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OPTICAL PHYSICS

Self-starting 12.7 fs pulse generation from a mode-locked Ti:sapphire laser pumped by a femtosecond Yb:KGW laser

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A self-starting femtosecond harmonic mode-locked Ti:sapphire laser is demonstrated, pumped by a 75.5 MHz frequency-doubled mode-locked Yb:KGW oscillator. The maximum average output power is 256 mW at the central wavelength of 811 nm with 3.6 W pump power. A pulse duration as short as 12.7 fs is obtained by using a 3% output coupler. The repetition rate of the Ti:sapphire laser is set to be 151 MHz, which is successfully locked to the twice that of the pump laser.

OCIS codes: (140.4050) Mode-locked lasers; (140.7090) Ultrafast lasers; (320.0320) Ultrafast optics.

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1. INTRODUCTION

High-repetition-rate ultrafast femtosecond laser sources are of great application in the fields of time-resolved spectroscopy [1,2], optical frequency metrology [3], optical communication systems [4], and difference-frequency terahertz-wave generation [5,6]. The high-repetition-rate pulses have a great advantage in promoting the signal-to-noise ratio (SNR), which is of significance in the optical frequency metrology and pump-probe measurement [3,7–9]. In addition, pulses with a high repetition rate are used as the pump laser and operate a synchronously pumped optical parametric oscillator (OPO) at equally high or even higher repetition rate [10–12]. Since the first Kerr lens mode-locked (KLM) titanium-doped sapphire (Ti:sapphire) laser was generated by Spence *et al.* in 1991 [13], Ti:sapphire has been the most commonly used for ultrashort solid-state lasers owing to its large stimulated emission section, broad absorption gain bandwidth, and high thermal conductivity. Up to now, several methods have been reported to generate a mode-locked pulse in Ti:sapphire laser system, such as acousto-optic mode locking [14], injection seeding [15], and passive mode locking [16]. The general method to obtain the mode-locking pulse is KLM by adjusting resonator cavity or using semiconductor saturable absorber mirror (SESAM) inside the cavity [17]. Recent years, the synchronous pump is a feasible method to generate a self-starting mode-locking Ti:sapphire femtosecond laser. In 1991, Spielmann *et al.* have demonstrated a mode-locked Ti:sapphire laser synchronously pumped by a mode-locked frequency-doubled Nd:YLF laser [18]. By 1994, Siders *et al.* have reported a 40 fs mode-locking Ti:sapphire laser synchronously pumped by a 100 ps mode-locked frequency-doubled Nd:YAG laser [19]. Several years later, Richard *et al.* obtained a sub-10 fs Ti:sapphire laser synchronously pumped by a 7 ps mode-locked frequency-doubled $Nd:YVO_4$ laser [20]. With this method, the Ti:sapphire laser system can obtain self-starting operation without cavity optimization and also without any additional triggering device. In 2017, Didenko *et al.* described a method of synchronous pumping of a Ti:sapphire laser by a high-power femtosecond Yb^{3+}-doped laser [21] with locking of the lasers due to the nonlinear coupling between the short pump pulses having a high peak power and the oscillation pulses inside the Ti:sapphire crystal. Compared to picosecond pump sources, the method of femtosecond pulsed pumping can also provide self-starting of the mode-locking operation and obtain the same output parameter. In addition, it has an advantage in locking accuracy of the repetition rate. The difference of the repetition rate is within millihertz between the pump laser and Ti:sapphire laser [21], providing that difference of the cavity lengths can be controlled within 1 μm. More importantly, for generation of high-repetition-rate mode-locked pulses, a femtosecond synchronously pumped Ti:sapphire laser can dramatically enhance the self-starting mode. It is feasible to utilize a low-repetition-rate laser pulse train to pump Ti:sapphire to generate a high-repetition-rate laser by matching the cavity length between the pump and the oscillator laser, which still leads to self-starting of the mode-locked process. In such a case of several hundred MHz up to a few gigahertz (GHz), it overcomes weak starting performance in the region of high-repetition-rate KLM lasers. In addition, because the repetition rate and the phase is precisely locked, it is a feasible method that a femtosecond pumped Ti:sapphire laser can be used as the front-end system in the optical parametric chirped pulse amplification (OPCPA) setup.

In this paper, we report self-starting femtosecond pulses from a Ti:sapphire laser synchronously pumped by a 75.5 MHz mode-locked, lithium triborate (LBO) frequency-doubled femtosecond Yb:KGW laser. Using a 3% output coupler (OC), the maximum power is 256 mW with 3.6 W pump power. The pulse duration is 12.7 fs by deploying dispersion compensation. The oscillator cavity length is 993 mm, and the corresponding repetition rate is 151 MHz, which is successfully locked to double the repetition rate of the Yb:KGW laser.

2. EXPERIMENTAL SETUP

The experimental setup is shown in Fig. 1. The pump source is a commercial femtosecond mode-locked Yb:KGW laser (Light Conversion, Flint6.0) delivering 90 fs pulses at 75.5 MHz repetition rate. The output power is 7 W at the central wavelength of 1030 nm. The LBO crystal is cut for type-I phase matching in the $X-Y$ plane ($\theta = 90°, \varphi = 13.6°$) with a length of 2.4 mm, coating with high transmittance at 1030 nm, and 515 nm on the both surface. A 100 mm focal length lens (L1) is used to focus the pump beam into the center of the LBO crystal and followed by a 150 mm focal length collimating lens (L2). Two dichroic mirrors (DM) spectrally separate the green pulses (reflecting) and the remaining pump pulses (transmitting). A half-wave plate (HWP2) and a polarizing beam splitter (PBS) are employed as a variable attenuator to change the green pump power. The Ti:sapphire oscillator is a linear standing wave cavity with six mirrors. The cavity length is 993 mm, corresponding to a repetition rate of 151 MHz, which is equal to double of that of pump laser. To match the cavity length between the Ti:sapphire oscillator and the pump laser, the cavity length can be fine-tuned by translating

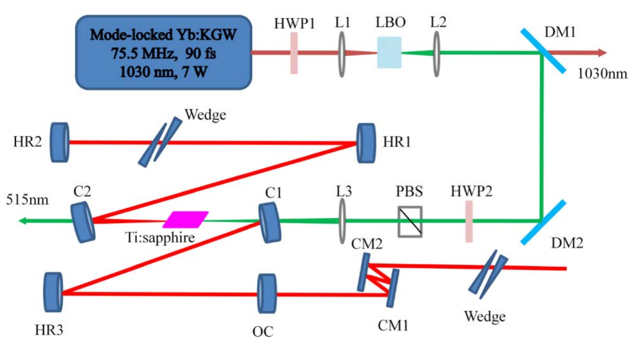

Fig. 1. Schematic of the experimental setup for Ti:sapphire laser. L1–L3, lenses with $f1 = 100$ mm, $f2 = 150$ mm, $f3 = 75$ mm; HWP, half-wavelength plate; PBS, polarizing beam splitter; DM1–DM2, dichroic mirrors; Cl–C2, concave spherical mirrors with $R = 100$ mm; HR1–HR3, plane mirrors; OC, 3% output coupler; CM1–CM2, chirped mirrors.

the output coupler (OC) mirror, which is fastened at the one-dimensional translation stage. The Ti:sapphire gain medium is cut at Brewster's angle with a size of $4 \times 4 \times 4$ mm and absorbs 93% of pump power at 515 nm. It is wrapped with indium film and then placed tightly on a water-cooling copper heat-sink block, where the temperature is maintained at 14°C. Two concave spherical mirrors C1 and C2 ($R = 100$ mm) comprise the pump mirrors, which have high reflection in the near infrared 550 to 1100 nm. In addition, a relatively thinner 3% OC is selected to improve the intra-cavity power density and also reduce the extra second-order material dispersion.

3. RESULTS AND DISCUSSION

At first, the LBO is considered as an excellent nonlinear crystal for second harmonic (SH) generation owing to its high optical damage threshold, large nonlinear coefficient, and small walk-off effect. With 7 W fundamental power, the SH maximum power is 3.6 W at 515 nm, and the corresponding conversion efficiency is 51.4%. Long-term stable mode operation for SH is achieved and the fluctuations are less than 1% with a diffraction-limited beam $M^2 < 1.2$. Based on this perfect green laser, we first align continuous-wave (CW) operation in the cavity with the maximum output power. After that, the self-starting mode-locked pulses are easily obtained when the cavity length is precisely fine-tuned to half that of the pump laser. The mechanism of the self-starting mode-locked laser is attributed to the nonlinear coupling between the Ti:sapphire oscillation and the short pump pulses with high peak power inside the Ti:sapphire crystal [21–23]. Except for self-phase modulation, it is worth noting that the high-efficiency cross-phase modulation of Ti:sapphire pulses and pump pulses spread together with high third-order nonlinearity in the crystal can generate efficient temporal absorption even if there exists negative dispersion in the cavity. Wavelength shifts of the pulses induced by cross-phase modulation combine with the wavelength dependence of the cavity round-trip time for the efficient synchronization of the femtosecond pulse trains [24,25]. For a synchronously pumped Ti:sapphire laser, it is important to clarify the relationship of the repetition rate between the pump and the oscillation pulses. It is feasible to utilize a low-repetition-rate laser pulse train to pump Ti:sapphire with an M times shorter cavity length, that is $L_T = L_P/M$, where L_T and L_P denote the corresponding cavity length of the Ti:sapphire and the pump laser, respectively, and M is a integer number. Similarly, it is can be inferred that pumping at a high harmonic of the fundamental repetition rate will generate low-repetition-rate pulses when the cavity length is matched and still lead to the self-starting of the mode-locked process. With the cavity length of Ti:sapphire appropriates alignment to half of the pump laser, the mode-locked pulses are achieved. Then the Ti:sapphire emits a pulse train with twice the pump repetition rate. In this mode of operation, no obvious modulation in the output pulses are observed because the repetition rate of Ti:sapphire is precisely locked to double that of the pump laser. It is noted that translating the OC mirror to change the cavity length within several tens of microns could not affect the laser steady operation once the femtosecond mode-locked pulses are

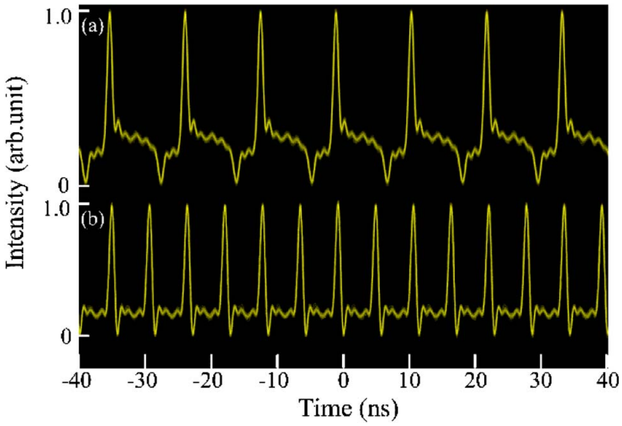

Fig. 2. Mode-locked pulse trains at 10 ns/div: (a) mode-locked Yb:KGW laser; (b) mode-locked Ti:sapphire laser.

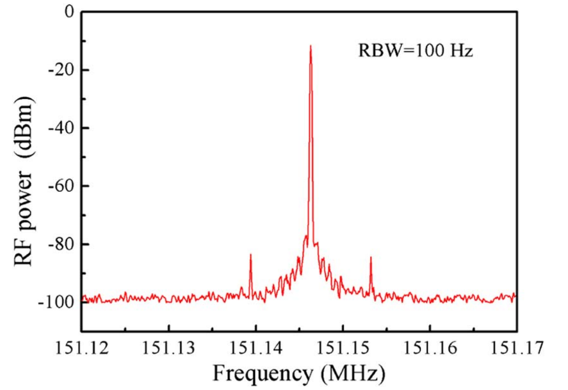

Fig. 4. Radio frequency spectrum of the mode-locked Ti:sapphire laser with RBW of 100 Hz.

established. Figure 2 clearly depicts the relationship of repetition rate between the mode-locked Yb:KGW laser and the Ti:sapphire laser. The stable pulse train is well synchronized to the pump laser at the maximum mode-locked output power and is detected by a fast photodiode and recorded with an oscilloscope. The repetition rate of Ti:sapphire is almost equal to twice that of the pump pulses, and the difference is more than 100 Hz. Due to the perturbation of the surrounding, the pulses train presents slight fluctuation. To optimize the mode-locked pulses for long-term operation, the cavity length is maintained at a fixed position. The stable operation is supported for several hours even though no behavior is introduced to disturb the laser. The loss of the mode locking is due to the perturbation of the surrounding environment, such as air turbulence and lab vibration. Fortunately, the femtosecond mode-locked pulse operation can easily be recovered by slightly translating the OC mirror. The typical radio frequency spectrum (RF) of the mode-locked Ti:sapphire laser pulses is recorded with a spectrum analyzer. As shown in Fig. 3(a), the high SNR is 78 dB at 151 MHz with the resolution bandwidth (RBW) of 1 kHz. Figure 3(b) also depicts the wide span measurement that exhibits the high harmonic of the fundamental frequency. The RF spectrum precisely indicates that femtosecond pumped Ti:sapphire laser pulses are stable in mode-locked operation.

For femtosecond pumped Ti:sapphire to obtain self-starting mode-locked pulses, the Ti:sapphire laser contains no modulation if the cavity length of two lasers are matched perfectly.

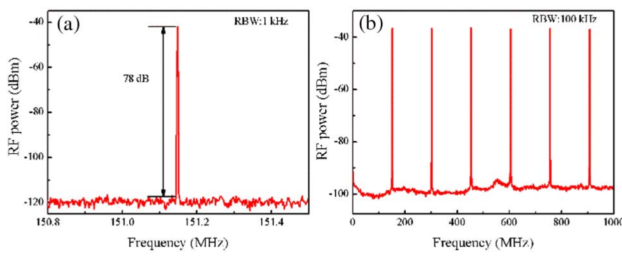

Fig. 3. Typical radio frequency spectrum of the Ti:sapphire laser. (a) RF spectrum of the fundamental beat note with the RBW of 1 kHz; (b) wide spectrum of 1 GHz with the RBW of 100 kHz.

However, the repetition rate of the pump and Ti:sapphire laser cannot be locked completely by a one-dimensional manual translation stage. Figure 4 shows the radio frequency spectrum of the mode-locked Ti:sapphire laser with RBW of 100 Hz. It can be noticed that the output pulse of Ti:sapphire is slight modulation and the trace has two side peaks due to the different repetition rate of the two lasers. The repetition rate of the femtosecond pump source is detuned at 6 kHz, corresponding to the detuning of cavity length of 39 μm. The parameters are similar to those for the case of picosecond pulse pumped source. Both sides of the trace present as smooth and below −78 dB resulting in low power modulation of the output pulse. It can be noticed that the fundamental beat note at 151.146 MHz reveals a high SNR of 70 dB from the central spike.

In our experiment, the group delay dispersion (GDD) from a 4 mm long Ti:sapphire laser is about 240 fs^2 at a near Brewster angle. The GDD induced by air with a length of 0.994 m is close to 21.2 fs^2 at the central wavelength of 811 nm. In order to optimize the GDD in the cavity, a pair of concave chirped mirrors (C1 and C2) with −70 fs^2 GDD for each piece is used to compensate for the positive intracavity dispersion, which is introduced by the gain medium and air. In addition, another double pair of plane chirped mirrors (HR2 and HR3 coated with −100 fs^2 GDD for each one, HR > 99.8% from 640 to 1000 nm) are employed to guarantee approximately −30 fs^2 net GDD in the cavity, which is near the empirical value. In order to control the temporal and spectral characteristics of the output laser to obtain Fourier-transform-limited pulse duration, another pair of chirped mirrors and wedges are used for extra-cavity dispersion compensation. Fine dispersion control is managed by changing the number of reflections between the chirped mirrors and the insert length of the wedges. As shown in Fig. 5, the pulse duration is measured by a commercial autocorrelator (Femtolasers V1.65). Assuming a $sech^2$-shaped pulse, the pulse duration is 12.7 fs. As shown in the inset of Fig. 5, the corresponding spectrum ranges from 680 to 930 nm and is relatively flat at different wavelengths. The full width at half-maximum (FWHM) of the spectrum is 156 nm, and the corresponding Fourier transform-limited pulse is 7.6 fs calculated by Fourier transforming the spectrum

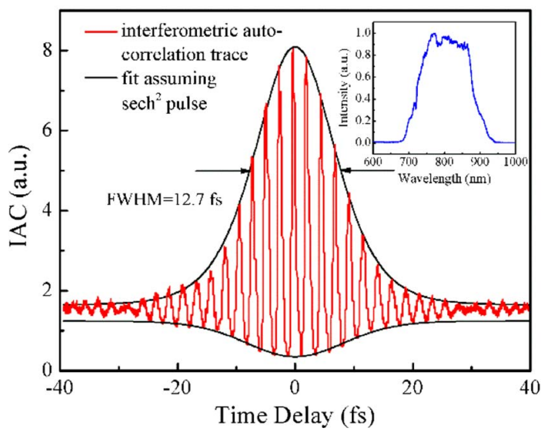

Fig. 5. Interferometric autocorrelation traces of the compressed 12.7 fs mode-locked pulse (red curve) with a sech^2 fitting (black curve) under 3% transmissions. Inset: corresponding the spectrum centered at wavelength of 811 nm.

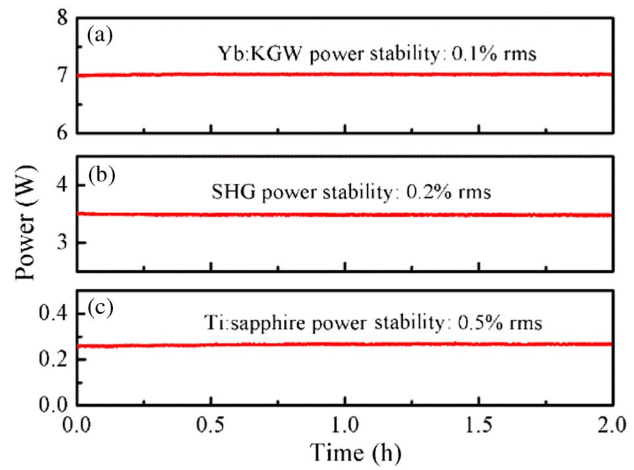

Fig. 7. Power stability of the output power in 2 h. (a) Yb:KGW laser; (b) SHG; (c) Ti:sapphire laser.

without dispersion. It indicates there is less residual chirp within the mode-locked pulses.

Figure 6 displays the output powers and pulse duration of the mode-locked laser versus different pump powers. With 3.6 W pump power, the maximum output power of the Ti:sapphire is 256 mW. The slope efficiency is close to 7%, and the pump threshold is 2.02 W. In this mode operation, the tolerance of the cavity length takes on a decreasing trend with the decline in pump power, which indicates it is limited by the level of the power density in the cavity. At the same time, the tolerance is shorted from several tens of micrometers to a dozen micrometers with the decline of the pump power from 3.6 to 2.02 W. It is difficult to obtain the self-starting mode-locked pulses when the pump power is below 2.02 W. Above the pump threshold, the pulse duration is in the range of 12.7 fs to 13.3 fs. In order to further reduce the pump threshold, a 1% OC replaces the prior one and the maximum mode-locked power is down to 117 mW, corresponding to the conversion efficiency of 3.2%. There is no obvious output spectrum broadening for the Ti:sapphire laser, although the pump threshold is down to 1.8 W. In addition, the long-term output power stability for Ti:sapphire is measured. Figure 7 depicts the power stability of the Yb:KGW, SH pulse, and Ti:sapphire. For a fixed pump power of 3.6 W, the Ti:sapphire output power is recorded to be stable with a fluctuation of less than 0.5% rms within 2 h. The fluctuation of the output power is due to the environmental perturbation, air flow, and the synchronization precision. The use of a precise motorized translation stage and active feedback control could result in stable output power and mode-locked operation.

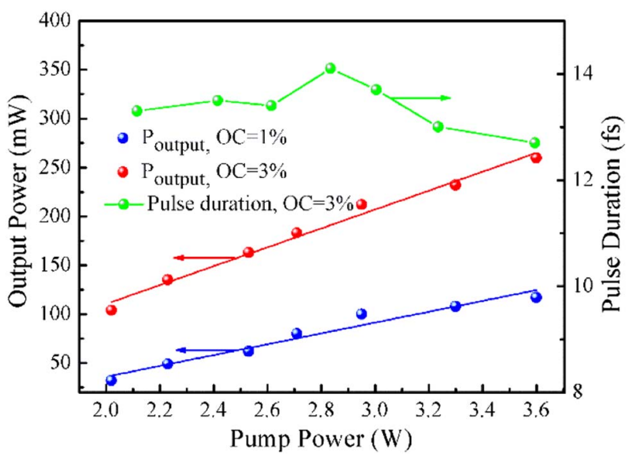

Fig. 6. Mode-locked output powers and pulses duration of Ti:sapphire as a function of the pump power.

4. SUMMARY

In conclusion, we have demonstrated a self-starting Ti:sapphire laser synchronously pumped by a 75.5 MHz frequency-doubled femtosecond mode-locked Yb:KGW laser. With 3.6 W pump power, the maximum mode-locked power is 256 mW. The pulse duration is 12.7 fs at the central wavelength of 811 nm, and the corresponding FWHM spectrum is 156 nm. To obtain the high repetition rate pulses, the cavity length matching is quite accurate between the Ti:sapphire oscillator and the pump laser. The Ti:sapphire oscillator operates at 151 MHz repetition rate, which is successfully locked to double that of the pump laser. Compared to CW and picosecond pumped methods, the femtosecond pumped Ti:sapphire is a potential means to obtain a high-repetition-rate self-starting femtosecond laser. Such a stable, high-repetition-rate femtosecond laser has many applications in multi-photon fluorescence microscopy and telecommunications.

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