1.2-GHz repetition rate, diode-pumped femtosecond Yb:KYW laser mode-locked by a carbon nanotube saturable absorber mirror

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Abstract: We demonstrate a 1.2-GHz repetition rate, diode-pumped, self-starting, 168-fs (FWHM) pulsewidth Yb:KYW laser mode-locked by a carbon nanotube (CNT) saturable absorber mirror. To our knowledge, this result corresponds to the highest repetition rate from CNT-mode-locked femtosecond bulk solid-state lasers, reaching the GHz regime for the first time.

OCIS codes: (140.3480) Lasers, diode-pumped; (140.4050) Mode-locked lasers; (140.5680) Rare earth and transition metal solid-state lasers; (320.7090) Ultrafast lasers.

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1. Introduction

High repetition-rate (e.g., >1 GHz) femtosecond mode-locked lasers are highly desirable for various applications such as frequency combs [1], astro-combs [2, 3], high-speed optical sampling and photonic analog-to-digital converters [4], remote timing transfer and synchronization [5] and multi-photon microscopy [6]. Diode-pumped high repetition-rate solid-state lasers have been considered as an attractive approach due to their lower cost (by using a diode laser for pumping) and easiness in repetition rate scaling (by reducing the free-space section in the cavity). In particular, Yb-doped potassium tungstate gain media, such as Yb:KYW and Yb:KGW, can provide stable, broadband and tunable outputs at useful 1-μm wavelength range when pumped by 980 nm diode lasers. As a result, various types of GHz repetition-rate Yb:KYW and Yb:KGW lasers have recently been demonstrated, most notably by Kerr-lens mode-locking (KLM) [7, 8] and by semiconductor saturable absorber mirror (SESAM)-based mode-locking [9–11]. In order to build more long-term stable and lower-cost Yb-doped potassium tungstate lasers, a single-walled carbon nanotube saturable absorber (SWCNT-SA) [12, 13] can be employed. For fiber lasers, CNT-SA-mode-locked Er:Yb-co-doped fiber lasers with ~20 GHz repetition rate and sub-ps pulse duration have recently been demonstrated [14]. However, most of SWCNT-SA-based femtosecond solid-state bulk lasers have been demonstrated for <100 MHz repetition rate [15–18], with the highest repetition rate of 194 MHz from a $Nd:BaY_2F_8$ gain medium (also note that the pulse duration of this laser was actually in the picosecond range (8 ps)) [19].

In this paper, we demonstrate a 1.2-GHz repetition rate, diode-pumped, self-starting, SWCNT-SA-mode-locked Yb:KYW laser with 168 fs full-width half maximum (FWHM) pulse duration and 8 nm FWHM optical bandwidth at 1047 nm center wavelength. To our knowledge, this corresponds to the highest repetition rate obtained from SWCNT-SA-mode-locked femtosecond bulk solid-state lasers, reaching the GHz regime for the first time. Beyond the specific Yb:KYW gain medium, this result shows the potential of diode-pumped, CNT-mode-locked solid-state lasers for robust, low-cost, and GHz repetition-rate femtosecond lasers.

2. Experimental setup

Figure 1(a) and 1(b) show the schematic and the photograph of the demonstrated Yb:KYW laser, respectively. The laser is constructed as a standard astigmatism-compensated X-cavity with one end mirror as an output coupler (OC in Fig. 1) and the other end mirror as an SWCNT-SA-coated dielectric mirror (M3 in Fig. 1). The oscillator is pumped by a polarization-maintaining single-mode fiber-pigtailed, 750 mW diode laser operating at 980 nm. The used gain medium (X in Fig. 1) is a Brewster-cut, 5%-doped, 2-mm thick Yb:KYW crystal, which is commercially available from Castech Inc. The crystal is mounted on an aluminum base at room temperature without active cooling. The 980-nm pump beam is focused by a 40-mm focal length lens, which results in a focus of ~20 μm beam radius in the crystal. The radius of curvature (ROC) of M1 and M2 mirrors is 30 mm. For astigmatism compensation, the folding angle of M1 and M2 mirrors is set to 9.6 degrees. We could obtain stable mode-locking condition when setting the M1-M2 separation around the middle of the inner stability region (~32 mm separation). In order to operate the laser in the soliton mode-locked regime with a slow saturable absorber [20], a Gires-Tournois interferometer (GTI) mirror with −800 fs^2/bounce dispersion at 1045 nm is employed for M2. Note that the contribution of the SWCNTs to the intra-cavity dispersion is negligible because the thickness of the coated SWCNTs is only about 250 nm. When adding the dispersion of the Yb:KYW crystal, the resulting net cavity dispersion for one round trip is −1200 fs^2 at 1045 nm. The M3 mirror is coated with SWCNTs and acts as a saturable absorber for mode-locking. The SWCNT-SA is fabricated by employing a similar method shown in [21]. The SWCNTs synthesized by Arc-discharge method is dispersed in dichlorobenzene (DCB) and mixed with PMMA solution. Subsequently, the well-dispersed SWCNTs/PMMA is deposited on the dielectric mirror by spin coating. The SWCNT-SA possesses saturation fluence of < 10 μJ/cm^2, modulation depth of about 0.2%, and non-saturable loss of 1%. Similar to the previous reports [16, 21], the nonlinear response is measured to be τ_1 < 150 fs and τ_2 ≈1.1 ps, corresponding to the intraband and interband relaxation processes of E_{22} transition in semiconducting SWCNTs, respectively. The beam size on the SWCNT-SA is set to ~30 μm radius. The used output coupler (OC) has a coupling ratio of 0.3%.

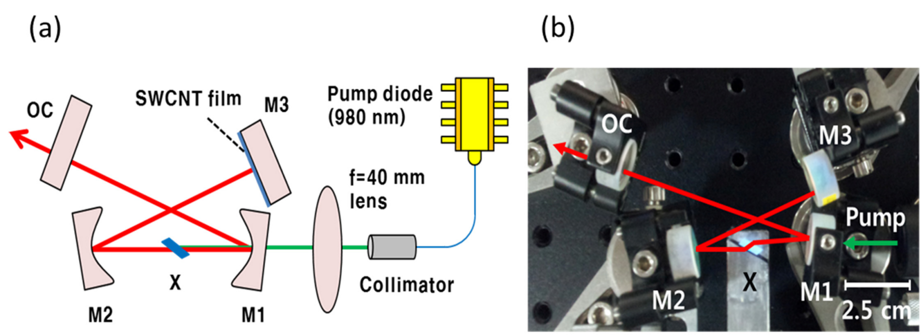

Fig. 1. (a) Schematic of the demonstrated 1.2-GHz repetition rate Yb:KYW laser. M1: broadband dielectric curved mirror with ROC = 30 mm. M2: GTI mirror with −800 fs^2 dispersion at 1045 nm and ROC = 30 mm. M3: broadband dielectric flat mirror with SWCNT-SA coating. OC: 0.3% output coupler. X: 2-mm, 5%-doped, Brewster-cut Yb:KYW laser crystal. Pump diode: 980 nm, 750 mW laser diode. (b) Photograph of the laser cavity.

3. Measurement results

Figure 2(a) shows the relationship between the pump power and the average output power of the Yb:KYW laser. The pumping threshold for mode-locking is measured to be 547 mW. The resulting energy fluence on the SWCNT-SA is ~302 μJ/cm^2 in this condition, which is ~30 times of the SWCNT-SA saturation fluence. A stable, broadband mode-locked operation is

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obtained at 743 mW pumping power, which results in 47 mW output power from the 0.3% output coupler. The optical-to-optical efficiency is 8.6% at 743 mW pump power and the slope efficiency is 6.3%. Note that the efficiency is lower than recently demonstrated SESAM-mode-locked Yb:KYW(KGW) lasers [10, 11] mainly due to the relatively large non-saturable loss of the SWCNT-SA (~1%). Figure 2(b) shows the far-field beam profile (at 430 mm distance from the output coupler) of the mode-locked laser output, which shows the ellipticity of 0.97. The measured M^2 for x-axis and y-axis are 1.3 and 1.2, respectively.

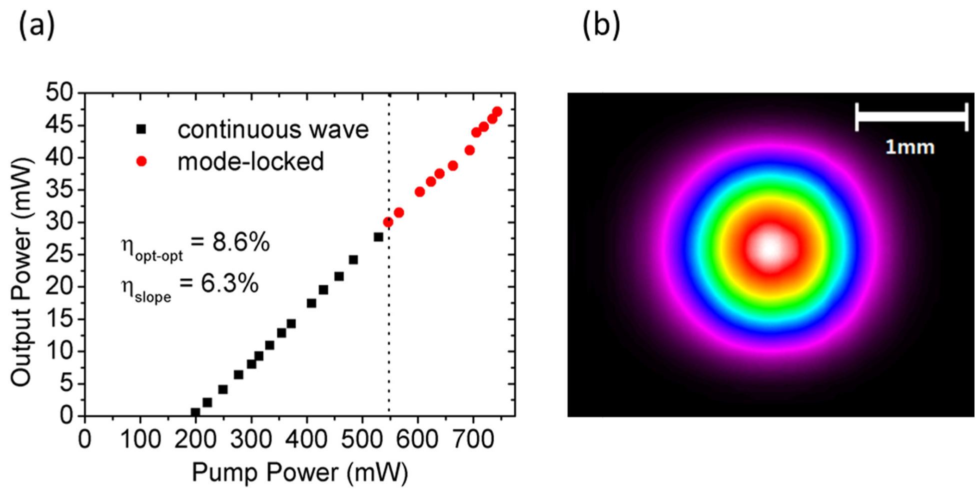

Fig. 2. (a) The average output power of the Yb:KYW laser versus input pump power. The dashed black line shows the threshold of the mode-locking operation. (b) Measured beam profile of the mode-locked Yb:KYW laser output at 430 mm distance from the output coupler (ellipticity = 0.97).

Figure 3(a) shows the measured output optical spectrum. The FWHM optical bandwidth is 8.0 nm at 1047 nm center wavelength, which corresponds to 144 fs transform-limited FWHM pulse duration. Figure 3(b) shows the measured interferometric autocorrelation (IAC) trace of the output pulses. The measured FWHM pulse duration is 168 fs when fitting the measured IAC trace to the ideal IAC of a $sech^2$-pulse shape. The measured pulse duration is 17% longer than the ideal transform-limited pulse duration (144 fs).

Figure 4(a) shows the measured RF spectrum with a 100 kHz resolution bandwidth and 5 GHz span. The measured fundamental repetition rate is 1.17 GHz, and clean single-pulse continuous wave mode-locked operation is observed without spurious frequency components or modulations over the entire 5 GHz span. Note that when a 1 kHz resolution bandwidth is used for narrower RF span, the measured extinction ratio is well above 80 dB (as shown in Fig. 4(b)). We also measured the relative intensity noise (RIN) to assess the intensity noise in the low (<10 MHz) offset frequency (as shown in Fig. 4(c)). The rms RIN is 0.27% when integrated from 10 Hz to 10 MHz offset frequency. The long-term output power stability is 0.63% (rms) measured over 1000 s (as shown in Fig. 4(d)).

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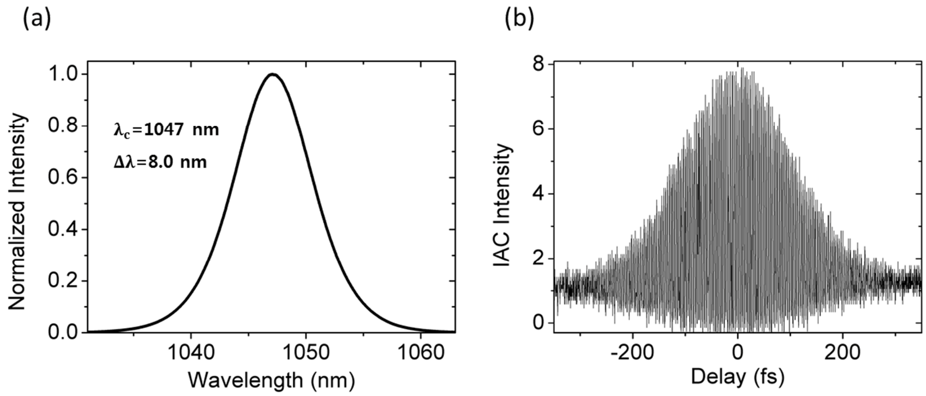

Fig. 3. (a) Measured output optical spectrum. The FWHM bandwidth is 8.0 nm at 1047 nm center wavelength. (b) Measured output interferometric autocorrelation (IAC) trace (168 fs FWHM pulse duration when fitted to the $sech^2$ shape).

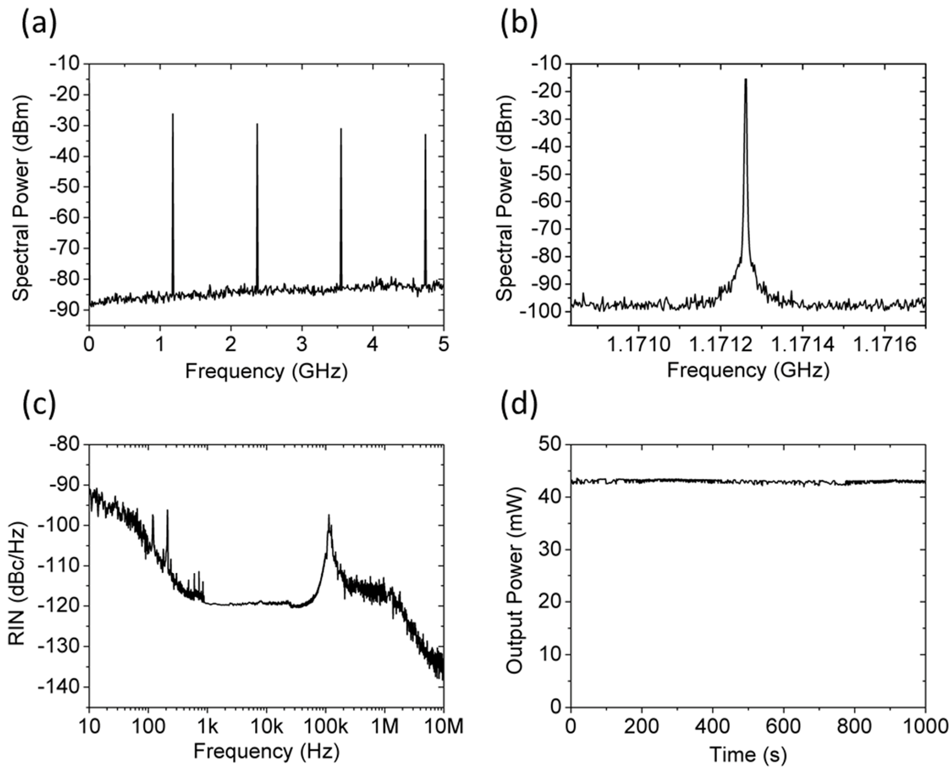

Fig. 4. (a) Measured RF spectrum with 100 kHz resolution bandwidth and 5 GHz span. (b) Measured RF spectrum with 1 kHz resolution bandwidth and 1 MHz span. (c) Measured RIN spectrum from 10 Hz to 10 MHz offset frequency (integrated RIN of 0.27% rms). (d) Measured output power stability (0.63% rms).

4. Conclusion

We developed a 1.2-GHz repetition rate, diode-pumped, self-starting, SWCNT-SA-mode-locked Yb:KYW laser with 168 fs FWHM pulse duration. To our knowledge, this result corresponds to the highest repetition rate demonstrated from SWCNT-SA-mode-locked femtosecond bulk solid-state lasers, reaching the GHz regime for the first time. Beyond the

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specific Yb:KYW gain medium, this result shows the potential of diode-pumped, CNT-mode-locked solid-state lasers for robust, low-cost, and GHz repetition-rate femtosecond lasers. As a future work, we will scale the repetition rate of SWCNT-SA-mode-locked laser into the multi-GHz regime [7, 11] by employing a transmission-type SWCNT-SA [21] in a ring cavity structure. Note that the efficiency and output power are currently limited by the non-saturable loss of the SWCNT-SA (~1%) and the available pump power from a 980-nm diode laser (~750 mW). To improve the efficiency and output power, we will investigate the feasibility of reducing the non-saturable loss of the SWCNT-SA, employing additional pump diodes from both sides of curved mirrors, and finding the optimal output coupling ratio. The demonstrated GHz SWCNT-SA-mode-locked Yb:KYW laser may serve as a useful seed source for various applications such as frequency metrology, optical sampling, and multi-photon microscopy in the near future.

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