Self-referenced frequency comb measurement by a polarization line-by-line pulse shaper

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Abstract: A polarization line-by-line pulse shaper is used in analytically measuring optical arbitrary waveforms (OAWs) of 100% duty cycle without reference, which is essential for high repetition rate OAWs.
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1. Introduction

The employment of a (scalar) pulse shaper in ultrafast waveform characterizations eliminates the need for an interferometer setup, avoids the extra dispersion, allows for simultaneous measurement and shaping, and improves on the precision of system calibration [1-4]. However, none of the demonstrated shaper-assisted measurement techniques can measure optical arbitrary waveform (OAW) with 100% duty cycle [5]. Dual-quadrature spectral interferometry (DQ-SI) [6], phase retrieval by omega oscillation filtering (PROOF) [7], and dual-quadrature spectral shearing interferometry (DQ-SSI) [8] succeed in OAW characterizations. However, they require a well characterized reference pulse, a synchronized temporal phase modulation, and a pair of coherent spectral lines (probe) with specified relative phases and detuned central wavelength, respectively. For OAW not arising from phase-modulated CW (PMCW) comb or with large (say >100 GHz) mode spacing, it is difficult to apply the phase modulation for PROOF or generate the probe for DQ-SSI in [8] (both relying on synchronous RF driving). In this work, a reference-free DQ-SSI system with a polarization line-by-line pulse shaper [9] successfully measured three types of OAW. The method is simple, accurate, and applicable to high repetition rate (mode spacing) frequency combs.

2. Theory

In DQ-SSI, the signal pulse of complex spectral envelope $A(\omega)=|A(\omega)|\times\exp[\,j\psi(\omega)]$ interacts with two probe lines spectrally separated by Ω (spectral shear), 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 $B(\omega)\equiv|A(\omega)|^2+|A(\omega+\Omega)|^2$, $M(\omega)\equiv 2|A(\omega)\times A(\omega+\Omega)|$ represent the 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 the phase difference between the two probe lines in the *i*th 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 $B+M\times\cos(\Delta\psi)$, $B-M\times\sin(\Delta\psi)$, and $B-M\times\cos(\Delta\psi)$ 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 $M\times\cos(\Delta\psi)$, $M\times\sin(\Delta\psi)$, $\tan(\Delta\psi)$, and $\Delta\psi(\omega)$ in turn. Finally, the unknown spectral phase $\psi(\omega)$ can be retrieved by concatenation with a resolution of Ω. Instead of using an extra CW laser, RF function generator, intensity modulator, and optical delay line as in [8], we propose to generate the precisely phased probe fields at an orthogonal polarization state (with respect to the signal) by a polarization line-by-line pulse shaper. In this way, any OAW signal (not limited to PMCW comb) can be simultaneously measured and shaped without RF source (thus applicable to high repetition rate frequency combs).

3. Experiment

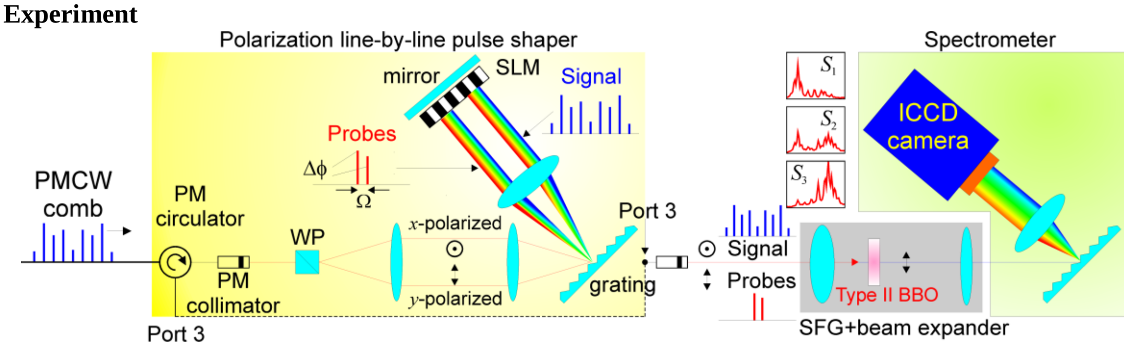

Fig. 1. Experimental setup. PC: polarization controller. PM: polarization maintaining. WP: Wollaston prism. SLM: spatial light modulator. ICCD: Intensified CCD.

The experimental setup is shown in Fig. 1. A PMCW comb with 20 GHz spacing (50 ps repetition period) is generated by injecting a 1 kHz-linewidth CW laser (NKT Adjustik) centered at 1545 nm into a low-V_π optical phase modulator. The signal pulse was polarization controlled and sent into a polarization line-by-line pulse 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 the two probe lines (with 35 dB side-mode suppression ratio) spaced by $\Omega=2\pi\times20$ GHz. The signal and probe were mixed in a 2-mm-thick Type II BBO for SFG and measured by a home-made high-resolution (0.03 nm) spectrometer.

Figure 2(a) shows the experimentally measured residual spectral phase $\psi_{res}(\omega)$ of the raw PMCW comb (open circles). The quasi-random $\psi_{res}(\omega)$ causes a temporal waveform filling the entire 50 ps repetition period [Fig. 2(d), inset]. 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). We then added two spectral phases, $1.5\times\sin(\tau\omega)$ with τ=6 ps [Fig. 2(b), solid], and alternating $\{0,\pi/2\}$ phases [Fig. 2(c), solid], for DQ-SSI measurement. The retrieved spectral phases [Figs 2(b), 2(c), open circles] and the measured IA functions [Figs 2(e), 2(f), solid] agree well with the added and simulated counterparts. The IA functions in Figs 2(e), 2(f) clearly show the 6 ps peak spacing and the doubled intensity repetition rate (due to the temporal Talbot effect [9]) as expectation. These results confirmed the integrity of our measurement.

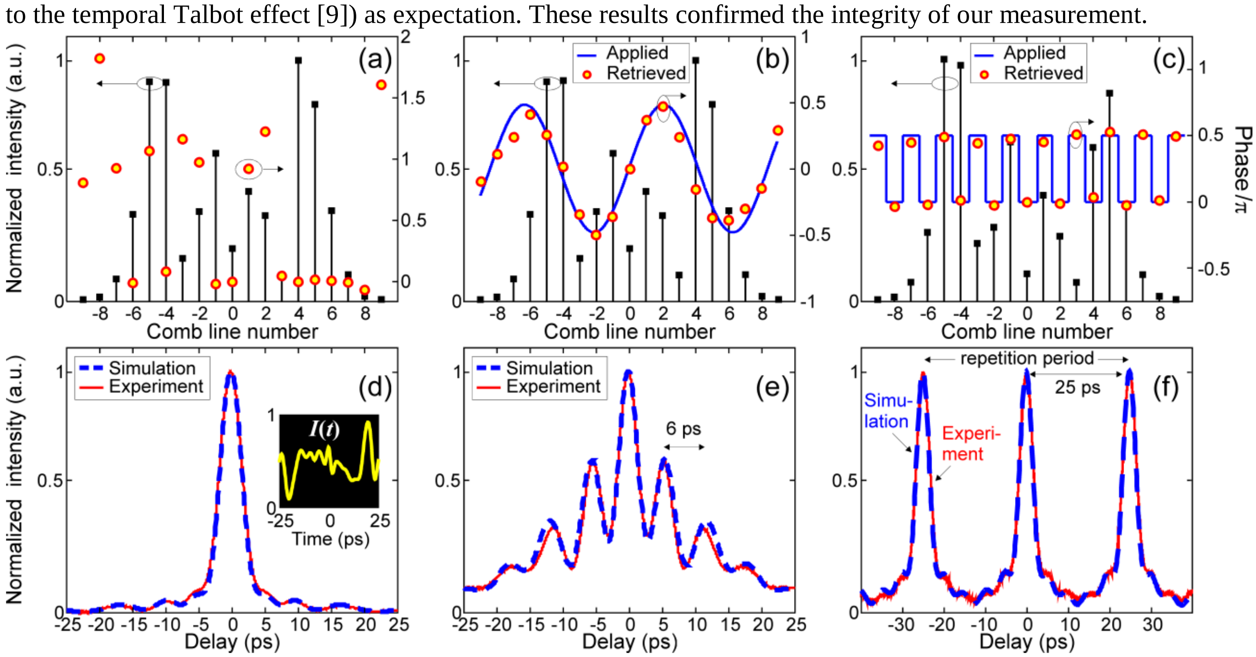

Fig. 2. Power spectrum (square), target (solid) and measured (open circles) spectral phases of (a) the raw PMCW comb, (b) the sinusoidal-shaped, (c) repetition-rate-multiplied pulses, respectively. (d-f) The corresponding IA functions obtained by simulation (solid) and experiment (dashed), respectively.

4. Conclusion

We proposed and experimentally demonstrated a self-referenced DQ-SSI scheme that can measure OAW arising from different comb sources. Compared with the previous DQ-SSI implementation, our scheme does not need an extra CW laser, RF function generator, intensity modulator, optical delay line, and can measure high repetition rate frequency combs. 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 grant NSC 100-2221-E-007-093-MY3.

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