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

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Literatur

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2-D WDM Optical Interconnections Using Multiple-Wavelength VCSEL's for Simultaneous and Reconfigurable Communication Among Many Planes

A. E. Willner, C. J. Chang-Hasnain, and J. E. Leight

***Abstract*—We propose and analyze a novel interconnection configuration in which one 2-dimensional plane can communicate simultaneously and reconfigurably with many planes by using WDM. This system incorporates arrays of multiple-wavelength VCSEL's as well as wavelength-selective detecting planes. High signal contrast ratio with low power penalty can be achieved for a channel separation > 30 nm, limited only by the detector spectral response. By using WDM pixels, the system capacity is significantly enhanced as compared to more traditional techniques.**

THE ability to efficiently connect many high-speed ports or 2-dimensional (2-D) sensor arrays is of critical importance for large-capacity data processing. By taking advantage of the parallel nature of light, high-bandwidth 2-D optical planes can be employed to avoid the eventuality of electronic bottlenecks [1]–[3]. However, this optical-plane solution does not resolve efficiently a situation in which one plane wishes to communicate simultaneously and reconfigurably with many subsequent planes. Previous systems solve this problem by two schemes. The first method is for each plane to detect a data packet and then, if the data was not intended for that plane, retransmit it to the next plane (denoted as "plane-to-plane"). The disadvantages include the potential for an electronic high-speed bottleneck as well as wasting valuable capacity, real estate and optical hardware. The second solution involves etching large via windows in each plane's substrate such that an unobstructed and permanent optical path is created between a transmitting pixel on plane A and a detecting pixel on plane D [see Fig. 1(a)] [4]. This second approach solves the electronic bottleneck but wastes real estate and allows only a predetermined static configuration between any two planes.

We propose and analyze a novel solution using wavelength-division-multiplexing (WDM) [5]–[8] to facilitate simultaneous and reconfigurable communication of one-to-many 2-D optical planes, dramatically increasing the functionality of optical-plane interconnections. Such a system is realized by incorporating several multiple-wavelength vertical-cavity surface-emitting lasers (VCSEL) [9] identically into each transmitting pixel and incorporating wavelength-selectivity into each subsequent detecting plane which will absorb one wavelength and be transparent to all others; these structures can be fabricated by modifying existing VCSEL technology. This system will allow for increased processing functionality of communicating both simultaneously and reconfigurably between many planes, enabling broadcasting and dynamic independent interconnections. Our analysis shows that a high contrast-ratio with low power-penalty can be achieved for a channel wavelength separation > 30 nm, limited only by the detector spectral response. Furthermore, we derive equations describing the enhanced achievable total system capacity when implementing WDM as compared to the aforementioned solutions. This WDM system can also be used for several λ-dependent layers inter-communicating in a multiple-level printed-circuit computer board.

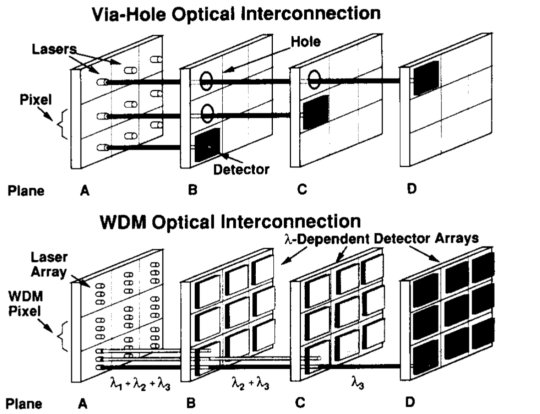

Fig. 1. 3-D view of one-to-many optical plane interconnections using (a) via holes which establish a permanent optical path, and (b) 2-D pixel array of identical 3-λ VCSEL mini-arrays and three λ-selective detector arrays.

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Fig. 1(b) illustrates the basic concepts for this WDM 2-D interconnection in which, for simplicity in this first example, only the first of M planes is transmitting and the rest 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, with all wavelengths being equally spaced apart. There are $(M - 1)$ lasers in each pixel corresponding to the $(M - 1)$ other planes which this pixel may wish to communicate with. This WDM pixel is repeated identically for the entire $N \times N$ plane array. The $(M - 1)$ detector planes each have N^2 pixels, and every p-i-n detecting pixel has a spectral response that is slightly offset from the corresponding pixel on the next plane. The detector planes are designed such that the cutoff wavelength increases for each subsequent plane. Therefore, each detecting plane will detect only the shortest-λ signal remaining in the beam and will be transparent to all the longer-wavelength signals. As an example, for $(M - 1) = 3$ and $\lambda_1 < \lambda_2 < \lambda_3$, detector plane B will absorb λ_1 only and be transparent to λ_2 and λ_3, detector plane C will absorb λ_2 only and be transparent to λ_3, and detector plane D will absorb λ_3. Communication can be accomplished from one transmitting plane to many detecting planes in a dynamic and reconfigurable manner by switching "ON" the single appropriate laser in the $\{\lambda_1, \lambda_2, \lambda_3\}$ VCSEL array.

The fabrication of WDM pixels can be achieved with alteration of existing multiple-λ VCSEL technology [9]. By fabricating a thickness gradient in a few layers of the VCSEL structure, a series of lasers can be made to emit distinct, equally-spaced wavelengths. Such a gradient can be periodic across the wafer to produce identical WDM pixels. Furthermore, the λ-selectivity of the detector planes can be tailored over a wide wavelength range by varying the material composition of the detector absorption layer. Additionally, because the pixel area is overwhelmingly dominated by the necessary laser and receiver electronics and not by the relatively-small VCSEL array, adding more lasers does not alter the pixel density on a chip.

Key performance parameters include the achievable contrast ratio and power penalty when a given plane absorbs one shorter-wavelength signal and rejects other longer-wavelength signals. All wavelengths are placed on the long-wavelength edge of a typical response curve of an InGaAs detector, as shown in Fig. 2(a) [10]; although the responsivity maximum for this detector is near 1600 nm, we consider this to be a non-specific wavelength enabling us to analyze a generic system. Fig. 2(b) plots the contrast ratio versus wavelength separation, $\Delta\lambda$, between a signal intended to be absorbed and a single rejected wavelength intended to be unaffected and passed. The contrast ratio is computed for different selected-signal wavelengths in comparison to the wavelength at which the responsivity curve is a maximum such that $(\lambda_{\text{select}} > \lambda_{\max})$; this is depicted as the percent of the responsivity at the selected wavelength in comparison to the responsivity maximum. If

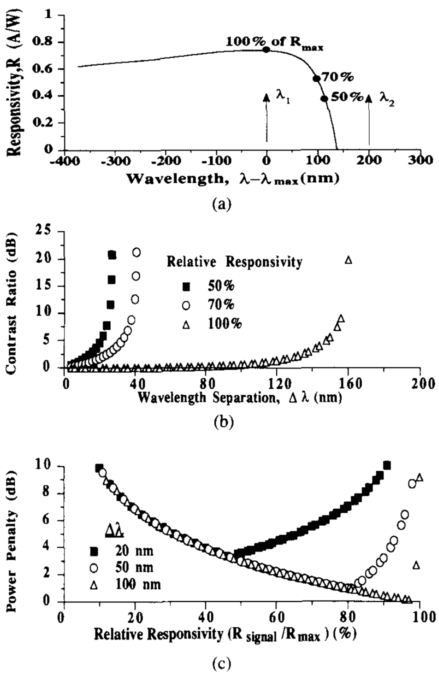

Fig. 2. Typical responsivity versus incident wavelength curve for an InGaAs detector. (b) Contrast ratio between a selected and rejected wavelength versus their wavelength separation. Curves represent different selected-channel responsivities in relation to the responsivity maximum, such that $(\lambda_{\text{select}} > \lambda_{\max})$. (c) Power penalty versus the percent of the responsivity of the selected channel in relation to the responsivity maximum.

the wavelength producing maximum responsivity (100%) is chosen for the selected signal, then a larger $\Delta\lambda$ is required to avoid absorption of the rejected signal. Furthermore, a $\Delta\lambda > 40$ nm for the 70%-of-maximum case and a $\Delta\lambda > 20$ nm for the 50%-of-maximum case will provide a contrast ratio > 20 dB. Fig. 2(c) shows the power penalty as a function of relative responsivity in which we derive the optimal responsivity level and wavelength for a selected signal, illustrating that a power penalty < 3 dB can be achieved; this power penalty takes into account not only the rejected signal absorption but also the added penalty due to detecting the selected signal off the responsivity peak. Note that each curve has two slopes representing the influence from the rejected wavelength (right slope) and from the reduced selected-channel responsivity (left slope).

We analyze the total system capacity of the proposed WDM configuration [Fig. 1(b)] as compared with the plane-to-plane and via (Fig. 1a) systems. The two basic scenarios include (a) **one** plane transmits and the rest either receive or relay information, denoted as 1T → MR, and (b) **all** intermediate planes can transmit their own data as well as receive, denoted as MT → MR; note that MT → MR would require each pixel to contain both a laser **and** a detector. Furthermore, we will examine three variations of the WDM pixel for both 1T → MR and

MT → MR categories: i) **individual mode**—the $(M-1)$ lasers can only be turned **reconfigurably** "ON" one at a time from the same driver, ii) **broadcast mode**—the $(M-1)$ lasers can all be turned "ON" **simultaneously** with the same data from a single driver, and iii) independent mode —the $(M-1)$ lasers can be turned "ON" **simultaneously** and **independently**, transmitting different data streams to different planes and requiring $(M-1)$ laser-driver electronics:

$(IT \rightarrow MR)$ & $(MT \rightarrow MR)$

A) Plane-to-Plane
B) Via Windows
C) WDM Pixels—i) Individual Mode—one laser "ON" singularly
—ii) Broadcast Mode—all lasers "ON" simultaneously with same data
—iii) Independent Mode—all lasers "ON" simultaneously with independent data

Our algorithm for deducing the maximum total system capacity in M planes (C_M) involves finding the total number of allowable channels transmitting new (**not relayed**) information for a given configuration. Furthermore, the broadcasting from m lasers in a pixel to m different planes establishes m different channels, assuming non-interfering channels. If all planes can receive information as well as transmit their own information (MT → MR), then we assume that each laser and receiver has a bit-rate of r. We allow the first plane to transmit with equal probability to any available subsequent planes. The next plane can then utilize with equal probability the remaining idle detectors on its subsequent planes to transmit its own information and communicate with a detector that does not already have an established channel. A laser can transmit to only one detector, and a detector can receive data from only one laser. Fig. 3 depicts the two individual-mode WDM scenarios [(1T → MR), (MT → MR)] and the probability for each channel being established.

1T → MR: For only the first plane transmitting, C_M for the plane-to-plane, via, and individual-mode WDM cases is (rN^2); plane-to-plane and via systems have identical capacities since the act of relaying information with a detector/laser pair or with a via does not add new data. We emphasize that in the WDM individual mode, the system is dynamically reconfigurable even though the capacity is not enhanced. For the broadcast and independent WDM modes in which all the lasers can be "ON" simultaneously, $C_M = ((M-1)rN^2)$ and increases by the number of lasers in each pixel. Thus, the capacity for these last two cases represents a significant advance by allowing all planes to simultaneously communicate with all planes.

MT → MR: For all intermediate planes transmitting, the capacity is analyzed by using combinatorics and probabilities for all the **allowable** channels. For the plane-to-plane and via cases, C_M is determined by the average

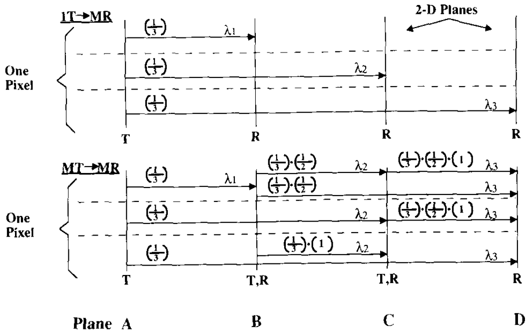

Fig. 3. All possible channels for each pixel in a 4-plane WDM system for (1T → MR) and (MT → MR), given only one pixel is "ON" per pixel. Each channel (arrow) is designated with a probability of occurrence and on which wavelength it is established. T and R denote the ability for a plane to transmit and receive, respectively.

number of allowable channels, and is given by

$$C_M = rDN^2/(M-1),\ D = 1 + \sum_{j=0}^{(M-3)} \cdot \left\{ 2 + (1/2^j)\left(\sum_{i=0}^{j} i(j!/(i!(j-i)!)) \right) \right\} \quad (1)$$

where D represents the average number of channels established given that plane j communicates with plane $M-(j+1)$. For example, if $M = 3$, then plane A can either communicate with plane B or plane C. If plane A communciates with plane B, then plane B can also communicate with plane C, thus establishing 2 links. If plane A communicates with plane C, then plane B lies dormant and only 1 link is established. On average, 1.5 links exist. At the other extreme, the WDM cases in which all the lasers can be "ON" simultaneously have $C_M = (M-1)rN^2$, which is their same ultimate capacity as in the (1T → MR) category.

The most interesting case is the WDM system with only a singular laser "ON" for (MT → MR), providing a significant capacity enhancement (see Fig. 4). As opposed to using vias, the WDM pixel can establish an **additional communications channel** between itself (B) and another plane (C) even if it is **concurrently** relaying data between another two planes (A, D) by being transparent to that other signal. For this case, C_M has been solved both by computer simulation, which counts the possible established channels, and by combinatoric analysis. The analytical solution involves a "cost function" which describes the capacity lost due to certain inter-plane connections, as illustrated by considering a 3 plane system. If plane A communicates with plane B and B with C, then 2 channels have been established. However, if plane A wishes to communicate with C, then B will not receive any data. Therefore, connecting A-to-C has a 50% probability of occurring but "costs" (reduces) some capacity. Furthermore, recursive relations also exist since an M-plane

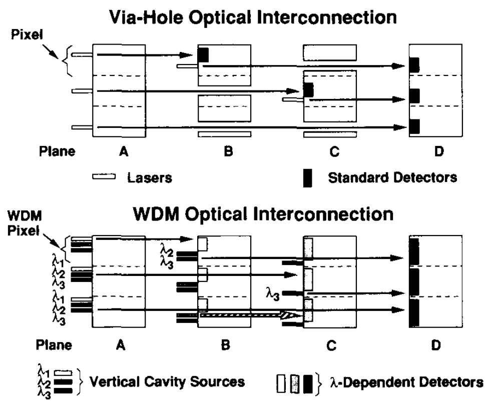

Fig. 4. Cross-sectional view of possible channels in a 4-plane system in which all intermediate planes have the ability to transmit (MT → MR), and given only one laser is "ON" per pixel. (a) Via-hole configuration and (b) individual-mode WDM pixels. The additional established WDM channel is highlighted.

system can be described by first considering the solutions to a combination of smaller $(M-1)$ or $(M-2)$ units. Consequently, the upper $(C_{U,M})$ and lower $(C_{L,M})$ total-capacity bounds are

$$C_{U,M} = ((C_{U,M-1}+1)/(M-1)) + ((M-2)/(M-1)B_{M-1}),$$
$$B_M = ((B_{M-1}+C_{U,M-2})/2)+1 \quad (2)$$
$$C_{L,M} = (C_{L,M-1}/(M-1)) + ((M-3)/(M-1))C_{L,M-2} + Q_{M-2}/(M-1)+1,$$
$$Q_M = (Q_{M-1}/(M-1)) + ((M-2)/(M-1))C_{L,M-1}+1 \quad (3)$$

in which $C_{U,2} = C_{L,2} = 1$, $C_{U,3} = C_{L,3} = 1.5$, $B_2 = Q_2 = 1$, and $B_3 = Q_3 = 2$. C_U and C_L must be multiplied by rN^2 for normalization. The computer simulation falls a mere 5% above and below the lower and upper bounds, respectively, for an 11-plane system. C_M is plotted in Fig. 5 for all the above cases except for 2 and 3. For 10 planes, WDM even with only one laser individually "ON" per pixel essentially **doubles** the capacity of the via-hole solution while providing reconfigurability.

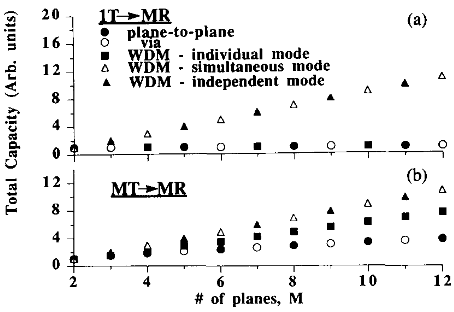

Fig. 5. Total system capacity versus number of optical planes for (a) only the first plane transmitting (1T → MR), and (b) all planes with the ability to transmit (MT → MR).

In summary, we have proposed and analyzed a novel optical interconnect configuration in which one 2-D plane can communicate simultaneously and reconfigurably with many planes by using WDM. Multiple-wavelength laser arrays and wavelength-selective detectors are used to provide high contrast ratio, increased system capacity, and efficient real-estate usage.

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