A Three-Dimensional (3-D) Substrate-Guided-Wave to Free-Space Multistage Optoelectronic Interconnection Using Wavelength Division Multiplexing and Space Division Demultiplexing

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***Abstract*—An integrated 3-D guided-free-space four-stage optoelectronic fan-out (6 × 6, 2 × 6, 6 × 6, and 2 × 6) interconnect using wavelength division multiplexing (WDM) is proposed and then demonstrated together with 40 (2 × 4 × 5) 3-D optoelectronic fan-outs using space division demultiplexing (SDDM). This channel separation is one order of magnitude smaller than that using wavelength-selective detecting techniques in WDM. A signal to noise ratio of 57 dB is experimentally determined, with two channel 40 (2 × 4 × 5) fan-outs having a channel separation of 600 μm in SDDM. The interconnection scheme presented herein allows each pixel in a transmitting plane to communicate simultaneously and reconfigurably with many pixels in the subsequent planes in a truly 3-D feature. This system can utilize vertical cavity surface emitting laser diodes, photo detecting planes, and planar compact guided-free-space fan-out interconnects, allowing compact multistage integration. By using 2-D spatially separated or multiplexed hologram arrays on a thin light guiding plate, the interconnection capability is greatly enhanced as compared to other techniques. This novel optoelectronic interconnect technology may have widespread applications in microelectronic systems and fiber-optic communication networks.**

I. INTRODUCTION

THE ABILITY to efficiently connect many high-speed ports or "smart" pixels is of critical importance for large-capacity communications. A high bandwidth, free-space optical interconnect can be used to achieve such an interconnection and to avoid the bottlenecks associated with electrical interconnects [1]–[3]. Some promising solutions have been investigated recently through employing 2-D vertical-cavity surface-emitting laser (VCSEL) arrays and microlens arrays [4]–[8]. These are all feasible approaches in which all of the "microbeams" propagate at the same angle, so that the difficulties associated with the multiple individual alignments in three spatial and three angular coordinates with very narrow tolerance are no longer present. However, existing solutions do not resolve the interconnection scenario where one pixel in one plane is required to communicate simultaneously and reconfigurably with many pixels in the subsequent planes. One of the previous solutions involves etching holes in each substrate plane, establishing a fixed configuration between any two planes [4]. Very recently, a novel solution [5], based on wavelength division (de)multiplexing [WD(D)M], is proposed to incorporate several multiple wavelength VCSEL's into each transmitting pixel and wavelength selectivity into each subsequent detecting plane. Because each subsequent detecting plane is designed to absorb only one wavelength and is transparent to all others, a 2-D transmitting plane can thus communicate simultaneously and reconfigurably with many subsequent detecting planes.

In this paper, we report the demonstration of a new solution that employs guided-free-space optical parallel fan-out interconnects. It provides the advantages of such exclusive characteristics of optical interconnects as high packing density, massive single-wavelength fan-outs, and wavelength multiplexibility [6], [7]. Unlike the previously reported research [4], [5], [8], the interconnection scheme presented herein (see Fig. 1) allows each pixel in a transmitting plane to communicate simultaneously and reconfigurably with many pixels in the subsequent planes with a truly 3-D feature. Moreover, WD(D)M configuration can be maintained while extending into space-division-demultiplexing (SDDM) based on the fact that each VCSEL is spatially separated in the transmitting plane. As a result, each channel does not need to have many laser diodes operating at different wavelengths in order to facilitate the spontaneous communications with many pixels in the detecting planes [5]. This new approach significantly reduces the fabrication requirements imposed on the laser diodes (with multiple output wavelengths) and on the photodetectors (with wavelength selectivity). A one-to-one 2-D interconnect scheme is extended into a one-to-many 3-D one.

The schematic of the new optical interconnect, illustrating the basic concepts of the 3-D multistage multichannel fan-out operation, is shown in Fig. 1. It consists of a transmitting plate, two receiving plates, and two light-guiding plates. The transmitting plate is composed of VCSEL's and their electronic driving circuits, emitting light beams at different wavelengths. It should be noted that the uniform VCSEL's, emitting light beams at a single wavelength, may also be employed as the case of a non-WDM multichannel optical

Manuscript received February 10, 1995; revised October 5, 1995. This work was supported by ARPA, AFOSR, BMDO, and Cray Research.

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Publisher Item Identifier S 0733-8724(96)02161-5.

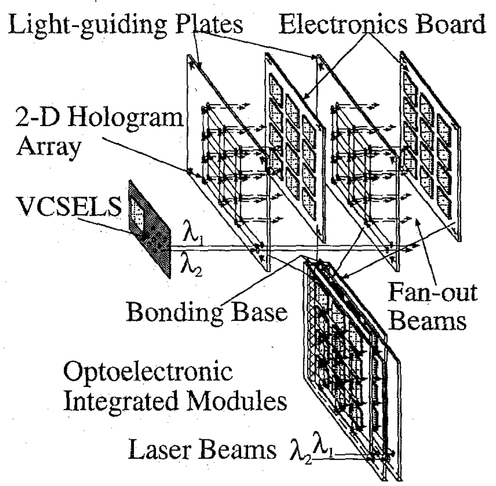

Fig. 1. A schematic diagram of the 3-D multistage multichannel optoelectronic fan-out interconnect.

interconnect system. Each detecting plate consists of a 2-D array of regular p–i–n detecting pixels. The light-guiding plates, shown in Fig. 1, are made out of thin light transparent plates in conjunction with 2-D arrays of multiplexed waveguide holograms fabricated on its surface. The laser beams from the transmitting plate can propagate through all light-guiding plates due to the transparent characteristic of the plates at the wavelengths of interest. An input holographic coupler is designed and fabricated on the surface of each light-guiding plate (see Fig. 1). A sizable portion of the laser beam can be coupled into the plate and then get guided within the plate due to total internal reflection (TIR) effects. Two-dimensional surface hologram arrays are further fabricated on the surface of the thin light-guiding plate to convert the input substrate guided waves into a linear array of parallel substrate waves and then to generate a 2-D array of surface normal beams. The optical signal carried by each fan-out beam is detected by the corresponding photodetector at the receiving plates.

Utilization of transparent plates as beam-guiding and fan-out devices provides the freedom of an additional interconnection dimension while maintaining the device packaging compactness. Formations of the surface normal fan-out beams and of the planarized compact device structure convert the difficult three spatial and three angular multiple alignment problems into a single step 2-D manageable one. Optical fan-out beams with different wavelengths can be distributed to all the pixels affiliated with the corresponding detecting planes. Any permutation of the fan-out beams can be arranged without blocking the substrate guided-wave propagation inside the light-guiding plates, and the presence of each fan-out beam for each channel (determined by the presence of the fan-out hologram), can be independently designed [7].

To demonstrate the proposed idea in our experiments, we use the He–Ne (632.8 nm) and Argon laser (514.5 nm) beams as the input signals instead of the VCSEL's. The 2-D waveguide hologram arrays are employed [6], [7], [9], [10], which are made out of a thin dichromate gelatin (DCG) film, having a measured thickness of ~30 μm. The DCG has a refractive index of ~1.5 which is equivalent to that of the thin glass (BK-7) substrate. Thus, the substrate guided beams interact with the holograms on the glass surface without facing an index change. There are many degrees of freedom to rearrange and then to select different kinds of holograms in the 2-D hologram arrays [6], [7], [9], [10]. The output power of a fan-out beam can be precisely calculated and experimentally controlled. Different methods to design and to construct the holograms discussed above have been given in our previous publications [11], [12].

Fig. 2(a) is an experimental demonstration of a two channel ($\lambda_1 = 0.6328$ μm and $\lambda_2 = 0.5145$ μm) four-stage optical multiplexing fan-out interconnect system using WDDM. In this demonstrated system, the optical signal carrying wavelength of $\lambda_1 = 0.6328$ μm is coupled into the first and the third stages, while the optical signal carrying wavelength of $\lambda_2 = 0.5145$ μm is coupled into the second and the fourth stages. 3-D 1- to 36-surface normal fan-out devices [6] are employed at the first and the third stage. And 3-D 1- to 12-surface normal fan-out devices are employed at the second and the fourth stages. The far field beam profiles of the two surface normal fan-out devices are shown in Fig. 2(b) and (c), respectively.

The analysis and the fabrication details of the 3-D 1- to 12-surface normal fan-out devices are about the same as those of the 3-D 1 to 36 surface normal fan-out devices. The only difference is the reconstruction wavelengths. For the 3-D 1- to 36-surface normal fan-out interconnect [Fig. 2(b)], each surface normal fan-out beam experiences three holograms, h_0, h_{mn}, and h_n, with diffraction efficiencies of $\eta_o = 70\%$, $\eta_{mn} = 10\%$, and $\eta_n = 19\%$, respectively. The hologram h_o is the input coupler designed to couple the surface normal input laser beam into a substrate guided beam with bouncing angle $\theta_m = 45°$. h_{mn} is designed to deflect the substrate-guided beam into a linear array of beams with bouncing angle $\theta_n = 45°$. h_n is designed to couple the linear array of substrate-guiding beams into a 2-D array of surface normal fan-out beams. The fan-out efficiency for each fan-out beam is given by [6]

$$\eta_{(m,1)} = \eta_o \eta_{mn1}(1 - \eta_{mn1} - \eta_{mn2})^{m-1} \qquad m = 1, 2, 3, \cdots \tag{1}$$

$$\eta_{(m,n)} = \eta_o \eta_n (1 - \eta_{mn1} - \eta_{mn2})^{m} (1 - \eta_n)^{n-1} \qquad n = 2, 3, 4, \cdots. \tag{2}$$

To construct the multi-stage optical interconnect system shown in Fig. 1, flip-chip bonding technology can be employed [13]. One of the most important concerns utilizing this technology is the optical/mechanical angular alignment tolerance. The angular misalignment tolerance of the device presented herein must be within the limits that the existing technology can provide. To determine the angular misalignment tolerance of the light-guiding plate, coupled-mode theory [14] can be applied with

$$\eta = \frac{\sin^2 (\nu^2 + \xi^2)^{1/2}}{(1 + \xi^2/\nu^2)} \tag{3}$$

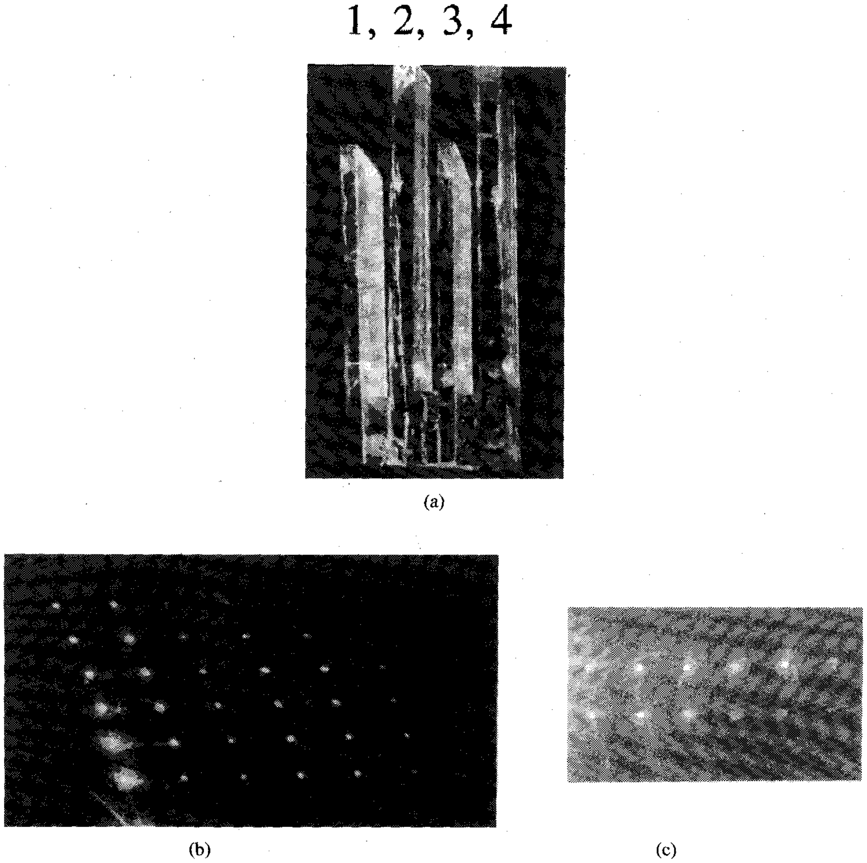

Fig. 2. (a) Photograph of a two-wavelength four-stage optical fan-out interconnect system using WDDM. (b) Photograph of the far field beam profiles of the first and the third stage 1- to 36-surface normal fan-out interconnect ($\lambda = 0.6328$ μm). (c) Photograph of the far field beam profiles of the second and the fourth stage 1- to 12-surface-normal fan-out interconnect ($\lambda = 0.5145$ μm).

where

$$\nu = \frac{\pi n_1 d}{\lambda(\cos^2\theta - K\cos\theta\cos\phi/\beta)^{1/2}} \tag{4}$$

and

$$\xi = \frac{\Delta\theta K d\sin(\phi - \theta)}{2(\cos\theta - K\cos\phi/\beta)} = -\frac{\Delta\lambda\, dK^2}{8\pi n(\cos\theta - \mathrm{K}\cos\phi/\beta)}. \tag{5}$$

In (3)–(5), θ is the incident angle, ϕ is the grating slant angle, d is the thickness of grating, K is the grating wave number, n and n_1 are the refractive index and the index modulation of the grating medium, respectively, and $\Delta\theta$ and $\Delta\lambda$ represent the angular and wavelength deviations.

Based on (1)–(5), the tolerance of device angular misalignment can be determined for any pixel of the multistage interconnects network. Both theoretical and experimental results of the diffraction efficiency are plotted in Fig. 3 where the normalized intensity of a fan-out beam (5, 5) (the 5th row and 5th column fanout) of Fig. 2(b) versus input angular misalignment is provided. The full-width at half-maximum (FWHM) of the diffraction efficiency curve is larger than ±0.5°. Such a large angular alignment tolerance is well within the limit that flip-chip bonding technology can provide (~0.01°) [13]. In our experiment, angular alignment is controlled within 0.1° and there is less than 5% intensity fluctuation.

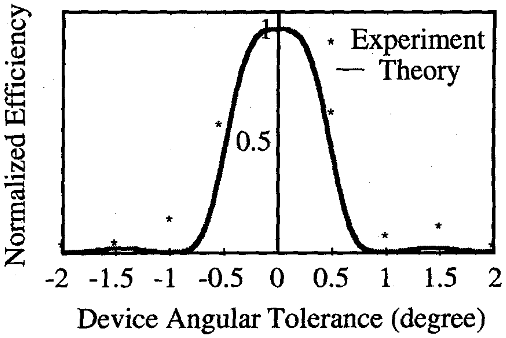

Fig. 3. Theoretical and experimental results of the fan-out efficiency versus angular misalignment of input beam, where incident angle $\theta_o = 0^\circ$, diffraction angle $\phi_o - 45^\circ$, $\eta_o = 70\%$, $\eta_{mn} = 10\%$, $\eta_n = 19\%$, and measured hologram thickness $d = 30$ μm.

As one of the exclusive characteristics of optical interconnect, WD(D)M can be employed to increase the information bandwidth of this multistage optical interconnect, involving

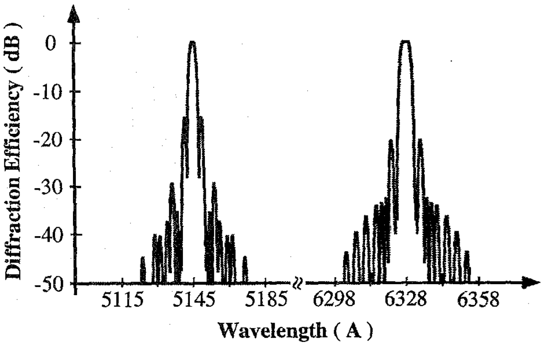

Fig. 4. Theoretical plot of fan-out efficiency versus wavelength deviations with the grating parameters of $\eta_o = 70\%$, $\eta_{mn} = 10\%$ and $\eta_n = 19\%$ of the fan-out interconnect shown in Fig. 2(b).

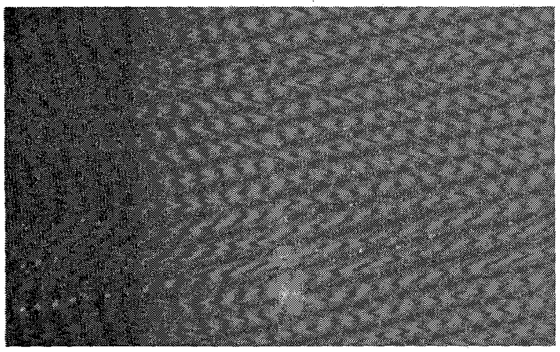

Fig. 5. Photograph of a compact optical interconnect with two channel 40 $(2 \times 4 \times 5)$ fan-out using SDDM.

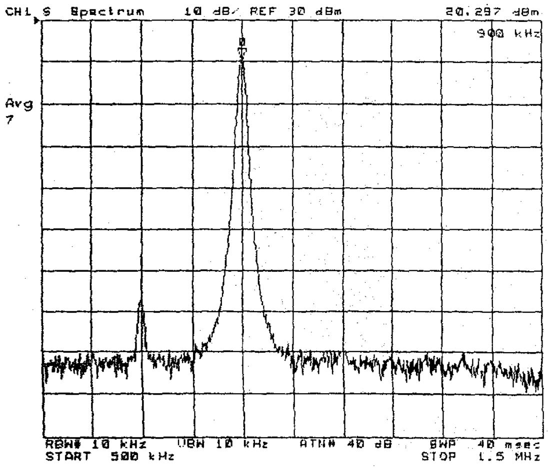

Fig. 6. The measured RF spectrum from the fan-out beam (4, 5) shown in Fig. 2(b).

massive surface-normal fanout beams. Using a DCG recording medium with a high index modulation of 0.2, we can spatially multiplex a large number of holograms designed for different wavelengths [11], [12]. In WD(D)M operations, the transmitting plane shown in Fig. 1 can be replaced by an input fiber array, where each fiber carries many wavelength channels.

The device wavelength selectivity, produced by the 2-D hologram array on the surface of the light-guiding plate, is an important design parameter. Fig. 4 plots the normalized fan-out efficiency versus wavelength deviations based on (1)–(5), using experimental parameters ($\eta_o = 70\%$, $\eta_{mn} = 10\%$, and $\eta_n = 19\%$) of the fan-out interconnect of Fig. 2(b). It shows that a minimum of 3 nm wavelength separation is needed to keep channel crosstalk under 30 dB in WD(D)M operation. This channel separation is one order of magnitude smaller than that obtained by wavelength-selective detecting technique [5].

For a VCSEL array, each laser diode is spatially separated. To take advantage of this fact, space-division-demultiplexing (SDDM) can be applied, where each laser diode is linked with its own 2-D waveguide hologram arrays on the light-guiding plates. Each 3-D massive fanout interconnection needs only one VCSEL and is separated from the other 3-D interconnects in space. With this novel approach, there is no need to operate each pixel with a different wavelength. Furthermore, there is also no need to have many laser diodes (operating at different wavelengths) in each pixel to facilitate the multiple inter-plane parallel communications with many pixels at different detecting planes. This approach significantly reduces the requirements imposed on the VCSEL array and photodetector array as compared to the previous research [5].

To demonstrate the SDDM, 2-D waveguide hologram arrays $(2 \times 4 \times 5)$ are fabricated on a glass substrate of thickness 1000 μm. They are designed for a Toshiba visible laser diode ($\lambda = 0.67$ μm). The designed spatial separation of the SDDM signal affiliated with each pixel is 600 μm. Fig. 5 is a photograph of the device, clearly showing two SDDM signals with 40 $(2 \times 4 \times 5)$ optical fan-outs. Two collimated Toshiba visible laser diodes are employed as two input lasers. In order to determine the crosstalk between the two channels, the two laser diodes with equal output power, are modulated at two different frequencies of 0.7 and 0.9 MHz, respectively. The crosstalk level at the position of (4, 5) of Fig. 2(b) is measured by Newport Optical Power Meter (Model 818J25) through a 15 μm diameter aperture carefully aligned to the center of one laser beam. Fig. 6 shows the measured RF spectrum, where the crosstalk level is determined to be -57 dB.

In conclusion, an integrated 3-D guided-free-space four-stage optoelectronic fan-out $(6 \times 6, 2 \times 6, 6 \times 6$, and $2 \times 6)$ interconnect using WD(D)M is proposed and demonstrated together with $2 \times 4 \times 5$ 3-D optoelectronic fan-out using SDDM. This channel separation is one order of magnitude smaller than that using the wavelength-selective detecting technique in WDDM. The signal to noise ratio of 57 dB is further experimentally determined, with two channel 40 $(2 \times 4 \times 5)$ fan-outs having a channel separation of 600 μm in SDDM. The interconnects presented herein allow each pixel in a transmitting plane to communicate simultaneously and reconfigurably with many pixels in the subsequent planes in a truly three-dimensional feature. More importantly, the 2-D arrays of the surface gratings on the thin light-guiding plate can be made out of surface-relief gratings, fabricated directly on the surface of any light transparent plates using standard VLSI fabrication technologies (binary optical technologies [15], [16]).

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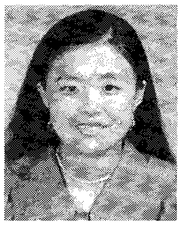

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