Solid-state Er:Yb:glass laser mode-locked by using single-wall carbon nanotube thin film

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We design single-wall carbon nanotube (SWNT) thin-film saturable absorbers (SAs) integrated onto semiconductor distributed Bragg reflectors for mode-locking solid-state Er:Yb:glass lasers. We characterize the low nonsaturable loss, high-damage-threshold SWNT SAs and verify their operation up to a pulse fluence of 2 mJ/cm^2. We demonstrate passive fundamental continuous-wave mode locking with and without group-delay dispersion compensation. Without compensation the laser produces chirped 1.8 ps pulses with a spectral width of 3.8 nm. With compensation, we obtain 261 fs Fourier-transform-limited pulses with a spectral width of 9.6 nm. © 2006 Optical Society of America

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Due to its low-dimensional quantum confinement, the single-wall carbon nanotube (SWNT) has many interesting and useful features for applications in optics, including all-optical switching and passive mode locking.[1,2] In the first demonstration, a SWNT thin-film saturable absorber (SA) was used to mode lock an erbium-doped fiber laser in the 1550 nm region.[2] This motivated mode locking of fiber lasers in other wavelength regions[3] and at high repetition rates.[4] Recently, there was also a demonstration of a mode-locked Er:Yb:glass laser using a SWNT doped polymer.[5] Despite these demonstrations, the actual performance and limitations of these devices remain uncertain because they have not been well characterized. For example, as SWNT SAs have been predominantly used in fiber lasers,[2–4] it is uncertain whether they can be engineered for solid-state lasers with much lower single-pass gain and higher intracavity power. Furthermore, knowing and controlling the key parameters of a saturable absorber (SA) are critical for stable pulse generation, especially for operation at high repetition rates without Q-switching instabilities.[6] They are also crucial for generating shorter pulses, as saturable absorbers can be engineered to function with additional pulse shaping or stabilizing mechanisms, such as soliton mode-locking.[7]

To clarify the applicability of SWNT SAs to mode-locking solid-state lasers and to investigate the effectiveness and customizability of SWNT SAs, we design and characterize integrated SWNT SA-semiconductor distributed Bragg reflector (DBR) mirrors and demonstrate mode-locking of solid-state Er:Yb:glass lasers. We also associate the lasers' performance with the parameters of the SWNT SA.

The important parameters for a typical saturable absorber are saturation fluence (F_{sat}), modulation depth (ΔR), nonsaturable absorption (ΔR_{ns}), and recovery time[8] (τ_c). ΔR_{ns} should be small for efficient operation and τ_c should be of the order of the desired pulse width.[7] F_{sat} and ΔR are designed according to the parameters of the laser cavity. As an initial design guide, we can apply the simplified condition for suppressing Q switching,[6,9]

$$E_p \left. \frac{\mathrm{d}R(E_p)}{\mathrm{d}E_p} \right|_{\overline{E_p}} < r\frac{T_R}{\tau_l}, \qquad (1)$$

$r=1+P/P_{sat,L}$, where P is the average intracavity laser power and $P_{sat,L}$ is the saturated power of the lasing medium. In a four-level laser with a fully saturated absorber, r is identical to the number of times above threshold the laser operates. T_R is the cavity round-trip time, and τ_l is the upper-state lifetime of the gain medium. R is the reflectivity, and E_p is the pulse fluence incident on the saturable absorber. To fully exploit the available ΔR, the operational E_p should be high enough to bleach the absorber, which is about 5 times F_{sat}.[6]

We design SWNT SAs for Er:Yb:glass lasers by applying Eq. (1): τ_l is 7.9 ms,[10,11] and for a 60 MHz repetition rate with a reasonable Q-switched mode-locking threshold ($r\sim 5$), the left-hand-side of Eq. (1) is of the order of $\sim 1\times 10^{-5}$. Therefore an operational E_p of about 200 $\mu J/cm^2$ would require an F_{sat} of 40 $\mu J/cm^2$ and a ΔR of 0.3%, approximately.

To realize these saturation characteristics, we select SWNT with appropriate diameters and control the deposition thickness. An approximately 100 nm thick layer of SWNT was spray deposited onto 30 pairs of antiresonant AlAs/GaAs DBR mirrors with a 3 dB spectral width of 172 nm centered at 1570 nm.[12] This resulted in a quasi-antiresonant design, and the

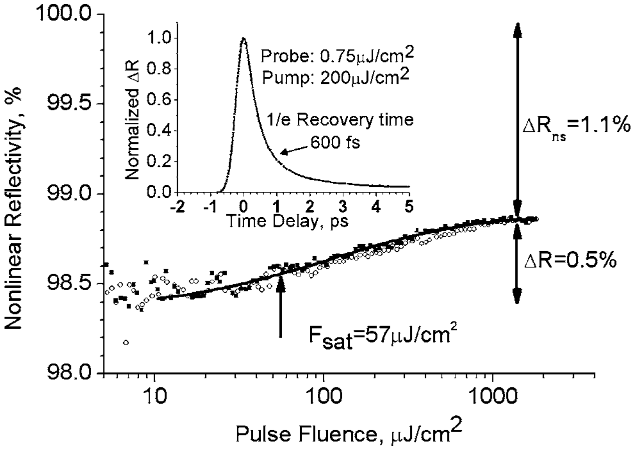

Fig. 1. Nonlinear reflectivity versus pulse fluence. Points, data; solid curve, fit. Inset, degenerate pump–probe measurement.

field enhancement factor in the SWNT layer is estimated to be 0.6. The SWNT SAs were characterized with high accuracy by methods similar to those developed for semiconductor saturable absorber mirrors (SESAMs) with an 80 MHz Ti:sapphire-laser-pumped commercial optical parametric oscillator producing 200 fs pulses at 1535 nm.[8] The absolute reflectivity of the device was recorded versus an input pulse fluence of up to 2 mJ/cm^2, as shown in Fig. 1. The measurement was repeated to investigate whether there was intensity-induced damage. Neither catastrophic damage nor significant degradation was observed. We estimated F_{sat} by fitting the data to the following expression[13,14]:

$$R(E_p) = 1 - \alpha/(1 + E_p/F_{\text{sat}})^{1/2} - \beta E_p - \Delta R_{\text{ns}}, \qquad (2)$$

α where β are coefficients of weak-field absorption and two-photon correction, respectively. From the fitted data, we estimated a ΔR_{ns} of 1.1%, a ΔR of 0.5%, and an F_{sat} of 57 μJ/cm^2. The F_{sat} is similar to that of traditional SESAM design and is well suited for passive mode locking of diode-pumped solid-state lasers.[9] However, ΔR_{ns} is still larger than what is achievable with SESAMs and needs further improvement.[9] The small differences in the designed and measured parameters were within tolerable range and could be compensated for by fine adjustments to the spot size on the SWNT SA.

The recovery time is characterized with degenerate pump–probe measurements by using the same laser source. The inset in Fig. 1 shows the normalized temporal response of the device. The measurement shows a $1/e$ recovery time of 600 fs, ideal for generating subpicosecond pulses.

We constructed two Er:Yb:glass lasers with standard delta cavities.[10,11] The gain media have different doping levels but in each case consisted of 2 mm Brewster-angled, erbium- and ytterbium-doped phosphate glasses diode pumped at 976 nm through folding mirrors. The first laser, without group-delay dispersion (GDD) compensation, had a 1% output coupler, and the output power was measured after two silver mirrors and an isolator, corresponding to a reduction of 21 dB compared with the intracavity power. The second laser had 3% output coupling, and negative GDD was introduced by including Gires–Tournois interferometer mirrors.[10,11]

We successfully mode locked both lasers with a SWNT SA. Without GDD compensation, a maximum average power of 14 mW was obtained without cw breakthrough or multiple pulsing. Output power is plotted versus the input pump power in Fig. 2. The output pulse has a spectral FWHM of 3.8 nm and a pulse duration of 1.8 ps, inferred from a second-harmonic intensity autocorrelation measurement with a hyperbolic-secant fit (Fig. 3). The time–bandwidth product is 0.87. We recorded the frequency spectrum with 1 kHz resolution within a span of 200 kHz [Fig. 4(a)] centered at the fundamental frequency of 60.715 MHz and observed 60 dB extinction with no sidebands that would arise due to relaxation oscillations. This absence confirms clean cw mode locking without Q switching. Wide span measurement up to 800 MHz [inset of Fig. 4(a)] indicates single-pulse operation.

From the second laser with GDD compensation, we obtained 261 fs pulses with a spectral FWHM of 9.6 nm centered at 1561.7 nm, as shown in Fig. 3(d). The time–bandwidth product is 0.31, indicating Fourier-transform-limited hyperbolic-secant shaped pulses. We obtained a maximum average power of 63 mW (Fig. 2). Again, we recorded the frequency spectrum with a resolution of 3 kHz within a span of 1 MHz [Fig. 4(b)] centered at the fundamental fre-

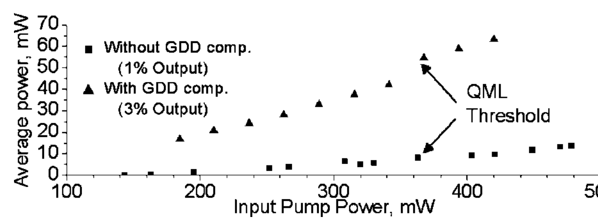

Fig. 2. Average output power versus input pump power. QML, Q-switched mode locking.

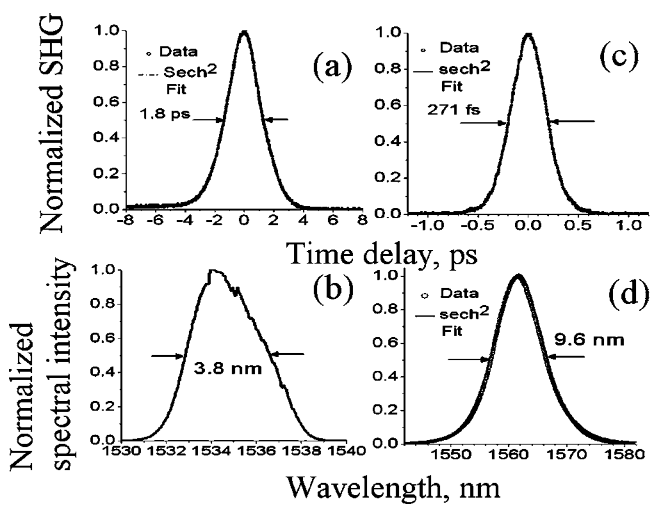

Fig. 3. (a), (c) Autocorrelation traces and (b), (d), spectral density; (a), (b) without GDD compensation and (c), (d) with negative GDD compensation.

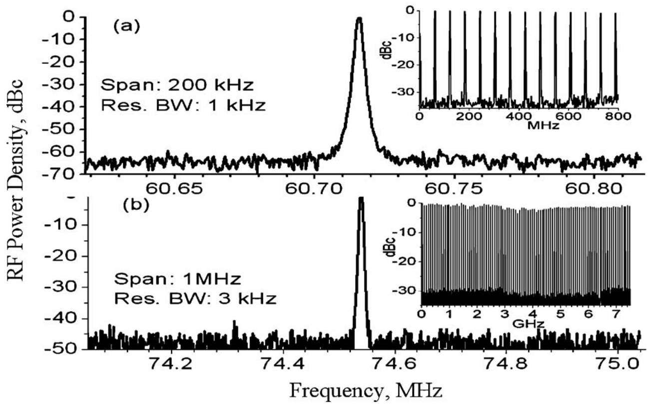

Fig. 4. (a), (b) Rf spectrum at fundamental repetition rates. Inset (a), dc to 800 MHz (1 MHz resolution). Inset (b), dc to 7.5 GHz (30 kHz resolution).

quency of 74.539 MHz and observed no indication of Q-switching instabilities. We observed no spectral modulation on the wide span measurement up to 7.5 GHz [inset of Fig. 4(b)]; this, together with the satellite-free autocorrelation, indicates single-pulse operation.

Both lasers required only a small perturbation, such as cutting across the path of the beam with a pencil, to start. This could be attributed to the fast response time of the SWNT SA, which is faster than is typically observed for SESAMs.[9–11] Once started, however, the lasers were stable. They were running continuously for hours, and the process was repeatable. Repeatable operation suggests that the SWNT SA did not suffer damage or degradation, and we conclude that operation in laser cavities with multikilowatt peak power is possible.

From the results, we can associate pulse duration with the recovery time of the SWNT SA. In a mode-locked laser with zero GDD and a fast saturable absorber, the pulse duration becomes equal to the absorber's recovery time. In the presence of GDD, pulses are broadened and chirped. Assuming a Fourier-transform-limited pulse, the 3.8 nm spectral width obtained from the first laser implies a pulse duration of 650 fs. This is very close to the 600 fs measured recovery time and shows clearly that a SWNT SA operates as a fast saturable absorber in this configuration. With GDD compensation, the balance of self-phase modulation and negative GDD results in soliton pulse shaping, which further shortens the pulse duration. In the second laser we obtained nearly Fourier-transform-limited 261 fs pulses. With further optimization, shorter pulses are possible.[8]

The low ΔR indicates hope for possible multigigahertz repetition rate operation. However, with reduced pulse fluence at higher repetition rates, both F_{sat} and ΔR_{ns} need to be lower. At present, because of the antiresonant DBR mirrors, the mean diameter and large bundle size of the SWNT, effective F_{sat} is higher than expected for a quantum-wire-type saturable absorber. Changing the design of the DBR mirrors and improving SWNT processing could lead to future improvements.

In conclusion, we have demonstrated that single-wall carbon nanotube thin-film saturable absorbers (SWNT SAs) are well suited for passive mode-locking solid-state lasers. We have measured all the important saturable absorber parameters and demonstrated a saturation fluence of 57 μJ/cm^2, a modulation depth of 0.5%, and a nonsaturable loss of 1.1%. At this point mode-locking is not fully self-starting because of the rather fast response time of the SWNT SA of only 600 fs. Without GDD compensation, the SWNT SA is fully responsible for shaping and stabilizing the chirped 1.8 ps, 3.8 nm pulses. With GDD compensation, soliton mode locking generates 261 fs, 9.6 nm Fourier-transform-limited pulses.

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