A Holographic Waveguide Microlens Array for Surface-Normal Optical Interconnects

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Abstract—**In this letter, we present an array of holographic focusing lenses for surface normal optical interconnects. The profile-mismatch-induced coupling problem between input lasers and high-speed photodetectors is solved by employing a holographic microlens array. The holographic microlens array demonstrated has 1-mm focal length at the wavelength of 632.8 nm, with a lens-to-lens separation of 0.58 mm. The measured 3-dB focal spot size is determined to be 15μm× 14 μm. The method for designing and recording a substrate mode surface-normal holographic lens array with different recording and readout wavelengths is also presented.**

OVER the past decade, the demand for more computing power has increased to such an extent that multiprocessor system has to be employed in many scenarios. These multiprocessors can be arranged in a single wafer or a single board (as MCM's) and in different board connected by electrical interconnects. As faster the processor speed arises, the electrical interconnects can no longer meet the requirement for high performance multiprocessor systems [1], [2]. The basic limitations of electrical interconnects include interconnection bandwidths, clock skew, resistance-capacitance (RC) time constants and fan-out capability due to the electrical parasitic capacitance, inductance coupling and electromagnetic wave interference [3]. In an effort to increase the interconnection capability, optical interconnection has been considered as an alternative for a long time. Recent development of efficient optoelectronic devices including vertical-cavity surface-emitting lasers (VCSEL's) and high-speed photodetectors has simulated researchers to seek feasible optical solutions. An array of novel optical interconnects using substrate guided waves in conjunction with holographic elements, has been proposed and then reported [4]–[10], which may satisfy the above requirements for high-speed multiprocessor systems. However, there is a coupling mismatch problem between the mode size of a transverse laser beam and the size of a photodetector active region. Such a problem becomes severe when the required interconnect distance becomes longer [11]. For example, the typical divergence angle for a VCSEL having an integrated microlens employed for optical interconnects is 1.9° with a 7-μm output beam diameter [12]. With shch a divergence angle, the beam size could expand to 667 μm over 10-mm interconnection distance at the photodetector end. On the other hand, the diameter of a typical high-speed photodetector to be employed is less than 50 μm. An effective method is certainly needed to solve such profile-mismatch related coupling problems.

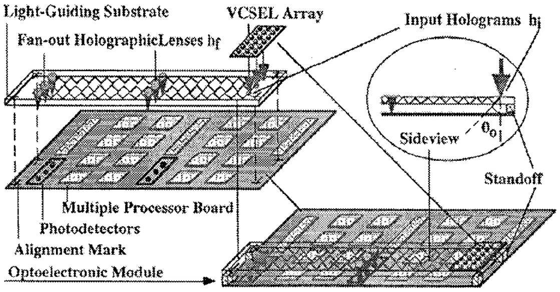

Fig. 1. Schematic of the optoelectronic interconnection bus for multiprocessor board.

In this letter, we present the demonstration of an integrated substrate-guided optoelectronic interconnect in conjunction with an array of holographic focusing lenses. Unlike the previously proposed works [4]–[10], the output beam size is compatible with the size of a high-speed photodetector for effective optical coupling. No additional lenses, such as GRIN lenses and/or planar microlenses, are required as reported in the earlier researches [11], [13]. As a result, the rugged compact packaging can be applied to enhance the packaging reliability at a reduced packaging cost. More importantly, the surface normal feature among the input and output beams and the planar compact device structure convert the difficult three spatial and three angular multiple alignment problem into a single step two-dimensional (2-D) planar one. The method for designing and recording an array of substrate mode surface-normal holographic lenses with different recording and readout wavelengths is presented. An integrated optoelectronic interconnect using substrate modes in conjunction with a surface-normal holographic lens array is also demonstrated experimentally in this paper.

The schematic of the optoelectronic interconnect involving an array of holographic lens presented is depicted in Fig. 1. It consists of a thin glass plate (BK-7) in conjunction with an array of input holographic couplers (h_i's) and output holographic lenses (h_f's). The glass plate is employed as a light guiding substrate. These holographic elements are made

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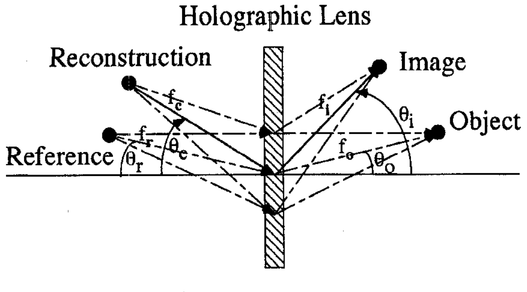


Fig. 2. Recording and readout geometry.

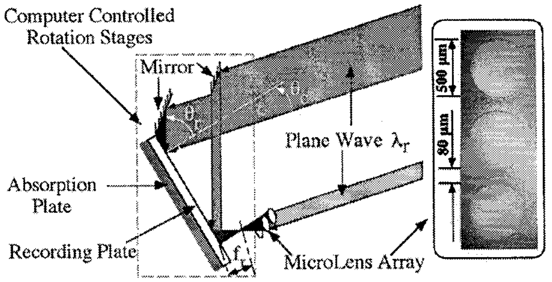


Fig. 3. Schematic of the holographic recording setup. The microlens array employed is also shown.

out of a DuPont holographic thin film laminated to the same surface of the glass substrate. The input holographic coupler of h_i is a volume phase grating designed to couple a surface-normal input laser beam from a VCSEL into a substrate guided wave with a bouncing angle of θ_m. The bouncing angle is designed at 45°, which is larger than the critical angle of the total internal reflection (TIR) of a BK-7 glass substrate ($n = 1.5$). The output holographic lens of h_f's is designed to couple a substrate-guided beam surface-normally out off the substrate with a focal length of f_o.

The DuPont holographic recording film (HRF-600X001-10) is employed that consists of several components including photosensitizing dyes, photoinitiators, chain transfer agents, plasticizers, stabilizers, polymerizable monomers and polymeric binders. It is a tacky thin film (10 μm) sandwiched between a protection base layer with a thickness of 50.8 μm (Mylar$^{\mathrm{R}}$ 200D) and a coversheet with a thickness of 23.4 μm (Mylar$^{\mathrm{R}}$ 92D) [14]. Prior to exposure, the coversheet was removed leaving the tacky photopolymer on its base. The photopolymer was then hand laminated under controlled lighting to the glass substrate using a soft rubber roller. For best quality, this lamination was performed in a clean air laminar flow bench. Note that the glass substrate employed has a refractive index of 1.5 equivalent to the index of DuPont holographic films employed.

To construct the holograms h_i's and h_f's (shown in Fig. 1), the recording and reconstruction phase matching condition in the meridional plane is given by [15]

$$\sin(\theta_i) = \sin(\theta_c) - \frac{\lambda_c}{\lambda_o}[\sin(\theta_o) - \sin(\theta_r)] \tag{1}$$

and

$$\frac{1}{f_i} = \frac{1}{f_c} - \frac{\lambda_c}{\lambda_o}\left(\frac{1}{f_o} - \frac{1}{f_r}\right) \tag{2}$$

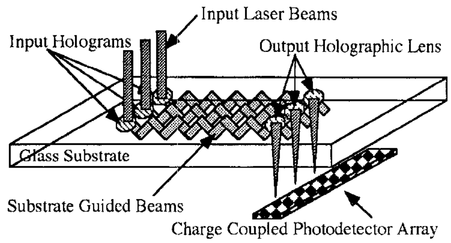
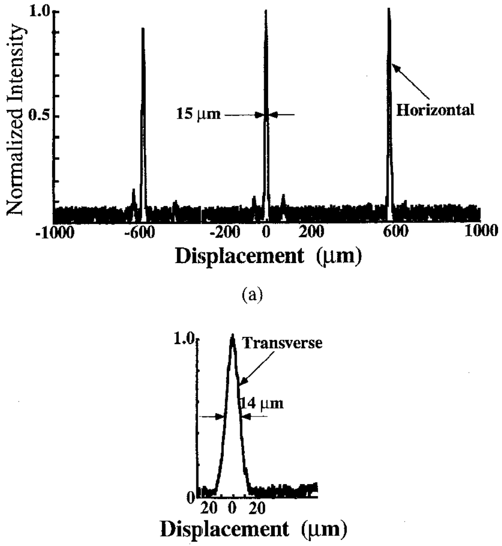


Fig. 4. Schematic diagram of the output beam profile measurement.



(a)

(b)

Fig. 5. Measured focal spot intensity distribution profiles using a linear charge coupled photodetector array. (a) Horizontal direction. (b) Transverse direction.

where f_q ($q = c, i, o, r$; defined in Fig. 2) is the distance between the corresponding point source and the center of the hologram, θ_q ($q = c, i, o, r$) is the respective off-axis angle as shown in Fig. 2. λ_c and λ_o represent the readout and recording wavelengths. In our case, as shown in Fig. 3, we have $f_i = \infty$ and $f_r = \infty$ because a plane wave is employed as the reference wave. Equation (2) thus becomes

$$f_o = (\lambda_c/\lambda_o)f_c. \tag{3}$$

A HeCd laser with an output wavelength of 442 nm is selected to record the required holograms. Reconstruction wavelengths can be designed ranging from 442 nm to 1500 nm, which corresponse to different wavevectors and thus different phase-matching conditions. Fig. 3 is the schematic of the recording setup that employs a microlens array. Because the phase matching condition for holograms h_i's is identical to that of holograms h_f's, except the reconstruction and image waves are exchanged, these two types of holograms h_i's and h_f's can be recorded in a single step as indicated in Fig. 3. The photograph of the analog microlens array employed to form the holographic microlens array is also shown in Fig. 3. Each microlens in the array has a 3 mm focal length and a 0.5 mm diameter. The center-to-center separation between two adjacent lenses is 0.58 mm. It should be noted that the index dispersion of holographic recording films is an important design concern, especially if there is a large difference between the recording wavelength and reading out wavelength. Such a wavelength difference will cause a change in the phase matching condition due to the index change. As a result, both coupling angle and coupling efficiency will be affected for a designed hologram. To obtain a precise design, the index dispersion of the holographic film must be determined and accounted into the phase matching condition.

To demonstrate the proposed concept, a substrate mode optical interconnect was fabricated by using a glass substrate in conjunction with an array of surface-normal holographic input couplers and an array of surface-normal holographic output lenses. All holograms were recorded in a single step at the wavelength of 442 nm and designed to operate at the wavelength of 632.8 nm. Fig. 4 is the schematic diagram used in the device characterization. Surface normal free-space HeNe laser beams with 500-μm beam diameter (1 mW) were coupled into the glass substrate through the input hologram h_i. A substrate guided mode was formed by the total internal reflection, propagating along the substrate at a bouncing angle of 45°. A portion of the substrate guided waves was coupled out of the substrate surface-normally by an output holographic lens h_f having a focal length of 1 mm away from the substrate surface. The output beam profiles were measured by a linear charged coupled photodetector array, mounted on a 5-axis micropositioner (MDT 165). Note that the remaining substrate guided wave can be used for next interconnection stages. In our demonstration, 90% coupling efficiency was obtained for an input hologram h_i. The coupling efficiency for the output lens was designed and fabricated at 25%. An 1-mm-thick BK-7 optical galss plate was employed as a light guiding substrate. A microlens array with a focal length of 3 mm and a diameter of 0.5 mm was employed to generate the object beam as shown in Fig. 3. Fig. 5 was the measured intensity distribution profile of three focused output beams from an array of three holographic lenses, using the linear charge coupled photodetector array. Both horizontal and transverse mode profiles are shown. The beam size measured for each focused output beam was 15 μm along the horizontal direction and 14 μm along the transverse direction.

In summary, we presented some of our effort in design and fabriation of surface-normal optical interconnects using an array of compact holographic lenses. The coupling mode mismatch between an input laser beam having a large spot size and a high-speed photodetector having a small active region is solved in a compact integrated feature. The holograms required for a surface-normal optical interconnect can be recorded in a single step on the same substrate by using an array of analog microlenses. A high coupling efficiency can be obtained for both input holographic couplers and output holographic lenses.

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