Synthesis and all-optical self-referenced measurement of vectorial optical arbitrary waveform

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Abstract: We demonstrated an integrated system that can manipulate and measure vectorial field spanning up to the entire repetition period without ambiguity, iteration, and reference.
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1. Introduction

Vectorial optical arbitrary waveform (V-OAW) with time-varying amplitude, phase, state of polarization (SOP) spanning up to the entire repetition period (100% duty cycle) is the most sophisticated optical field in the time/frequency domain [1]. Scalar OAW (with static SOP) and vectorial ultrashort pulse (with <<100% duty cycle) have been applied to radio-frequency (RF) photonics [2], intensity repetition rate multiplication of a pulse train [3], background-free single-pulse coherent anti-Stokes Raman spectroscopy [4], and selective spatiotemporal excitations in nanometer and femtosecond scales [5], respectively. The greater flexibility of V-OAW is expected to enable unique applications in ultrafast plasmonics. Unfortunately, the existing vectorial ultrashort pulse measurement techniques cannot characterize V-OAW. To implement tomographic ultrafast retrieval of transverse light E-fields (TURTLE) [6] or dual-channel spectral interferometry [7,8], one needs a variable or fixed delay that is large enough to separate the signal waveform into two isolated replicas. This requisite cannot be satisfied when the waveform is of 100% duty cycle. Besides, the large (>100 GHz) mode spacing of Kerr frequency combs and the fact that transient SOP is vulnerable to environmental perturbation restrict the usefulness of measurement techniques relying on RF or optical reference. In this paper, we report full-Vectorial E-field Characterization Through all-Optical and self-Referenced (VECTOR) method that can analytically retrieve V-OAW without any reference or ambiguity for the first time (to the best of our knowledge).

2. Theory

The complex spectral envelope of a V-OAW can be expressed as $\boldsymbol{A}(\omega)=A_x(\omega)\boldsymbol{x}+rA_y(\omega)\times\exp[j(\omega\tau_{xy}+\theta)]\boldsymbol{y}$, where r, τ_{xy}, θ are the relative amplitude, delay, and constant phase between x- and y-polarizations, $A_{x,y}(\omega)\equiv|A_{x,y}(\omega)|\times\exp[j\phi_{x,y}(\omega)]$ is the spectral envelope determining the temporal shape of x- or y-polarization. In the first step, $\phi_x(\omega)$ is measured by the OAW-compatible orthogonally probed dual-quadrature spectral shearing interferometry (DQ-SSI) [9]. Secondly, the phase difference between x- and y-polarizations, $\Delta\phi_{xy}(\omega)\equiv[\phi_y(\omega)+\tau_{xy}\omega+\theta]-\phi_x(\omega)$, is measured by a wavelength-parallel polarimeter (WPP) [10]. Note that WPP retrieves the frequency-dependent Stokes elements $S_{0,1,2,3}(\omega)$ by measuring the power spectra of four particular polarization components $I_x(\omega)$, $I_y(\omega)$, $I_{45}(\omega)$, $I_{RHC}(\omega)$, where $S_2(\omega)=2|A_x(\omega)\times A_y(\omega)|\times\cos[\Delta\phi_{xy}(\omega)]$ and $S_3(\omega)=2|A_x(\omega)\times A_y(\omega)|\times\sin[\Delta\phi_{xy}(\omega)]$. As a result, $\Delta\phi_{xy}(\omega)$ [and thus $\phi_{y,tot}(\omega)\equiv\phi_y(\omega)+\tau_{xy}\omega+\theta$] can be unambiguously retrieved from $S_2(\omega)$ and $S_3(\omega)$. Finally, $|A_x(\omega)|$ and $r|A_y(\omega)|$ are determined by $I_x(\omega)$ and $I_y(\omega)$, form which the full vectorial field $\boldsymbol{A}(\omega)$ is reconstructed. By comparison, the procedures used in [1] involve with (1) two nonlinear, iterative measurements to get $\phi_x(\omega)$ and $\phi_y(\omega)$, (2) two linear measurements assisted by a transform-limited (TL) reference comb to retrieve τ_{xy}, and (3) a phase-scanning interferogram to determine θ; which are far more complicated and need interferometric stability.

3. Experiment

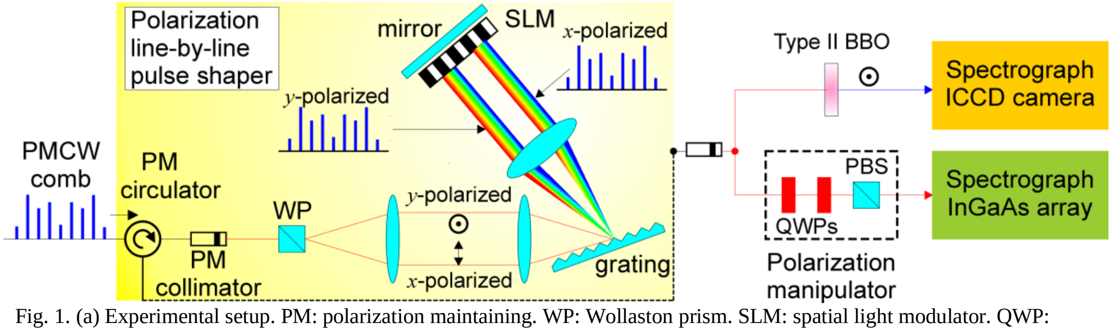

Fig. 1. (a) Experimental setup. PM: polarization maintaining. WP: Wollaston prism. SLM: spatial light modulator. QWP: quarter wave plate. PBS: polarization beam splitter. ICCD: Intensified CCD.

The experimental setup is shown in Fig. 1. The light source was a phase modulated continuous-wave (PMCW) comb with 1545 nm central wavelength and 20 GHz mode spacing. A polarization line-by-line pulse shaper introduced independent amplitude and phase modulations on the *x*- and *y*-polarizations, respectively [11]. In performing DQ-SSI and WWP measurements, the shaper output was connected to a 2-mm-thick Type II BBO for sum-frequency generation and a polarization manipulator for SOP samplings, respectively. The resulting power spectra were recorded by a spectrograph and an intensified CCD camera or an InGaAs detector array, respectively. Figure 2 shows the measurement results of a raw V-OAW, where $\phi_{x,y}$ varied wildly with ω and $\Delta\phi_{xy}(\omega)$ mainly resulted from the imbalanced paths of the system. Figures 2(a) and 2(b) illustrate the $\phi_x(\omega)$ and $\phi_{y,tot}(\omega)$ measured by DQ-SSI [9] and WWP [10], respectively. The values of (τ_{xy},θ) retrieved by VECTOR and the procedures used in [1] are (-6.306 ps, 0.316π) and (-6.277 ps, 0.317π), in good agreement with each other. The reconstructed V-OAW [Fig. 2(c)] clearly exhibits time-varying SOP, strong chirp, and 100% duty cycle. In another demonstration, we generated an intensity-rate doubled pulse train by applying periodic spectral phases of {0, π/2} and {π, π/2} [solid, Figs 2(d), 2(e)] to the dispersion-compensated *x*- and *y*-polarized comb lines. The phase jumps were accurately resolved by VECTOR [circles, Figs 2(d), 2(e)]. The synthesized V-OAW [Fig. 2(f)] shows doubled (40 GHz) intensity repetition rate and alternating handedness between adjacent pulses due to the alternating ±π/2 temporal phase differences.

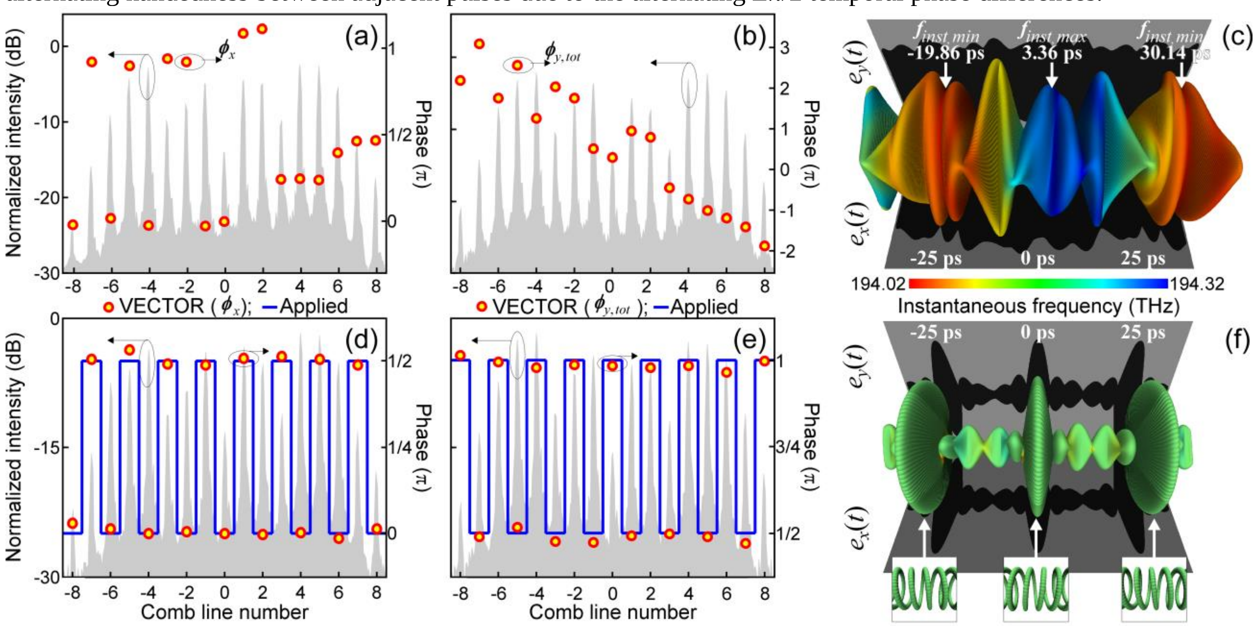

Fig. 2. (a,b,d,e) Power spectrum (shaded), applied (solid) and measured (circles) spectral phases of the (a,b) raw V-OAW and (d,e) repetition-rate-doubled V-OAW, respectively. (c,f) Quasi-three-dimensional electric field representation of the reconstructed V-OAWs.

4. Conclusion

We demonstrated an integrated system that can simultaneously manipulate and measure full-vectorial frequency combs without RF or optical reference. The field retrieval is non-iterative and unambiguous, only utilizing the data sets from one nonlinear (DQ-SSI) and one linear (WPP) measurements. VECTOR is readily applicable to frequency combs of ultrahigh bandwidth (10s THz) and mode spacing (>100 GHz). This work was supported by the National Science Council of Taiwan under grant NSC 100-2221-E-007-093-MY3.

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