CW-pumped short pulsed 1.12 μm Raman laser using carbon nanotubes

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We demonstrate passive mode-locking of a Raman fiber laser at 1.12 μm, using a nanotube-based saturable absorber. A regular train of pulses, with a duration of 236 ps at the fundamental repetition frequency of the cavity, are generated by the all-normal dispersion cavity. Importantly, this simple system is pumped with a continuous wave Yb fiber laser, removing the need for complex synchronous pumping schemes, where pulse-shaping depends on the action of the saturable absorber and a balance of dissipative processes. These results illustrate the flexibility of combining Raman amplification with a nanotube-based absorber for wavelength versatile pulsed sources.

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1. Introduction

Passive mode-locking of fiber lasers is a reliable and well-developed technique to generate short pulses in simple and compact schemes [1]. Whereas optical cavities with anomalous dispersion can take advantage of soliton pulse shaping to generate transform-limited pulses [2], an overall normal dispersion can be used to generate pulses in the so-called dissipative soliton regime [3, 4], with durations up to nanoseconds due to a strong chirp created by the intra-cavity pulse propagation dynamics [3, 4]. Lasers operating in the dissipative soliton regime are at the center of an ever increasing research field [5–8], because this is an effective solution to expand the achievable pulse energy from mode-locked fiber lasers [6].

In principle, mode-locking can be achieved at any wavelength. However, there are several practical constraints to generate short-pulses at wavelengths where no gain media are available [1]. This is particularly true for wavelengths not covered by rare-earth doped elements, such as Yb, 1.06 μm, and Er, 1.55 μm, by far the most used in fiber lasers. Another difficulty is that typical saturable absorbers (SAs) used in mode-locking, such as semiconductor saturable absorber mirrors (SESAMs), do not provide broadband absorbance in a single device, being limited to narrow spectral regions, usually not broader than a few tens nanometers [9]. Carbon nanotubes (CNTs) [10–17] and graphene [17–23] have recently emerged as viable SAs, due to their low fabrication cost [17, 18], sub-picosecond recovery time [17, 18], broadband operation [12, 20], low saturation power [12, 19], polarization insensitivity [17, 18] and environmental robustness [19–21]. Broadband operation is achieved in CNTs using a distribution of tube diameters [12, 17], while this is an intrinsic property of graphene, due to the linear dispersion of Dirac electrons [18–20].

The development of a wavelength versatile mode-locking device is necessary to realize a concept of a universal short-pulse laser sources. An attractive candidate is the combination of Raman amplification with CNTs and graphene in a fiber oscillator. Raman gain is a nonlinear amplification scheme [24]: a signal at the Stokes-shifted wavelength experiences amplification by stimulated Raman scattering [25]. Raman gain can be achieved over the whole silica transparency window (300-2200 nm) [24]. Although a pump laser is required [24], this is not necessarily a wavelength limitation, as the Raman process can be efficiently cascaded many times [26].

Ref.10 combined Raman gain with CNTs in a mode-locked laser. An oscillator pumped by a high power continuous-wave (CW) Er laser produced picosecond pulses at 1666 nm [10]. However, since the main attractive feature of using Raman gain is its wavelength versatility [24], it is imperative to extend our previous results to other regions of the spectrum, where the difference in parameters, such as Raman gain and dispersion, could potentially lead to dissimilar behavior. Yb-doped fiber lasers are one of the most common fiber sources due to various advantages (e.g. wide-absorption bandwidth, high-efficiency) [27]. They can generate up to few tens of kWs [28], with potential for high-power Raman lasers. Here, we demonstrate a Raman oscillator pumped by a high-power CW Yb-doped fiber laser, mode-locked by CNTs. An all-fiber configuration with all-normal dispersion is used, generating dissipative solitons at 1120 nm.

2. Experimental Setup

To match the operation wavelength ($\sim$1.1 μm) of the Raman laser pumped with a Yb-doped fiber laser, we require CNTs whose lowest excitonic transition energy (eh_{11}) is $\sim$1.1 eV [17]. Thus, an absorption peak centered $\sim$1.1 μm [28], would maximize the change in absorption due to saturation [17]. Commercially available CoMoCAT CNTs (Southwest Nanotechnologies, Batch CAU-A002) with ∼0.75-0.8 nm diameter are ideal for this [29]. The CoMoCAT sample we use predominantly consists of (6,5), (7,5) and (7,6) tubes, as determined by Raman spectroscopy [30], transmission electron microscopy [31] and Photoluminescence Excitation spectroscopy [32]. The diameter range for these chiralities is ∼0.75-0.9 nm, corresponding to a ∼1-1.3 eV gap [31]. The CNT saturable absorber (CNT-SA) is fabricated using solution processing [17]. 2 mg of CNTs are sonicated in 20 ml deionized water for 2 hr at 10-12 °C. The CNT dispersion is then centrifuged at 20,000 g using a MLA-80 fixed-angle rotor (Beckman) for 2 hr, and the top 70% decanted to obtain an aggregation-free CNT dispersion. This is then mixed with polyvinyl alcohol (PVA) in de-ionized water with a homogenizer and drop cast in a Petri dish. Slow evaporation at room temperature in a desiccator yields a ∼50 μm CNT-PVA composite. Its absorbance is plotted in Fig.1. This shows a peak ∼1170 nm, close to the desired operation wavelength of 1120 nm, corresponding to eh_{11} of (7,6) tubes (∼0.895 nm diameter) [31]. Another peak ∼1028 nm is also seen, due to (6,5),(7,5) CNTS with 0.757, 0.829 nm diameter [31].

The laser setup (Fig.2), consists of a high-power CW Yb-laser operating at 1070 nm coupled by a pump combiner into the cavity in a counter-propagating geometry. The active medium is a 60 m GeO_2-doped highly-nonlinear single-mode-fiber from OFS. The fiber has normal dispersion at both pump (1070 nm) and Stokes wavelength (1120 nm). An isolator ensures unidirectional propagation. After the 60 m fiber, two wavelength division multiplexers (WDMs) extract undepleted pump light from the cavity to prevent damage to other passive optical components. A polarization controller allows fine tuning of the birefringence. The CNT-SA is integrated into the cavity between a pair of fiber connectors. Light is extracted from the cavity by a 5% output coupler. The cavity output is then amplified in another Raman amplifier using 400 m of the same fiber used as the gain media inside the cavity. The residual pump power extracted from the cavity is used as a counter-pump for the external amplification, enhancing the overall conversion efficiency of the laser. A beam splitter is used after the cavity output in order to have direct access to the pulse parameters before the amplification stage.

3. Results

Self-starting stable single pulse per round trip operation is achieved for pump power above the threshold value of 6.87 W. The presence of CNTs in the system is a necessary condition to obtain pulsed outputs. Their absence causes the laser to operate in the CW regime. Fig.3(a) plots the oscilloscope trace at the amplified output and its optical spectrum. The pulse width is 236 ps, with an average power of 2.6 mW and a repetition rate of 2.87 MHz. The 3 dB bandwidth of the spectrum is 0.7 nm, Fig.3(b). Its square shape is typical of dissipative solitons [3,5,6]. The pulse and spectrum shape before the external amplification are exactly the same, the only main difference accounts for the optical power which is -13 dBm (0.05 mW).

In order to show temporal coherence on the laser output, the autocorrelation trace of the pulses is shown on Fig.4(a). The 60 ps window of the autocorrelator does not allow to resolve the entire pulse, however the absence of a spike on the top of a pedestal is an clear indication that the laser is indeed mode-locked, and it is not just a burst of noise [1]. The natural technique to show coherence would be to temporally compress the pulse by means of anomalous dispersion, showing that the pulses are positively chirped [1]. However, to the best of our knowledge, there is no standard fiber with anomalous dispersion at 1120 nm. The pulse has a time-bandwidth product of 26.2, highlighting the larger chirp of the output pulses; 8.4 km of a photonic crystal fiber (PCF) with dispersion of 40 ps nm^{-1} km^{-1} at 1120 nm would be needed to fully compensate the chirp, assuming it is linear across the pulse, making this approach impractical, given the current technology limitations. Fig.4(b) plots the radio-frequency (RF) spectrum of the central peak and as an inset the first ten harmonics are shown. The trace centered at 2.87 MHz corresponds to one cavity round trip, and it presents no significant pedestal on a span of 1 MHz, with a noise floor ~31 dB (a 10^3 contrast) down from the peak.

Mode-locking is still achieved under a pump power of 7.52 W, when the pulses break down. After external amplification, both pulse duration and output power increase by increasing pump power, which is shown in Fig.5. Under 7.52 W pumping, average powers of 59 mW can be achieved, giving pulse energies of approximately 20 nJ and peak powers of 13.8 W.

4. Conclusion

In conclusion, we demonstrated a passively mode-locked Raman laser using CNTs at 1120 nm. This operates in the dissipative soliton regime generating 236 ps pulses at the fundamental repetition frequency of the cavity. Our ultrafast laser at 1.1 μm, pumped with a Yb fiber laser, showcases the flexibility in terms of output power and wavelength of the combination of CNT based saturable absorbers and Raman amplification. Such a technique can become an interesting source of high-power and wavelength versatile short-pulses in simple and compact all-fiber configurations, and could be further extended to the visible region.

4.A. Acknowledgments

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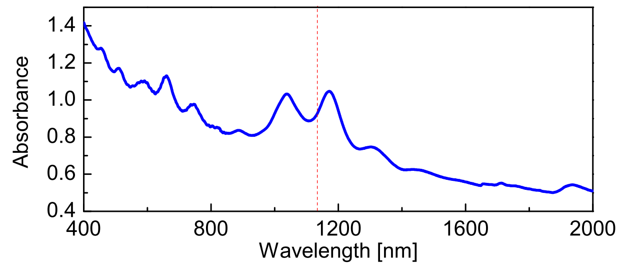
List of Figure Captions

Fig. 1. Absorbance of our CNT-SA. The desired operation wavelength is marked.
Fig. 2. Experimental setup. HNLF, Highly nonlinear fiber; SWCNT, Single-wall carbon nanotube saturable absorber; PC, polarization controler; Iso, Isolator; PE, Pump extractor; BS, Beam splitter.
Fig. 3. (a) Oscilloscope trace of the pulse at the output of the cavity. (b) Optical spectrum.
Fig. 4. (a) Expanded autocorrelation trace. (b) Radio-frequency (RF) trace.
Fig. 5. Pulse duration and output power on the amplified output against pump power.

Figures



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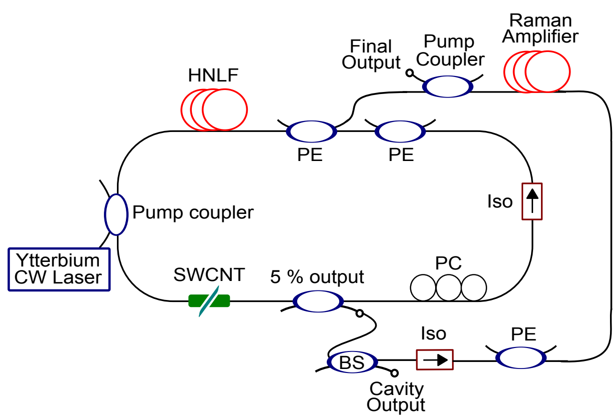

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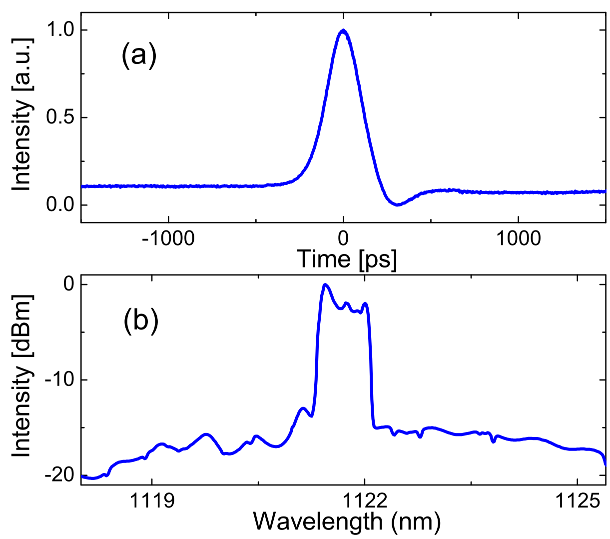

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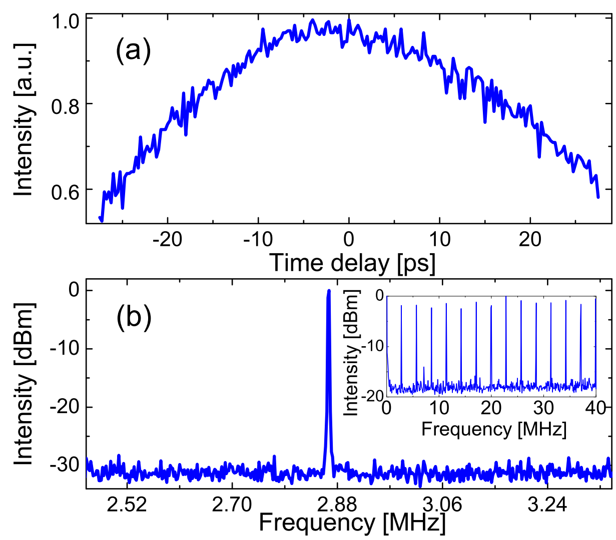

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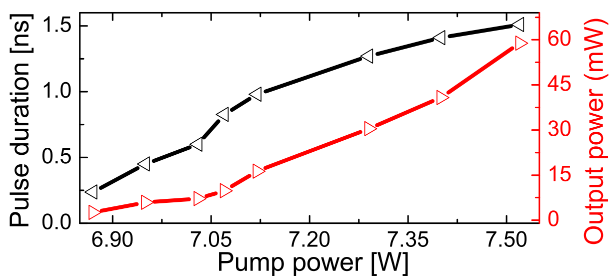

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