SPECTRAL PHASE CHARACTERIZATION OF ULTRASHORT PULSE USING FRINGE FREE INTERFEROMETRY

© 2014 г. **Liang Lei*; Anquan Sun*; Wei Yuan**; Jinyun Zhou*; Bo Wang*; Xiaobo Xing*****

*School of Physics and Optoelectronic Engineering, Guangdong University of Technology, Guangzhou, China
**Zhengzhou Railway Vocational and Technical College, Zhengzhou, China
***MOE Key Laboratory of Laser Life Science and Institute of Laser Life Science, South China Normal University, Guangzhou, China

E-mail: leiliang@gdut.edu.cn

There are presented analytical and experimental results of a novel method which enables significant simplifications in spectral shearing interferometry as applied for ultrashort optical pulse measurements. The method attempts to improve the superiority in conventional Spectral Phase Interferometry for Direct Electric-field Reconstruction (SPIDER). It doesn't split a test pulse into two parts, but compensate for the delay time between two quasi-monochromatic frequency components in a chirped pulse with spectral and temporal shear to produce an interferogram without fringe. Fringe free interferogram could simplify data processing procedure and reduce the restriction on resolution of spectrometer. The experimental setup avoids the influence of material dispersion with real-time and single-shot nature, and could be made up as a miniaturization measurement device. Although being short of the beauties in SPIDER, it still could be an optional femtosecond pulse measurement method in certain condition.

Keywords: *femtosecond pulse, ultrafast measurements, spectral phase interferometer.*

OCIS codes: 120.3180, 120.5050, 320.7100.

Submitted 08.10.2013.

Many applications of ultrashort pulse require the knowledge of both pulse amplitude and phase. Continuous progress in the field of ultrashort pulse generation has lead to pulse durations up to 5 fs in the visible and near-infrared spectral range [1]. A lot of laser sources exhibit broad and complex spectra, making characterization of their pulses a demanding task. Especially an accurate, full characterization and stability of the spectral phase is necessary in the production of attosecond pulses [2]. Conventional autocorrelation technique can only provide rough estimate of the pulse duration. Several ultrashort pulse measurement techniques, such as the most popular methods, frequency-resolved optical gating (FROG) [3] and spectral phase interferometry for direct electric-field reconstruction (SPIDER) [4], allow a precise characterization of full amplitude and phase. These techniques even get excellent performance in the sub-10fs range [5], but some limitation can not ignore under certain conditions.

FROG requires a 2D data set near the spectral sampling limit (Whitaker–Shannon theorem), and the size of data and convergence time increase nonlinearly with the pulse complexity, iterative and complicated algorithm consumes a great deal of calculating time. In SPIDER, a dense interference fringe with comb-like structure depends on accurate spectrometer resolution constraint. If the spectral amplitude has a detail structure, very high spectral resolution may be necessary to resolve the fringes, especially in regions of low spectral intensity. Another issue with conventional SPIDER is the use of a splitter to split the test pulse, so that phase distortion is introduced especially for broadband pulses. Up to now, some improvements in SPIDER have been reported (ZAP-SPIDER [6], SEA-SPIDER [7], CAR-SPIDER [8], SEA-CAR-SPIDER [9], 2DSI [10], GRENOUILLE [11], ARAIGNEE [12]). The early technology ZAP-SPIDER avoids phase distortion problem by using two noncollinear chirped pulses, but still suffers from the delay calibration and the multiple path geometry, making the method most appropriate for externally amplified chirped pulses. SEA-SPIDER also performs shearing interferometry with zero delay, yet its separate path taken by the pulses means that even subwavelength imaging aberrations or nanometer intersection misalignments of the auxiliary pulses could become an issue for extremely short pulses. 2DSI and the latest SEA-CAR-SPIDER has the superiority just like ours, however it acquires two dimensions data set without single shot features.

There are presented a novel femtosecond pulse's amplitude and phase measurement named Fringe-free Interferometry of Spectral High-resolution (FISH) method based on the SPIDER's theory. The paper analyzes the causes of a dense fringe interferogram in SPIDER and how it transfers to the novel method in a practical experiment system. The key technology is to compensate for the time delay between two quasi-monochromatic waves in a chirped pulse to produce an interferogram without fringe, so that FISH could achieve a high-resolution spectral phase in only one step calculation without ambiguity. An effective experiment compared between FISH and SPIDER is presented in the end.

Either SPIDER or FISH treats spectral phase of test pulse $\varphi(\omega)$ as their final objective, by concatenating of spectral phase difference $\Delta\varphi(\omega)$ in up-converted pulse's replicas (spectral domain written as $\tilde{E}_1(\omega)$ and $\tilde{E}_2(\omega)$, temporal domain written as $\tilde{E}_1(t)$ and $\tilde{E}_2(t)$). In SPIDER, shown as fig. 1a, the up-converted replicas origins in the delay pair of test pulse, which is up-converted in Barium Boron Oxide (BBO) crystal by a strongly chirped long pulse, so that it contains the two quasi-monochromatic waves ($\tilde{E}_1(\omega)$ and $\tilde{E}_2(\omega)$) mentioned above. Provided their frequency difference is Ω ($\Omega = \omega_2 - \omega_1$) and time delay is τ, spectrally and temporally the up-converted replicas would be written as

$$\tilde{E}_2(\omega) = \tilde{E}_1(\omega - \Omega),\ \tilde{E}_2(t) = \tilde{E}_1(t - \tau). \quad (1)$$

Their interference signal $D(\omega)$ in spectrometer expresses as [4]

$$D(\omega) = \left|\tilde{E}(\omega)\right|^2 + \\ + \left|\tilde{E}(\omega - \Omega)\right|^2 + 2\left|\tilde{E}(\omega)\right|\left|\tilde{E}(\omega - \Omega)\right|\cos[\Delta\varphi(\omega) + \omega\tau], \quad (2)$$

here $\Delta\varphi(\omega)$ is the spectral phase difference $\varphi(\omega - \Omega) - \varphi(\omega)$. Seen from expression (2), $\Delta\varphi(\omega)$ and $\omega\tau$ in cosine term are the two spectral modulation in SPIDER's interferogram, while $\omega\tau$ is much greater than $\Delta\varphi(\omega)$. (For example, one picosecond delay contributes dozens of periods in 20 nm bandwidth test pulse, while the phase difference is usually less than a periods. One period stands for one interference fringe). To prevent the measured small value from being buried in an appendant large phase difference from τ, $\Delta\varphi(\omega)$ need a spectrometer with great resolution in SPIDER. Moreover, to remove τ is a complicated data processing, such as Fourier Transform, filter window, temporal shift, inversion Fourier Transform, which could induce systematic error.

FISH presents another way to obtain an up-converted pulse's replicas with spectral shear

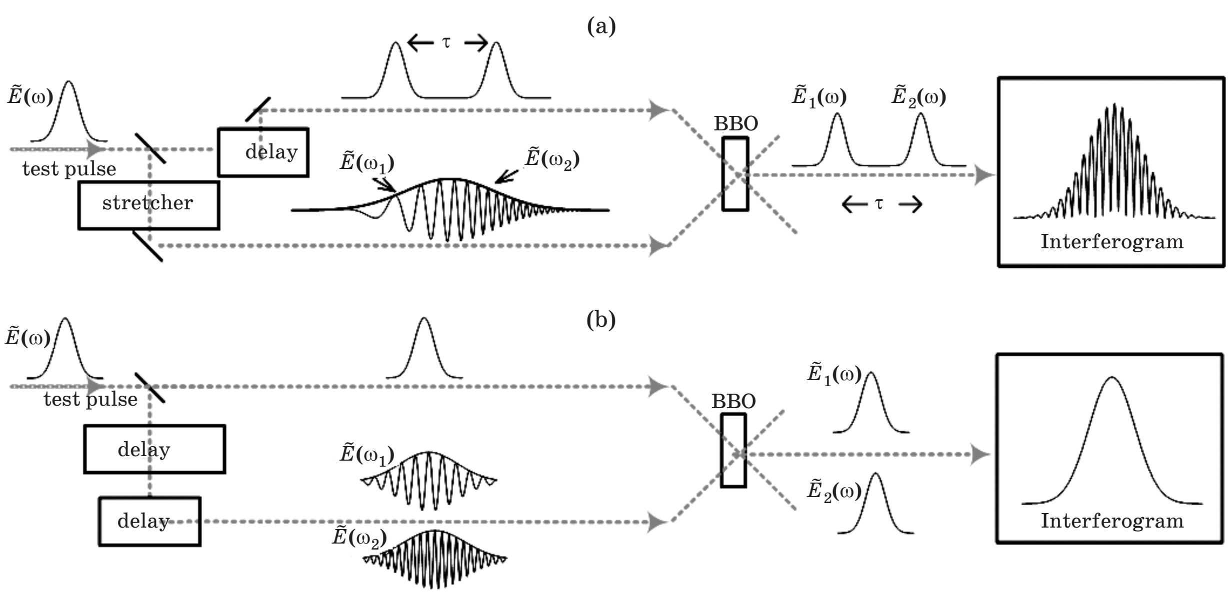

Fig. 1. Schematic of SPIDER (a) and FISH (b).

but no time delay, producing an interferogram without $\omega\tau$ modulation (fringe free). Shown as fig. 1b, the test pulse isn't separated temporally but injected into BBO directly. The other part is divided by dispersion system into lots of parallel quasi-monochromatic waves light with different frequency. Two of them (just like $\tilde{E}(\omega_1)$ and $\tilde{E}(\omega_2)$ mentioned above in SPIDER) selected by two slit aperture up-convert the test pulse in BBO. To guarantee the quasi-monochromatic waves synchronized with the test pulse, we should compensate for the time delay τ between $\tilde{E}(\omega_1)$ and $\tilde{E}(\omega_2)$ to observe two most powerful up-converted pulse's replicas intensity. After compensation, we get an up-converted pulse's replicas with spectral shear Ω benefited from the distance of two slit aperture by eliminating temporal difference. That means we originally remove the modulation by $\omega\tau$ on the spectral signal using optical way and achieve a fringe free interferogram. We can more easily get such an interferogram and two individual spectrums ($|E(\omega)|^2$ and $|E(\omega-\Omega)|^2$), then $|\Delta\varphi(\omega)|$ is calculated accurately by a simple formula:

$$\left|\Delta\varphi(\omega)\right| = \cos^{-1}\left(\frac{D(\omega) - \left|E(\omega)\right|^2 - \left|E(\omega-\Omega)\right|^2}{2\sqrt{\left|E(\omega)\right|\left|E(\omega-\Omega)\right|}}\right). \quad (3)$$

It's the transform of expression (2) in condition $\tau = 0$ and $D(\omega)$ is interference signal in spectrometer. Because the range of arc-cosine function is $[0, \pi]$ but general $\Delta\varphi(\omega)$ shifts from $-\pi/2$ to $\pi/2$, what can be obtained is only the absolute value of spectral phase difference, and its sign needs additional condition to be judged. In fact the sign can be decided by the direction of low approaching high frequency (or high approaching low frequency, depending on definition) during the time compensation in two quasi-monochromatic waves.

According to the theoretical discussion above, we build the experiment setup of FISH shown as fig. 2. It's easily rebuilt from a familiar autocorrelation system, just a pair of gratings and a time delay line in low frequency quasi-monochromatic light path replacing the stretcher in SPIDER. The short pulse duration and large bandwidth from Kerr Locked Mode (KLM) Ti: sapphire oscillator allow the use of a grating pair as dispersion system to generate the chirped pulse. In order to obtain $\tau = 0$, firstly the test pulse should set to synchronize with one of the chirped pulse (given high frequency light path) by seeking for the most powerful intensity up-converted pulse, then the low frequency light path is set to be synchronized with test pulse in a same way. Meanwhile we record the direction of moving the delay to judge the positive of the calculation. Using such a geometry, a set of experiment data using FISH to reconstruct pulse's full information from a KLM Ti: sapphire oscillator in our laboratory is presented, shown as fig. 3.

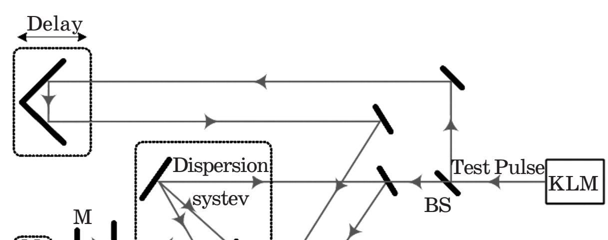

Fig. 2. FISH experimental setup: KLM – Kerr Locked Mode Ti: sapphire oscillator, BS – beam splitter, dispersion system – grating pair (1200 grooves/mm), M – mirror, CM – concave mirror (f = 100 mm), DS – double slit aperture, BBO – up-converting Barium Boron Oxide crystal (30 μm, type II), SP – spectrometer.

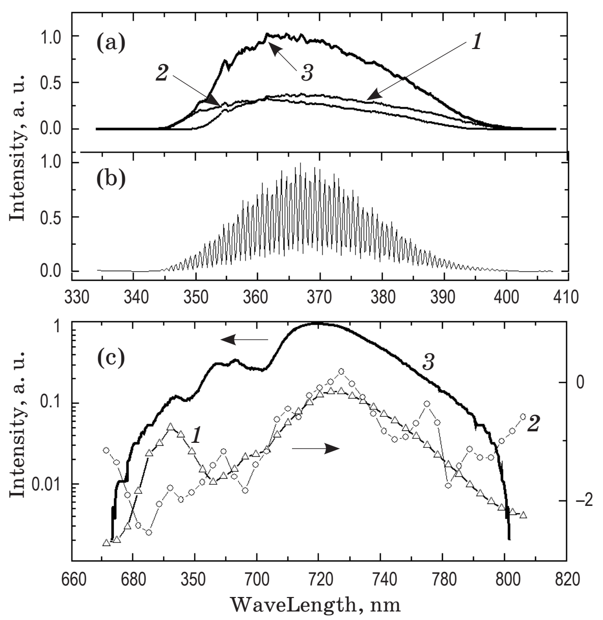

Fig. 3. Experimental interferogram (curve *3* – $|\tilde{E}(\omega_1) + \tilde{E}(\omega_2)|^2$) and individual spectrums of up-converted replica in FISH (curve *1* – $|\tilde{E}(\omega_1)|^2$, curve *2* – $|\tilde{E}(\omega_2)|^2$)(a). Experimental interferogram in SPIDER (b). Experimental spectrum of the test pulse (curve *3*), retrieved phases in FISH (curve *1*) and SPIDER (curve *2*) (c).

The individual spectrums of the low ($\tilde{E}(\omega_1)$ – the curve *1*) and high ($\tilde{E}(\omega_2)$ – the curve *2*) upconverted pulses are shown as dash-lines in fig. 3a, from those we can judge the spectral shear $\Omega = 1.52$ Thz (3.45 nm), which is an important parameter in phase concatenating. Their interferogram (the curve *3*) is shown as solid-line in the same graph. They are sufficient to calculate the objective $|\Delta\varphi(\omega)|$ with formula (3). The sign of $\Delta\varphi(\omega)$ is decided as minus, because the experiment confirms that the low frequency light compensates the high frequencies' delay time with a positive direction defined above. Eventually $\varphi(\lambda)$ is reconstructed by concatenating $\Delta\varphi(\lambda)$ shown as the triangle-dot line (curve *1* in fig. 3c). In order to exhibit the FISH's superiority compared to SPIDER, we get the SPIDER's experiment data to reconstruct the same test pulse, as the interferogram in fig. 3b, corresponding to spectral phase curve shown as the circle-dot line (curve *2* in fig. 3c). The curve *1* is generally in agreement with the later from SPIDER especially around the center of the test pulse's spectrum. Nevertheless, the two curves do not fit well in low power spectrum region. It seems the spectral phase from FISH is the reliable one, because moderately broadband pulse out of an oscillator should not have excessive fluctuating spectral phase such like SPIDER's experiment result (curve *2*). The large phase variation might be attributed to the absence of spectrometer's resolution.

Step forward to analysis the data in temporal domain. The logarithmic solid-line (curve *3* in fig. 3c) is the spectrum of the test pulse, from which we can see a spectral range from 672 to 803 nm. Calculated from FISH's and SPIDER's spectral phase curves and spectrum, the temporal domain full information of the test pulse is achieved using inversion Fourier-Transfer, seen as solid-line (FISH) and dash-line (SPIDER) (curve *4* and curve *5* in fig. 4a respectively). The curve *4* shows a hyperbolic secant intensity and negative chirped phase approximately (Group Velocity Dispersion ≈ -150 fs^2/rad), yet the curve *5* is fluctuant dramatically and appears a great disagreement to curve *4* around the pulse's sidelobe, which seems illogical to be a test pulse's intensity and phase in KLM Ti: sapphire oscillator. To validate the FISH's measurement, an autocorrelation is experimentally required. In fig. 4b, solid-line (curve *6*) is autocorrelation experiment data of test pulse, while triangle-dot line (curve *7*) and circle-dot line (curve *8*) are the theoretical autocorrelation curves calculated from FISH's and SPIDER's experiment result respectively. The former curve *7* agrees more precisely with the experimental curve *6* than the later curve *8*, proving the novel method's success in pulse measurement on the condition of resolution restriction.

In conclusion, there is presented an optional spectral phase direct reconstruction scheme for characterizing the temporal amplitude and phase of ultrashort optical pulses. Theory and experiment have been demonstrated to confirm the validity in FISH compared to conventional SPIDER.

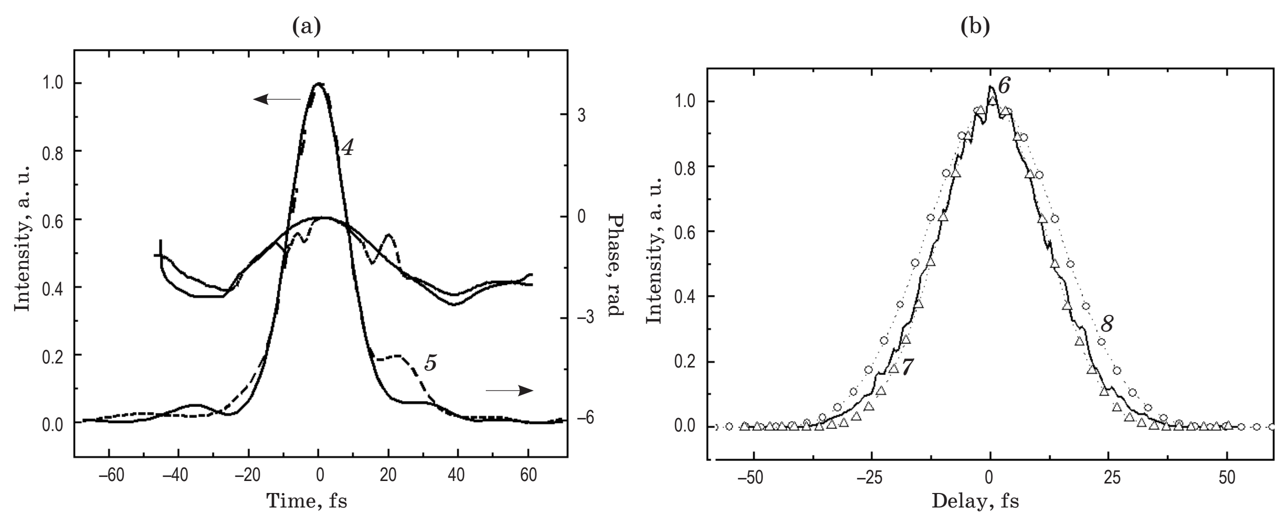

Fig. 4. Temporal intensity and phase in FISH (curve *4*) and SPIDER (curve *5*) (a). Experimental autocorrelation curve (curve *6*), theoretical autocorrelation curves calculated from FISH's (curve *7*) and SPIDER's (curve *8*) experiment (b).

The novel method doesn't split a test pulse into two parts, but compensate for the delay time in two quasi-monochromatic frequency components with spectral and temporal shear in stretched chirped pulse, so that they can be synchronized with the test pulse to achieve up-converted replicas and fringe free interferogram. In the absence of dispersion material throughout the light path, FISH avoids inducing additional dispersion or bandwidth restriction to test pulse through splitter. Because of its simplified setup, single shot nature and seldom data processing, it could work as a real-time miniaturization measurement device. The simple reconstruction procedure and one-step calculation may improve the demands on resolution of apparatus and Fourier Transform in SPIDER, reducing the influence of noise and experimental conditions. Therefore, FISH could be an optional, convenient and accurate technology in characterizing femtosecond pulse.

The authors acknowledge the financial support from National Natural Science Foundations of China Grant Nos. 61107029, 11304044 and 61177077.

* * * * *

ЛИТЕРАТУРА

1. *Kienberger R., Krausz F.* Attosecond metrology comes of age // Physica Scripta. 2004. V. 110. P. 32–38.
2. *Hentschel M., Kienberger R., Spielmann C., Reider G.A., Milosevic N., Brabec T., Corkum P., Heinzmann U., Drescher M., Krausz F.* Attosecond metrology // Nature. 2001. V. 414. P. 509–513.
3. *Kane D.J., Trebino R.* Characterization of arbitrary femtosecond pulses using frequency-resolved optical gating // IEEE J. Quantum Electron. 1993. V. 29. P. 571–579.
4. *Iaconis C., Walmsley I.A.* Spectral phase interferometry for direct electric-field reconstruction of ultrashort optical pulses // Opt. Lett. 1998. V. 23. P. 792–794.
5. *Wen J.H., Zhang H., Lu J., Jiao Z.X., Lei L., Lai T.S.* Spectral shearing interferometer with broad applicability // J. Opt. Soc. Am. B. 2011. V. 28. P. 1391–1395.
6. *Baum P., Lochbrunner S., Riedle E.* Tunable sub-10-fs ultraviolet pulses generated by achromatic frequency doubling // Opt. Lett. 2004. V. 29. P. 1686–1688.
7. *Kosik E.M., Radunsky A.S., Walmsley I.A., Dorrer C.* Interferometric technique for measuring broadband ultrashort pulses at the sampling limit // Opt. Lett. 2005. V. 30. P. 326–328.
8. *Gorza S.P., Wasylczyk P., Walmsley I.A.* Spectral shearing interferometry with spatially chirped replicas for measuring ultrashort pulses // Opt. Exp. 2007. V. 15. P. 15168–15174.
9. *Austin D.R., Witting T., Walmsley I.A.* Resolution of the relative phase ambiguity in spectral shearing interferometry of ultrashort pulses // Opt. Lett. 2010. V. 35. P. 1971–1973.
10. *Birge J.R., Ell R., Kartner F.X.* Two-dimensional spectral shearing interferometry for few-cycle pulse characterization // Opt. Lett. 2006. V. 31. P. 2063–2065.
11. *Gorza S.P., Radunsky A.S., Wasylczyk P., Walmsley I.A.* Tailoring the phase-matching function for ultrashort pulse characterization by spectral shearing interferometry // J. Opt. Soc. Am. B. 2007. V. 24. P. 2064–2074.
12. *Radunsky A.S., Walmsley I.A., Gorza S.P., Wasylczyk P.* Compact spectral shearing interferometer for ultrashort pulse characterization // Opt. Lett. 2007. V. 32. P. 181–183.