PERGAMON

Materials Science in Semiconductor Processing 3 (2000) 455–458

MATERIALS SCIENCE IN SEMICONDUCTOR PROCESSING

Compact and dynamic optical bypass-exchange switch

R. Oron*, W.H. Huang, E. Jönnson, Y. Amitai, A.A. Friesem

Department of Physics of Complex Systems, Weizmann Institute of Science, Rehovot 76100, Israel

Abstract

A novel, compact and dynamic optical bypass-exchange switch is presented. It is based on a planar optics configuration with polarization-sensitive linear grating holographic optical element, and a polarization rotator light modulator. Representative switches were designed, fabricated and experimentally evaluated. The results indicate that relatively low crosstalk level can be reached to make such switches suitable for practical optical interconnect networks. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Planar optics; Holographic optical elements; Optical bypass-exchange switches; Optical interconnects

1. Introduction

Optical cross-bar and bypass-exchange switches for optical interconnects have been extensively investigated over the last decades [1–4]. Those that are potentially more efficient in terms of light throughput are based on polarization [3,4]. All, however, involve free-space optics, so they are relatively cumbersome and usually not practical for most applications.

Here we present a novel, compact dynamic bypass-exchange switch. It exploits planar optics configuration that can be modularized and cascaded, and a liquid crystal cell that can rotate the polarization of the incident light.

2. Basic optical configuration

The compact optical bypass-exchange switch configuration is presented in Fig. 1. It is comprised of two substrates on each of which are recorded four holographic optical elements (HOEs), and a dynamic $\lambda/2$ polarizer. The HOEs H_1 and H_2 are linear diffractive gratings that couple the input waves, one having s-polarization and the other p-polarization, into a planar substrate, with an off-axis angle inside the substrate set at 45°. The internal waves propagate inside the substrate, by total internal reflection, to a polarization-sensitive HOE H_3 where they are combined. This HOE has a high diffraction efficiency for one polarization and negligible diffraction efficiency to the other. The adjacent HOE H_4 couples the waves out of the first substrate, towards a dynamic $\lambda/2$ polarizer. This polarization can be controlled so as to rotate by 90° the polarization of the incident light, i.e. incident light with s-polarization emerges as light with p-polarization. After passing through the polarizer, the waves are coupled into a second substrate by the HOE H_5. The adjacent HOE H_6 has a polarization-sensitive diffraction efficiency as H_3. The HOEs H_7 and H_8 couple the light out of the substrate onto the detectors.

3. The basic and polarization-sensitive HOEs

Consider the simple linear grating HOE that is recorded in thick materials, with the readout ray geometry shown in Fig. 2. The grating coupling coefficients for the s- and p-polarizations [5] are

$$\varphi_s = \frac{\pi v_1 D}{\lambda\sqrt{\cos\alpha_s \cos\alpha_r}} \quad \text{and} \quad \varphi_p = -\varphi_s(\mathbf{r}\cdot\mathbf{s}) \tag{1}$$

where v_1 is the maximum modulation of the refractive index of the recording material, D is the thickness of the

*Corresponding author. Tel.: +972-8-9342695; fax: +972-8-9344109.

E-mail address: ram.oron@weizmann.ac.il (R. Oron).

PII: S1369-8001(00)00073-1

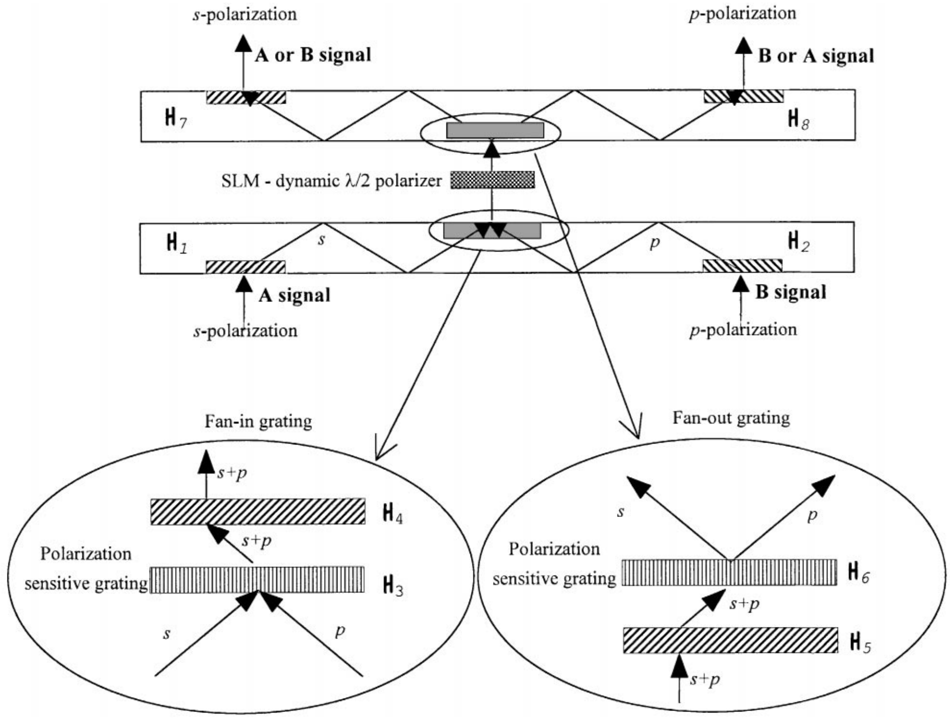

Fig. 1. The compact optical bypass-exchange switch configuration.

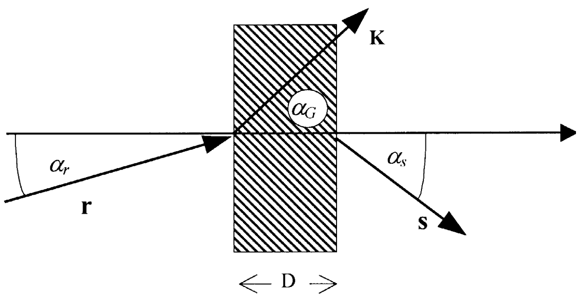

Fig. 2. Schematic geometry of a thick phase transmission hologram.

recording material, **r** and **s** are the unit vectors of the readout and the signal rays, respectively, and α_r, and α_s, are the off-axis angular orientations of the readout and signal waves inside the recording materials. The diffraction efficiency of the HOE is given by

$$\eta = \frac{\sin^2\sqrt{\varphi^2+\psi^2}}{1+(\psi^2/\varphi^2)}, \tag{2}$$

where ψ is the Bragg deviation coefficient, defined as

$$\psi \equiv \frac{(\alpha_r - \alpha_r^B)\mathbf{K}D\sin(\alpha_G - \alpha_r^B)}{2\cos\alpha_s} - \frac{(\lambda-\lambda^B)\mathbf{K}^2D}{8\pi\nu\cos\alpha_s}. \tag{3}$$

In Eq. (3), **K** is the three-dimensional grating vector of the HOE, λ and λ^B are the actual and the designed readout wavelengths, α_G is the angular orientation of the grating vector, and α_r^B the angular orientation of the designed readout beam.

Exact Bragg conditions, namely, $\psi = 0$, yields a diffraction efficiency of

$$\eta_{s,p} = \sin^2(\varphi_{s,p}). \tag{4}$$

Since in accordance with Eq. (1), the coupling coefficients for the p- and s-polarizations differ, it can be deduced from Eq. (4) that the diffraction efficiencies for the s- and p-polarizations will also be different. This is illustrated in Fig. 3 for a thick phase transmission linear grating HOE, with $D = 15\,\mu m$; $\alpha_r = 0$; $\alpha_s = 45°$; $\lambda = 850\,nm$; $\nu = 1.51$, where ν is the average refractive index, and the angle α_s is *inside* the emulsion. Consequently, the signal wave is trapped inside the substrate due to total internal reflection.

There are two situations where the HOE can have high polarization-selective characteristic [6]. In one

$$\eta_s = 100\% \text{ and } \eta_p = 0\%, \tag{5}$$

with $\varphi_s = (n+0.5)\pi$ and $\varphi_p = n\pi$. In the other

$$\eta_s = 0\% \text{ and } \eta_p = 100\% \tag{6}$$

with $\varphi_s = n\pi$ and $\varphi_p = (n+0.5)\pi$, where n is a natural number. For the readout angular orientation of $\alpha_r = 0 \Rightarrow \cos\alpha_r = 1$, the angular orientation of the signal beam with the s-polarization is

$$\alpha_s = \arccos\frac{n}{n+0.5}, \quad \frac{v_1 D}{\lambda} = \sqrt{n(n-0.5)}. \tag{7}$$

Similarly, with the p-polarization it is

$$\alpha_s = \arccos\frac{n-0.5}{n}, \quad \frac{v_1 D}{\lambda} = \sqrt{n(n+0.5)}. \tag{8}$$

Another situation for obtaining high polarization-selective characteristics from a HOE is by recording it in such geometry, so that the reconstructed wave would be normal to the readout wave [7]. In this case, the unit-vector of these two waves fulfills the condition $\mathbf{r}\cdot\mathbf{s}=0$. Thus, Eq. (1) yields $\varphi_p = 0$ so the diffraction efficiency for the p-polarization is zero ($\varphi_p = 0$). Here, the diffraction efficiency does not depend on parameters, which are difficult to control precisely, like index modulation or emulsion thickness, but only on the readout geometry, which can be precisely and easily controlled.

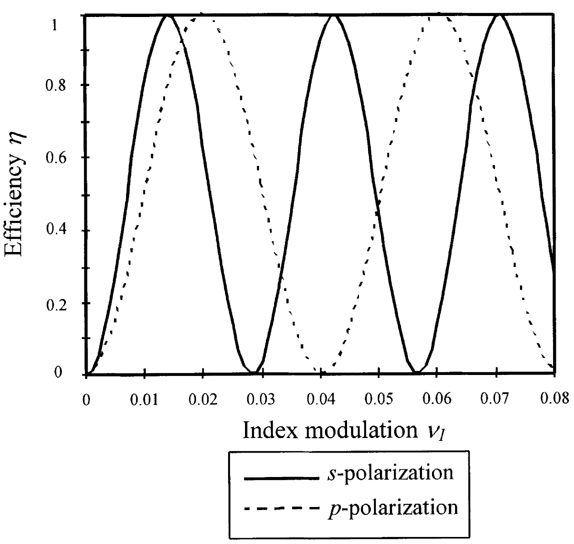

Fig. 3. Diffraction efficiencies of a thick phase transmission HOE for s- and p-polarizations.

4. Experimental procedure and results

For our experiments, we recorded the HOEs on Agfa holographic plates with silver halide photographic emulsions (8E75). These have little, if any, birefringence. A krypton laser ($\lambda = 647.1$ nm) served both for recording and readout. In order to obtain the configuration shown in Fig. 1, it was necessary to record the HOEs on three separate substrates (photographic plates), and attach them afterwards. To ensure that the internal waves will be trapped inside the substrate, the HOEs were recorded with a prism, as shown in Fig. 4. The polarization-sensitive HOE was recorded on the middle plate, as shown in Fig. 4(a). This plate was sandwiched between two plates on which three input- or output-coupling HOEs were recorded. These simpler HOEs were recorded as shown in Fig. 4(b). The distance between the two input HOEs, H_1 and H_2 was 32 mm and the overall length of the bypass-exchange switch was approximately 30 mm. We used a developing process, which minimizes shrinkage of the emulsion. This undesired shrinkage cause changes in the readout Bragg angle, thereby degrading the throughput light efficiency of the switch. Specifically, we used a developer that contained non-complexing developing agents, such as ascorbic acid and metol. These do not remove any material from the emulsion, so no shrinkage occurs. Bleaching was performed with ethylene-diamine-tetra-acetic acid (EDTA), which removes the silver from the negative fringes and deposits it as silver bromide on the positive fringes, again, not removing material. The active component of the switch was a ferro-electric liquid-crystal light modulator (LM), which can reach a 1000:1 cross-talk ratio, and switching rates of 40 kHz [8].

In order to evaluate the operation of the bypass-exchange switch we measured the crosstalk between the

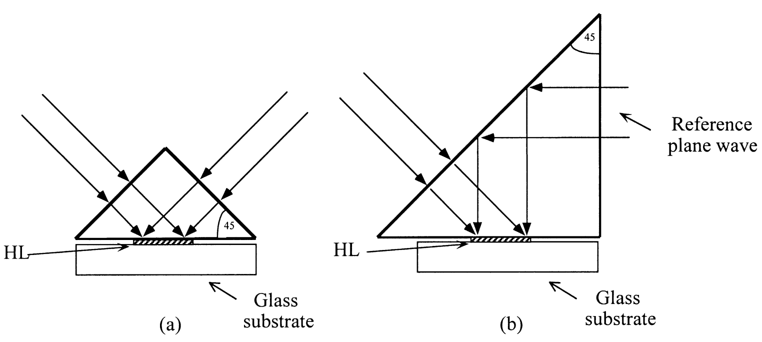

Fig. 4. Recording geometries for the HOEs: (a) polarization-sensitive HOEs; (b) input- or output-coupling HOEs.

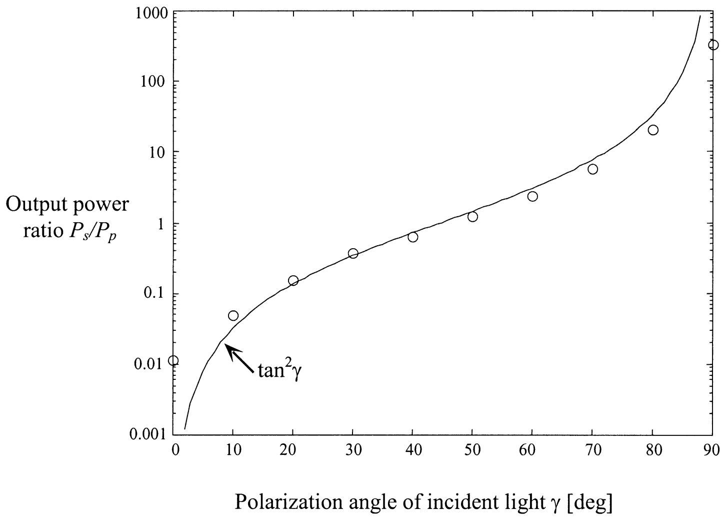

Fig. 5. Power ratio between the two output beams as a function of the input polarization angle γ. The solid line corresponds to the theoretical value of $\tan^2\gamma$.

two polarizations in each substrate. This was done by varying the polarization of the plane wave incident on either H_3 or H_4 combination or H_5 or H_6 combination, and measuring the output power of the beams emerging from the two output HOEs, each having a different polarization. The ratio between these powers as a function of polarization angle of the incident beam is shown in Fig. 5. Theoretically, with no crosstalk, the power ratio should act like $\tan^2\gamma$, where γ is the linear polization angle. As evident, there is good agreement between the experimental measurements and the $\tan^2\gamma$ graph. At the two extremes, when either the incident light is p-polarized ($\gamma = 0$) or s-polarized ($\gamma = 90°$), a crosstalk of 1:100 was obtained. This crosstalk is mainly limited by misalignment and scattering, both of which could be improved. Indeed, with our planar configuration, the potential crosstalk should reach 1:1000, limited by the LM.

The diffraction efficiency of each HOE, at the required angle, was approximately only 50%. This low diffraction efficiency, together with spurious scattering and reflections, resulted in relatively poor throughput efficiency. However, by increasing the diffraction efficiency for each HOE to 90%, and with low scattering and anti-reflection coatings, the throughput light efficiency of the overall bypass-exchange switch can be more than 50%.

5. Concluding remarks

A compact bypass-exchange switch, based on planar optical configuration with polarization-sensitive HOEs, and polarization rotator LM, was designed and evaluated. The results reveal that such a switch can be modularized and cascaded, so it can be useful for various optical interconnection networks.

Acknowledgements

This research was supported in part by the Israeli Ministry of Science.

References

[1] White HJ, et al. Opt Comput 1995;139:183.
[2] Wu Y, Liu L, Wang Z. Appl Opt 1994;33:175.
[3] Krishnamoorthy AV, Xu F, Ford JE, Fainman Y. Appl Opt 1997;36:997.
[4] Marom DM, Mendlovic D. Appl Opt 1996;35:248.
[5] Kogelnik H. Bell Systems Technol J 1969;48:2909.
[6] Huang Y-T. Appl Opt 1994;33:2115.
[7] Kostuk RK, Kato M, Huang Y-T. Appl Opt 1990;29:3848.
[8] Reinhorn S, et al. Opt Engng 1999;38:1396.