

500fs wideband tunable fiber laser mode-locked by nanotubes

R. Going¹, D.Popa¹, F. Torrisi¹, Z. Sun¹, T. Hasan¹, F. Wang¹, A. C. Ferrari¹¹Department of Engineering, University of Cambridge, 9 JJ Thomson Avenue, Cambridge, CB3 0FA, UK**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 33nm range at $1.5\mu\text{m}$. This outperforms the current achievable pulse duration from tunable nanotube mode-locked lasers.

Keywords:

Nanotubes, mode-locking, lasers, photonics

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, 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 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 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 3nm 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].

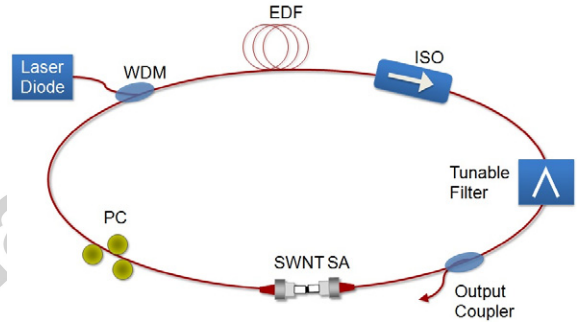


Figure 1: Laser cavity layout, showing laser diode pump, erbium doped fiber (EDF), isolator (ISO), tunable filter, SWNT-saturable absorber (SWNT-SA), wavelength division multiplexer (WDM), polarization controller (PC)

Here we report a 500fs fiber laser mode-locked with SWNTs across a 33nm 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]: 2.7mg SWNTs are ultrasonicated in 70mg polymer in 10ml 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 30,000rpm ($\sim 72,000g_{avg}$) using a Beckman-Coulter Optima Max E centrifuge for 1hr. 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 $30\mu\text{m}$ thick SWNT-polymer composite film.

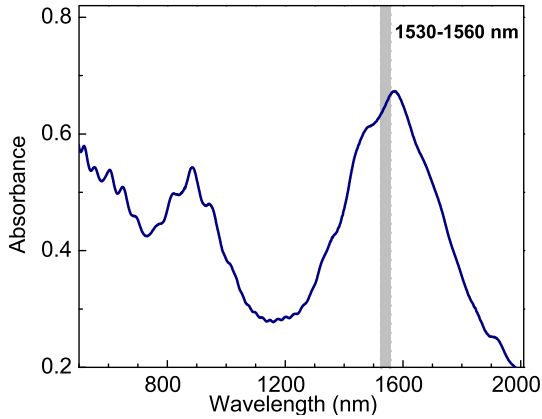


Figure 2: Absorption spectrum of the SWNT composite. The desired operation wavelength range is marked.

The laser (Fig. 1) consists of a cavity with 1.25m highly doped Er-doped fiber (EDF), having a group delay dispersion (GDD) $\sim 0.06\text{ps}^2$. This is pumped with a 980nm laser diode coupled to the cavity with a wavelength division multiplexer (WDM), made of 1.8m single mode fiber (Flexcor-1060) with GDD $\sim 0.013\text{ps}^2$. An isolator (ISO) ensures unidirectional operation. A tunable filter (TECOS, TFM) with a 12nm 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 a polarization controller (PC). The rest of the cavity is composed of single mode fiber (SMF-28) with GDD $\sim 0.052\text{ps}^2$.

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). 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 $\sim 2\text{ps}$ fiber source[42], tuned with a 3nm bandpass filter amplified with an EDF amplifier.

3. Results and Discussion

The tube diameter ranges from 1 to 1.4nm, as determined by Raman spectroscopy[6], transmission electron microscopy (TEM)[57] and photoluminescence[6]. The corresponding band-gap is $\sim 0.7\text{-}1\text{eV}$ [56]. The absorption spectrum of the SWNT-polymer composite in Fig.2 shows a peak $\sim 1568\text{nm}$, very close to the desired operation wavelength, in correspondence to the first transition of semi-conducting SWNTs[56]. Another band $\sim 900\text{nm}$ 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.

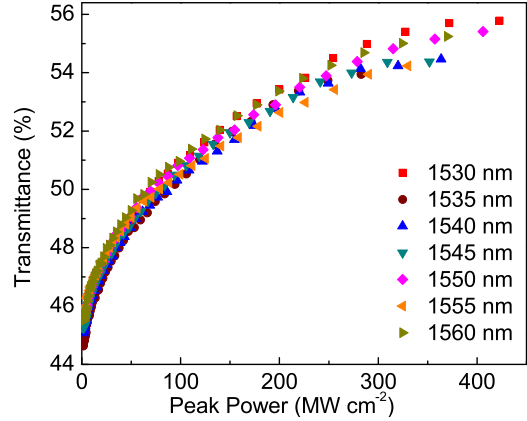


Figure 3: Power dependent transmission of the SWNT-SA taken at different wavelengths within the tuning range

From the power dependent transmission data (Fig.3) the non-saturated transmittance is $\sim 56\%$. 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 ~ 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 $\sim 4.6\text{mW}$ pump power. The laser is self-starting, for pump power $\geq 15.4\text{mW}$. While at the edges of the filter (i.e. 1530 and 1563nm), we need around 20mW pump power to self-start mode-locking. This is because the filter has much higher insertion losses 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 to 1560nm[55]).

Fig.4(a) plots the output spectra. The laser can continuously operate over a 33nm range ($\sim 1530\text{-}1563\text{nm}$), just by tuning the filter, with no need to adjust pump power, nor 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 $537 \pm 55\text{fs}$. The shortest pulse being 486fs, at 1545nm. 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 1.72mW at

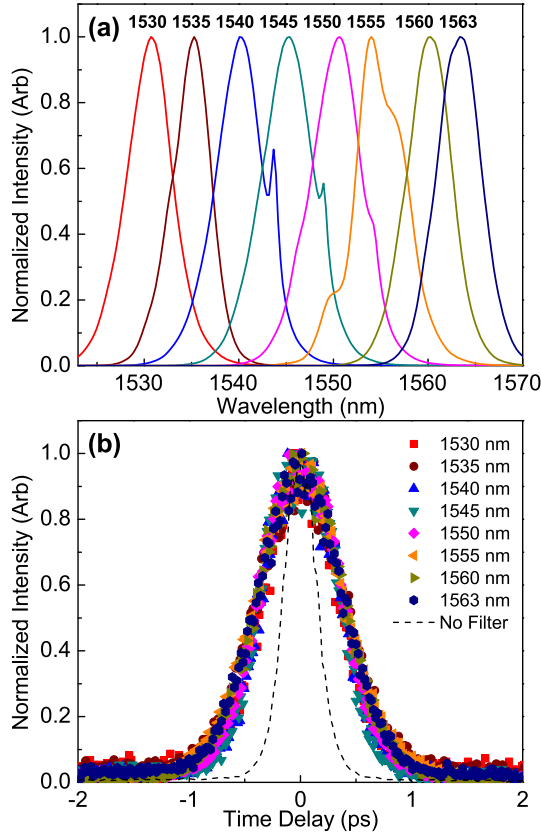


Figure 4: (a) Output spectra with the laser tuned to various wavelengths; (b) corresponding autocorrelation traces

1530nm, the power incident on the SA is 197MWcm^{-2} , calculated using the 19.88MHz repetition rate, 493fs measured pulse width, and a $10\mu\text{m}$ core diameter. The highest output power is $\sim 2.72\text{mW}$, with a 567fs pulse width, giving a peak incident power $\sim 270\text{MWcm}^{-2}$. Thus, throughout the entire tuning range, the incident power within the cavity is ~ 2 -3 times the saturation power of the SWNT-SA, similar to other SWNT mode-locked fibre 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 $\sim 19.88\text{MHz}$ (period $\tau=50.3\text{ns}$). To study the operation stability, we measure the RF spectrum using a photodetector connected to a spectrum analyzer with 18Hz 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 $>80\text{dB}$ 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 $\Delta\lambda=20.64\text{nm}$, when the filter is used this becomes 5-7nm. The output pulse spectral width of mode-locked lasers with an

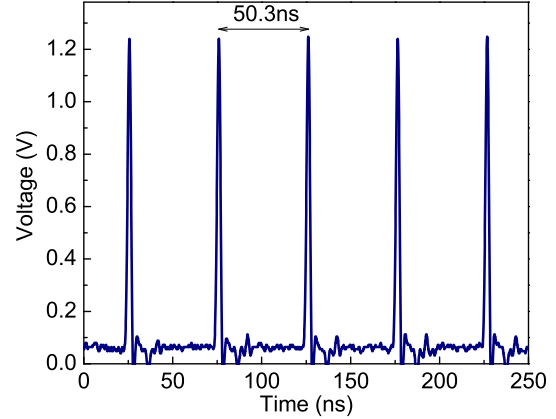


Figure 5: Oscilloscope trace.

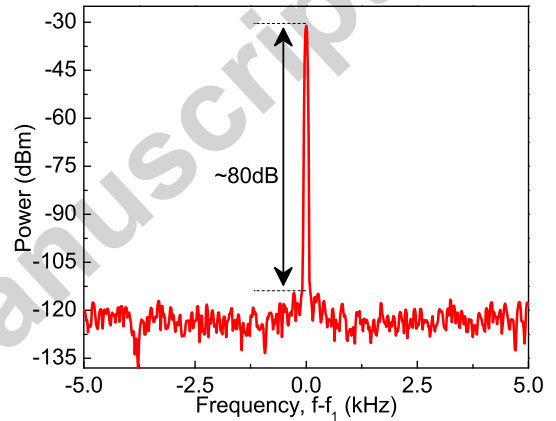


Figure 6: RF spectrum of pulse train centered around first harmonic, $f_1=19.88$ MHz.

intracavity filter is roughly half the spectral width of the filter itself, which has a bandwidth of 12nm. This fits well the suggestion of Ref.[8] that, in order to avoid having a filter limit 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 40nm 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 500fs pulses, without the filter the pulse width is 220fs. Thus, with a significantly wider filter ($>40\text{nm}$) 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 500fs in a tuning range of 1530-1563nm. 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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