

Three-Dimensional Guided-free-space Multi-stage Optoelectronic Fan-out Interconnection Using Wavelength Division Multiplexing and Space Division Multiplexing

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Abstract

An integrated 3-D guided-free-space 4-stage optoelectronic fan-out (6x6, 2x6, 6x6 and 2x 6) interconnect using WDDM is proposed and demonstrated together with 2x4x5 3-D optoelectronic fan-out using SDDM. This channel separation is one order of magnitude smaller than that using wavelength-selective detecting technique in WDDM. Signal to noise ratio of 57 dB is experimentally determined, with two channel 40 (2x4x5) fan-outs having a channel separation of 600 μm in SDDM. The interconnection scheme presented herein allows each pixel within a transmitting plane to communicate simultaneously and reconfigurably with many pixels in the subsequent planes in a truly three-dimensional feature. This system can utilize vertical cavity surface emitting laser diodes, photo detecting planes and planarized guided-free-space fan-out interconnects, allowing compact multi-stage integration. By using two-dimensional 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 should find widespread applications in microelectronics systems and fiber-optic communication networks.

The ability to efficiently connect many high-speed ports or "smart" pixels is of critical importance for large-capacity communications. 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 two-dimensional (2-D) vertical-cavity surface-emitting laser (VCSEL) array and microlens array[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 an 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], was proposed to incorporate several multiple-wavelength VCSELs 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 with many subsequent detecting planes. Reconfiguration of plane-to-plane interconnects is realized by wavelength tuning which selects the appropriate phase-matching condition.

In this paper, we report the demonstration of a new solution that employs guided-free-space optical parallel fan-out interconnects. It takes the advantages of such exclusive characteristics of optical interconnects as high packing density, massive single-wavelength fan-out and wavelength multiplexibility[6,7]. Unlike the previously reported researches[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 three-dimensional (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.

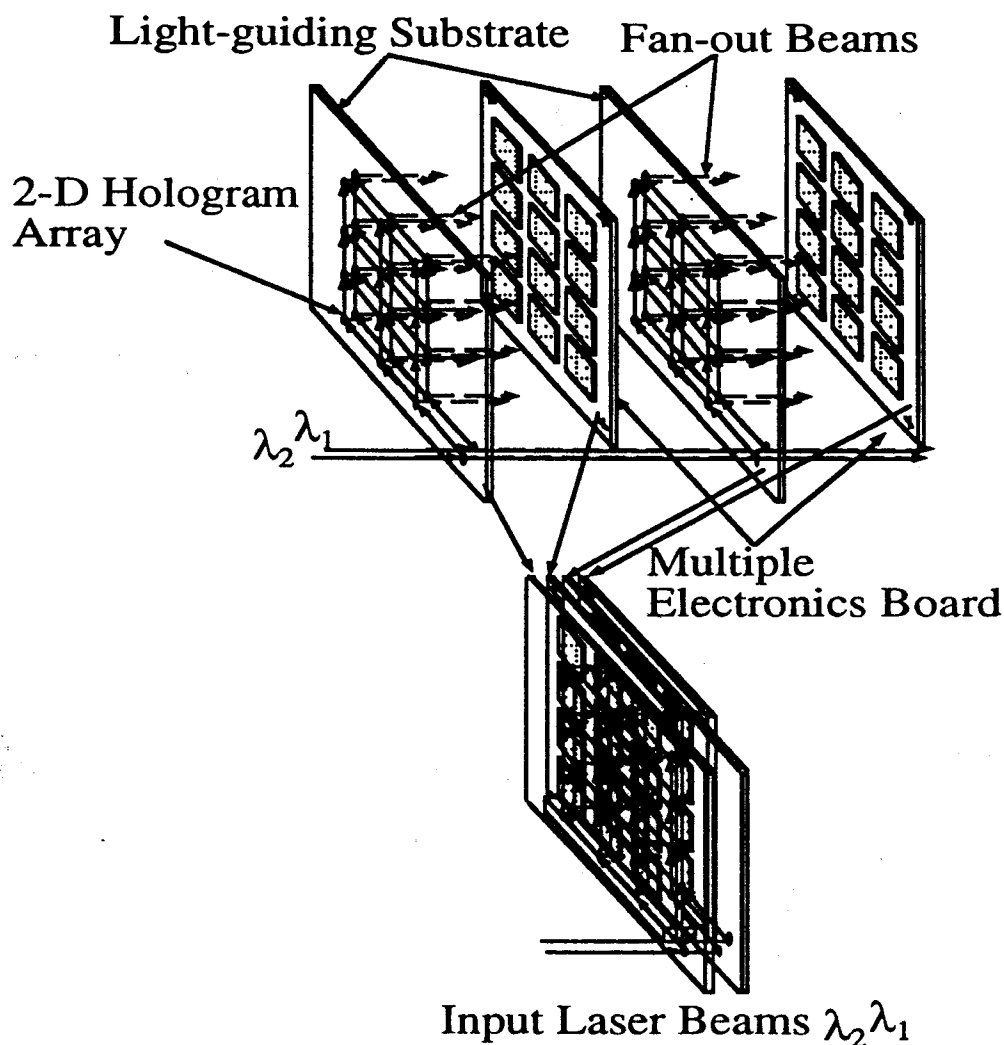


Figure 1. A schematic diagram of the 3-D multi-stage multi-channel optoelectronic fan-out interconnect.

The schematic of the new optical interconnect, illustrating the basic concept of the 3-D multi-stage multi-channel 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 VCSELs and their electronic driving circuits, emitting light beams with either different wavelengths or same wavelength. 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 plate 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) effect. 2-D surface hologram arrays are further fabricated on the surface of the thin light-guiding plate to fan-out the input substrate guided waves into a linear array of parallel substrate waves and then fan out 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 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].

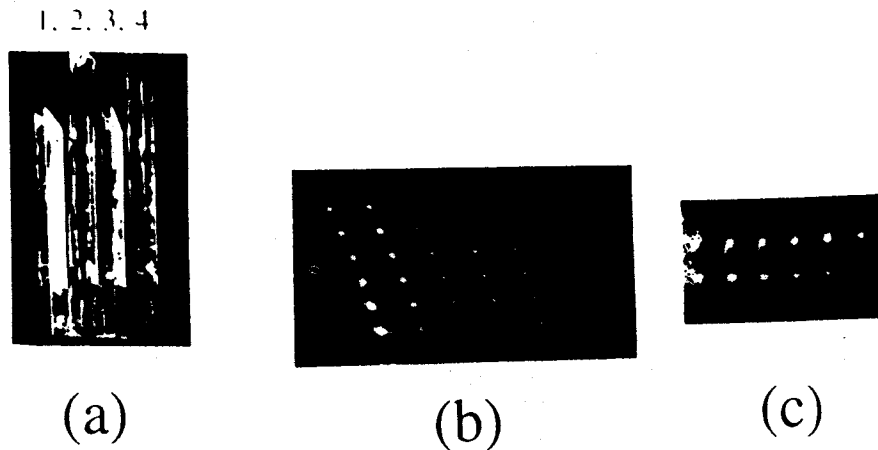
To demonstrate the proposed idea, in our experiments we use a He-Ne (632.8nm) and an Argon laser (514.5nm) as the input beams instead of the VCSELs. The 2-D waveguide hologram arrays are employed[6,7,9,10], which are made out of a thin dichromated gelatin (DCG) film, having a measured thickness of ~30 μm . The DCG has a refractive index of ~1.5 which is equivalent to that of the thin glass (BK-7) substrate, thereby 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 two channel ($\lambda_1=0.6328 \mu\text{m}$ and $\lambda_2= 0.5145 \mu\text{m}$) four-stage optical multiplexing fan-out interconnect system using WDDM. In this demonstrated system, the optical signal carrying wavelength of $\lambda_1=0.6328 \mu\text{m}$ is coupled into the 1st and 3rd stages, while the optical signal carrying wavelength of $\lambda_2 = 0.5145 \mu\text{m}$ is coupled into the 2nd and the 4th stages. 3-D 1-to-36 surface normal fan-out devices[6] are employed at the 1st and the 3rd stage, and 3-D 1-to-12 surface normal fan-out devices are employed at the 2nd and the 4th stages. The far field beam profiles of the two surface normal fan-out devices are shown in Figs.2(b) and 2(c) respectively. It is clear from Fig.2 that reconfiguration of interconnects can be realized by either independently turning on/off any lasers or tuning the operating wavelengths which provide the required optical signals to the selected modules as indicated in Fig.1.

The fabrication details of the 3-D 1-to-12 surface normal fan-out devices is similar to that 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 $\eta_0 = 70\%$, $\eta_{mn} = 10\%$ and $\eta_n = 19\%$, respectively. The hologram h_0 is the input coupler designed to couple the surface normal input laser beam into a substrate guided beam with bouncing angle $\theta_m = 45^\circ$. h_{mn} is designed to deflect the substrate-guided beam into a linear array of beams with bouncing angle $\theta_n = 45^\circ$. h_n is designed to couple the arrays of substrate-guided beams into 2-D surface normal fan-out beams. The fan-out efficiency for each fan-out beam is given by[6]

$$\eta_{(m, 1)} = \eta_0 \eta_{mn1} (1 - \eta_{mn1} - \eta_{mn2})^{m-1} \quad \left\{ \begin{array}{l} m = 1, 2, 3, \dots \\ n = 2, 3, 4, \dots \end{array} \right. \quad (1)$$

$$\eta_{(m, n)} = \eta_0 \eta_n (1 - \eta_{mn1} - \eta_{mn2})^m (1 - \eta_n)^{n-1} \quad (2)$$



Figures 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 ($\lambda=0.6328 \mu\text{m}$). (c) Photograph of the far field beam profiles of the second and the fourth stage 1-to-12 surface-normal fan-out interconnect ($\lambda=0.5145 \mu\text{m}$).

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] is employed to determine the diffraction efficiency which is given by

$$\eta = \frac{\sin^2 (v^2 + \xi^2)^{1/2}}{(1 + \xi^2/v^2)}, \text{ where} \quad (3)$$

$$v = \frac{\pi n_1 d}{\lambda(\cos^2\theta - K\cos\theta\cos\phi/\beta)^{1/2}}, \text{ and} \quad (4)$$

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

In Eqs. (3), (4) and (5), θ is the incident angle, ϕ is the grating slant angle, d is the thickness of grating, K is the grating wave number, and n and n_1 are the refractive index and the index modulation of the grating medium, respectively. $\Delta\theta$ and $\Delta\lambda$ represent the angular and wavelength deviations.

Based on Eqs. (1)-(5), the tolerance of device angular misalignment can be determined for any pixel of the multi-stage interconnect 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 (inout) 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 $\pm 0.5^\circ$. Such a large angular alignment tolerance

is well within the limit that flip-chip bonding technology can provide ($\sim 0.01^\circ$)[13]. In our experiment, angular alignment is well controlled within 0.1° and there is less than 5% intensity fluctuation.

As one of the exclusive characteristics of optical interconnect, WD(D)M can be employed to increase the information bandwidth of this multi-stage optical interconnect, involving massive surface-normal fanout beams. Using DCG recording medium with high index modulation to 0.2, we can spatially multiplex a large number of holograms operating at different wavelengths[11,12]. In WD(D)M operation, the transmitting plane shown in Fig.1 can be replaced by an input fiber array, where each fiber carries many wavelength channels.

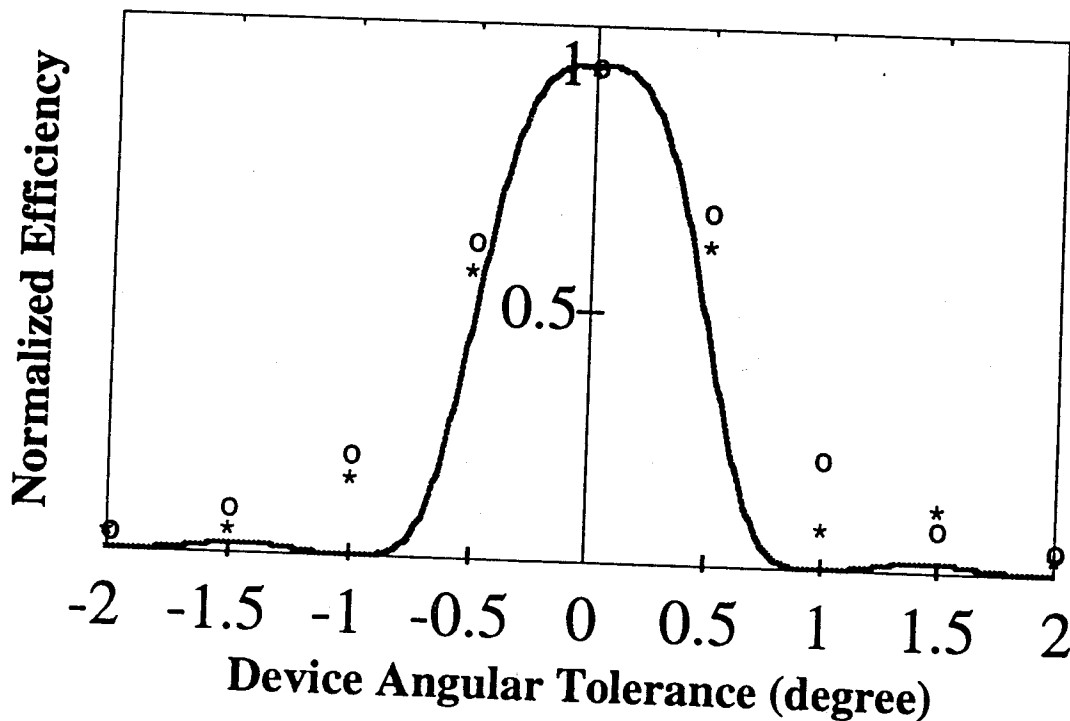


Figure 3. Theoretical and Experimental results of the fan-out efficiency versus angular misalignment of input beam. Where with incident angle $\theta_0 = 0^\circ$, diffraction angle $\phi_0 = 45^\circ$, $\eta_0 = 70\%$, $\eta_{mn} = 10\%$ and $\eta_n = 19\%$ and measured hologram thickness $d = 30 \mu\text{m}$.

The device wavelength-selectivity, produced by the 2-D hologram array on the surface of light-guiding plate, is an important design parameter. Fig. 4 plots the normalized fan-out efficiency versus wavelength deviations based on Eqs.(1)-(5), using experimental parameters ($\eta_0 = 70\%$, $\eta_{mn} = 10\%$ and $\eta_n = 19\%$) of the fan-out interconnect of Fig.2(b). It shows that a minimum of 3 nm wavelength separation may be 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].

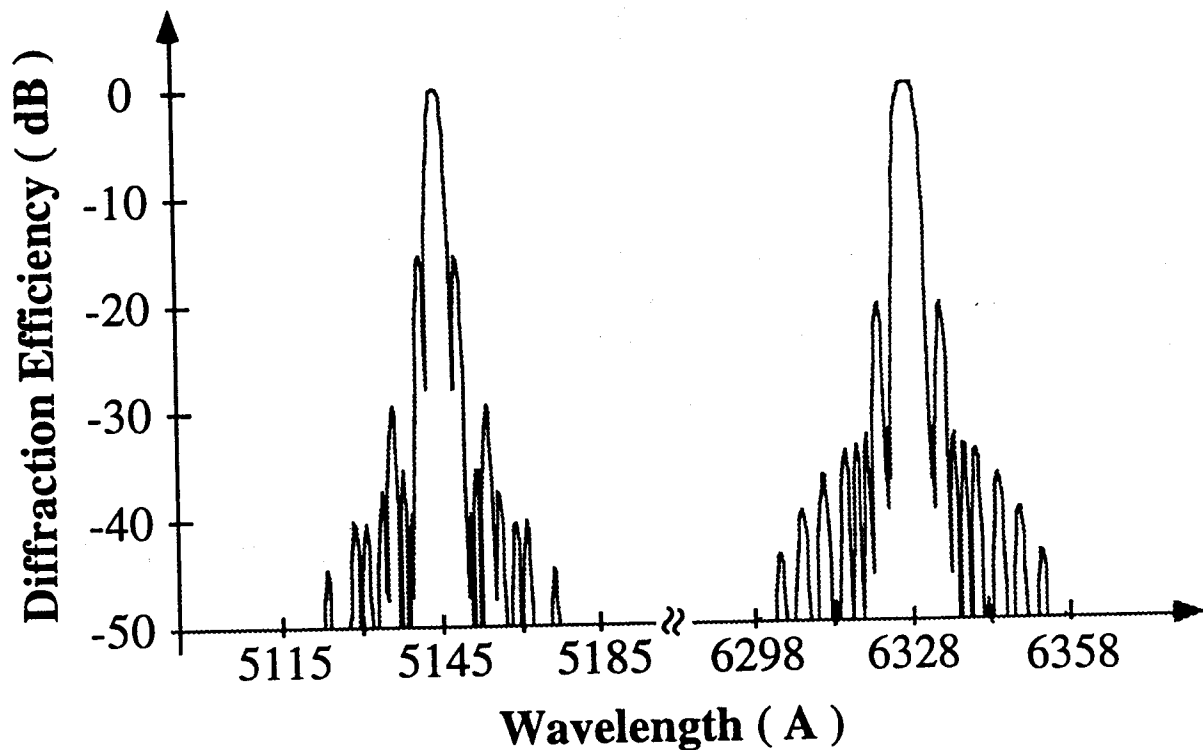


Figure 4. Theoretical plot of fan-out efficiency versus wavelength deviations with the grating parameters of $\eta_0 = 70\%$, $\eta_{mn} = 10\%$ and $\eta_n = 19\%$ of the fan-out interconnect shown in Fig.2(b).

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 array 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. Further more, 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 (2x4x5) are fabricated on a glass substrate 1000 μm thick. They are designed for Toshiba visible laser diode ($\lambda=0.67 \mu\text{m}$). The designed spatial separation of the SDDM signal affiliated with each pixel was 600 μm . Fig. 5 is a photograph of the device, clearly showing two SDDM signals with 40 (2x4 x 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 were modulated at two different frequencies of 0.7 MHz 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.

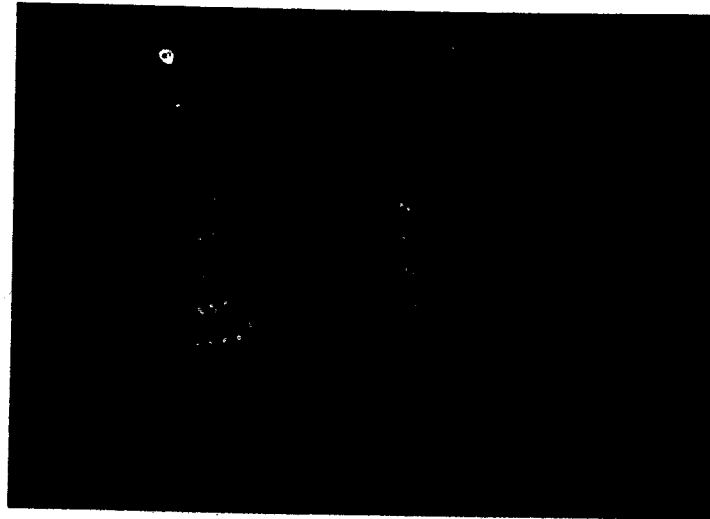


Figure 5. Photograph of a compact optical interconnect with two channel 40 (2x4x5) fan-out using SDDM.

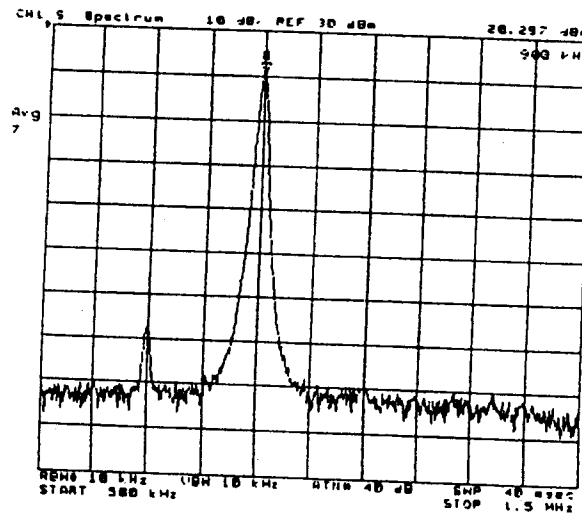


Figure 6. The measured RF spectrum from the fan-out beam (4, 5) shown in Fig.2(b).

In conclusion, an integrated 3-D guided-free-space 4-stage optoelectronic fan-out (6x6, 2x6, 6x6 and 2x6) interconnect using WD(D)M is proposed and demonstrated together with 2x4x5 3-D optoelectronic fan-out using SDDM. This channel separation is one order of magnitude smaller than that using wavelength-selective detecting technique in WDDM. Signal to noise ratio of 57 dB is further experimentally determined, with two channel 40 (2x4x5) fan-outs having a channel separation of 600 μm in SDDM. The interconnects presented herein allows 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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