

550 MHz carbon nanotube mode-locked femtosecond Cr:YAG laser

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We demonstrate a femtosecond Cr:YAG laser mode-locked by a carbon nanotube saturable absorber mirror (CNT-SAM) at a repetition rate of 550 MHz. By employing the CNT-SAM, which exhibits a modulation depth of 0.51% and a saturation fluence of 28 $\mu\text{J}/\text{cm}^2$ at 1.5 μm , we achieved a compact bulk Cr:YAG laser with self-starting mode-locked operation near 1.5 μm , delivering an average output power of up to 147 mW and a pulse duration of 110 fs. To our knowledge, this system provides the highest repetition rate among reported CNT-SAM mode-locked Cr:YAG lasers and the shortest pulse duration among saturable absorber mode-locked Cr:YAG lasers with repetition rates above 500 MHz.

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Femtosecond coherent sources with high repetition rates operating near 1.5 μm have been widely investigated for applications in optical communications, optical clocks, analogue-to-digital conversion, electro-optical sampling, and high signal-to-noise ratio nonlinear spectroscopy^[1-5]. Mode-locked fiber lasers can operate stably near 1.5 μm in a compact cavity configuration^[6,7], but it is quite difficult to achieve a high average output power above 100 mW, a pulse duration as short as ~ 100 fs, and a high repetition rate above 500 MHz all at the same time because of the long cavity length and large nonlinearity of the optical fiber. The Cr:YAG laser crystal, one of the representative solid-state laser crystals emitting near the 1.5 μm wavelength, is able to simultaneously provide a high average output power and a high repetition rate with short pulse duration because of its broad gain bandwidth, near 1.5 μm ^[8,9]. To date, most demonstrations have been based on Kerr-lens mode locking, because the small gain and low thermal conductivity of the Cr:YAG crystal make the laser cavity susceptible to intracavity loss^[10-13]. There has only been one report of a high-repetition-rate saturable absorber mode-locked Cr:YAG laser that adopted a saturable Bragg reflector; it exhibited a relatively long pulse duration of about 200 fs^[14].

Carbon nanotube saturable absorbers (CNT-SAs) have been widely employed in a variety of bulk solid-state lasers operating in the 0.8–2.1 μm spectral range because of their broadband nonlinear optical characteristics, including low saturation fluence, controllable modulation depth, and ultrafast recovery time^[15,16]. For high-repetition-rate lasers, the precision of these SA parameters is more important because of the relatively low intracavity peak intensity due to the short cavity length. Near the 1 μm wavelength

range, CNT-SAs with small modulation depths and negligible nonsaturable losses turned out to be applicable for high-repetition-rate mode-locked bulk solid-state lasers^[17,18]. Near the 1.5 μm wavelength range, a CNT-SA that is inserted into the second intracavity of a Cr:YAG laser also provides stable and self-mode-locked operation at a repetition rate of 85 MHz and a pulse duration below 100 fs^[19,20]. However, a CNT-SA mode-locked Cr:YAG laser in a compact scheme with a high repetition rate of above 500 MHz has not been reported until now.

In this work, we demonstrate a CNT-SA mirror (CNT-SAM) mode-locked femtosecond Cr:YAG laser above 500 MHz for the first time. By employing a CNT-SAM, the stable and self-starting mode-locked laser delivers a maximum output power of 147 mW and a 110 fs pulse duration at 550 MHz. To our knowledge, this is the highest repetition rate among CNT-SAM mode-locked Cr:YAG lasers and the shortest pulse duration among saturable absorber mode-locked Cr:YAG lasers with a repetition rate above 500 MHz.

The fabrication process of the CNT-SAM is similar to the one described in Ref. [15]. We used commercially available single-walled CNTs grown by employing the high-pressure carbon monoxide (HiPCO) method. The CNT bundles distributed in the absorber layer show a broadband E_{11} electronic transition located around 1.5 μm . As the first step, the CNTs were dissolved in 1,2-dichlorobenzene (DCB) with a concentration of 0.1 mg/mL and centrifuged. The well-dispersed CNT solution was then mixed with polymethyl methacrylate (PMMA) at a volume ratio of 1:1. Finally, the CNT/PMMA mixture was directly spin-coated onto a high-reflection plane dielectric mirror. At the end of the fabrication process the prepared CNT-SAM was dried

on a hot plate and subsequently in a vacuum oven. The thickness of the SA layer, measured by alpha-step method, was about 200 nm.

To certify the nonlinear optical characteristics of the fabricated CNT-SAM, its nonlinear reflection was investigated using a synchronously pumped near-infrared optical parametric oscillator, delivering 150 fs pulse duration with an output power of 50 mW at 1.5 μm .

From the nonlinear reflection measurement, shown in Fig. 1, we extracted a modulation depth (ΔR) of 0.51%, linear reflection (R_{lin}) of 98.87%, and nonsaturable loss (R_{ns}) of 0.62%, with a saturation fluence (F_{sat}) of 28 $\mu\text{J}/\text{cm}^2$, respectively. The low modulation depth of about 0.5% plays a crucial role in solid-state lasers to suppress undesired Q -switched mode locking and instabilities^[21,22]. The saturation fluence, corresponding to a peak intensity of 0.68 MW/cm², is sufficiently low compared to the intracavity peak intensity, corresponding to the mode-locked threshold.

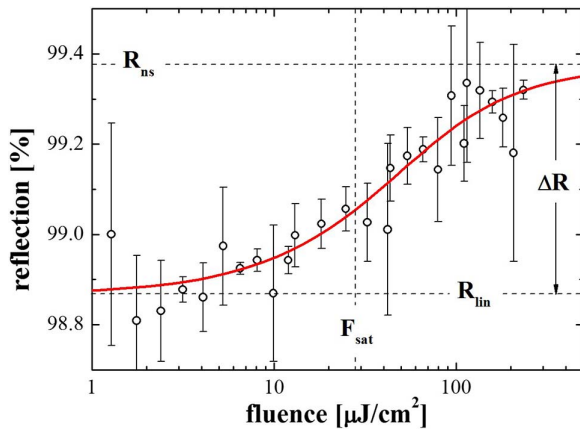


Fig. 1. Nonlinear reflection measurement of the CNT-SAM at 1.5 μm .

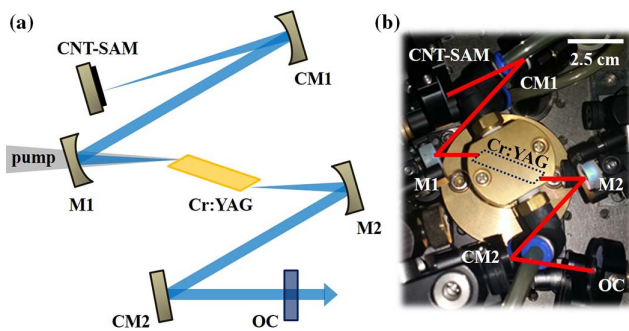


Fig. 2. (a) Schematic and (b) photograph of 550-MHz femtosecond Cr:YAG laser. Cr:YAG: 20-mm-long Cr:YAG gain crystal; M1, M2: HR-coated concave mirrors with ROC = -50 mm; CM1: HR-coated concave GTI mirror with ROC = -100 mm and with one bounce dispersion of -225 fs²; CM2: HR-coated plane GTI mirror with one bounce dispersion of -375 fs²; CNT-SAM: carbon nanotube saturable absorber mirror; OC: output coupler with 0.5% or 0.8% transmission.

Schematic and photographic images of the Cr:YAG laser are shown in Fig. 2. For the short cavity length for a compact laser configuration, a z -folded cavity configuration compensating astigmatism was adopted.

The laser was pumped by a 10 W continuous-wave (cw) single-mode Yb fiber laser (IPG Photonics, YLF-10-LP) operating at 1.064 μm . A 20-mm-long Brewster-cut rod-type Cr:YAG crystal with a diameter of 6 mm was used as the gain medium (MolTech GmbH). Its absorption coefficient was $\alpha = 1$ cm⁻¹ at 1.064 μm and a small single-pass absorption was expected, because more than 30% of the incident pump power was transmitted through the Cr:YAG crystal in the range of pump powers above 5.0 W.

The crystal was mounted in a water-cooled copper block whose temperature was maintained at 12°C. It was positioned between two concave mirrors with a radius of curvature (ROC) of -50 mm, M1 and M2, respectively. In the present study, the calculated waist of the cavity mode at the crystal center was 52.7 μm , which is slightly larger than the focused pump beam waist of 44.7 μm . Such relatively large beam waists at the crystal center were used because of the low thermal conductivity of the Cr:YAG crystal.

By enlarging both the pump and cavity mode size at the crystal center, we optimized the output power and the thermal condition of the Cr:YAG laser. For the compact cavity configuration and dispersion compensation, a chirp concave mirror of CM1 and a plane chirp mirror of CM2 were used as folding mirrors. The group delay dispersion (GDD) per bounce of each mirror was -225 fs² of CM1 and -375 fs² of CM2 at 1.5 μm , respectively. Considering a Cr:YAG crystal GDD of 522 fs² at 1.5 μm , the total net cavity dispersion was negative and slightly below -678 fs², which led to a stable and self-starting mode-locking. In the arm side of CM1, CNT-SAM was positioned as the end mirror where the beam waist was estimated to be 92.3 μm . On the other side of the cavity, output couplers (OCs) with 0.8% and 0.5% transmission at the lasing wavelength were used.

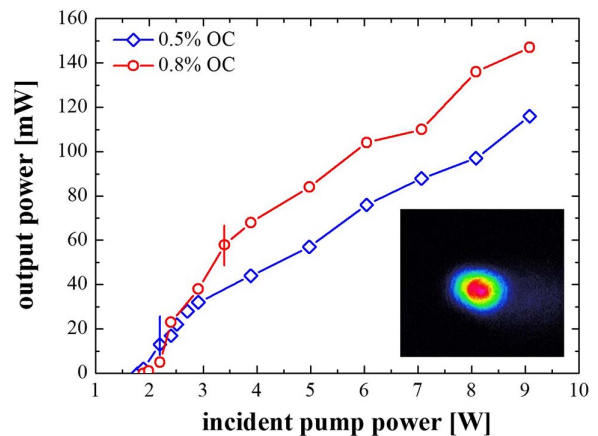


Fig. 3. Average output power versus incident pump power in the femtosecond mode-locked regime, and beam profile of second harmonic generation of mode-locked pulses (inset).

The mode-locked output power generated with the CNT-SAM is depicted in Fig. 3. For the 0.5% OC, the mode-locked threshold was measured to be 13 mW at 3.1 W pumping and the maximum output power was 116 mW at a pump power of 9.1 W. By replacing the OC by 0.8% transmission, the mode-locked threshold was 58 mW at 3.4 W pumping and the maximum output power was 147 mW at a pump power of 9.1 W. In the overall pumping range of the above mode-locked threshold, self-starting mode-locked operation was achieved without spectral modulation or cw spectral components. The intracavity peak intensities corresponding to the mode-locked thresholds were 2.8 MW/cm² for 0.5% OC and 7.9 MW/cm² for 0.8% OC, respectively. These values are much higher than the 0.68 MW/cm² corresponding to the saturation intensity of CNT-SAM. The inset of Fig. 3 shows the far-field beam profile of the mode-locked pulse. Because of the wavelength range limit of the beam profiler (Coherent LaserCam HR), we measured the beam profile of the second harmonic generation of the mode-locked pulse and it clearly exhibited a well-defined single spatial mode.

Figure 4 shows the measured autocorrelation trace and the corresponding spectrum. The intensity autocorrelation function of the pulse was fitted well by assuming a sech² pulse shape and extracting a pulse duration of 110.4 fs. The simultaneously measured spectral bandwidth of 22.6 nm at the center wavelength of 1507 nm leads to a time-bandwidth product of 0.330, which is close to the Fourier transform-limited value of 0.315.

The recorded radio-frequency (RF) spectrum of the laser output is shown in Fig. 5. A pointed peak at the fundamental beat note of 550.0 MHz was measured with a resolution bandwidth of 0.1 kHz within a 400 kHz span. The spectrum shows a high extinction ratio of 67.4 dBc from the background noise level. The inset of Fig. 5 shows the harmonics of the fundamental beat note from the 7.5 GHz wide span measurement of the RF signal. The measured RF spectra clearly indicate a stable single-pulse

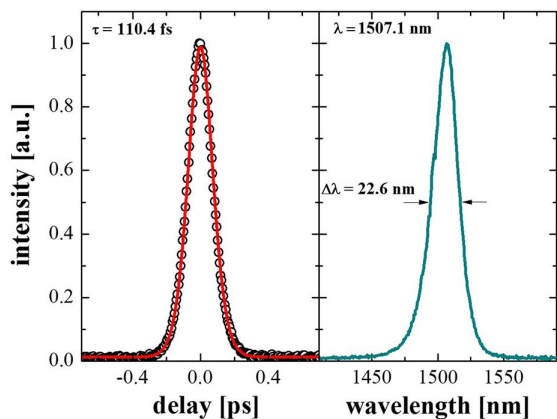


Fig. 4. Autocorrelation trace (left) and the corresponding laser spectrum (right).

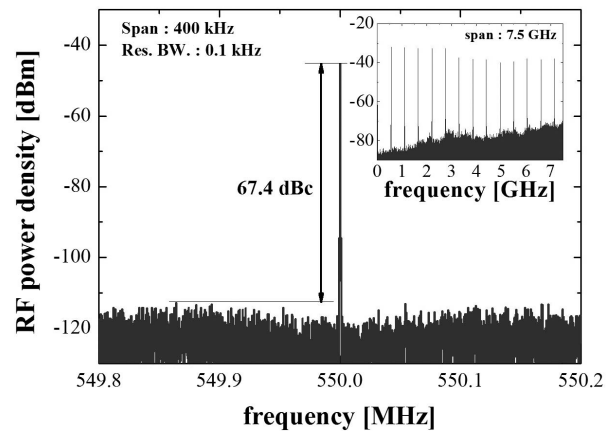


Fig. 5. RF spectra at the fundamental beat note and in a 7.5 GHz span (inset).

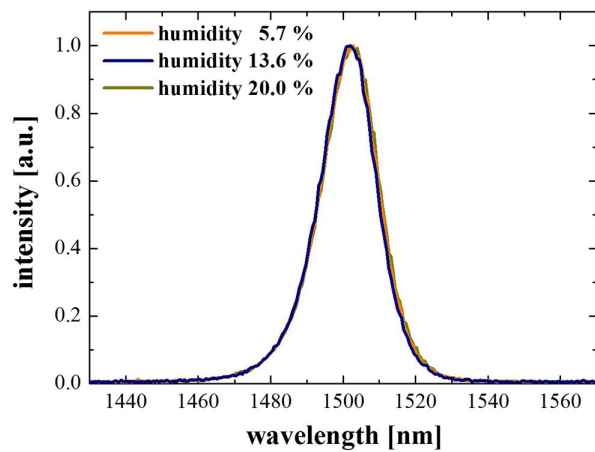


Fig. 6. Mode-locked laser spectra measured at different humidity conditions.

mode-locked operation without any signature of Q -switching instabilities or multiple pulsing.

Figure 6 shows the mode-locked spectra for different humidity conditions. To control the humidity, the sealed 500-MHz Cr:YAG laser was purged with nitrogen gas. As shown in Fig. 6, there are no spectral differences for humidity levels of 20.0%, 13.6%, and 5.7%, respectively. Generally, the Cr:YAG laser is quite sensitive to humidity due to the strong water absorption lines around 1.4 μ m. However, in our case, the center wavelength was above 1.5 μ m, so water absorption can be effectively avoided.

In summary, we developed a 550 MHz carbon nanotube mode-locked Cr:YAG laser operating near 1.5 μ m. A CNT-SAM was fabricated for a high-repetition-rate Cr:YAG laser and its nonlinear reflection properties were characterized. By employing the CNT-SAM, we achieved stable and self-starting single-pulse operation of the compact Cr:YAG laser, delivering a maximum output power of 147 mW and a pulse duration of \sim 110 fs at a repetition rate of 550 MHz. To our knowledge, the results present the highest repetition rate among CNT-SAM mode-locked Cr:YAG lasers and the shortest pulse duration among

saturable absorber mode-locked Cr:YAG lasers at a repetition rate of >500 MHz. Considering the low mode-locking thresholds, the CNT mode-locked femtosecond Cr:YAG laser is expected to be used for developing GHz-level bulk laser oscillators near $1.5\ \mu\text{m}$. In terms of applications, such $1.5\ \mu\text{m}$ coherent sources, which deliver high average output power, short pulse duration, and high repetition rate simultaneously, will improve the signal-to-noise ratio and resolution in nonlinear and time-resolved spectroscopy.

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