Single-shot detection time-stretched interferometer with attosecond precision

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Abstract: A single-shot time-stretched interferometer for femtosecond and picosecond time detection is proposed and demonstrated. The time precision is ~40 attosecond. This technique succeeds in charactering the motion of delay-line and in fabricating vibrating sensor.

1. Introduction

Precise time detection, by virtue of its application in sensor, gyroscopic, precise timing, frequency stabilization, has attracted intense attention over the past decades [1-3]. Up to now, several time-detect methods have been developed. The fastest real-time oscilloscope has a temporal precision of 9 ps, which is adequate to most time detection in nanosecond scale, but is helpless within several picosecond and femtosecond scale. The sampling oscilloscope has a precision of sub-picosecond [4], while intensity correlation measurement can detect pulse width down to ~1fs level, but they are not single-shot but require the signal to be repetitive with the same shape. Using phase detection technique, tiny time delay within one optical period can be located, but the time variation larger than optical period is beyond its ability. Beat frequency technique can transfer tiny phase variation into frequency shift, as is employed in gyroscopic, but its speed depends on the frequency spectrograph, who exhibit a long-time average signal. However, in some physics or chemistry operation like dynamics in lasers or electronic transition, the phonon variation is in sub-picosecond range, which is so fast that only one signal can be captured each process. To character the process, a single-shot high-precision time detect technique with range of picosecond is essential. Hence, how to single-shot detect the time delay in femtosecond or picosecond scale precisely is still a fascinating question.

In this paper, we demonstrated a time-stretched interferometer (TiSIF). Utilizing TiSIF, tiny time-separation in the range of picosecond and femtosecond can be single-shot captured with precision of ~40 as, which impels ultrafast precise time detection from several picosecond into sub-optical-period range. The TiSIF has successfully character the motion of a delay-line, involving location, velocity and acceleration. Furthermore, a vibrating sensor is fabricated by means of TiSIF.

2. Theory and experiment setup

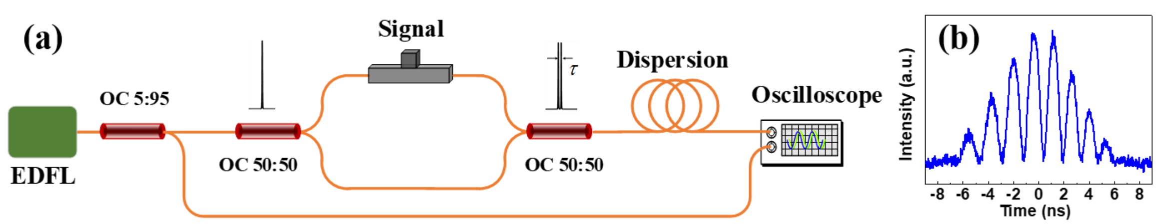

Figure 1. (a) The time-stretched interfermeter system. (b) Interferogram form oscilloscope

The TiSIF setup is shown in Fig. 1. The pulse from mode-locked laser is separated into two arms, one of which is exerted a signal while the other is served as reference. Then assembled into a doublet soliton with a separation of τ. After the dispersion device, the doublet soliton structure, coming from the same soliton with envelope $E_0(t)$, can be stretched into nanosecond with interferometric fringe by dispersion device. The time interferogram write as:

$$I(t-t_0) \propto 1+\cos\left[\tau\left(t-t_0\right)/\beta+\omega_0\tau\right] \qquad (1)$$

with β being the total dispersion of the dispersion device, t_0 the time of the pulse center, $I(t-t_0)$ the intensity envelop of the interferogram, ω_0 the angular frequency of the center wavelength. A time interferogram is shown in Fig. 1(b). Hence, the interferometric fringe period encoding the separation by $\Delta t = 2\pi\tau/\beta$, and the fringe places encoding the separation by $\Delta\varphi=\omega_0\tau+2k\pi$ with k is an integer. Nevertheless, the separation encoded by phase represents one of a series of discrete dot. By virtue of the separation encoded by interferometric fringe period, the dot can be located. Therefore, through the fringe period and fringe places, the separation can be located with a precision down to sub-optical-period.

The ultrafast laser used in the experiment is a home-made mode-locked erbium-doped fiber laser (EDFL) as is introduced in [5]. 5% of the output laser is extracted to monitor the output pulses and to trigger signals. The other 95% is inject into a 50:50 optical coupler (OC) to fabricate TiSIF. An electric fiber-delay-line is inserted in one arm of the OC as the signal pulse, while the other is adopted as reference pulse. Then, the two arms are combined by a 50:50 OC with the total time difference of the two pulse being ~1ps. Benefit from the ultrashort pulse duration from the laser, the two pulse experience no spatial overlapping in the OC to prevent from spatial interference. Then, the doublet soliton is immitted into the dispersion device, a reel of dispersion compensation fiber (DCF), after which the doublet soliton is stretched to nanosecond with time interference fringe. The DCF has a total length of 1km with a group velocity dispersion (GVD) of 197 ps^2/km. The signal is detected by a high-speed real-time oscilloscope with a bandwidth of 45 GHz and sampling rate of 120 GHz.

3. Result and discussion

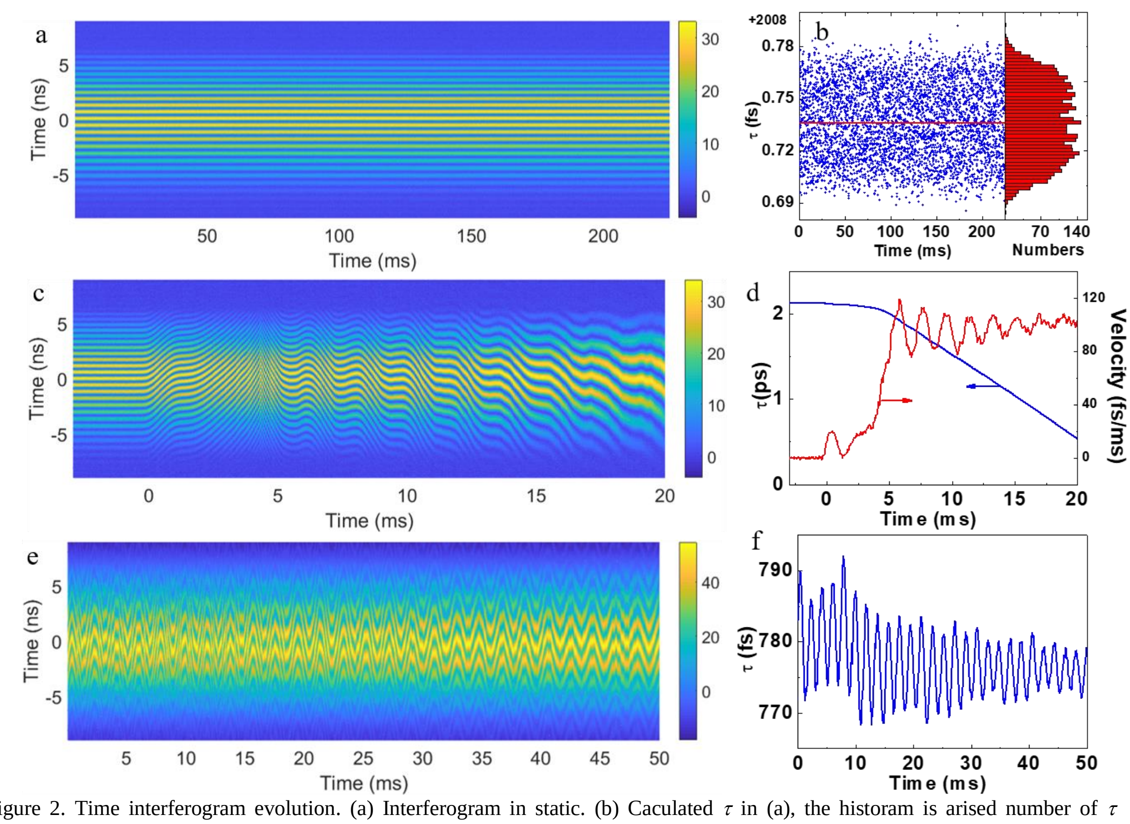

Figure 2. Time interferogram evolution. (a) Interferogram in static. (b) Caculated τ in (a), the historam is arised number of τ (c) Interferogram variation with the movement of delay-line. (d) Caculated variation of τ from (c) (left) and the instantaneous velocity of τ (right). (e) time interferograms of the vibrating sensor. (f) the oscillation of τ in (e).

At a separation of 2008 fs, the stability of our divice is characterized. The variation of the time interferogram is sketched in Fig. 2(a). As for the finite memory of the oscilloscope, we record 4500 interferogram in a time window of 0.25s, during which the interferogram exhibit no obvious joggle (Fig. 2(a)). To observe the presision of our experiment, the corresponding τ of Fig. 2(a) is shown in Fig. 2(b). The dots picture the distribution of τ , while the redline is the average of τ , indicating the fluctuation of τ is within ± 40 as. The standard deviation of τ is 21.4 as.

The statistical histogram, right of Fig. 2(b), exhibits a super-Gaussian shape with a terrace in the center, indicating the precision is limited by the measuring error, which is cause by the sampling rate of the oscilloscope.

To verify the ability of TiSIF to detect tiny time-delay, the motion of delay-line is captured. Fig. 2 (c) exhibits transformation of time interferogram with the movement of delay-line and fig. 2(d) sketches the corresponding separation and velocity. The captured movement process takes about 20 ms, during which the separation declines from 2.12 ps to 1.40 ps, indicating the forward soliton shifts backward, as skitched in Fig. 2 (d). From the accelerating process in Fig. 2(c), the fringe moves upward at the beginning, indicating a positive velocity. At the time of 4-5 ms, the soliton moves so fast that the fringe place cannot be distinguished. After 5ms, the fringes move downword, because the phase variation between two adjacent interferogram is larger than π and approach 2π, reaulting in the fringe misplaced and this is beyond the discernibility of encoding fringe place. Hence, its essentially to encode fringe period when the saparation varies fastly. The separation in Fig. 2(d) is extracted by caculated the fringe period and fringe places.

The delay-line does not accelerate to an uniform motion state directly, but has a preaccerlaration process when accerlerate to a small speed and then slow down to zero, after which the delay-line accelerates to a large speed. After the accelerating process, the delay-line has a period of volocity-oscillation process until reach to an eauilibrium. The velocity of 100 fs/ms indicate a speed of 3 cm/s in the delay-line. The total motion of 4 ps dictating a spatial motion range of 1.2mm. This motion process cannot be probed by real-time oscilloscope for the ultra-tiny variation less than 4 ps. The sampling oscilloscope and intensity correlation measurement has no such fast sampling rate, so they cannot characterize this process. Hence, TiSIF is an efficient method to observe the time variation in this window. Furthermore, it exhibits brilliant ability in measuring location, velocity and acceleration.

To character the ability of TiSIF in fabricating sensors, we make a vibrating sensor by replacing each arm with 10m SMF. The separation of the doublet pulse is 776 fs. When flipping the fiber slightly, the vibration of the fiber causes an oscillation of τ . The time interferograms are skipped in Fig. 2(e) and the corresponding τ are shown in Fig. 2(f), which proves the ability of TiSIF in fabricating vibrating sensor. Theoretically, vibrating amplitude of ~20 nm can be detected by TiSIF in our experiment, while the maximum vibrational frequency detectable is ~10 MHz. Actually, higher precision can be obtained if larger dispersion is introduced.

4. Conclusion

A single-shot time-detection technique named TiSIF is proposed. Employing the TiSIF, tiny time-separation at the scale of picosecond and femtosecond can be detected at a precision of ~40as using only one pulse. The motion process, namely location, velocity and acceleration, of an electric delay line is character with TiSIF. A vibrating sensor is fabricated using TiSIF, which can locate vibrating amplitude of ~20 nm. By means of this technique, quantities of internal dynamic of laser can be revealed, from pulse formation to soliton collision and soliton motion. Furthermore, the ultrafast precision time detect can be applied in velocity detection, vibrating sensor, gyroscopic, precise timing, frequency stabilization, and even gravitational-wave observatory.

References

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