Polarization shaper-assisted dual-quadrature spectral shearing interferometry

Chi-Cheng Chen, Hung-Wen Chen, Po-Ya Wu, Chen-Bin Huang, and Shang-Da Yang*
Institute of Photonics Technologies, National Tsing Hua University, Hsinchu 30013, Taiwan
Email:shangda@ee.nthu.edu.tw

Abstract: Polarization pulse shaper is used in spectral phase retrieval for the first time (to our best knowledge). The implemented dual-quadrature spectral shearing interferometry is self-referenced and can measure pulse trains of 100% duty cycle.
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1. Introduction

Ultrashort pulse shaper has been applied to a series of pulse measurement techniques, such as SPIDER [1], FROG [2], and modified interferometric field autocorrelation (MIFA) [3]. The employment of a (scalar) pulse shaper eliminates the need for an interferometer setup, avoids the extra dispersion, allows for simultaneous measurement and shaping, improves on the precision of system calibration [1], and enables ultrahigh sensitivity (40 photons per pulse) by artificially reducing the fringe density of interferometric traces [3]. However, none of these techniques can measure waveforms with 100% duty cycle [4]. This goal can be met by dual-quadrature spectral shearing interferometry (DQ-SSI) [5], where two coherent probe spectral lines with specified relative phase are needed. In the previous implementation of DQ-SSI [5], the signal and probe fields came from a phase-modulated CW (PMCW) comb and an intensity-modulated CW laser (both are driven by the same RF source) plus an optical delay line, respectively. In addition to the increased complexity, this scheme may not measure signal source other than PMCW comb for lack of mutual coherence between signal and probe. In this contribution, we demonstrated the polarization shaper-assisted [6] DQ-SSI by measuring the spectral phase function of a mode-locked laser. Compared with scalar shaper-assisted FROG and SPIDER, our scheme is attractive in terms of (1) fast data acquisition and iteration-free data inversion, (2) easy and precise calibration of spectral shear and probe phase, (3) no error due to violation of quasi-CW reference when the signal is highly chirped [7], (4) relaxed resolution of the spectrometer, (5) more compact geometry for lack of a pulse stretcher made of a prism/grating pair or a dispersive medium.

2. Theory

In DQ-SSI, the signal pulse of complex spectral envelope $A(\omega)=|A(\omega)|\times e^{j\psi(\omega)}$ interacts with two probe lines separated by spectral shear Ω, producing a sum-frequency generation (SFG) spectrum

$$S_i(\omega)= B(\omega)+M(\omega)\times\cos[\Delta\psi(\omega)+\Delta\phi_i],\ i=1, 2, 3, \tag{1}$$

where $B(\omega)\equiv|A(\omega)|^2+|A(\omega+\Omega)|^2$, $M(\omega)\equiv2|A(\omega)\times A(\omega+\Omega)|$ represent background and modulation envelope spectra, $\Delta\psi(\omega)\equiv\psi(\omega+\Omega)-\psi(\omega)$ and $\Delta\phi_i$ are the spectral phase difference function of the signal pulse and phase difference between the two probe lines in the ith measurement, respectively. The spectral phase difference function $\Delta\psi(\omega)$ can be obtained by measuring three SFG spectra at three different probe phases $\Delta\phi_{1,2,3}$. For example, $S_{1,2,3}(\omega)$ become $B(\omega)+M(\omega)\times\cos[\Delta\psi(\omega)]$, $B(\omega)-M(\omega)\times\sin[\Delta\psi(\omega)]$, and $B(\omega)-M(\omega)\cos[\Delta\psi(\omega)]$ if $\Delta\phi_{1,2,3}$ equals 0, $\pi/2$, π, respectively. The background spectrum $B(\omega)$ is calculated by $[S_1(\omega)+S_3(\omega)]/2$, from which one can get $M(\omega)\times\cos[\Delta\psi(\omega)]$, $M(\omega)\times\sin[\Delta\psi(\omega)]$, $\tan[\Delta\psi(\omega)]$, and $\Delta\psi(\omega)$ in turn. The unknown spectral phase $\psi(\omega)$ can be retrieved by concatenation with a resolution of Ω. Instead of using extra CW laser, RF function generator, intensity modulator, and optical delay line [5], we can generate two precisely phased probe lines at an orthogonal polarization state by modulating the amplitude and phase of the signal field in a polarization shaper. In this way, any signal source can be measured, and the spectral shear Ω and probe phase $\Delta\phi$ can be controlled independently and precisely.

3. Experiment

The experimental setup is shown in Fig. 1(a). A homemade all normal dispersion (ANDi) Er-doped fiber laser produced a pulse train of 8.3-MHz repetition rate, 1.9-THz rms bandwidth [Fig. 1(b)], centered at 1551.3 nm (193.3 THz). The signal pulse was polarization controlled and sent into a polarization shaper consisting of a Wollaston prism, a two-lens telescope, a folded zero-dispersion compressor, and a liquid crystal spatial light modulator (SLM-640-D-NM, CRI). The y-polarization component was spectrally shaped to generate two probe lines (with 20-dB contrast) spaced by $\Omega=2\pi\times0.16$ THz [Fig.1(c)]. The signal and probe were mixed in a 2-mm-thick Type II BBO crystal for SFG and measured by a spectrometer with a spectral resolution of 0.2 nm.

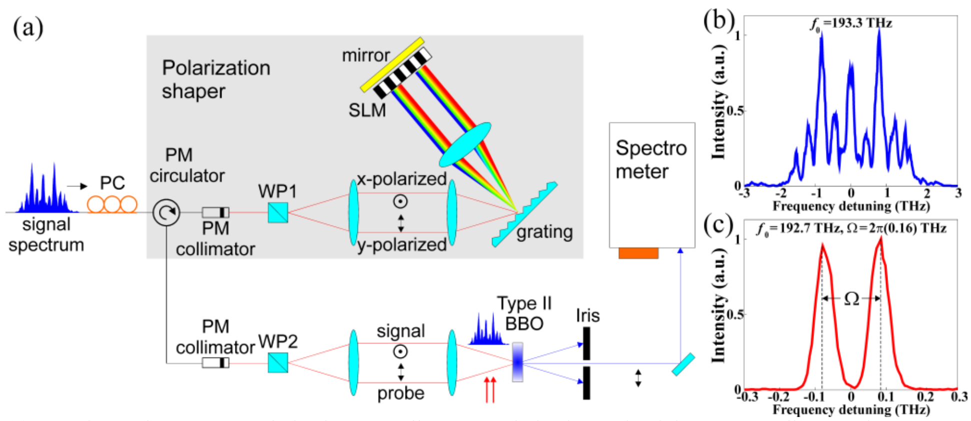

Fig. 1. (a) Experimental setup. PC: polarization controller. PM: polarization maintaining. WP: Wollaston prism. SLM: spatial light modulator. The power spectra of (b) signal, and (c) probe are also shown.

As shown in Fig. 2(a), the residual spectral phase $\psi_{res}(\omega)$ of the signal is experimentally measured (open circles) and fit by a third order polynomial (solid) $-(0.15\ \mathrm{ps}^2)\omega^2-(0.0025\ \mathrm{ps}^3)\omega^3$. By applying $-\psi_{res}(\omega)$, we could compress the signal pulse close to its transform limit. The experimentally measured intensity autocorrelation (IA) function [Fig. 2(d), dashed] is in good agreement with that obtained by simulation (solid), proving the integrity of our phase measurement. We then applied extra spectral phases $-(0.1\ \mathrm{ps}^2)\omega^2 +(0.0015\ \mathrm{ps}^3)\omega^3$ and $-0.5\pi\sin[(0.75\ \mathrm{ps})\omega]$ to the compressed pulse [Figures 2(b), 2(c), solid] for measurement (open circles). The good agreement between the experimentally measured and simulated IA functions [Figures 2(e), 2(f)] further confirmed our measurement results.

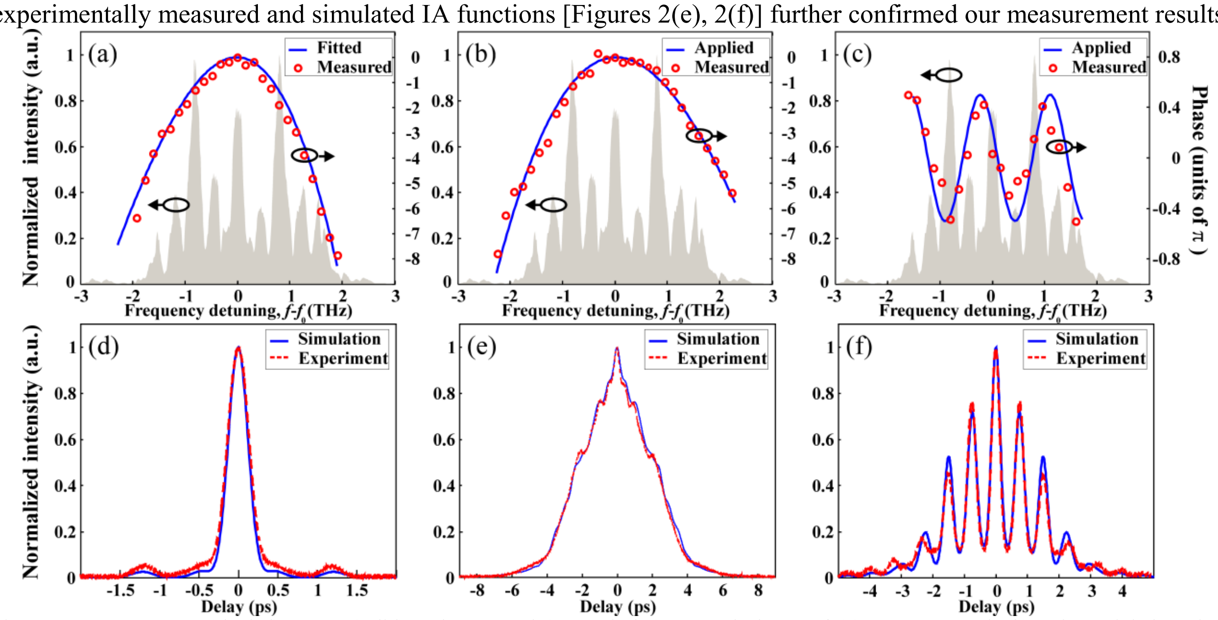

Fig. 2. Power spectrum (shaded), target (solid) and measured (open circles) spectral phases of (a) uncompressed, (b) polynomial-shaped, (c) sinusoid-shaped pulses, respectively. (d-f) The corresponding IA functions obtained by simulation (solid) and experiment (dashed), respectively.

4. Conclusion

We have experimentally demonstrated that the polarization shaper-assisted DQ-SSI can retrieve the spectral phase profile without using extra CW laser, RF function generator, intensity modulator, and optical delay line. The apparatus can be easily and precisely calibrated for accurate spectral phase recovery. This work was supported by the National Science Council of Taiwan under grants NSC 100-2221-E-007-093-MY3, 100-2112-M-007-007-MY3, 99-2120-M-007-010, and by the National Tsing Hua University under grant 101N2081E1.

References

[1] B. von Vacano, T. Buckup, M. Motzkus, J. Opt. Soc. Am. B, **24**(5), 1091-1100 (2007).
[2] A. Galler, T. Feurer, Appl. Phys. B, **90**, 427-430, (2008).
[3] C. -S. Hsu, H. -C. Chiang, H. -P. Chuang, C. -B. Huang, S. -D. Yang, Opt. Lett., **36**(14), 2611-2613 (2011).
[4] S. T. Cundiff and A. M. Weiner, Nat. Photon., **4**(11), 760-766 (2010).
[5] H. X. Miao, D. E. Leaird, C. Langrock, M. M. Fejer, A. M. Weiner, Opt. Express, **17**(5), 3381-3389 (2009).
[6] C. -C. Chen, I. -C. Hsieh, S. -D. Yang, C. -B. Huang, Opt. Express, **20**(24), 27062-27070 (2012).
[7] J. Wemans, G. Figueira, N. Lopes, and L. Cardoso, Opt. Lett., **31**(14), 2217-2219 (2006).