Linear time-lens techniques based on intensity modulation

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Abstract: We propose alternative optical time-lens techniques, namely temporal zone plates, based on intensity modulation, instead of the conventional phase modulation processes. An experimental time-bandwidth product > 31 is achieved in linear optical pulse compression experiments.

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The space-time duality, which relies on the equivalence between the paraxial diffraction of a spatial field and the dispersive propagation of a temporal field, has been used for a wide range of high-speed all-optical temporal processing functionalities [1-6], including linear compression [1], temporal imaging [2], time-to-frequency mapping [3], compensation of linear distortion [4], optical synchronization [5], and optical transmultiplexing [6] of optical waveforms. An essential device in these applications is a time lens, which is the temporal counterpart of a space thin lens. Conventional time lenses are implemented by temporal quadratic phase modulation. 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 approaches, the TBP is limited by the achievable phase modulation amplitude. Here we propose alternative time-lens techniques based on temporal intensity modulation, referred to as “temporal zone plates”. They are designed according to the corresponding zone plates in the spatial domain [7]. Ideally, the temporal aperture and the associated TBP of temporal zone plates can be infinite. In practice, the device temporal aperture will be limited only by the achievable dispersion amount to be introduced in the system. We demonstrate an implementation of temporal zone plates using electro-optic intensity modulators (EOIMs) and their use for linear optical pulse compression. In the experiment, we achieve a resolution < 49 ps over a time aperture of 1.5 ns, representing a TBP > 31. This value is hardly achievable by conventional linear electro-optic time-lens methods, since a phase-modulation peak of 62π radians would then be required [8].

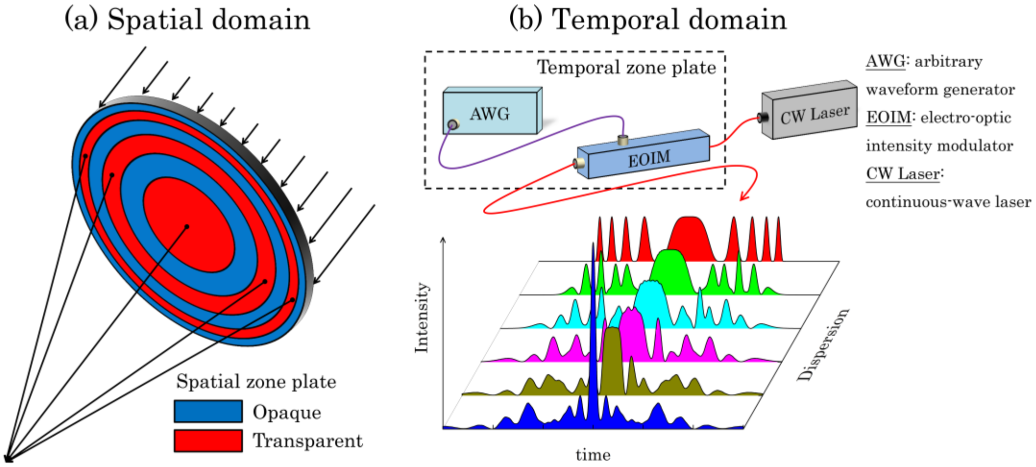

Fig. 1. Space-time duality. (a) Light focusing by a spatial zone plate. (b) Pulse compression by a temporal zone plate.

In the spatial domain, there are two kinds of zone plates, called Fresnel zone plates (FZPs) and Gabor zone plates (GZPs) [7]. They are both based on spatial intensity modulation, with well-defined modulation functions. As shown in Fig. 1, the time-domain analogs of these spatial zone plates would be temporal intensity modulation devices, which have the same modulation functions but along the time axis (t). Mathematically, the complex amplitude of the temporal intensity modulation for temporal FZPs and GZPs are given as $A_F(t)=1/2+(1/2)\operatorname{sgn}\left[\cos\left(at^2\right)\right]$ and $A_G(t)=1/2+(1/2)\cos\left(at^2\right)$, respectively, for $-\Delta t/2<t<\Delta t/2$, where Δt is the time aperture, and $\operatorname{sgn}\left[\cos\left(at^2\right)\right]=\pm 1$ depends on the sign of $\cos\left(at^2\right)$. These modulation functions can be represented by Fourier series, which are given as $A_F(t)=\sum_{n=-\infty}^{\infty}\left[\sin(n\pi/2)/n\pi\right]\exp\left(jnat^2\right)$ and $A_G(t)=\sum_{n=-1}^{1}\left(1/2-n^2/4\right)\exp\left(jnat^2\right)$, respectively. Noting that temporal quadratic phase structures can be interpreted as being equivalent to time lenses, we confirm that these modulation functions are equivalent to a set of positive and negative time lenses at different focal times, depending on the integer order *n*.

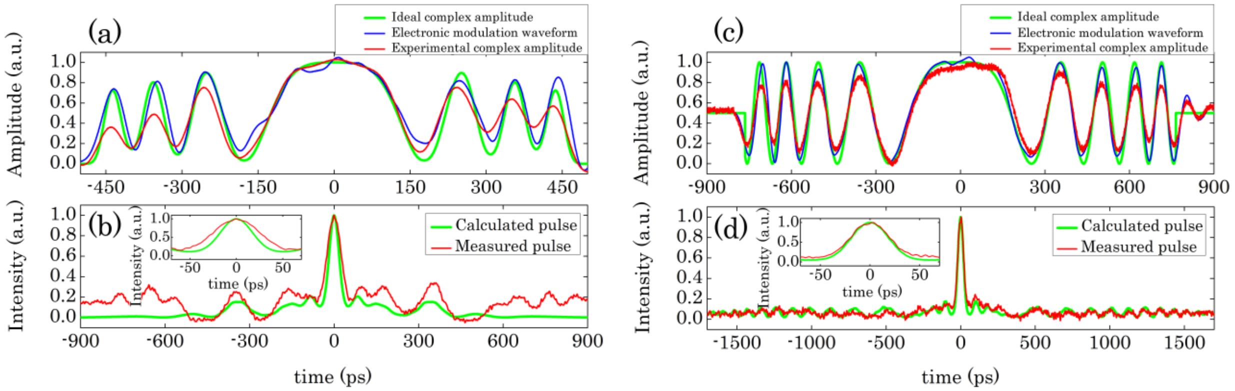

Fig. 2 (a) The ideal complex amplitude of the EOIM, electronic modulation waveform (from AWG), and the experimental complex amplitude of the optical waveform, when dispersion value is -3976 ps/nm. (b) Compressed optical pulses in the experiment and in the simulation, when dispersion value is -3976 ps/nm. (c) The same curves as in (a), when dispersion value is -7939 ps/nm. (d) The same curves as in (b), when dispersion value is -7939 ps/nm. The insets in (b) and (d) 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 EOIM, which is driven by electronic waveforms generated by a 24Gsamples/s AWG. The intensity modulated light is amplified and sent through several dispersion-compensating modules (DCMs). After the DCMs, the light is measured with a 45-GHz photo-detector coupled to a sampling oscilloscope. We characterized our system in two regimes of dispersion, which are -3976 ps/nm and -7939 ps/nm, respectively. Figures 2(a) and 2(c) show the ideal complex amplitude of the EOIM, electronic modulation waveforms (from AWG), and the experimental complex amplitude of the optical waveforms for the dispersion values of -3976 ps/nm and -7939 ps/nm, respectively. The time apertures are 1 ns and 1.528 ns, respectively. The slight distortions between the electronic modulation waveforms and intensity modulated optical waveforms are mainly due to the limited bandwidths of the EOIMs, which are 10 GHz and 40 GHz for Figs. 2(a) and 2(c), respectively. Figures 2(b) and 2(d) shows the corresponding compressed signals measured in the experiment and calculated in the simulation. For the two dispersion values, the full width at half maximum (FWHM) of the compressed pulses are 62.5 ps and 48.5 ps, respectively, while the corresponding values obtained in the simulation are both 45ps. The excellent agreement for the second experiment clearly confirms our theoretical prediction, while the distortion in the first experiment is due to insufficient EOIM bandwidth. There is also a fairly good agreement between the simulation and experiment concerning the temporal side-lobe structures, which are induced by the presence of higher-order focal terms.

In summary, we have introduced two alternative time-lens techniques, namely temporal FZP and GZP, based on intensity modulation, in contrast to phase-modulation conventionally used for time lens implementation. Experimental TBPs of 16 and 31, hardly achievable by conventional electro-optic time-lens methods, have been achieved in linear optical pulse compression experiments. This technique effectively enables high TBPs and efficiencies using a simple configuration and should prove particularly useful for optical processing applications with picosecond resolutions over long (nanosecond) time apertures.

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