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# Optimization of Fan-out Intensity Distribution for Bi-directional Photopolymer-Hologram-Based Optical Backplane Bus

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**Abstract** — Optimized design for a bi-directional optical backplane bus, containing 72 ( $9 \times 8$ ) interconnects and employing arrays of multiplexed polymer-based waveguide holograms on a waveguiding plate, is presented in this paper. After an objective function for the system is established, the fan-out intensity fluctuations among all the different channels are minimized by solving a set of non-linear equations numerically. Particularly, the fan-out distribution for the case in which nine boards on one side of the optical bus are optimized. A global optimized diffraction efficiency distribution exists and the minimum fan-out intensity after optimization is 1.5% of the incident power.

Currently, most of computer backplane buses are electrically interconnected. Due to the increase of clock speed and data transfer rate, electrical interconnection imposes many limitations on high performance computer. These include wide interconnection time bandwidths, large clock skew and large RC and RLC time constraints[1]. Contrary to electrical interconnection, optical interconnection has drawn significant interest[2, 3], owing to its high data transfer rate, large fan-out densities and the elimination of capacitive and inductive loading effects. Recently we presented a bi-directional optical backplane bus for a high performance system containing nine multi-chip module (MCM) boards, operating at 632.8 nm and 1300 nm[4]. This backplane bus employs arrays of multiplexed polymer-based waveguide holograms in conjunction with a waveguiding plate within which bi-directional substrate guided waves are generated. For a single bus line, we demonstrated a data transfer rate of 1.2 Gbit/sec at 1.3  $\mu\text{m}$  wavelength. The cascaded characteristic of the fanout beams away from the incident channel was demonstrated.

For the cascaded fanout system reported in Ref [4], its performance is always limited by the output channel with the lowest fanout intensity within the 72 ( $9 \times 8$ ) interconnects. To accurately analyze this limitation is one of the major concerns in designing a many-to-many cascaded fanout system. In this paper, we embark upon this problem by minimizing the fluctuations among all the output channels so that all the fan-out beam intensities are closest to their average value. The analysis is suitable for general-purpose optical backplane bus. To fully understand the working mechanism of the bi-directional optical bus, a theoretical analysis for the holographic grating diffraction is carried out first. An objective function for the system aimed at providing an optimized result is further established together with a set of non-linear equations as functions of the diffraction efficiencies of all the channels. Finally, theoretical results equivalent to the experimentally demonstrated system previously reported[4] are presented.

Fig. 1 is a schematic of how the optical bus can be used as a backplane in multi-processor, high performance optoelectronic computers. Bi-directional signal flow is illustrated between the backplane and the processor/memory boards, where the multichip modules (MCMs) are located. With the design that we employed, the optical backplane can serve the purpose of a bi-directional bus. Multiplexed waveguide holograms are employed to facilitate two-way communications among boards that are connected to the backplane.

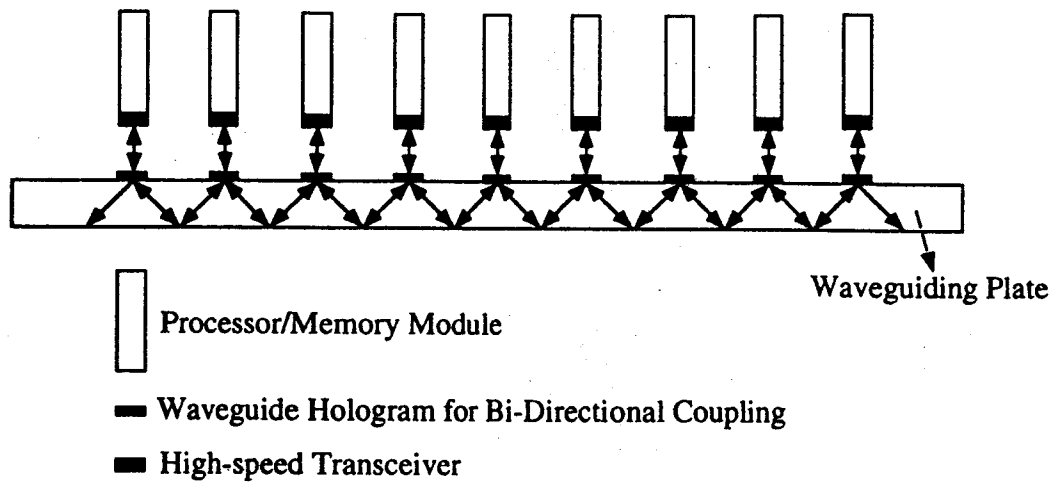


Figure 1. Schematic of the bi-directional optical backplane bus in a multi-transceiver system containing the demonstrated multiplexed waveguide hologram arrays in conjunction with a waveguiding plate.

The physical layer of the optical backplane bus is essentially a thin waveguiding plate with one dimensional (1-D) multiplexed waveguide hologram arrays integrated on its surface[4]. The substrate serves as the light-guiding medium. Dichromated gelatin(DCG)[5] was used as the hologram recording medium. Two hologram arrays were fabricated on the substrate to provide the required bi-directional surface-normal coupling. Both arrays are volume holograms[6].

As the bi-directional substrate guided waves propagate, their intensities will be decreased after each fanout[4]. The intensity of each surface-normal fanout beam is determined by the diffraction efficiency of the corresponding holographic grating. By changing the diffraction efficiency distribution of the holographic grating arrays, we can precisely manipulate the fanout intensity distribution. Due to the bi-directionality of the optical bus, it is not feasible to get a uniform fanout intensity distribution for all the cases where modulated optical signals are incident from different channels. For example, a multiprocessor system containing  $n$  MCM modules requires  $n(n-1)$  interconnects to fulfill the broadcasting nature of the backplane bus protocols. Each module needs to be interconnected with the other  $n-1$  modules. A uniform fanout intensity with the 1st module as the input module and the rest as receiving ports will make the power budget the worst when treating the  $n$ th module as the input and all the other ones as the outputs. In other word, an optimal design shall provide us with a minimized power fluctuation rather than an equalized power distribution among  $n(n-1)$  interconnect scenarios.

Fig. 2 also shows a schematic of the bi-directional optical bus with  $N$  boards on one side of the substrate. To provide the bi-directionality, there two arrays of holograms recorded. In this figure we assume that the diffraction efficiencies of the first set of hologram array are, from left to right,  $\eta_1, \eta_2, \dots$  and  $\eta_N$ , respectively. Due to symmetric requirement for optimization, the diffraction efficiencies for the second hologram array are  $\eta_1, \eta_2, \dots$  and  $\eta_N$  from right to left. To provide the optimized power budget, we have to impose the following criteria:  $\eta_1 = 1$  and  $\eta_N = 0$  for both sets (Fig. 2), i. e., there is only one hologram at the first and the  $N$ th channels. ( $\eta_N (\eta_N = 0)$  associated with the 2nd set serves as the input coupler to  $N+1, N+2, \dots$  modules which do not exist). If we denote  $P_{ij}$  to be the

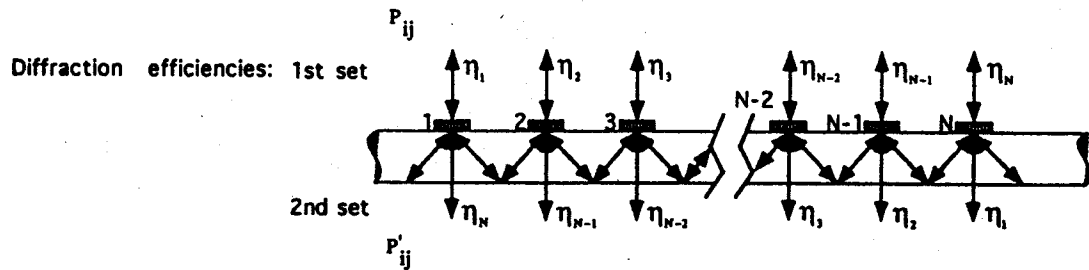


Figure 2. Schematic of the bi-directional backplane optical bus with  $N$  boards on one side of the substrate.

output power at the  $j$ th channel when optical signal is incident from the  $i$ th channel, and the same holds for  $P'_{ij}$ , except that they have a reversed fanout direction (Fig. 2), which has not been employed in the previous demonstration. It is to be noted that the bi-directional hologram arrays provide surface normal fanout in both directions. Based on these notations, we have

$$P_{ij} = 0 \quad \text{whenever } i = j, \quad (1)$$

$$P'_{i1} = P'_{iN} = 0 \quad i = 1, \dots, N. \quad (2)$$

Furthermore, the nature of fanout symmetry of the backplane bus also suggests that we can consider only the cases in which the light signal beams are incident from the  $i$ th channel, with  $i=1, \dots, M$  ( $M=N/2$  when  $N$  is an even number, and  $M=(N+1)/2$  when  $N$  is an odd number).

The general expressions for  $P_{ij}$  and  $P'_{ij}$ , with  $i=1, \dots, M$  and  $j=1, \dots, N$ , can be represented as

$$P_{im} = \left[ \eta_{(N+1)-i} - \sum_{k=i-1}^{m+1} (P_{ik} + P'_{ik}) \right] \eta_m \quad \text{for } m = i-1, i-2, \dots, 1,$$

$$P_{ii} = 0,$$

$$P_{in} = \left[ \eta_i - \sum_{k=i+1}^{n-1} (P_{ik} + P'_{ik}) \right] \eta_{(N+1)-n} \quad \text{for } n = i+1, \dots, N, \quad (3)$$

and

$$P'_{im} = \left( \eta_{(N+1)-i} - \sum_{k=i-1}^m P_{ik} - \sum_{k=i-1}^{m+1} P'_{ik} \right) \eta_{(N+1)-m} \quad \text{for } m = i-1, i-2, \dots, 1,$$

$$P'_{ii} = 1 - \eta_i - \eta_{(N+1)-i},$$

$$P'_{in} = \left( \eta_i - \sum_{k=i+1}^n P_{ik} - \sum_{k=i+1}^{n-1} P'_{ik} \right) \eta_n \quad \text{for } n = i+1, \dots, N. \quad (4)$$

After having been incident onto the  $i$ th channel of the optical bus, light beam is diffracted into the glass substrate and propagates to both ends of the backplane bus. Also, the cascaded feature of the outputs (i. e.,  $P_{ij}$ 's and  $P'_{ij}$ 's) from the input channel to both ends of the bus, are clearly shown in the above expression.

The description of power budget optimization process now follows. The goal is to find an optimized distribution of diffraction efficiencies leading to a fan-out intensity distribution with a minimum power fluctuation and therefore an optimized power budget. For this purpose, an objective function[7] relating all terms of power fluctuations is generated. By optimizing the objective function, a well balanced fan-out distribution can be reached. For our problem, an obvious objective function is the sum of the square value of the differences between the fan-out intensities and their average. If we define the intensity of the incident signal beam as 1, after taking into account of Eqs. (1) and (2), the average fan-out intensity is given by

$$\bar{P} = \frac{1}{2N-3}. \quad (5)$$

The objective function is then expressed as

$$E = E_1 + E_2 \quad (6)$$

where

$$E_1 = \sum_{i=1}^M \left[ \sum_{j=1}^N W_{1ij} \left( \frac{P_{ij}}{\bar{P}} - 1 \right)^2 + \sum_{j=2}^{N-1} W'_{1ij} \left( \frac{P'_{ij}}{\bar{P}} - 1 \right)^2 \right] \quad \text{for } P_{ij} \text{ and } P'_{ij} \geq \bar{P}, \quad (7)$$

$$E_2 = \sum_{i=1}^M \left[ \sum_{j=1}^N W_{2ij} \left( \frac{\bar{P}}{P_{ij}} - 1 \right)^2 + \sum_{j=2}^{N-1} W'_{2ij} \left( \frac{\bar{P}}{P'_{ij}} - 1 \right)^2 \right] \quad \text{for } P_{ij} \text{ and } P'_{ij} \leq \bar{P}, \quad (8)$$

where  $W_{ij}^{(c)}$  and  $W'_{ij}^{(c)}$  are weight factors,  $M=N/2$  when  $N$  is an even number, and  $M=(N+1)/2$  when  $N$  is an odd number.

An optimized fan-out distribution should result in a minimum value in the objective function  $E$ , which implies that the first derivative of  $E$  with respect to each  $\eta_i$  ( $i=2, \dots, N-1$ ) is equal to zero, i.e.,

$$\frac{\partial E}{\partial \eta_i} = 0 \quad i = 2, \dots, N-1. \quad (9)$$

In accordance with our previous work[4], we optimize the fan-out distribution for the case in which  $N=9$  (see Fig. 2). A computer program was employed to provide the fan-out intensities and other related parameters. The seven non-linear equations(Eq. (9) with  $i=2, 3, \dots, 8$ ) are then solved numerically using the Levenberg-Marquardt algorithm[8] and a finite-difference approximation to the Jacobian, subject to the constraint of

$$0 < \eta_2, \dots, \eta_8 < 1. \quad (10)$$

The statistical weight we used in our calculation has the exponential form, i.e.,

$$W_{ij}^{(')} = \exp\left[A\left(\frac{P_{ij}}{\bar{P}} - 1\right)\right] \quad \text{for } P_{ij}^{(')} \geq \bar{P}, \quad (11)$$

$$W_{ij}^{(')} = \exp\left[B\left(\frac{\bar{P}}{P_{ij}} - 1\right)\right] \quad \text{for } P_{ij}^{(')} \leq \bar{P}, \quad (12)$$

where the superscript (') means with or without the prime.

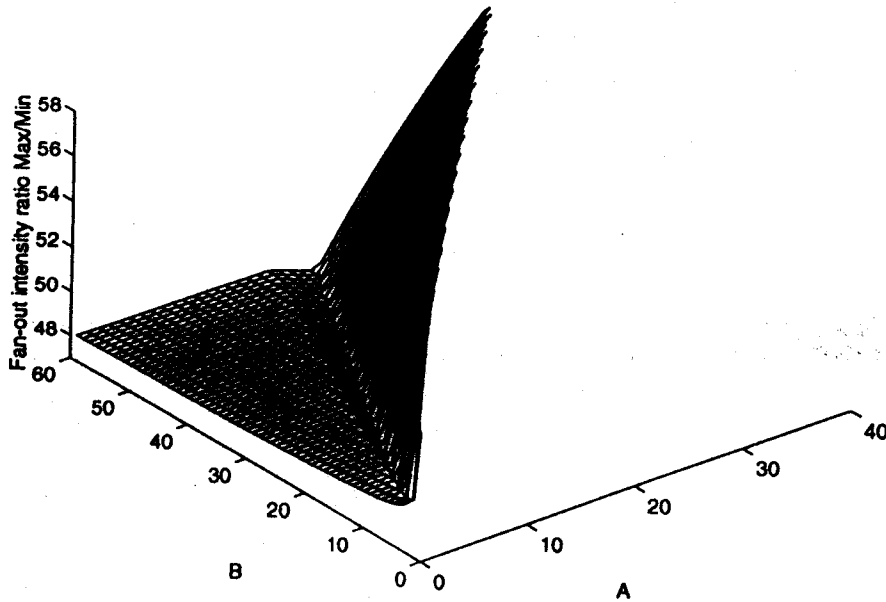


Figure 3. Ratio between the maximum and minimum fan-out intensities among 72 ( $9 \times 8$ ) beams as a function of coefficients A and B.

The change of the statistical weight is carried out by increasing the A and B values. In Fig. 3, we give the plot of the variation of the ratio of the maximum and minimum fan-out intensities as a function of A and B for the case of  $N=9$ . In this case, we have 72 ( $9 \times 8$ ) interconnects. The maximum and minimum fanout intensities are selected for each arrangement. These maximum and minimum values are obtained by comparing the optimized  $P_{ij}$ 's ( $i=1, \dots, 5, j=1, \dots, 9, i \neq j$ ) and  $P'_{ij}$ 's ( $i=1, \dots, 5, j=2, \dots, 8$ ) under a selected pair of A and B. The optimized fan-out distribution for the 72 interconnects can be located by finding the minimum ratio. Fig. 4 gives the equal topological lines of Fig. 3. From this figure and our calculation result, it's clear that this minimum ratio is 47.47, and this occurs only after A reaches 6.0 and B reaches 16.0. For calculation of the optimized diffraction distribution, we took A and B up to 22 and 58, respectively. The optimized diffraction efficiency distribution is determined to be

$$(\eta_1, \eta_2, \dots, \eta_9) = (1.0, 0.3341, 0.2005, 0.1435, 0.1548, 0.1665, 0.2492, 0.4984, 0.0), \quad (13)$$

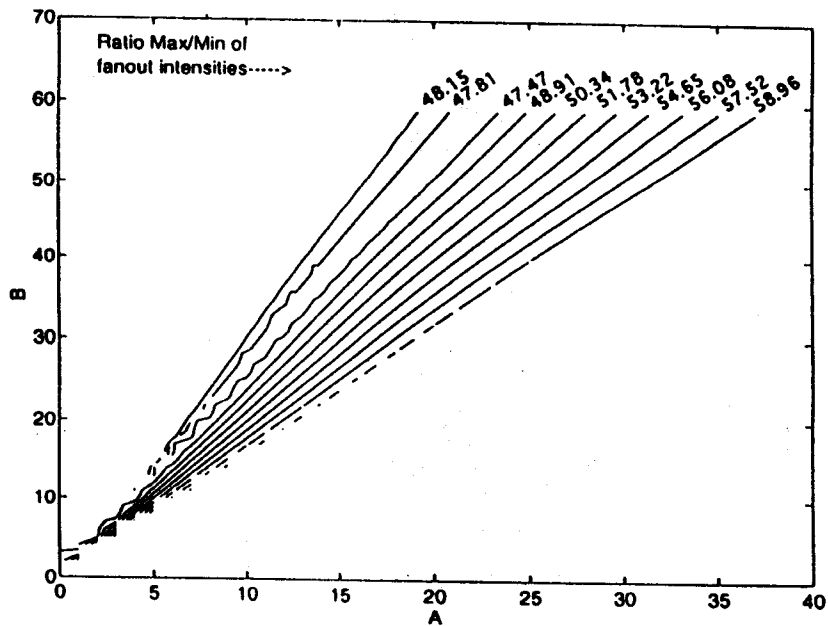


Figure 4. Equal topologies plot of Fig. 3.

and the optimized fan-out intensities are given in Table 1. The average value of the fan-out (from Eq. (5)) intensities is 0.0667. The minimum of the optimized fan-outs is 0.0146, while the maximum is 0.6904. This set represents the optimized solution with minimized power fluctuation among 72 interconnects.

Fanout \ j	1	2	3	4	5	6	7	8	9
$P_{11}$	0	0.49836	0.08324	0.03338	0.02216	0.01468	0.01464	0.01464	0.01464
$P_{12}$	0	0.16758	0.05030	0.02399	0.01873	0.01458	0.01454	0.01454	0
$P_{13}$	0.49836	0	0.08324	0.03338	0.02216	0.01468	0.01464	0.01464	0.01464
$P_{14}$	0	0.16758	0.05030	0.02399	0.01873	0.01458	0.01454	0.01454	0
$P_{15}$	0.08324	0.08324	0	0.03338	0.02216	0.01468	0.01464	0.01464	0.01464
$P_{16}$	0	0.08270	0.55030	0.02399	0.01873	0.01458	0.01454	0.01454	0
$P_{17}$	0.03338	0.03338	0.03338	0	0.02222	0.01472	0.01468	0.01468	0.01468
$P_{18}$	0	0.03317	0.03317	0.68998	0.01878	0.01462	0.01458	0.01458	0
$P_{19}$	0.02216	0.02216	0.02216	0.02222	0	0.02222	0.02216	0.02216	0.02216
$P_{19}$	0	0.02202	0.02202	0.02207	0.69038	0.02207	0.02202	0.02202	0

Table 1. Optimized fanout distribution from our calculation.

In this paper, we present the theory of optimization of the fan-out intensity distribution of the bi-directional backplane optical bus, aimed at balancing the fan-out intensities among different channels using an objective function. For an bi-directional optical bus with 9 boards on one side, the optimization result shows that the minimum fan-out intensity is 1.5% of the incident power. Based on the phase-

matching condition, the surface normal fanout beams come out of both directions (see Fig. 2). Therefore, the best hardware implementation scheme shall integrate the MCM modules in both sides of the backplane bus. As a result, the optimal member of MCM module shall be 16, i.e.,  $9+(9-2)$ , rather than 9, when both sides of the backplane are employed.

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