Measurement and Synthesis of Ultrafast Scalar and Vectorial Optical Arbitrary Waveforms

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Abstract: The latest methods to simultaneously characterize and synthesize ultrafast optical arbitrary waveform in the scalar and vectorial regimes are reviewed.

Summary

Scalar optical arbitrary waveform (OAW) with ultrafast evolution of amplitude, phase, and up to 100% duty cycle (the waveform fill the entire repetition period) has been realized by combining optical frequency combs and line-by-line pulse shaping [1]. It has been used in radio-frequency (RF) photonic filters [2] and intensity repetition rate multiplication of a pulse train [3]. Meanwhile, vectorial ultrashort pulse train produced by mode-locked laser and polarization “group-of-lines” pulse shaper [4] has a time-varying state of polarization (SOP) but small duty cycle, which has been applied to isolated attosecond burst generation [5] and selective spatiotemporal excitations with nanometer and femtosecond resolutions [6]. It becomes intuitive to generalize scalar OAW to the vectorial regime by manipulating an optical frequency comb with a polarization line-by-line pulse shaper. The increased degree of freedom of vectorial OAW (V-OAW) is conceptually the optical field of extreme complexity in the time/frequency domain (if a large number of comb lines are accessed) and is expected to enable unique applications in ultrafast plasmonics.

Unfortunately, it is difficult to measure either scalar OAW or vectorial ultrashort pulse; and there was virtually no characterization method for vectorial OAW (V-OAW) until recently [7,8]. The main challenge of OAW measurement lies on the 100% duty cycle in the time domain (i.e. the requirement of resolving phases of individual comb lines in the frequency domain), prohibiting the employment of conventional spectrographic and interferometric techniques (notably FROG and SPIDER families). The difficulty exacerbates when measuring OAWs generated from Kerr frequency combs, where the large (>100 GHz) mode spacing would disable the techniques needing a synchronous RF reference wave [9,10]. In terms of vectorial ultrashort pulse measurement, tomographic ultrafast retrieval of transverse light E-fields (TURTLE) [11] or dual-channel spectral interferometry [12] are two demonstrated methods. However, there is no well-behaved spectrogram (required by TURTLE for delay and absolute phase reconstruction) for OAW with 100% duty cycle and the transient SOP of a V-OAW could be easily destroyed by the environmental perturbation in an interferometer without common-path geometry or active path-length stabilization.

In this report, we review a series of new techniques developed for simultaneously measuring and synthesizing scalar OAW and V-OAW, respectively. First, an non-iterative data inversion procedure [13] was introduced to the phase retrieval by omega oscillating filtering (PROOF) method that had been established for the measurement of isolated attosecond pulses in the extreme ultraviolet regime [14]. Our procedure can retrieve not only the phases of individual comb lines (thus the scalar OAW) but the temporal modulation depth (a key parameter that typically relies on an independent experiment to calibrate) from the PROOF trace itself (Fig. 1).

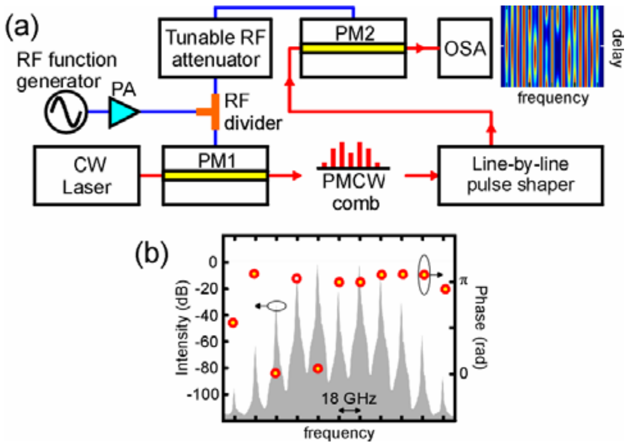

Fig. 1. PROOF measurement of a 18 GHz comb. (a) Setup. PA, power amplifier; PM#, phase modulator; PMCW, phase modulation continuous-wave; OSA, optical spectrum analyzer. (b) Power spectrum (shaded) and an example of retrieved spectral phase (circles), respectively.

Second, the orthogonally probed dual quadrature spectral shearing interferometry (DQ-SSI) was proposed to characterize scalar OAW by a polarization line-by-line pulse shaper with nearly common-path geometry [15]. In this scheme, the orthogonally polarized probe filed made of two coherent spectral lines with certain relative phases $\{0, \pi/2, \pi\}$ is created by the signal OAW itself. Three interferograms are produced by sum-frequency mixing between the signal and probe fields at the three probe phases in a type II BBO crystal, from which the comb line phases can be algebraically reconstructed (Fig. 2).

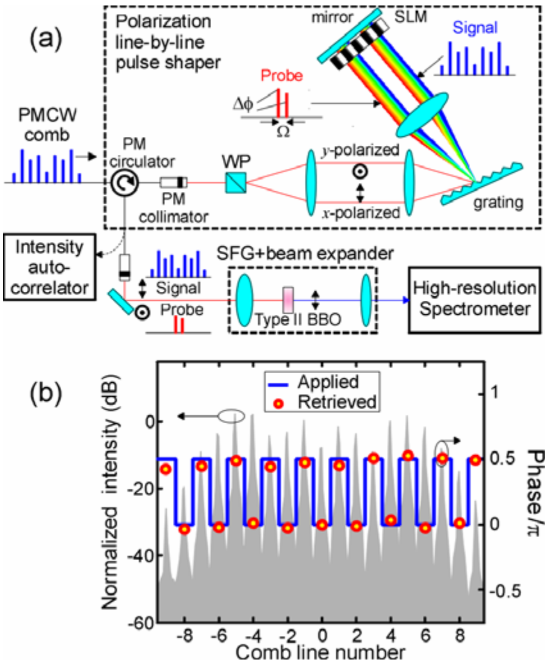

Fig. 2. Orthogonally probed DQ-SSI experiment of a 20 GHz comb. (a) Setup. (b) Measured power spectrum (shaded) and an example spectral phase (circles). The applied phases (solid) are depicted for comparison.

Finally, the information of x-polarized OAW measured by orthogonally probed DQ-SSI is combined with the SOP spectrum obtained by a wavelength-parallel polarimeter (WPP) [16], arriving at the desired V-OAW (Fig. 3) [8]. The novel technique, coined as vectorial e-field characterization through all-optical and self-referenced (VECTOR) method, is non-iterative, unambiguous, only utilizing the data sets from one nonlinear (DQ-SSI) and one linear (WPP) measurements, and does not need a RF or optical reference. It is readily applicable to frequency combs of ultrahigh bandwidth (10s THz) and mode spacing (>100 GHz).

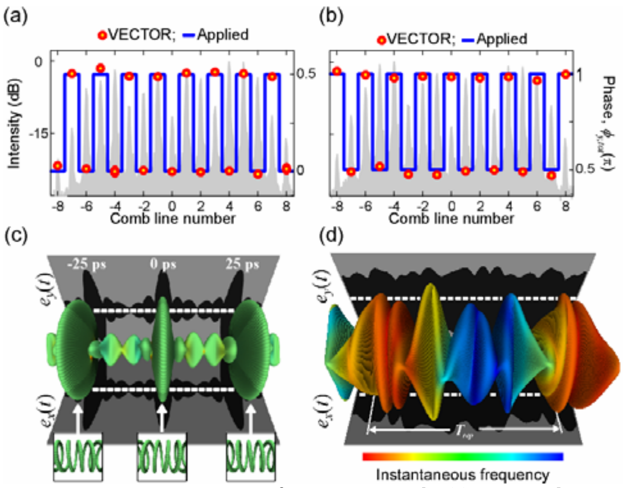

Fig. 3. VECTOR experiment of a 20 GHz comb. (a) Measured power spectrum (shaded) and spectral phase (circles) of the x-polarization component. The applied phases (solid) are for comparison. (b) The counterparts of (a) for the y-polarization component. (c) The quasi-3D representation of the VECTOR-reconstructed e-field. Note the fields at 0 ps and ±25 ps have opposite senses of rotation (insets), which is only possible through the temporal Talbot effect of V-OAWs. (d) Another VECTOR-reconstructed e-field with 100% duty cycle.

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