Mode locking of a Cr:YAG laser with carbon nanotubes

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We report on mode locking of a bulk Cr:YAG laser by using a transmission-type single-walled carbon nanotube saturable absorber. Stable and self-starting laser operation in the picosecond and femtosecond regimes is obtained at wavelengths around 1.5 μm. Tunable transform-limited sub-100 fs pulses are generated at a repetition rate of 85 MHz with an output power up to 110 mW.

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Laser sources generating ultrashort pulses near 1.5 μm are important for optical communications, remote sensing, and bioimaging. Compact and robust passively mode-locked Er-doped fiber lasers operate around 1550 nm, but the soliton regime requires precise balance of the intrinsic fiber dispersion and nonlinearity, and normally the generated pulses exhibit picosecond duration while the energy is much lower than 1 nJ [1]. Thus, generation of sub-100 fs pulses with multinanojoule pulse energy still needs development in fiber lasers. Regarding bulk solid-state lasers operating near 1.5 μm capable of producing higher single-pulse energy at sub-100 fs pulse duration, the Cr:YAG laser has been widely studied, using both Kerr-lens mode locking and self-starting mode locking with semiconductor saturable absorber mirrors (SESAMs) [2–4]. SESAMs are fabricated by sophisticated epitaxial growth techniques, and post-treatments are also often required to reduce recovery time [5,6]. Moreover, limitations in the selection of semiconductor materials restrict the useful tuning range and the supported spectral bandwidths of SESAMs.

In comparison to SESAMs, single-walled carbon nanotube saturable absorbers (SWCNT-SAs), first proposed by Set *et al.* [7], are very promising broadband passive mode-locking devices with low insertion loss. SWCNT-SAs with ultrafast response on the (sub)picosecond time scale and high damage threshold are fabricated in a relatively easy way with spin coating, optically driven deposition, and electrospray methods [8–10]. While most previous realizations of laser mode locking based on SWCNT-SAs have been carried out with fiber lasers because of their relatively high round-trip gain [7,10], there are only a few demonstrations of passive mode locking in bulk solid-state lasers using SWCNT-SAs, which are more sensitive to linear losses in the laser cavity: these include Er^{3+}, Nd^{3+}, Yb^{3+}, Tm^{3+}, and Cr^{4+} lasers, operating in the 1 to 2 μm spectral range [8,11–14].

Recently, we reported on the first mode locking of a Cr:forsterite laser using transmitting SWCNT-SAs [14]. This laser delivered 120-fs-long pulses near 1.25 μm. The SWCNT-SAs showed ultrabroad absorption around 1.4 μm, which corresponds to the E_{11} transition. Further optimization of the manufacturing procedure [15] enables very low linear losses of $<1\%$ while maintaining this ultrabroad absorption, which can be used for passive mode locking of other bulk lasers operating at adjacent spectral regions. In the present Letter, we report on the passive mode locking of the related Cr:YAG laser by using such SWCNT-SAs. Output characteristics in wavelength-tunable picosecond and femtosecond operation around 1.5 μm are presented. Average powers up to 110 mW were achieved in the femtosecond regime at a repetition rate of 85 MHz, and transform-limited sub-100 fs pulses were generated near 1.5 μm.

The transmission spectrum of the SWCNT-SA used shows an extremely broad absorption band covering more than 700 nm around 1.4 μm. Time-resolved pump-probe measurements yield a biexponential response with fast and slow components of about 100 fs and 2 ps, respectively. Other parameters essential for mode locking, such as saturation fluence and modulation depth, are expected to be $<10\ \mu J/cm^2$ and $<0.5\%$, respectively, from previous investigations [14].

For the passively mode-locked Cr:YAG laser, an astigmatically compensated x-fold cavity configuration was used (Fig. 1). A 10 W cw Nd:YAG laser (Spectra-Physics) operating at 1.064 μm was used as the pump source. The Brewster-cut Cr:YAG crystal had a length of 20 mm and a diameter of 6 mm, with its axis along the $[0,0,1]$ crystallographic direction. Its absorption coefficient was $\alpha = 1\ cm^{-1}$ at 1.064 μm. The crystal was mounted in a water-cooled copper block whose temperature was stabilized at 12 °C. The cavity waist for the active element was formed by two concave mirrors with a radius of curvature (ROC) of −100 mm, M_1 and M_2. The pump beam waist was measured to be 1.34 mm and 32 μm before the focusing lens and in the gain medium, respectively, whereas the calculated beam waist of the laser mode

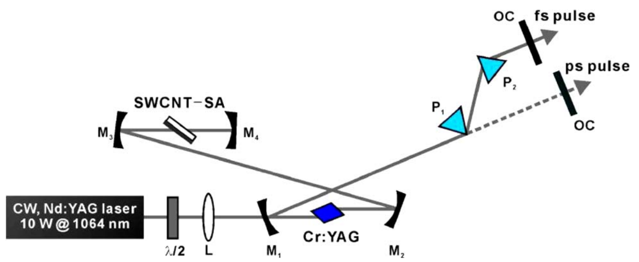


Fig. 1. (Color online) Configuration of the SWCNT-SA mode-locked Cr:YAG laser: Cr:YAG, 20-mm-long Cr:YAG crystal; M_1–M_3, HR-coated concave mirrors with a ROC = −100 mm; M_4, HR-coated concave mirrors (ROC = −75 mm); P_1 and P_2, fused-silica prisms; OC, 2% output coupler.

in the Cr:YAG crystal was 33 μm. Two extra concave mirrors with ROCs of −100 mm and −75 mm, M_3 and M_4, formed an additional cavity waist ($w \approx 80\ \mu$m) in the shorter cavity arm for the transmitting SWCNT-SA in order to obtain sufficient energy fluence for bleaching the absorption. The SWCNT-SA was mounted at the Brewster angle to minimize the reflection loss. To achieve stable and efficient mode-locked operation, the laser spot size on the SWCNT-SA was varied by moving it along the beam path between M_3 and M_4. At the other end of the cavity, a flat-wedged output coupler with a 2% transmission at the lasing wavelength was used. Because there is a series of water absorption lines between 1.36 μm and 1.5 μm that negatively affect laser stability [16], for femtosecond operation, the whole oscillator was enclosed in an acrylic box purged with dry nitrogen.

Without intracavity dispersion compensation, the passively mode-locked self-starting Cr:YAG laser produced stable picosecond pulses as short as 4.4 ps, with a spectral bandwidth of 1.4 nm at the central wavelength of 1505 nm. The corresponding time-bandwidth product was 0.823. The repetition rate was 87.9 MHz. Figure 2 shows the tuning characteristics and measured pulse duration. Tunable operation over 70 nm was achieved between 1435 and 1505 nm by using a 3-mm-thick single-plate Lyot filter inserted under the Brewster angle between M_1 and OC. We observed rapid decrease of the laser spectral width at wavelengths below 1450 nm, which is attributed to the increasing residual water absorption and the short-wave limit of the dielectric mirrors used.

For dispersion compensation, a pair of fused-silica Brewster prisms with a separation of 17 cm was inserted in the longer resonator arm shown in Fig. 1, and the birefringent filter, which usually limits the spectral bandwidth, was removed. From previous reports [17], the round-trip group-delay dispersion (GDD) and third-order dispersion (TOD) of the 20-mm-long Cr:YAG rod at 1.5 μm are known to be about 454 fs^2 and 6000 fs^3, respectively. The calculated round-trip refractive GDD and TOD of the prism pair amount to −1286 fs^2 and 4985 fs^3, respectively, while the material dispersion is small (−22 fs^2/mm) and can be ignored. Thus the Cr:YAG laser operated in a net negative dispersion regime, which led to stable and self-starting mode locking. The

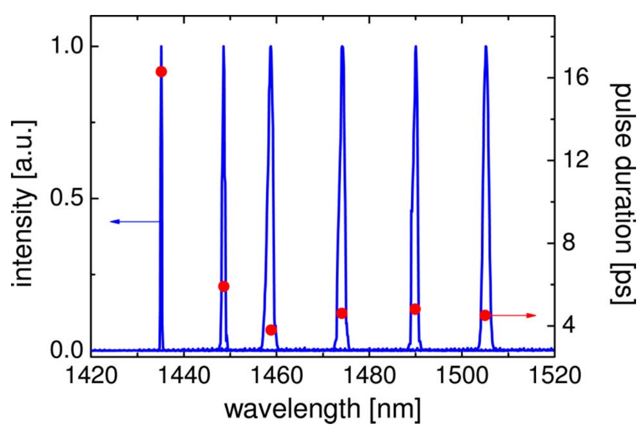


Fig. 2. (Color online) Spectral tunability of the SWCNT-SA mode-locked Cr:YAG laser in the picosecond regime. Data points (dots) indicate the measured pulse duration.

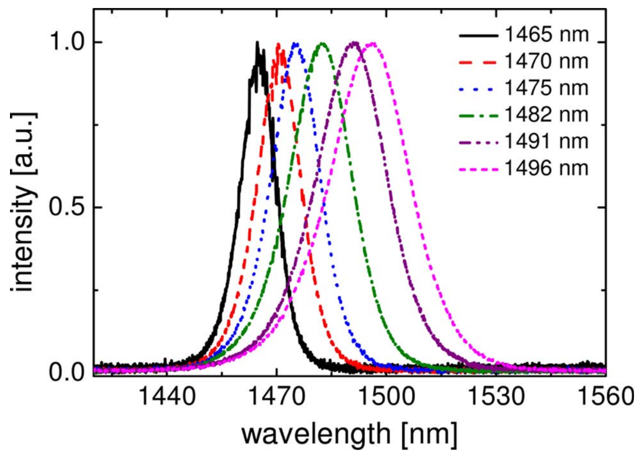


Fig. 3. (Color online) Spectral tunability of the SWCNT-SA mode-locked Cr:YAG laser in the femtosecond regime.

center wavelength of the laser could be slightly tuned only by adjusting the second prism in combination with a knife edge, from about 1.46 to 1.50 μm (Fig. 3). We observed narrower optical spectra at shorter wavelengths, and the mode-locked operation was also unstable. By applying a longer N_2 purging time, stable mode locking was sustained in the entire tuning range. Figure 4 shows the average output power versus the input pump power measured for femtosecond operation at 1.5 μm. Slope efficiency of $\sim$10% was obtained. In the whole power range from the threshold (3.2 W of input pump power) up to the maximum of 110 mW (at 4.26 W of pump power), stable self-starting mode-locked operation was achieved. In this range, the incident pump fluence on the SWCNT-SA was 0.05–0.33 mJ/cm^2, enough for bleaching the absorption. At higher pump powers, strong spectral modulations and multiple pulsing occurred, which restrict stable mode-locking for the available 2% output coupler. Figure 5(a) shows the measured autocorrelation trace and the corresponding optical spectrum (inset). The intensity autocorrelation function of the laser pulses was fitted well by assuming a sech^2 pulse shape, yielding a pulse duration of 92 fs. The simultaneously measured spectral bandwidth of 27 nm at 1495 nm leads to a time-bandwidth product of 0.33, which is close to the transform-limited value of 0.315. The recorded rf spectrum of the laser output is shown in Fig. 5(b). A sharp peak at the fundamental beat note of 84.55 MHz was

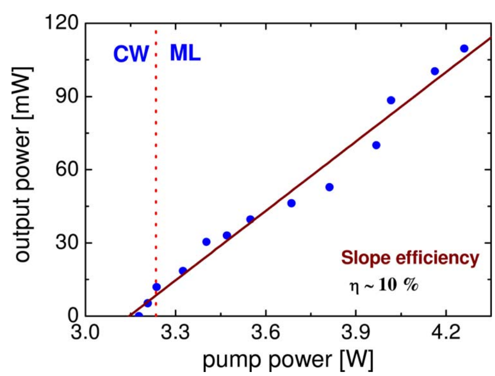
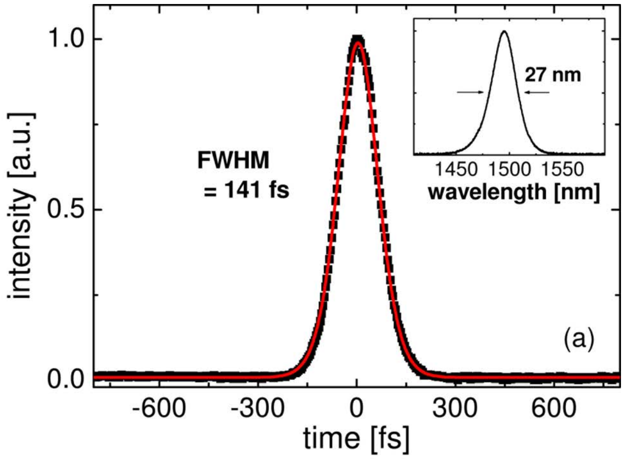


Fig. 4. (Color online) Average output power in the femtosecond mode-locked regime. The vertical line indicates the transition from the continuous-wave (CW) to the mode-locked (ML) regime.



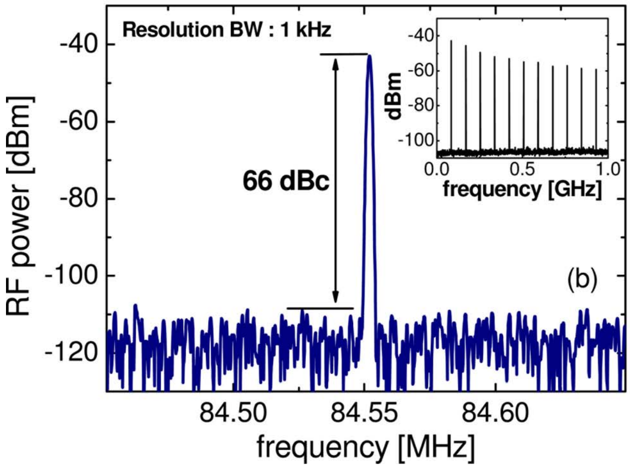


Fig. 5. (Color online) (a) Autocorrelation trace and the corresponding laser spectrum (inset) of the femtosecond SWCNT-SA mode-locked Cr:YAG laser and (b) RF spectrum of the fundamental beat note and 1 GHz span (inset).

measured, as well as a high extinction ratio of 66 dBc from the noise level. The inset of Fig. 5(b) shows the high harmonics of the fundamental beat note from wide span measurement of the rf signal. The measured rf signal spectra clearly indicate stable single-pulse mode-locking operation without any signature of Q-switching instabilities and multiple pulsing.

In conclusion, passive mode locking of a bulk Cr:YAG laser was successfully demonstrated using a SWCNT-based transmitting broadband saturable absorber for the first time. Nearly Fourier-transform-limited pulses with a pulse duration of 92 fs and a spectral bandwidth of 27 nm were generated near 1.5 μm. The maximum average power of 110 mW was achieved at 85 MHz. The recorded rf spectrum indicates stable single-pulse mode locking without any instabilities. In comparison with the SWCNT-SA mode-locked Er-doped bulk lasers operating at similar wavelengths, the present saturable absorber mode-locked Cr:YAG laser satisfies the requirements of having a sub-100 fs pulse duration with a single-pulse energy in excess of 1 nJ for the first time, to our knowledge.

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