Intraplane guided wave massive fanout optical interconnections

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One-to-30 guided wave optical interconnections are demonstrated at 632.8 nm using a highly multiplexed waveguide volume hologram. This technology is capable of providing intrachip and intrawafer optical interconnections. The theoretical limit of the fanout number is addressed and experimentally confirmed. The measured data show that the diffracted beams have an average diffraction efficiency of 2.3% with ±0.2% variation. The demonstrated results can save surface space of electronic chips and also provide a large fanout capability due to the high index modulation of the volume hologram. Further applications based on this technology are very promising. Head-up display, high-speed optical data bus, surface enhanced Raman spectrometer, and optical sensors are some of the attractive ones.

Electrical interconnections have limitations when used in interconnection schemes. These limitations are most serious in applications where a high degree of interconnectivity is required, such as in parallel distributed processing. In such an application, there is electrical interference between chips on the same circuit board, as well as among different circuit boards. This interference is induced by electromagnetic interaction between waves that are generated by scattering, reflection, and resonance through the electrical interconnections. In addition to their susceptibility to microwave interference, metal wires and data buses are severely limited in packing density and transmission bandwidth. The last limitation is due to parasitic effects such as capacitive loading and inductive coupling in the electrical interconnections.

Optical interconnections have already demonstrated their superiority for telecommunications because of their high speed, low volume, high bandwidth, and low attenuation.[1] They also have the potential to overcome the serious electrical interconnect limitations. Furthermore, the same optical path can route different optical signals while maintaining negligible cross talk. The combination of these outstanding features makes optical interconnection an attractive alternative to electrical interconnection to increase the speed and the parallelism and, therefore, the throughput of microelectronic systems.

In this letter we present the first intraplane 1-to-30 optical interconnection based on a high-efficiency multiplexed dichromated gelatin (DCG) hologram. The high index modulation of the DCG polymer grafts (DPG)[2] allows us to provide highly multiplexed gratings on the same volume holographic emulsion. For fixed emulsion thickness, the total number of gratings, the therefore fanouts, that can be multiplexed in the same hologram is controlled by either the optical power budget or the available maximum index modulation. The power budget correlates with the sensitivity of the receiver, which demodulates the optical signal, and the base bandwidth of the transmitter. The availability of high-power laser diodes can ease the requirement of a power budget for high data rate communication.[3] In this letter we address the fanout limitation based on maximum index modulation.

The theoretical work discussed in this letter is primarily based on Kogelnik's coupled wave theory,[4] which details the diffraction of a volume hologram. Transverse electric (TE) and transverse magnetic (TM) mode conversion, needed for our three-dimensional coupling, complicated the theoretical calculation.[5] A new coordinate system was chosen so that, in the newly defined x-z plane, the diffraction of $\|$ (parallel) and $\perp$ (perpendicular) polarizations can be treated separately.[6] When the electric field of the optical wave is parallel to the x-z plane, it is defined as $\|$ polarization. $\perp$ polarization is when the electric field is perpendicular to the plane. The resultant diffracted beams are the vector summation of the diffracted $\|$ and $\perp$ polarized beams. Figure 1(a) shows the x-y-z coordinate system. The z axis is perpendicular to the grating vector $\mathbf{K}$. The x-z plane is overlapped with the triangle constructed by $\mathbf{k}_d$ (diffracted), $\mathbf{k}$ (incident), and the grating vector $\mathbf{K}$.

For the transmission hologram shown in Fig. 1(b), the diffraction efficiencies $\eta_\perp$ and $\eta_\|$ for each individual hologram are given by[4,6]

$$\eta_\perp = \frac{4\kappa^2}{(C_r/C_\delta)\vartheta + 4\kappa^2} \sin^2\left[\frac{1}{2}\left(\frac{\vartheta^2}{C_\delta{}^2} + \frac{4\kappa^2}{C_r C_\delta}\right)^{1/2} d\right] \tag{1}$$

and

$$\eta_\| = \frac{4\kappa^2(\hat{k}\cdot\hat{k}_d)^2}{(C_r/C_\delta)\vartheta + 4\kappa^2(\hat{k}\cdot\hat{k}_d)^2} \times \sin^2\left[\frac{1}{2}\left(\frac{\vartheta^2}{C_\delta^2} + \frac{4\kappa^2(\hat{k}\cdot\hat{k}_d)^2}{C_r C_\delta}\right)^{1/2} d\right], \tag{2}$$

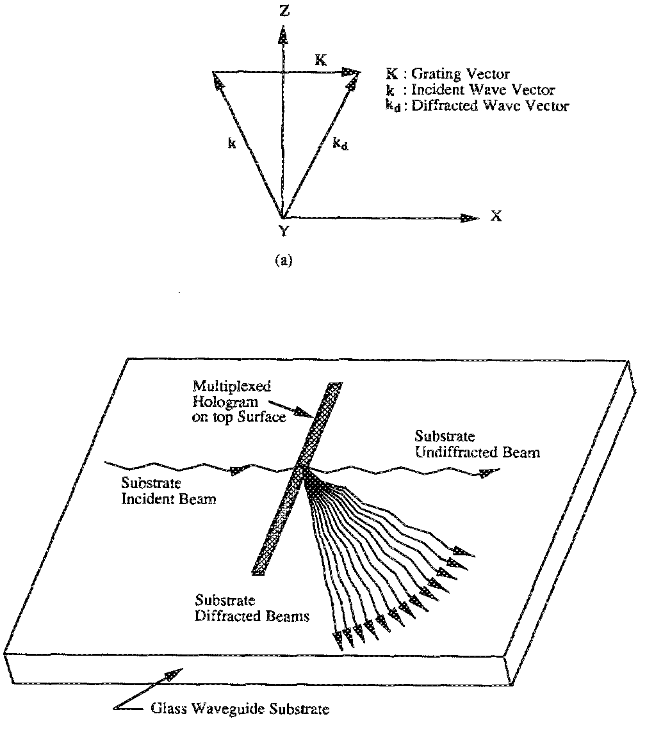
where

$$C_r = k_z/k_0, \quad C_\delta = k_{dz}/k_0, \quad \kappa = \pi\Delta n/\lambda,$$

k_z and k_{dz} are the $\hat{z}$ components of $\mathbf{k}$ and $\mathbf{k}_d$, $k_0 = 2\pi n/\lambda$, ϑ is the dephasing factor.[4] $\hat{k}$ and $\hat{k}_d$ are unit vectors for incident and diffracted wave propagation constants. As indicated in Fig. 1(a), the x-z plane is defined by the plane of the triangle constructed with $\mathbf{K}$, $\mathbf{k}$, and $\mathbf{k}_d$. $\eta_\|$ and $\eta_\perp$ are the diffraction efficiencies of substrate guided waves with polarization parallel and perpendicular, respectively, to the x-z plane.

In the case of Bragg condition, which implies perfect phase machine, we have

$$\eta = \sin^2\left(\frac{\Delta n d\pi}{\lambda\cos\theta}\varphi\right), \tag{3}$$



(a)

(b)

FIG. 1. (a) Definition of *x*-*y*-*z* coordinate and (b) schematic of intraplane one-to-many fanout using transmission hologram.

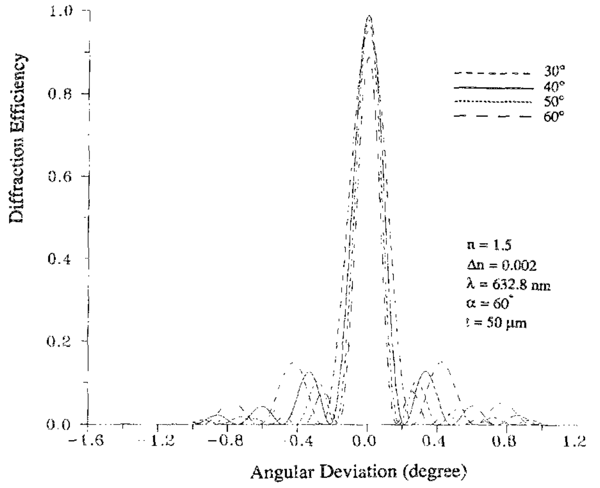


FIG. 2. Angular selectivity of the substrate guided mode at four different planar diffraction angles seen from the top surface.

where $\varphi = 1$ for $\eta_\perp$ and $0 < \varphi < 1$ for $\eta_\parallel$, depending on the inner product of $\hat{k} \cdot \hat{k}_d$, Δn is the index modulation, d is the grating interaction length measured along the z axis, and λ and θ are the reconstruction wavelength and Bragg diffraction angle, respectively. d is much larger than the film thickness t for a large bouncing angle which is measured between the substrate normal direction and the direction of the vector **k**. To provide high-efficiency diffraction for $\perp$ or $\parallel$ polarized beams, the index modulation Δn associated with the grating should be

$$\Delta n = \lambda \cos \theta / 2d\varphi. \quad (4)$$

If all gratings in the one-to-many interconnection architecture have similar Δn values, the maximum numbers of gratings, N, that can be implemented in the same holographic emulsion is estimated to be

$$N = \Delta n_{\max} 2d\varphi / \lambda \cos \theta. \quad (5)$$

In Eq. (5), $\Delta n_{\max}$ is the maximum achievable index modulation of the DPG. For a fixed reconstruction wavelength, we can either adjust the Bragg diffraction angle θ or increase the interaction length d to increase the number of fanouts. The angular selectivity of the intraplane diffraction of a TE incident beam with the index modulation fixed at 0.002 for each grating and **K** parallel to the wafer surface is shown in Fig. 2. The film thickness used in the calculation is 50 μm. The dephasing term is included in generating the data of Fig. 2. Due to the output of phase behavior of $\perp$ and $\parallel$ couplings, the resultant maximum diffraction efficiency is less than 100%, in general, though 100% diffraction efficiency is achievable theoretically for $\perp$ or $\parallel$ polarized beams. The spreading of Bragg diffraction limits the number of feasible fanouts. The result shown in Fig. 2 provides us with the angular allocation for each individual hologram formation. We have demonstrated 1-to-20 and 1-to-30 massive intraplane fanouts at 632.8 nm wavelength with the diffraction angles from 30° to 49° and 30° to 59°, respectively. One degree diffraction angle separation was assigned for each adjacent grating. The result is shown in Fig. 3. The guided wave shown in this photograph employs the whole substrate as the guiding medium.[7,8] The bouncing angle of the guide wave is 60°. The intensity of fanout beams was extremely uniform for both cases. The diffraction efficiency of each individual beam of the 1-to-30 fanouts is shown in Fig. 4. The average diffraction efficiency is 2.3% with a maximum variation of $\pm 0.2\%$. Uniformity of these 30 beams and the diffraction efficiency of each individual hologram can be controlled by adjusting the exposure time for each hologram. To introduce the desired index modulation, the exposure time t_i for the ith hologram shall satisfy the following equation:

$$t_i = \frac{1}{e\beta} \ln \left[-\Delta n_i + \left(\Delta n_{\max} - \sum_{j=1}^{i-1} \Delta n_j \right) \right] \Big/ \left[\Delta n_{\max} - \sum_{j=1}^{i-1} \Delta n_j \right], \quad (6)$$

where β is a film sensitivity constant correlated with the DPG material and can be experimentally determined, E is the exposure intensity of the laser beam, Δn_j is the index modulation for the jth exposure, and $\Delta n_{\max}$ is the maximum index modulation for the holographic material. Our calculation shows that the diffraction efficiency is angular dependent, and therefore, to generate equal diffraction efficiency for one-to-many fanouts, the Δn for each hologram needs to be independently determined. In our angular selectivity calculations, the index modulation for each individual waveguide hologram was fixed at 0.002. The nonlinear response of DPG in Eq. (6) is derived from a first-order differential equation representing the film characteristic.

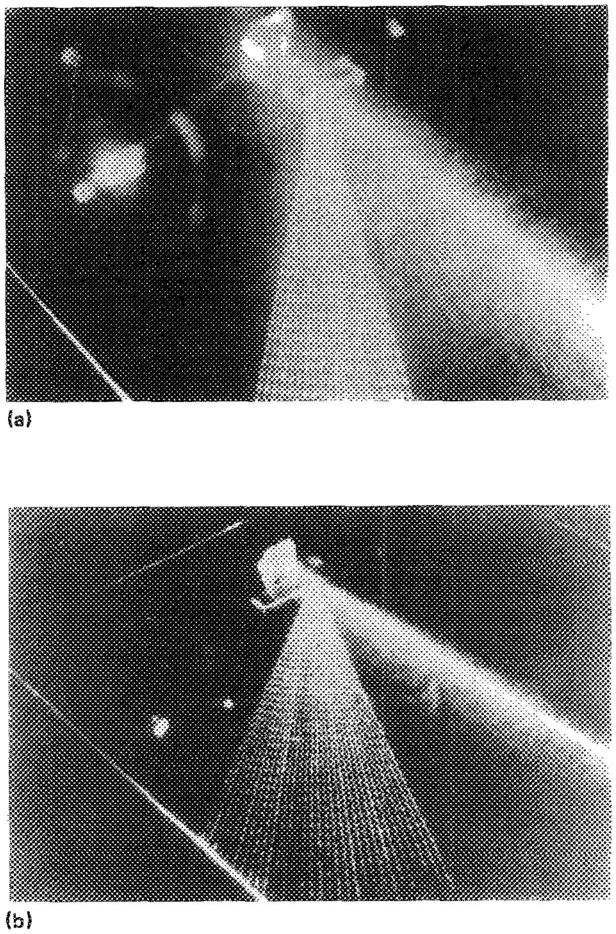


FIG. 3. Massive fanout optical interconnects (a) 1-to-20, (b) 1-to-30. (Prism base length is 1 cm.)

Massive fanout with higher than 95% combined efficiency is theoretically achievable with our present device geometry. Currently, our experimental results give us reproducible data in the neighborhood of 70%. The important features of the aforementioned results are: (1) Employment of high index modulation (up to 0.2) volume holographic material DPG allows us to multiplex many gratings in the same emulsion area[9]; (2) By enlarging the bouncing angle of the substrate guided wave, one can perform intrachip and intrawafer optical interconnects[10] without occupying the chip or wafer surface which is intensively used by electronic components such as logic gates and memory devices; (3) The phase matching condition for substrate wave diffraction can be easily achieved due to the continuous spectrum of the effective index of the substrate mode[7]; and (4) An infinite number of photons can be multiplexed into the same space which implies that a large number of optical paths can overlap one another without any significant interference. This statement is valid for both monolithic and hybrid mode[11] integrated optoelectronic circuitry.

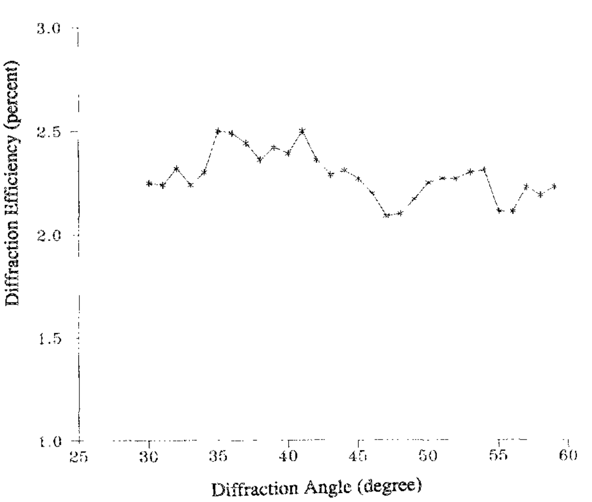


FIG.4. Diffraction efficiency of 30 different beams of the 1-to-30 massive fanouts.

A myriad of applications are plausible based on this technology such as heads-up display, high-speed data bus, surface enhanced Raman spectrometer, and optical sensors. Currently, intrawafer optical interconnects on a semi-insulating GaAs substrate using an aberration-corrected hologram are under investigation. Further results will be presented in future publications.

In summary, we report the first 1-to-30 guided wave intraplane optical interconnects on a thin glass substrate using a multiplexed DCG transmission hologram. The proposed concept can save the surface space of the wafer and can also provide us with large fanout capability due to the high index modulation of DPG. Due to the difference of photons and electrons, an infinite number of optical paths can be overlapped with each other without generating electromagnetic interference (EMI). The limitation of fanouts owing to the availability of maximum index modulation is also addressed. The number of fanouts can be increased by expanding the emulsion thickness, i.e., the interaction length d.[12] Our theoretical study shows that with a 200 μm interaction length d, index modulation as low as 0.0018 is enough to generate 100% diffraction at 30° diffraction angle for a || polarized beam. The number of fanouts is actually a trade-off between index modulation and interaction length. To date, the availability of a high-power laser diode can ease the requirement of a power budget for high-bit-rate communication.[3] The fanout number is mainly limited by the maximum index modulation of the holographic materials.

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