

# OPTICAL DATA STORAGE IN PHOTOREFRACTIVE MATERIALS

T. A. Rabson, F. K. Tittel and D. M. Kim  
Electrical Engineering Department  
Rice University  
Houston, Texas 77001

## Abstract

The basic physical theory of the photorefractive effect will be presented. Methods will be discussed for utilizing the effect for the storage of information as well as optical display of information. The fundamental limits on writing time, access time and storage density will be related to the physical properties of the materials involved. Particularly promising materials, such as  $\text{LiNbO}_3$  will be discussed in detail.

## Introduction

The incidence of light on certain ferroelectric crystals can alter the index of refraction of the crystal<sup>(1)</sup>. This physical phenomenon is known as the photorefractive effect. Although the physical behavior of this effect has been well studied the fundamental photoexcitation process is still not well understood. This lack of understanding does not prevent the application of the effect to the storage of data in crystals either holographically or by point by point scanning. The basic characteristics of the process hold out the possibility that memories utilizing the photorefractive effect could be built with high storage densities ( $> 10^8$  bits/cm<sup>3</sup>), fast access time ( $< 1 \mu\text{sec}$ ), and high data rates ( $> 10^9$  bits/sec).

The desirable properties for a photorefractive material to be used in a memory system are that it have a high writing sensitivity, a large decay time, a high persistence during read-out, and high resolution. Although no one material scores highest for all of these properties, iron doped lithium niobate looks like one of the more promising materials and for this reason its properties will be discussed in detail.

## Theory of the Photorefractive Effect

The photorefractive effect was first observed as optical damage in crystals of  $\text{LiNbO}_3$  and  $\text{LiTaO}_3$  where it produced unwanted scattering and decollimation of light in nonlinear optical experiments<sup>(2)</sup>. The first stage of the photorefractive effect consists of the photoexcitation of electrons from localized donor sites in the crystal. The next stage of the process involves the electron transport in the crystal and the subsequent retrapping of the electrons. Electric fields are consequently produced because of the space charges produced and these fields then alter the index of refraction of the crystal through the electrooptic effect. Figure 1 illustrates these processes. There is general agreement that the index changes are produced as a result of the space charge fields in the crystal. There is still some controversy over the electron photoexcitation and transport processes.

In order to understand the current theories of the electron generation and transport, a brief review of the process is given below.

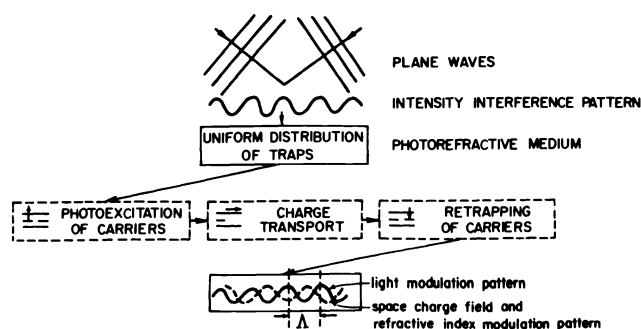


Fig. 1. Schematic explanation of the photorefractive effect.

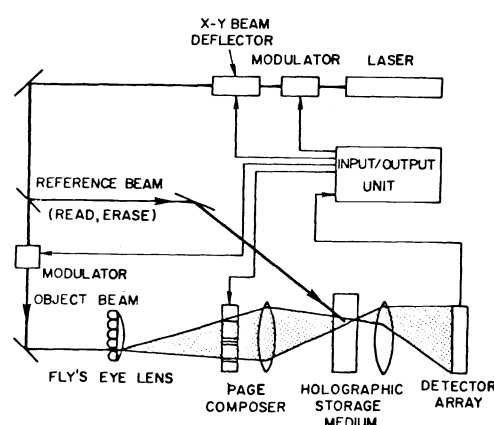


Fig. 2. Experimental arrangement for a holographic read-write memory.

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:

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

where  $I$  = Intensity of the light,

$\alpha$  = Attenuation coefficient of the crystal,

$h$  = Planck's constant,

$\nu$  = Frequency of light.

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

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

where  $\tau$  = 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.

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

where  $\mu$  = 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  $\text{LiNbO}_3$  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 was assumed<sup>(1)</sup>. Glass has suggested that the photoexcited carriers have a preferred average velocity upon excitation<sup>(3)</sup>. 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,  $\bar{E}_{\text{int}}$ , is included then the drift current becomes

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

where  $\mathcal{E}(x)$  includes all real electric fields. Another more realistic description of the current is to describe the drift current as Glass et al<sup>(4)</sup> did as the sum of a bulk photovoltaic current and a standard photo current.

$$\bar{j} = \kappa_1 \alpha I + e \mu n(x) E(x) \quad (5)$$

where  $\kappa_1$  is a constant depending on the nature of the absorbing center and the wavelength and independent of the crystal geometry, the electrode configuration, and the impurity concentration. One can see that there is a direct relation between the equivalent internal field  $E_{\text{int}}$  and  $\kappa_1$ . Some measurements of the value of  $E_{\text{int}}$  for  $\text{LiNbO}_3$  will be reported here.

#### Utilization for Data Storage

Figure 2 illustrates how the photorefractive effect can be utilized in a holographic read write memory. The system consists of a coherent light source, beam deflector, a data input element or page composer, a recording medium, and a detector matrix. Considerable research has gone into each of these principal components<sup>(4)</sup> and considerable progress has been made. This has led to the development of several memory and display prototypes but in order to develop the potentials of holographic optical storage on a commercial scale, further progress needs to be made in the areas of low-cost, coherent light sources, fast and effective beam deflectors, high-speed page composers, and optical storage materials. It is obvious that the above described system can also be utilized as a real time display system by directly observing the output where the photodetector is located.

The speed of a memory system based on the photorefractive effect is not limited by any of the time constants involved in the effect. The photoexcitation process occurs in less than  $10^{-12}$  seconds and the mean free time until the first scattering of the photoelectron is also less than this. With mode locked lasers enough light intensity can be generated in less than  $10^{-11}$  seconds to write a discernible hologram. The erasure and reading processes are also possible with such pulses. The time limitation is currently caused by the beam steering and detection processes.

#### Experimental Studies of Lithium Niobate

Experimental studies have been made of various  $\text{LiNbO}_3$  crystals using the arrangement shown in Figure 3. Although the object beam was planar and not modulated the basic principle is the same as if information were contained in the beam through spatial modulation. The interference pattern generated by these two beams of wavelength  $\lambda$  and intensity  $I_0$  intersecting at an angle  $2\theta$  is given by

$$I(x) = I_0 (1 + \cos Kx) \quad (6)$$

where  $K = 2\pi/\Lambda$  is the grating vector, and  $\Lambda = \lambda/2 \sin\theta$  is the wavelength of the grating. By observing the diffracted beam intensity when the object beam is interrupted one can observe the rate of hologram formation in the crystal. For a thick sinusoidal grating phase hologram Kogelnik<sup>(5)</sup> has derived the following expression for the diffraction efficiency

$$\eta = \frac{I_{\text{Diffacted}}}{I_o} = \sin^2\left(\frac{\pi d \Delta n}{\lambda \cos \theta}\right) \quad (7)$$

where  $\Delta n$  = Change in index of refraction  
 $d$  = Grating thickness

Observations of  $\eta$  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 dependence is shown in Figure 5. This field has a linear dependence on intensity.

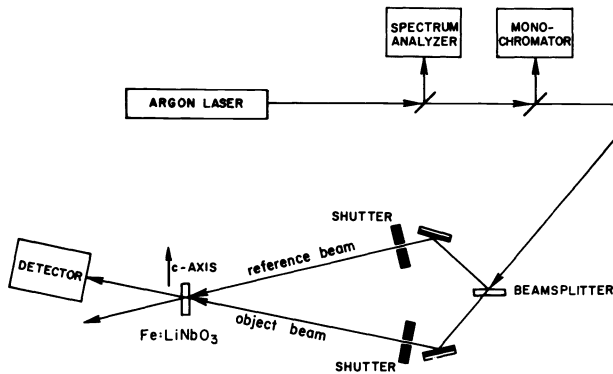


Fig. 3. Experimental arrangement for measuring writing sensitivity.

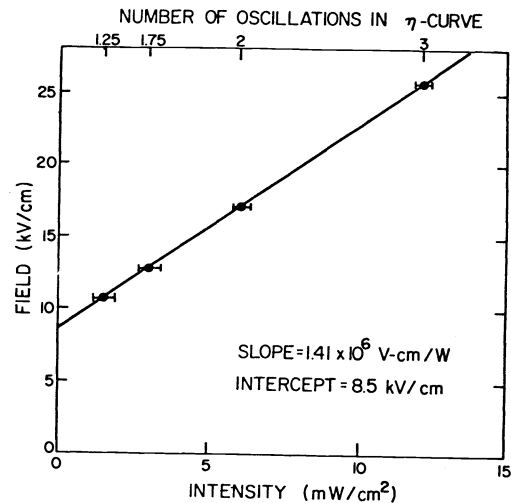


Fig. 5. Dependence of equivalent internal field on light intensity.

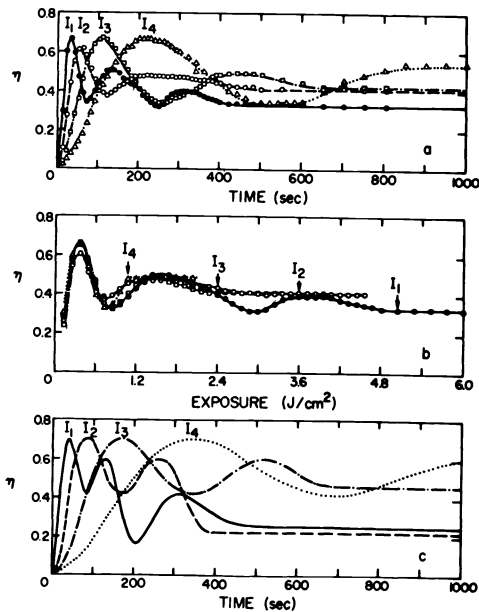


Fig. 4. Diffraction efficiency as a function of time for four different writing intensities. The two upper curves are experimental results, the lower is based on calculation.

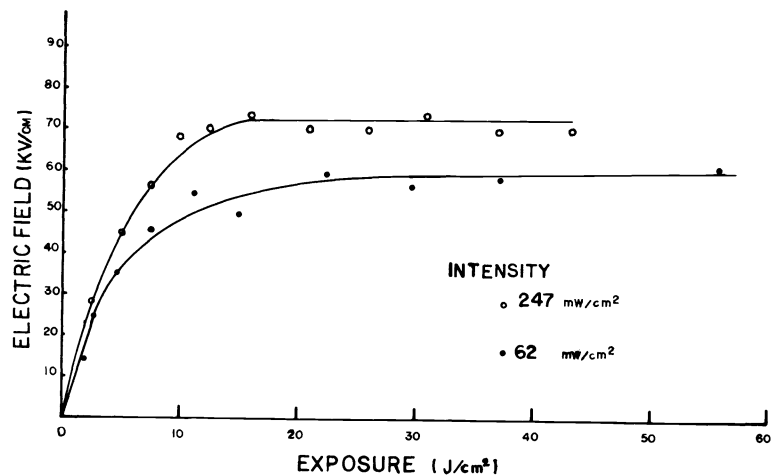


Fig. 6. The electric field as a function of time based on interferometric measurements.

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  $\Delta n$ , of the crystal by measuring the fringe shift as a function of writing time for two different beam intensities.  $\Delta n$  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 6 is presented the space charge field  $E$  thus measured as a function of writing time for two different intensities. Clearly  $E$  is enhanced rather significantly with increasing writing intensity.

Glass et al.<sup>(3)</sup> 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<sub>3</sub> with  $\alpha = 38 \text{ cm}^{-1}$ , the photocurrent was zero for an external field of 60 kV/cm at .32 W/cm<sup>2</sup> input intensity and decreasing to 38 kV/cm for 0.08 W/cm<sup>2</sup>.

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 7. 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. Figure 8 shows the dependence of the writing sensitivity on wavelength. It can be concluded that the sensitivity increases for shorter wavelengths.

In the process of writing certain beam coupling effects can occur. Those are illustrated in Figure 9. This is manifested by the switching of beam energy between the object and reference beams after they have passed through the crystal.

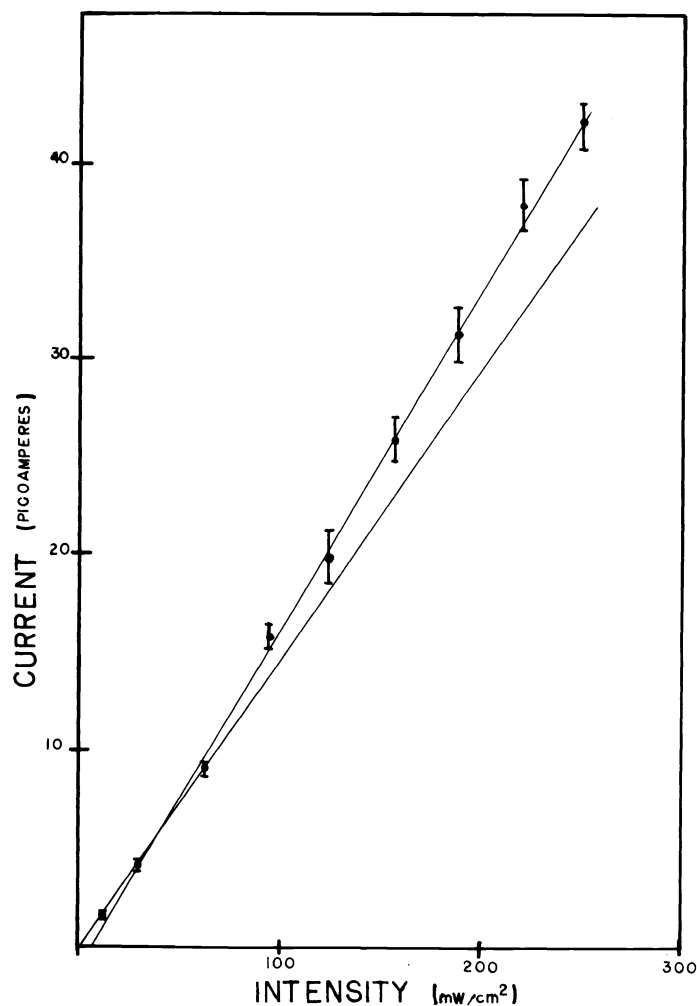


Fig. 7. Photocurrents as a function of incident light intensity with no applied voltage.

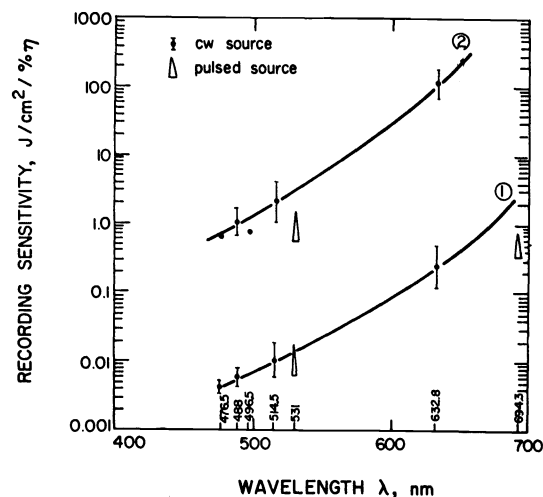


Fig. 8. Writing sensitivity as a function of wavelength

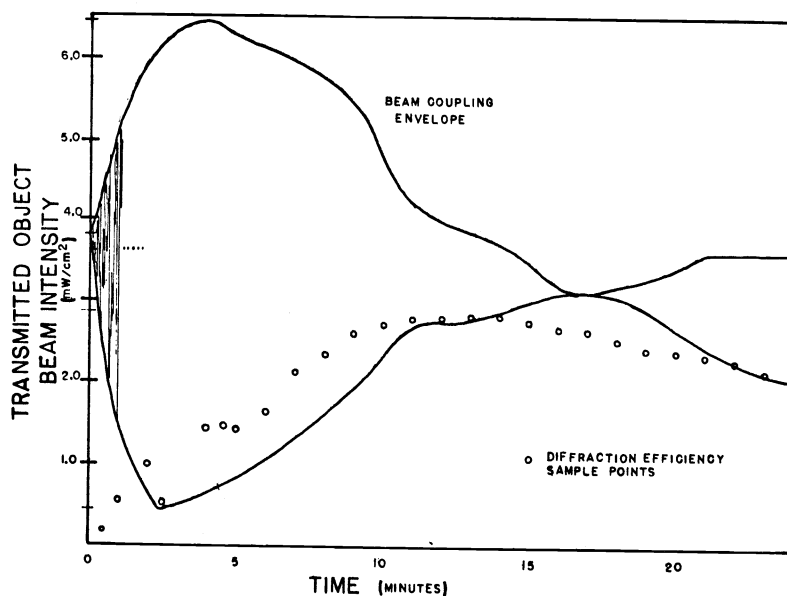


Fig. 9. Beam coupling effects in the writing process.

#### Conclusions

The properties of photorefractive crystals make them attractive candidates for constructing optical memory systems with fast read, write and erase times, high storage density, and long lifetime. Further study is indicated to optimize all of these parameters. In addition, fundamental studies of the bulk photovoltaic effect are needed to understand the basic photoexcitation and charge transport processes.

#### References

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