Optical sampling by laser cavity tuning

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Abstract: Most time-resolved optical experiments rely either on external mechanical delay lines or on two synchronized femtosecond lasers to achieve a defined temporal delay between two optical pulses. Here, we present a new method which does not require any external delay lines and uses only a single femtosecond laser. It is based on the cross-correlation of an optical pulse with a subsequent pulse from the same laser. Temporal delay between these two pulses is achieved by varying the repetition rate of the laser. We validate the new scheme by a comparison with a cross-correlation measurement carried out with a conventional mechanical delay line.

OCIS codes: (030.1640) Coherence; (060.5530) Pulse propagation and temporal solitons; (070.4550) Correlators; (120.0120) Instrumentation, measurement, and metrology; (320.7100) Ultrafast measurements.

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1. Introduction

The invention of modelocked femtosecond lasers in 1991 has enabled a large variety of time resolved experiments. Very common are pump and probe experiments which have provided a deeper understanding of dynamical processes in femtochemistry [1], femtobiology [1,2], and semiconductor physics [3,4]. Other research fields which rely on femtosecond pulses with a variable time delay in between are optical coherence tomography [5], coherent control [6] and terahertz time-domain spectroscopy [7,8]. In most of the above experiments an optical pulse is split into two parts. These two parts are then superimposed on the sample (or at some other place in the experiment). Mostly, mechanical delay lines are employed to temporally delay one pulse with regard to the other [9–12]. These include linearly moving stages, or rotating mirrors or fibre-stretchers [13,14]. They comprise free-space optics and moveable components and are demanding in terms of mechanical stability. Even worse, it requires considerable effort to determine the position and linearity during the scan.

Recently, it was shown that asynchronous optical sampling overcomes these drawbacks as it does not require any mechanical delay lines. The technique relies on two synchronized pulsed femtosecond lasers which are slightly detuned in the repetition rate [15–17]. This technique is known as asynchronous optical sampling (ASOPS). However, such systems need a complex control for the stabilization of the pulse repetition rates of both lasers. Additionally, the price of the measurement setup, which is mainly determined by the laser, increases by the use of two laser units.

In the following, we present a new method [18] which allows for a well defined time delay between two pulses by varying the pulse repetition rate of only one single femtosecond laser. The possibility of changing the pulse repetition rate is already given in most femtosecond sources. Hence, no laser redesign is required. The new technique allows for very robust, compact and cost-efficient experimental setups in the above mentioned fields. We call this technique optical sampling by cavity tuning (OSCAT).

2. Theoretical foundations

Up to now, in most time-resolved experiments pump and probe pulses result from the same optical pulse which is split into two portions by an optical beam splitter. However, if the phase jitter of the femtosecond source is negligibly small, it is, in principle, also possible to employ pump and probe pulses that origin from sequenced optical pulses. Thus, a change in the lasers repetition rate f_{rep} modifies the distance between pump and probe pulses and a time shift between both pulses can be generated. This is illustrated in Fig. 1 which shows a simplified sketch of the experimental setup. A pulse source generates a train of optical pulses where the time τ_{rep} in between subsequent pulses is $\tau_{\mathrm{rep}} = 1/f_{\mathrm{rep}}$. In the following i shall denote a reference pulse which arrives at $t = 0$ at a certain position (e.g. the position of the sample). $i + a$ (with i and a being integers) shall denote a subsequent pulse which arrives at $t = a \cdot \tau_{\mathrm{rep}}$ at the reference position.

The laser pulse train is split into two parts by a beam splitter. Within the time t_p a pulse from pulse train #1 propagates the distance l_p between the beam splitter and the target (in most cases the sample). The same pulse (in the sense that it originates from the same initial pulse with the same index i) in pulse train #2 propagates a longer distance to the sample. This distance may be $l_d + l_{\mathrm{p}}$ such that the pulse requires the time $t_d + t_{\mathrm{p}}$.

At the target, the time delay between a pulse i and a pulse $i + a$ propagating the upper and the lower beam path, respectively, is

$$\Delta t = t_d - a \cdot \tau_{rep}. \tag{1}$$

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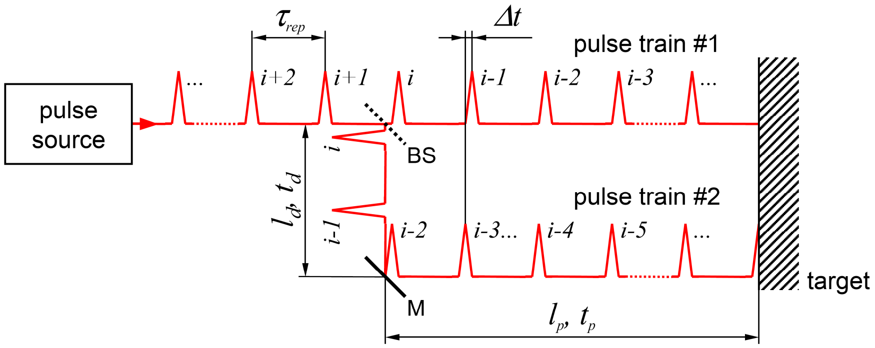

Fig. 1. Visualization of the working principle of the new method: A pulse source continuously generates a regular pulse sequence. Two partial beams are split via a beam splitter (BS) and each of it arrives at a target. A temporal delay t_d between the two pulse trains is caused by an additional fixed path length l_d the beam splitter and the deflection mirror (M). Two different pulses are considered ($a \neq 0$).

In a typical setup that exploits a standard mechanically moveable optical delay line the index difference between the two employed pulses is $a = 0$. The temporal delay Δt between the two pulses is then only given by the variable additional path l_d which corresponds to a non-constant t_d.

Here, in contrast, we consider a ≠ 0. In this case the time delay Δt correlates with the laser's repetition rate. While the optical path lengths are maintained unchanged (i.e. l_d remains constant) the pulse delay is varied by changing the repetition rate of the laser if a is unequal to zero ($a \neq 0$). Typically, the range in which the laser's pulse repetition rate is variable is limited to $f_{\min}$ and $f_{\max}$. The possible temporal scanning range range $\Delta t_{\mathrm{var}} = \Delta t_{\max} - \Delta t_{\min}$ is given by

$$\Delta t_{\mathrm{var}} = a\left(f_{\min}^{-1} - f_{\max}^{-1}\right). \tag{2}$$

Hence, executable scanning range of the pulse delay scales with a. The necessary optical path length l_d for a given a is

$$l_d = \frac{a \cdot c_0}{f_{\min} \cdot n}, \tag{3}$$

with the speed of light in vacuum c_0 and the refractive index n of the medium the laser pulse is guided in, e.g. an optical fiber.

The scanning range in the time domain will be limited by three factors: the laser tuning range, the length of the passive delay line and the timing jitter of the laser source. We will discuss the possible scanning speed and range in Section 3.

3. Experimental demonstration

The functionality of the new scanning technique is demonstrated by means of a cross-correlation measurement via second harmonic generation [19]. The setup is shown schematically in Fig. 2. The average repetition rate of the Menlo Systems M-Comb femtosecond fiber laser [20] with a central wavelength of 1560 nm and a pulse width of less than 90 fs is adjustable in the range of 250 ± 1.25 MHz. The femtosecond pulse is split into two parts by a fiber splitter. The beam from port A is collimated and guided directly in free space to a non-linear BBO crystal via free space optics. The second beam is launched into a passive glass fiber delay line.

The fiber delay line consists of different fiber types (i.e. standard single mode fiber and telecom dispersion shifted fiber) in order to achieve total zero group-velocity dispersion operation. Therefore we use a single mode fiber combined with an inverse dispersion fiber that are commercially available on the market. The total fiber length of 1.6 m with a refractive index of about 1.47 leads to an index change of $a = 2$. After propagating through fiber the beam passes a free-space optical delay line, and is focused onto the same spot of the BBO crystal.

λ/2 and λ/4 wave plates and polarization beam splitter cube are needed for delay line operation. The length of free-space paths in beam A and B is equal. The optical power in port A and B is $P_A = P_B = 125$ mW.

A filter located behind the BBO crystal effectively blocks the laser pulses with a fundamental wavelength of 1560 nm. Therefore, only frequency doubled light around 780 nm is measured by the photo-detector.

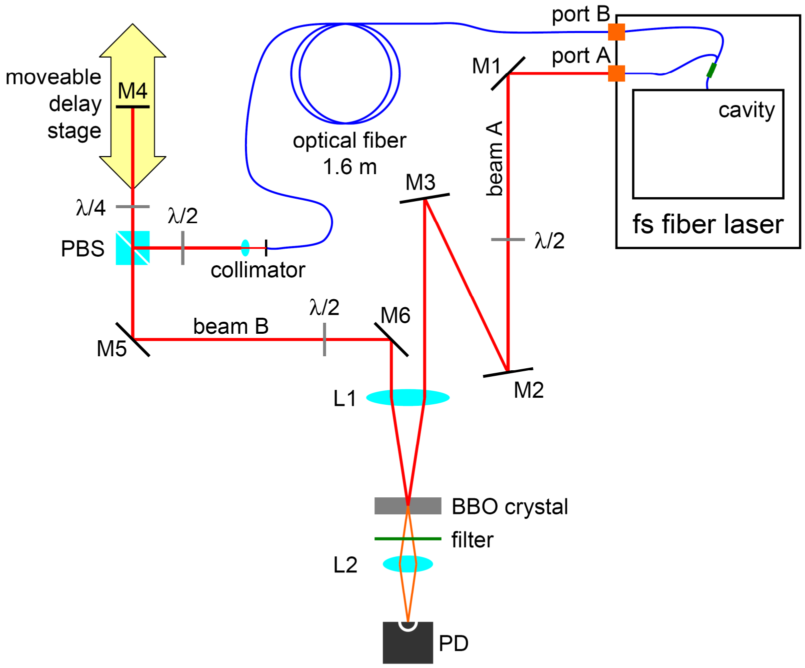

Fig. 2. Experimental setup for the cross-correlation measurements. The femtosecond fiber laser has a fiber-coupled and a free-space exit. The optical fiber with a length of 1600 mm was dispersion pre-compensated. Further components: conventional mechanical delay line (M4), lenses (L), mirrors (M), photodiode (PD), polarization beam splitter cube (PBS) and a short wavelength pass filter.

For a quantitative comparison the cross-correlation signal is recorded in two different ways. In the first experiment the laser repetition rate is kept constant and a reference measurement is performed with the conventional delay line. The mechanical stage scans a 1.4 ps range with a step width of 5.2 fs. The cross-correlation curve is shown in red in Fig. 3. Secondly, the delay stage is kept at a fixed position and the laser repetition rate is swept form 250.003666 MHz to 250.047546 MHz with a step width of approx. 150 Hz. The laser's repetition rate is measured with a frequency counter. The cross-correlation measurement obtained with this novel technique is shown in black in Fig. 3. An excellent agreement between both curves is observed. Additionally, both signals show that jitter effects and issues with the coherence length of the laser can be neglected at least for small index differences between pump and probe pulses. Typical timing jitter measurements for such lasers show values below 10 fs for integration times from several MHz down to 10 kHz. This implies that our method can be used without any problem for indices a up to several 10,000. Therefore, the length of the passive delay line will be the most limiting factor. With the optical fibers used in our experiment, a passive delay line with a length of up to 40 m can be easily realized with only minor distortion of the optical pulse. Therefore, a scanning range of 2 ns will be covered for a cavity tuning from 248.75 MHz to 251.25 MHz.

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Since all pulses from femtosecond fiber laser are nearly identical one would expect a symmetrical autocorrelation-like signal even in the case of cross-correlation between pulse *i* and *i* + 2. However, the optical pulses in the beam of port B travel through additional 1.6 m of optical fiber. Due to nonlinear effects like self-phase-modulation and four-wave-mixing present in the fiber the pulses are slightly distorted which in turn leads to an asymmetrical cross-correlation signal.

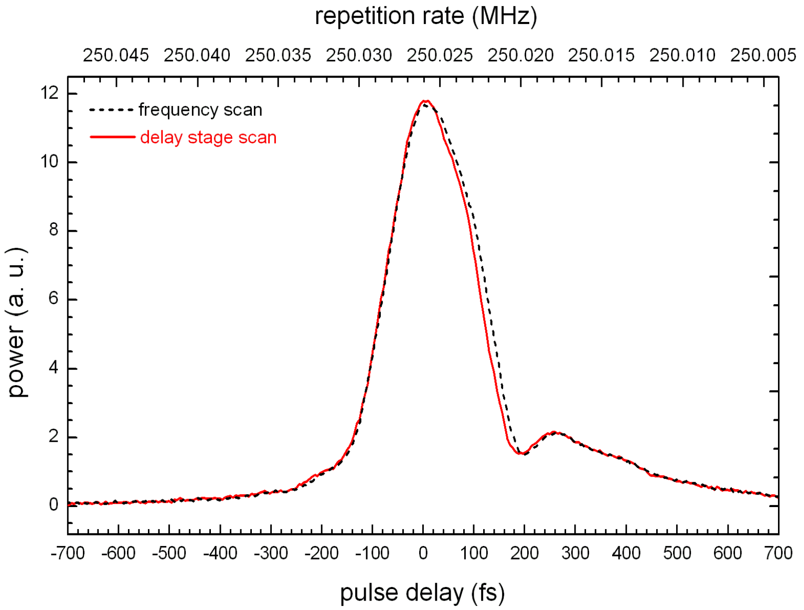

Fig. 3. Cross-correlation measurements. Red: delay stage scan with a fixed repetition rate. Black: frequency scan with a fixed delay line position. The top x-axis represents the repetition rate corresponding to the pulse delay.

4. Conclusion and outlook

We have introduced Optical Sampling by CAvity Tuning (OSCAT), a new technique which enables time-resolved experiments with a single laser and without any external delay lines. It relies on a defined variation of the laser pulse repetition rate. The technique is validated by demonstration cross-correlation measurements which are compared to data obtained with a conventional delay line. Since a large number of femtosecond lasers already provide the possibility of varying the pulse repetition rate this new technique very applicable.

In contrast to ASOPS which requires two synchronized femtosecond lasers, OSCAT uses only one femtosecond source which lowers the system purchasing and maintenance costs. The limited tunability of the pulse repetition rate can be compensated by extending the optical path length difference between pump and probe beam. Thus, large scan ranges of several nanoseconds are accessible.

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