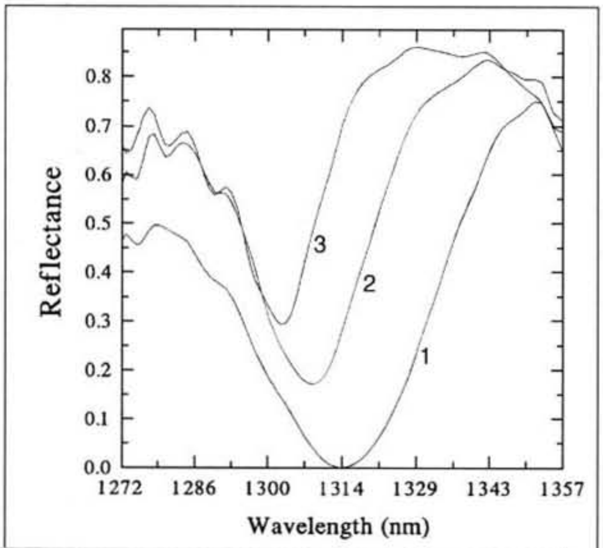

Measured reflectance spectra of the GaAlInAs/AlInAs asymmetric reflection modulator for pump intensities of (1) 0.0 (linear), (2) 6.6, and (3) 41 kW/cm². The measured data points were connected using a spline plot.

the pump intensity is increased. Assuming the device begins to enter saturation when the instantaneous slope of the transfer characteristic is less than unity, the saturation reflectance value for the modulator is approximately 0.6. This value of reflectance corresponds to an on/off contrast ratio of 1060:1 (exceeding 30 dB) and an insertion loss of 2.2 dB at a pump intensity of 30 kW/cm², corresponding to a carrier density of $4.5\times10^{17}$cm$^{-3}$. The large contrast ratio and low insertion loss result from the combined absorptive and refractive nonlinearities near the heavy-hole exciton peak. The 3 dB optical bandwidth, defined as the spectral band over which the on/off contrast ratio is greater than 500:1, is ~ 3.3 nm.

The recovery dynamics of the modulator were also measured in a time-resolved pump/probe geometry using 1.5 psec pulses. The modulator recovery time was 725 psec, making it potentially useful in optical processing systems where bandwidths approaching 1 GHz are required.

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# 2-D WDM Optical Interconnections Using Multiple-wavelength VCSELs for Simultaneous and Reconfigurable Communication Among Many Planes

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The ability to efficiently connect many high-speed ports or "smart" pixels is of critical importance for large-capacity communications. High bandwidth, 2-D optical planes can be used to achieve such an interconnection and avoid eventual electronic bottlenecks.[1] However, existing solutions do not efficiently resolve a situation in which one plane is required to simultaneously and reconfigurably communicate with many subsequent planes. One previous solution involves etching large holes in each plane's substrate establishing only a predetermined static configuration between any two planes (see Fig.1(a)).[2]

We propose and analyze a novel solution[3] that uses wavelength-division-multiplexing (WDM)[4,5] to facilitate one 2-D optical plane communicating simultaneously and reconfigurably with many other planes. Such a system can be realized by incorporating several multiple-wavelength vertical-cavity surface-emitting lasers (VCSEL)[6] into each transmitting pixel and incorporating wavelength-selectivity into each subsequent detecting plane. Each detecting plane absorbs only one wavelength and is transparent to all oth-

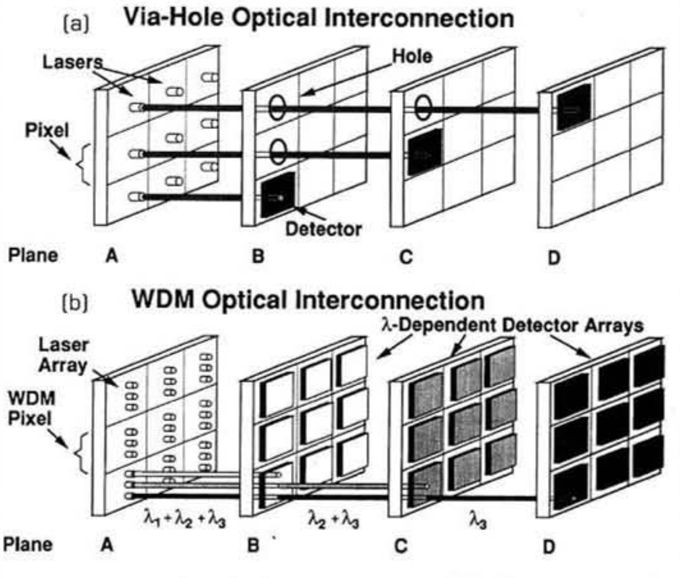

**Figure 1.** 3-D view of one-to-many optical plane interconnections using **(a)** large holes that establish a permanent optical path, and **(b)** 2-D pixel array of identical 3-λ VCSEL mini-arrays and three λ-selective detector arrays.

ers. This advance dramatically increases the functionality and capacity of optical-plane interconnections. Moreover, this WDM configuration can also be used with several wavelength-dependent layers that inter-communicate in a multiple-level, printed-circuit board.

Figure l(b) illustrates the basic systems concepts in which, for simplicity, only the first of M planes is transmitting and the rest are receiving. The transmitting plane is composed of an $N \times N$ pixel array with each transmitting pixel containing a miniature multiple-wavelength VCSEL array. Each laser in a pixel emits light at a different wavelength, $\lambda_i$. There are (M-l) lasers in each pixel corresponding to the (M-l) other planes with which this pixel can communicate. This WDM pixel is identically repeated for the entire plane array. The (M-l) detector planes each have $N^2$ pixels, and every p-i-n detector has a spectral response that is offset from that of the next plane. The cutoff wavelength of the detector planes increases for each subsequent plane.

Therefore, each detecting plane will capture only the shortest-$\lambda$ signal remaining in the beam and will be transparent to all the longer-wavelength signals. Thus, communication can be accomplished in a dynamic and reconfigurable manner by switching "ON" the appropriate laser in each pixel. It should be emphasized that adding more lasers does not alter the pixel density on a chip because the pixel area is overwhelmingly dominated by the necessary electronics and not by the relatively-small VCSEL array. Furthermore, high contrast ratio can be achieved using detectors with sharp spectral cutoffs, with all wavelengths placed on the long-wavelength edge of a detector responsivity curve. Assuming a typical detector, high contrast ratio can be achieved for a channel wavelength separation >30 nm.

WDM interconnections have two system scenarios: (I) one plane transmits and the rest receive, and (II) all intermediate planes transmit as well as receive. Furthermore, three variations for both these categories are: (a) *individual mode*—only one laser per pixel can be turned "ON" at a given time (reconfigurable); (b) *broadcast mode*—all lasers per pixel can be turned "ON" simultaneously but with the same data; and (c) *independent mode*— all (M-l) lasers can be turned "ON" simultaneously and independently, transmitting different data streams to different planes. In the "One Plane Transmitting" scenario using the "individual" mode, the system is dynamically reconfigurable even though the capacity is not enhanced. For both the "broadcast" and "independent" modes, the first plane is allowed to communicate with all planes simultaneously. In the "All Planes Transmitting," the "broadcast" and "independent" modes in which all the lasers can be "ON" simultaneously always have (M-l) possible links, providing the highest system capacity. The most interesting and non-obvious, case is the individual mode. The capacity enhancement is due to the WDM pixel establishing an additional communications channel between its own plane (B) and another plane (C) while it concurrently relays data between two other planes (A,D) by being transparent to that other signal. Analysis shows that for a 10-plane system, WDM involving only one laser individually "ON" per pixel essentially doubles the capacity of the via-based solution while also providing reconfigurability!

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# Acousto-optic Switch Matrices

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The vast information capacity of optical fiber is widely touted, but substantial problems remain—multiplexing many sources of data onto the same optical carrier. The technique of time division multiplexing involves sorting and packing bits into ever smaller time slots as the information rate increases—something that becomes ever more difficult with increasing capacity. A very different two-tiered approach is to subdivide the useful optical spectrum into many independent wavelength channels, each of which carries a more manageable electronic information bandwidth.

The two-tiered approach, known as wavelength division multiplexing (WDM), requires the use of wavelength-selective components (multiplexers and switches) to gain access into and out of a transparent optical network, since different "colors" carry unrelated information and have to be distinguished and sorted. A particularly promising component for WDM systems is the acousto-optic (AO) wavelength switch which functions as the optical equivalent of the double-pole, double-throw switch. In fact, the routing for each wavelength channel is set simultaneously and independently in a single AO filter/switch. This parallel processing is achieved by establishing a set of non-interacting coexisting photoelastic gratings, generated by surface acoustic waves (SAWs), that diffract narrow phase-matched bands of light from one state of polarization into its orthogonal state. Polarization splitters, positioned before and after the narrowband acousto-optic polarization converter, achieve both polarization insensitivity and spatial separation of switched channels.[1]

Current AO switches are fabricated using integrated optical techniques and SAW technology on lithium niobate substrates.[2] The simplest AO switch does not perform with the high degree of wavelength channel isolation (low interchannel crosstalk) thought to be required by practical optical networks of the future (perhaps 20-30 dB isolation will be demanded). The main barrier to low crosstalk is the