Temporal magnification and reversal of 100 Gb/s optical data with an up-conversion time microscope

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We have developed an up-conversion time microscope capable of expanding ultrafast optical wave forms to a time scale accessible to ordinary sampling oscilloscopes. In this system, a 100 Gb/s optical word is magnified (slowed down) to a rate of 8.55 Gb/s with a time lens placed between two dispersive delay lines. The time lens is a nonlinear crystal which mixes the dispersed data with a linearly chirped pump pulse thus imparting a linear frequency sweep to the unconverted wave form. A second dispersive delay line completes the arrangement and forms the temporal analog of a single lens spatial imaging system resulting in a time reversed wave form with a magnification $M=-11.7$. *© 1994 American Institute of Physics.*

Direct measurement of ultrafast electromagnetic wave forms is currently limited to several picoseconds resolution based on the performance of state-of-the-art photodetectors, oscilloscopes, and streak cameras. In an effort to extend the range of these devices and thus direct measurement capability, we have been developing a technique for expanding ultrafast wave forms of arbitrary shape to a time scale that is accessible to modern high-speed instruments. Based on the space-time duality, we use the principle of temporal imaging to expand the wave form under study while preserving its overall envelope profile.[1] This achieves in the time domain what microscopes achieve in space. Therefore, we have dubbed our instrument the "time microscope." The two essential features are dispersion, which plays the role of free-space diffraction, and quadratic phase modulation, which functions as a "time lens." When these elements are combined in a fashion analogous to a spatial imaging system, a temporal imaging system is formed.

A temporal imaging system is shown schematically in Fig. 1. A wave form enters the system and propagates a distance ξ_1 through a medium characterized by the normalized dispersion $d^2\beta_1/d\omega^2$. The effect of the dispersion is to introduce a phase filtering in the frequency domain that is quadratic in frequency ω and linear in the propagation distance ξ. The wave form next encounters a quadratic phase modulation process characterized by a focal time $f_T \equiv \omega_0/(d\omega/dt)$, where ω_0=optical carrier frequency and $d\omega/dt$=linear chirp rate impressed by the lens. Finally, the wave form propagates a distance ξ_2 through the output dispersion $d^2\beta_2/d\omega^2$ and emerges expanded in time by a magnification factor

$$M=-\xi_2\frac{d^2\beta_2}{d\omega^2}\bigg/\xi_1\frac{d^2\beta_1}{d\omega^2} \tag{1}$$

provided the temporal imaging condition

$$\frac{1}{\xi_1\dfrac{d^2\beta_1}{d\omega^2}}+\frac{1}{\xi_2\dfrac{d^2\beta_2}{d\omega^2}}=-\frac{\omega_0}{f_T}=-\frac{d\omega}{dt} \tag{2}$$

is satisfied.[2]

Like its spatial counterpart, the performance of a temporal imaging system is determined by the attributes of the time lens. These are most conveniently expressed by the temporal focal time-to-aperture ratio or $f^{\#}$ For a quadratic phase modulation process, this can be shown to be given by the inverse of the fractional bandwidth $f^{\#}=\omega_0/\Delta\omega$, where $\Delta\omega$ =total bandwidth induced by the lens. For a time lens realized with an electro-optic phase modulator, the net modulation bandwidth $\Delta\omega=\Gamma_0\omega_m$, where Γ_0=peak phase deviation and ω_m=modulation frequency. The magnitude of $\Delta\omega$ for an electro-optic time lens is somewhat limited by technological considerations and thus so is the performance of the lens. Nonetheless, it has been used to successfully demonstrate active pulse compression and even imaging.[3–6]

We have been investigating a different approach to time lens design which may circumvent the difficulties in obtaining high peak phase modulation from electro-optic modulators. Since the goal is to impart a large linear frequency sweep (quadratic phase) to the wave form under study, we

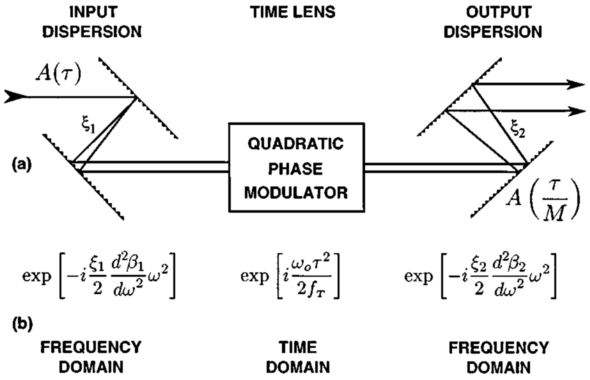

FIG. 1. (a) Temporal imaging system. Input and output dispersions play the role of free-space diffraction while quadratic phase modulation acts as a time lens. Output wave form envelope is a magnified version of the input envelope. (b) Analysis is carried out by cascading the three processes: input dispersion (quadratic phase filtering in frequency domain), time lens (quadratic phase modulation in time), output dispersion.

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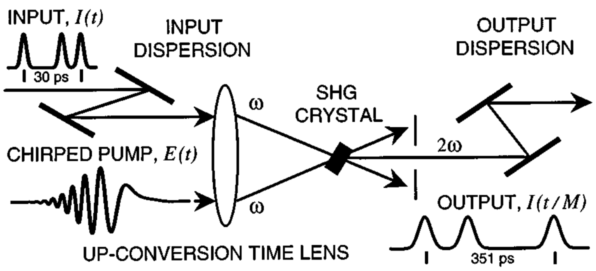

FIG. 2. Schematic diagram of up-conversion time microscope. Input wave form $I(t)$ is a 4 bit 100 Gb/s word. Input and output dispersion is obtained by two sets of diffraction grating pairs. The up-conversion time lens is achieved by sum frequency generation of the input wave form and a linearly chirped pump $E(t)$. The output wave form is the magnified and inverted $I(t/M)$.

mix the wave form in a nonlinear crystal with a separate pump that has been chirped by self-phase modulation (SPM) in an optical fiber (Fig. 2). The sum-frequency signal now has the requisite frequency sweep for lens action. Combining this time lens with proper input and output dispersion forms the up-conversion time microscope.

The experiment consists of two distinct parts; generation of a test pattern and magnification with the imaging system. To generate a suitable high-speed test wave form, we use reflections off of several air–glass interfaces appropriately spaced to simulate a 100 Gb/s digital word (Fig. 3). Optical pulses of 71-ps duration from a mode-locked Nd:YAG laser are coupled into 70 m of single mode polarization preserving fiber and emerge with a spectral bandwidth of 620 GHz. These pulses had a peak power of 67 W and were limited by stimulated Raman scattering. The 100 Gb/s optical test word is created by three 4% surface reflections from two optical components. The first component is an uncoated 1 mm thick fused silica etalon. The front and back reflections are separated by a measured round-trip delay of 9.2 ps. The second component is an uncoated fused silica wedge positioned such that its front surface reflection is delayed 30 ps (round trip) from the front surface reflection of the etalon. These three reflections form the bits of the optical word. They are then compressed by a pair of diffraction gratings so that each bit has an autocorrelation width of 2.1 ps while the interpulse spacing of ≈10 ps is maintained. The final digital word is **1101** at a data rate of 100 Gb/s and is used as the test pattern for the time microscope.

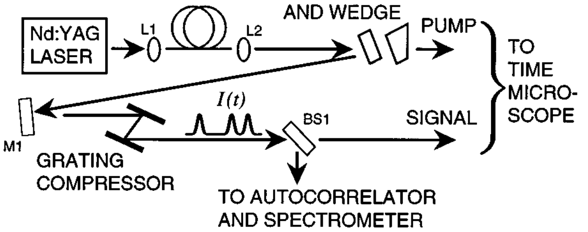

FIG. 3. Generation of the input test pattern (1101 at 100 Gb/s) and chirped pump for the up-conversion time microscope.

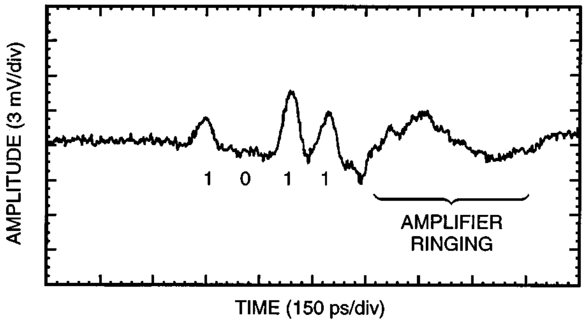

FIG. 4. Measured temporal image of 100 Gb/s wave form demonstrating magnification (slowing down) to 8.55 Gb/s and time reversal.

The remaining optical power transmitted through the back of the wedge serves as the chirped pump for the time lens (Fig. 2). The nonlinear crystal is a 500 μm thick piece of $LiIO_3$ cut for noncollinear second harmonic generation. The rate of linear chirp due to SPM in the fiber was calculated from the group delay dispersion required to optimally compress the digital test word.[7] The resulting chirp of 11.15 GHz/ps gives a focal time of 50.56 ns. The input and output group dispersions were set to satisfy the imaging condition Eq. (2) and provide a temporal magnification of $M=-10$. The input gratings are 1700 ℓ/mm and provide a net dispersion of $\xi_1 d^2\beta_1/d\omega^2=-15.7$ ps^2 at $\lambda=1.06$ μm. The output gratings are 3350 ℓ/mm and provide a net dispersion of $\xi_2 d^2\beta_2/d\omega^2=-157.7$ ps^2 at $\lambda=0.532$ μm. Both grating pairs were used in double pass configurations.

The magnified optical wave form, now at 0.532 μm, was measured with a high-speed photodiode with a response time of 20 ps. Because of the high conversion loss to second harmonic and the 20% throughput efficiency of the output gratings, electronic amplification was required to yield a measurable signal. Amplifiers with 35 dB gain from 2–20 GHz were used. The measured output shown in Fig. 4 demonstrates a time reversed and magnified **1011** pulse train followed by ringing due to elimination of spectrum below 2 GHz. We verified the origin of the first pulse by misaligning the wedge and observing the disappearance of the first pulse in the temporal image. The delay from the first bit to the last bit of the magnified optical word is 351 ps, corresponding to a magnification of $M=-11.7$.

As a second verification of the temporal magnification, the etalon was moved 600 μm further away from the wedge, moving the etalon reflections 4 ps earlier in time. The temporal image showed a corresponding delay of 48 ps for the etalon pulses, consistent with a magnification of $M=-12$. The arrival time of the wedge bit and the separation of the two etalon bits were unchanged in the temporal image, as expected.

In summary, we have demonstrated a time microscope using a time lens based on the up-conversion of an input wave form with a linearly swept pump. The net bandwidth achievable with this technique can be substantially larger than that from an electro-optic phase modulator and can thus form the basis for effective temporal imaging systems. By changing the time scale, this technique allows direct measurement of ultrafast wave forms with current state-of-the-art instruments.

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