(in this case distinct add–drop filters) to behave in a polarization-transparent way, offering an almost identical response to the different input polarizations.

Such an approach is conceptually rather simple: as each filter receives only one polarization, its mismatched response to the other polarization does not matter. However, to implement this known approach, the team had to overcome some technological challenges. Not least, polarization diversity calls for extra complexity and the design of new elements in addition to the microrings that do the filtering. One such component is an elegant polarization splitter and rotator, which manipulates light in an intricate three-dimensional structure that can be constructed from just two flat silicon layers. Moreover, the filters in the device must be very nearly identical so that they offer the same response, otherwise the overall device will process the two incoming polarizations differently.

This advance is a culmination of several refinements that have been made in recent years, pulling together clever designs and fabrication techniques. By integrating these new building blocks, Barwicz and co-workers not only address the specific needs of polarization diversity, but they also move a step closer to producing sophisticated optical devices with improved functionality.

The emerging silicon photonics toolbox is impressive, and its ability to put optics on a chip with standard silicon electronics already has enormous potential. Nevertheless, tantalizing questions remain about the development of light sources that are compatible with silicon. In the meantime, non-silicon platforms are showing promise for optical integration[6]. Regardless of the eventual winner, in order to substantially change the way optical networks are made — and get other applications such as light-based computing and sensors moving — we will need to bring together the capabilities demonstrated at MIT and other research labs. With exciting improvements in the pipeline, the long-awaited impact of integrated photonics should be arriving soon.

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SILICON PHOTONICS

An exercise in self control

Controlling light with light using devices small enough to fit on a chip is tricky, but it is crucial for any integrated all-optical logic scheme. Scientists have now produced modulators that control light at breakneck speeds, bringing the vision of all-optical chips closer to reality.

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We all expect fast, free-flowing data whenever and wherever we connect with the world. Optical devices built onto microelectronic chips[1–4] could bring us computers that process and deliver information faster than ever before. A possible path along this route is to construct purely light-based networks on a single chip, in which electro–optic components are replaced by their faster photonic counterparts, and a key ingredient for this is the all-optical modulator, which controls one light signal with another. As reported in *Nature Materials*, Michael Hochberg and collaborators have now successfully demonstrated all-optical modulation at unprecedented speeds, suggesting that chip-scale all-optical networks are indeed within reach[5].

Within the coming decade, the circuitry embodied by a rack of today's network servers will in theory fit onto a single silicon chip half the size of a postage stamp. But can we really expect the available bandwidth to continue to increase? This is not clear. One of the bandwidth bottlenecks is the type of interconnect that feeds processors within computers and servers: existing copper interconnecting wires are becoming incapable of handling today's overwhelming tides of data because they create too much heat. By replacing electrical interconnects with optical ones, we could create radically new flexible architectures capable of processing large amounts of information while dissipating acceptably small amounts of heat. And by implanting the photonic technology on silicon wafers[6,7] (as opposed to other, more traditional substrates such as gallium arsenide and indium phosphate), manufacturers can use the same methods and equipment they now use for ordinary integrated circuits.

Over the past 20 years most progress in silicon photonics has been targeted towards making passive devices — waveguides, filters and the like — in which the flow of light is predetermined by the geometry of the structure. It was only very recently that efficient active devices such as modulators, which work by controlling light transmission externally, were shown to be feasible on a silicon platform, thanks to advances in nanofabrication techniques. Such devices operate through the so-called plasma-dispersion effect[8], in which changes in electrical-carrier concentration affect the overall optical behaviour.

Electro–optic modulators control light using electrical signals — essentially they take small changes in the optical properties of a material (which arise in response to an electric field) and translate them into an intensity change in the light. Although such modulation has been demonstrated at gigahertz speeds, the question is can we go further and faster by modulating one light wave with another? All-optical modulators and switches that exploit an effect similar to the one used in previously demonstrated electro–optic modulators[9] have been built, but the speed of such devices is limited by how fast carriers can be moved across the photonic structures (a speed now in the gigahertz domain). Until now, this limitation seemed to be a fundamental one.

Hochberg and colleagues at Caltech and the University of Washington have broken this speed limit. Instead of relying on carrier-induced effects, they exploit the Kerr phenomenon — whereby an

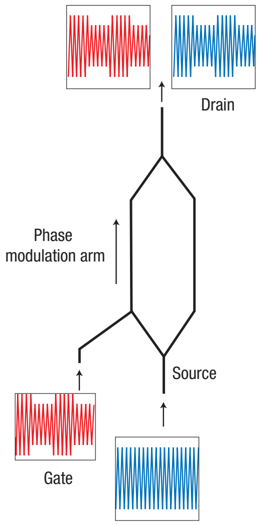

Figure 1 The all-optical modulator that breaks speed limits[5]. The gate signal (red) has its intensity modulation transferred to the source signal (blue) through nonlinear phase modulation in one arm of the interferometer. The whole structure consists of a silicon waveguide clad with a specially engineered nonlinear polymer and could be manufactured using conventional back-end silicon technology. With operation frequencies larger than 1 THz, the modulator is two orders of magnitude faster than existing silicon devices.

intense modulation beam induces optical nonlinearities in the waveguide material that carries it. However, the nonlinearities in silicon are relatively weak, and for the purposes of a chip-sized modulator, the nonlinearity needs to be boosted to a useful level. The authors have achieved this by cladding a silicon waveguide with a specially engineered nonlinear polymer[5].

Their hybrid structure is based around a Mach–Zehnder interferometer (see Fig. 1). A source laser signal enters the interferometer and is divided into two components at a beamsplitter. One part is mixed with a modulation, or gate, signal, which induces a phase shift in the source through the Kerr effect. This shifted beam is then recombined with the non-shifted portion of the source beam, passed through a second beamsplitter and the two beams are allowed to interfere. It is this interference that causes the desired intensity modulation.

By integrating a polymer with the silicon waveguide, the team takes advantage of not only efficient light confinement in the low-loss silicon medium, but also the strong nonlinear properties of the polymer. Moreover, the whole process might be compatible with silicon back-end technology. Although the current experiment demonstrates modulation up to a frequency of 10 GHz, indirect evidence indicates that the same technique can be extended to frequencies in excess of 1 THz. Such modulators could provide optical networks with unparalleled bandwidth and enable different parts of a processing chip to be linked in more complex ways.

When or whether all-optical networks will find their way into everyday personal computers is not clear, but if recent research results are anything to go by, we are well on the way. Quoting Intel's Senior Vice President[10]: "Today, optics is a niche technology. Tomorrow, it's the mainstream of every chip that we build." The work by Hochberg and colleagues brings this vision closer to reality.

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