MHz. However, if the resistor is replaced with a tuned impedance-matching circuit,\textsuperscript{7} the gain increases to ~11 dB with a center frequency of ~60 MHz and a 3 dB bandwidth of ~20 MHz. With the tuned circuit on the modulator, the link noise figure is 6 dB and the IM-free dynamic range is 111 dB within a 1 Hz bandwidth. The range from maximum input signal to the noise floor is 155 dB/Hz. With some sacrifice in sensitivity, a higher IM-free dynamic range can be obtained by the dual-polarization approach described by Johnson and Roussell.\textsuperscript{8} These measured values agree well with theoretically calculated values over the entire 150 dB input power range.

Extrapolation to higher center frequencies is straightforward. Since the modulator can be modeled as a capacitor, the maximum possible response decreases inversely with the square of the increase in frequency. As the frequency increases, the gain decreases and the noise increases, but the dynamic range remains nearly unchanged. Thus, for low-to-moderate frequencies and moderate-to-high optical bias powers, the externally modulated link is expected to provide lower insertion loss or actual insertion gain, a larger IM-free dynamic range, and less noise than a directly modulated link.\textsuperscript{9}

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Dynamic optical interconnects

L. Hesselink, Stanford University

Dynamic optical interconnects are reconfigurable routing networks that can interconnect high bandwidth optical data paths. The optical crossbar is an example of an attractive architecture that can be implemented using photorefractives. Once the routing network has been established, optical inputs are reflected, refracted, or diffracted passively to their respective outputs. Upon termination of the task, the network can be reconfigured and adapted to new routing requirements. The major advantage of this approach is the high optical transmission bandwidth (GHz), although the reconfiguration time may be slow (on the order of msecs or μsecs).

Architectures involving photorefractive crystals have been implemented for this purpose, but several limitations need to be overcome to fully exploit the potential advantages of these systems. As is well known, readout of holographic gratings in photorefractives is destructive, unless fixing procedures are applied or the wavelength of the readout light is used in a regime where the photorefractive crystal is not sensitive. In this case, however, the Bragg condition still needs to be satisfied to achieve high diffraction efficiency. We have recently devised a new architecture to achieve prolonged readout.\textsuperscript{1}

In this approach, the interconnect gratings are written by beams of wavelength $\lambda_w$ and readout by using signal beams of longer wavelength $\lambda_s$. Unlike previously proposed networks, the writing wavelength does not have to be tunable. The Bragg condition is still maintained by locating the recording and readout beams on a conical geometry, as shown in the figure. The writing $k$-vectors $K_{wi}$ lie on the surface of a cone and emanate from the cone apex. The signal $k$-vectors $K_{si}$ (either inputs or outputs) lie on a second cone, which has the same base, but whose height is scaled by the ratio of the wavelengths. We estimate that in SBN, approximately 5,000 interconnections could be established and used for prolonged time periods (hours) without significant erasure.

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The conical geometry can also be implemented in a novel architecture involving very high density optical interconnects on a photorefractive substrate. In other recent work, we have designed and studied a 100 × 100 optical switch on a 1 cm² substrate of LiNbO₃. Planar interconnect holograms are located in a rectangular grid pattern. Each hologram (grating) is written by short wavelength out-of-plane writing beams located on a conical surface at angles of incidence chosen to facilitate Bragg diffraction at a longer wavelength guided mode. This approach has the advantage that many intersections are simultaneously written and coherency and erasure problems are avoided.

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Optical modulation using silicon

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Light modulators are important components for optical communications systems and optical interconnection strategies. III-V semiconductors, as well as non-semiconductor crystals such as LiNbO₃, are the traditional materials of choice for these modulators, but there is mounting evidence that silicon can also be used. The central role of silicon in the microelectronics industry makes this an interesting possibility.

Silicon is a centrosymmetric crystal, so it does not exhibit a Pockels (linear electro-optic) effect. It does, however, exhibit a free-carrier effect, in which the real and the imaginary parts of the refractive index are changed when carriers are introduced either through doping or injection. The electrically-induced free-carrier effect is known to be appreciable in GaAs/AlGaAs, for which refractive index changes that exceed Δn = 0.01 have been reported. A large free-carrier effect in the wavelength range 1<λ<2 μm would make silicon an attractive candidate for optical modulation.

There have been several demonstrations of the use of the free-carrier effect in silicon. Grodnenskiy et al. used the carriers injected into a silicon p-n junction to attenuate the intensity of light of wavelength λ = 1.15 μm passing through the junction. Lorenzo and Soref obtained 50% modulation at wavelength λ = 1.3 μm in a multimode silicon 2 × 2 rib optical waveguide structure. Both devices required current densities in excess of several hundred Amperes/cm² to achieve modulation.

In a paper published in July 1989, Hemenway, Solgaard, and Bloom described the performance of an all-silicon, reflection-type, silicon optical modulator (dubbed SIMOD). The modular uses the free-carrier effect in a forward-biased integrated pin diode to achieve 10% peak-to-peak intensity modulation over a 200 MHz bandwidth. The device has an active area of 3 × 6 μm² and requires 10 mA of current modulation and a current density >10⁴ Amperes/cm², when used at wavelength λ = 1.3 μm. Small size and potential compatibility with silicon processing technology are important features of this integrated device.

The size of the electrically-induced change in the real part of the refractive index of silicon at the important wavelength λ = 1.3 μm was measured in a recent experiment. The sample geometry is shown in the accompanying figure, and consists of a silver (Ag) electrode deposited onto a corrugated n-type epitaxial silicon layer grown on an n⁺ silicon substrate. When biased as shown, the structure functions as a reverse-biased Schottky diode. In addition, the sample supports TM-polarized electromagnetic surface waves known as surface plasmons, localized at the Ag/air and Ag/Si interfaces. The surface grating of period Λ allows a beam of light incident through the substrate at a particular angle Θ to excite the surface plasmon at the Ag/Si interface.

The electric and magnetic fields associated with this surface plasmon decay exponentially away from the interface, a fact that results in a significant spatial overlap between these fields and the carriers introduced into the n-type silicon layer. Changes in the refractive index nₑ of the epitaxial layer produce changes in the propagation constant of the surface plasmon, which shift the angle Θ required to excite this wave.

The measured shifts in the resonance angle Θ = Θ(V) using reflection (see figure) reveal a large change in nₑ. A