

Broad Bandwidth Substrate-Mode Holograms for Optical Interconnects

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ABSTRACT

Broad-bandwidth substrate-mode holograms for optical interconnect applications are investigated. These devices use total internal reflection to translate optical beams, and holographic elements to couple light in and out of the guiding substrate. Transmission and reflection-types of substrate-mode holograms are compared, and the reflection-type of devices give a broader angular bandwidth. The fabrication technique of reflection substrate-mode holograms are discussed and experimental results are given.

1. INTRODUCTION

Since optical interconnects were suggested as a method to improve the performance of very-large-scale-integrated (VLSI) systems,¹ many researchers have been investigating holographic optical elements (HOEs) for this application.²⁻⁹ These elements have several advantages over conventional refractive and reflective components. For example, holographic components can be made which combine several optical functions such as beam splitting and multiple focusing into a single thin film element. However, the area over which imaging or interconnection can be achieved is limited to approximately the size of the aperture by projection effects.³ If large regions must be addressed, the HOE must be positioned at a greater distance from the receiver plane. This makes alignment more difficult. Another problem arises when semiconductor light sources are used with these diffractive elements. The dispersive properties of HOEs and variation in the emission wavelength from a laser diode introduce chromatic aberrations which can seriously degrade the image quality and overall system performance.⁵

In order to reduce image degradation of a holographic element due to misalignment and chromatic dispersion a substrate-mode structure shown in Fig. 1 was induced and have been further investigated.⁴⁻⁸ This component combines totally internally reflected (TIR) beams within a dielectric substrate with several volume holograms which perform different beam directing functions. Light enters the multiplexed hologram normal to the surface and is diffracted into several different directions. Each diffracted beam with a diffraction angle greater than the critical angle within the substrate propagates through the substrate as a TIR guided wave, then illuminates a hololens, and is focused to a detector. This approach has several advantages. First, all holographic elements can be formed in a monolithic block which helps reduce misalignment and mounting problem, and simplifies the fabrication process. Next, the optical beam can be transmitted over a relatively large distance without the need to increase the height of the hologram plate above the detector substrate. Also since pairs of holograms are used, chromatic compensation can be built into the element. This reduces the required size of light receiving detector and improves system performance.⁵

In this presentation transmission and reflection-types of substrate-mode holograms (SMHs) are investigated to provide a broad angular bandwidth of the diffraction efficiency. In our substrate-mode structure, the grating pair can have a flexible combination to perform different optical interconnect configurations. Fig. 2(a) shows two same gratings formed on the same film to perform a transmission propagation, which has been suggested for applications on board-to-board two-way communications.⁸ Fig. 2(b) shows two symmetrical gratings formed on the same film to perform a reflection propagation, which has been suggested for applications on optical holographic backplane interconnect systems.⁹ The design and fabrication technique of these devices will also be discussed.

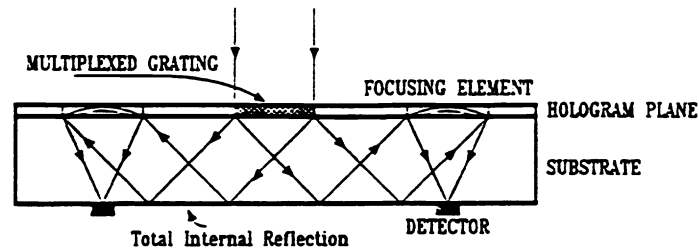


Fig. 1 The basic configuration of substrate-mode holographic optical interconnects.

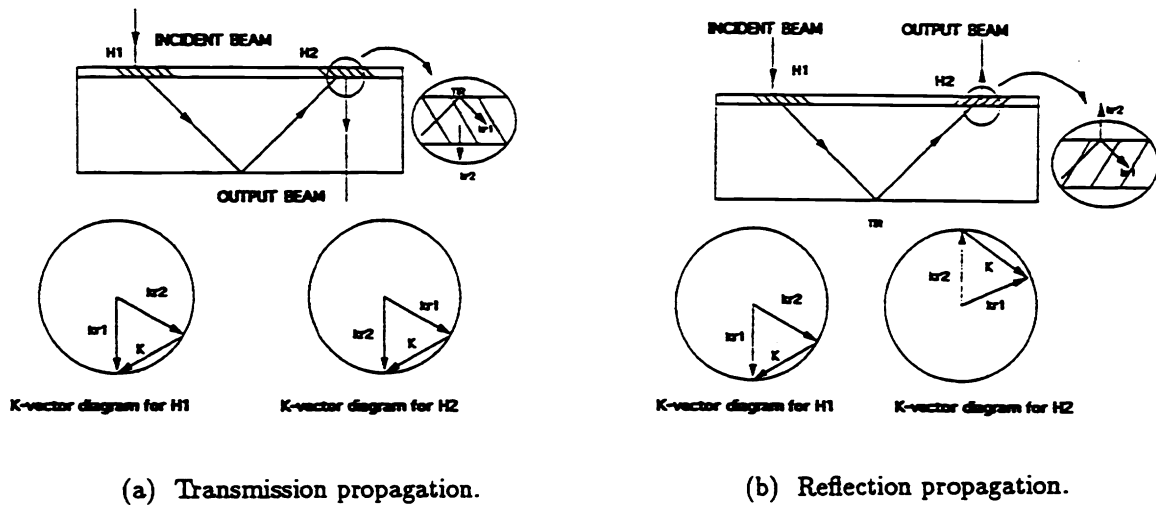


Fig. 2 Optical interconnects with a transmission-type of substrate-mode hologram.

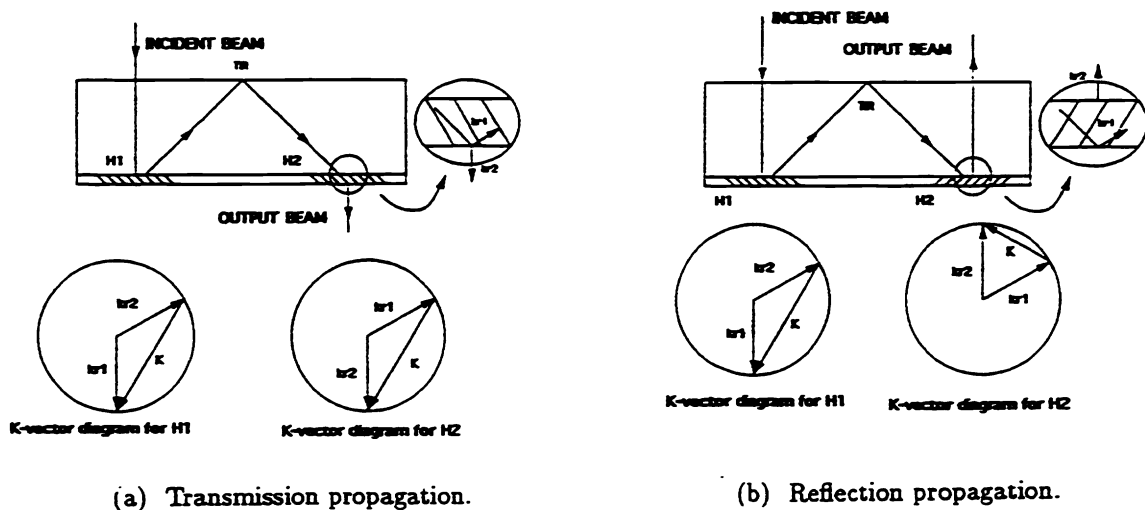


Fig. 3 Optical interconnects with a reflection-type of substrate-mode hologram.

2. TRANSMISSION-TYPE OF SUBSTRATE-MODE HOLOGRAMS

The efficiency of a hologram defined as the diffracted optical power relative to the incident power can be calculated using Kogelnik's coupled wave relation.¹⁰ For a phase modulated transmission-type of hologram the efficiency is given as

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

where

$$\nu = \frac{\pi n_1 d}{\lambda_r (c_R |c_S|)^{\frac{1}{2}}}, \quad (2)$$

$$\xi = \frac{(k_{r1}^2 - k_{r2}^2)d}{4k_{r1}|c_S|}, \quad (3)$$

λ_r is the reconstruction wavelength, d is the emulsion thickness, n_1 is the amplitude of the refractive index modulation, and k_{r1} and k_{r2} are wavenumbers, and c_R and c_S are the obliquity factors of the reconstruction and diffracted beams respectively. When $\nu = (m + \frac{1}{2})\pi$, the diffraction efficiency η reaches a maximum value of 100% at the Bragg condition, i.e. $\xi = 0$, where m is an integer. When the reconstruction beam is not at the Bragg angle due to angular misalignment deviation, ξ is no longer equal to zero and the efficiency is reduced. In this case the efficiency depends on the value of ξ/ν as shown in Eq. (1). Therefore, for a higher value of ν the effect of ξ due to these deviations can be reduced. In our substrate-mode hologram structure, the Bragg reconstruction beam is normal to the substrate and the diffracted beam is 45° in the film. For the hologram with the film thickness of $17 \mu\text{m}$ and the operating wavelength of 780 nm , n_1 is 0.020 for the first peak ($\nu = \pi/2$) and 0.061 for the second peak ($\nu = 3\pi/2$). For dichromated gelatin (DCG) holograms, these index modulation values can be achieved,^{11,12} and the calculated angular sensitivity of the efficiency are illustrated in Fig. 4. The results show that the FWHM (full angular width at half maximum) of 3.5° with n_1 of 0.020 is improved to 6.5° with n_1 of 0.061 . The shorter wavelength recording technique for fabricating transmission-type substrate-mode holograms have been discussed and the bandwidth improvement have been verified.^{6,8}

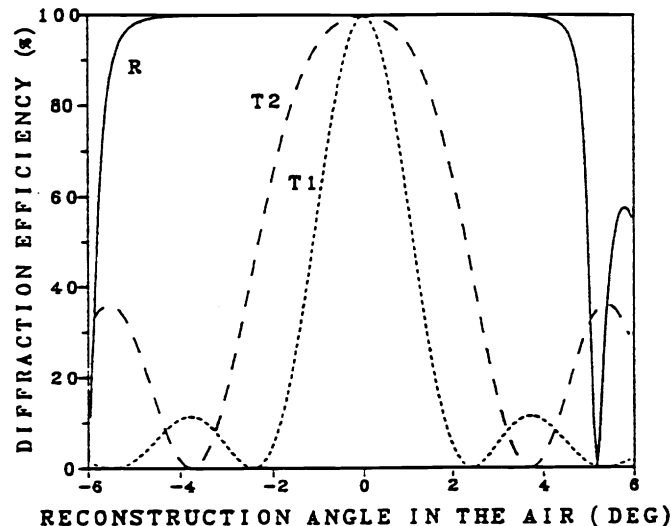


Fig. 4 The calculated diffraction efficiencies of three types of substrate-mode holograms. T₁: transmission-type, $n_1 = 0.020$; T₂: transmission-type, $n_1 = 0.061$; R: reflection-type, $n_1 = 0.070$.

3. REFLECTION-TYPE SUBSTRATE-MODE HOLOGRAMS

2.1 Diffraction efficiency

In order to improve the angular bandwidth of the efficiency further, we are investigating the reflection-type of substrate-mode holograms. For a phase modulated reflection type of hologram, the diffraction efficiency is given as¹⁰

$$\eta = \frac{1}{1 + \frac{1 - \xi^2/\nu^2}{\sinh^2(\nu^2 - \xi^2)^{\frac{1}{2}}}}, \quad (4)$$

where ν and ξ are given by Eqs. (2) and (3) respectively. With a larger index modulation a higher efficiency and broader angular bandwidth can be obtained. Similar to the transmission type of substrate-mode hologram, the designed reconstruction beam is normal to our reflection type of device as shown in Fig. 4. However, the diffraction angle is 45° reflection from the film hologram. Using different combinations of input and output gratings, both transmission and reflection propagation as shown in Figs. 3 (a) and (b) can be performed. With an index modulation of 0.070 and the operating wavelength of 780 nm, the calculated angular sensitivity of the efficiency is also illustrated in Fig. 4. The diffraction efficiency is close to 100% and the angular bandwidth is greater than 12° . This bandwidth is much broader than that of the transmission-type of devices and also provides a better efficiency characteristics as compared in Fig. 4. This gives a much better alignment tolerance of the system. The index modulation value of 0.070 can be achieved with dichromated gelatin (DCG) processing.^{11,12}

3.2 Longer-Wavelength Recording Technique

Fig. 5 shows the construction and Bragg reconstruction geometry in the hologram medium for reflection type substrate-mode hologram. In this figure, $\mathbf{K}$ is the grating vector. For an input-coupling SMH, $\mathbf{k}_{r1}$ and $\mathbf{k}_{r2}$ are wavevectors of the reconstruction and diffracted beams respectively at a wavelength of λ_r , and $\mathbf{k}_{c1}$ and $\mathbf{k}_{c2}$ are wavevectors of the construction reference beam and object beam respectively at a wavelength of λ_c . For an output-coupling SMH, $\mathbf{k}_{r2}$ becomes the wavevector of the reconstruction beam, and $\mathbf{k}_{r1}$ the diffracted beam; similarly $\mathbf{k}_{c2}$ represents the construction reference beam and $\mathbf{k}_{c1}$ the object beam. Hence, in reconstruction,

$$\mathbf{k}_{r1} - \mathbf{k}_{r2} = \mathbf{K}, \quad (5)$$

$$|\mathbf{k}_{r1}| = |\mathbf{k}_{r2}| = \frac{2\pi n}{\lambda_r}, \quad (6)$$

and, in recording,

$$\mathbf{k}_{c1} - \mathbf{k}_{c2} = \mathbf{K}, \quad (7)$$

$$|\mathbf{k}_{c1}| = |\mathbf{k}_{c2}| = \frac{2\pi n}{\lambda_c}, \quad (8)$$

where n is the average refractive index of the grating film.

In our substrate-mode hologram structure, $\mathbf{k}_{r1}$ is normal to the substrate, and the diffracted beam angle in the glass substrate satisfies the condition of total internal reflection. If $\lambda_c = \lambda_r$, then $\mathbf{k}_{c1} = \mathbf{k}_{r1}$ and $\mathbf{k}_{c2} = \mathbf{k}_{r2}$. The wavevector $\mathbf{k}_{c2}$ is at an angle (θ_{c2}) beyond the critical angle, and this grating cannot be constructed without using a prism to directly guide the beam into the medium at this angle. When a longer wavelength is used for recording, i.e. $\lambda_c > \lambda_r$, the lengths of $\mathbf{k}_{c1}$ and $\mathbf{k}_{c2}$ become shorter, and the angle of defined by $\mathbf{k}_{c1}$ and $\mathbf{k}_{c2}$ becomes greater, and the angle defined by $\mathbf{k}_{c2}$ and the plate normal becomes smaller. When the angle defined by $\mathbf{k}_{c2}$ and the plate normal is smaller than the critical angle, this grating can be formed with two free-space input beams.

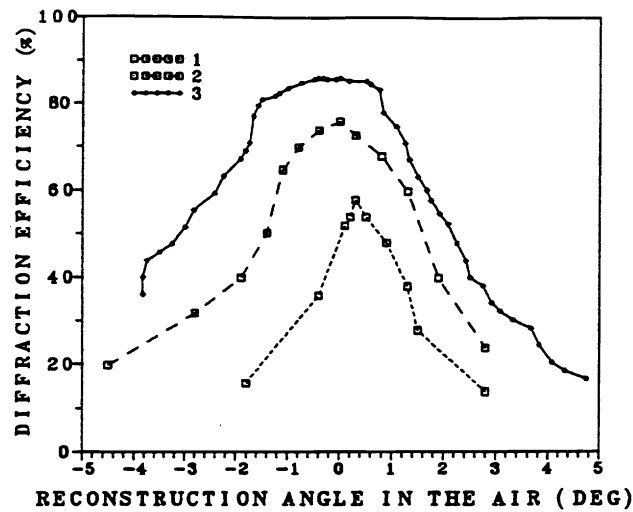
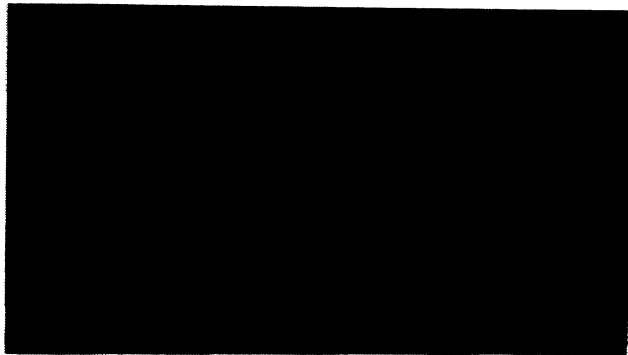
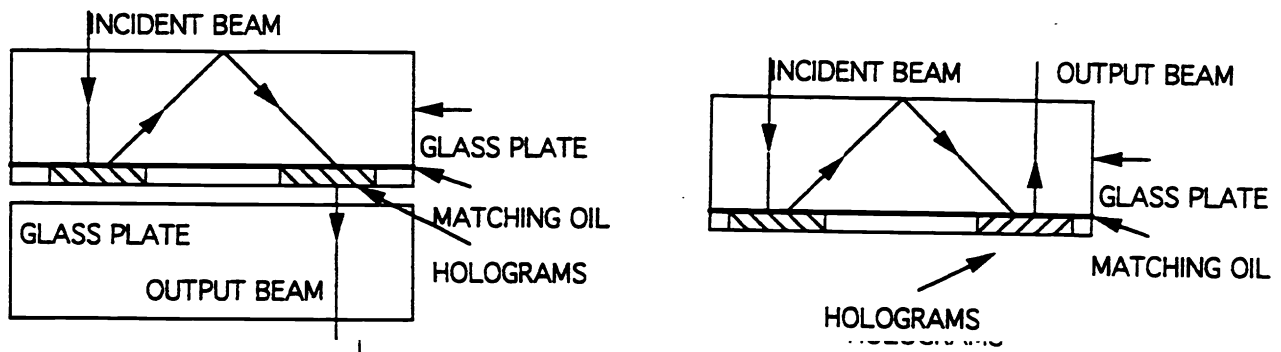
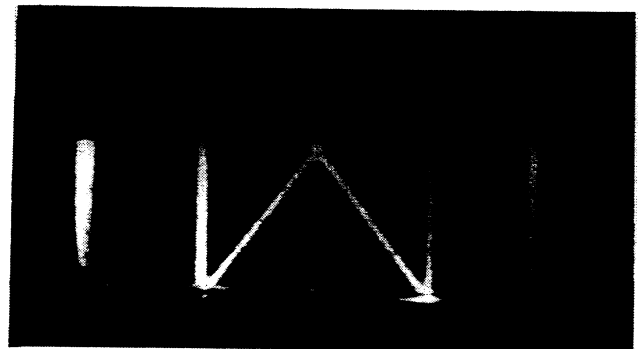


Fig. 7 The measured angular sensitivity of the diffraction efficiency for a reflection SMH.



(a) Transmission propagation.



(b) Reflection propagation.

Fig. 8 The photograph of the beam propagation through a reflection SMH.

5. SUMMARY

In summary, substrate-mode holograms for optical interconnect applications are discussed. Several different types of these elements are compared. A reflection-type of substrate-mode hologram is introduced

to provide a broad angular bandwidth of high diffraction efficiency. Both transmission and reflection propagation can be performed with these elements. The longer-wavelength recording technique for a reflection SMH is discussed and experimental results are given.

6. ACKNOWLEDGEMENT

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