Complete Pulse Characterization Based on Temporal Interferometry Using An Unbalanced Temporal Pulse Shaping System

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***Abstract* — In this paper, we demonstrate a simple method for the full characterization of an ultrashort optical pulse based on temporal interferometry using an unbalanced temporal pulse shaping (UB-TPS) system. The UB-TPS system is functioning to generate and stretch two time-delayed replicas of the input pulse. The magnitude and phase information of the input pulse is reconstructed from the recorded temporal interference of the two time-delayed and dispersed pulses based on a Fourier transform algorithm.**

Index terms — **Chromatic dispersion, pulse characterization, real-time Fourier transform, spectral interferometry, suppressed-carrier modulation, temporal pulse shaping**.

I. INTRODUCTION

Ultrashort optical pulses have found wide applications in various scientific and engineering fields [1]. Precise and complete characterization (of magnitude and phase) of an optical short pulse is essential to evaluate and improve the performance of optical systems based on ultrafast optics. A variety of methods have been developed to retrieve the magnitude and phase information of an ultrashort optical pulse. A widely used technique for ultrashort optical pulse characterization is the frequency-resolved optical gating (FROG) technique [2], which is implemented based on nonlinear interaction between the probe and the gate pulses. On the other hand, linear interferometric methods enabling simple and direct pulse characterization with higher sensitivity has also be proposed. For example, spectral phase interferometry for direct electric-field reconstruction (SPIDER) [3] is a well-known pulse reconstruction method implemented in the spectral domain based on spectral shearing interferometry [4]. Linear interferometric measurement can also be done in the time domain based on temporal interferometry where two time-delayed replicas of the input pulse are generated using an interferometer and then temporally stretched in a dispersive medium. The magnitude and phase of the input pulse are reconstructed from the temporal interference of the two time-delayed and stretched pulses using Fourier-transform [5], [6] or Hilbert-transform [7] algorithms. Since a fiber-optic Sagnac interferometer [6] or a free-space Michelson interferometer [7] is usually used to generate two delayed replicas of the input pulse, the performance of pulse characterization methods is greatly affected by the instability of the interferometer due to its sensitivity to environmental perturbations, leading to considerable errors in the phase measurement process. A feedback control loop can be introduced in the interferometer to minimize the measurement errors [8]. However, the whole system becomes complicated and, moreover, the feedback loop can only be updated at a relatively slow rate (usually below one megahertz), which is not suitable for characterizing an optical pulse train with a very high repetition rate.

In this study, we propose and demonstrate a simple and linear pulse characterization technique based on temporal interferometry using an unbalanced temporal pulse shaping (UB-TPS) system. It is different from a conventional balanced temporal pulse shaping system in which the two dispersive elements (DEs) have complementary dispersion, in the proposed UB-TPS system, two DEs have opposite dispersion, but are not identical in magnitude [9]. The UB-TPS system is equivalent to a conventional TPS system to perform a real-time Fourier transform to generate two time-delayed replicas of the input optical pulse and a residual DE to perform a second real-time Fourier transform to convert the two time-delayed replicas to a temporal interference pattern. The magnitude and phase information of the input pulse to be measured are reconstructed from the recorded temporal interferogram based on a Fourier transform algorithm [5]. Unlike the previous systems in [5-8], no interferometer is involved in the proposed method. The system stability is significantly improved, enabling complete characterization of a sub-picosecond optical pulse with high accuracy. In addition, the temporal interference pattern can be easily tuned by controlling the frequency of the microwave modulation signal applied to the electro-optic modulator (EOM). This feature is ideally desirable for practical applications, where optical

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pulses with a variety of magnitudes and phases are to be tested. The proposed approach is experimentally demonstrated. The characterization of a ~550-fs transform-limited optical pulse train with a repetition rate of 48.6 MHz after propagating through a 105-m long single-mode fiber (SMF) is performed.

II. Principle

The proposed pulse characterization system based on unbalanced temporal pulse shaping is illustrated in Fig. 1. The UB-TPS system consists of an EOM and two DEs having opposite dispersion, but non-identical in magnitude. Under the first-order dispersion approximation, the DEs can be characterized by transfer functions given by $H_i(\omega)=\exp\left(-j\ddot{\Phi}_i\omega^2/2\right)$, $(i=1,\ 2)$, where $\ddot{\Phi}_1$ and $\ddot{\Phi}_2$ (ps^2/rad) are the group velocity dispersion (GVD) of the two DEs which should satisfy $\ddot{\Phi}_1\ddot{\Phi}_2<0$, and $\left|\ddot{\Phi}_1\right|\neq\left|\ddot{\Phi}_2\right|$. Therefore, the entire UB-TPS system can be modeled as a conventional balanced TPS system [10] having a pair of DEs with complementary dispersion of $\ddot{\Phi}_1$ and $-\ddot{\Phi}_1$, followed by a residual DE with a transfer function given by $H_\Delta(\omega)=\exp(-j\Delta\ddot{\Phi}\omega^2/2)$, where $\Delta\ddot{\Phi}=\ddot{\Phi}_1+\ddot{\Phi}_2$ is defined as the residual dispersion.

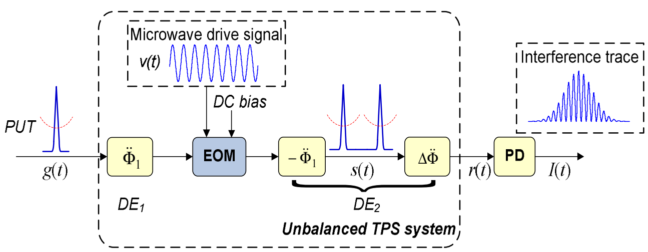

Figure 1. Schematic of the proposed pulse characterization system. PUT: pulse under test; DE: dispersion element; EOM: electro-optic modulator; PD: photodetector.

The input pulse under test (PUT), expressed as $g(t)=\left|g(t)\right|\exp[j\varphi(t)]$, is first stretched by the first DE ($\ddot{\Phi}_1$), then modulated by a sinusoidal microwave signal $v(t)=\cos(\omega_m t)$ at the EOM, and then completely compressed by the matched DE ($-\ddot{\Phi}_1$). If the EOM is dc-biased at the minimum transmission point to suppress the optical carrier, the signal at the output of the balanced TPS system is given by [9]

$$s(t)\propto g(t+\omega_m\ddot{\Phi}_1)+g(t-\omega_m\ddot{\Phi}_1) \qquad (1)$$

Therefore, two time-delayed replicas of the input pulse are obtained at the output of the balanced TPS system.

The two generated optical pulses are finally stretched by the residual DE with a residual dispersion of $\Delta\ddot{\Phi}$. If the residual dispersion is properly selected such that the condition $\left|\Delta\ddot{\Phi}\right|\geq\left(\omega_m\ddot{\Phi}_1\right)^2/2\pi$ is satisfied, then the output signal of the entire UB-TPS system, $r\left(t\right)$, can be approximated by the real-time Fourier transformation of $s\left(t\right)$ in the residual DE [11],

$$\begin{aligned} r(t) &\propto \exp[jt^2/(2\Delta\ddot{\Phi})]S(\omega)\big|_{\omega=t/\Delta\ddot{\Phi}} \\ &= \exp[jt^2/(2\Delta\ddot{\Phi})][G(\omega+\Delta\omega)+G(\omega-\Delta\omega)]_{\omega=t/\Delta\ddot{\Phi}} \end{aligned} \qquad (2)$$

where $G(\omega)=\left|G(\omega)\right|\exp[j\Psi(\omega)]$ is the spectrum of the input pulse with $\left|G(\omega)\right|$ and $\Psi(\omega)$ being the magnitude and phase terms, respectively, and $\Delta\omega=\omega_m\ddot{\Phi}_1/\Delta\ddot{\Phi}$ is the corresponding frequency shear resulted from the time delay difference between the two time-delayed pulse replicas.

The electrical current at the output of the photo-detector (PD) is proportional to the intensity of the input electrical field, $|r(t)|^2$, which is given by

$$\begin{aligned} I(t) &\propto \left|r(t)\right|^2=\left|G(\omega+\Delta\omega)\right|^2+\left|G(\omega-\Delta\omega)\right|^2+ \\ &\quad 2\left|G(\omega+\Delta\omega)\right|\left|G(\omega-\Delta\omega)\right|\cos[2\Delta\omega t+\Delta\Psi(\omega)]_{\omega=t/\Delta\ddot{\Phi}} \\ &\approx 2\left|G(\omega)\right|^2\{1+\cos[2\Delta\omega t+\Delta\Psi(\omega)]\}_{\omega=t/\Delta\ddot{\Phi}} \end{aligned} \qquad (3)$$

where $\Delta\Psi(\omega)=\Psi(\omega+\Delta\omega)-\Psi(\omega-\Delta\omega)\approx 2(d\Psi/d\omega)\Delta\omega$ is the relative phase difference between the two sheared spectral phases. Note that since $\Delta\omega$ is small enough, it is neglected in $G(\omega+\Delta\omega)$ and $G(\omega-\Delta\omega)$. From (3), we can find that the measured temporal interferogram gives a spectral intensity $\left|G(\omega)\right|^2$, and hence the spectral magnitude $\left|G(\omega)\right|$, of the input pulse to be measured according to the linear frequency-to-time mapping relationship given by $t=\omega\times\Delta\ddot{\Phi}$. In addition, the spectral phase difference $\Delta\Psi(\omega)$ is also included in $I(t)$, which can be extracted by using a conventional phase retrieval procedure [12]. Therefore, the spectral phase information $\Psi(\omega)$ is then obtained by integrating the spectral phase difference $\Delta\Psi(\omega)$ within the whole spectral range. Finally, the temporal magnitude $\left|g(t)\right|$ and phase $\varphi(t)$ of the input pulse is reconstructed by calculating a Fourier transform of the complex pulse spectrum.

It is worth pointing out that the accuracy of the spectral phase retrieved by the Fourier transform algorithm depends on the visibility of the measured temporal interferogram. In the previous approaches, the back reflections [5] and poor alignment of the polarization states [6], [7] of the two interfering light beams in the interferometer would significantly affect the interferogram visibility. In our proposed method, however, the two interfering signals, which are generated by a balanced TPS process incorporating double-sideband with suppressed-carrier (DSB-SC) modulation, always maintain an identical magnitude and the polarization states are always well assigned. Therefore, an interferogram with the highest visibility can be achieved, leading to improved spectral phase measurement accuracy.

III. Experiment

The proposed approach is experimentally demonstrated based on the setup shown in Fig. 1. A passively mode-locked fiber laser (MLFL) is used to generate a transform-limited optical pulse train with a full-width at half-maximum (FWHM) of 850 fs, a central wavelength of 1558 nm, a 3-dB bandwidth of 8 nm and a repetition rate of 48.6 MHz, which is slightly dispersed by propagating through a 105-m long SMF, and is then employed as the PUT. The peak power of the transform-limited optical pulse is properly controlled to avoid any nonlinear effects in the SMF.

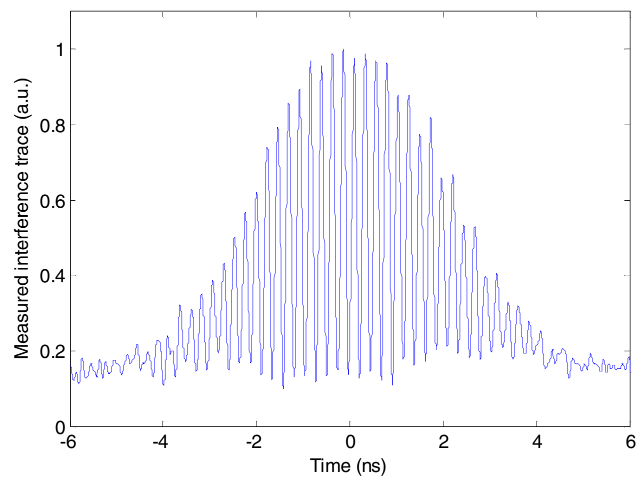

Figure 2. Measured interference pattern between two stretched and time-delayed replicas of the PUT using a real-time oscilloscope.

As shown in Fig. 1, the PUT is first dispersed by the first DE, which is a 2-km long dispersion compensating fiber (DCF) with a dispersion of $\ddot{\Phi}_1 = 438.5$ ps^2/rad. The stretched optical pulse is then modulated by a 4-GHz sinusoidal microwave signal at a Mach-Zehnder modulator (MZM). DSB-SC modulation scheme is employed by dc-biasing the MZM to operate at the minimum transmission point. The modulated optical pulse is then sent to the second DE, which is a 60-km SMF with a dispersion of $\ddot{\Phi}_2 = -1260.5$ ps^2/rad. The UB-TPS system here is equivalent to a balanced TPS system with two complementary DEs followed by a residual DE with a residual dispersion of $\Delta\ddot{\Phi} = -822$ ps^2/rad. Therefore, two time-delayed replicas of the PUT are generated at the output of the balanced TPS system, which correspond to the two optical sidebands at the output of the DSB-SC modulator. The two replicas have a time delay difference of 20.6 ps according to (1). The two time-delayed optical pulses are then stretched by the residual DE. The temporal interference between the two dispersed and delayed pulse replicas is measured by a PD and a real-time oscilloscope. The recorded temporal interferogram is shown in Fig. 2.

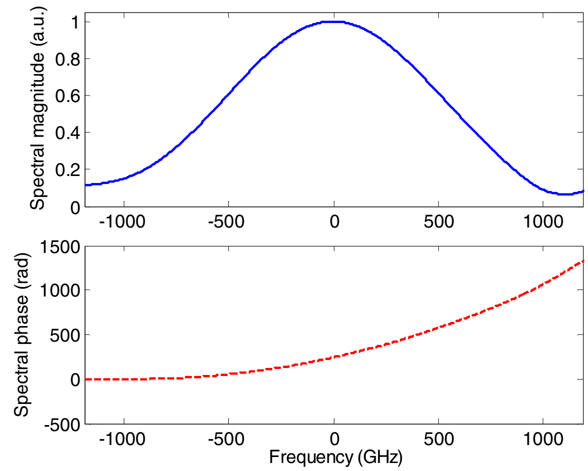

Figure 3. (a) Spectral magnitude and (b) spectral phase of the PUT, reconstructed from the measured temporal interferogram.

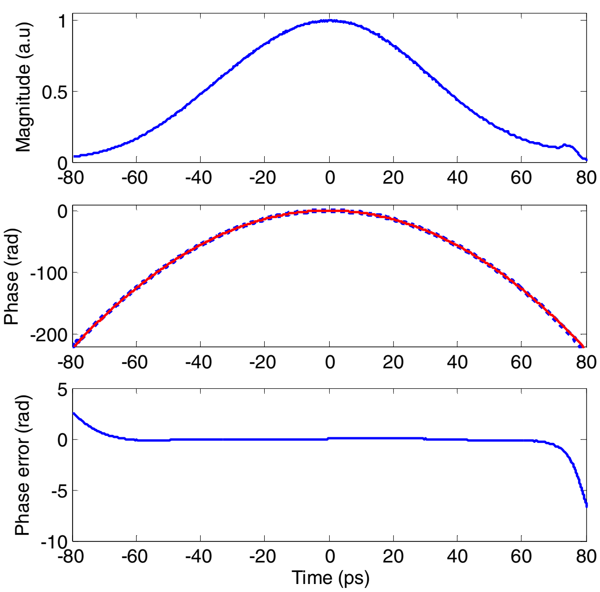

Figure 4. Reconstructed (a) temporal magnitude and (b) temporal phase of the PUT, calculated by the Fourier transform of Fig. (3) (Dashed line: measured phase, solid line: calculated phase. (c) Temporal phase measurement error.

Although the interferometry is performed in the time domain, spectral interferometry can be directly obtained from the measured temporal interferogram thanks to the linear frequency-to-time mapping relationship given by $t = \omega \times \Delta\ddot{\Phi}$. Then the spectral magnitude and phase of the PUT are reconstructed from the spectral interferometry using a conventional phase retrieval procedure as described in [12], with the results shown in Fig. 3. By calculating the Fourier transform of the pulse spectrum shown in Fig. 3, we obtain the temporal magnitude and phase of the PUT, with the results shown in Fig. 4. The temporal phase calculated from the spectral phase response of the 105-m long SMF is also plotted in Fig. 4(b) for comparison. Fig. 4(c) shows the temporal phase measurement error between the measured and calculated results. An average error as small as 0.3 rad is achieved within the main pulse window.

IV. Discussion and Conclusion

In our analysis, only the second-order dispersion (GVD, $\ddot{\Phi}$) was considered for the balanced TPS process and pulse stretching process. This treatment was valid for the TPS process where the DCF having a length of 2-km with small and negligible higher-order dispersion was employed. For the pulse stretching process using a 60-km SMF, however, the third-order dispersion (TOD, $\dddot{\Phi}$) is large and has to be taken into account. In fact, the measured temporal interference trace has a slightly nonuniform period caused by the higher-order dispersion, leading to a nonlinear frequency-to-time mapping [13]. In order to precisely retrieve the spectral phase information, an accurate nonlinear frequency-to-time mapping relationship should be established [6].

The proposed UB-TPS system has been applied to achieve microwave frequency multiplication [9]. In fact, by properly controlling the dispersion values of the DEs in the system, frequency division can also be realized. The significance is that the measured temporal interference trace may have a much lower frequency than that of the microwave modulation signal, thus a very low-speed PD and oscilloscope are required, which makes the system less costly.

According to the sampling theorem, the sampling rate of the real-time oscilloscope must be high enough to precisely measure the temporal interference pattern. In the proposed system, for a given input optical pulse, the required sampling bandwidth is only determined by the system dispersion and microwave modulation frequency. According to our analysis, characterization of a sub-picosecond optical pulse can be realized with the required sampling bandwidth less than 10 GHz. Therefore, our proposed method can find practical applications in the characterization of ultrashort optical pulses with conventional MZM, PD and oscilloscope.

In conclusion, a simple approach to achieving complete ultrashort optical pulse characterization based on temporal interferometry without using an optical interferometer was proposed and demonstrated. An UB-TPS system was used to simultaneously generate and stretch two time-delayed replicas of the input optical pulse to be measured. Complete magnitude and phase information of the input pulse was reconstructed from the recorded temporal interference pattern by using a Fourier transform algorithm. Since no optical interferometer was involved, the system was stable, leading to improved measurement accuracy.

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