Double-wall carbon nanotube Q-switched and mode-locked two-micron fiber lasers

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Abstract: We fabricate double-wall carbon nanotube polymer composite saturable absorbers and demonstrate stable Q-switched and Mode-locked Thulium fiber lasers in a linear cavity and a ring cavity respectively.

OCIS codes: (320.7090) Ultrafast lasers; (160.4330) Nonlinear optical materials

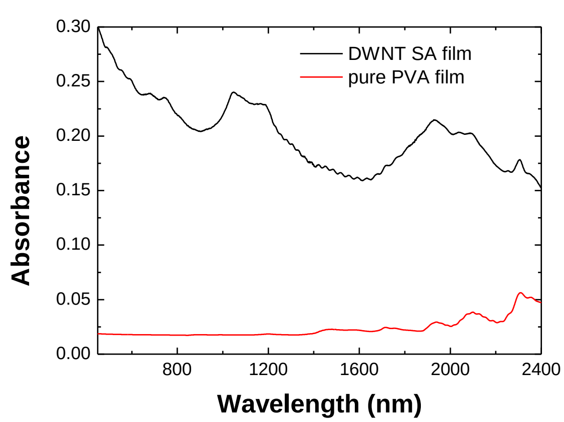
1. Introduction

Q-switched and mode-locked lasers operating in the eye-safe two-micron spectral range are useful for a number of applications, including material processing, laser range finding, environmental sensing, and surgery [1-4]. Thulium (Tm)-doped silica fibers are a promising two-micron gain media. They exhibit high quantum efficiency as well as a broad gain spectrum extending from 1.8 to 2.1 μm [5]. They are becoming an important platform for constructing compact two-micron pulsed laser sources [5]. Both carbon nanotubes (CNTs) and graphene are promising saturable absorbers for fiber lasers [6-14]. They have key advantages such as ultrafast recovery time and wide operating bandwidth, which make them excellent candidates for mode-locking long-wavelength lasers [15, 16]. One species of CNTs, namely double-wall carbon nanotubes (DWNTs) have recently draw attention as they possess many of the advantages offered by single-wall nanotubes [17]. In addition, when the inner wall and outer wall diameters fall within 0.8-1.1nm and 1.6-1.8nm respectively, these DWNTs can offer wide absorption bands at ~ 1.0 and 2.0 μm, making them a suitable saturable absorber across 1.0 – 2.0 μm [17].

Here, we fabricate DWNT composite saturable absorbers, featuring a broad absorption band covering 1.8-2.1μm. The absorption peak is further shifted into the two-micron region compared to single-wall carbon nanotubes [15]. Based on the DWNT SA, we demonstrate both Q-switched and Mode-locked Tm fiber lasers. For Q-switched operation, we achieve ~ 1.4μs, ~ 60nJ pulses with repetition rate between 15-55 kHz. For mode-locked operation, we achieve ~ 1ps, 0.35nJ pulses with a repetition rate of 21.5MHz. Both lasers can sustain stable operation for several hours, demonstrating the robustness of DWNT SAs.

2. Experimental Setup and Results

We use DWNTs grown by Catalytic Chemical Vapour Deposition (CCVD)[18]. The purified DWNTs, characterised by Transmission Electron Microscopy (TEM), absorption and multi-wavelength Raman spectroscopy, contains >90% DWNT population with 1.1 nm inner and 1.8 nm outer mean diameter [17]. DWNT polyvinyl alcohol (PVA) composites are prepared following the methods in [17]. The SA device is formed by sandwiching a small piece of the DWNT-PVA film between two fiber ferrules using index-matching gel. Fig. 1 shows the linear absorbance of the DWNT SA, with the absorption curve of a pure PVA film as reference.



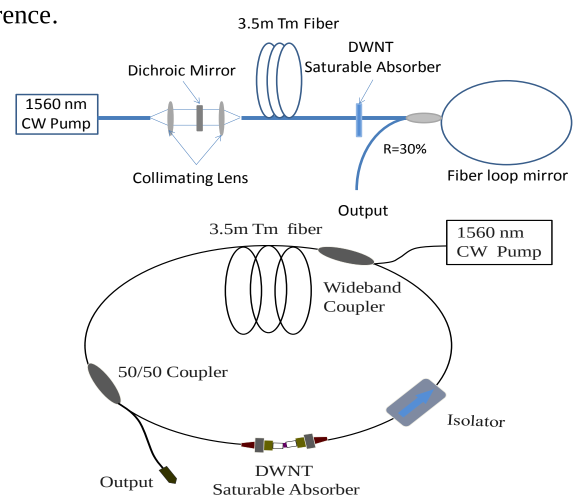


Fig.1 *Linear absorption of DWNT SA film.* ***Fig.2*** *Q-switched (linear) and Mode-locked (ring) cavity setup.*

Fig.2 illustrates the schematic setup for both laser cavities. The gain fiber is Tm-doped silica fiber (NUFERN) which has a 9/125 core/cladding geometry. The core absorption of the Tm fiber is ~10dB/m at the pump wavelength of 1560nm. A 3.5m span of Tm fiber is used in both cavities to provide optical gain. A diode laser emitting at 1560nm is amplified by an erbium-doped fiber amplifier (EDFA) to provide optical pumping into the core of the Tm fiber.

The Q-switched cavity is formed by a 1550/1950nm Dichroic mirror (80% transmittance at 1550nm and >99% reflectance at 1900-2000nm) and a 30% reflectance fiber loop mirror respectively. The total cavity length is ~ 7m. Q-switching is observed at a pump power ~ 260mW. The initial pulse repetition rate is ~ 15 kHz with an output power of 0.9 mW, which corresponds to a pulse energy of 60nJ. Stable Q-switching operation can be maintained up to 400mW pump power, when the repetition rate reaches ~ 55 kHz. The laser's output spectrum is measured using a scanning spectrometer (Bristol Instrument 721b). Multiple-peak structures within a total bandwidth of ~ 10nm can be observed, similar to other reports [19]. Fig.3 shows the typical output characteristics at a pump power of 320mW.

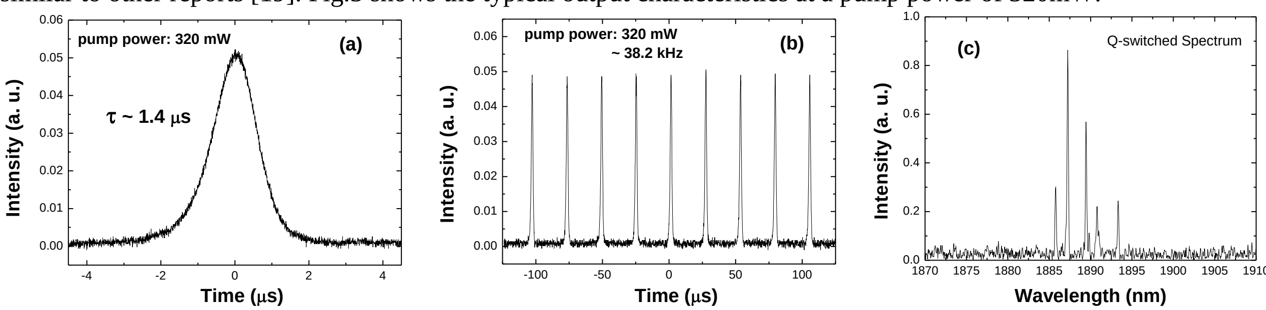


Fig.3 *Q-switched (a) pulse profile, (b) pulse train, (c) optical spectrum.*

The mode-locked laser is based on a ring cavity (Fig.2). An isolator is used to ensure single direction propagation and a 1550nm 50%-50% coupler is used to guide part of the circulating light out of the cavity. The total cavity length is ~ 10.8m. Mode-locking self-starts at a pump power of ~ 345mW. The output power is about 5mW at this condition. As pump power increases, pulse duration decrease and spectral width increase are observed, as expected from soliton fiber lasers. Single-pulse operation can be maintained up to a pump power of ~ 370mW where 7.6mW output power is measured. The output pulse duration is estimated to be 0.98ps, assuming a $Sech^2$ profile. The spectrum is recorded using a high resolution OSA (Yokogawa) and exhibits typical soliton sidebands. The central wavelength, spectral bandwidth and time-bandwidth product are 1889nm, 4.2nm and 0.34 respectively. Fig.4 shows the typical characteristics of mode-locked output pulses.

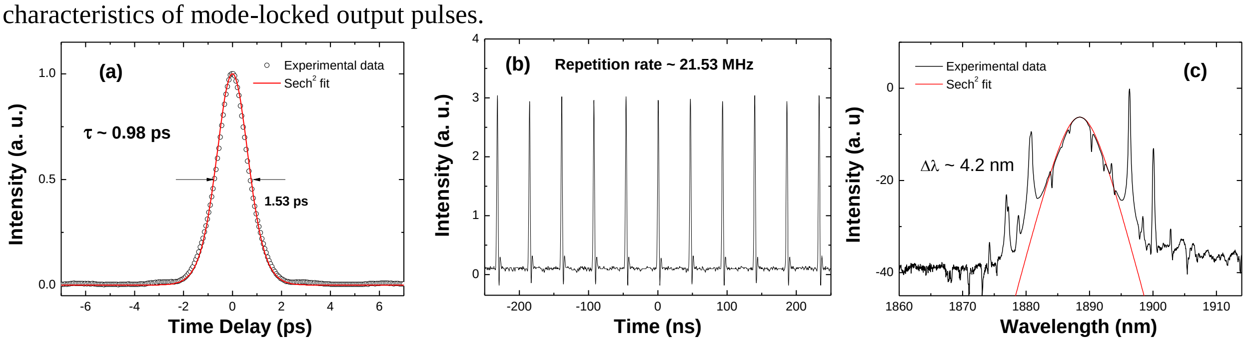


Fig.4 *Mode-locked (a) autocorrelation trace, (b) pulse train, (c) optical spectrum.*

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