Signal processing for the next generation of the Internet

CUDOS researcher Neil Baker holds a chalcogenide glass photonic chip, which allows all-optical signal processing.

Chalcogenide Glass Photonic Chips

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The Internet has experienced strong, sustained growth for many years now. And the optical communications backbone of the Web has also been expanding at a high rate. In fact, an optical equivalent of Moore's law indicates that "capacity × distance" has been increasing by an order of magnitude every four years—faster than the original Moore's law for integrated circuits! Despite this progress, however, recent estimates indicate that significant problems are likely to occur in the communications capacity of optical fiber within the next 10 years.

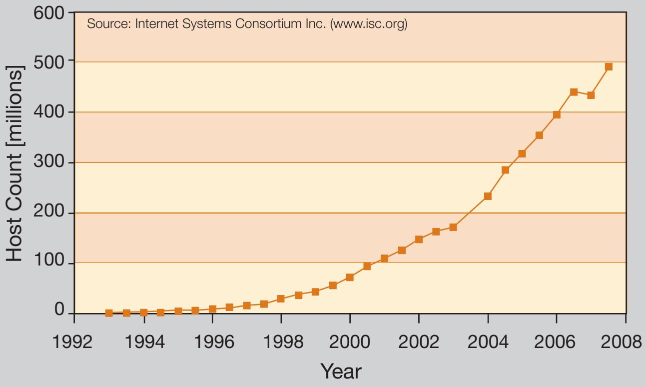
In the 1990s, the high level of demand led to the development of wavelength division multiplexing (WDM), which allowed for many different data channels to be multiplexed together to better leverage the available transparent wavelength spectrum provided by optical fiber. Modern systems now allow more than 200 such channels, each operating at between 10 and 40 gigabits per second, to be multiplexed together to provide an aggregate rate in excess of a terabit per second.

Looking ahead, it is becoming increasingly clear that adding more wavelength channels is not the complete solution to future capacity demand, as each channel results in increased equipment costs and added network complexity. Consequently, increasing the data rate of each individual channel (via optical time division demultiplexing or OTDM) might be the means by which the capacity of future transmission systems will be expanded.

To operate at such high bit rates (160 gigabits per second and beyond), optical communications systems will need to process signals entirely in the optical domain to overcome the speed limitations associated with opto-electronic conversion. All-optical signal processing involves the control of light by light, and this is only possible in a nonlinear optical material. By monolithically integrating several all-optical signal-processing functions into a photonic chip, we can envision an optical equivalent to the modern electronic chip.

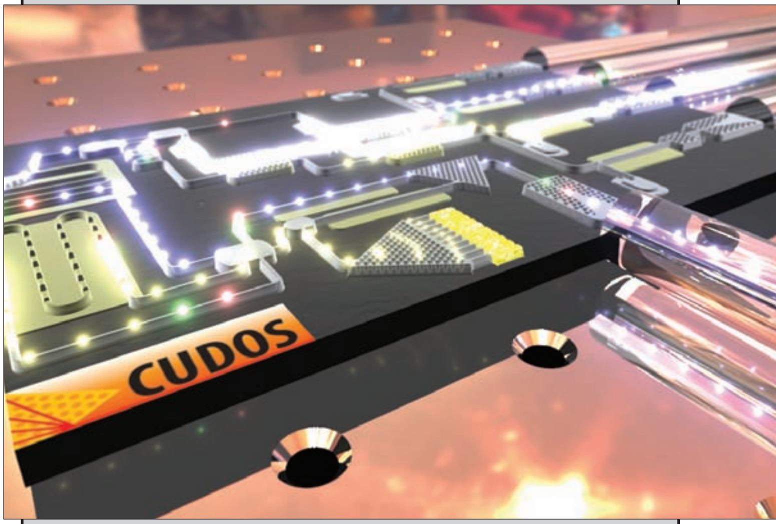
Many nonlinear optical materials have been studied (semiconductor optical amplifiers; nonlinear fiber; lithium niobate). However, no single platform yet stands out in providing a large ultrafast nonlinear response and low nonlinear absorption while allowing compact, easy-to-fabricate circuits. Silicon has been attracting strong attention recently due to the enormous potential for fabricating high-performance, low-cost devices. However, silicon also exhibits strong nonlinear absorption and free-carrier effects, which can inhibit the speed of the nonlinear response required for the signal processing of high data rate signals.

[The growth of the Internet]



Results from an Internet domain survey that tracked the minimum number of computers connected to the Internet per year. Growth is driven by video over Internet and technologies such as fiber to the home and wireless communication.

[The photonic chip: the optical equivalent of an electrical chip]



Artistic rendering of the photonic chip. Optical fibers transmit optical data signals to and from the photonic chip, which integrates several optical signal processing functions, including wavelength conversion, optical demultiplexing, buffering and switching. For more details, please visit www.cudos.org.au.

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Chalcogenide glass planar waveguides are a new contender in this race. These glasses meet the requirements for all-optical signal processing and have already led to a number of exciting results here at Australia's Center for Ultrahigh-bandwidth Devices for Optical Systems (CUDOS).

Introducing the chalcogenide glasses

Chalcogenide glasses, based on the Group IV chalcogen elements sulfur, selenium and tellurium, are of significant interest to optics. These glasses stand out for their unusually strong nonlinear optical response—which is typically several hundred times that of silica, the defacto standard. At telecommunications wavelengths, the nonlinearity is of a non-resonant variety, meaning that it has an ultra-fast response time (10 fs for the optical Kerr effect, and 100 fs for Raman scattering) without the slower effects that occur in resonantly enhanced nonlinear materials (e.g., free carrier absorption observed in silicon).

This is an area that is still in an embryonic phase with, until recently, only a few journal publications demonstrating relatively simple device concepts. Asobe et al. conducted initial work that utilized nonlinear optical processes in the early 1990s, just as WDM technology was taking off. His group demonstrated all-optical (i.e., no electronics involved) switching of a 10 gigabits per second signal using chalcogenide-glass-based fiber. Over the past three years, there has been an explosion of sophisticated device demonstrations designed for telecommunication applications based on sophisticated planar waveguide circuits.

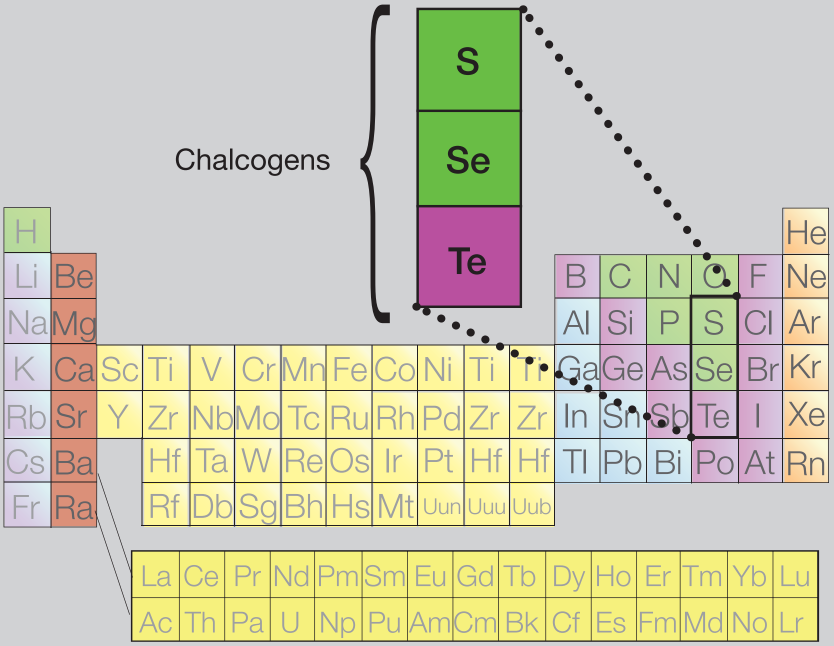
Serpentine shaped waveguides

Over the past 10 years, a diverse range of techniques have been used to fabricate planar chalcogenide glass waveguides resulting in propagation losses around 0.2 dB/cm for tightly confined, etched waveguides. However, to attain low operating power for all-optical processing of high data rate (160 Gb/s) telecommunications signals, researchers need to make advances that will increase the nonlinear optical interaction.

This can be achieved by simultaneously reducing the mode area of the waveguide (and so increasing the optical intensity for the nonlinearity process) and increasing the waveguide length (thus increasing the length of the interaction). So far, the usable length of chalcogenide planar waveguides has been loss-limited, and this has required improved process technology to reduce waveguide surface roughness during fabrication in order to decrease the propagation losses associated with surface scattering.

We have recently reported significant advances on both of these aspects, resulting in chalcogenide glass planar waveguides with lengths up to 24 cm and optical losses as low as 0.05 dB/cm at 1,550 nm (Opt. Express **15**, 14414-21). By using a serpentine pattern, the waveguides can be squeezed onto a much smaller chip, potentially allowing many waveguides and various functions to be integrated into the one compact device.

[The chalcogenide glasses]



The chalcogenide glasses are named after the chalcogen elements, which include sulfur, selenium and tellurium. These elements can be combined with various others, such as germanium and arsenic, to form stable glasses that exhibit several interesting phenomena, including transparency into the mid-infrared wavelength lengths (silica absorbs at wavelengths longer than 2 μm) and high optical nonlinearities. The composition and stoichiometry of the glasses can be adjusted to tune physical and optical properties such as refractive index, nonlinearity and even melting temperature.

Eliminating wavelength-continuity constraints

In the absence of wavelength conversion technology, communication over WDM networks relies on the concept of optical circuit links, or light paths. This gives rise to the wavelength-continuity constraint, requiring that the same wavelength channel is used from source to destination between each intermediate network node. Wavelength continuity results in low network efficiency and reduced network flexibility. This constraint can be

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alleviated through the introduction of wavelength conversion functionality.

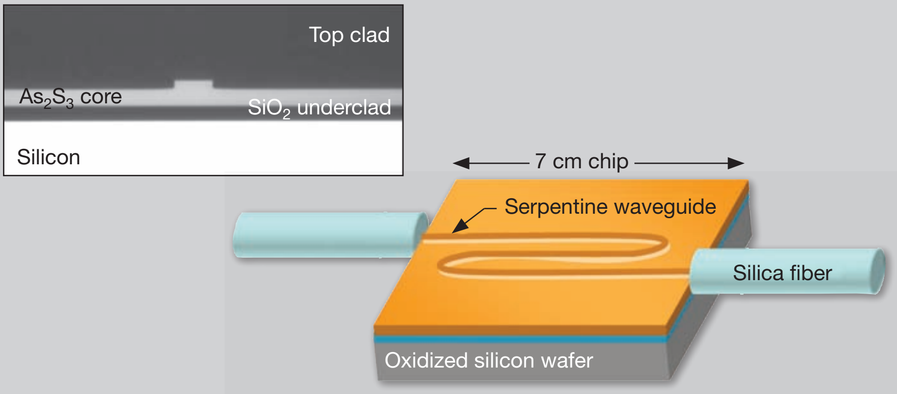
Currently, this wavelength conversion can only be achieved through optical-to-electronic conversion, followed by the modulation of the output of another laser operating at the desired wavelength. This process is thus limited to the data rate allowed by the opto-electronic conversion. By demonstrating an all-optical device capable of such a feat, we can remove one of the constraints to delivering more communications capacity from current optical fibers.

Cross-phase modulation is a nonlinear optical process by which wavelength conversion can be achieved using chalcogenide glass waveguides. The device principle is based on the use of an intense signal pulse to impress a phase modulation onto a co-propagating CW via the optical Kerr nonlinear effect. The phase modulation results in the generation of optical side bands on the CW (carrier), which contains the original signal data.

By extracting one sideband using an optical bandpass filter, we can achieve wavelength conversion from the original wavelength to the wavelength just offset from the CW. Adjusting the center wavelength of the CW, as well as tuning the bandpass filter, allows the signal to be converted to any other wavelength.

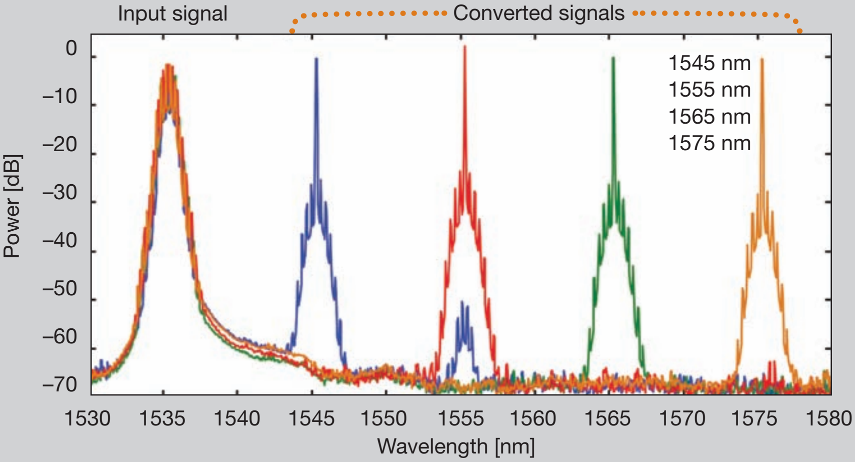
We have used this technique to achieve wavelength conversion of a 40 Gb/s signal over 40 nm. The figure on the right shows the optical spectra taken directly at the output of the chalcogenide waveguide during the experiment. The generation of sidebands on the CW via cross-phase modulation is clearly evident.

[Planar chalcogenide glass waveguides]



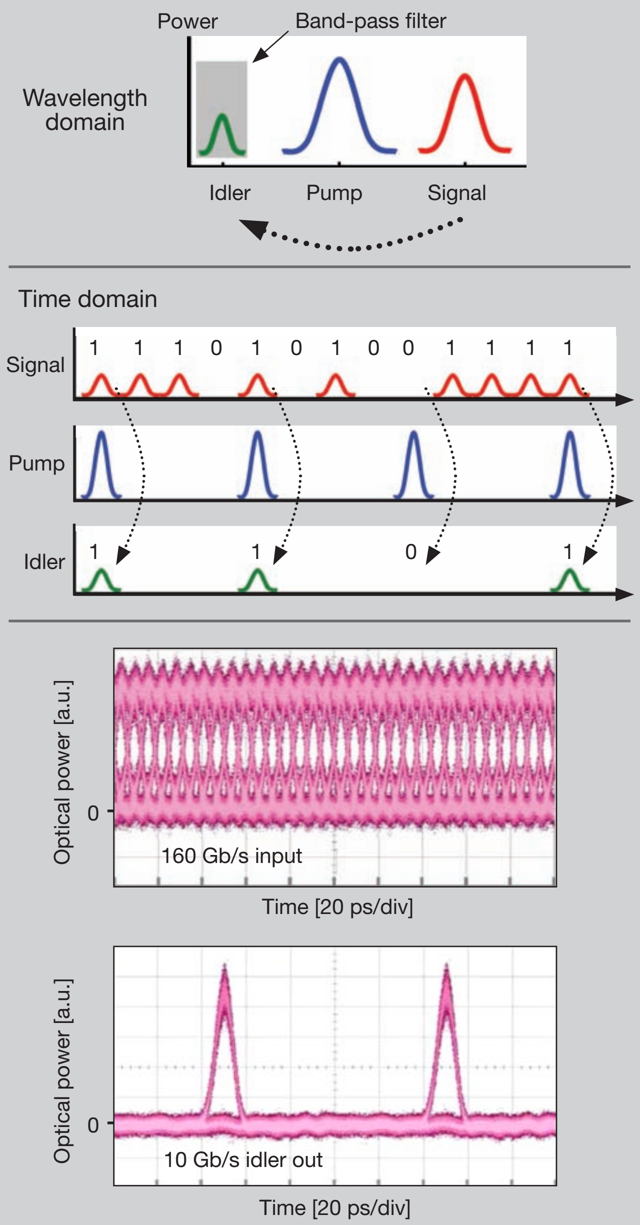
Planar chalcogenide glass waveguides form the basis for photonic-chip-based all-optical signal processes. (Left) Optical image of the cross-section of a planar waveguide fabricated from thin films of chalcogenide glass deposited on oxidized silicon wafers. (Right) Long serpentine-shaped waveguides can be easily squeezed onto an optical chip. The high refractive index of the chalcogenide glasses means that tight bends are essentially lossless.

[All-optical wavelength conversion]



All-optical wavelength conversion of an amplitude modulated 40 Gb/s signal. Each spectrum shows the input signal centred at 1535 nm and a cross-phase modulated CW at longer wavelength (1545, 1555, 1565 or 1575 nm). Cross-phase modulation results in the generation of optical sidebands, seen as a pedestal on each CW. Spectral filtering one sideband converts the phase modulation into amplitude modulation, allowing wavelength conversion of the data to a wavelength specified by the CW and filter. The narrow sidebands generated in this demonstration imply the converted signal will consist of pulses that are longer than the original input. Increasing the nonlinear interaction will generate stronger sidebands, allowing better reproduction of the input signal.

[All-optical demultiplexing]



All-optical demultiplexing of a very high-bit-rate signal into lower bit-rate individual channels using nonlinear signal processing techniques. The two views (wavelength and time domain) show a high bit-rate signal (red: 160 Gb/s) combined with a lower repetition rate intense optical pump (blue: 40 GHz). Nonlinear wave-mixing between the signal and pump results in the generation of pulses at a wavelength symmetric around the pump wavelength.

This new demultiplexed signal (green: 40 Gb/s), termed the idler, can be extracted spectrally by using a simple band-pass filter. Experimental results (bottom) of a 160 Gb/s signal before and after being demultiplexed to 10 Gb/s show preservation of signal quality as determined by the variation in the "ones" and "zeros" levels.

Modeling and experiment show that the device is able to convert a given input signal over a spectral region wide enough to cover the standard near infrared telecommunication band. We have recently achieved operation of this device with 80 Gb/s signals and foresee optimization of the waveguide properties, allowing operation at 160 Gb/s.

Optical switching

While the interleaving of several optical data signals to create a higher data rate optical time division multiplexed signal is relatively simple to implement, the demultiplexing of such signals is significantly more difficult. Once again, chalcogenide waveguides offer a convenient platform for realizing such functionality using Kerr-nonlinearity-based four-wave mixing.

The figure on the left shows the principle of operation for demonstrating demultiplexing of an OTDM signal. The high data rate signal is combined with a low duty cycle optical clock (the pump that drives the nonlinear process). Nonlinear wave mixing between the signal in the presence of a pump pulse generates a demultiplexed signal at a new idler wavelength.

We have used this technique to achieve high-quality demultiplexing of a 160 Gb/s signal down to 10 Gb/s (IEEE Photon. Technol. Lett. **19**, 1496-8). The figure compares the original and demultiplexed signals measured with a fast sampling scope. The clear, open region within each pulse indicates that the signal quality (i.e., optical signal-to-noise ratio) has been nearly preserved through this process. As the nonlinear process used for this device responds much faster than the pulse duration, this device can, in principle, be scaled to operate at data rates approaching 640 Gb/s. Such a rate is equivalent to transmitting approximately 17 complete DVDs per second!

Interestingly, wave-mixing is a phase-preserving nonlinear process, meaning that it can be used to process signals that use advanced coding techniques that rely on both phase and amplitude to encode data. Such concepts, while widely used in electronic communications networks, are only recently being implemented in the optical domain to more efficiently use the available optical bandwidth.

Waveguide Bragg gratings for filtering

Waveguide Bragg grating devices are critical for optical communication systems; they act as filters, multiplexers and dispersion compensators. Their importance derives from their ability to precisely manipulate the optical field, in both amplitude and phase space. Chalcogenide glasses exhibit several types of photo-induced phenomena that have been used in the formation of various optical components, including Bragg gratings. The ability to photo-induce high-quality Bragg gratings in chalcogenide glass waveguides via their photosensitivity is another advantage of using these materials for photonic devices.

The first demonstration of a waveguide (fiber) Bragg grating was by Tanaka et al. In more recent studies, researchers have analyzed growth dynamics and stability. The spectral response

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of chalcogenide gratings, in terms of rejection, operating bandwidth and apodisation, has been modest. Using a Sagnac-based interferometer, we have achieved high-quality chalcogenide glass waveguide Bragg gratings that exhibit sharp spectral features, wide rejection bands (5 nm wide corresponding) and deep transmission rejection (50 dB); they are suitable for many telecommunication applications (Opt. Express **14**, 9451-9).

Conclusion

Chalcogenide glasses offer an interesting and exciting new platform for developing all-optical signal processing devices for the photonic equivalent of the electronic chip. These devices will be able to demultiplex high data rate signals, convert the carrier wavelength, and perform other functions, such as optical signal regeneration and packet buffering and switching.

Further improvements in device performance are needed in order to achieve all-optical signal processing at data rates for future telecommunications applications (e.g., at 160 to 640 Gb/s). The key issue is to lower the operating power, given that these chalcogenide glass waveguide devices have required powers of several watts. Fortunately, there is a clear path to a reduction of a factor of 30-50 and a more speculative path to a further factor of 5-10. The attainment of these goals requires an increase in the waveguide length, the use of glasses with high optical nonlinearities, and a reduction in mode area of the waveguide.

Chalcogenide glass research is pushing ahead on a number of frontiers. The mid-infrared transparency of these materials, in contrast to silica, is of significant interest, and we expect to see an increasing number of sensing devices for applications in molecular analysis and astronomy.

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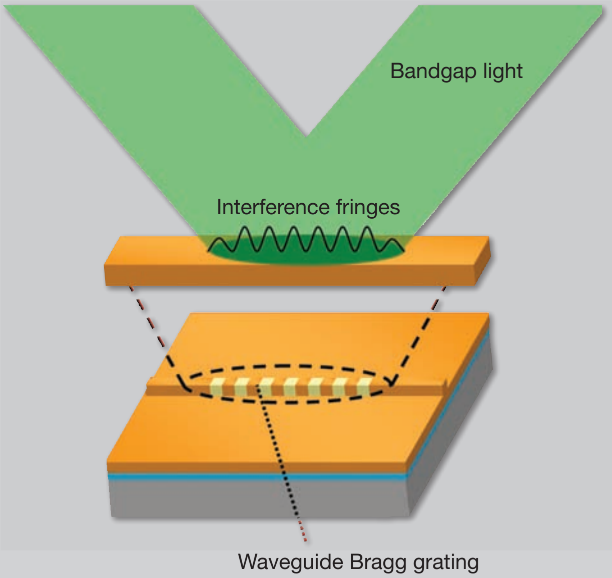
[Inscribing waveguide Bragg gratings]



Inscribing waveguide Bragg gratings via chalcogenide glass photosensitivity. The refractive index of chalcogenide glass can be permanently changed using the photosensitivity of these glasses to light an energy that falls within the material's optical bandgap. Interfering two such beams at a chalcogenide glass waveguide surface can induce a waveguide Bragg grating structure, which can act as a filter to reflect light at the resonant wavelength.

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