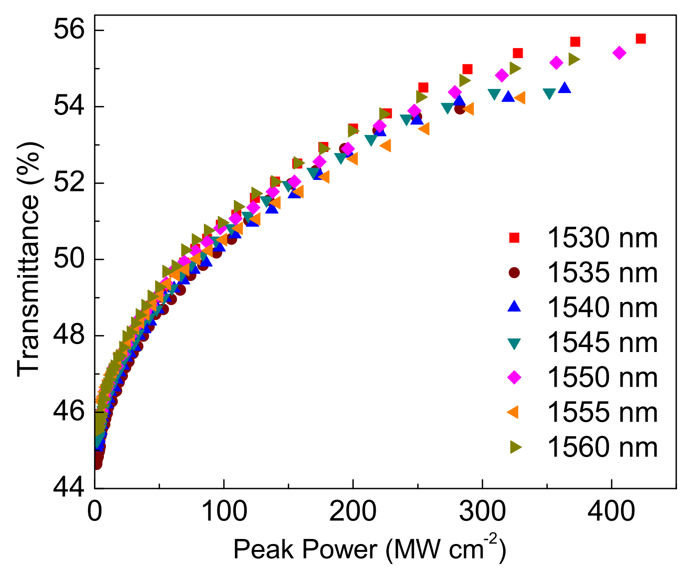

Fig. 3. Power dependent transmission of the SWNT-SA taken at different wavelengths within the tuning range.

Fig. 4(a) plots the output spectra. The laser can continuously operate over a 33 nm range ($\sim 1530-1563$ nm), just by tuning the filter, without the need to adjust pump power or any other parts of the laser. Autocorrelation traces of the output pulses at each tuned wavelength are presented in Fig. 4(b). Assuming a sech^2 temporal profile, we get that for all tuned peak wavelengths the output pulse is 537 $\pm$ 55 fs. The shortest pulse being 486 fs, at 1545 nm. The time-bandwidth product varies from 0.36 to 0.45, slightly higher than the 0.315 expected for transform-limited *sech*^{2} pulses [59], indicating the pulses are slightly chirped. Chirp-free pulses could be achieved by employing external dispersion compensation (e.g. using gratings) [55]. At the lowest output power, measured to average 1.72 mW at 1530 nm, the power incident on the SA is 197 MW cm^{-2}, calculated using the 19.88 MHz repetition rate, 493 fs measured pulse width, and a 10 μm core diameter. The highest output power is $\sim$2.72 mW, with a 567 fs pulse width, giving a peak incident power $\sim$270 MW cm^{-2}. Thus, throughout the entire tuning range, the incident power within the cavity is $\sim 2-3$ times the saturation power of the SWNT-SA, similar to other SWNT mode-locked fibre

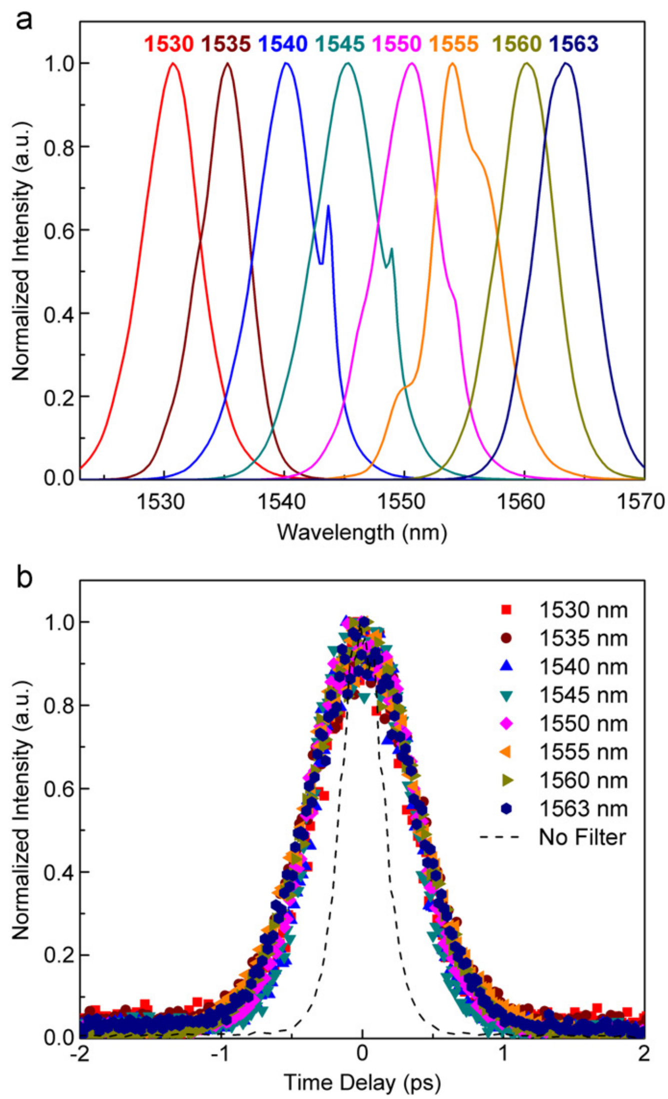

Fig. 4. (a) Output spectra with the laser tuned to various wavelengths; (b) corresponding autocorrelation traces.

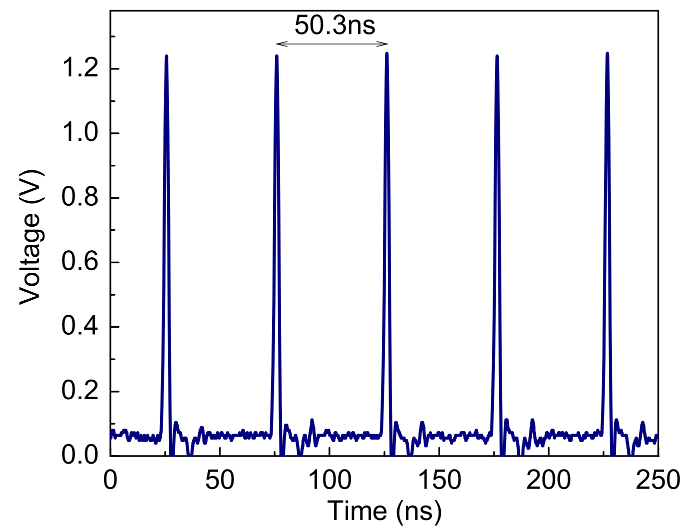

Fig. 5. Oscilloscope trace.

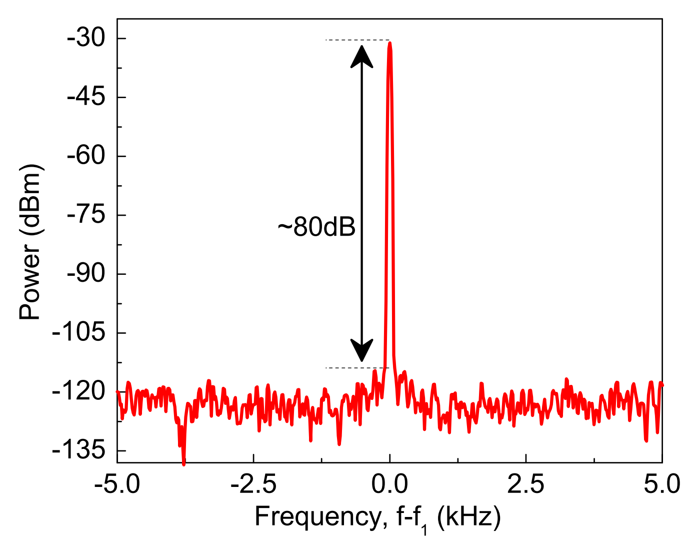

Fig. 6. RF spectrum of pulse train centered around first harmonic, $f_1 = 19.88$ MHz.

lasers [6,42]. Higher output power is possible by increasing the output coupler ratio [53], or evanescent field interaction [36].

Using a photodetector, the pulse train is captured by an oscilloscope, Fig. 5. The repetition rate of our pulses is ~ 19.88 MHz (period $\tau = 50.3$ ns). To study the operation stability, we measure the RF spectrum using a photodetector connected to a spectrum analyzer with 18 Hz resolution. The stability of mode-locking in the tuning range is also demonstrated by the ability to tune the pulse to a peak wavelength, while the laser remains mode-locked, as shown in Fig. 6. A signal-to-noise ratio >80 dB is observed, implying high stability of the output pulses. A similar performance is observed at the other wavelengths.

While the unfiltered laser has a spectral width $\Delta\lambda = 20.64$ nm, this becomes 5–7 nm when the filter is used. The output pulse spectral width of mode-locked lasers with an intracavity filter is roughly half the spectral width of the filter itself, which has a bandwidth of 12 nm. This fits well the suggestion of Ref. [8] that, in order to avoid having a filter limiting the spectral width, its bandwidth should be roughly twice the spectral width of the unfiltered pulse [8]. This would imply that for the spectral width in this laser not to be limited, the tunable filter would need at least a 40 nm pass-band in our experiments. With the spectral width unconstrained by the tunable filter, the output pulses spectral width could be as broad as without filters. The limiting effect of the filter is further demonstrated when it comes to pulse duration. As mentioned earlier, very short pulses are highly desirable and, although we demonstrated tunable 500 fs pulses, without the filter the pulse width is 220 fs. Thus, with a significantly wider filter (>40 nm) the pulse width of the laser could be halved.

4. Conclusions

We reported a widely tunable fiber laser mode-locked with nanotubes. This can produce stable pulses shorter than 500 fs in a tuning range of 1530–1563 nm. This demonstrates the ability of SWNT composites to mode-lock wideband sub-picosecond fiber lasers. Such tunable ultrafast light sources, only using single-mode fibers and standard telecom components, are ideal for applications such as metrology, spectroscopy, and biomedical diagnostics.

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