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Sub-picosecond timing jitter between optically synchronized femtosecond and picosecond laser systems

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Abstract

Synchronized optical pulses are widely used. We report here characterization and measurement of synchronized femtosecond and picosecond pulses from a Ti:Sapphire laser (nominally 800 nm) and a Nd:YAG laser (1064 nm), respectively. Synchronization is achieved by utilizing soliton self-frequency shift in a photonic-crystal fiber that allows the 800 nm femtosecond oscillator to seed the third-harmonic generation (355 nm) of picosecond regenerative amplifier. The relative timing jitter between the amplified femtosecond and the third-harmonic generation of picosecond pulses is (710 ± 160) fs, which is only (1.17 ± 0.26)% of the picosecond pulse duration. This work paves way for applications in stimulated Raman scattering spectroscopy and amplification.

Supplementary material for this article is available online

Keywords: synchronization, femtosecond and picosecond laser, relative timing jitter

(Some figures may appear in colour only in the online journal)

1. Introduction

Timing is everything [1], from devices we use in everyday life to high precision synchronization on remote platforms [2]; from atoms emitting light collectively [1] to super-charged quantum beat engines [3]; there is no better time to improve our understanding and technologies for good timing. Developments in ultrafast optics have facilitated direct optical frequency/time measurements [4], as well as tools to probe the fast microscopic world of atoms and molecules. Nowadays, picosecond, femtosecond, and even attosecond optical pulses can be routinely obtained. While dynamics of electronic bound states can be as fast as attosecond [5], molecular dynamics often lays between femtosecond to picosecond time scale. To this end, synchronized femtosecond and picosecond laser systems are of great importance in physics and physical chemistry due to their many valuable applications such as pump-probe spectroscopy, stimulated Raman scattering spectroscopy, coherent anti-Stokes Raman spectroscopy

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surface properties probing by using vibrational sum frequency generation spectroscopy, two-photon laser scanning fluorescence microscopy, coherent synthesis, and optical parametric chirped-pulse amplification [6–13]. It has also been shown that stimulated Raman scattering in plasma can compress and amplify laser pulses [14], potentially to reach petawatt power [15]. In such a system, synchronized picosecond pump and femtosecond seed pulses need to interact in high density plasma in a counter-propagating manner.

In general, to synchronize the outputs of independent femtosecond and picosecond lasers, one can either synchronize two oscillators with at least one having tunable cavity length, or use a single oscillator to seed separate picosecond and femtosecond regenerative amplifiers. There are many works in literature which have achieved optical synchronization between independent femtosecond laser pulses using the tunable cavity method, e.g. optical clock synchronization [2], synchronization of mode-locked lasers [16, 17] and seeded synchronization of coupled optical microresonators [18]. Otherwise, Zou *et al* have experimentally demonstrated the synchronization between the internal dynamics of optical soliton molecules and external signals [19]. In another example of synchronization between femtosecond and picosecond pulses, Juhasz *et al* synchronized pulses from a stabilized femtosecond and a tunable picosecond laser using a linear cavity configuration in both lasers [20]. Zhu *et al* generated synchronous femtosecond and picosecond pulses by achieving cross mode locking in a double-cavity, dual wavelength Ti:Sapphire laser [11]. In their work, the femtosecond pulse width is $\tau_{2\mathrm{FWHM}} = 45.2$ fs and the picosecond pulse width is $\tau_{1\mathrm{FWHM}} = 0.89$ ps, which is about 20 times longer than the duration of the femtosecond pulse. The jitter is calculated to be 41 fs, which is about 4.6% of the duration of the picosecond pulse. The latter method obviously can be complicated by the use of different gain media and corresponding lasing wavelengths. Hommel and Allen reported broad-bandwidth sum frequency generation (BBSFG) techniques, which used infrared broad-bandwidth femtosecond pulses overlapped with narrow-bandwidth picosecond pulses to obtain BBSFG spectra [21]. In their system, by splitting a single seed source for injection into the amplifiers, the femtosecond pulse and the picosecond pulse were generated in separate regenerative amplifiers and temporally overlapped. Nonetheless, the difficulty can be lifted by soliton self-frequency shift (SSFS).

SSFS is a consequence of Raman self-pumping that continuously red-shifts a soliton pulse. Recently, it has been widely investigated for applications in fiber-based sources and signal processing [22–25]. Due to Raman gain, the blue portion of the soliton spectrum pumps the red portion, causing a continuous red-shift in the soliton spectrum as it propagates. The first observation of SSFS in a standard photonic-crystal fiber (PCF) structure was reported in 2002 [26]. It was closely followed by a study in which Raman-shifted outputs were observed from a PCF pumped by 800 nm femtosecond pulses [27]. After that, many different kinds of fiber platforms, such as single-mode fiber, microstructured fiber, and higher order mode fiber were investigated [28–31]. Meanwhile, a number of applications, including wavelength-agile lasers, analog-to-digital conversion, and slow light, were considered [28]. Worth noting, A. Baltuska and his collaborators were the first to report a method of red-shifting a soliton in a photonic-crystal fiber to allow 800 nm Ti:Sapphire oscillator to seed a 1 µm Nd regenerative amplifier [32]. They first proposed and demonstrated the use of SSFS in photonic-crystal fibers to generate picojoule-level seed energy for high-power ytterbium- or neodymium-based amplifiers. The method attracted much attention and was commercialized by EKSPLA [33, 34]. However, the relative timing jitter, as an important quantity and can determine whether the laser source is 'quite' enough for the intended application, had not been measured by optical cross-correlation techniques. Depending on the photonic-crystal fiber and frequency-shifted mechanism, the amplitude noise will translate to the frequency-shifted radiation, resulting in a timing jitter. And the timing jitter is a crucial issue for all timing sensitive applications [35]. For instance, a detailed analysis of optical frequency-shifting mechanisms in photonic-crystal fibers has been presented by Rothhardt *et al* [36]. In addition, a relative intensity noise and timing jitter of a Raman soliton has been studied by Zhou *et al* [37]. Both laser sources in above works are femtosecond pulses and have short pulse duration. To our best knowledge, there is no report on timing jitter between a femtosecond laser and a picosecond laser system seeded by a SSFS pulse from a PCF. In this work, we report a technique for characterization of the relative timing jitter between femtosecond and picosecond pluses. The relative timing jitter is measured as (710 ± 160) fs, which is only (1.17 ± 0.26)% of the picosecond pulse duration.

2. Description of laser systems and pulse characterization

The schematic of our laser systems is shown in figure 1. The femtosecond system consists of an oscillator (Spectra-Physics, MaiTai SP) and an amplifier (Spectra-Physics, Spitfire Ace, SPTF-35F-1-HPACE). The picosecond laser system includes a regenerative amplifier and a power amplification stage (EKSPLA, PL2251-10-P60) and an amplifier with integral harmonic upconversion of the fundamental beam (EKSPLA, APL2101-10-P60-SH-TH-FH). A phase-locked loop circuit converts the 47.5 MHz photodiode signal, originates from the pulse round-trip time in the oscillator cavity, to a 10 MHz clock signal, which is used to achieve electronic synchronization on the order of 1 ns to 2 ns between the femtosecond and picosecond systems. Key to the function, a PCF is installed between the femtosecond and picosecond laser systems, to allow the 800 nm Ti:Sapphire femtosecond oscillator to seed the 1064 nm picosecond regenerative amplifier, achieving synchronization of the two lasers. The photonic-crystal fiber (Product code: PL2250-FS Option) is a commercial

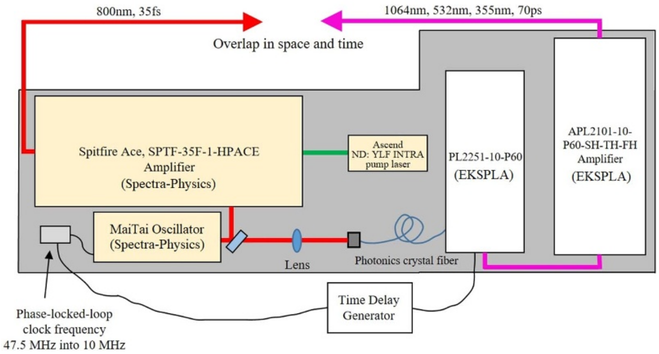

Figure 1. Schematic diagram of femtosecond and picosecond laser systems.

off-the-shelf solution produced by EKSPLA. The authors have been requested to withhold description of its characteristics.

Our femtosecond laser oscillator has a pulse duration about 35 fs according to the specification. To verify this, we use a lab-built spatial autocorrelation to measure the duration of the pulses, in the manner of Raghuramaiah's work [38]. The setup is shown in figure S1(a). By integrating over the spatial dimension that is perpendicular to the plane P (in this case the vertical y direction, as shown in figure S1(c)), an intensity as a function of time is obtained. This is shown in figure 2(a), where the x-axis represents time and the y-axis denotes the intensity of the pulse. The transform-limited full-width at half-maximum (FWHM) pulse duration is $\bar{\tau}_{\text{FWHM}} = 38.5$ fs. Worth noting, the FWHM pulse duration is calculated based on a fitted curve which is generated from a Gaussian function.

The duration of the picosecond pulse is measured with a streak camera (C10910-02, Hamamatsu) after passing through absorptive filters. The picosecond pulse is the third harmonic generation of the Nd:YAG laser, which has a wavelength of 355 nm. The statistics result of 100 shots is shown in figure 2(b), and it presents a Gaussian-like temporal profile with pulse duration of $\bar{\tau}_{\text{FWHM}} = 57.72$ ps. Similarly, the FWHM pulse duration is calculated from the Gaussian fitted curve.

3. Jitter between pulses

In general, relative timing jitter between ~40 fs and ~60 ps pulses is difficult to measure because the duration of the picosecond pulse is about 1500 times longer than the duration of the femtosecond pulse. We accomplished accurate jitter characterization through calibrated use of a high-resolution streak camera (C10910-02, Hamamatsu). The setup is shown in figure 3. Importantly, we measured the error in the timing between the femtosecond and picosecond pulses by splitting the femtosecond pulse into two and using the second pulse as a timing reference, assumed to have a negligible jitter with respect to the first femtosecond pulse. We split the femtosecond pulse into two by reflecting the femtosecond beam off a 5 mm thick fused silica window. One pulse is reflected by the front surface, and the second pulse is reflected by the back surface. Worth noting, there is no appreciable spatial separation of the pulses, only temporal. The pulses subsequently pass through an absorptive neutral density filter, a wedge, and an iris. Both femtosecond and picosecond signals are collected by the streak camera which is used to characterize the duration of the picosecond pulses. In addition, the half wave plate and thin film polarizer are used to control the laser power.

A single measurement is shown in figure 4. During the analysis, a Gaussian function $I(t) = I(0)\,\mathrm{e}^{-(t-t_0)^2/2\sigma_G^2}$ is used to fit the pulses, where t_0 denotes the central time and σ_G denotes a standard deviation measure of the pulse duration. We denote T_1 as the timing between the picosecond pulse and the first femtosecond pulse, while T_2 is the timing between two femtosecond pulses. A finite width in the T_2 distribution represents the instrument error, since the second femtosecond pulse has negligible jitter with respect to the first femtosecond pulse. By analyzing the statistics of 1000 individual shots, we can calculate the distributions of T_1 and T_2, from which the jitter between the femtosecond and picosecond pulses is derived. The distributions of T_1 and T_2 are shown in figure 5. They represent the time jitter distributions of femtosecond and picosecond pulses respectively. In figure 5, σ denotes the standard deviation width of the time distribution. The nonzero distribution in the timing T_2 between two femtosecond pulses with physically negligible jitter shows that the distribution of the timing T_1 is actually a convolution of two Gaussian distributions: the first is the true timing jitter between the picosecond and femtosecond pulses, and the second is the distribution in T_2, which signifies the measurement error of the streak camera. Since the convolution of two Gaussian distributions is again a Gaussian distribution [39], the true timing jitter between the picosecond and femtosecond pulses is shown to be $\sqrt{\sigma_1^2 - \sigma_2^2} = (710 \pm 160)$ fs [39]. The uncertainty in this jitter is derived from the uncertainty in the Gaussian fits. It is worth pointing out, when the duration of the picosecond pulse is about 1500 times longer than the duration of the femtosecond pulse, our jitter is just $(1.17 \pm 0.26)\%$ of the picosecond pulse duration.

There are several possible sources of timing jitter. For our system, air current fluctuations affected the coupling efficiency of the femtosecond seeding pulses into the photonic-crystal fiber, resulting in spectrum fluctuations at the output. Stability was improved upon shielding the system from these air current fluctuations. A second source of timing jitter results from intensity fluctuations in the femtosecond laser itself, leading to spectral and temporal fluctuation at the fiber output. These laser intensity fluctuations were present but they were of minimal consequence. Finally, a possible source of the picosecond amplified pulse jitter is the amplification process seeded by the output of the PCF.

The sensitivity of our jitter measurement system, based on a streak camera, depends on several factors, including the temporal resolution of the streak camera and the

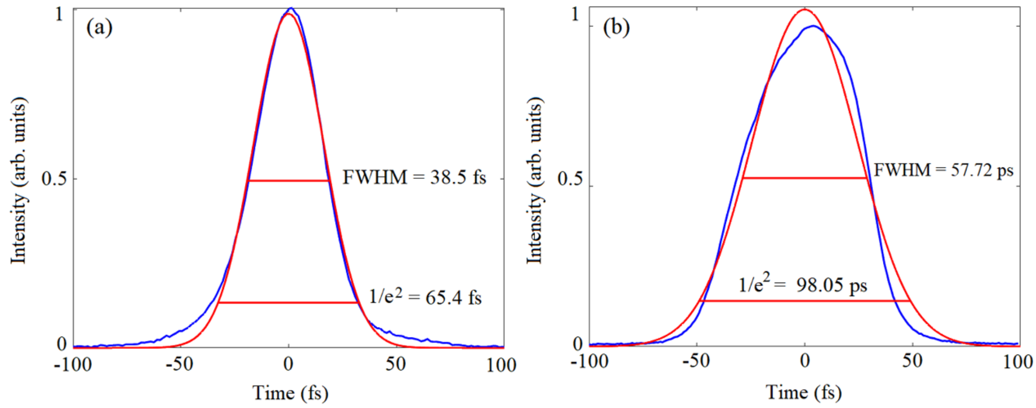

Figure 2. Intensity of femtosecond and picosecond laser pulses. Blue line is real data we collected while red line is a fitted curve. (a) Femtosecond pulse duration $\bar{\tau}_{\mathrm{FWHM}}$ is 38.5 fs, and full width at $1/e^2$ is 65.4 fs; (b) picosecond pulse duration $\bar{\tau}_{\mathrm{FWHM}}$ is 57.72 ps, and full width at $1/e^2$ is 98.05 ps.

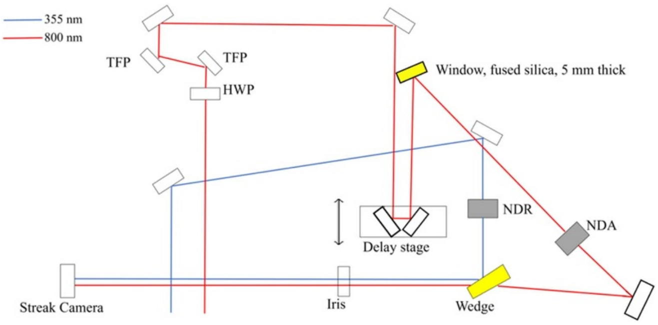

Figure 3. Setup to measure relative timing jitter between femtosecond and picosecond pulses. NDR: neutral density reflective filter, NDA: neutral density absorptive filter, HWP: half wave plate, TFP: thin film polarizer.

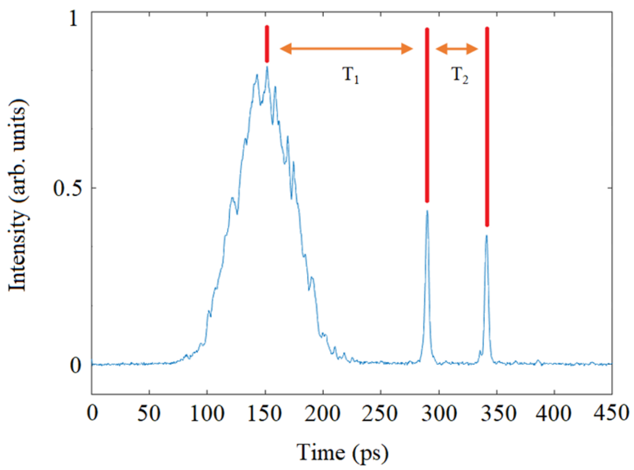

Figure 4. Intensity of femtosecond and picosecond laser pulses. T_1 is the timing between the picosecond pulse and the first femtosecond pulse. T_2 is the timing between two femtosecond pulses, and it is the instrument error since one assumed the second femtosecond pulse is timing reference.

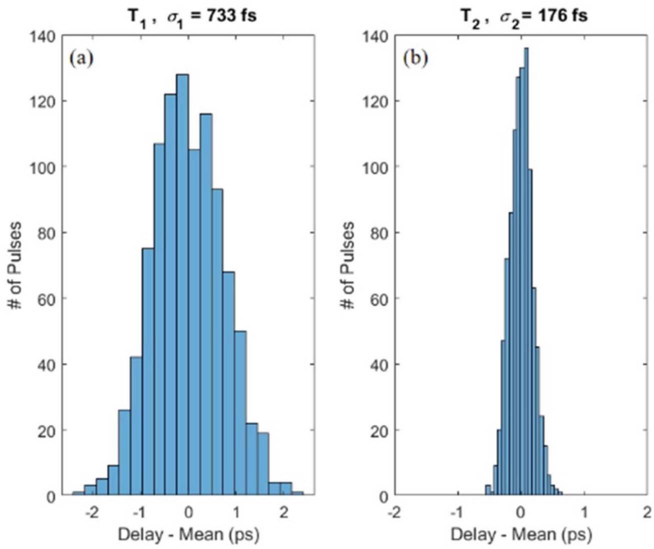

Figure 5. (a) Delay between picosecond and the first femtosecond pulses. (b) Delay between two reference femtosecond pulses. Each figure contains 1000 shots of the timing measurement. σ denotes the standard deviation width of time distribution.

signal-to-noise ratio (SNR) of the detection procedure. The temporal resolution of the streak camera is a crucial factor in determining its sensitivity to jitter. The higher the temporal resolution, the finer the measurement of the jitter in the signal. Our measurements used a streak camera with temporal resolution of 1.1 ps per pixel. In addition, the SNR of the detection system is also an important factor. A higher SNR means that the measurement system can detect smaller variations in the signal, which can lead to a higher sensitivity to jitter. The sensitivity of the jitter measurement procedure can be improved by using techniques such as averaging and signal filtering. Here, the total sensitivity of our jitter measurement system is about 34 fs because we averaged 1000 pulses. Consequently, our jitter measurement of (710 ± 160) fs is well-resolved.

The measured value of the jitter is comparable to that achieved in other works. In Chen's work, synchronization of the femtosecond and picosecond laser regenerative amplifiers with two different cavities was achieved by utilizing an electronic phase-locked loop and global clock techniques [6]. The timing jitter of the two regenerative amplifiers was measured as 0.66 ps.

4. Conclusion

In summary, we have characterized the duration and relative timing jitter of femtosecond and picosecond laser pulses generated from separate laser cavities that have been optically synchronized through SSFS. Although the method was first demonstrated by Baltuska [32], we have characterized the jitter between the femtosecond and picosecond laser system seeded by a SSFS pulse in a photonic-crystal fiber for the first time. Experimental results show that the relative timing jitter between the femtosecond and picosecond pulses is only $(1.17 \pm 0.26)\%$ of the picosecond pulse duration, while the duration of the picosecond pulse is about 1500 times longer than the duration of the femtosecond pulse. Our results pave the way for measuring and improving the temporal resolution in stimulated Raman scattering spectroscopy and amplification. It is worth pointing out that getting a good jitter will contribute to our future work in stimulated Raman scattering spectroscopy. Relative timing jitter plays an important role in many scattering media, such as plasma channels. As discussed in the [40], two separate pulses are counter-propagating and synchronizing with the plasma channel. The length of plasma channel is about 4 mm. Since our jitter is less than 1 ps, it means two pulses can be synchronized within the length range of 0.3 mm. This is an excellent range and shows that our system is good for experiments with plasma channel length of less than 1 mm.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://osf.io/thw69/.

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Conflict of interest

The authors declare no conflicts of interest.

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