Multiple diffraction of massive fanout optical interconnects based on multiplexed waveguide holograms

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ABSTRACT

Experimental results of 1-to-2 intra-plane and of 1-to-32 inter-plane v-shaped fanouts are delineated. Coupling efficiencies of 48% for surface-normal and of 45% for near-surface-normal inter-plane fanout beams are theoretically and experimentally confirmed. The influence of the angular fluctuation of a device having two multiplexed waveguide holograms with film thickness of 15μm and index modulation of 0.04 is studied. The angle between the two grating vectors is determined to be less than 26° to keep the near-surface-normal fanout beams.

INTRODUCTION

Optical interconnects are of choice to replace conventional electrical interconnects in high-speed multi-processor digital computers[1-3] where electrical interconnects face such fundamental limits as clock skew, RLC (resistance, inductance, and capacitance) time delay, and electromagnetic interference (EMI) effect.

Recently polymer-based integrated photonic circuit elements have been employed for a myriad of applications in optically interconnected systems due to their suitability to various substrates and low material dispersion. These system demonstrations include intra-plane[4-7] and inter-plane[8, 9] optical interconnects, and wavelength division (de)multiplexers[9, 10]. Very recently, two new 1-to-many three dimensional (3D) board-to-board and backplane optical interconnect schemes were demonstrated using the substrate guided waves[11,12]. Intra- and inter-plane optical interconnects with parallel fanout beams and v-shaped fanout beams are important building blocks for intra-wafer and chip-to-chip interconnects[4]. For chip-to-chip optical interconnects, v-shaped fanout pattern has the advantage of providing straight optical path which reduces the loss of optical bus significantly[13].

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In this letter, we present for the first time the theoretical analysis together with the experimental demonstration of v-shaped optical interconnects based on 2D multiplexed hologram arrays along substrate guided waves. Two multiplexed waveguide holograms are employed to convert one surface normal incident beam into two intra-plane substrate guided waves. The intra-plane guided waves are then coupled with two hologram arrays integrated along the optical paths on intra-plane beams to provide arrays of 1-to-2 inter-plane fanouts. As a result, multiple diffraction of massive optical fanout arrays can be provided at both intra- and inter-plane levels.

DEMONSTRATIONS OF INTRA- AND INTER-PLANE V-SHAPED OPTICAL INTERCONNECTS

1. Intra-plane v-shaped optical interconnects:

The schematic illustrating how the multiplexed waveguide holograms convert one surface normal incident beam into two substrate guided waves is shown in Fig.1. The diffraction angle θ is greater than the critical angle θ_c of total internal reflection (TIR), i.e., $\theta \geq \theta_c$. The two holograms shown in Fig.1 are recorded with

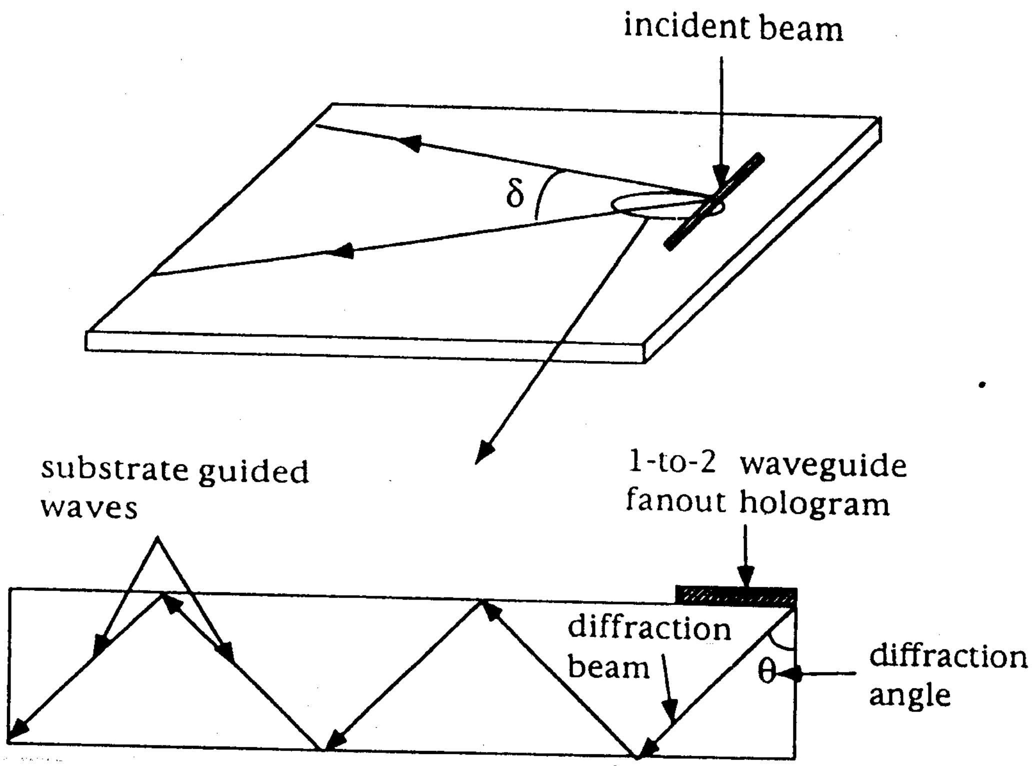


Fig.1 Schematic of the demonstrated 1-to-2 intra-plane interconnects with a surface-normal incident beam

the same diffraction angle which is 45° in our experiment. Different intra-plane fanout directions are realized by rotating the recording plate about its surface-normal axis. The rotation angle δ shown in Fig.1 is also the angle between the two grating vectors of the multiplexed holograms. Each hologram was fabricated using the two-beam interference method[11]. In our experiment, we use an Argon laser operating at 488nm as the recording beam, and a He-Ne laser as the reconstruction beam (λ_r=632.8nm).

The photograph of the intra-plane v-shaped 1-to-2 optical interconnects is shown in Fig.2, where two substrate guided waves are clearly displayed with δ=15°. He-Ne laser beam with TE transverse electric polarization was employed in the reconstruction. Coupling efficiency of 48% for each hologram was measured. For the intra-plane optical interconnects shown in Fig.2, by using substrate guided waves, a multiplexed hologram with linear dimension equivalent to that of the incident TEM_{00} He-Ne laser beam is enough, which greatly reduces the surface area employed when compared with the conventional guided-wave devices.

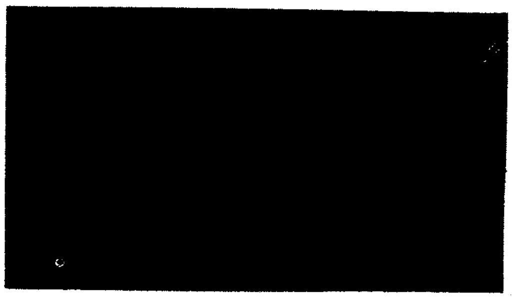
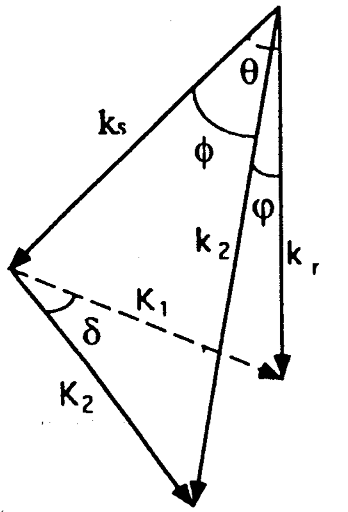


Fig.2 The phototgraph of the v-shaped intra-plane optical interconnects

2. Inter-plane v-shaped optical interconnects

For the inter-plane optical interconnects, we need 2D arrays of multiplexed hologram to convert intra-plane substrate guided waves into inter-plane optical interconnect fanout beams. Fig.3 shows the phase-matching diagram of each multiplexed hologram containing two gratings which provide surface-normal (90°) and near-surface-normal (11° deviation from surface normal) fanouts. Note that the two grating vectors associated with each multiplexed hologram for intra- and inter-plane fanouts are formed with the same recording geometry.



$\mathbf{k}_s$: substrate guided wave vector
$\mathbf{k}_r$: wave vector of surface-normal fanout beam
$\mathbf{k}_2$: wave vector of near-surface-normal fanout beam
$\mathbf{K}_1$, $\mathbf{K}_2$: two grating vectors of the multiplexed hologram
θ: diffraction angle of perfectly phase-matched case
ϕ: diffraction angle of not perfectly phase-matched case
φ: angle deviation of the near-surface-normal fanout beam from the substrate surface normal

Fig.3 Phase-matching diagram within the substrate for surface-normal and near-surface-normal fanout beams

A schematic of the inter-plane v-shaped optical interconnects demonstrated herein is shown in Fig. 4(a) where the far field v-shaped fanouts resulting from the 2D hologram arrays are illustrated. Each intra-plane fanout beam on the master plate is coupled with two gratings associated with the multiplexed hologram arrays along the zig-zag optical paths. Two inter-plane fanout beams are generated each time when the intra-plane guided wave comes across a multiplexed hologram. One beam results from the coupling between the substrate guided wave vector $\mathbf{k}_s$ and the grating vector $\mathbf{K}_1$ of one hologram. This represents the perfectly phase-matched case. The fanout beam is normal to the substrate surface. The other beam is activated due to the interaction between the substrate guided wave vector $\mathbf{k}_s$ and the grating vector $\mathbf{K}_2$ of the other hologram. This is designed to provide near-surface-normal with a deviation angle of 11° which is not perfectly phase-matched in our case.

Fig.4(b) shows the photograph of an inter-plane v-shaped 1-to-many optical interconnects consisting of the 2D multiplexed hologram arrays with $\delta=15^\circ$. It shows the far field pattern of 1-to-32 inter-plane fanouts containing 16 surface-normal and 16 near-surface-normal beams.

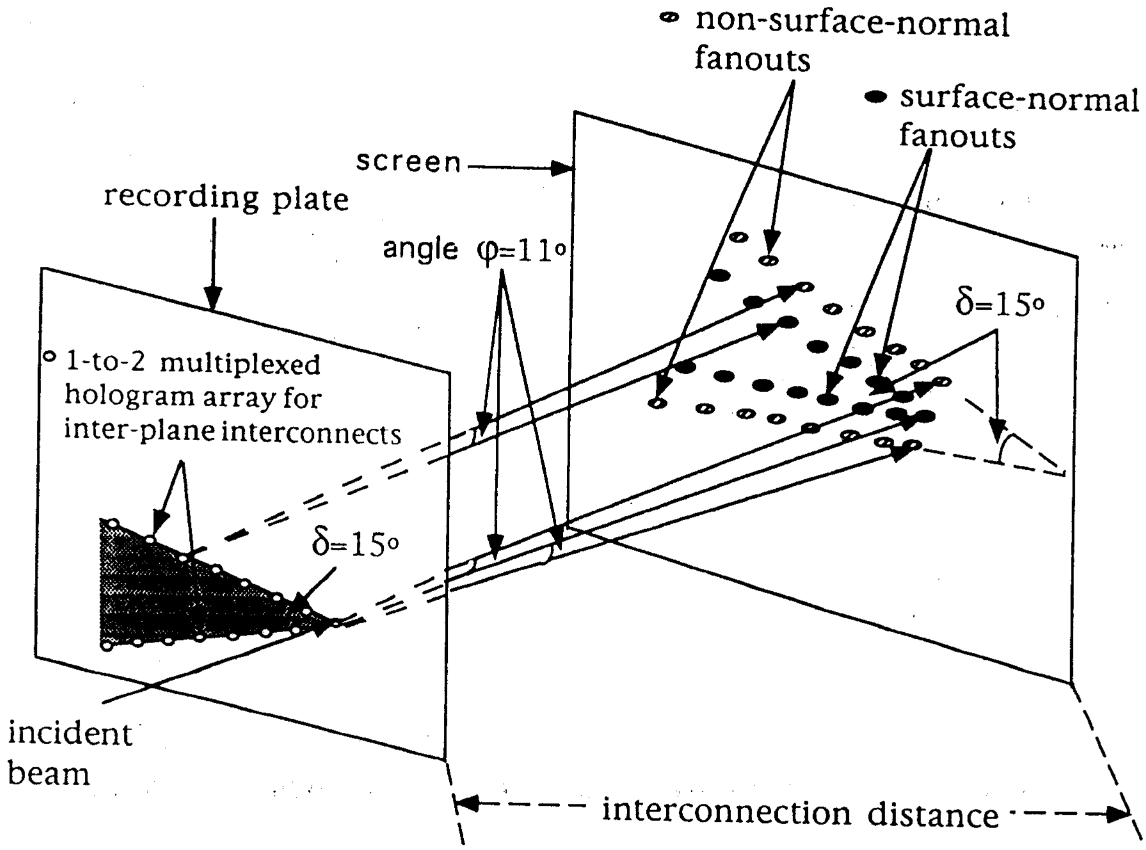


Fig.4(a) The schematic of inter-plane v-shaped 1-to-many optical interconnects

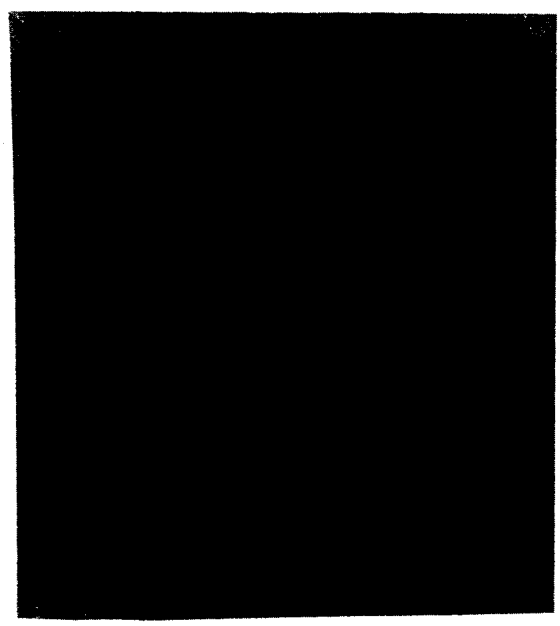


Fig.4(b) The photograph of v-shaped 1-to-32 inter-plane fanouts

THEORETICAL ANALYSIS

To understand the influence of the angles of δ and φ on the grating coupling efficiency of the near-surface-normal fanouts for inter-plane optical interconnects, the coupling efficiencies of the surface-normal fanout beam (η_0) and of the near-surface-normal fanout beam (η) were further studied using coupled wave theory[14]. For the substrate guided mode, the inter-plane fanout hologram is a transmission hologram. The coupling efficiency η is[14]

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

where

$$\nu = \pi \Delta n d/\lambda_r(c_r c_s)^{1/2} \tag{2}$$

$$\xi = \Delta\psi K d \sin(\theta - \psi_0)/2c_s = -\Delta\lambda K^2 d/8\pi n c_s \tag{3}$$

$$c_r = \cos\psi_0 \tag{4}$$

and

$$c_s = \cos\psi_0 - K/k_r \cos\theta \tag{5}$$

In above equations, Δn is the modulation of the refractive index of the holographic film, d is the thickness of the film, ψ_0 is the incident angle, $\Delta\psi$ is the deviation of the diffraction angle, and K is the magnitude of the grating vector **K.**

For the perfectly phase-matched case, i.e. the surface-normal fanouts, $\Delta\psi = 0$. For the near-surface-normal case $\Delta\psi=\phi-45^\circ$ where ϕ is the diffraction angle which is not perfectly phase-matched (see Fig.3). We use η to represent the near-surface-normal coupling efficiency and φ to represent the deviation angle of the near-surface-normal beam from the surface-normal beam. From Fig.3 the expressions for ϕ and φ can be derived as

$$\cos\phi = (k_r^2 + k_2^2 - K^2)/2k_r k_2 \tag{6}$$

$$\cos\varphi = \{k_r^2 + k_2^2 - [2K\sin(\delta/2)]^2\}/2k_r k_2 \tag{7}$$

and

$$k_2 = \{ K^2 + k_r^2 - 2k_r K \cos\delta \cos[(\pi - \theta)/2]\}^{1/2} \tag{8}$$

Where λ_r=632.8nm, Δn=0.04, d=15μm, ψ_0=0, θ=45°, and n=1.512 are chosen in our experiment. Using these parameters, we have η_0=48.7% using the Eq.(1) with ξ=0. The calculated result of η/η_0 with different δ and φ is shown in Fig.5. It is clear that when δ=15° and φ= 11° which is equivalent to our experiment, we have η/η_0=0.926, therefore η=45.1%. To eliminate or to keep the near-surface-normal fanouts, appropriate ranges of δ and of φ have to be chosen when designing the device. From Fig.5 we know that for our parameters, δ should be bigger than 30° to eliminate the near-surface-normal fanout beam, while δ should be less than 26° and φ should be less than 16° if the near-surface-normal fanout beams are desired.

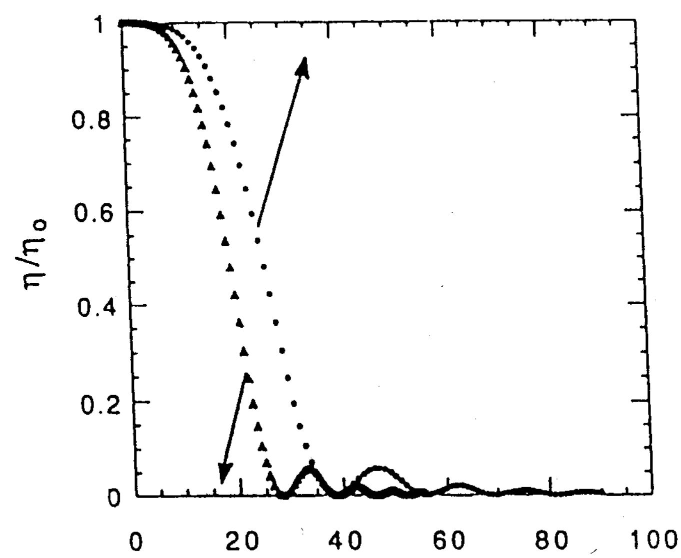


Fig.5 Normalized coupling efficiency (η/η_0) of the near-surface-normal fanout beams as functions of angles δ and φ

Once the coupling efficiencies of the surface-normal and of the near-surface-normal fanouts are determined, we can derive the intensity of each fanout beam. Figs.6(a) and (b) show the normalized intensities of the eight surface-normal and of the eight near-surface-normal fanout beams from one branch of the v-shaped inter-plane fanouts. The measured coupling efficiencies for our device are 48% for the surface-normal fanout beam and 45% for the near-surface-normal fanout. An excellent agreement between our experimental results and theoretical analysis is provided.

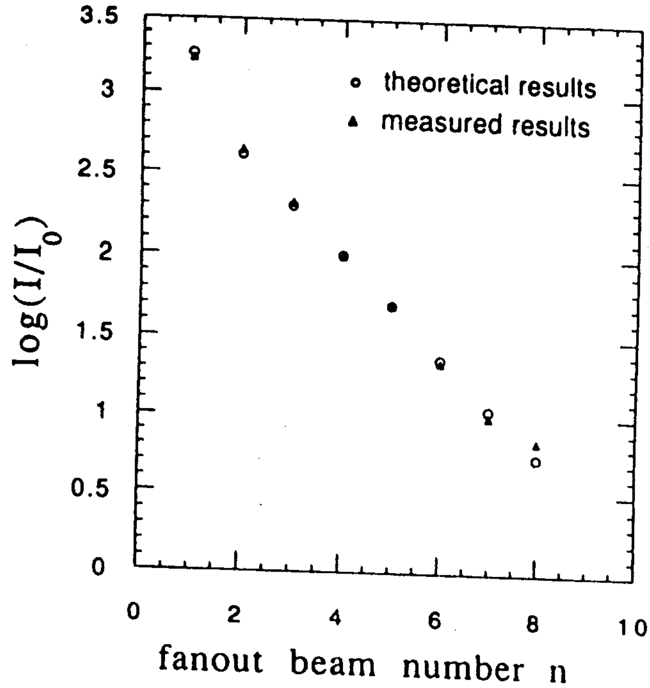


Fig.6 (a) Normalized intensities of the eight surface-normal beams from one branch of the v-shaped inter-plane fanout array

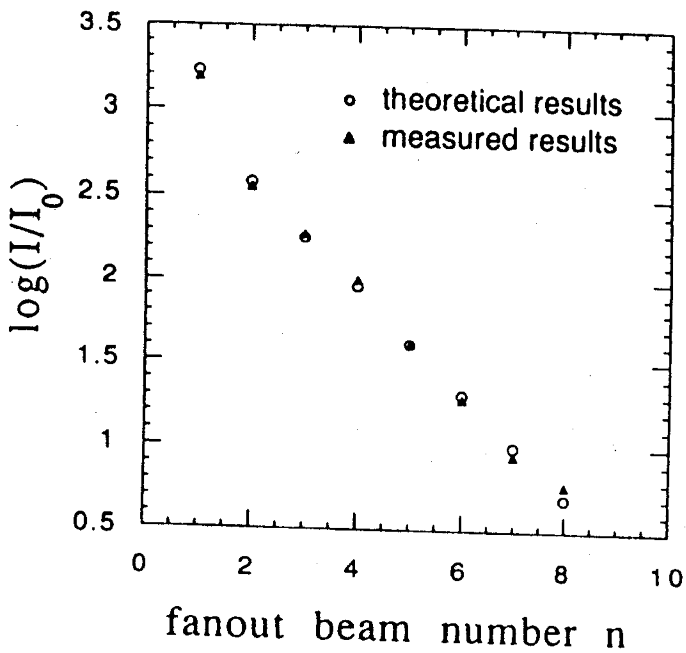


Fig.6 (b) Normalized intensities of the eight near-surface-normal beams from one branch of the v-shaped inter-plane fanout array

SUMMARY

In summary, we report, for the first time, the theoretical analysis and the experimental results for a novel intra-plane and inter-plane v-shaped 1-to-many optical interconnect that uses a 2D multiplexed waveguide hologram arrays and substrate guided waves. 1-to-2 intra-plane optical interconnect fanouts and 1-to-32 inter-plane fanouts containing 16 surface-normal and 16 near-surface-normal beams are delineated. We further measured the throughout of each inter-plane fanout beam. An excellent agreement between the measured results and our theoretical analysis is obtained. The influence of the angles δ and φ on coupling efficiency of the near-surface-normal beam is detailed and appropriate design criteria for δ and for φ are provided.

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