NONLINEAR OPTICS

Nanoscale signal regeneration

The regeneration of weak and distorted optical signals is vital in long-haul optical communication systems. Now scientists at Cornell University have developed an all-optical scheme that performs the task and is small enough to fit on a chip.

Ozdal Boyraz

is in the Department of Electrical Engineering and Computer Sciences, University of California, Irvine, California 92697, USA.

e-mail: oboyraz@uci.edu

The maximum reach of an optical communication link is ultimately limited by signal distortion and the accumulation of noise. Although optical amplifiers located periodically along the link can extend transmission distances by boosting signal power, they unfortunately also add optical noise, which degrades the signal to noise ratio. When signal distortion and noise reach an intolerable level, inline optical repeaters (also known as regenerators) are required to completely regenerate the optical signal. Unfortunately such regenerators are inconvenient and expensive, as they require receivers to perform optical-to-electronic conversion, electronics for data recovery, and then transmitters for electronic-to-optical reconversion.

A highly attractive alternative is a low-cost all-optical regenerator, which can restore the distorted pulse shape without optical-to-electronic and electronic-to-optical conversion. On page 35 of this issue, Alexander Gaeta and colleagues from Cornell University experimentally show that tiny silicon nanowires can perform this task on the scale of a chip by exploiting extremely high optical nonlinearity[1].

The biggest challenge in optical regeneration is the simultaneous restoration of a signal's amplitude, pulse shape and timing (also known as 3R regeneration). Amplifiers can compensate for loss and hence provide amplitude restoration (so-called 1R regeneration) but unfortunately cannot restore the shape or timing of signal pulses. As optical signal bits propagate along the fibre link (Fig. 1), noise and random distortions cause them to shift away from their intended time slots — a phenomenon known as timing jitter.

In the past, several configurations based on optical fibres and III–V compound semiconductors have been investigated to perform all optical 2R (amplification and reshaping) and 3R regeneration[2–5]. However, the complexity and lack of stability of these devices means that they do not suit practical deployment. Gaeta *et al.* use a nonlinear process in silicon nanowires to extract the distortion-free information content of the incoming signal and copy it to a new wavelength so that it can continue to travel along a new length of fibre.

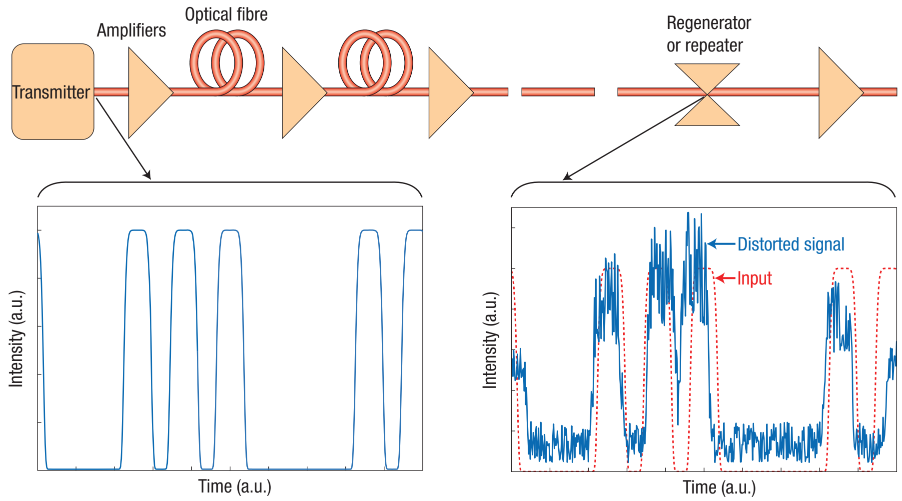

Figure 1 In a communication link, digital bits in a fibre will be deformed owing to noise, nonlinear phase shift and jitter accumulation. Optical repeaters or regenerators need to be inserted to reconstruct the original transmitted signal to achieve the maximum reach. Silicon nanowires can perform regeneration by increasing the extinction ratio, reshaping the deformed signal and reducing the accumulated timing jitter.

Silicon is well known as the core material of the electronic industry, but it is rarely seen in photonic applications. However, in the past few years, silicon-based nonlinear optical devices have progressed very rapidly. For example, recent developments in silicon-on-insulator technology have enabled the demonstration of chip-scale active photonic devices, such as Raman amplifiers and lasers[6–8], parametric amplifiers[9], wavelength converters[10] and pulse shapers[11]. Because of silicon's mature fabrication technology, low cost, CMOS compatibility and compactness, the development of silicon photonics is welcomed by many scientists. In their work, the Cornell University scientists prove that the high optical nonlinearity of silicon nanowaveguides with cross-sections as small as 300 × 500 nm^2 can provide a stable and low-cost solution to complex problems, such as all optical regeneration.

The physics behind the silicon nanowire regenerator is based on a nonlinear process called four-wave mixing (FWM), where an intensity-dependent refractive index mixes two photons from a pump wave with a photon from a probe wave. The process results in amplification of the probe wave (addition of one photon) and the generation of an idler wave with an opposite phase (Fig. 2).

The efficiency of the FWM is intensity dependent and also strongly depends on the phase difference between the pump, probe and idler optical waves. In the experiment by Gaeta and colleagues, three distinct techniques based on the FWM effect were exploited to increase the signal's extinction ratio and to re-shape and re-time it. In particular, mixing of the incoming distorted optical signal with a local light source creates a clean idler wave with information replicated from the incoming optical signal.

In the first approach, the input signal at 1,552 nm acts as the pump wave and is input to the silicon nanowaveguide along with a continuous-wave probe at 1,546 nm. The idea behind this approach is that whenever both pump and probe wave are present in silicon simultaneously, an idler wave is generated at 1,558 nm. As the efficiency of FWM is intensity dependent, a strong idler wave is generated only when the incoming optical bit has a high intensity. When the pump intensity is low, the background noise does not contribute to the generation of the idler wave. As a result, the proposed technique inherently suppresses the low-intensity noise components along with low-intensity tails of the optical signal, copying only the high-intensity optical bits to the idler. The experiment shows a 4.2-dB enhancement (about a factor of three) in the signal extinction ratio at less than 100 mW peak pump intensity. As the incoming signal is being used as the pump of the FWM process and the probe is a continuous wave, all of the timing information is copied into the idler. As a result, this technique falls short of providing timing-jitter reduction.

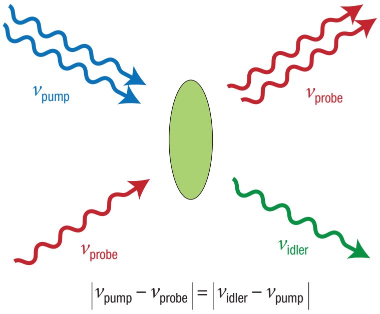

Figure 2 Four-wave mixing explained. The intensity dependence of the refractive index facilitates the mixing of two pump waves and a probe wave to amplify the probe wave by one photon and produce an idler wave, a mirror image of the probe with the opposite phase. ν represents the frequency of the corresponding optical wave.

To provide timing-jitter reduction as well as improving the extinction ratio, the continuous-wave probe is replaced by a pulsed optical clock, which is frequency and phase synchronized to the incoming data signal. As a result, the generation of an idler wave, which carries the regenerated signal, will be controlled by the overlap between pump and probe pulses. Assuming that the clock generator is well designed with a fixed data rate, the timing jitter on the incoming optical data can be filtered by the FWM process. Similar to the first method, the multiplication of data and clock bits will generate an idler bit. As, only those data bits with high intensities can contribute to the generation of the idler, the FWM process will crop the tails of the incoming data bits and low-intensity noise components and provide a compressed and high-extinction-ratio idler wave with low timing jitter. Timing jitter can be reduced further if the optical clock is used as the pump by swapping the pump and the probe wavelengths at the input. However, in this configuration, an exact amplitude replica of the probe wave will be copied to the idler without improving the extinction ratio.

In summary, these techniques provide a low-cost, chip-scale solution to all-optical regeneration and show that silicon photonics has a bright future ahead for real-life applications. Future work may start with addressing how the requirement for synchronization can be avoided and how bit-rate transparency can be provided. In addition, as the current configuration provides channel-by-channel regeneration, the configuration should be updated for use with multichannel communication systems.

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MICROSCOPY

Brillouin bioimaging

Researchers at Harvard Medical School have developed a highly sensitive microscope that can image the mechanical properties of living tissues.

Peter So
is in the Department of Mechanical Engineering and Biological Engineering at the Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, Massachusetts 02139, USA.
e-mail: ptso@mit.edu

Changes in tissue can often be a symptom of disease in the body. For example, coronary disease is accompanied by the loss of elasticity in arterial walls, fibrosis is marked by the hardening of the liver, osteoporosis involves weakening of the skeleton, and the calcification of some tissues can indicate the onset of cancer. Aside from indicating disease onset, the physical properties of tissues also regulate a variety of normal biological functions. The mechanical stress exerted by muscle-like cells initiates wound closure, for example, and compressive forces are crucial for the functioning of cartilage cells.

Clearly, the ability to map the rheological characteristics — that is, mechanical properties such as elasticity and viscosity — of biological tissues *in vivo* is important. The latest work from Giuliano Scarcelli and Seok Hyun Yun, described on page 39 of this issue[1], reports a new optical method — Brillouin microscopy — that can measure the viscoelastic properties of biological tissues, *in vivo* and non-invasively, with microscopic resolution.

Brillouin light scattering is an inelastic process that occurs when light interacts with density fluctuations in a medium. These spontaneous fluctuations are driven by collective acoustic vibrational modes (phonons) within the medium. Brillouin scattering is similar to Raman scattering, a well-known effect exploited by those working in the field of biophotonics. Raman