

nation in this mesh-structured city. The concept behind this transportation pattern can be found in a communication network, commonly known as the Clos 3-stage network.¹ The mesh-connected bus (MCB)² topology is one way of laying out the Clos network in a 2D format (see Figure 1(a)). It has been shown that any permutation can be arranged, without experiencing internal blocking, in three global routing steps; permuting along the row buses, then along the column buses, and finally along the row buses.

Research leading to the implementation of a wavelength-division multiplexing (WDM) MCB free-space optical network is progressing at NEC Research Institute.³ Compared to the existing single star-coupler-based WDM approaches in which each node experiences a power fan-out of N and a bandwidth capability of N wavelength channels, each WDM MCB node requires only a power fan-out of with a total required wavelength channels. The three hop routing speed compares favorably against $\log_2 N$ hop multi-stage networks, such as the shuffle and the butterfly networks.⁴ An additional feature here is that the MCB topology is suitable for a free-space optical implementation in the sense that each of the three required routings uses only one cylindrical optical component—a lens or a mirror. This is because cylindrical optics can convert a 2D dot pattern into an array of parallel lines each of which forms a WDM broadcast bus. Thus, a compact network architecture could probably take the form of Figure 1(b) in which the wavelength tuned transmitters and receivers are located on both sides of the middle block which is sandwiched between the perpendicularly oriented cylindrical lenses and right-angle reflectors.

With commercially available components, we have recently implemented an experimental prototype of the WDM MCB network to transmit 10 MHz multimedia signals formed by multiplexing video, stereo audio, and RS-232 data bands. Fixed-tuned lasers with output power of -5.2 dBm and with wavelengths around 1310 nm, and fiber Fabry-Perot type tunable filters and receivers with sensitivity of -31 dBm were used as transceivers. Some short fibers were used to link between the free-space bus routers and the transceivers. The power at each of the cylindrical lens-formed buses was enough to support 36 nodes with a signal-to-noise ratio better than 52 dB. The four quadrants of Figure 1(c) (our prototype) show the original camera picture and the pictures received at the outputs of stages 1 through 3, respectively. An overall signal-to-noise ratio of 49 dB was obtained at the last stage after the multimedia signals passed through three free-space routers and six supporting electric-to-optic or optic-to-electric conversion steps. The optical portion of the prototype, which has a power capability of supporting a total of $36^2 = 1296$ nodes, occupies no more than a 15×10 cm² area.

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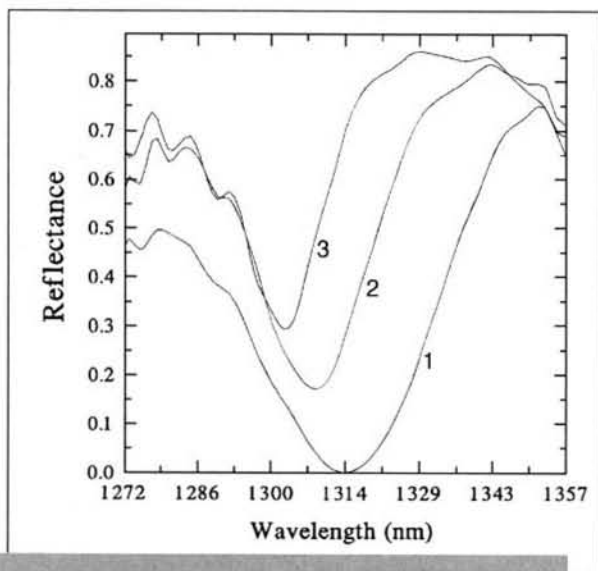
30 dB Contrast GaAlInAs Multiple Quantum Well Asymmetric Reflection Modulator at 1.3 μm

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High-speed optical communication interconnects and networks will require the use of high-contrast optical processing elements to fully use the bandwidth available in state-of-the-art optical fibers. Semiconductor quantum well modulators may be used for such applications. We have demonstrated^{1,2} an all-optical GaAlInAs/AlInAs multiple quantum well (MQW) asymmetric reflection modulator for use at 1.3 μm with an on/off contrast ratio exceeding 1000:1 and an insertion loss of 2.2 dB at a pump intensity of 30 kW/cm², corresponding to a carrier density of 4.5×10^{17} cm⁻³. The recovery time of the modulator is measured at ~ 725 psec, indicating that the operating speed of the device approaches 1 GHz.

Asymmetric reflection modulators consist of an asymmetric Fabry-Perot étalon formed by an optically nonlinear spacer between a low reflectivity front mirror and high reflectivity back mirror. Our asymmetric reflection modulator consists of a 65 period 69 Å Ga_{0.376}Al_{0.094}In_{0.53}As well/89 Å Al_{0.48}In_{0.52}As barrier MQW nonlinear spacer on top of a 24 period 936 Å Ga_{0.3}Al_{0.18}In_{0.52}As/1003 Å Al_{0.48}In_{0.52}As quarter-wave stack back mirror. This structure was grown lattice-matched on a semi-insulating InP substrate by molecular beam epitaxy. The étalon front mirror is formed by the air/spacer interface with a reflectance of $R_f \approx 0.31$, and the quarter-wave stack back mirror has a reflectance of $R_b \approx 0.92$. The total spacer thickness was $L = 1.027$ μm . The modulator was designed such that the Fabry-Perot resonance is located on the long wavelength side of the heavy-hole exciton peak to take advantage of pump-beam induced, large absorptive and refractive nonlinearities. In the absence of the pump, the absorption near the heavy-hole exciton is high, resulting in a balanced cavity and near-zero reflectance at resonance. When the pump is present, the photogenerated electron and hole populations saturate the absorption near the heavy-hole exciton and result in an increase in the reflectance at resonance by unbalancing the Fabry-Perot cavity. A considerable shift occurs in the Fabry-Perot resonance due to the change in refractive index related by the Kramers-Kronig transformations to the pump-induced absorption change.

The nonlinear reflectance spectra at pump intensities of 0.0, 6.6, and 41 kW/cm² are shown in the figure (next page). The reflectance rapidly increases from a value of 0.00055 ± 0.0008 at zero pump intensity to a value approaching 0.72 as



Measured reflectance spectra of the GaAlInAs/AlInAs asymmetric reflection modulator for pump intensities of (1) O.O (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 $4.5 \times 10^{17} \text{ cm}^{-3}$. 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 $\sim 3.3 \text{ nm}$.

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 solution³ 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-

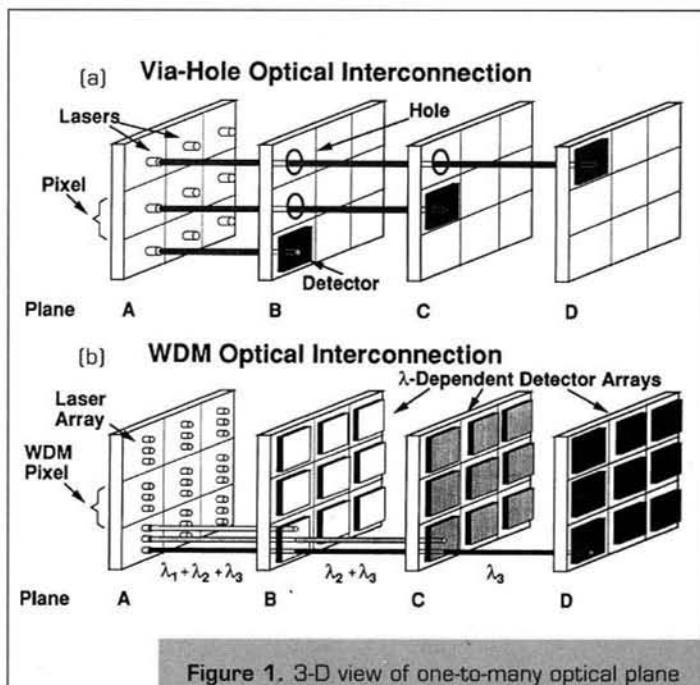


Figure 1. 3-D view of one-to-many optical plane interconnections using (a) large holes that establish a permanent optical path, and (b) 2-D pixel array of identical 3- λ VCSEL mini-arrays and three λ -selective detector arrays.