Temporal phase zone plates for linear optical pulse compression

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Abstract: We demonstrate linear optical pulse compression by using temporal phase zone plates based on electro-optic phase modulation, achieving experimental time-bandwidth products (or equivalent time compression factors) > 150 using phase-modulation amplitudes of only π radians.

OCIS codes: (070.1170) Analog optical signal processing; (320.5520) Pulse compression.

The space-time duality arises from the mathematical equivalence between the paraxial diffraction of a spatial field and the dispersive propagation of a temporal field. Using the mature concepts of free-space Fourier optics, researchers have developed a wide variety of equivalent methods for temporal processing based on this space-time duality. Among many others, systems for temporal imaging [1], linear compression [2], and time-to-frequency mapping [3] of optical waveforms have been realized by suitably combining dispersion and time lenses, which are the respective temporal counterparts of diffraction and lenses in the space domain. A time lens is conventionally implemented by imparting a quadratic phase shift across a signal (e.g. a pulse) in the time domain, which is equivalent to imparting a linear frequency chirp across the pulse. A main figure of merit of a time lens is its time-bandwidth product (TBP), namely the product of its temporal aperture (typically defining the maximum duration of the signal under analysis) and its spectral bandwidth (typically defining the system temporal resolution). In conventional time-lens methods, the TBP is limited by the achievable phase modulation amplitude [1-4]. Here, we propose alternative time-lens techniques, referred to as "temporal phase zone plates". They are designed as the time-domain equivalents of spatial phase zone plates [5-7]. The TBP of temporal zone plates can be ideally infinite, being practically limited only by the achievable dispersion amount. In the experiment reported here, we demonstrate an implementation of temporal phase zone plates using electro-optic phase modulators (EOPMs). Using a phase amplitude of only π radians, we achieve an experimental resolution < 30 ps over a time aperture of 4.59 ns, representing a TBP > 150. Notice that conventional time lenses require a higher phase amplitude even to process a signal with the minimum possible TBP (> 1) [4]. Moreover, since the proposed implementation is a linear process, it provides other important practical advantages, such as high-speed operation, wavelength preserving operation, and easy reconfiguration.

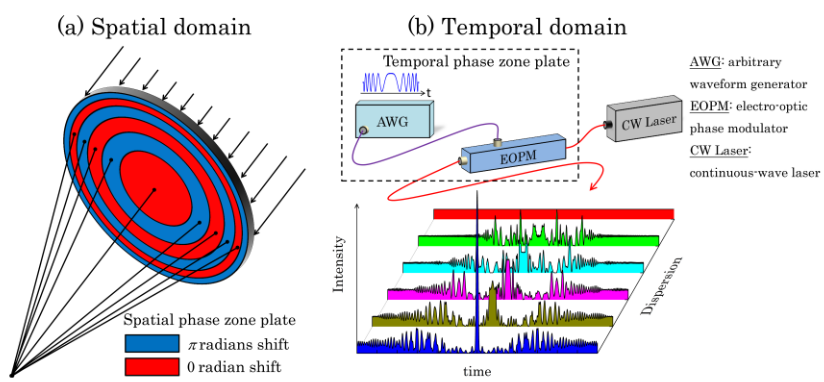

Fig. 1. Space-time duality. (a) Light focusing by a spatial phase zone plate. (b) Pulse compression by a temporal phase zone plate.

In the spatial domain, there are two kinds of phase zone plates, called Rayleigh-Wood phase reversal zone plates (RWPRZPs) and Gabor phase-shift zone plates (GPSZPs) [7]. Specifically, they are both spatial phase modulation devices, with well-defined phase-modulation functions [7]. As illustrated in Fig. 1, the time-domain analogs of these spatial phase zone plates would be temporal phase modulation devices introducing equivalent phase shifts but along the time axis (t), particularly, $\phi_{RW}(t) = \pi/2 + (\pi/2)\operatorname{sgn}\left[\cos\left(at^2\right)\right]$ and $\phi_G(t) = \Gamma_0 \cos\left(at^2\right)$, respectively, for $-\Delta t/2 < t < \Delta t/2$, where Δt is the time aperture, a is a constant, Γ_0 is the phase modulation amplitude, and $\operatorname{sgn}\left[\cos\left(at^2\right)\right] = \pm 1$ depends on the sign of $\cos\left(at^2\right)$.

Using Fourier series and a Bessel function identity [5, 6], the instantaneous phase transformations of the temporal RWPRZP and the temporal GPSZP can be obtained by re-writing the modulation functions as $H_{RW}(t)=2\sum_{n=-\infty,n\neq 0}^{\infty}\left[\sin(n\pi/2)/n\pi\right]\exp\left(jnat^{2}\right)$ and $H_{G}(t)=\sum_{n=-\infty}^{\infty} j^{n} J_{n}(\Gamma_{0})\exp\left(jnat^{2}\right)$, respectively. Noting that temporal quadratic phase structures can be interpreted as being equivalent to time lenses, we confirm that these phase-modulation functions are equivalent to a set of positive and negative time lenses at different focal times, depending on the integer order *n*.

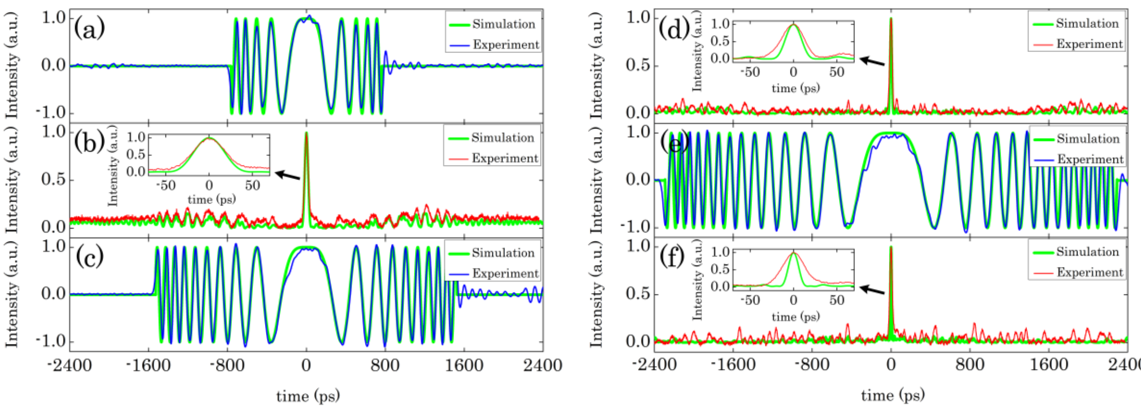

Fig. 2. Electronic waveforms (with the same profiles as the ideal phase modulations) and corresponding compressed optical waveforms. (a) Electronic waveform when order *n*=1. (b) Compressed optical waveform when order *n*=1. (c) Electronic waveform when order *n*=2. (d) Compressed optical waveform when order *n*=2. (e) Electronic waveform when order *n*=3. (f) Compressed optical waveform when order *n*=3. The insets in (b), (d), and (f) show a closer view of the compressed optical pulses. All waveforms are represented in normalized units.

The experimental setup is shown in Fig. 1(b). Light from a continuous-wave (CW) laser at a wavelength of 1,550 nm is sent through an EOPM, which is driven by electronic waveforms generated by a 24 Gsamples/s AWG. The phase modulated light is amplified and sent through several dispersion-compensating modules (DCMs), with a total dispersion amount of -7939 ps/nm. After the DCMs, the light is measured with a 45-GHz photo-detector coupled to a sampling oscilloscope. The ideal electronic waveforms, which are defined according to the target phase modulation profiles, for 1st-order, 2nd-order, and 3th-order temporal GPSZP are shown in Figs. 2(a), 2(c), and 2(e) (green curves), respectively. The measured electronic waveforms [blue curves in Figs. 2(a), 2(c), and 2(e)], generated by the AWG, are slightly distorted mainly due to the limited bandwidth of the AWG. Nonetheless, the compressed waveforms obtained in the experiment (green) following linear propagation through a suitable dispersive optical fiber are in fairly good agreement with those calculated in the simulation (red), as shown in Figs. 2(b), 2(d), and 2(f). The time apertures, which are 1.53 ns, 3.06 ns, 4.59 ns, respectively, increase as the order grows from 1 to 3. For the case of order *n*=1, 2, 3, the full width at half maximum (FWHM) of the compressed temporal pulses in the experiment are 44.4 ps, 30 ps, and 30 ps, respectively, whereas the corresponding values obtained in the simulations are 40.3 ps, 20.8 ps and 13 ps. The excellent agreement for the 1st-order experiment clearly confirms our theoretical predictions, whereas the faster compressed pulses for *n*=2, 3 cannot be accurately captured due to insufficient photo-detector bandwidth. There is also a good agreement between the simulation and experiment concerning the temporal side-lobe structures, which are mainly induced by the presence of higher-order focal terms.

In summary, we have demonstrated temporal phase zone plates capable of compressing optical pulse waveforms. Using electro-optic temporal GPSZPs of 1st, 2nd, and 3th orders, three different TBPs (or equivalent compression factors), i.e., 34.5, 102, and 153, are experimentally obtained using a phase modulation amplitude $< \pi$ radians. This technique is an alternative, highly-efficient time-lens approach, effectively enabling significantly higher TBPs than conventional methods under similar configurations. The linear pulse compression demonstrated here is a promising approach to increase the energetic efficiency of previous schemes based on electro-optic time-lenses by acting over longer input signal durations (higher input signal energies). Moreover, the wide range of applications of conventional time lenses may all greatly benefit from the introduced temporal phase zone plate concept.

References

[1] B. H. Kolner, "Space-time duality and the theory of temporal imaging," IEEE J. Quantum Electron. **30**, 1951-1936 (1994).
[2] J. van Howe, J. Hansryd, and C. Xu, "Multiwavelength pulse generator using time-lens compression," Opt. Lett. **29**, 1470-1472 (2004).
[3] M. A. Foster, R. Salem, D. F. Geraghty, A. C. Turner-Foster, M. Lipson, and A. L. Gaeta, "Silicon-chip-based ultrafast optical oscilloscope," Nature **456**, 81-84 (2008).
[4] B. H. Kolner, "Generalization of the concepts of focal length and f-number to space and time," J. Opt. Soc. Am. A **11**, 3229-3234 (1994).
[5] M. H. Horman, "Efficiences of zone plates and phase zone plates," Appl. Opt. **6**, 2011-2013 (1967).
[6] L. F. Collins, "Diffraction theory description of bleached holograms," Appl. Opt. **7**, 1236-1237 (1968).
[7] J. Kirz, "Phase zone plates for x rays and the extreme uv," J. Opt. Soc. Am. **64**, 301-309 (1974).