1-to-27 Highly Parallel Three-Dimensional Intra- and Inter-Board Optical Interconnects

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***Abstract*— We present a novel interconnection scheme for highly parallel three-dimensional (3-D) optical intra- and inter-board fan-out using substrate guided waves in conjunction with a two-dimensional (2-D) multiplexed hologram array. 1-to-27 passive highly parallel optical fan-out was demonstrated for the first time. Optimum design rules are presented together with experimental results. The effort of employing substrate guided waves in conjunction with a 2-D multiplexed holograms array provides us the capability of 3-D multi-stage intra- and inter-board massively parallel interconnects. As the result, the coupling from a laser diode to multi-stage two dimensional detector arrays and/or fiber array can thus be realized.**

I. Introduction

The intrinsic limitations of the current generation of computers have led researchers to seriously consider new computing architecture based on optical interconnects. The basic limitations of electrical interconnects include interconnection time bandwidths, clock skew, resistance-capacitance (RC) time constants and even the distributed line resistance-inductance-capacitance (RLC) time constant (for chip-to-chip interconnects and higher level architecture). As the number of components per chip, number of chips per computer, modulation speed and the degree of integration continue to increase, the architecture of computers becomes more parallel, electrical interconnections will soon become inadequate on module-to-module and board-to-board level, especially on the fan-out capabilities due to the electrical parasitic capacitance and inductance coupling and electromagnetic wave interference [1]. High-speed performance, massively parallel fan-out capability with reasonable interconnection distance are required for future interconnects.

Optical interconnect has been widely agreed as a better choice for interconnecting different processors and memories whenever the conventional electrical interconnect can not fulfill the system requirements [2]–[5]. Among the optical interconnect architecture demonstrated thus far, optical interconnects based on two-dimensional waveguide array and free-space interconnections represent current technology trends [6]–[8]. Each of these optical interconnect technologies has its own appealing properties. Waveguide-based optical interconnects are suitable for in-plane bus-connections, while free-space interconnects are suitable for board-to-board interconnections.

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In this paper, we present a unique optical interconnect scheme for highly parallel massively optical fan-out. Unlike the previous work we presented [4], [9], both intra- and inter-board highly parallel massive fan-out can be realized, using a light guiding substrate in conjunction with a 2-D array of multiplexed holograms. Optimum design rules are developed together with experimental results. 1-to-27 surface normal optical fan-out is demonstrated for the first time.

The schematic of the optical interconnect presented is shown in Fig. 1. It consists of a glass substrate integrated with a 2D multiplexed hologram array, made out of dichromated gelatin (DCG) film. The glass substrate with thickness of t is employed as a light-guiding plate. The 2-D hologram array consists of holograms of h_m and multiplexed holograms of h_{mn}. The multiplexed holograms h_{mn}, having two gratings, is designed to couple the surface normal input laser beam into two substrate guiding beams with coupling efficiency η_m and η_n, and diffraction angle θ_m and θ_n, respectively. Both θ_m and θ_n (not shown in Fig. 1) are larger than the critical angle of total internal reflection (TIR) of the substrate. Holograms h_{mn} and h_m also function as the surface normal fan-out gratings. As the results, part of the surface normal fan-out beams on the upper row (acting as input beams) is coupled into substrate guiding beams in m direction (see Fig. 1), and normally coupled out by the holograms h_m at the middle row and the third row. Highly parallel massive fan-out beams are created inside the light-guiding plate together with surface normal massive fan-out beams, which is parallel to the input laser beam.

In designing massively parallel optical fan-out interconnect shown in Fig. 1, the fan-out packaging density is an important parameter of system performance. The fan-out packaging density is determined by the substrate thickness, hologram coupling angle θ_n and θ_m as well as the angle α between the two projection of holographic grating vectors on the surface of a glass substrate. We select $\alpha = 90°$ and set $\theta_n = \theta_m = \theta$ for symmetric purpose. Therefore, the separation between any two nearest fan-out beams is given by

$$s = (2t)\tan(\theta). \quad (1)$$

By selecting the glass thickness and/or coupling angles, the desired packaging density of fan-out beams can be obtained.

The optical throughput of each fan-out beam is another important design parameter, which is determined by the coupling efficiencies of the two holograms employed, and of course, the

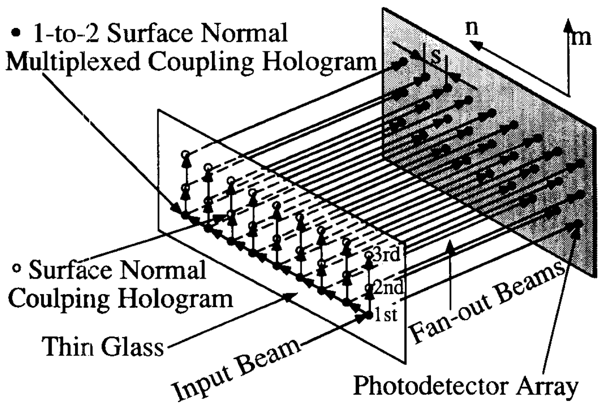

Fig. 1. Schematic of the surface normal highly parallel massive optical fan-out interconnect.

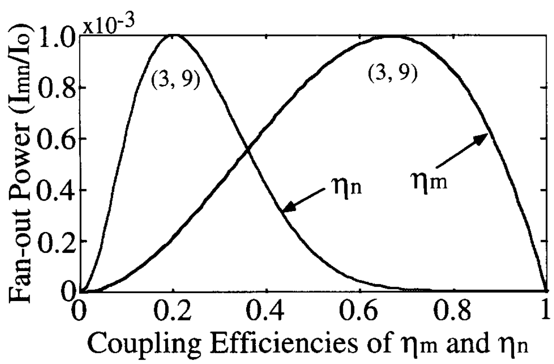

Fig. 2. Optical power for the weakest beam versus the coupling efficiencies of the holograms.

number of fan-out beams. The type of hologram employed here is reflection hologram with diffraction efficiency increasing as the index modulation and thickness of hologram increase [9, 10]. Thereby, the diffraction efficiency of hologram is easy to control experimentally [4, 9]. In our experiments, coupling efficiency is consistently adjustable to 70%.

The output power of a fan-out beam shown in Fig. 1 can be presented as

$$\begin{aligned} I_{11} &= I_0(1-\eta_m-\eta_n)\\ I_{m1} &= I_0(\eta_m)^2(1-\eta_m)^{m-2}\\ I_{1n} &= I_0(\eta_n)^2(1-\eta_m)(1-\eta_n)^{m-2} \qquad \begin{cases} m = 2\text{–}3\\ n = 2\text{–}9\end{cases} \qquad (2)\\ I_{mn} &= I_0[\eta_m\eta_n]^2(1-\eta_m)^{m-2}(1-\eta_n)^{n-2}\end{aligned}$$

where I_0 is the power of input beam, m and n stand for the sequence of columns and rows of the 2-D array of the parallel fan-out beams, respectively. As indicated by Eq. (1), a tradeoff exists between the fan-out power and the grating fan-out efficiencies. There are optimum values of η_m and η_n for a desired 2-D 1-to-many parallel fan-out with maximum throughput power for $I_{(3,9)}$. Through re-designing the grating vectors of holograms h_m and h_{mn}, and gradually increasing the coupling efficiency, i.e., increasing the hologram thickness and/or index modulation along with the fan-out beam sequences, equal fan-out intensity of the fan-out beams can be realized. A detailed description will be presented in a future publication.

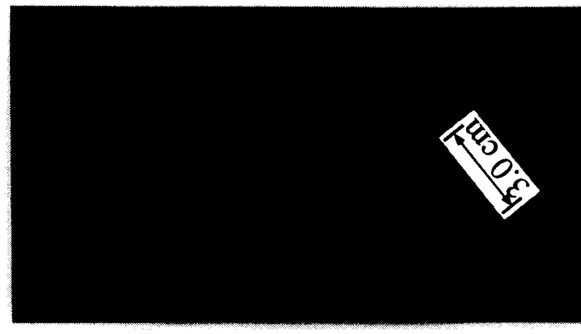

Fig. 3. Photograph of an integrated optical interconnect with highly parallel 1-to-27 surface normal fan-out.

Fig. 2 is the plot of optical fan-out power versus the coupling efficiency η_m and η_n, for the weakest beam in a 1-to-27 (3×9) surface normal fan-out array, based on Eq. (1). It indicates that the optimum coupling efficiency is around $\eta_m = 67\%$ and $\eta_n = 21\%$. As far as the maximum diffraction efficiency of the TIR hologram is concerned, the measured values are above 70% in our experiments.

To construct the holographic gratings, proper wavelength of recording beams need to be chosen, depending on the absorption characteristic of the holographic emulsion. The holographic material has a strong absorption band at 488 nm which was chosen as the recording wavelength. The reconstruction wavelength is fixed at 632.8 nm which has a different wavevector and thus a different phase-matching condition for surface normal coupling in and highly parallel fan-out interconnect. The method to construct the holograms was detailed in [10].

Fig. 3 is a photograph of surface normal 1-to-27 highly parallel optical interconnect using a glass substrate, integrated with a 2-D DCG based multiplexed hologram array. The holograms are fabricated with diffraction angles of 45° working at wavelength of 632.8 nm, where $\eta_m = 50\%$ and $\eta_n = 23\%$ are experimentally confirmed. In this photograph, a surface normal laser beam is coupled into the glass substrate through the surface normal multiplexed hologram. The parallel fan-out beams are generated by the 2-D hologram array either propagating along the substrate or normally coupling out off the substrate. The far field pattern of the 27 surface normal fan-out beams is also displayed in Fig. 3. Note that the mode dots preserve the azimuth symmetry of TEM_{oo} beam of the input laser. As a result, coupling to fiber array (or photodetector array) in later stage of the multi-stage interconnects will be much easier when compared with the conventional single-mode guided wave devices. Fig. 4 is the measured throughout intensity of the 27 surface normal fan-out beams. The maximum power variation of fan-out beams is within 25 dB.

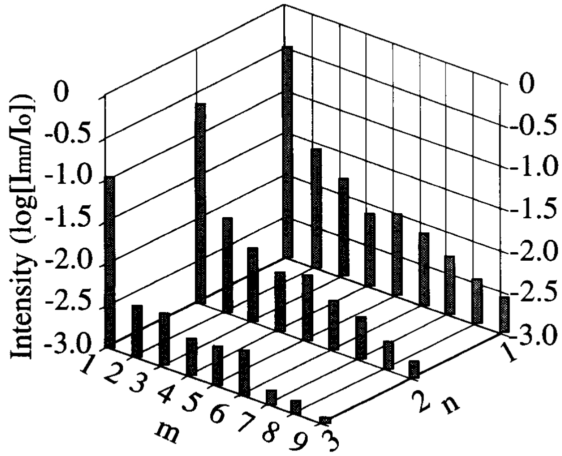

Fig. 4. Measured optical power of the 27 surface normal fan-out beams.

The result reported herein represents the first effort to construct an optical interconnection scheme for both intra- and inter-board massively parallel optical fan-out. The effort to utilize a thin light-guiding substrate, in conjunction with 2-D multiplexed holograms array, provides us the possibility of 3-D multi-stage intra- and inter-board massively parallel optical fan-out. As the result, the coupling from a single laser diode to multi-stage two dimensional detector arrays and/or a fiber array can be realized in a single coupling step.

In summary, we present a new interconnection scheme for highly parallel 3-D optical intra- and inter-board massive fan-out. 1-to-27 passive highly parallel optical fan-out was demonstrated for the first time. Optimum design rules are provided together with experimental results. Such a new interconnection scheme provides us with 3-D 1-to-many and many-to-many parallel fan-out capability, by using a light guiding plate integrated with a 2-D array of multiplexed holograms made out of DCG film. Such an interconnection scheme is applicable to a myriad of large scale multi-stage optical intra- and inter-board parallel fan-out applications.

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