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Silicon Modulator Operates at Terahertz Frequencies

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Scientists at California Institute of Technology in Pasadena and at the University of Washington in Seattle have demonstrated what they believe is the fastest all-optical silicon amplitude modulator. It can operate at frequencies in excess of 1 THz, about two orders of magnitude faster than any similar silicon-based device.

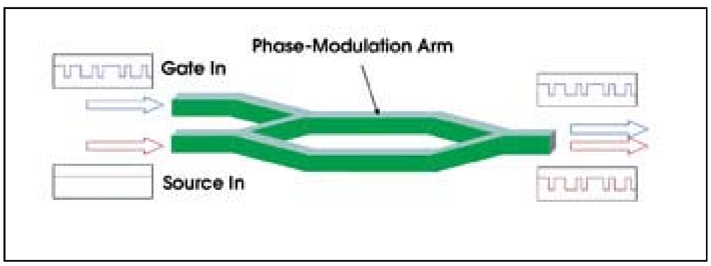

Figure 1. *This simple schematic of the terahertz modulator shows that the gate signal caused a phase change to the source signal in one arm of the Mach-Zehnder interferometer, so that the output at the source wavelength was modulated by the gate.*

No electronics are involved in an all-optical modulator; one beam of light modulates another. Such devices are indispensable in any approach to optical computing and likewise are an integral component of any telecom wavelength converter.

To date, the most successful demonstrations of all-optical modulation in silicon have involved the excitation of free carriers via two-photon absorption or through pumping with short-wavelength light. Conceptually, a light beam is incident upon a resonator whose resonant frequency is tuned to its optical carrier frequency, and the light is transmitted through the device. A second beam hits the resonator and excites free carriers, whose presence shifts the resonator’s refractive index so that the first beam is no longer resonant. Thus, when the second beam is switched on, the first beam is switched off, and vice versa.

There are variations on this theme that avoid the signal inversion resulting from the method described above, and various types of resonators, including microrings and photonic-crystal cavities, have been used. Nonetheless, they all depend on the creation of free carriers by the modulating light signal and, therefore, have been limited to an upper frequency of a few tens of gigahertz. In contrast, the Caltech/Washington approach relies on the optical Kerr effect and is capable of terahertz modulation frequencies.

Most readers are familiar with four-wave mixing, which is one manifestation of the optical Kerr effect and is the bane of telecom engineers because it diminishes the signal-to-noise ratio over long-haul fiber optic links. Simply put, four-wave mixing is a nonlinear effect between two lightwaves at different frequencies. It creates sidebands on each of the original waves, with each of the sidebands separated from its parent by the frequency spacing of the two original waves.

Readers may be less familiar with the phase shift introduced to the two original waves by four-wave mixing, but this shift is the key to the new modulator. The scientists constructed a waveguide Mach-Zehnder interferometer using silicon-on-insulator wafers, and employed four-wave mixing to cause a phase shift in one of the interferometer's arms. This phase shift, in turn, modulated the light that was transmitted through the device

Modulator geometry

The geometry of the modulator is refreshingly simple (Figure 1). In the straightforward silicon-waveguide Mach-Zehnder interferometer, the incoming "source" signal splits between the two arms and interferes at the output. If the two arms are of equal optical length, the interference will be constructive. But the researchers coupled a "gate" signal into one arm of the interferometer, and that signal induced a phase shift in the source light in that arm via four-wave mixing. Thus, the gate signal could alter the transmission of the source signal through the Mach-Zehnder. In other words, the gate modulated the source.

But it wasn't quite that easy. Silicon is known for its weak ultrafast nonlinearity, which until now has been one of the major roadblocks to fast modulators. In the short silicon waveguide that is the Mach-Zehnder's arm, the effect of four-wave mixing normally would be very difficult to observe. The scientists overcame this obstacle by cladding the silicon waveguide with a specially engineered, highly nonlinear polymer. The light traveling in the waveguide was evanescently coupled into the polymer, where the nonlinear phase shift was imposed via four-wave mixing.

(Interestingly, in several recent experiments, evanescent coupling has proved a successful technique for bestowing silicon with properties not really its own and thereby finessing its poor optical qualities. Researchers at Intel and the University of California, Santa Barbara, have bonded indium phosphide to a silicon waveguide so that the laser light produced in the InP is evanescently coupled into the silicon waveguide resonator, producing what is, in effect, an electrically pumped silicon laser.)

The scientists first demonstrated their modulator's capability at gigahertz frequencies by directly modulating the gate signal at those frequencies and observing the corresponding frequencies on the source output (Figure 2). Although this experiment established that the gate was modulating the source, it did not unequivocally prove that four-wave mixing — and not free-carrier generation, for example — was the mechanism.

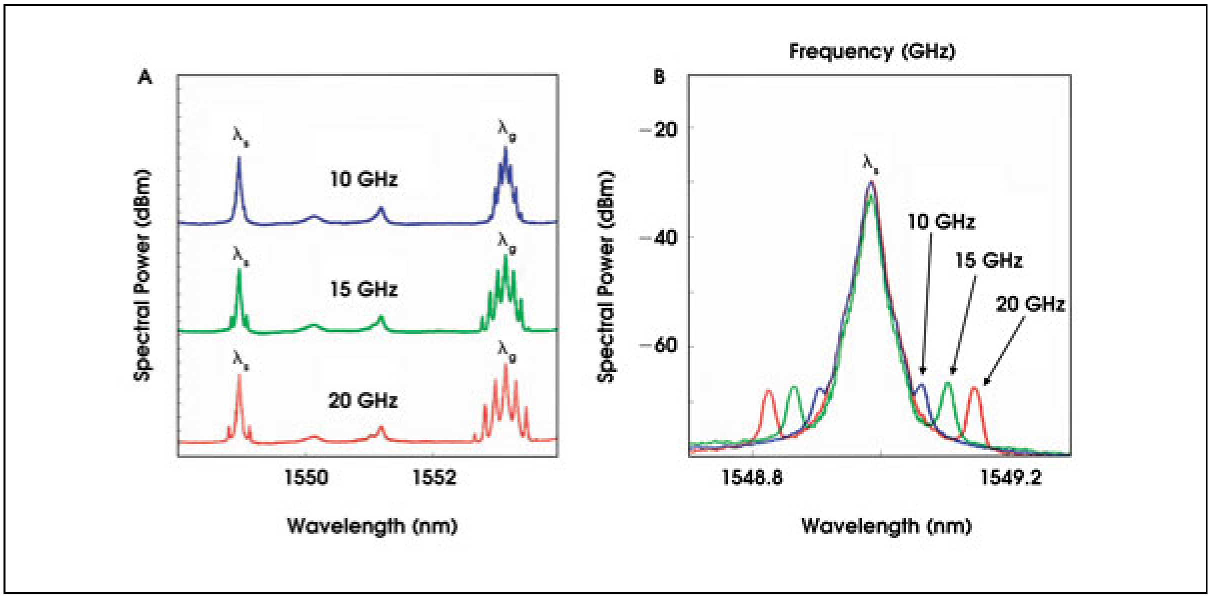

***Figure 2.** (a) The scientists modulated the gate wavelength (λ_g) at 10, 15 and 20 GHz, producing sidebands on that signal. Similar sidebands appeared at the source wavelength (λ_s), indicating that the gate was modulating the source. (The small features between λ_g and λ_s are not significant.) (b) An expanded view of the source spectra for all three cases clearly shows the modulation sidebands. Reprinted from Nature Materials with permission of the researchers.*

To build credibility for four-wave mixing, they repeated the experiment in a Mach-Zehnder without the nonlinear-polymer cladding and observed no modulation on the source wavelength passing through the device. Free carrier generation in silicon does not depend on evanescent coupling into a nonlinear medium and, hence, would not be diminished by its absence.

Demonstrating modulation at terahertz frequencies was a more challenging task. The straightforward approach — applying terahertz frequencies to the gate and observing terahertz sidebands on the source wavelength emerging from the Mach-Zehnder — was eliminated because neither generators nor detectors at terahertz frequencies are readily available.

Instead, the scientists capitalized on the fact that they knew theoretically (and could show mathematically) that four-wave mixing always produces the accompanying phase shift. All that they had to do was show that four-wave mixing occurred in the interferometer's arm with sufficient amplitude at terahertz frequencies. Then they could logically conclude that the principle of the Mach-Zehnder modulator was equally valid at those frequencies.

To do so, they sent two laser wavelengths separated by, for instance, 1 THz into the gate of the device, and a third into the source. The Kerr effect will create, as before, a phase shift in the source wavelength, though this will create an amplitude modulation that is too fast to be observed directly, as it is with terahertz modulation. But, crucially, a number of optical frequencies also will be created by this nonlinear effect, spaced 1 THz from the input signals. It is straightforward to relate the strengths of these new optical signals, which can be directly measured via a spectrometer, to the phase shift that must have been induced. The researchers found that this phase shift was nearly the same as that seen directly at slower speeds (Figure 3), and so concluded that their modulator was indeed capable of terahertz performance.

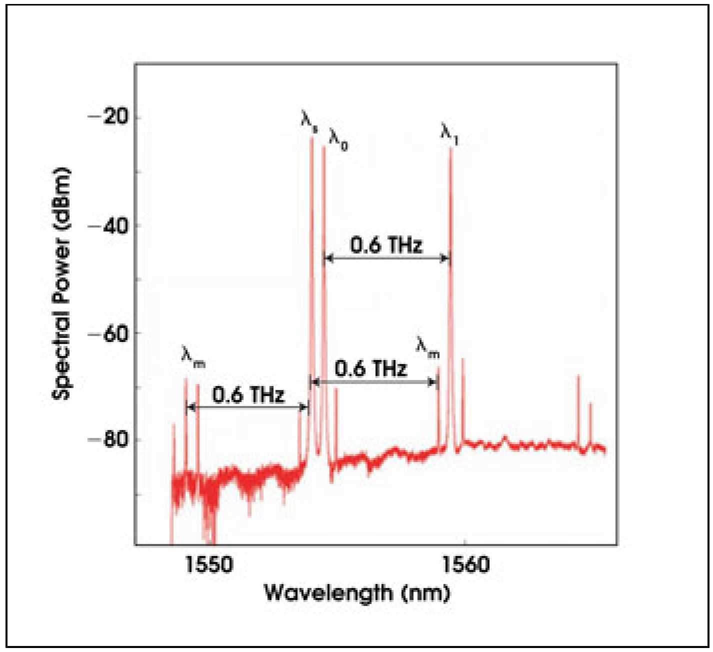

Figure 3. *By inputting two wavelengths, separated in this case by 0.6 THz, on the gate, the scientists created four-wave-mixing sidebands (labeled (λ_m) on the source wavelength. They observed similar results when the gate wavelengths were separated by 0.25 THz and by 2.6 THz. Reprinted from Nature Materials with permission of the researchers.*

The scientists expect that refinements of their modulator will improve its extinction ratio. Ideally, the relative phase shift between the two arms of Mach-Zehnder should approach π radians for the optimal extinction ratio, but the phase shift in the experimental device to date has been small. Nonetheless, they believe that, as the nonlinearity of polymers increases and the waveguide loss of their device decreases, the extinction ratio of the modulator will rise to the point where it becomes a practical device in both telecom and optical-computing applications.

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