Passive mode locking of Yb:KLuW using a single-walled carbon nanotube saturable absorber

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Mode locking of an Yb-doped bulk laser in the 1 μm spectral range using a single-walled carbon nanotube saturable absorber (SWCNT-SA) is demonstrated for the first time, to our knowledge. Passive mode locking of an Yb:KLuW laser resulted in nearly transform-limited pulses as short as 115 fs at 1048 nm. In addition, the nonlinear response of the SWCNT-SA was measured, yielding a modulation depth of 0.25% and a relaxation time of 750 fs.

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Recently, single-walled carbon nanotube saturable absorbers (SWCNT-SA) have gained much attention as potential replacements for semiconductor-based ultrafast passive mode lockers and limiters [1]. Semiconductor saturable absorber mirrors (SESAM) must be fabricated by very complex epitaxial processes, and further treatment is often required for reducing the recovery time of the absorbing layer [2]. The SWCNT-SA mirrors can be produced by the well-established spin-coating process, a much less costly way than for a typical SESAM. Furthermore, SWCNT-SAs enable the fabrication of new types of broadband SAs with ultrashort recovery times and can be deposited on a large variety of substrate materials. Reflection- and transmission-type SWCNT-SAs can be fabricated, the latter being a rather difficult approach for the case of semiconductor based SAs. So far, SWCNT-SAs have been utilized to mode lock lasers in the 1.5 μm wavelength range. The first laser of this kind used an Er-doped fiber as the gain medium [3]. Impressive results were also achieved with Er:Yb:glass bulk lasers [4,5], demonstrating a pulse duration of 68 fs at 1.5 μm [5]. These encouraging results motivated mode-locking investigations in other wavelength regions. Using a flash-lamp-pumped $Nd:GdVO_4$ laser, 30 ps pulses in a 200 ns long train were achieved at 1.34 μm [6]. SWCNT-SAs were also successfully applied to mode lock Yb-doped fiber lasers in the 1 μm spectral range. With SWCNT-SA coating directly deposited onto the fiber end face, such a fiber laser delivered 137 fs pulses with 0.1 mW of output power at 20 MHz [7].

In this Letter, we report about SWCNT-SA, fabricated for passive mode-locked bulk lasers in the 1 μm spectral range. A monoclinic Yb:KLuW crystal served as the laser gain medium, which was previously shown to deliver pulse durations down to 83 fs using a SESAM for passive mode locking at 1049 nm [8]. In addition, we present results on the characterization of the nonlinear reflectivity and pump–probe measurements of the SWCNT-SA used in the present work.

For fabrication of the SWCNT-SA, dried arc-made SWCNTs were first dispersed in dichlorobenzene via ultrasonic agitation, while poly(m-phenylene vinylene-*co*-2,5-dioctoxy-*p*-phenylenevinylene) (PmPV) was added to enhance solubility of the SWCNTs during the ultrasonic process. The SWCNT dispersion was then mixed with the prepared polymethyl methacrylate (PMMA) solution in the volume ratio of 1:1. Finally, the SWCNT/PMMA mixture was deposited onto a quartz substrate by the spin-coating technique and baked at 90°C for several minutes.

The resonant response and the saturation fluence of the SWCNT-SA were characterized by pump–probe and nonlinear transmission measurements. For both purposes, 150 fs pulses from a mode-locked Nd:glass laser (High-Q Laser Inc.) operating at 1060 nm were focused on the sample, yielding pump-pulse fluences of up to 500 $\mu J/cm^2$.

The pump–probe trace and a fit to the data are shown in Fig. 1, revealing a nearly instantaneous (<100 fs) response together with a fast exponential decay with 750 fs recovery time, which is substantially shorter than the values recently reported for SESAMs [8]. The measurement indicates a relative weight of the quasi-instantaneous response of about 30%. The saturation fluence and the modulation depth of the SWCNT-SA were measured with a high accuracy in a setup similar to the one reported in [9]. This setup repetitively scans the nonlinear transmission characteristics of the sample, using an acousto-optic modulator for high-dynamic range attenuation, and allows resolving modulation depths well below 1%. The absolute transmission of the SWCNT-SA versus input pulse fluence was recorded and is depicted in Fig. 2. From a fit to the data we extract a saturation fluence of about 10 $\mu J/cm^2$, a modulation depth of 0.25%, and a nonsaturable loss of 2.3%. The corresponding values that were measured for the

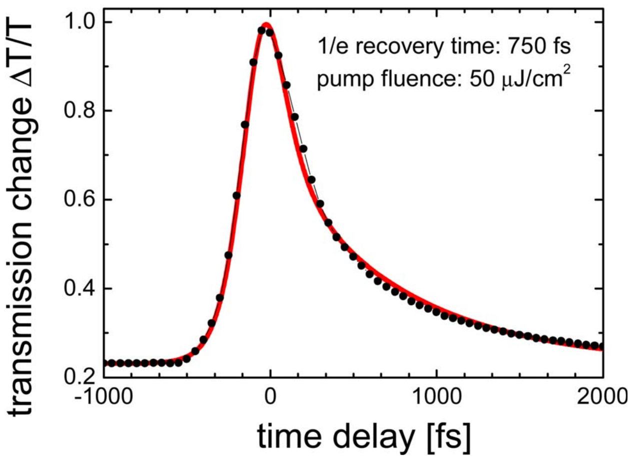

Fig. 1. (Color online) Pump–probe trace of the SWCNT-SA (excitation wavelength, 1058 nm). Dots, measured data; solid curve, fit to the data.

10-nm-thick InGaAs surface-quantum-well SESAM used for mode locking the Yb:KLuW laser are a 0.5% modulation depth, 2% nonsaturable loss, a 10 μJ/cm^2 saturation fluence, and a 2 ps relaxation time. Therefore, with the noted exception of the relaxation time, all measured nonlinear parameters of the SWCNT-SA are rather close to those of the SESAM.

The laser experiments were performed with a Ti:sapphire laser as a pump source that emitted up to 2 W of output power near 980 nm. For diode-pumped operation, a single-stripe diode laser was used at the same wavelength, delivering up to 4 W. We studied longitudinal pumping in a Z-shaped astigmatically compensated resonator, employing two folding mirrors in the center. The laser setup is depicted in Fig. 3. The 3-mm-thick 5% Yb-doped crystal was oriented for polarization parallel to the N_p-optical axis. No special provision was made for cooling the crystal. One resonator arm was additionally folded, using two highly reflecting focusing mirrors. The SWCNT-SA was positioned at Brewster's angle in this second resonator waist of ~60 μm to enhance the intensity on the absorber. The SESAM used for mode locking the Yb:KLuW laser in [8] was placed at the same position on a plane Bragg mirror, as shown in Fig. 3.

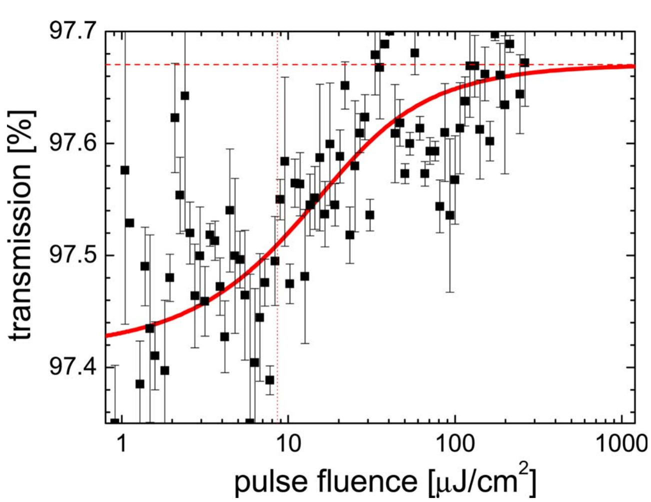

Fig. 2. (Color online) Nonlinear transmission of the SWCNT-SA. Single-pass transmission at Brewster angle versus incident pulse fluence (dots, measured data; solid curve, fit to the data).

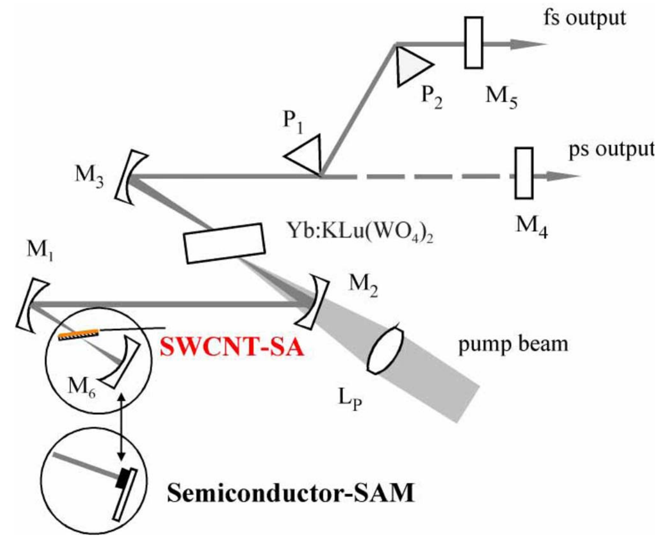

Fig. 3. (Color online) Setup of the SWCNT-SA mode-locked Yb:KLuW laser. M_1, M_2, and M_3, focusing mirrors with radius of curvature (ROC) = −10 cm; M_6, focusing mirror with ROC = −5 cm; P_1, P_2, SF10 prisms; M_4, M_5, plane output couplers; SAM, saturable absorber mirror.

In this configuration, without the prisms for dispersion compensation, pulses with a duration of 9.2 ps at a repetition rate of 88 MHz were achieved under Ti:sapphire laser pumping. The laser was self-starting but exhibited tendencies toward Q switching. The incident pump power amounted to 1.34 W, yielding an average output power of 53 mW at 1046 nm.

For femtosecond operation, we optimized the cavity design in order to obtain the shortest pulse duration. For this purpose two SF10 Brewster prisms with a tip-to-tip separation of 38 cm were introduced (Fig. 3). The resulting pulse-repetition rate was 89 MHz. Pumping with the Ti:sapphire laser, the mode-locking threshold was approximately 270 mW of incident pump power for 1% transmission of the output coupler. The intensity autocorrelation trace together with the corresponding fit and the spectrum of the shortest pulses are shown in Fig. 4(a). The deconvolved FWHM of the pulse was 115 fs, with an average power of 30 mW. The corresponding output spectrum was centered at 1048 nm and had a bandwidth of 11.3 nm. This results in a time–bandwidth product of 0.355, corresponding to nearly transform-limited sech^2-pulses. These pulses are significantly shorter than those described in the only previous reference on SWCNT-SA mode-locked bulk lasers near 1 μm, where a pulse duration of ≈200 fs for a Nd:glass laser was reported [5]. Figure 4(b) shows the radio-frequency spectrum of our SWCNT-SA mode-locked Yb:KLuW laser. From the 1 GHz span (inset) and the first beat note, recorded at 1 kHz resolution, no spurious modulations are visible down to 54 decibels relative to the carrier (dBc), i.e., clear evidence of stable cw mode locking. The laser is operating in the

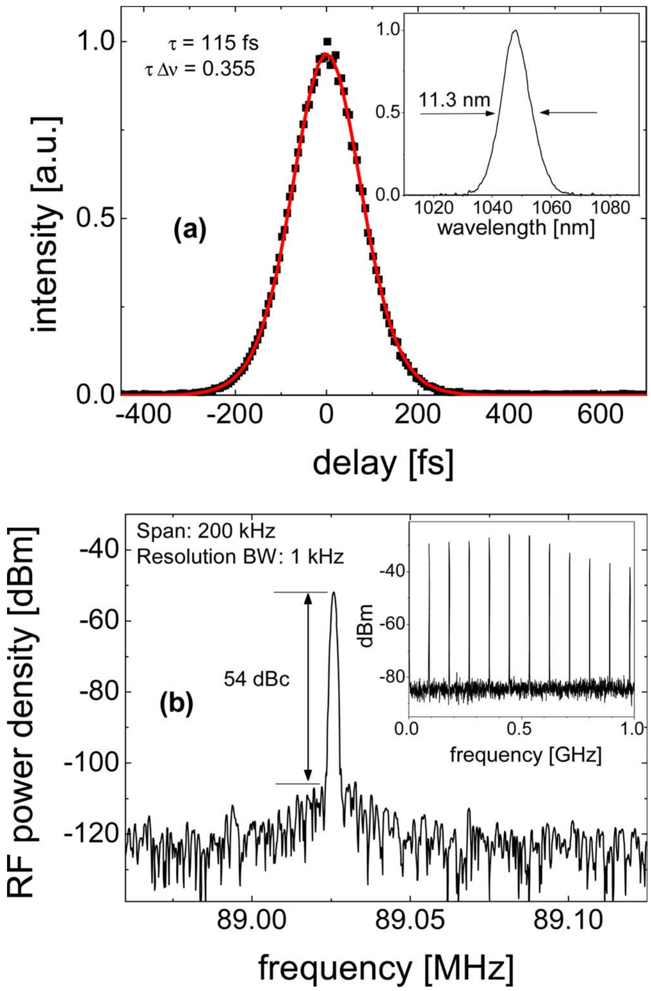

Fig. 4. (Color online) SWCNT-SA mode-locked Yb:KLuW laser. (a) Autocorrelation trace (τ, FWHM of the pulse; $\tau\Delta\nu$, time-bandwidth product; the solid curve indicates the $sech^2$-pulse shape fit) and (inset) optical spectrum; (b) radio frequency spectrum (first beat note). Inset, 1 GHz scan of the radio-frequency spectrum.

negative dispersion regime with soliton-like mode locking.

Using the diode laser as a pump source, the same pump-and-cavity configuration with the SF10 prisms yielded stable femtosecond mode locking. With 1.5 W pump power incident on the Yb:KLuW crystal, we measured a maximum mode-locked output power of 16 mW. The lower efficiency compared to the experiments with Ti:sapphire laser pumping is caused by imperfect matching between pump and resonator modes and the lower beam quality of the diode emission. At the pulse-repetition rate of 89 MHz, a pulse duration of 170 fs was achieved. The corresponding spectrum, centered at 1045 nm, had a spectral FWHM of 7.2 nm, which yields a time–bandwidth product of 0.334; hence the pulses are almost transform limited. Again, we recorded the radio-frequency spectrum, indicating a 61 dBc extinction ratio of the fundamental beat note at 88.85 MHz, as measured with 3 kHz resolution. Wide-span measurements up to 1 GHz confirm single-pulse operation.

Neither with Ti:sapphire laser pumping nor with diode laser pumping, mode locking in the femtosecond regime was reliably self-starting but required only a small perturbation for initiation of the pulsed regime. Once started, however, laser operation was stable, which is mainly attributed to the measured very fast response time of the SWCNT-SA of 750 fs. No damage occurred at the embedded SWCNT-SA, despite the high incident laser fluences.

In conclusion, we have demonstrated that SWCNT-SAs are well suited for passive mode locking of solid-state lasers in the 1 μm spectral range. We have measured the relevant parameters of the SWCNT-SA, which is favorably characterized by a low modulation depth of 0.25% and a very fast recovery time of 750 fs. Using this novel saturable absorber for passive mode-locking of an Yb:KLuW laser, nearly transform-limited pulses with a duration of 115 fs in a soliton-like regime were achieved.

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