ELECTRIC FIELD AND PHOTOCURRENT CONSIDERATIONS IN PHOTOREFRACTIVE MEMORY MATERIALS*

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Abstract

High density storage of data in photosensitive electrooptic crystals has been achieved. One of the crystals with the highest writing sensitivity is $LiNbO_3$ doped with iron. A key factor in its high sensitivity involves the nature of the charge transport in the crystal. A series of measurements has been carried out to study the charge transport by photocurrent measurements and electrooptic measurements. The two techniques are shown to give consistent results. When described in terms of an equivalent internal electric field a dependence on light intensity is required.

Introduction

The relative advantages of optical memory systems compared to other existing and emerging systems based on other technologies have been enumerated in a previous paper.(1) In the present paper the basic principles of operation of optical memories based on the photorefractive effect will be reviewed.

Because the writing efficiency of a photorefractive crystal depends critically on the rate at which photoexcited electrons can be removed from the donor sites from which they are excited, the electron transport process constitutes an important part of optical data storage and display. A number of theories(2,3,4,5) have been set forth to explain the transport process, but there are still some unsettled issues that need discussion and further investigation. In the second portion of this paper a brief review of the electron excitation and transport process in photorefractive crystals will be given.

In the third section of the paper some of our recent experimental results will be given along with a discussion of how these results bear on current theories.

Photorefractive Memory Systems

The basic property of a photorefractive crystal that allows it to be used in a holographic memory system is that its index of refraction changes in the presence of optical illumination. The change in index is attributed to the linear electrooptic effect. The electric field that must be present to produce the observed change in refractive index results from static charge accumulation due to transport of the photoexcited carriers.

A typical memory system using the photorefractive effect is shown schematically in Figure 1. The basic technique involves storing information in a page format in the form of a phase hologram in the ferroelectric crystal. Readout is achieved by shining only the reference beam at the same angle used as in writing. The detector array at the output then converts the memory signal from optical to electrical form. An intense reference beam can be used for the erasure process. It is obvious that the less light that it takes to perform the processes of writing, reading, and erasing, the more efficient and faster the system is. The following two sections report on a study of the electron transport process and how it affects the writing and erasure processes.

Theory

If light of sufficient frequency interacts with donor sites within a crystal it will have a certain probability of photoexciting electrons into the conduction band. The rate of excitation of the donor sites is as follows:

$$g = \frac{I\alpha}{h\nu} \quad , \tag{1}$$

where I = Intensity of the light,
α = Attenuation coefficient of the crystal,
h = Planck's constant,
ν = Frequency of light.

The continuity equation for the conduction band electronic concentration n is given by

$$\frac{dn}{dt} = g(x) - \frac{n}{\tau} + \frac{1}{e}\nabla\cdot\bar{j} \tag{2}$$

where τ = Electron trapping time,
$\bar{j}$ = Current density,
e = Electronic charge magnitude.

The current density of the electrons can be divided into drift and diffusion currents.

$$\bar{j} = e\,\mu n(x)\,\bar{E} + eD\,\nabla n \tag{3}$$

where μ = Electron mobility
D = Diffusion constant
E = Electric field

The first term represents drift current and the second term diffusion current. Under most circumstances diffusion currents in $LiNbO_3$ can be neglected as far as the photorefractive effect is concerned, however, there is general agreement as to how to calculate the diffusion current term if it is significant. With regard to the drift current term in order to reconcile experiment with theory a constant internal electric field is assumed.(2) Glass has suggested that the photoexcited carriers have a preferred average velocity upon excitation.(5) Under circumstances where the trapping time is short and the dark conductivity small, the results of the two theories are equivalent and the purpose of this paper is not to choose between the two theories. If an equivalent internal field, $\bar{E}_{int}$, is included then the drift current becomes

$$j_{drift} = e\mu n(x)\,[E_{int} + E(x)] \tag{4}$$

where E(x) includes all real electric fields.

This work reported on here is an investigation by many different techniques of the dependence of E_{int} on the light intensity I .

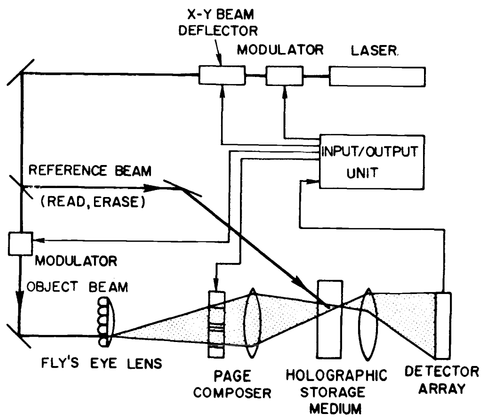

Fig. 1. Experimental arrangement for a holographic read-write memory.

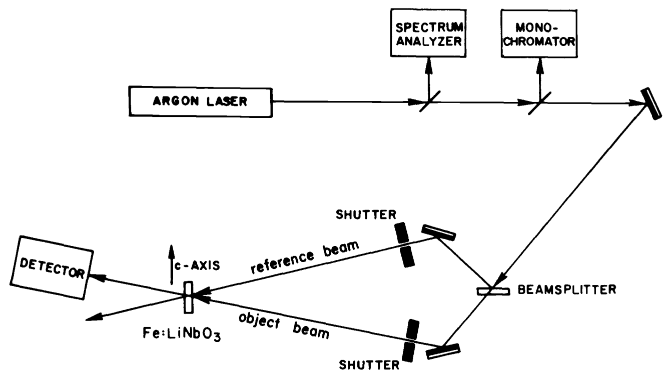

Fig. 2. Schematic for recording volume holograms with plane waves.

Experimental Results of E_{int} Measurements

Holographic Experiments

Using the experimental configuration of Figure 2, holograms were written with plane waves. When the two waves of intensity I_0 and wavelength λ are incident on the crystal at an angle 2θ, interference effects result in an intensity I(x) given by

$$I(x) = I_0\,(1 + \cos Kx) \tag{5}$$

where $K = \frac{2\pi}{\Lambda}$ is the grating vector and $\Lambda = \lambda/2\sin\theta$ is the grating wavelength. Typical fringe spacings are of the order of 1 to 10 μm. The resultant photogeneration and space charge configuration are shown in Figure 3.

For a thick, sinusoidal grating phase hologram Kogelnik(9) has derived the following expression for the diffraction efficiency

$$\eta = \frac{I_{diffracted}}{I_0} = \sin^2\left(\frac{\pi d\,\Delta n}{\lambda\cos\theta}\right) \tag{6}$$

where Δn = Change in index of refraction
d = Grating thickness

Observations of η as a function of time for various writing intensities are shown in Figure 4. These measurements allow one to infer the value of internal equivalent field which must exist for these different intensities in order to have the observed charge transport. This field has a linear dependence on intensity.

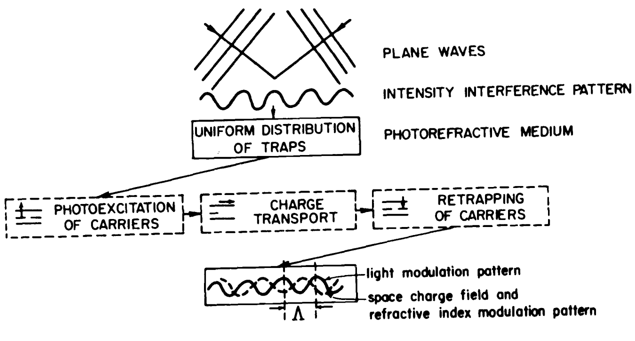

Fig. 3. Basic processes involved in the photorefractive effect.

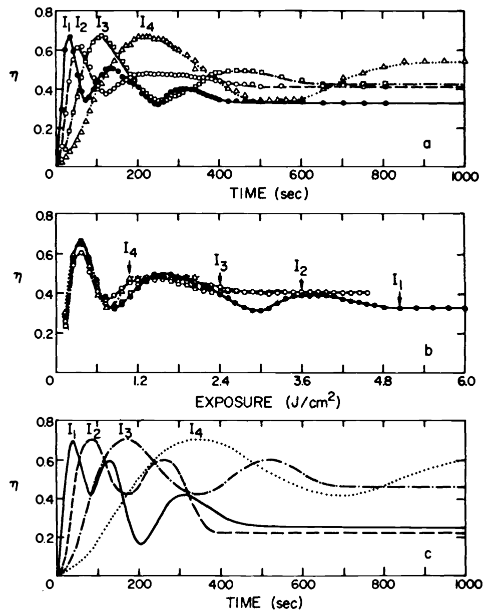

Fig. 4. Diffraction efficiency as a function of time for various writing intensities. The two upper curves are experimental results, the lower is based on calculations.

Interferometric Experiments

Because the change in index of refraction is a good measure of the electric field producing it, we carried out some experiments to monitor the change in index as a hologram was written. We used a Mach-Zehnder interferometer in one arm of which was placed an .05% iron doped lithium niobate crystal. An input beam at 4880 Å from an argon ion laser was split into two beams and a hologram was recorded inside the crystal with writing angle of approximately 12°. Simultaneously a weak HeNe laser beam was used to measure the ensuing change in the index of refraction Δn, of the crystal by measuring the fringe shift as a function of writing time for two different beam intensities. Δn can then be attributed to the space charge field and this is equal to the equivalent internal field when steady state is achieved if the dark conductivity is sufficiently low. In Figure 5 is presented the electron drift field E thus measured as a function of writing time for two different intensities. Clearly E is enhanced rather significantly with increasing writing intensity.

Photoconductive Experiments

Glass et.al.[10] have reported that the bias external field necessary to reduce the photocurrent to zero was greatly dependent on the input intensity. For example, in $Fe:LiNbO_3$ with $\alpha = 38\ cm^{-1}$, the photocurrent was zero for an external field of 60 kV/cm at $.32 w/cm^2$ input intensity and decreasing to 38 kV/cm for $0.08\ w/cm^2$.

We have carried out a similar experiment but measured the photocurrent produced through a short circuit when the crystal is illuminated with various light intensities. The results are shown in Figure 6. The two straight lines are for a least square fit to the first four points and a least square fit to all points. This indicates that a significantly higher field is produced at higher intensities.

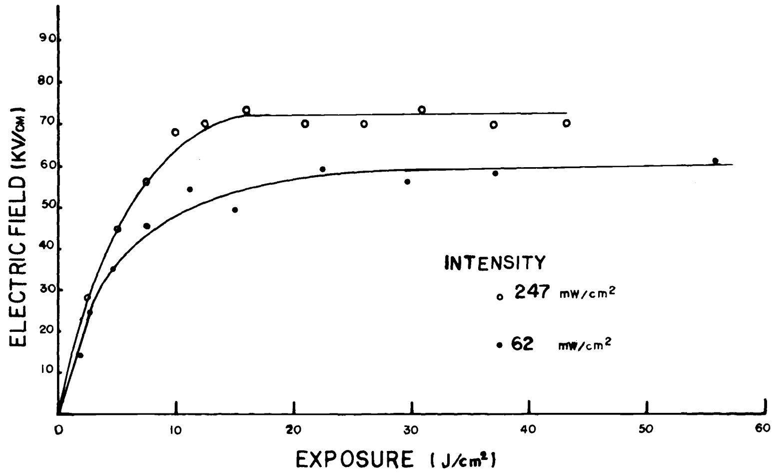

Fig. 5. The electron drift field as a function of time based on interferometric measurements.

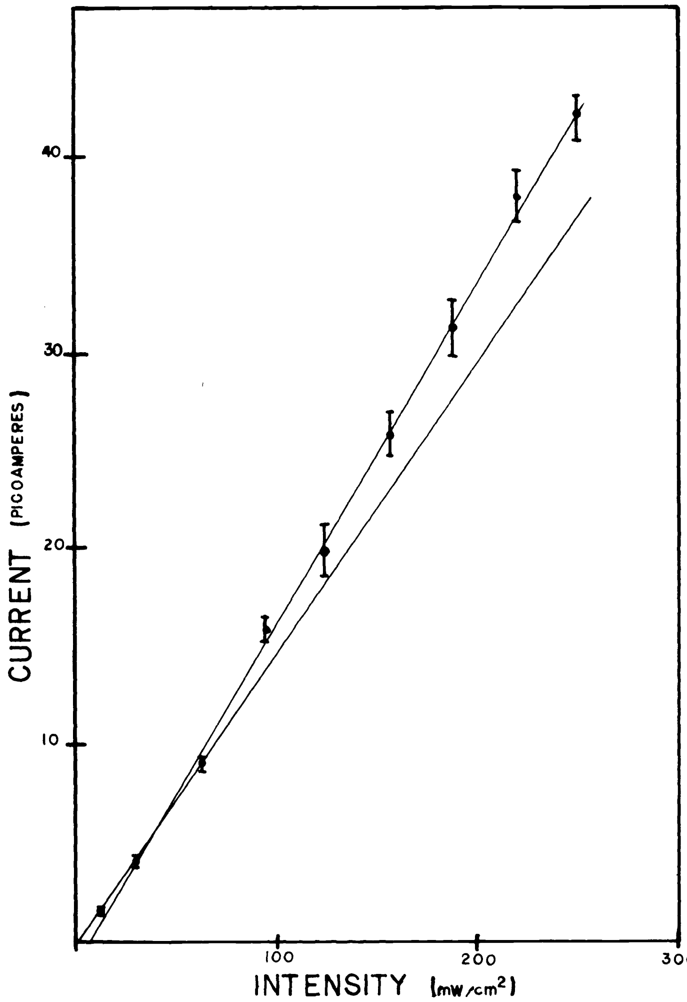

Fig. 6. Photocurrents as a function of incident light intensity with no applied voltage.

Conclusions

Through a series of measurements of photocurrents, indices of refraction and holographic writing efficiency, it has been determined that a quantity describable by an equivalent internal field has a dependence on the intensity of the incident light, becoming larger with greater light intensity. These results are also consistent with Glass's finding that short high intensity pulses were more efficient for writing holograms. From a practical point of view these results are important for improving hologram writing efficiency. From a theoretical point of view they indicate that further mechanisms must be considered for explaining the photorefractive effect and the bulk photovoltaic effect.

References

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*Work supported in part by NASA, NSF, and the Army BMDATC.