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, λ_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-λ 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 inability to reach more than 98% of polarization conversion, limiting the channel isolation to about -17 dB. However, if one thinks of AO filters as the building blocks of wavelength crossconnects (like transistors in electronic circuits) then a four element sub-network or switch matrix can perform the same switching function as a simpler switch, but with far better fidelity, much like a four transistor radio sounds a lot better than a one-transistor one. The price one pays for enhanced device performance is increased complexity; however, improvements in device compactness, loss, and uniformity should offset the added complexity.

The AO switch matrix, in its simplest form is made by expanding ("dilating") the AO switch (left side of the figure) to a 2 × 2 matrix of these elements (right side). The switch achieves the desired goal of dilation. In dilation, different input ports never share the same switch element, a major step toward removing the compromise factor that degrades switch performance.[3] In the figure shown, B and C are bar and cross-state wavelength channels, respectively, and b and c are leaked signals (caused by incomplete polarization conversion, polarization leakage, sidelobe excitation). In a single stage, leakage signals directly pollute the opposite (active) port, while in two stages, misdirected light is peeled off and diverted to unused ports. The oscilloscope trace insets show bar and cross state scans for the first stage and second stage of the switch matrix, showing light transmitted as a function of wavelength (a 25 nm scan is shown about a center of 1540 nm). These traces correspond to a fixed wavelength input and a 3 MHz RF scan about a center drive frequency of about 177 MHz. After two stages, the cross states (bandpass spectra) improve in narrowness and out-of-band rejection, while the bar-state scans (band-reject spectra) improve in degree of depletion at resonance, evidence of more perfect switching. In the dilated AO switch used in these experiments, the degree of channel isolation improved from −14 to −23 dB, and from −16 to −25 dB for bar and cross states, respectively.

Dilation expands component count for an $N \times N$ switch, of course, but the increase in complexity becomes more modest for larger networks, approaching a factor-of-two expansion for large networks. Dilating the simplest AO switch requires the four times the complexity. Since these devices are already fabricated by monolithic technology in compact integrated optic and SAW elements, the price of expansion is much less costly than in hybrid networks. Aside from the benefits of dilation to achieve excellent device performance with less-than-excellent subcomponents, improvements are being made in polarization splitter compactness. Advances are also being made to reduce drive power and improve "passband engineering," by which the transmission band is made more square (fully switching in-band and fully retained out-of-band). It is hoped that such progress will make acousto-optic wavelength-multiplexed optical transmission systems a strong competitor to ultrafast modulation rate single-wavelength systems.

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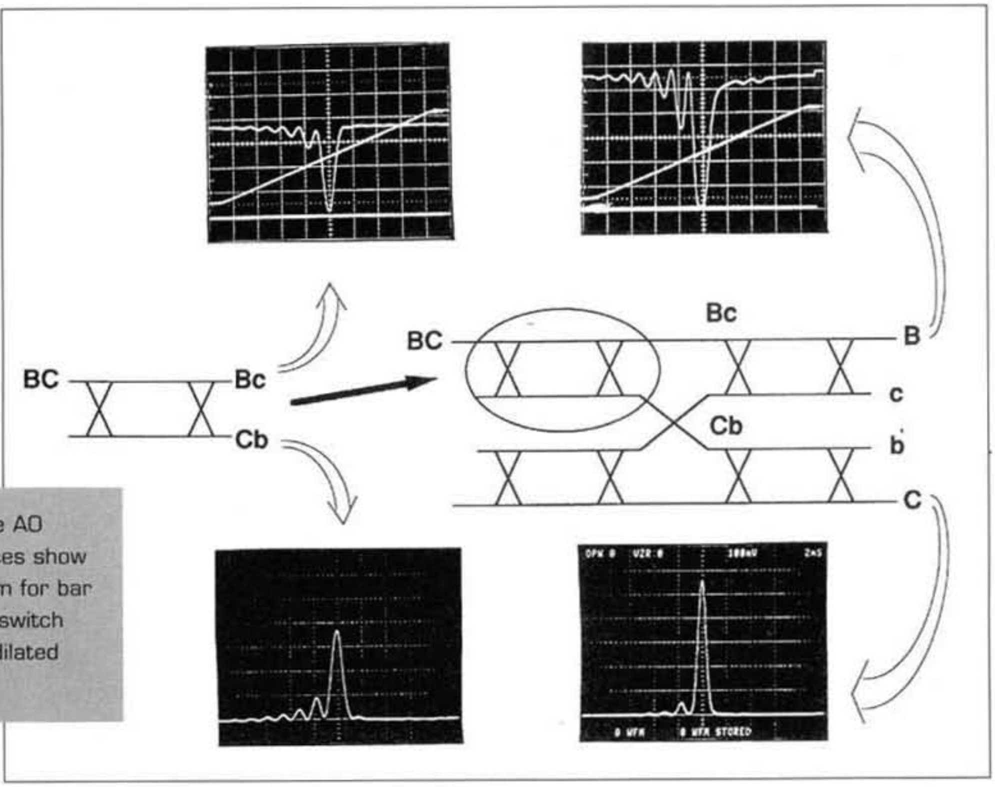

Single-stage (left) and two-stage AO switch (right). Oscilloscope traces show optical transmission over 25 nm for bar (B) and cross (C) states of the switch matrix for both one-stage and dilated switch structures.