Optical time lens based on four-wave mixing on a silicon chip

Reza Salem,[1,*] Mark A. Foster,[1] Amy C. Turner,[2] David F. Geraghty,[1] Michal Lipson,[2] and Alexander L. Gaeta[1]

[1]*School of Applied and Engineering Physics, Cornell University, Ithaca, New York 14853, USA*
[2]*School of Electrical and Computer Engineering, Cornell University, Ithaca, New York 14853, USA*
*Corresponding author: rs435@cornell.edu

Received January 23, 2008; revised March 26, 2008; accepted March 29, 2008; posted April 9, 2008 (Doc. ID 91905); published May 8, 2008

We propose a new technique to realize an optical time lens for ultrafast temporal processing that is based on four-wave mixing in a silicon nanowaveguide. The demonstrated time lens produces more than 100π of phase shift, which is not readily achievable using electro-optic phase modulators. Using this method we demonstrate 20× magnification of a signal consisting of two 3 ps pulses, which allows for temporal measurements using a detector with a 20 GHz bandwidth. Our technique offers the capability of ultrafast temporal characterization and processing in a chip-scale device. © 2008 Optical Society of America

OCIS codes: 320.7100, 190.4380, 130.3120, 190.5970, 230.7370.

Space–time duality has been used as a technique for high-speed temporal processing [1–7]. This duality is based on the parallel between paraxial diffraction of a beam through space and pulse propagation through a dispersive medium. Pulse compression [8], time magnification [3,5], tunable delay [9], and timing-jitter reduction [7] have been demonstrated using this concept. To realize a spatial imaging system in the time domain, a temporal equivalent of the spatial lens is required. Such a device, which is often referred to as a time lens, imparts a quadratic phase to the input waveform. A simple way to realize a time lens is to modulate the phase of the optical signal using a phase modulator driven with a quadratic voltage. In practice, a modulating voltage with a sinusoidal waveform is used that provides a locally quadratic phase [1,7]. Therefore, the time-window over which the lens operates with low aberration is limited to a fraction of the modulating signal period. Another difficulty with using this type of time lens arises from the fact that the driving voltage is limited by the maximum voltage tolerable by the modulator. This limits the maximum phase shift that can be imparted to the input signal.

Nonlinear optical processes can be applied to impart a quadratic phase to the input signal. For example, cross-phase modulation between a pump pulse with a quadratic temporal profile and the input signal results in adding a quadratic phase to the signal [4]. However, to impart large phase shifts to the input signal, high pump powers are required. In addition, the quadratic temporal shape of the pump pulse can be maintained only within a portion of the pulse duration. Another technique to realize a time lens is to use a parametric process [3,5,10] such as sum-frequency or difference-frequency generation with chirped pump pulses. This method allows large phase shifts to be applied to the input signal, which extends the use of the temporal imaging technique to the subpicosecond regime.

We propose and demonstrate that the parametric process of four-wave mixing (FWM) can be used to produce a time lens. Unlike the sum- and difference-frequency generation that occur only in materials with a second-order nonlinearity, FWM occurs in any material, including silica glass and silicon. Therefore, other classes of optical devices with mature fabrication processes, including fibers and silicon-on-insulator devices, can be used for the implementation of the FWM time lens. In addition, the converted wavelength in the FWM process is generated at nearby wavelengths, which makes it easier to detect or transmit the signal for telecommunication applications. The Kerr nonlinearity in centimeter-long silicon nanowaveguides has been successfully used to build nonlinear devices such as FWM-based wavelength converters [11–13], parametric amplifiers [14], and signal regenerators [12,15]. In the parametric time-lens scheme, the bandwidth of the conversion process determines the temporal resolution of the imaging system. It has been shown that the dispersion [16] in silicon nanowaveguides can be controlled with high accuracy by changing the waveguide dimensions. This dispersion tailoring allows for conversion bandwidths as large as 150 nm [11], which enables the characterization of single transient phenomena or rapidly changing waveforms with femtosecond resolution.

Figure 1 shows the concept of temporal imaging using a time lens. An ideal lens imparts a quadratic phase $\varphi_f(t)$ to the signal such that

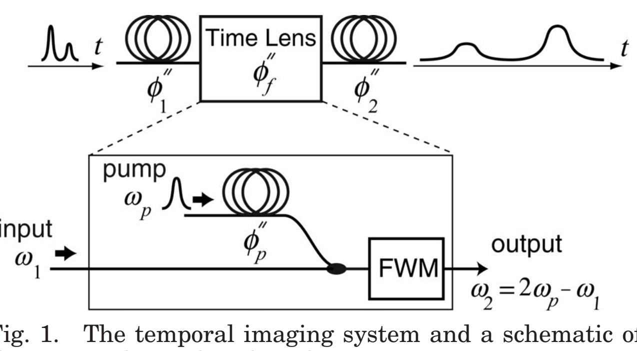

Fig. 1. The temporal imaging system and a schematic of the proposed time lens based on FWM.

0146-9592/08/101047-3/$15.00

$$\varphi_f(t) = -\frac{t^2}{2\phi_f''}, \tag{1}$$

where ϕ_f'' is the focal group-delay dispersion (GDD) associated with the lens and is equal to the inverse of the second derivative of the phase. The dispersive elements before and after the lens are characterized by their GDD parameters $\phi_1''=\beta_2^{(1)}L_1$ and $\phi_2''=\beta_2^{(2)}L_2$, where $\beta_2^{(1,2)}$ and $L_{1,2}$ are the group-velocity dispersion (GVD) and the length of the dispersive elements, respectively. It has been shown that a relationship analogous to the one used for a spatial lens describes this imaging system, that is,

$$\frac{1}{\phi_1''} + \frac{1}{\phi_2''} = \frac{1}{\phi_f''}, \tag{2}$$

where the magnification is given by $M=-\phi_2''/\phi_1''$, which is analogous to that of spatial imaging.

The system we use as a time lens is depicted in Fig. 1. Consider a Gaussian pump pulse propagating through a dispersive medium that is much longer than the dispersion length of the pulse. As a result, the pulse undergoes temporal broadening and is linearly chirped. The phase of the chirped pump pulse varies quadratically with time as $\varphi_p(t)=t^2/2\phi_p''$, where $\phi_p''=\beta_2^{(p)}L_p$ is the GDD experienced by the pump, $\beta_2^{(p)}$ is the GVD, and L_p is the length of the dispersive element. If an input signal with an electric field amplitude $E_s(t)$ is mixed with the chirped pump electric field amplitude $E_p(t)$ via the FWM process, the resulting idler electrical field is $E_i(t)\propto E_p^2(t)E_s^*(t)$, which adds a quadratic phase to the input signal. Based on Eq. (1), the time lens has a focal GDD of $\phi_f''=-\phi_p''/2$. The input GDD of the signal in Eq. (2) appears with the opposite sign, since the converted signal is proportional to the conjugate of the input signal.

Figure 2(a) shows the experimental setup used for demonstrating this concept. The pump pulse and the signal under test are generated from a broadband optical parametric oscillator by spectral filtering. A 6 nm bandpass filter at a 1557 nm center wavelength yields the pump pulse, and a 1 nm bandpass filter at 1543 nm produces the signal. We split the signal pulse into two pulses, delay one with respect to the other, then add them together to produce a two-pulse signal. The measured autocorrelation of the input is plotted in Fig. 2(b), which shows two pulses with 3.3 ps pulse widths and separated by 14.5 ps. The dashed curve shows the calculated autocorrelation assuming a Gaussian profile for the pulses. The calculated input signal assuming Gaussian pulse shapes is plotted in Fig. 2(c). We use 1000 and 1900 m spools of standard fibers for the input signal and pump dispersive elements, respectively. The pump pulses are broadened from 0.6 to 200 ps, and the signal pulses are broadened from 3.3 to 18 ps. As a result, the amplitude of the chirped pump pulse is approximately constant over the time span of the chirped signal. The pump and signal peak powers

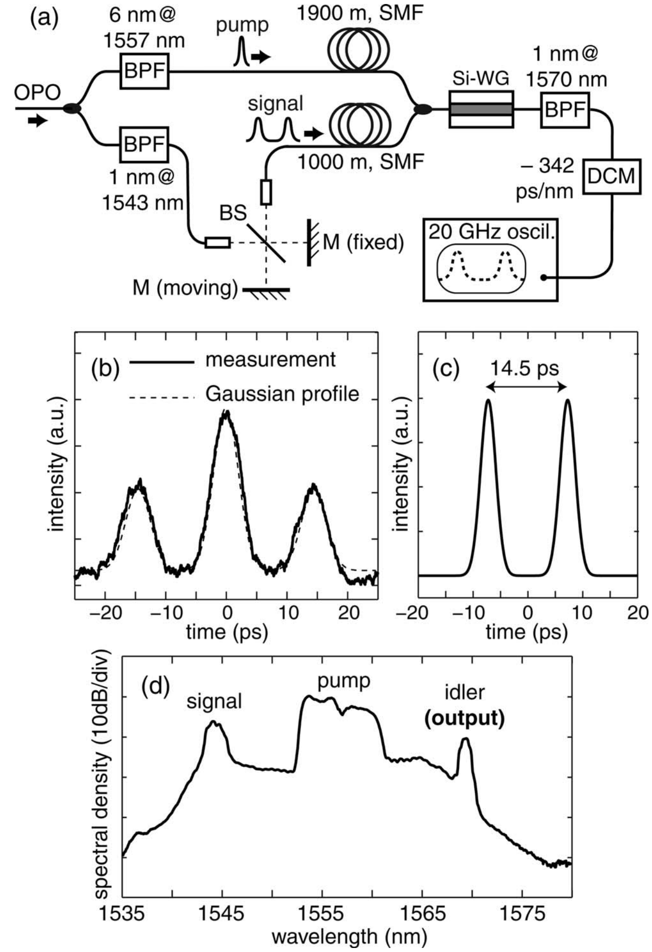

Fig. 2. (a) Experimental setup used to demonstrate FWM-based time lens. (b) Autocorrelation of the input signal, which consists of two pulses with 3.3 ps pulse width and 14.5 ps separation. (c) Calculated input signal assuming the Gaussian pulse profile. (d) Optical spectrum at the output of the silicon waveguide.

are kept at sufficiently low levels that the effects of self-phase modulation are negligible. The signal and pump are then combined, amplified, and sent into a 1 cm long embedded silicon-on-insulator nanowaveguide with a cross-sectional size of 300 $\times$750 nm and a linear propagation loss of 3 dB/cm. The peak pump power inside the waveguide is kept below 200 mW to avoid substantial free-carrier effects. The FWM process between the pump and the signal generates an idler at 1570 nm, as shown in Fig. 2(d). After selecting this converted signal using a bandpass filter, it is sent into a dispersion compensation module with −342 ps/nm dispersion (Corning DCM-F-020). Using the value of the dispersion parameter for the standard single-mode fiber and the correct sign for the three GDD elements, Eq. (2) is satisfied, and the magnification coefficient is $M=-20$. The minus sign shows that the magnified signal is inverted in time with respect to the input signal. The magnified signal is then measured using a 20 GHz detector and an electrical sampling oscilloscope. Figure 3 shows the magnified signal when one of the pulses is turned off [Figs. 3(a) and 3(b)] and when both pulses are on [Fig. 3(c)]. The separation

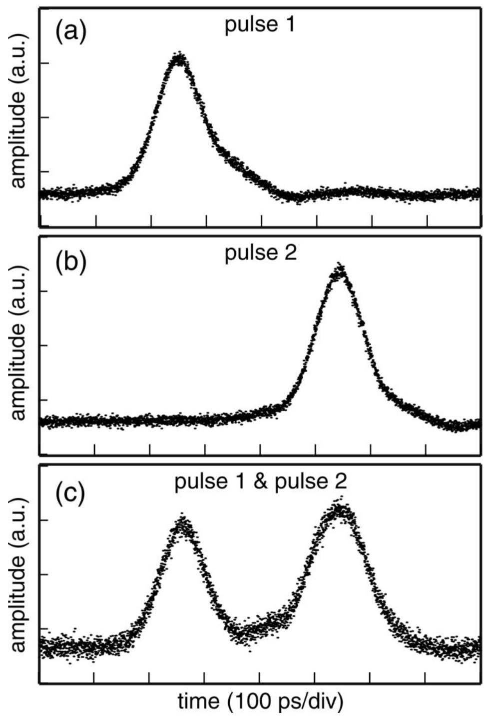

Fig. 3. Magnified signal measured using a 20 GHz detector (a) and (b) when only one of the two pulses is present and (c) when both pulses are present.

between the pulses is 290 ps, which demonstrates the 20× magnification. The pulse width measured on the oscilloscope is longer than the desired value (66 ps) owing to the long time response of the detector. The dispersive elements in this temporal imaging system can be implemented using chirped Bragg gratings to make more compact systems with much lower latencies. Using Eq. (1) and the approximate width of the pump pulse after the dispersive element (200 ps), we estimate that the total phase shift applicable using this time lens is more than 100π, which is not readily achievable using electro-optic phase modulators.

In summary, we have demonstrated a new time lens based on FWM in a silicon nanowaveguide. The time lens can be used for temporal processing of ultrafast optical signals, and advantages of the new technique include broad conversion bandwidth, leading to enhanced time resolution and its potential for integration in a chip-scale device.

We acknowledge financial support from the Defense Advanced Research Project Agency (DARPA) OAWG Program and the Center for Nanoscale Systems, supported by the National Science Foundation (NSF), and the New York State Office of Science, Technology and Academic Research.

References

1. M. T. Kauffman, W. C. Banyai, A. A. Godil, and D. M. Bloom, Appl. Phys. Lett. **64**, 270 (1994).
2. B. H. Kolner, IEEE J. Quantum Electron. **30**, 1951 (1994).
3. C. V. Bennett, R. P. Scott, and B. H. Kolner, Appl. Phys. Lett. **65**, 2513 (1994).
4. L. K. Mouradian, F. Louradour, V. Messager, A. Barthelemy, and C. Froehly, IEEE J. Quantum Electron. **36**, 795 (2000).
5. C. V. Bennett and B. H. Kolner, IEEE J. Quantum Electron. **36**, 430 (2000).
6. J. Azaa, N. K. Berger, B. Levit, and B. Fischer, Appl. Opt. **43**, 483 (2004).
7. J. van Howe and C. Xu, J. Lightwave Technol. **24**, 2649 (2006).
8. B. H. Kolner, Appl. Phys. Lett. **52**, 1122 (1988).
9. J. van Howe and C. Xu, Opt. Lett. **30**, 99 (2005).
10. C. V. Bennett, B. D. Moran, C. Langrock, M. M. Fejer, and M. Ibsen, in *Conference on Lasers and Electro-Optics/Quantum Electronics and Laser Science Conference and Photonic Applications Systems Technologies*, OSA Technical Digest Series (CD) (Optical Society of America, 2007), paper CFF1.
11. M. A. Foster, A. C. Turner, R. Salem, M. Lipson, and A. L. Gaeta, Opt. Express **15**, 12949 (2007).
12. R. Salem, M. A. Foster, A. C. Turner, D. F. Geraghty, M. Lipson, and A. L. Gaeta, Nat. Photonics **2**, 35 (2008).
13. Y.-H. Kuo, H. Rong, V. Sih, S. Xu, M. Paniccia, and O. Cohen, Opt. Express **14**, 11721 (2006).
14. M. A. Foster, A. C. Turner, J. E. Sharping, B. S. Schmidt, M. Lipson, and A. L. Gaeta, Nature **441**, 960 (2006).
15. R. Salem, M. A. Foster, A. C. Turner, D. F. Geraghty, M. Lipson, and A. L. Gaeta, Opt. Express **15**, 7802 (2007).
16. A. C. Turner, C. Manolatou, B. S. Schmidt, M. Lipson, M. A. Foster, J. E. Sharping, and A. L. Gaeta, Opt. Express **14**, 4357 (2006).