Letter of Significance

This paper presents the first demonstration of passively mode-locked lasers based on a novel saturable absorber incorporating carbon nanotubes (SAINT). This device offers several key advantages over the conventional semiconductor saturable absorber mirror (SESAM) such as: ultra-fast recovery time (<1ps), polarization insensitivity, exceptionally high optical damage threshold, mechanical and environmental robustness, chemical stability, and the ability to operate both in transmission, reflection and bi-directional modes. Moreover, the fabrication cost and complexity of SAINT devices are potentially much lower than that of the conventional SESAM devices. Therefore, we expect that SAINT will greatly impact future pulsed laser design and development, revolutionizing this industry.

Mode-locked Fiber Lasers based on a Saturable Absorber Incorporating Carbon Nanotubes

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Abstract: A novel passively mode-locked fiber laser is demonstrated using saturable absorber based on single-walled carbon nanotubes. This is the first demonstration of an optical pulsed laser based on carbon nanotube technology.

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1. Introduction

Optical pulsed lasers offer a broad-range of applications in various fields, such as optical communications, optical signal processing, two-photon microscopy, laser surgery etc. Passively mode-locked fiber lasers are amongst the best pulsed sources available today due to their simplicity and their ability to generate transform-limited optical pulses in the picosecond and sub-picosecond regimes [1][2]. Such lasers offer superb pulse quality and there is no need for costly modulators as required in actively mode-locked lasers. Instead, a passively mode-locked fiber laser employs a mode-locker, a device that possesses an intensity-dependent response to favor optical pulse formation over continuous-wave lasing. This is usually a fast saturable absorber, such as a semiconductor saturable absorber [3,4], or an “effective” saturable absorber, such as a nonlinear polarization switch [5], a nonlinear optical loop-mirror [6] (NOLM) and its variants [7,8]. Amongst these mode-lockers, the semiconductor-based multi-quantum-well (MQW) device, commonly referred as the semiconductor saturable absorber mirror (SESAM) [3], has become the main device used in almost all commercial passively mode-locked fiber lasers.

SESAMs require complex and costly clean-room-based fabrication systems such as MOCVD, MOVPE or MBE to grow, and may require additional substrate removal process. Furthermore, high-energy heavy-ion implantation is required to reduce the device recovery time (typically a few nanoseconds) to a few picosecond for laser mode-locking applications. Since SESAM is a reflective device, its use is restricted to only certain types of linear cavity topologies. Other laser cavity topologies such as the ring-cavity design, which require a transmission-mode device, is not possible unless an optical circulator is employed, which increases cavity loss and laser complexity making it costly and impractical. Additionally, SESAM may require expensive hermetic packaging for long-term environmental stability, and may suffer from a rather low optical damage threshold. So far, there are no alternative saturable absorbing materials to challenge the SESAMs for the passive mode-locking of fiber lasers. We propose and demonstrate a carbon-nanotube-based saturable absorber for passive mode-locking of fiber lasers.

In this paper, we present, for the first time, passively mode-locked fiber lasers using a device we call “Saturable Absorber Incorporating NanoTube” (SAINT) as a mode-locker. We demonstrate picosecond fiber lasers in both linear- and ring-configurations using a SAINT in transmission- and reflection-mode, respectively. These first results confirm the potential of a SAINT for laser mode-locking applications with performance comparable to that of a conventional SESAM.

2. Device Fabrication

The SWNTs were grown using the laser ablation technique [9]. High energy laser pulses from a Nd:YAG laser were used to ablate a metal catalyzed carbon target placed in a quartz tube filled with 500 Torr of Ar gas. The quartz tube was heated in an electric furnace. The optical absorption characteristics of SWNTs are related to the tube diameters. By careful control of the furnace temperature and the adoption of specific catalysts with appropriate relative concentrations, diameter-selective SWNTs can be grown [10]. Through a series of purifying processes, high purity semiconductor carbon nanotubes were obtained with the S1 absorption band located at ~1680nm (Fig. 1a), corresponding to a gap energy of 0.738eV and a mean nanotube diameter of ~1.1nm, according to the Kataura plot [11]. The AFM image (Fig. 1b) shows meshes of SWNT ropes with a bundle diameter ~20nm. Further TEM image (Fig. 1c) on one of the bundles reveals each SWNT strains with diameter indeed of around 1nm.

The construction of a SAINT is shown in the inset of Fig. 2. A thin layer of purified SWNTs with thickness ~1ìm was sandwiched between two 1mm-thick quartz substrates, which were anti-reflection (AR) coated on the outer surface.

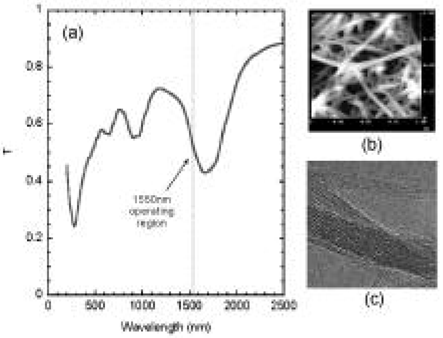

Fig.1 (a) Transmittance, (b) AFM and (c) TEM.of SWNTs.

3. Experiments and Results

The schematics of the mode-locked fiber ring laser are shown in Fig. 2. A length of erbium-doped fiber (EDF), backward pumped by a 980nm laser diode (LD), is used as the laser gain medium. Two optical isolators are inserted to prevent back-reflection in the cavity and to ensure unidirectional operation. The output light from the EDF is launched through a fiber collimator and a focusing aspherical lens onto the SAINT. The output light from the SAINT is collected and launched back into the fiber cavity via another set of matching aspherical lens and collimator. An angle-tunable thin-film bandpass filter with 7nm bandwidth is inserted for wavelength tuning. A short length of single-mode fiber (SMF) is used for pulse shaping. The output of the laser is tapped through a 95% port of a fiber coupler, whereas the other 5% port is used to feed back into the cavity.

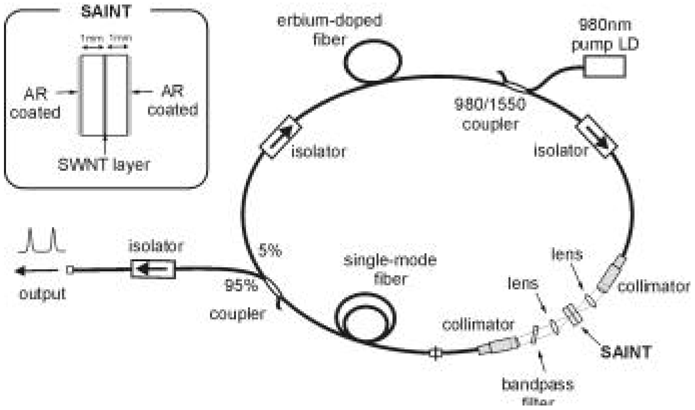

Fig. 2. Schematics of the mode-locked fiber laser in ring configuration.

With a pump power of around 18mW, the laser starts to mode lock and produce multiple pulses in a round trip time. After that, the pump power can be reduced to a level around 14mW and the laser will maintain pulsing in single-pulse mode at a fundamental repetition rate of 6.1 MHz. The output average optical power is about –5.8 dBm. At higher pump powers, the laser will operate in multiple-pulse mode resulting in a higher-harmonic repetition rate at the multiple of the fundamental round trip frequency. The output spectrum and SHG autocorrelation trace of the output mode-locked pulses are shown in Fig. 3a and 3b, respectively. The autocorrelation trace and spectrum are well fitted by a sech^2 pulse profile, indicating that soliton pulses are generated. The inferred full-width half-maximum (FWHM) width from the autocorrelation trace is estimated to be 1.1 psec, whilst the 3-dB spectral width is ~ 3.7 nm. The resulting time-bandwidth product of 0.52 indicates that the pulses are chirped. This could be caused by the 5m-length of SMF on the coupler and isolator. By using low dispersion fiber at the output, it is possible to reduce the chirp in the pulses. The laser has very little polarization sensitivity even without the use of polarization maintaining (PM) fiber or any other means of polarization control. When the SAINT is removed from the laser cavity, it is not possible to mode-lock the laser even with 100mW of pump power. It is evident that the SAINT provides the mechanism required to initiate and sustain mode-locking operation, particularly at a very low threshold pump power.

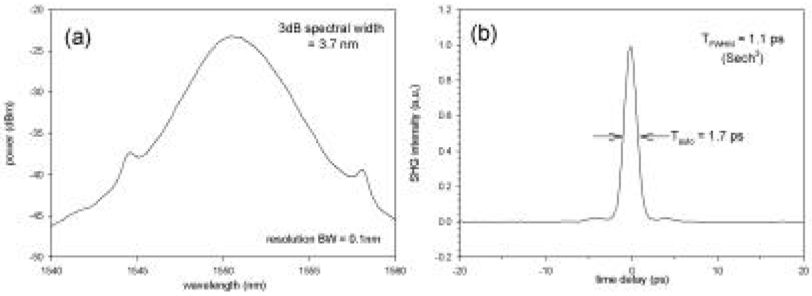

Fig. 3. Ring laser output: (a) Spectrum, and (b) SHG autocorrelation trace..

FIG. 4 shows the fiber laser in a linear resonator configuration. All the components have their usual functions as described earlier. At one end of the cavity a Faraday mirror is used to compensate for birefringence in the cavity. A reflective-SAINT (R-SAINT) is employed at the other end of the cavity. In the R-SAINT structure, the SWNT layer is deposited on a high-reflection (HR) coated surface of a quartz substrate, sandwiched by another AR-coated substrate. Two lenses are employed to focus the incident beam into a tiny spot on the R-SAINT. In order to maximize the gain bandwidth, an optical bandpass filter is not used. The laser center wavelength is defined by the EDF's gain profile. Pulse shaping SMF is not inserted in the cavity intentionally, to remove soliton effects.

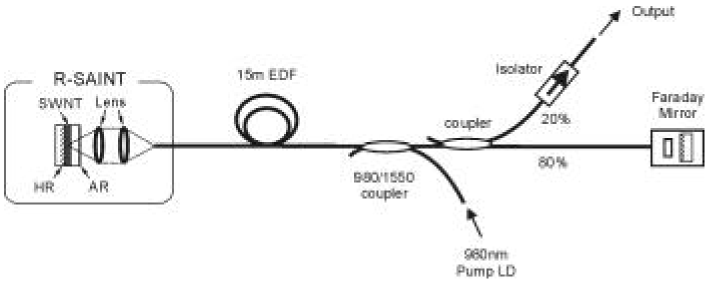

Fig. 4. Linear cavity configuration employing a reflective-SAINT.

The output pulses of the linear laser operate at a fundamental cavity repetition rate of 9.85MHz. The output spectrum of the pulses is shown in Fig. 5a, with a 3-dB spectral width of 13.6 nm. The spectral shape is following a Gaussian profile as expected, due to the absence of soliton pulse shaping. The laser is mode-locked solely by the saturable absorbing effect. Fig. 5b shows the SHG autocorrelation trace of the mode-locked pulses with an inferred FWHM width of 318 fs (Gaussian). The time-bandwidth product is 0.54, compared to an unchirped transform limited value of 0.441. The output average power is nearly at 1 mW, when pumped with 25mW of pump power.

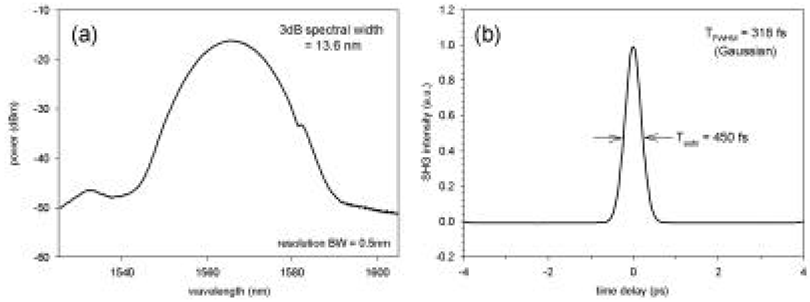

Fig. 5. Linear-cavity laser output: (a) Spectrum, and (b) SHG autocorrelation trace.

4. Conclusion

We have demonstrated for the first time, optical pulse lasers employing novel saturable absorbers based on carbon nanotube technology as mode-lockers. The Saturable Absorber Incorporating NanoTubes (SAINT) offers several advantages such as: ultra-fast recovery time (<1ps), polarization insensitive, exceptionally high optical damage threshold, mechanically and environmentally robust, chemical stability, and the ability to operate both in transmission, reflection and bi-directional modes. Moreover, the fabrication cost and complexity of SAINT devices are potentially much lower than that of the conventional SESAM devices. The SAINT is expected to greatly impact future pulsed laser design and development.

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