at 1.3 μm. The excess noise factor — about 2.7 at a gain level of 10 — offers a significant improvement on previous devices. And the sensitivity reaches −28 dBm at 10 Gbit s⁻¹, which is comparable to that of commercial InP-based APDs. These results show that it may be possible to build low-cost, CMOS-compatible, silicon-based devices that are superior in performance to APDs based on the more traditional III–V materials.

The team's careful device design played an important role in achieving these performance statistics. First, the authors increased the doping of the charge layer to confine the electric field inside the silicon better. Second, their fabrication process aimed to eliminate impact ionization in the germanium. The germanium annealing temperature was lowered substantially to reduce the inter-diffusion of the silicon and germanium atoms, and to prevent the germanium from diffusing into the gain region where it would increase the effective impact ionization ratio. Finally, the introduction of a floating guard ring – which surrounded the multiplication region within the strong electric field – helped to

reduce the surface electric field strength at the silicon/insulator interface and prevent premature avalanche breakdown along the device perimeter, which leads to high gain operation.

In the future, the authors will need to demonstrate operation of their APD at the important wavelength of 1.5 μm, which may prove tricky because germanium's absorption coefficient decreases for larger wavelengths. In addition, they will need to demonstrate high-speed operation at bit rates beyond 40 Gbit s⁻¹, and show that the device is sufficiently reliable and can be manufactured relatively easily. For monolithic integration of the APD into silicon-based circuits, the APD fabrication process will need to be completely compatible with metal-oxide-semiconductor field-effect transistor (MOSFET) production; however, through recent successes in producing strained-silicon MOSFETs[6], germanium has become a familiar material in the CMOS process, so the germanium absorption layer should not pose a significant problem.

Lastly, for the realization of the ultimate silicon photonic system, the most difficult

issue to overcome is integrating light detectors with light-emitting elements, which is not made easier by the fact that bulk silicon and germanium have very low internal quantum efficiencies (as a result of their indirect band gaps). Despite the challenges that remain, it is a great advance for silicon photonics that high-performance APDs for optical communications can be formed monolithically with only group IV semiconductors on a silicon wafer. ❑

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SILICON PHOTONICS

Silicon's time lens

How can we capture ultrafast optical signals in real time? A time lens is one possibility — able to image the temporal profile of a short optical signal, analogous to a conventional lens. Such a device has now been created on a silicon chip.

B. Jalali*, D.R. Solli and S. Gupta

Ultrafast, transient phenomena harbour a wealth of fascinating science that normally lies hidden from view. Conventional sampling oscilloscopes operate like a strobe light, missing short, non-repetitive events as they operate not in real time, but in equivalent time. This limitation becomes especially problematic when attempting to observe extreme, rare events. Real-time measurements have the potential to expose new scientific phenomena[1]. Mark Foster and colleagues from Cornell University, reporting in *Nature*[2], have now demonstrated a method of implementing a useful component for ultrafast optical measurements — a time lens — on a silicon chip.

Ultrafast real-time measurements also have important industrial applications such as characterization of transient errors in high-speed data communications. Whether the signal itself is optical or electronic in nature, the final acquisition must be performed by an

electronic instrument. The fastest single-shot electronic recording-instruments at our disposal — real-time oscilloscopes — have acquisition rates on the order of tens of billions of samples per second. Although this represents a very impressive time resolution, it is often insufficient to characterize ultrafast waveforms. The goal then is to slow down the signal, without adding distortion or noise, so that it can be acquired by a real-time digitizer.

Fortunately, optical techniques exist that can slow down both optical and electrical signals — functions that are on the verge of being fully realized on a silicon chip. Such techniques fall in two categories: the time-lens method, best suited for slowing down ultrafast transient optical waveforms[3,4]; and the so-called photonic time-stretch (PTS), a technique developed to slow down electrical waveforms[5].

The time-lens concept relies on the mathematical equivalence between spatial diffraction and temporal dispersion, the

so called space–time duality. As we know, a lens held a fixed distance from an object produces a magnified image visible to the eye. The lens imparts a quadratic phase shift to the spatial-frequency components of the optical waves; in conjunction with free-space propagation (object-to-lens and lens-to-eye), this generates a magnified image. Owing to the space–time duality, an optical waveform can be temporally imaged by an equivalent three-step process: dispersing it in time, subjecting it to a phase shift that is quadratic in time (the time lens itself), and dispersing it again (Fig. 1a). Theoretically, a focused aberration-free image is obtained under a specific condition when the two dispersive elements and the phase shift satisfy the temporal equivalent of the classic lens equation. Alternatively, the time lens can be used without the second dispersive element to transfer the waveform's temporal profile to the spectral domain. This, again, is analogous to an

ordinary lens, which produces the spatial Fourier-transform of an object at its focal point[2,6] (Fig. 1b).

Now, Mark Foster and colleagues have demonstrated an innovative and promising means to implement a time lens in silicon, the medium of choice for optoelectronics[2]. Their device uses a third-order nonlinear optical process known as four-wave mixing (FWM) to impart the necessary quadratic phase shift to the signal[7]. This approach can apply large phase-shifts, expanding the power of the time lens. Although this time-lens component has been previously demonstrated with second-order nonlinearity[8], such implementations require widely spaced optical wavelengths, and are not compatible with silicon, which has no second-order nonlinearity[2].

The difficulty with any parametric process, whether second or third order, is that phase matching is needed for efficient operation. Waveguide dispersion engineering[9] is a solution. Although silicon possesses normal dispersion at wavelengths of interest, the dispersion of a small silicon waveguide (a nano-waveguide) can become anomalous owing to waveguide dispersion — a feature that can be used to phase-match FWM. Using their novel FWM time lens, the Cornell team has succeeded in transferring the temporal profile of an optical waveform to the spectral domain, so that they can image its profile with a spectrometer. They achieve a resolution of 220 fs over a recording length of more than 100 ps in time-averaged measurements, and a resolution of 766 fs in single-shot operation[2].

Although able to image optical waveforms, the time-lens approach is not well-suited for capturing and digitizing wideband electrical signals because the necessary highly dispersive devices with uniform dispersion and low-loss over broad bandwidths do not exist in electronics. For electrical signals, PTS is needed — a technique that was developed specifically to slow down electrical waveforms. In contrast to the time-lens approach, PTS is not based on the space–time duality[10,11], but is based on an application of analogue optical (or microwave photonic) fibre links such as those used in cable TV (Fig. 2a). Although the dispersion of fibre is a nuisance in conventional analogue optical links, PTS exploits it to slow down the electrical waveform in the optical domain (Fig. 2b). Extremely large stretch-factors can be obtained in PTS systems using long lengths of fibre, but at the cost of larger loss — a problem that has been overcome by using Raman amplification within the dispersive fibre itself, leading to the world's
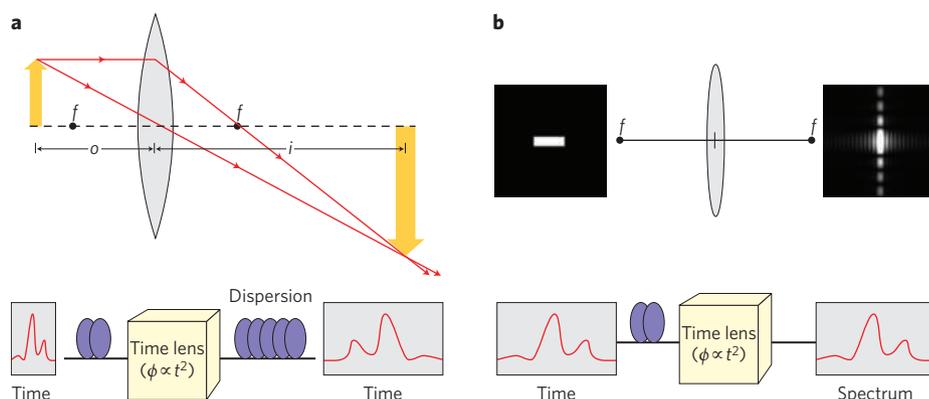

Figure 1 | Temporal imaging for measurement of ultrafast optical waveforms. **a**, Top: An ordinary lens spaced from an object produces a magnified, inverted image. Bottom: A time lens, which imparts a quadratic phase to incoming signals, produces a temporally-magnified, inverted version of an input optical waveform when combined with the proper dispersive elements. **b**, Top: An object spaced from a lens by the focal length (f) is transformed into its spatial Fourier-transform at a distance f on the opposite side of the lens. Bottom: A time lens with two dispersive elements maps the temporal profile into the spectral domain and the spectral profile into time. As a spectrometer provides a convenient way to measure the spectrum, the second dispersive element is not required in the latter case.
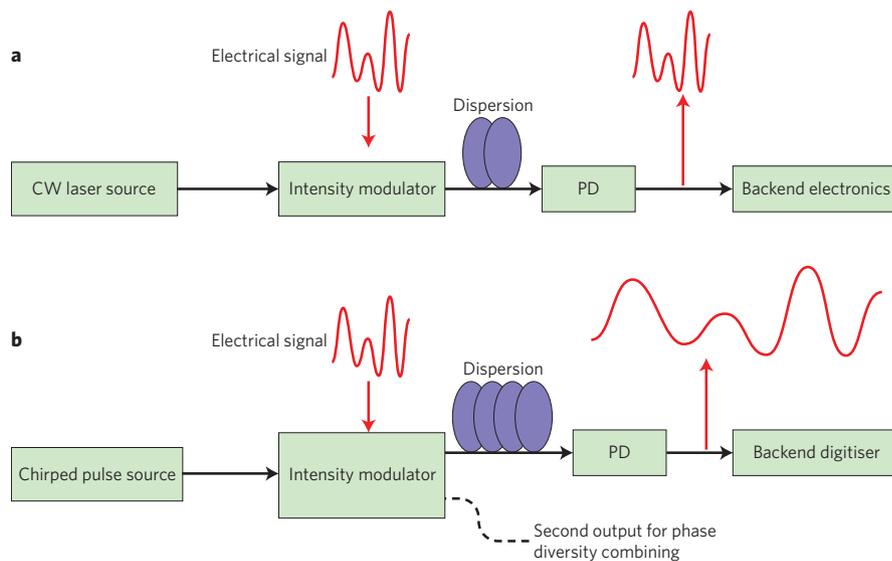

Figure 2 | Photonic time-stretch (PTS) system slows down ultrafast electronic signals for digital acquisition. **a**, A typical analogue optical link that is used for transmitting wide-bandwidth radiofrequency signals. In analogue optical links, such as those used in distribution of cable TV or radio-over-fibre, an electrical waveform is modulated onto a continuous-wave (CW) optical carrier and transmitted over a span of fibre[14]. **b**, PTS-based analogue-to-digital conversion. In the PTS system, the analogue optical link uses a chirped pulse source instead of a CW source, and takes advantage of the high dispersion-to-loss ratio in the fibre to stretch the electrical signal. The amount of stretching depends on the chirp rate of the source and the amount of dispersion in the fibre. Several techniques (for example, phase diversity) can be used in PTS systems to achieve practically unlimited analogue bandwidth (ideal impulse response)[14]. For electrical measurements, this bandwidth is limited only by the modulator, which at present is around 120 GHz – sufficient for almost all waveforms. PD: photodetector.

fastest real-time digitizer[12]. In addition, PTS offers continuous-time acquisition performance[10,13], a feature needed for mainstream applications of oscilloscopes.

Future attempts at integrating the entire time-lens and the PTS systems on a single chip require the development of low-loss

high-dispersive optical devices in silicon. At present, dispersion engineering in silicon nanowires is a candidate, although significant improvements must be made for silicon-based dispersive elements to compete with the dispersion-to-loss ratio and uniform group delay offered

by optical fibre. Given the spectacular progress occurring in silicon photonics, a solution may be on the horizon. Another direction would be to increase the single-shot duty cycle of the time-lens system (approximately 10^{-4}) by using dispersive elements and fast silicon-based detectors to detect the signal in the time domain, eliminating the need for an infrared camera. Such capability would provide a path to extend the time-lens approach to continuous-time operation.

Although it remains to be seen when and how these improvements will be realized, the work of the team at Cornell

has already shown impressive performance and represents a novel application of silicon photonics with significant potential. ❒

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IMAGING

Direct observation of an exoplanet

NASA's Hubble Space Telescope has captured the first visible-light image of a planet orbiting a star outside our solar system (*Science* 10.1126/science.1166609; 2008). This image shows the new planet, Fomalhaut b, orbiting Fomalhaut, a star nearly twice as massive and 16 times brighter than the Sun, and located 25 light years from Earth.

According to Paul Kalas of the University of California, Berkeley, and one of the authors of the *Science* paper, making a direct observation of the distant planet was very challenging.

"The star Fomalhaut is one of the 20 brightest stars in the sky, and

Fomalhaut b is 1 billion times fainter than the star," he told *Nature Photonics*. "Therefore, suppressing the glare from the star and detecting the faint light from Fomalhaut b was extremely difficult."

The scientists got around the problem by using an imaging technique called 'coronagraphy', which effectively masks the direct bright star, allowing its corona and surrounding weaker reflected and scattered light to be observed.

The technique, inspired by the phenomenon during a solar eclipse where the Moon blocks the central disc of the Sun, was first explored by the French astronomer Bernard Lyot who made the first coronagraph in 1930.

The Advanced Camera for Surveys on the Hubble Space Telescope is equipped with a coronograph that allowed it to eclipse the star Fomalhaut artificially (cental dark area in the figure). The planet Fomalhaut b was observed at two wavelengths (0.6 μm and 0.8 μm) and can be seen in the lower right of the figure. Images taken almost 2 years apart (inset) reveal the motion of the planet and suggest that it has an orbit with an estimated period of 872 years and a semi-major axis of 115 astronomical units. All other apparent objects in the image are either stars or galaxies in the background, or false positives.

As a second success for planet hunters, Christian Marois and co-workers from the Herzberg Institute of Astrophysics in Canada also report in *Science* the ground-based capture of infrared images of three planets an impressive 130 light years away (*Science* 10.1126/science.1166585; 2008). Such ground-based observations require special adaptive optics to overcome the scattering of incoming electromagnetic waves in the Earth's atmosphere.

Apart from offering unequivocal proof of the existence of a planet, such direct imaging at near-infrared and visible wavelengths is useful because it enables spectroscopic analysis of a planet's atmosphere. Kalas's team say that they now plan to look for evidence of clouds of water vapour in the atmosphere of Fomalhaut b.

Fomalhaut b Planet
2006
2004

DAVID PILE