Nanotube-based passively mode-locked Raman laser

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Abstract: We demonstrate passive mode-locking of a Raman fiber laser using a nanotube-based saturable absorber. The normal dispersion cavity generates highly-chirped 500 ps pulses that are compressed down to 2 ps, with 1.4 kW peak power.
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1. Introduction

Mode-locked lasers have been widely deployed in time-resolved studies for nearly fifty years [1]. While many mode-locking approaches exist, allowing an extensive range of pulse durations and energies to be achieved, passive techniques are particularly attractive because of their inherent simplicity and associated lower costs of production [2]. Over the past two decades passively mode-locked fiber lasers have been extensively refined and developed. However these systems have almost exclusively been based on rare-earth doped gain media, consequently presenting limited operational bandwidths. Raman based amplification is attractive to overcome this spectral limitation since Raman gain is available at any wavelength across the transparency window of the medium (300 nm – 2300 nm), provided a suitable pump source is available [3].

There have been a number of reports utilising Raman gain in an ultrashort pulse source [4-7], however to date none of these systems have reached a level of performance comparable with state-of-the-art rare-earth based lasers. Availability of a broadband saturable absorber to achieve mode-locking at any desired wavelength across the transmission window of silica is an essential pre-requisite to fully exploit the flexibility of Raman as a gain medium in ultrashort pulsed sources across the visible and near infrared. Recent interest in the application of nano-materials, in particular carbon nanotubes (CNT) and graphene, as saturable absorbers in mode-locked lasers allow us to move a step closer to a fully universal device [8-17]. Here, we report a passively mode-locked laser combining both Raman gain and a nanotube-based saturable absorber in a normally dispersive cavity, confirming the potential of this flexible approach.

2. Experimental setup

The all-fiber geometry is in Fig. 1. The cavity consists of 100m single-mode speciality optical fiber (OFS Raman Fiber), with an enhanced germanium oxide (GeO) concentration for an increased Raman gain (2.5 $W^{-1}km^{-1}$), core pumped through a wavelength-division multiplexer (WDM) by a continuous-wave (CW) 15 W Er amplified spontaneous emission (ASE) source at 1555 nm wavelength, with no need of synchronous pumping.

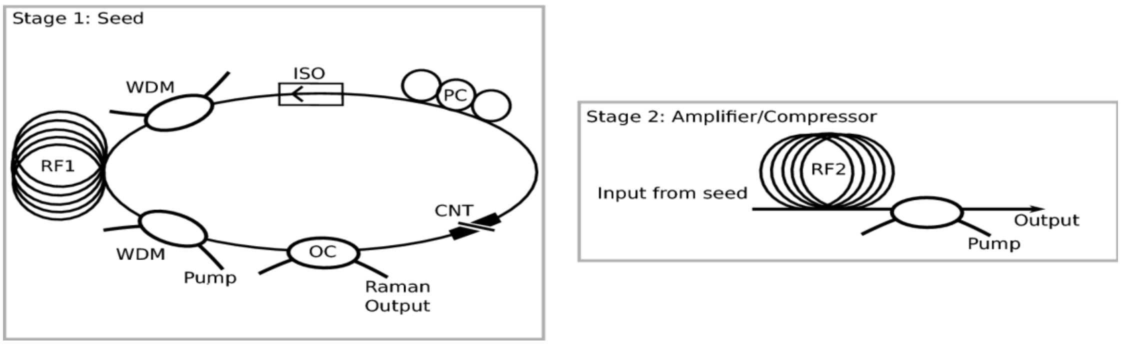

Fig. 1. Experimental setup. RF1, Raman fiber 1; RF2, Raman fiber 2; ISO, polarization- insensitive inline optical isolator; WDM, wavelength division multiplexer; PC, polarization controller; CNT, carbon nanotube saturable absorber; OC, output coupler.

Self-starting mode-locked operation is initiated and maintained by a saturable absorber interface formed by a ~30 μm CNT-polymer composite integrated into the cavity between a pair of fiber connectors. A polarization insensitive inline optical isolator and fiber-based polarization controller stabilize the mode-locking. Light is extracted from the unidirectional cavity through a 5% coupler. In order to prevent high-levels of un-depleted pump power damaging the passive cavity components, a second WDM couples out residual pump light.

The normal dispersion of the Raman active fiber resulted in a net normal dispersion cavity, operating at the first Stokes order of 1666 nm from a pump at 1555 nm. Such systems, with large normal dispersion, have been shown to support highly linearly chirped pulses [10], therefore being suitable for compression. A second, 10km long Ge-doped fiber with a zero dispersion wavelength (ZDW) at 1320 nm, was used as a combined amplifier and compressor. The residual pump dumped out of the seed oscillator was used to counter-pump the Ge-doped fiber for a compact GCO-type master-oscillator power fiber amplifier (MOPFA) solution.

3. Results

The first stage seed oscillator produces chirped 500 ps pulses with -11 dBm average output power, with a single pulse per round trip. The fundamental repetition rate is 1.72 MHz, defined by the cavity round trip time. After the second stage the pulses are compressed to 2 ps and amplified to 7 dBm. The autocorrelation function, fitted with a $sech^2$ shape, of the compressed pulse, and the spectrum before and after the compression are in Fig. 2.

The spectra have a square shape, characteristic of dissipative solitons supported by a normally dispersive cavity [10]. Both spectra have a -3 dB bandwidth of ~1.6 nm. Moreover, the spectral shape is preserved, indicating linear compression. The peak power of the compressed pulse after 18 dB amplification is 1.4 kW. Scalability of peak power to higher levels should be possible by decoupling the amplifier from the compressor.

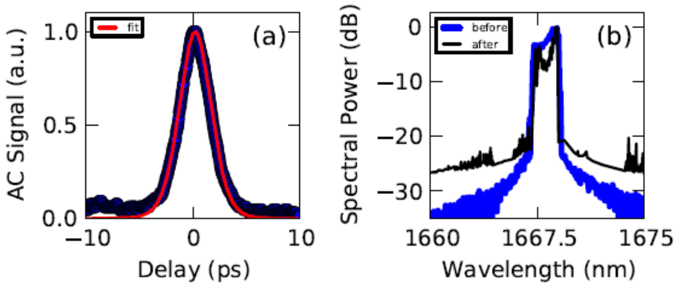

Fig.2. (a) Autocorrelation of the compressed optical pulse. (b) Corresponding spectra, before and after the combined compression/amplification stage.

4. Conclusions

We have demonstrated an all-fiber passively mode-locked Raman laser utilizing a nanotube-based saturable absorber. The oscillator was formed from a cavity with dominant normal dispersion, allowing the generation of high energy pulses, up to ~3 nJ after amplification. This system confirms the potential of combining Raman gain and a nanotube-based saturable absorber, for the development of flexible ultrashort pulse sources across the transparency window of silica fiber.

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