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Substrate mode hologram for optical interconnects

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Abstract

A novel method of substrate mode hologram (SMH) design and fabrication is presented. The coupling between a homogeneous plane wave and an arbitrary free propagating wave is achieved via a total internally reflected (TIR) wave. The input slanted plane grating, recorded in an orthochromatic holographic medium, accomplishes the homogeneous plane wave to TIR wave coupling. The TIR wave is transformed to the free propagating wave by the output aperiodic aplanar inhomogeneous grating recorded in a panchromatic holographic medium. Aberration-free conversion between the incident plane wave and the Gaussian wave is reported for coupling efficiency of 57%. © 1998 Elsevier Science B.V.

1. Introduction

A variety of holographic techniques employing the total internally reflected wave have been proposed since 1967, when the method for hologram recording using a TIR wave was introduced by Stetson [1]. The U.S. patent due to Phillips [2] discloses a method of manufacturing integrating circuits using a holographic technique in which a wave total internally reflected in the emulsion–air interface has been used as a reference beam. This recording method permits to perform a very close spacing between the object and the hologram, leading to the possibility of achieving the diffraction limited resolution owing to the aberration reduction. The edge-illuminated holograms, proposed by Lin [3], have been extensively analyzed by Upatnieks [4–7], Benton and Birner [8] and Huang and Caulfield [9]. Potential applications of Holographic Optical Elements (HOEs) in various hierarchical levels of optical interconnections (e.g. intra-chip, intra-MCM (Multi-Chip Module), or inter-MCM), estimulated recently the research of TIR wave diffraction by SMHs [10–13]. Kostuk et al. [12] have analyzed experimentally the properties of SMHs recorded in 8E56HD (Agfa-Gevaert) holographic plates. In principle, using a reconstruction wavelength different from the one employed during hologram recording in combination with emulsion shrinkage (after the rehalogenating bleaching process), the total internal reflection condition can be satisfied for the beam diffracted within the holographic plate substrate. However, difficulties arise if a precise control and a high repeatability of the reconstruction angle are required, or if one works with uncollimated beams (coupling to or from optical waveguides, coupling from semiconductor lasers or LEDs, etc.). If the coupling grating is aperiodic and aplanar and if the reconstruction wavelength differs from the recording one, a decrease in the diffraction efficiency accompanied by severe aberrations can be expected [14]. In this paper a simple and easily implementable solution in order to overcome the mentioned problems is presented. A two-step two-wavelength hologram recording process is proposed. First, the input coupler holographic slanted planar grating is recorded by radiation of wavelength λ_0 (514.5 nm in this experiment). The angles of incidence for the two recording beams are chosen in order to satisfy the condition of total internal reflection of the Bragg-diffracted beam during the hologram reconstruction process performed at wavelength λ (632.8 nm in this experiment). In the second step, the TIR wave reconstructed by the input coupler hologram is used as a reference wave for the output coupler hologram recording. In this step, an object wave with arbitrary phase and amplitude can be used. The inhomogeneous character of the phase and amplitude functions of the object wave

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determines the aperiodic, inhomogeneous and aplanar character of the output coupler grating. During the reconstruction of the output coupler hologram by a TIR wave of wavelength λ (identical to the recording wavelength for this hologram), high-efficient abberation-free coupling is obtained.

2. Input coupler hologram

The input coupler grating should accomplish an efficient coupling between the incident homogeneous plane wave and the total internally reflected wave. The grating recording and reconstruction geometry is presented in Fig. 1. Two plane waves of wavelength λ_0 with associated wave vectors $\boldsymbol{k}'_{10}$ and $\boldsymbol{k}'_{20}$ are striking asymmetrically on the holographic emulsion (refraction index n_e, thickness T_e) from the incident medium (air, refraction index $n_a \approx 1$). The refracted waves with wave vectors $\boldsymbol{k}_{10}$ and $\boldsymbol{k}_{20}$ are coherently superposed within the holographic emulsion, giving rise to a periodic interference pattern of spatial period Λ'. After the holographic processing of the emulsion, a slanted plane grating of spatial period Λ (grating vector $\boldsymbol{K}$) can be obtained. In the experiment described in this paper, the appropriate holographic processing technique (a fixation free rehalogenating bleaching) is chosen in order to avoid emulsion shrinkage or swelling and, consequently, it can be assumed that $\Lambda = \Lambda'$.

We consider that the grating is illuminated by a plane wave of wavelength λ (wave vector $\boldsymbol{k}'_1$). With regard to the practical implementation of the coupler, it is convenient to choose $\boldsymbol{k}'_1$ orthogonal to the air–holographic emulsion interface. The refracted incident wave with wave vector $\boldsymbol{k}_1$ is diffracted by the grating. If the Bragg condition is satisfied for the -1st diffraction order, one can expect an efficient coupling between the incident wave and the diffracted field. If, moreover, the angle $\tilde{\gamma}_2$ exceeds the critical angle γ_c for the substrate–air interface ($\gamma_c = \arcsin(n_a/n_s)$, n_s is the substrate refraction index, T_s is the substrate thickness, see Fig. 1), then the -1st diffraction order is totally reflected in this interface. From the momentum conservation conditions for the recording and the reconstruction waves:

$$\boldsymbol{k}_{20} - \boldsymbol{k}_{10} = \boldsymbol{k}_2 - \boldsymbol{k}_1 = \boldsymbol{K}, \tag{1}$$

one can obtain easily the two following equations for γ_{10} and γ_{20}:

$$\frac{\lambda_0}{\lambda} = \frac{\sin\gamma_{20} - \sin\gamma_{10}}{\sin\gamma_2}, \tag{2}$$

$$\frac{\lambda_0}{\lambda} = \frac{\cos\gamma_{20} - \cos\gamma_{10}}{\cos\gamma_2 - 1}. \tag{3}$$

From Eqs. (2) and (3), the recording angles γ_{10} and γ_{20} can be calculated. If, moreover, the condition for total reflection holds:

$$\gamma_2 > \arcsin\left(\frac{n_s}{n_e}\sin\gamma_c\right), \tag{4}$$

the input coupler grating construction geometry is uniquely determined for a fixed value of γ_2.

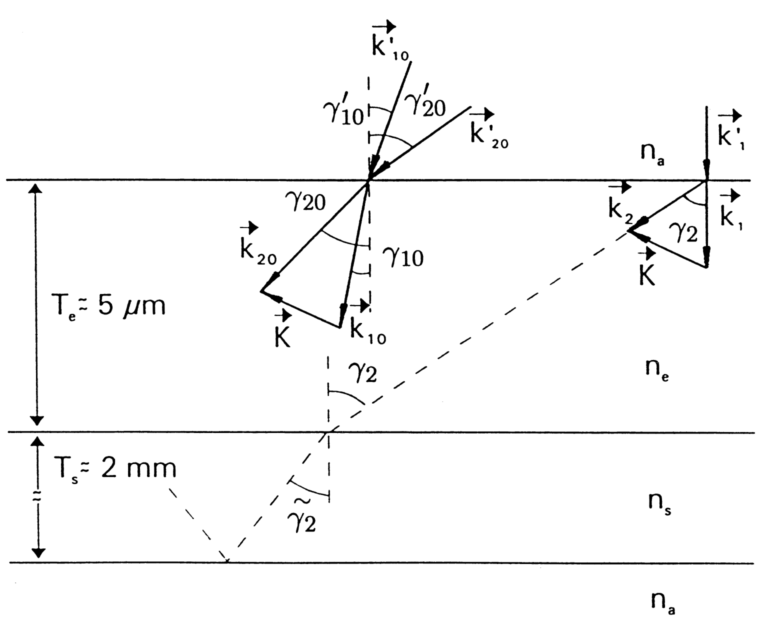

Fig. 1. The input coupler hologram recording and reconstruction geometry (see text for details).

3. Output coupler hologram

The output coupler hologram recording geometry has been chosen as in Fig. 2, attempting to achieve aberration-free coupling between a TIR wave and an arbitrary free-propagating wave. The TIR wave can be considered as the reference wave and the free-propagating wave with amplitude $a(\boldsymbol{r})$ and phase $p(\boldsymbol{r})$ functions, as the object wave. As the functions $a(\boldsymbol{r})$ and $p(\boldsymbol{r})$ are arbitrary, the output coupler grating can be in general aperiodic, inhomogeneous and aplanar. In order to avoid chromatic aberrations during the output coupler hologram reconstruction, a replay wavelength identical to the recording one should be used. In that case, the object wave properties ($a(\boldsymbol{r})$ and $p(\boldsymbol{r})$) can be exactly reconstructed if the reconstruction TIR wave is identical to the reference wave. In this experiment, the object wave (from a monomode optical fibre) was a free-propagating wave with Gaussian amplitude distribution and spherical phase function. The TIR reference wave was coupled into the substrates by the input coupler. The recording and reconstruction wavelength was $\lambda = 632.8$ nm.

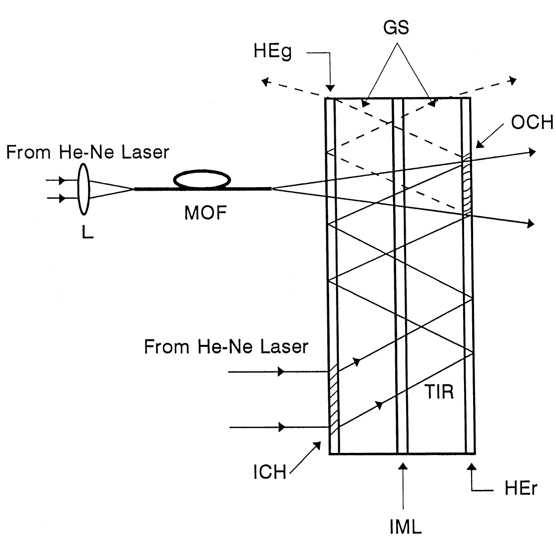

Fig. 2. The experimental setup for the output coupler hologram recording. During the recording process, the TIR wave coupled into the glass substates interferes at the output coupler area of the red sensitive holographic emulsion with the object wave proceeding from the monomode optical fibre. During the reconstruction process, the TIR wave is diffracted by the output coupler hologram. HE_g, HE_r – green and red sensitive holographic emulsions, respectively; GS – glass substrate; L – lens; MOF – monomode optical fibre; ICH – input coupler hologram; OCH – output coupler hologram; IML – index matching liquid; TIR – total internally reflected wave.

4. Experimental results

The substrate mode hologram has been constructed in two steps (the input coupler and the output coupler).

The input coupler hologram has been recorded in green-sensitive silver halide holographic plates 8E56HD (Agfa-Gevaert) and in dichromated gelatin (DCG) emulsion derived from the Kodak 649F spectroscopic plates. An asymmetric two-beam interferometric setup has been used to generate a slanted plane Bragg grating (see Fig. 1). The incidence angles $\gamma'_{10} = \arcsin[(n_e/n_a)\sin\gamma_{10}]$ and $\gamma'_{20} = \arcsin[(n_e/n_a)\sin\gamma_{20}]$ have been calculated from Eqs. (2) and (3) ($\gamma'_{10} \approx 6°$ and $\gamma'_{20} \approx 70°$ for $\tilde{\gamma}_2 = 43°$, $n_a = 1$ and $n_e = n_s = 1.51$). Various gratings have been recorded in the 8E56HD plates using an Ar^+ laser beam ($\lambda_0 = 514.5$ nm) with irradiance $I = 460$ μW cm^{-2}, varying the total exposure level. After the exposure, the following developer recommended by Phillips especially for Agfa and Ilford materials [15], has been used:

Part A:

catechol	20 g,
hydroquinone	10 g,
sodium sulfite	60 g,
distilled water	1 l.

Part B:

sodium carbonate	120 g,
distilled water	1 l.

Mix solutions $A + B$, were used at 21 to 23°C, after achieving optical density of ≈ 2, and washed in deionized water for 1 min. In order to obtain the maximum diffraction efficiency, the developed samples were processed using the fixation-free rehalogenating ferric EDTA (ethylenediaminetetraacetic acid) bleaching solution mixed in the following way:

ferric sulfate	30 g
disodium EDTA	20 g
sulfuric acid	10 ml
potassium bromide	30 g
distilled water	1 l.

Bleaching was followed by washing in deionized water (3 min), soaking in humectant solution (Photoflo, ≈ 10 s) and drying in normal ambient conditions (22°C, 40% RH). The input coupler diffraction efficiency has been determined by He-Ne laser beam (632.8 nm) diffraction and using the following formulas:

$$\eta = \frac{P_t - P_0}{P}, \quad (5)$$

$$\eta_c = \frac{P_t - P_0}{P_t}, \quad (6)$$

where P_0 is the radiant flux of the zeroth diffraction order, P_t is the radiant flux transmitted by the emulsion closed to

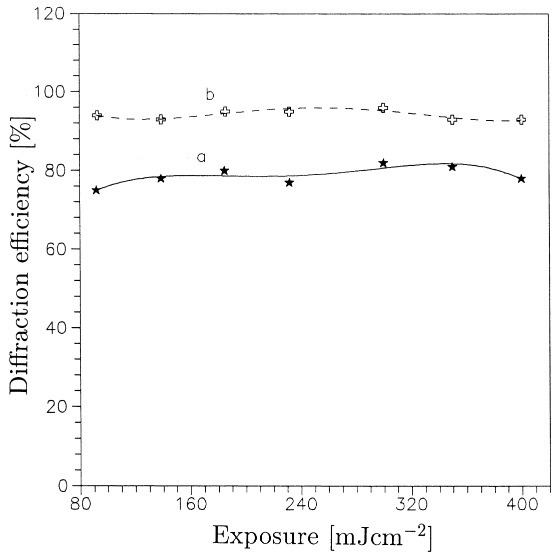

Fig. 3. The DCG input coupler hologram diffraction efficiency. $I = 30$ mW cm^{-2}. Curve a: efficiency η; curve b: efficiency η_c.

(but not within) the grating area during illumination by the incident radiant flux P. As it can be observed, η_c is a corrected diffraction efficiency, where losses due to absorption, scattering and Fresnel reflection have been elliminated. The maximum values of $\eta \approx 61\%$ and $\eta_c \approx 97\%$ were obtained for exposure $E \approx 160$ μJ cm^{-2}.

The DCG input coupler hologram has been recorded using the setup of Fig. 1, with irradiance level $I \approx 30$ mW cm^{-2} ($\lambda_0 = 514.5$ nm). The DCG emulsion has been obtained from the Kodak 649F plates using the modified desensitization procedure [16]:

1. soak in Unifix (Kodak)	15 min
2. soak in Unifix + 3% (weight) alum	15 min
3. wash in deionized water	15 min
4. wash in 100% methanol	15 min
5. wash in 100% clean methanol	15 min
6. dry at 22 °C and 40% RH	> 15 h,

where alum is aluminum potassium sulfate. Dry gelatin emulsions were sensitized as follows:

7. soak in ammonium dichromate 5% (weight) + Photoflo	10 min
8. dry at 22 °C and HR = 40%	6 h.

The plates, once exposed to the actinic radiation, were developed in the following steps:

9. wash in deionized water	1 h
10. dehydrate in 50% isopropanol	2 min
11. dehydrate in 90% isopropanol	2 min
12. dehydrate in 100% isopropanol	5 min
13. dry at 22 °C and HR = 40%	> 15 h.

Fig. 3 represents the DCG input coupler hologram diffraction efficiencies η (curve a) and η_c (curve b) measurement data as a function of the recording exposure E. Very low variations in η and η_c can be observed for a range of E from 90 to 400 mJ cm^{-2}. Maximum input coupler diffraction efficiencies of $\eta = 82\%$ and $\eta_c = 96\%$ have been determined for an exposure of $E \approx 300$ mJ cm^{-2}.

The output coupler hologram has been recorded in the red-sensitive silver halide holographic plate 8E75HD (Agfa-Gevaert). Various gratings have been recorded following the geometry of Fig. 2. The unexposed 8E75HD plate has been stacked with the plate corresponding to the input coupler grating, introducing the index matching liquid (xylene, $n = 1.449$) between the two substrates. The reference He-Ne laser beam is diffracted by the input coupler grating and guided via succesive total internal reflection towards the output coupler zone where it interferes with the object beam (from the monomode optical fibre). As it has been mentioned in Section 3, a wave with arbitrary amplitude and fase distributions can be employed as the object wave. The beams having the following irradiances were used during the recording process: $I_1 \approx 35$ μW cm^{-2} (Gaussian beam, I_1 was measured in the central zone of the beam), $I_2 \approx 35$ μW cm^{-2} (TIR wave). A holographic processing identical to that used for the green-sensitive silver halide plates (8E56HD) was followed. Fig. 4 represents the dependence of η (curve a) and η_c (curve b) on the exposure E. The Gaussian beam ($\lambda = 632.8$ nm), identical to the object wave, was used as the reconstruction wave during the diffraction efficiency measurement. The maximum measured output coupler

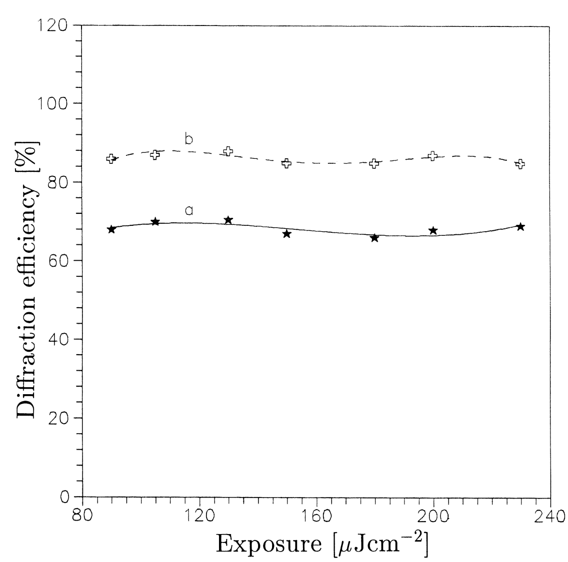

Fig. 4. The silver halide output coupler hologram diffraction efficiency. $I = 70$ μW cm^{-2}. Curve a: efficiency η; curve b: efficiency η_c.

hologram diffraction efficiencies were $\eta \approx 70\%$ and $\eta_c = 88\%$ for $E \approx 130$ μJ cm^{-2}.

Finally, the input and the output coupler holograms exhibiting maximum diffraction efficiency were sandwiched and cemented by an index matching adhesive (TRA-BOND). The coupling efficiency between the incident plane wave and the Gaussian wave (via TIR wave) was determined to be 57%.

5. Conclusions

A simple and easy implementable solution for design and fabrication of a specific type of substrate mode hologram has been proposed. In particular, high-efficient aberration-free coupling has been accomplished between a homogeneous plane wave and a free propagating wave via a total internally reflected wave. Coherent radiation of two different wavelengths (514.5 nm and 632.8 nm) has been used for holographic recording of the input and output couplers, respectively. This two-wavelength approach permits aberration-free reconstruction of the output-coupled wave of arbitrary phase and amplitude distributions. The technique can be applied to optical interconnections for various hierarchic levels (intra-chip, intra-Multi-Chip Module (MCM), inter-MCM) of electronic systems.

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References

[1] K.A. Stetson, Appl. Phys. Lett. 11 (1967) 225.
[2] N.J. Phillips, Manufacture of integrated circuits using holographic techniques, U.S. Patent 4,857,425, 1989.
[3] L.H. Lin, J. Opt. Soc. Am. 60 (1970) 714.
[4] J. Upatnieks, in: I. Cindrich (Ed.), Holographic optics: design and applications, SPIE vol. 883, 1988, p. 171.
[5] J. Upatnieks, Method and apparatus for recording and displaying edge-illuminated holograms, U.S. Patent 4,643,515, 1987.
[6] J. Upatnieks, J. Opt. Soc. Am. A 2 (1985) 86.
[7] J. Upatnieks, Appl. Optics 31 (1992) 1048.
[8] S.A. Benton, S.M. Birner, A. Shirakura, in: S.A. Benton (Ed.), Practical holography IV, SPIE vol. 1212, 1990, p. 149.
[9] Q. Huang, H.J. Caulfield, in: S.A. Benton (Ed.), Practical Holography V, SPIE vol. 1461, 1991, p. 303.
[10] J. Jahns, A. Huang, Appl. Optics 28 (1989) 1602.
[11] P. Cinato, K.C. Young, Opt. Eng. 32 (1993) 852.
[12] R.K. Kostuk, Y.-T. Huang, D. Hetherington, M. Kato, Appl. Optics 28 (1989) 4939.
[13] Q. Huang, J.A. Gilbert, Opt. Eng. 34 (1995) 2891.
[14] P. Cheben, Contribution to the study of light diffraction by volume gratings [in Spanish], Ph.D. Dissertation, Faculty of Physics, Complutense University, Madrid, Spain, 1996.
[15] N. Phillips, in: T.H. Jeong (Ed.), Proc. Intern. Symp. on Disp. Hol., Proc. Lake Forest College, IL 60045, vol. 3, 1989, p. 35.
[16] M. Ulibarrena, Tarea Optkodak, internal report, Empresa Nacional de Óptica, Madrid, Spain, 1990.
[17] P. Cheben, T. Belenguer, A. Nuñez, M.L. Calvo, in: 17th Congress of the International Commision for Optics: Optics for Science and New Technology, Proc. SPIE vol. 2778, 1996, p. 153.