Diode-Pumped Rational Harmonic Mode-Locked Yb:GSO Laser

Qiang Hao, Wenxue Li, E Wu, and Heping Zeng

***Abstract*—We experimentally demonstrated a sub-picosecond laser based on $Yb{:}Gd_2SiO_5$ crystal and obtained stable rational harmonic mode-locked laser output. Along with the fundamental repetition rate of 100 MHz, we observed the generation of the 200-MHz harmonics and pulse bunches, depending on the balance between the laser gain and incident pulse energy fluence on the semiconductor saturable absorber mirror. The pulse duration in harmonic mode-locking operation was measured as 600 fs, while pulses in bunch were measured with a duration of 1 ps separated by 20-ps time interval.**

***Index Terms*—Mode-locked lasers, pulse generation, ytterbium lasers.**

I. Introduction

ULTRASHORT lasers of high repetition rates up to tens of gigahertz are of advantage to high-capacity telecommunication systems, and also are attractive for metrological and spectroscopic applications [1], [2]. Passively mode-locked all-solid lasers are typically limited to a few hundred megahertz by the laser cavity lengths, and higher repetition rate requires shorter cavity length. However, shorter cavity inevitably induced both Q-switching instability and put serious restriction on output power. An effective method for building high-repetition-rate lasers is based on rational harmonic mode-locking. Multi-gigahertz and terahertz repetition rate have been achieved in mode-locked fiber lasers and semiconductor diode lasers, but the pulse energies are much less than 1 pJ [3], [4]. Furthermore, multiple pulses are observed in solid-state bulk lasers mode-locked by semiconductor saturable absorber mirrors (SESAMs) and Ti:sapphire lasers mode-locked by Kerr lens effect, but accompanied with uncontrollable time interval between adjacent pulses [5]–[7]. All correlative reports have employed dispersion-element to control the group delay dispersion (GDD) which is the primary factor to affect multiple pulse generation. The distinct difference between harmonic mode-locking and multiple pulses lies on equal or unequal time intervals of adjacent pulses. Harmonic mode-locking outputs equally-spaced pulses in one round-trip while multiple-pulse lasing has two or more bunched pulses due to temporal breakup of the fundamental pulses. It is possible to realize high-order harmonic mode-locking by collaboration of the two effects in solid bulk lasers.

Harmonic mode-locking, or so-called spontaneous pulse breaking has been reported on Yb:KGW laser as well as on Nd:glass laser mode-locked by SESAM [5], [6]. Harmonic mode-locking operation requires a strong gain in the laser cavity to sustain over-saturation of the SESAM. Owing to the simple energy-level scheme, many Yb^{3+}-doped materials have proved their excellent laser performance, such as Yb:YAG, Yb:KGW, Yb:LSO, and Yb:YSO. Recently, a series of experiments have been reported on efficient diode-pump Yb:GSO laser [8]–[11], which is a very appropriate candidate for harmonic mode-locking operation. In Yb:GSO, Yb^{3+} ion exhibits large fundamental manifold splitting up to 1067 cm^{-1} and a broad emission bandwidth with a full-width at half maximum of 77 nm. In this paper, up to fourth-order harmonic mode-locked Yb:GSO lasers were reported. Fifteen pulses in a 100-ps envelop modulated at 101.6 MHz of the fundamental repetition rate was also realized. The time interval between adjacent pulses was 20 ps determined by the slow recovery time of the SESAM.

II. Experimental Setup and Results

Fig. 1(a) shows the configuration of mode-locked Yb:GSO laser. The laser cavity consists of four mirrors, an input flat mirror M_1 with high transmission at 976 nm and high reflection from 1020 to 1120 nm, an output coupler (OC) flat mirror with a transmission of 3.5%, two folded concave mirrors M_2 (ROC $=$ 500 mm) and M_3 (ROC $=$ 300 mm) both with high reflection from 1020 to 1120 nm. Passive mode-locking was started by a SESAM (sam1064-2, BATOP), with saturation fluence of 70 μJ/cm^2, modulation depth of 2%, a fast recovery time of 500 fs and a slow recovery time of 20 ps, and the nonsaturable loss less than 0.3%. The GVD parameter for our SESAM was -85 fs^2 at 1030 nm. The SESAM was mounted on a heat sink but no active cooling was applied. Yb:GSO crystal was grown by the Czochralski method with 5at.% of Yb ion doped, and was cut to 2-mm-thick, 5×6 mm^2 aperture. Particularly, Yb:GSO crystal was antireflection-coated from 1020 to 1120 nm for the purpose of diminishing laser self-oscillation. A white-light interferometer measurement gives the group velocity dispersion (GVD) of Yb:GSO as $+86$ fs^2/mm [11]. The pump source was a 5-W diode laser at 980 nm and the pump laser beam was focus on Yb:GSO with approximately 50 μm beam diameter by a series of lens. We recorded the laser pulse train with a fast photodiode with a bandwidth of 3-GHz and a 1-GHz oscilloscope (Agilent).

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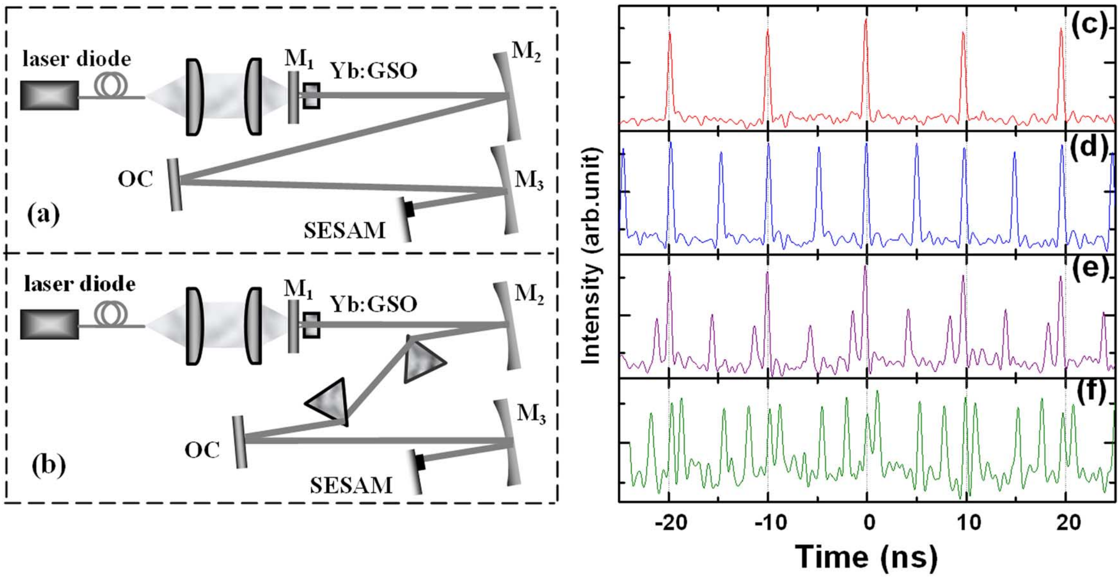

Fig. 1. Experimental setup (a) without and (b) with the insertion of the prism-pair; Pulse trains with (c) 100-MHz, (d) 200-MHz, and (e)–(f) pulse bunches.

The fundamental continuous-wave (CW) mode-locking was self-started and stable for several hours. Fig. 1(c) shows the mode-locked pulse train of 101.6 MHz. The standard deviation of the CW mode-locked pulse train was as good as that reported in [9]. Second harmonic mode-locking operation appeared when we carefully adjusted the position of both the SESAM and crystal, indicating that the intracavity dispersion and insertion loss determined the mode-locking change from fundamental to harmonic. In order to realize higher order harmonic mode-locking, a silica prism-pair was inserted in the cavity to compensate the positive dispersion. In the present work, we observed multi-pulse operation instead of soliton-pulse operation. The reason lies in the fact that the SF10 prism-pair used in the previous work [9], which were separated by 200 mm, provided GVD of -1462 fs^2. And here, we used a silica prism-pair also separated by 200 mm, providing GVD of -380 fs^2. Therefore, the net negative dispersion of GVD in the present oscillator was much larger than that in the previous work. As expected, we obtained rational harmonic mode-locking [Fig. 1(d)] and pulse bunches with unequal time intervals [Fig. 1(e) and (f)). Fig. 2(a) and (b) shows the autocorrelation traces of fundamental and second harmonics, with the corresponding output spectra shown in the insets. The autocorrelation traces fit well with a Gaussian shape, and pulse as short as 743 fs for 100-MHz operation and 606 fs for 200-MHz operation were obtained. The corresponding spectral bandwidths were roughly 3 nm centered at 1030 nm for both cases. The time-bandwidth value was calculated as 0.630 and 0.514, which were a little larger than the theoretical value of 0.441 with Gaussian line-shapes. However, it was difficult to measure the autocorrelation traces of high order harmonics, because energy exchanged continually among pulses. As shown in Fig. 1(e), two pulses emerged between the adjacent fundamental pulses and the splitting harmonic mode-locking pulse train could only maintain for minutes. Pulse energy fluctuation was typically observed along with gradual changes of time interval between adjacent pulses. This change was intensified as the splitting pulses were separated with a smaller time interval, and eventually combined into the 200-MHz harmonic pulse. The fragile pulse-splitting can be destroyed by any slight adjustment on laser cavity and subtle change in the environment. Interestingly, transformation of the repetition rate from pulse-splitting to 200-MHz is a reversible process. The time jetting and energy fluctuation in the higher order harmonic mode-locking becomes more serious [Fig. 1(f)].

Over-saturation in SESAM could bring about harmonic mode locking and multiple pulses of high repetition rates. We next explored experimentally the generation of high-repetition pulse train up to 50 GHz embedded in a 100-MHz mode-locked envelop. In the above laser setup, several pulses were observed to wrap in bunch with the inter-pulse interval of 19.50$\pm$0.57 ps. A bunch of thirteen autocorrelation traces was shown in Fig. 3(a), and a single trace was zoomed in Fig. 3(b). By induction principle, we can approximate estimate $N_{\min} = 2n-1$ and $N_{\max} = n^2-n+1$, where n is the pulse number, N is the autocorrelation trace number, and $N_{\min}$ is minimum available autocorrelation trace corresponding to equal time interval pulses, while $N_{\max}$ is the maximum available autocorrelation trace, corresponding to unequal time interval pulses. So, the 13 well-regulated autocorrelation curves shown in Fig. 3(a) were formed by 6 equal time interval pulses. Increasing the intracavity negative GDD, we observed unequal-spacing pulse breakup [Fig. 3(c)]. Three adjacent curves (showed in red pane) with ceaseless fluctuation on the intensity indicated that pulse energy was unstable. Typically, three adjacent traces were formed by double pulses correlation. The triple curves (0.91, 0.84, and 0.89 ps) were correlated by double 760-fs pulse with 4-ps time interval. The 4-ps time interval associates with the fast recovery time of the SESAM. Finally, as many as 15 pulses per round-trip were realized and the time interval between adjacent coherent pulses was measured as 19.30$\pm$0.58 ps. The periodic autocorrelation trace of $N = 31$ envelop was shown in Fig. 3(e). Fig. 3(f) shows the duration of the pulse bunch and the single pulse energy as a function of pulse number n. The duration of the pulse bunch was expanding with the increasing pulse breakup and was measured as wide as 137

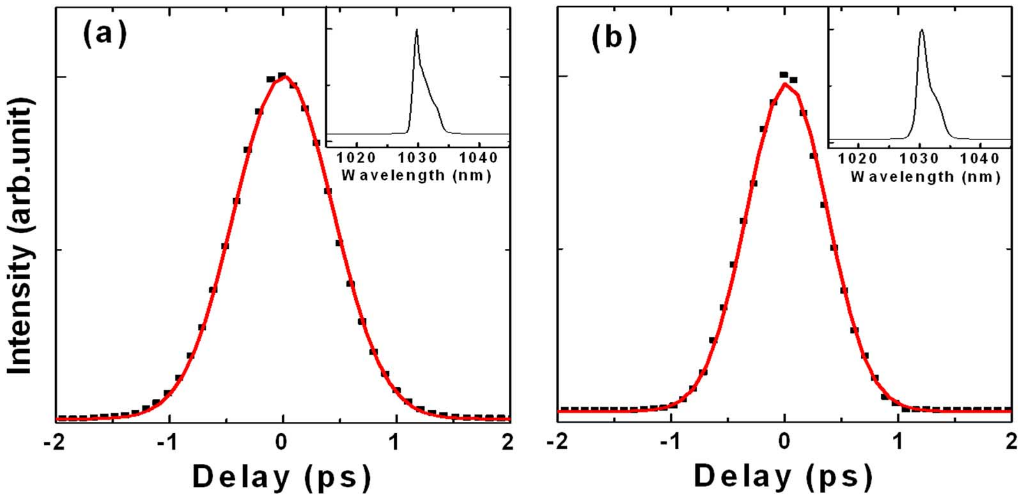

Fig. 2. Pulse duration for (a) 100-MHz and (b) 200-MHz operation with the corresponding output spectra in the insets.

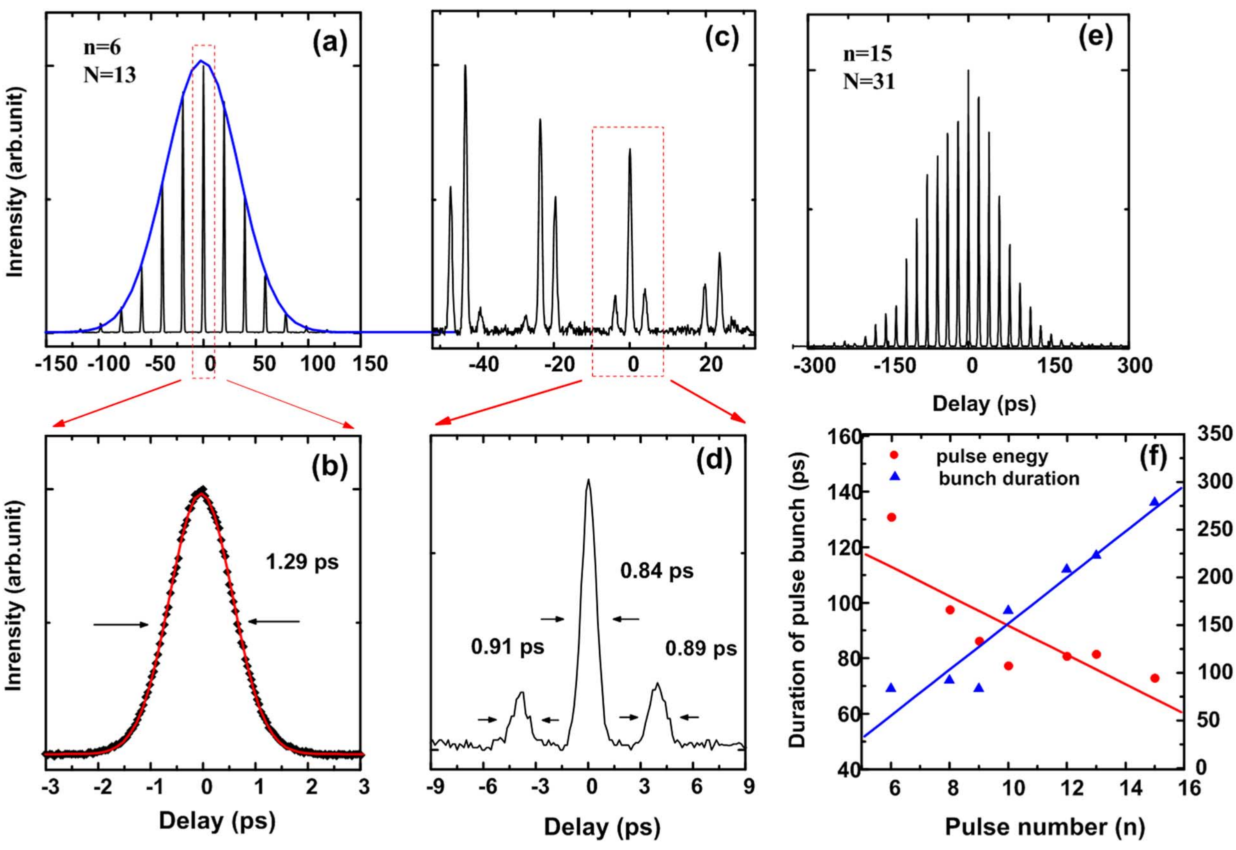

Fig. 3. (a) Pulse duration for $n = 6$ multiple pulse operation and (b) a single carve zoomed in (a). (c) Duration of unequal-spacing pulse bunches and (d) triple curves formed by double pulses. (e) Pulse duration for $n = 15$ multiple pulse operation. (f) Duration of pulse bunch and single pulse energy verse pulse number n.

ps when $n = 15$ or $N = 31$. The maximum pulse energy 260 pJ with 1.07$\pm$0.05 ps pulsewidth was obtained at $n = 6$, while the minimum pulse energy 94 pJ with 1.07$\pm$0.04 ps pulsewidth was obtained at $n = 15$. The intracavity laser beam diameter was estimated as 100 μm on the Yb:GSO crystal and 60 μm on the SESAM. The incident energy intensity was estimated as 1.0 mJ/cm^2 on the SESAM, which was fourteen times stronger than the saturation fluence 70 μJ/cm^2. In such a situation, the SESAM worked on the multiple pulse regions and its reflectivity was no longer as strong function of the pulse energy [12]. Another proof for the over-saturation was the bright green spot on the SESAM resulting from strong double-photon absorption.

III. Conclusion

We have shown a new method to realized high repetition rate at multi-MHz and 50 GHz. Pulse number in the bunch was controllable with the total intracavity GVD which was dominated by the gain material, SESAM and the insertion of the prism. More than 100 pJ pulse energy was obtained from Yb:GSO laser with 50 GHz pulse bunch, which may promote applications in metrology and spectroscopy.

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