Dispersive Temporal Interferometry toward Single-Shot Probing Ultrashort Time Signal with Attosecond Resolution

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1. Introduction

Nowadays, the ultrafast physical and chemical processes, like nonlinear effect, chemical reaction, electron decay, and energy relaxation,[1–5] have attracted increasing interest, making it much important to develop single-shot time measurement technique with subfemtosecond resolution. To date, there are several techniques that can single-shot probe the ultrashort time change.[6–8] In telecom waveband, state-of-the-art oscilloscope can probe the events with 10 ps resolution. With the assistance of time lens,[7] the time resolution can reach to ≈100 fs (20 optical cycle) for single-shot measurement. Meanwhile, optical interferometer can single-shot probe phase difference of two waves within a range of 2π/5 fs.[9–11] but it cannot recognize the cycle number in single-shot measurement if the phase difference beyond 2π.[12] Hence, the time events under the resolution of time lens but longer than a cycle cannot be single-shot probed. However, many ultrafast phenomena arise in this time range,[13,14] and some of them are rapid varying or may occur only once, so that they cannot be probed using the multi-shot measurements. Thus, it is still of great demand to develop the technique that enables single-shot time measurement from attosecond to picosecond.

To measure time signal with traditional interferometers is implemented by measuring optical intensity that varies with relative phase, the precision of which suffers from the quantization error and time drift.[13] Due to quantization error, the a long-term average is required to obtain accurate time signal. Moreover, the frequency of environmental noise that introduces time drift is kilo-Hertz of sub-kilo-Hertz, corresponding to period microsecond or millisecond.[15] In some applications, people use two or more devices to measure the same parameter to reduce the influence of time drift, but the time drift cannot be eliminated despite that the measurement is complicated. Therefore, the time evolution in nanosecond scale cannot be accurately measured using traditional interferometers.

Here, we proposed a new technique, the dispersive temporal interferometer (DTI). It is insensitive to the quantization error and the time drift, and can single-shot probe the time signal with resolution of sub-20 as (0.004 optical cycle), four order-of-magnitude higher resolution than the time lens, range of 2 ps (400 optical cycle), three order-of-magnitude larger range than interferometers for single-shot measuring time. The range-to-resolution ratio is larger than 10^5. The sampling time for a single interferogram is 23.36 ns, corresponding to the sampling rate of 42.8 MHz. Moreover, to illustrate that the DTI can be used to fabricate time-measurement optical sensors, we fabricate a gyroscope employing DTI, which can characterize the transient parameter evolution. The transient angular velocity of the gyroscope is monitored as well. The DTI can also be used to reveal the soliton interaction of ultrafast laser, and to single-shot, observe some other ultrafast phenomena, like terahertz detection.[16]
2. Concept of Dispersive Temporal Interferometry

Owing to the equivalence of light propagations between spatial diffraction and temporal dispersion, most spatial optical components have their own temporal counterparts, such as time lens and time prism.[7,17] An emerging time-stretch technique, which stretches the ultrashort pulse into giant-chirp nanosecond pulse to write the spectral information into the temporal signal and thus is called Dispersive Fourier Transform (DFT),[18–22] can be seen as an analogue of spatial single-slit diffraction.

Spatially, two parallel slits can split a light beam off two coherent portions, and interferogram arises on the screen far from them (Figure 1a).[23] Temporally, an ultrashort pulse is split off two portions and reassembled into a pulse pair, which works as a temporal double-slit; after dispersive propagation, the time interferogram arises on the oscilloscope (Figure 1b). Similar to spatial interferogram, the time interferogram encodes both the time separation and the relative phase of the two pulses, from which the time event imposed on the slits (Figure 1b) can be retrieved from a single interferogram.

An ultrashort pulse with the envelop $2E_0(t)$ and the carrier frequency $\omega_0$ passes through two different paths to reassemble a pulse pair, as shown in Figure 1b. The Fourier transform of the initial pulse can be expressed as $2E_0(\omega - \omega_0)$. The time separation of the pulse pair are determined by the time difference of the two paths. An event (time event), like refractive index change, distance change, or motion of the reflective mirror, can make the total time to pass one path change but leave the other fixed. To read out $\tau$, the pulse pair is stretched with large dispersion to map the frequency spectrum of the pulse pair into time domain. Then, the time interferogram can be captured by oscilloscope.

The corresponding relation among the frequency $\omega$ and the time location in the interferogram $t$ is $\omega - \omega_0 = t/\beta$, note that frequency $\omega_0$ corresponds to $t = 0$ and $\beta$ is the total dispersion exerted into the pulse pair. Therefore, the time interferogram that captured by oscilloscope can be represented as

$$I(t) \approx \left(1/\beta\right)\widetilde{E}_0(t/\beta)\left[1 + \cos\left(\pi t/\beta + \omega_0\tau\right)\right]$$

(1)

In Equation (1), the cos item introduces interference fringe with period $T = 2\pi\beta/\tau$, and the phase of interferogram, corresponding to the relative phase of the pulse pair, $\varphi = \omega_0\tau + 2k\pi$ with $k$ an integer to make $0 \leq \varphi < 2\pi$. The relative phase of the two pulse changes with their separation (Figure 1c), resulting in the movement of fringe location (interferogram phase) synchronously, as shown in Figure 1d. For a slight motion in separation, the change of $\tau$ and $\varphi$ ($\delta\tau$ and $\delta\varphi$, respectively) have the relation $\delta\varphi = \omega_0\delta\tau$. Therefore, the time separation can be retrieved from both the fringe period and interferogram phase two-dimensionally by

$$\tau = 2\pi\beta/T$$

(2a)

$$\tau = (\varphi/2\pi + k)T_0$$

(2b)

Figure 1. Dispersive temporal interferometer. a) Diagram of double-slit interference. b) Schematic of the DTF. c) Relative phase evolution with the pulse location. The ball represents the pulse, and the arrow is its phase. d) Interferogram evolution with the separation. e) The relation of relative phase and time separation. The radius (angle) represents the time separation (relative phase). Both axis is in arbitrary unit.
where $T_o = 2\pi/\omega_0$ is the optical cycle at $\omega_0$. From Equation (2), the value $\beta$ can be measured from the change of phase ($\delta \phi$) and the change of the reciprocal of fringe period [$\delta (1/T)$] by slightly changing the time separation $\tau$, $\delta \phi = \frac{1}{2\pi} \delta (1/T)$.

Then, we illustrate how to retrieve separation from Equation (2). On the one hand, Equation (2a) shows the time separation $\tau$ can be retrieved from the fringe period. The resolution and range can be expressed as

$$\tau_{\text{re},a} = \tau T_{\text{osc}} / 2 \pi \beta$$

$$\tau_{\text{range},a} = \pi \beta / \tau_{\text{re}}$$

with $t_{\text{re}}$ the resolution of the oscilloscope. On the other hand, with $r$ the radius and $\phi$ the angle, Equation (2b) constitutes a continuous curve in the polar coordinates (Figure 1e). For each phase $\phi$, the $\tau$ that can match it constitute arithmetic progression with step of optical cycle, illustrated as olive points in Figure 1e. Therefore, the time separation can be retrieved only when $k$ is a constant or measurable. If $k$ is known, the resolution and range of retrieved time separation is

$$\tau_{\text{re},b} = \tau T_{\text{osc}} / 2 \pi \beta$$

$$\tau_{\text{range},b} = T_0$$

where $T_o = 2\pi/\omega_0$ is the optical cycle. For most ultrafast laser, $\tau_c \gg T_o$, and thus, $\tau_{\text{re},b} \ll \tau_{\text{re},a}$, which means the resolution of retrieved $\tau$ from phase is much higher than that from fringe period. Nevertheless, the measurement range with Equation (2b) is several femtoseconds for 1550 nm while the measurement range with Equation (2a) is in picoseconds if $t_{\text{re}} > 100$ ps and $\beta > 100$ ps$^2$. Thus, the measurement range to retrieve $\tau$ from fringe period is much longer than that from phase.

To retrieve $\tau$ with long range and high resolution, the time separation should be retrieved in both the two dimensions. First, from the fringe period (Equation (2a)), the time separation can be retrieved (denoted as $\tau_1$) with weaker resolution to determine the approximate location, corresponding to the gray ring in Figure 1e. Second, the phase can determine the direction (the olive points in Figure 1e). If $\tau_{\text{re},a} < T_o$, only one point (the red point) locates at the ring, and this point corresponds to the time separation retrieved from the time interferometer (denoted as $\tau_2$). Because the interference arises in time domain, and is implemented by large dispersion, this technique is named as the dispersive temporal interferometry.

### 3. Experimental Results and Discussion

#### 3.1. Fixed Time Signal

To carry out the time measurement experimentally, we first measure the resolution of DTI. Figure 2a displays a typical DTI with a fixed time difference between the two parts. Two 1:1 optical couplers (OC), with one arm a little longer ($\approx 2$ ps) than the other, assemble the pulse pair. The dispersion is implemented by 1 km dispersion compensating fiber (DCF) with total dispersion $\beta = 195$ ps$^2$ at 1570 nm. The laser source is a home-made ultrafast laser (UL) that works at 1570 nm with pulse duration of 83 fs. [24] 95% of the laser is injected into the DTI, which is detected via a high-speed photodetector (PD, 40 GHz), and visualized by a real-time oscilloscope (OSC, 120 GHz). The other 5%, detected by another PD, serves as the timing trigger. The reference pulse location $t_p$, detected by the trigger port, has a fixed separation $t_{\text{separation}}$ with the interferogram. Hence, the time of interferogram is $t = t_{\text{raw}} - t_p = t_{\text{separation}}$, where $t_{\text{raw}}$ is the raw data detected by oscilloscope.

Figure 2b shows an exemplary interferogram detected by oscilloscope. The interferogram is monitored over 4 s, as shown in Figure 2c, which displays no obvious variation on fringe period and phase. We retrieve $\tau_1$ and $\tau_2$ from the time interferograms (see Supporting Information) in Figure 2c, as shown in Figure 2d,e. Each data is retrieved from a single interferogram, ensuring the single-shot measurement. The average time separation $\tau$ is 2008.85 fs, indicating 410 nm optical path difference. $\tau_1$ and $\tau_2$ fluctuate randomly with no apparent trajectory. The statistics histograms of $\tau_1$ and $\tau_2$ are shown in Figure 2f,g. Figure 2f displays a clear Gaussian profile with full width at half maximum (FWHM) 1.13 fs in the fitting (blue line). Moreover, most of the 4000 shots locate between $\tau \pm 1.5$ fs. Therefore, the resolution is 1.13 fs, much better than one cycle (5.27 fs).

From the Gaussian profile in Figure 2f and the random evolution in Figure 2d, it can be deduced that the resolution of $\tau_1$ is limited by the time resolution of the oscilloscope, because other noise, like setup instability, will introduce a trace to the evolution of Figure 2d rather than the random evolution. The statistical result of $\tau_2$ is presented in Figure 2g, which shows a plateau in the center of Figure 2g. This can be explained by the deviation of the real pulse location $t_{p,\text{real}}$ and the detected $t_p$ due to the limit of oscilloscope resolution: $t_{p,\text{real}}$ has uniform probability in the range $t_p - t_{\text{re}}/2 < t_p < t_{\text{re}}/2$. The FWHM in Figure 2g is 76 as, close to the calculated value of 71.5 as from Equation (4).

Using the interpolation method (see Supporting Information), the resolution of DTI is improved to sub-20 as (Figure 2h, FWHM 15.0 as), smaller than 0.004 optical cycle. We’d like to point out that this resolution is much smaller than the pulse duration of initial pulse. This can be analog to spatial dual-slit interference: although the wavelength of light source is much smaller than the slit separation, the wavelength is also measurable from the interferogram. Additionally, from Equation (4), it can be inferred that the resolution can be further improved by reducing time separation and/or adding dispersion.

#### 3.2. Time-Varying Time Signal

To verify that DTI can probe time difference over a long range, a delay line is used to provide tunable time difference (Figure 3a). By tuning the delay, the evolution of interferogram is tracked, as shown in Figure 3b. We retrieve retrieved $\tau_1$ and $\phi$ from each interferogram and plot their phase map in Figure 3e, which displays no overlap in adjacent screws. $\tau_1,2$ (Figure 3c) shows a total time change of 211 fs, and their largest bias is 2.25 fs (Figure 3d), smaller than $T_o/2$, which verifies that the time event can be single-shot probed over such range. Moreover, we also test a fast-varying process of delay line, the evolution of interferogram is presented in Supporting Information. The retrieved data shows that the time separation $\tau_{1,2}$ decreases from 2.436 ps to 321 fs,
and their relation is sketched in Figure 3f. These results indicate that the DTI can probe the time over a range of 2.1 ps, about 400 optical cycles, much longer than the range of conventional interferometers (one optical cycle). The range-to-resolution ratio is larger than $10^5$, which highlights that DTI is effective over a very long range compared with its resolution. Moreover, the time difference is retrieved with only one interferogram, which guarantees the single-shot measurement. Thus, its sampling rate is identical to the repetition frequency of source pulse, which is 42.8 MHz in our experiment. Such superior performance of DTI on time measurement makes it possible to fabricate time-measurement optical sensor.

3.3. Applications in Optical Sensor

The DTI can monitor the time difference of two optical paths with resolution of sub-20 as and range of 2 ps, indicating that it can be used to fabricate optical sensor, based on the time measurement. As a typical example, we fabricate a gyroscope based on the DTI, as depicted in Figure 4a. The light in counter-propagating paths have a travel time difference $\delta t$ when rotation due to the Sagnac effect.$^{[25–27]}$ Moreover, the linear relation between $\delta t$ and $\Omega$ makes the gyroscope an ideal test bed for DTI because the ultrashort time difference change is measurable based on the angular velocity.

The pulse source is identical to that in Figure 2a, with 95% of the laser injected into gyroscope and the other 5% serving as trigger. The pulse is split into two portions: one portion (red) is injected into the fiber reel after the lower circulator (CIR), and propagates in clockwise (CW) direction, after which passes the upper CIR; the other portion (green) propagates in counter clockwise (CCW) direction in the fiber reel after the upper CIR, and then passes the lower CIR. The two portions encounter after another OC, which is detected by the oscilloscope (real time,

Figure 2. Measuring the resolution of DTI. a) Sketch of the experimental setup. b) Exemplary single-shot time interferogram. c) The interferogram evolution over 4 s. The adjacent shots have 1 ms interval, and 4000 shots in total are recorded. d) Retrieved time separation $\tau_1$ in (c). e) Retrieved $\tau_2$ in (c). f) Statistics histogram of $\tau_1$. g) Statistics histogram of $\tau_2$. h) Histogram of $\tau_2$ after improving the resolution using interpolation method. The blue line in (f) and (h) are the Gaussian fitting. $\tau$ is the mean of $\tau$. 

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10 GHz). The length of the fiber reel is 10 km with total dispersion of 230 ps², which can stretch the pulse into nanosecond. Therefore, time interference arises when the two portions encounter, and the time interferogram is caught by oscilloscope. Here, the two CIRs is used to make the two paths have an initial difference \( t_0 \). Hence, the relation of \( \tau \) and \( \Omega \) can be expressed as

\[
\delta \tau = \tau - t_0 = 2L\Omega r/c^2
\]

where \( L \) and \( r \) are the length and the radius of the path, and \( c \) is the light speed in vacuum.

First, the gyroscope was placed on a rotation stage without motor. Given an initial velocity, the gyroscope can run freely for several minutes before stopping, during which the rotation velocity declines uniformly because of the resistance. The angular velocity is monitored with a camera, and simultaneously, the time interferogram is captured by oscilloscope. Figure 4b displays the dependence of the time interferogram on rotation velocity. The retrieved \( \delta \tau \) from the interferograms as a function of \( \Omega \) over seven experiments are plotted in Figure 4d. All the results locate almost at the same line, proving the stability and repeatability of the apparatus. The line slope is 348 as/(deg s/C₀)¹, conforming well to the prediction from Equation (4) of 346 as/(deg s/C₀)¹, which proves the retrieved time separation exactly indicates the exerted time event.

As a high-data-rate gyroscope, its transient angular velocity can be measured. Then, the gyroscope is placed on a motorized rotation stage. As presented in Figure 4c,e, when the angular velocity is set 24 deg s⁻¹, a transient angular velocity drift is revealed. This is not due to the thermal drift because no such drift is observed when the gyroscope is placed on a manual rotation stage (Figure 4b and Figure S6, Supporting Information). Therefore, it is attributed to the angular velocity drift: the work the electromotor does is not uniform, leading to the rotation velocity change over time. Meanwhile, because the gyroscope is on an optical flat with a large mass, the inertance of the flat can retard the angular velocity change. The interaction between flat and electromotor will introduce vibration along rotation direction. As shown in Figure 4e, the drift is 23 deg s⁻¹, near 100% of the average velocity. The vibration frequency is about 3 kHz, corresponding to the vibration frequency of aluminum alloy. Meanwhile, these results highlight that the DTI can be used to monitor transient angular velocity of gyroscope. In some areas, like the rocket launching, the vibration will seriously impact the performance of device. To observe the temporal evolution of the vibration can help human to find out the source of vibration, and to reduce or restrain it, which will help to improve the device performance. The vibration in Figure 4e present that the DTI can temporally unveil such vibration.

The concept of DTI is a novel method to probe the time difference. With only a single interferogram, a rough time difference is retrievable from the fringe period, and a more precision signal is available after the assistance of interferogram phase. Such two-dimensional measurement endows the DTI the ability to probe time difference with range-to-resolution ratio larger than 10⁵ with a single interferogram. The single-shot measurement makes the sampling rate of DTI is the pulse repetition rate, 42.8 MHz, which is inaccessible for interferometric or ring-
cavity-based sensors.\cite{28,29} The short-term thermal drift, ubiquitous in interferometric sensors,\cite{15,30} is not observed in our experiments (Figure 2b and 4b), which highlights their high stability. Hence, by probing the time difference, the effective optical path difference can be accurately measured using DTI. In this way, the parameter to be measured can change the effective optical path, it is retrievable from the signal. Therefore, DTI can be used to fabricate various optical sensors, like displacement sensor (sub-nanometer resolution, millimeter range). Moreover, the interferogram measurement is much faster than the wavelength or frequency measurement, which is a prominent advantage of DTI-based sensor.

Additionally, DTI can also serve for the observation of dynamical evolution in ultrafast optics like breather soliton and soliton interaction,\cite{31–33} which may spur a new course of ultrafast dynamics in this area. Furthermore, injecting a closely-spaced pulse train into the target (Figure S7 and Vid. 2, Supporting Information), some ultrafast phenomena that occurs in femtosecond can be recorded.\cite{34}

4. Conclusion

In conclusion, we have proposed and demonstrated a new technique, the DTI, to single-shot probe the time event from attosecond to picosecond. As an analogy to spatial double-slit interference, this technique can encode the time difference into interferogram, and the time difference can be decoded from both the fringe period and the phase of the interferogram. Such measurement can determine the cycle number when phase change is beyond optical cycle, which make it possible to single-shot probe time difference that traditional interferometer is inaccessible. Experimentally, we show that such time detector has resolution of sub-20 as (0.004 optical cycle), range of more than 2 ps (400 optical cycle), range-to-resolution ratio of $10^5$. Moreover, its sampling rate is 42.8 MHz. As a typical example of the application in sensors, we fabricated a novel gyroscope and recorded its transient angular velocity drift, proving that this technique may achieve a breakthrough on high-data-rate sensors. This technique may be used to probe ultrafast physical or chemical reaction, and some other ultrafast dynamical phenomena.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.
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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available in the supplementary material of this article.

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