Sum-frequency generation between an actively synchronized ultrashort Ti:sapphire laser and a Nd:YVO_4 laser

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We realized stable synchronization between a femtosecond Ti:sapphire laser and a picosecond Nd:YVO_4 laser by using a precise phase-locked loop technology; ultrashort laser pulses at a wavelength around 460 nm were generated by frequency mixing both laser branches. This work demonstrated a feasible way to extend the available ultrashort laser wavelength through nonlinear frequency mixing technology. © 2008 Optical Society of America

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1. INTRODUCTION

Extending the available ultrashort laser wavelength is an interesting topic in ultrafast laser science. Because of the limited laser gain media for femtosecond generation, optical parametric oscillation and amplification are widely used to generate tunable ultrashort laser pulses for application research [1–4]. Although the technologies of femtosecond optical parametric oscillation and amplification have developed greatly in the past decade, their total efficiency and stability are worse than those of nonlinear sum-frequency technology. In particular, as an ideal way to extend laser frequencies, second-harmonic generation (SHG) performs with high efficiency and stability [5–7]; however, because of the limited available femtosecond laser sources, we can obtain only some special laser wavelengths with SHG.

In recent years, we have developed techniques for synchronizing two femtosecond lasers with low timing jitter and long-term stability [8,9]. Based on this work, it is possible to generate ultrashort laser pulses at a new wavelength by frequency mixing two synchronized laser branches, either by sum-frequency generation (SFG) or difference-frequency generation. As the nonlinear technology for frequency convension, SHG and SFG can be used for frequency upconversion, and difference-Frequency generation for frequency downonversion, even to terahertz radiation. Thus frequency mixing two laser branches from a synchronized mode-locked laser may help us to develop a new technique to generate new ultrashort laser wavelengths with higher conversion efficiency, superior stability, and lower cost than optical parametric oscillation and amplification. In fact, femtosecond laser pulses at a wavelength near 500 nm has been demonstrated by SFG with a passively synchronized Ti:sapphire laser and Cr:forsterite laser [10], in which SFG performed with a nonlinear efficiency similar to SHG.

To generate the new ultrashort laser pulse with the mixing frequency technology, stable synchronization between two mode-locked lasers is necessary. There are two types of scheme for synchronizing independent mode-locked lasers, which may be passive or active. In general, the passive scheme is of all-optical technology [11,12], where the cross-phase modulation effect in a Kerr medium is responsible for the mechanics of synchronization. Although passive synchronization performs with an extremely low timing jitter, it is accompanied by some disadvantages in its complex optical configuration and spatial dependence. In contrast, the active scheme utilizes an electronic phase-locked loop (PLL) to match the cavity lengths of two laser oscillators to lock their repetition rates and hence to realize synchronous laser operation [13,14]. Although the active scheme allows both lasers to be freely set in space and is suitable for more lasers, normally it performs with a relatively larger timing jitter than the passive scheme. With the recent development in carrier envelop phase (CEP) control and an optical frequency comb with femtosecond laser pulses, the precision of active synchronization is approaching that of the passive [15]. Therefore, the technique of active synchronization provides a flexible way to synchronize any two mode-locked lasers that may have completely different wavelengths and pulse widths.

In this paper we report active synchronization between a picosecond Nd:YVO_4 laser and a femtosecond Ti:sapphire laser; a timing jitter of less than 350 fs was realized. Based on this work, we generate a broadband ultrashort laser pulse at the central wavelength of 460 nm by frequency-mixing two synchronized laser branches in a β-BaB_2O_4 (BBO) crystal. The typical rms stability is about 5%. This work demonstrates a new way to extend the wavelength of ultrashort laser pulses with nonlinear frequency mixing technology.

2. EXPERIMENTAL SETUP

The schematic experiment setup is shown in Fig. 1. A commercial picosecond $Nd:YVO_4$ laser (High Q Laser Production GmGH) and a homemade femtosecond Ti:sapphire laser were used as two sources for synchronization. For the $Nd:YVO_4$ laser, a semiconductor saturated absorption mirror is used to start and sustain mode-locked operation at the repetition rate of 68 MHz; a laser pulse as short as 6.8 ps is generated with an average power of 3 W. The femtosecond Ti:sapphire laser is designed with a prism-dispersion-controlled scheme [16]; under the pump power of a 5 W CW 532 nm laser (Verdi 5), it can generate stable laser pulses shorter than 50 fs at the central wavelength of about 810 nm with bandwidth wider than 20 nm. In order to synchronize the Ti:sapphire laser with the $Nd:YVO_4$ laser, we preset the cavity length at 2.2 m, and mount the end mirror on a piezo transducer (PZT), which is controlled by self-designed PLL electronics. To lighten the load of the PZT, the end mirror is manufactured with a 6 mm diameter and 1 mm thickness. Changing the voltage on the PZT will enable us to adjust the cavity length finely and quickly for accurate synchronization. The mirror mount, on which the PZT is installed, is fixed on a motorized linear fine stage so that the cavity length of the Ti:sapphire laser can also be controlled by the computer on a larger scale and at a much lower speed. Then the dual-color laser beams are focused inside a BBO crystal with separate lenses. Adjusting the delay line in the Ti:sapphire laser arm can optimize the overlap between the two laser pulses in the temporal and spatial domains. Two fast-response photodetectors (S5973 and G8376, Hamamastu Photonics, Inc.) are utilized to detect the mode-locked laser pulses from both branches, and both the fundamental and the 12th harmonic of the repetition rate are extracted to two sets of PLLs, in which the repetition rates of the two lasers are compared and the feedback control voltage is generated to drive the PZT inside the Ti:sapphire cavity. The operating principle of the two PLLs is discussed in detail as follows.

As shown in Fig. 1, we designed two PLLs with repetition rates of 68 and 816 MHz for different capture ranges and locking precision. The first has a wide capture range so that the initial synchronization can be established easily, while the second can be switched instead of the first for fine locking.

The scheme of the 68 MHz PLL is indicated in Fig. 2. The fundamental frequency (i.e., 68 MHz) signals are filtered and amplified from two photodetectors and are divided by 256 at 265.6 kHz. The signal from the Ti:sapphire laser passes through an adjustable delayer and is fed into the phase–frequency detector (PFD) together with the signal from the $Nd:YVO_4$ laser. The output from the PFD goes into an active second-order filter (loop filter); after further amplification, it finally generates the control voltage to drive the PZT for tuning the cavity length of the Ti:sapphire laser. In Fig. 2 we also show the principle that the PFD compares two signals with a frequency of 1/256 of the laser repetition rate, so that the output should include relatively less error information on the frequency and phase of two series of mode-locked laser pulses. Therefore, if this PLL is used to control the synchronization between two lasers, the precision is relatively low and the timing jitter is about 10 ps. Considering the pulse duration of the two lasers, such precision is not high enough for stable SFG. However, the large capture range makes it easy to establish synchronization between the two lasers. Furthermore, by adjusting the delayer in this PLL, the relative temporal position between two pulses can be changed into a desirable value (more than 10 nanosecond range), which is very helpful For SFG between the two branches.

Figure 3 indicates the schematic of the 816 MHz PLL scheme. The pulse signal from the mode-locked $Nd:YVO_4$ laser first passes through a band filter and an amplifier, by which its 12th-harmonic frequency (816 MHz) signal is extracted. Then the harmonic signal is input to the RF port of one double-balanced mixer, the local oscillator port of which is loaded by the 816 MHz sine signal derived from synthesizer. Thus the harmonic signal is downconverted into a low-frequency signal with a frequency of 300 kHz output from the intermediate frequency port of the double-balance mixer. Then this 300 kHz signal is

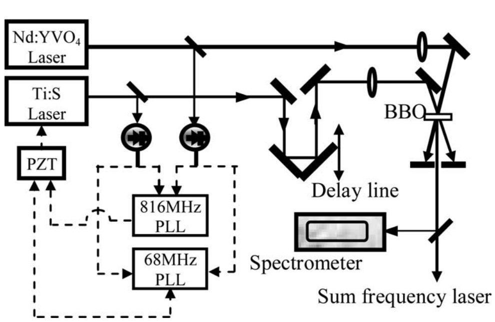

Fig. 1. Schematic diagram of synchronized lasers and SFG.

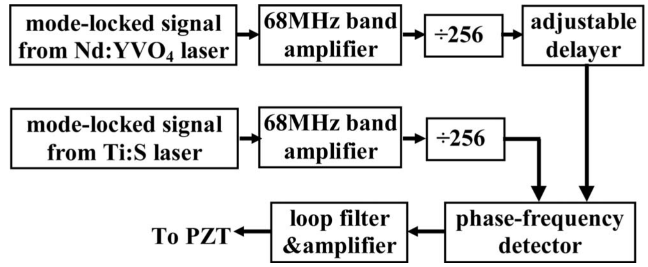

Fig. 2. Schematic diagram of 68 MHz PLL.

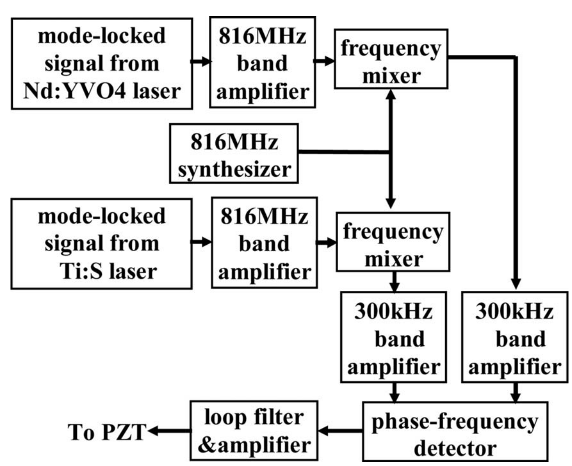

Fig. 3. Schematic diagram of 816 MHz PLL.

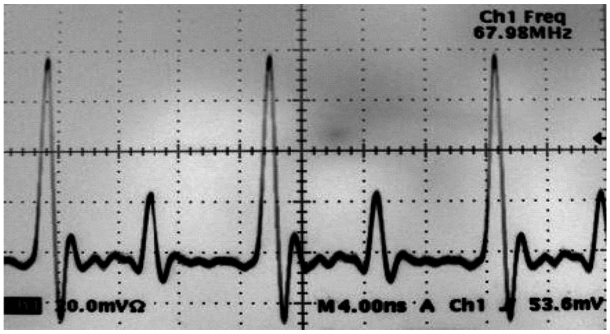

Fig. 4. Synchronized laser trace acquired by an oscilloscope.

amplified and translated into a TTL (transistor–transistor logic) signal. The other 300 kHz TTL signal, going through identical signal processing, is from the Ti:sapphire laser. Both TTL signals are fed into a PFD. Its output also goes through the loop filter and the amplifier and finally generates the control voltage to drive the PZT in the Ti:sapphire laser. Since the 300 kHz signal is derived by the same downconversion scheme, the phase detection process is equivalent to comparing two 816 MHz signals directly, which are the 12th harmonic of the repetition rate. Application of high-harmonic phase detection provides higher sensitivity to phase error [17] and therefore results in much better synchronization precision. Compared with the 6.8 ps pulse duration of the Nd:YVO_4 laser pulse, the timing jitter here is low enough to enable stable SFG.

Either of these two PLLs has its own inherent advantages and disadvantages, and the solution to this problem is to combine the best properties of them to lock two lasers, which is accomplished by sequential application of two PLLs. First the output signal of the 68 MHz PLL is used to drive the PZT in the Ti:sapphire laser, and then it is locked to unambiguously establish the synchronization between two laser pulses. Once the synchronizion is started, we can adjust the delayer in this PLL to set the relative timing between two pulses to a preferable value. Then the driving voltage to the PZT is quickly switched from 68 MHz PLL to the 816 MHz PLL, and the harmonic loop then takes over for the former loop to lock the two lasers and result in low timing jitter. During this process, the relative temporal position between the two laser pulses almost does not change. Once the laser operates at the synchronous mode with the 816 MHz PPL, tight phase-locking can be maintained for several hours continuously.

3. SUM-FREQUENCY GENERATION

To generate the sum-frequency, we focus each of the the two synchronized laser branches into a BBO crystal with separate lenses. Considering the different wavelengths of each laser beam, it is helpful to obtain an optimized focus with two independent lenses. A high-speed photodiode is used to detect both laser pulses and roughly determine their temporal collapse inside the crystal. We first connect the PZT drive input to the 68 MHz PLL. When the two lasers are successfully locked, we can observed the pulse trains from the oscilloscope as shown in Fig. 4, in which both laser trains with different amplitudes represent the two synchronized mode-locked laser pulses. By adjusting the delayer in the PLL, we can make the two series of pulse signals lie on top of each other. After that, we quickly switch the driving voltage to the PZT from this PLL to the 816 MHz PLL, and the pulse trains on the oscilloscope (with sampling frequency of 500 MHz) do not change, which means that the variation of relative temporal position between the two laser pulses is less than 200 ps. To determine the timing jitter exactly, we further carried out the cross-correlation measurement by changing the time delay between the two pulses. Figure 5(a) is the typical trace of SFG when the delay is swept; it shows that the FWHM of the cross correlation is about 7 ps. Figure 5(b) is the time record of the intensity fluctuation of the SFG at a fixed delay when the cross-correlation signal was half the height of the peak, which indicates that the standard deviation is about 0.6, corresponding to a stability of about 5%, implying that the rms timing jitter between the two lasers is less than 350 fs (500 Hz bandwidth) in 10 s.

Once two laser pulses are precisely synchronized, the SFG signal can be further optimized by improving their spatial overlap inside the BBO crystal and fine-tuning the delay line between two lasers. Figure 6 shows photographs of laser beams taken by a digital camera; Fig. 6(a) represents three lasers beams at different wavelengths

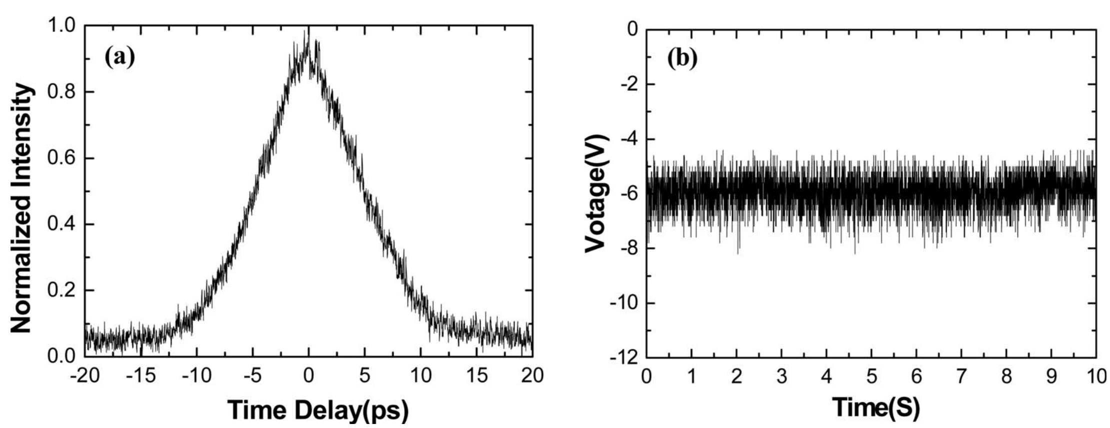

Fig. 5. (a) Cross-correlation trace between the Nd:YVO_4 laser and Ti:sapphire laser and (b) fluctuation record of the SFG at half-peak. The corresponding rms stablity is about 5%; we infer that the timing jitter is less than 350 fs in 10 s (500 Hz bandwidth).

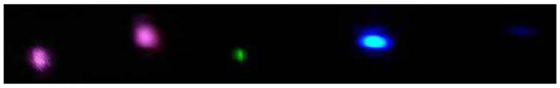

Fig. 6. (Color online) Fundamental and second-harmonic as well as sum-frequency laser beams.

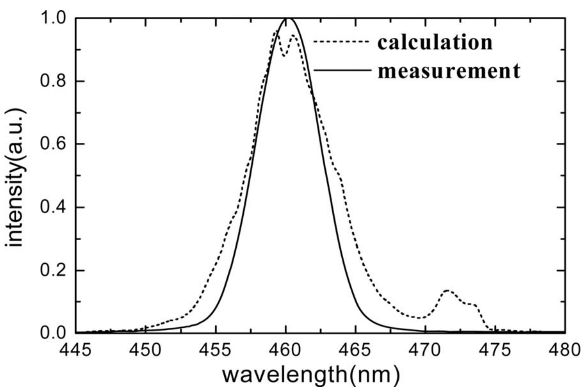

Fig. 7. Spectra of sum-frequency laser emission.

output from the BBO crystal directly. The middle beam is the SFG laser at the central wavelength of 460 nm; the sides are laser spots from the Ti:sapphire laser and the $Nd:YVO_4$ laser. Further observing the laser beams with a high-dispersion prism, we found five separate spots on the screen as in Fig. 6(b), which displays the laser beams at the wavelengths of 1064, 810, 532, 460, and 405 nm from left to right, corresponding to the fundamental waves of the $Nd:YVO_4$ and Ti:sapphire lasers, the second harmonic of the $Nd:YVO_4$ laser and the sum-frequency and second harmonic of the Ti:sapphire laser, respectively. Obviously, the intensity of the SFG (460 nm) is much higher than that of the two SHGs (532 and 405 nm). We measured the average power of SFG as about 10 mW, while the synchronized output powers of the $Nd:YVO_4$ and Ti:sapphire lasers are 2 W and 500 mW, respectively. We consider the main reason for the lower conversion efficiency to be the unmatched pulse widths between the two laser sources, which limits the nonlinear process that occurs in the temporal domain because of the sub−7 ps pulse width for the $Nd:YVO_4$ laser and 50 fs pulse width for the Ti:sapphire laser. Nevertheless, this result demonstrated a new way to generate laser frequencies by frequency mixing between synchronized laser branches. With similar pulse widths for two synchronized laser branches, we believe that the conversion efficiency can be remarkably increased. Considering that the bandwidth of the Ti:sapphire laser is about 22 nm, it is much wider than that of the $Nd:YVO_4$ laser (less than 0.5 nm); therefore the process of SFG can be regarded as the nonlinear interaction between a broadband laser and single-frequency CW laser [18], which makes all the frequency components of the femtosecond pulse increase by a constant of $\Omega=2\pi c/\lambda_p$ (c is the velocity of light and λ_p is the central wavelength of picosecond laser). Assuming that the spectrum of the femtosecond pulse is $E_f(\omega)$ (ω is angular frequency), that of the SFG pulse should be $E_s(\omega)=E_f(\omega-\Omega)$. According to the stated assumption and the above relation, we derived the SFG spectrum as the dashed curve in Fig. 7, which indicates a bandwidth of about 7 nm. The direct measurement shows that the bandwidth is about 5 nm (see the solid curve in Fig. 7), which is narrower than the theoretical value and supports a pulse duration of about 45 fs for the hyperbolic secant pulse. We infer that the bandwidth difference may have two causes: one is the imperfection of the theoretical calculation; the other is that in the BBO crystal, with 2 mm thickness, the long crystal constrains the spectrum of the sum-frequency laser because of the phase-matched bandwidth.

In the experiment, a computer is also utilized to monitor the real-time variation of the cavity length difference between the synchronized laser branches. Controlling the motion of the fine linear stage inside the Ti:sapphire laser may compensate for the variation of the relative cavity length caused by the surrounding environmental influence. Therefore, once two lasers have been successfully locked, they will maintain synchronization with low timing jitter; the SFG performs with excellent long-term stability, as long as 4 h within the observed time. In some sense, we have demonstrated a new technology to extend an ultrafast laser to a relatively shorter wavelength.

4. CONCLUSION

In conclusion, we have realized synchronization between a picosecond $Nd:YVO_4$ laser and a femtosecond Ti:sapphire laser, which can be stably locked for several hours based on the combination of two electronic PLLs at 68 and 816 MHz, with a timing jitter of less than 350 fs. By frequency mixing both synchronized laser branches, we generate ultrafast laser pulses at the wavelength of 460 nm; the typical rms stability is about 5%. The measured bandwidth of 5 nm supports a pulse duration of about 45 fs for the hyperbolic secant pulse. Compared with the conventional techniques of frequency conversion, this work provides a new way to generate stable ultrashort laser pulses by synchronizing any ultrafast lasers with different wavelengths or pulse widths.

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