Polarization line-by-line pulse shaping for the implementation of vectorial temporal Talbot effect

Chi-Cheng Chen, I-Chun Hsieh, Shang-Da Yang, and Chen-Bin Huang*

Institute of Photonics Technologies, National Tsing Hua University, Hsinchu 30013, Taiwan *robin@ee.nthu.edu.tw

Abstract: Vectorial optical arbitrary waveform generation is experimentally demonstrated by applying polarization line-by-line pulse shaping on a phase-modulated continuous laser frequency comb. Polarization shaped optical waveforms extending a 50-ps time window are successfully synthesized. Temporal Talbot effect is extended into the vectorial regime, where the distinct periodic temporal phases of the two orthogonally polarized pulse trains are exploited. In one example, we generate repetition-rate doubled circularly polarized pulses with alternating pulse-by-pulse handedness. In another example, complex instantaneous field polarizations are synthesized through the combination of line-by-line amplitude and temporal Talbot phase shaping. Our experimental results are measured through a dual-quadrature spectral interferometry system and are found in excellent agreements to the applied shaping controls.

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1. Introduction

Spectral line-by-line pulse shaping, in which discrete frequency components of the laser source are independently controlled, allows optical arbitrary waveform generation (OAWG) [1–4]. In performing line-by-line pulse shaping, a laser source with a low offset frequency variation (optical frequency comb laser) becomes essential [5]. The integration of pulse shaping and an optical frequency comb allows generation of waveforms with both controllable ultrafast time structure and long term coherence. This cutting-edge technology extends the time-window limitation in conventional group-of-line pulse shaping, permitting user-desired optical waveforms spanning across a full 100% duty cycle. OAWG has been successfully applied to microwave/millimeter-wave photonics [6,7], the generation and delivery of ultrahigh-rate optical pulse trains over long fiber link [8,9], and the synthesis of

few-cycle optical fields [10]. However, in the above OAWG works, only a single optical polarization has been utilized.

It is well-known that optical fields are vectorial in nature. Various quantum, physiochemical, and biophysical systems are known to react adaptively according to the input optical waveforms [11]. The ability to control the two orthogonally polarized fields for the synthesis of optical waveforms with desired instantaneous field polarizations is therefore vital. Polarization optical pulse shapers with various geometries [12–16] and different targeted wavelength regimes [17–20] have been developed in this context. However, in these seminal works, optical frequency combs were not used and the pulse shapers were not designed to operate in the line-by-line regime. It is noteworthy that high resolution polarization mode dispersions [21] rather than on vectorial waveform synthesis.

Temporal Talbot effect, in which the pulse train repetition-rate may be multiplied through the temporal self-imaging, has been investigated extensively by Azaña and associates [22,23]. Temporal Talbot repetition-rate multiplication is achieved as the pulses propagate through a first-order dispersive medium, or equivalently when the spectral lines are applied with periodic spectral phase values [24]. We note here that temporal Talbot effect enables repetition-rate multiplication for the pulse *intensity*. The resulting *temporal phase* repetition-rate remains the same as the input pulse train, and develops a periodicity which can be deterministically derived [22]. Various theoretical and experimental works on repetition-rate multiplication have been carried out using fiber Bragg gratings [25–27], planar lightwave circuits [28, 29], and spectral line-by-line shaping [9]. However in these reports, temporal Talbot effect has not been implemented in the vectorial regime.

In this Letter, vectorial optical arbitrary waveform generations are experimentally demonstrated. Polarization spectral line-by-line pulse shaping is applied on a phasemodulated continuous-wave (PMCW) laser frequency comb with 20 GHz comb spacing. The procedures in characterizing the spectral phase difference between the two orthogonal polarizations are described in details. Vectorially synthesized optical waveforms with a 50-ps time window, corresponding to a 100% duty cycle of the PMCW comb, are experimentally achieved. Temporal Talbot effect is extended into the vectorial regime for the first time to our best knowledge, where we exploit the periodic temporal phases for interesting field polarization synthesis. In one example, we generate intensity repetition-rate doubled circularly polarized pulses with alternating pulse-by-pulse handedness. In another example, deterministic syntheses of complex vectorially shaped electric fields are also performed through the combination of Talbot phase shaping and line-by-line amplitude pulse shaping. Our experimental results are measured through a dual-quadrature spectral interferometry (DQSI) system [30] and are found in excellent agreements to the applied shaping controls. Our results manifest the capacity of vectorial optical arbitrary waveform generation, and may find interesting applications such as the optimization of quantum ionization yield [31] and the control of optical near-fields [32].

2. Experimental setup

Figure 1 shows the schematics of our experimental setup. A PMCW laser frequency comb with 20 GHz spacing (50 ps repetition period) is generated by injecting a 1 kHz-linewidth CW laser (NKT Adjustik) centered at $\lambda_0 = 1545$ nm into a low-V_π optical phase modulator [2,6]. The frequency comb is sent to a homemade reflective polarization line-by-line pulse shaper. The x- and y-polarized frequency comb lines are spatially separated by a Wollaston prism and the incident angles upon a 52.67 grooves/mm gold-coated Echelle grating working in 22nd diffraction order are adjustable through the lateral positioning of the telescope [16]. The diffraction efficiency is about 70% for both the x- and y-polarizations. Discrete comb lines are diffracted by the grating and focused by a lens with 500 mm focal length. A fiberized polarization controller is used to ensure balanced amplitudes between the two polarizations. A computer controllable 2 × 640 pixel liquid crystal modulator array (LCM, CRi SLM-640-D-NM) with 100 µm pitch and 2 µm inter-pixel gap is positioned before the

mirror (the Fourier plane) to provide independent control to the amplitude and phase of each comb line for both polarizations. Our pulse shaper is designed so that a LCM pixel width of 100 μ m corresponds to a 10 GHz frequency separation. On the Fourier plane, each comb line is focused to 160 μ m diameter (1/e²) and controlled using two LCM pixels. The Wollaston prism provides gray-level intensity control with a nominal extinction ratio of 27 dB. The total insertion loss, including the circulator, is 8 dB.



Fig. 1. Experimental setup. PC: polarization controller; WP: Wollaston prism; LCM: liquid crystal modulator; DQSI: dual-quadrature spectral interferometry; LP: linear polarizer; PD: photodetector.

Prior to performing polarization pulse shaping, the phase difference between the two orthogonal polarizations due to dispersion and the slight path difference must be carefully characterized. The spectral phase difference can be mathematically formulated as

$$\Delta \Psi(\tilde{\omega}) = \theta + \tau_{xy} \tilde{\omega} + [\Psi_{x,NL}(\tilde{\omega}) - \Psi_{y,NL}(\tilde{\omega})].$$
(1)

Here, $\tilde{\omega}$ denotes the frequency detuning from λ_0 , θ and τ_{xy} denote the absolute phase difference and the relative temporal delay between the two polarizations, respectively. $\Psi_{x,NL}$ and $\Psi_{y,NL}$ stand for the nonlinear spectral phase terms for the x- and y-polarizations, respectively.

3. Experimental result and discussion

3.1 Characterization of spectral phase difference

Our procedures in retrieving/compensating the three phase difference terms in Eq. (1) are described as follows. First, nonlinear spectral phases Ψ_{NL} of both the x- and y-polarized comb lines are compensated so that transform-limited (TL) pulse trains are generated. This is achieved by sending in a single polarized comb at a time while maximizing the second-harmonic yield using an intensity autocorrelator positioned at zero time delay through an automated shaper LCM phase control process [1,9]. After this process, only θ and τ_{xy} in Eq. (1) remain undetermined.

Secondly, the relative temporal delay τ_{xy} between the two orthogonally polarized TL pulse trains is determined through a dual-quadrature spectral interferometry (DQSI) system [30] as depicted in Fig. 1. The temporal delays τ_x and τ_y for the x- and y-polarized pulse train relative to a TL reference pulse train (derived by using another homemade reflective line-by-line pulse shaper) are individually measured. The measured spectral phases are depicted in Fig. 2(a), where the circles denote the average values after 10 DQSI measurements. The average retrieved spectral phase standard deviations (for each comb line over 10 separate measurements) are 0.05 and 0.04 radian for x- and y-polarizations, respectively. The slopes of the two fit traces give $\tau_x = 11.88$ ps and $\tau_y = -11.97$ ps. The relative temporal delay $\tau_{xy} = 23.85$ ps between the two polarizations is thus experimentally determined. A linear spectral phase of $\tau_{xy} \tilde{\omega}$ is applied to the y-polarized comb lines to ensure the two orthogonally polarized pulse trains have zero temporal delay.

Lastly, the absolute phase difference θ is determined for complete knowledge over the instantaneous vectorial field. Our pulse shaper is programmed to block all the comb lines except the central one at λ_0 for both polarizations. The shaper amplitude control is applied to ensure equal amplitudes between the two polarizations. The combined x- and y-polarized single comb line passes through a linear polarizer positioned at 45 degree. The resulting interferometric signal strength versus the extra phase added to the y-polarized comb line by the pulse shaper is shown in Fig. 2(b). The perfect agreement between the measurement (circles, averaged over 50 interferometric data) against the cosine-squared fit (line) is a manifestation of our excellent LCM calibration. The absolute phase difference of $\theta = 1.375\pi$ is determined when the applied LCM phase gives the in-phase condition between the two polarizations, leading to a maximum interferometric signal. After this procedure, all of the y-polarized comb lines are applied with $\theta = 1.375\pi$ to completely eliminate the spectral phase difference between the two orthogonally polarized pulse trains.



Fig. 2. (a) Linear spectral phases measured by DQSI (open circles) for x- and y-polarizations. (b) Characterization of the absolute phase difference between x- and y-polarizations.

3.2 Polarization shaped waveform filling 100% duty cycle

We now demonstrate full-vectorial optical arbitrary waveform generation. In the first example, the y-polarized frequency comb is unaltered after the phase calibration process, corresponding to a TL pulse train. The x-polarized frequency comb lines are modulated by a quadratic spectral phase (coefficient of -236.87 ps^2) via the LCM to generate a linearly positively-chirped waveform filling the entire 50-ps window (100% duty cycle). The shaped waveform is then carefully characterized by the DQSI system. Figure 3(a) shows that the measured (circles) and the LCM-applied spectral phase (line) for the shaped x-polarized comb are in excellent agreement. The average phase error (defined by the modulus of the difference between the phases measured by DQSI and applied by LCM, respectively) over all frequency comb lines is 0.07 radian, and the averaged standard deviation of the retrieved phases over 10 measurements is 0.05 radian.

Based on the experimentally measured power spectra and spectral phases shown in Fig. 3(a), the vectorially-synthesized OAWG is displayed in Fig. 3(b) using the colored quasithree-dimensional electric field representation [13]. The x- and y-polarized pulses are independently depicted using the black projection traces onto the corresponding axes. The instantaneous field near 0 ps time location is magnified within the inset, being left-hand elliptically polarized. The instantaneous frequency of the waveform, defined by taking the inverse of the piecewise time required for the field amplitude in passing through the maximum twice along the polarization ellipse [13], is represented by the color tone (blue and red for higher and lower frequencies). In this example, the instantaneous frequency is dominated by the x-polarized up-chirped pulse, increasing linearly with time across the entire 50 ps period (the y-polarized TL pulse has constant instantaneous frequency).

We make two notes here over the unique characteristics of the temporal waveforms derived from a PMCW comb: (1) The inherent highly structured power spectrum of the PMCW comb is determined by Bessel function of the first kind [33]. This in term produces sinc-like temporal pulse TL envelope, and is evident in the projection in the y-polarization.

(2) The linearly chirped x-polarized waveform does not have the maximum amplitude at time 0. With the strong linear chirp applied here, the temporal waveform resembles the PMCW power spectrum. This in turn can be understood as a manifestation of direct frequency-to-time mapping [34]. These are in contrast to a typical laser with Gaussian-like spectral envelope, which still gives a Gaussian temporal envelope under frequency-to-time mapping.



Fig. 3. (a) Characterization of the strongly chirped x-polarized field. (b) Quasi-threedimensional electric field representation for the vectorially shaped waveform. The color tone represents the instantaneous frequency of the waveform.

3.3 Vectorial temporal Talbot effect

Temporal Talbot effect is now implemented in the vectorial regime. It is well-known that although the pulse *intensity* rate can be multiplied through temporal Talbot effect, the *temporal phase* rate remains fixed and develops a deterministic periodical variation [22]. We exploit this unique periodic temporal phase behavior in generating circularly polarized pulses with alternating pulse-by-pulse handedness. We generate intensity-rate doubled pulse trains by applying periodic spectral phases of $\{0, \pi/2\}$ and $\{\pi/2, \pi\}$ [24] to the x- and y-polarized comb lines, respectively. Application of such periodic spectral phase is only possible through clean line-by-line control. Figures 4(a,b) show the measured power spectra and spectral phases of the shaped x- and y-polarized combs, respectively. The average phase error is 0.08 radian, and the average standard deviation of the retrieved phases for all spectral lines is 0.04 radian.

The resulting intensity-rate doubled x-polarized pulses have periodic pulse-by-pulse temporal phases of $[0, 3\pi/2]$. On the other hand, the y-polarized pulses have periodic temporal phase of $[\pi/2, -\pi]$. Through this design, adjacent pulses will have alternating handedness since the pulse-by-pulse phase difference is $[-\pi/2, \pi/2]$. Figure 4(c) shows the

resulting instantaneous electrical field. The intensity-rate doubling is evident: the temporal period is reduced to 25 ps. To confirm our design principle, the pulses at time locations of -25, 0, and 25 ps are magnified within the insets. It is evident that the handedness of the - 25 and + 25 ps pulses is right-handed, while the 0 ps pulse being left-handed. The instantaneous frequency in this example remains constant.



Fig. 4. (a,b) Characterization of repetition-rate doubled fields for the x- and y-polarizations, respectively. (c) Quasi-three-dimensional electric field representation.

3.4 Vectorial amplitude and Talbot phase shaping

We now generate intensity-rate multiplied pulse trains through a mixture of temporal Talbot shaping (implemented through line-by-line phase control) to the x-polarized comb lines and line-by-line amplitude shaping to the y-polarized comb lines. The x-polarized comb lines are applied with periodic spectral phases of $\{0, 2\pi/3, 2\pi/3\}$ for the generation of intensity-rate tripled (60 GHz) pulse train [24]. Figure 5(a) shows the retrieved optical power spectrum and the spectral phase of the shaped x-polarized comb. The average phase error and the average standard deviation of the retrieved phases for all spectral lines are 0.04 and 0.02 radian, respectively. The y-polarized comb lines are applied with line-by-line amplitude control with every other line being suppressed to yield a 40 GHz comb. Such comb generates intensity-rate doubled (compared to the initial 20 GHz comb) optical pulse train. Figure 5(b) shows the retrieved optical power spectrum and the spectral phase of the amplitude shaped y-polarized comb. In our experiment, a nominal 27 dB extinction ratio is achieved for the line suppression. The average phase error and the average standard deviation of the retrieved phase error and the average standard deviation of the retrieved phase of all spectral phase of the amplitude shaped y-polarized comb. In our experiment, a nominal 27 dB extinction ratio is achieved for the line suppression. The average phase error and the average standard deviation of the retrieved phases for all spectral lines are 0.03 and 0.02 radian, respectively.

The resulting vectorial arbitrarily shaped electric field within a 50 ps original comb period is depicted in Fig. 5(c) and discussed as follows: Four x-polarized main pulses at times [0, 16.7, 33.3 and 50] ps are generated through the application of temporal Talbot intensity-rate tripling. The corresponding pulse temporal phases are $[0.5\pi, -0.77\pi, 0.45\pi, and 0.5\pi]$. The

observed increased fields between two adjacent main pulses are attributed to two reasons: (1) Finite number of comb lines and (2) the unequal amplitudes of the comb lines. On the other hand, three y-polarized pulses at times [0, 25, and 50] ps are generated through the amplitude intensity-rate doubling. As a result of pure amplitude filtering, these pulses have a common temporal phase. The quasi-three dimensional electric field representation reveals the instantaneous polarization of the five main pulses at time [0, 16.7, 25, 33.3, and 50] ps. The corresponding temporal phase-to-pulse phase difference between the two polarizations are $[0.5\pi, -0.77\pi, 0.6\pi, 0.45\pi, \text{ and } 0.5\pi]$, respectively. In making the pulse at times 0 and 50 ps right-hand circularly polarized, an amplitude suppression of 1.8 dB is applied to all the remaining y-polarized comb lines (shown in Fig. 5(b)) to equalize the field amplitudes of the two polarizations. The pulses generated at 16.7, 25 and 33.3 ps are slightly left-, right-, and right-hand elliptically polarized, respectively. Magnified views for closer inspection over the pulse handedness are provided within the insets of Fig. 5(c). The slight ellipticity observed here is due to the inherent PMCW spectral envelope, in accord to the discussion made in section 3.2. If a broad laser frequency comb with smooth spectral envelope (e.g. Gaussian with twice the optical bandwidth) is used to perform the vectorial OAWG, the 16.7 ps and 33.3 ps pulses could then be x-linearly polarized while the 25 ps pulse y-linearly polarized.



Fig. 5. (a) Characterization of intensity-rate tripled fields through line-by-line phase control for the x-polarization. (b) Characterization of repetition-rate doubled fields using line-by-line amplitude control for the y-polarization. (c) Resulting quasi-three-dimensional shaped electric fields generating circularly and elliptically polarized pulses.

4. Conclusion

In summary, vectorial optical arbitrary waveforms are experimentally demonstrated by applying polarization line-by-line pulse shaping to a 20 GHz phase-modulated CW laser frequency comb. Polarization shaped waveforms spanning a 100% duty cycle (50 ps) is successfully synthesized and characterized. Vectorial temporal Talbot effect is also experimentally realized. In one demonstration, repetition-rate doubled circularly polarized pulses with alternating pulse-by-pulse handedness are generated through the unique pulse-bypulse periodic temporal phase relation. In another example, complicated instantaneous field polarizations are synthesized through the combination of line-by-line amplitude and temporal Talbot phase shaping. Our experiments are measured using a dual-quadrature spectral interferometry system. The retrieved spectral phase and optical spectra are found in excellent agreements to the experimentally applied shaping controls. We note here our vectorial pulse shaping results may find interesting correspondence to the Pancharatnam-Berry phase, in which the adiabatic polarization variations of a light traversing along a closed loop along the Poincaré sphere acquires an extra geometric phase [35]. Typical experiment in extracting such geometric phase would require measuring the interference between an unaltered field with the altered field in the time- or spatial-domains [36]. Here our phase retrievals are performed in the spectral domain. Recently, closed-form expression for the Pancharatnam-Berry phase generated by an arbitrary polarization control device has been formulated [37]. which may facilitate in finding the direct linkage between vectorial optical waveform generations and the associated geometric phase.

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