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Photorefractive materials for optical computing and image processing

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Photorefractive materials have been used as the nonlinear optical media in various optical computing and image processing applications. Devices such as passive phase conjugate mirrors, image subtractors, optical limiters and thresholders can be constructed with materials whose index of refraction is a function of light intensity. It is the purpose of this paper, then to describe some of these materials on the basis of their nonlinear optical response.

1. INTRODUCTION

Photorefractive crystals are promising materials for optical data processing applications. A large number of parallel operations can be processed in a single crystal. Photorefractive materials can store optical holograms for time durations of hours to years, depending on their dark conductivity. Optical amplifiers with gain factors of 4000 have been constructed¹, and phase conjugate reflectivities greater than 20 have been observed in BaTiO₃ with four-wave mixing². Operation on nanosecond time scales has been demonstrated³⁻⁵ with Q-switched pulses from doubled Nd:YAG lasers. Finally, the requirements on write and erase energy density in photorefractive crystals such as BSO⁶ are comparable to the best photographic plates.

There are two major factors that limit widespread application of photorefractive materials at present. First, some of the promising crystals such as BaTiO₃, SBN, and KNbO₃ are not widely available in large samples with high optical quality. Second, the crystals that are available are not optimal in all respects. For instance, in order to demonstrate high speed, low write energy, long memory, or large gain, it is necessary to use several different types of materials. The purpose of this paper is, therefore, to compare photorefractive materials including BaTiO₃, SBN, and BSKNN on the basis of several figures of merit which are introduced in the next section. Both ferroelectric and non-ferroelectric materials will be considered in the comparison.

2. FIGURES OF MERIT2.1 Steady-state index change

The steady-state change in the refractive index is defined as the index change after illumination for a time that is long compared to the photorefractive response time τ . The index change is related directly to the space charge field through

$$\Delta n_{ss} = 1/2 n_b^3 r_{eff} E_{sc}, \quad (1)$$

where n_b is the background refractive index, r_{eff} is the effective electrooptic coefficient, and E_{sc} is the internally generated space charge electric field. E_{sc} is given by

$$E_{sc} = -iE_q \frac{E_o + iE_d}{E_o + i(E_d + E_q)} \quad (2)$$

where E_o = externally applied electric field

$E_q = eN_A/(\epsilon K) =$ limiting space charge field

$E_d = k_B T K / e =$ diffusion field.

The steady-state index change is also related to the two beam coupling coefficient Γ by

$$\begin{aligned} \Delta n_{ss} &= \Gamma c / \omega \\ &= \lambda \Gamma / 2\pi, \end{aligned} \quad (3)$$

where λ is the wavelength of light.

In order to determine the materials dependence of Δn_{ss} , the space charge field E_{sc} needs to be considered. Three limits for E_{sc} exist:

(1): $E_{sc} \approx E_d$. From Eq. (2), this occurs when $E_o < E_d < E_q$ which is a common condition when no electric field is applied and the grating period is large. In this case

$$\begin{aligned}\Delta n_{ss} &\propto n_b^3 r_{eff} E_d \\ &\propto n_b^3 r_{eff},\end{aligned}\tag{4}$$

since E_d does not depend on material parameters.

(2) $E_{sc} \approx E_q$. This occurs when $E_q < E_d$ or E_o ; that is, when a large electric field is applied or when the grating period is small. In this case

$$\begin{aligned}\Delta n_{ss} &\propto n_b^3 r_{eff} E_q \\ &\propto n_b^3 r_{eff} / \epsilon\end{aligned}\tag{5}$$

where ϵ is the dielectric constant of the material.

(3) $E_{sc} \approx E_o$. This occurs when $E_d < E_o < E_q$ which holds in cases where moderately large electric fields are applied to the crystal. Hence,

$$\begin{aligned}\Delta n_{ss} &\propto n_b^3 r_{eff} E_o \\ &\propto n_b^3 r_{eff},\end{aligned}\tag{6}$$

Therefore, photorefractive crystals with large values of $n_b^3 r_{eff}$ and $n_b^3 r_{eff} / \epsilon$ are desirable for applications such as passive phase conjugation that require large steady-state index changes.

2.2 Response time

The photorefractive response time τ is a useful figure of merit for applications in which available energy limits the illumination time, or in which the grating must be written or erased in a set time scale. The response time scales with intensity until times as short as either the time for a charge carrier to move one grating period or the time necessary for the electrooptic effect to respond to the Coulomb field of the displaced charge. The longer of these times is the fundamental limit. Diffusion times in semiconductors such as GaAs are known to be < 10 psec⁷. The electrooptic response time is of the order of attoseconds for the electronic component of the electrooptic coefficient, r_{eff} , and picoseconds for the ionic part. The mix of these two components varies, but the ultimate response time of a photorefractive crystal is in the pico-second range.

2.3 Photorefractive sensitivity

The photorefractive sensitivity S is defined as the index change per absorbed energy per unit volume⁸⁻¹¹. That is

$$S = \frac{\Delta n}{\alpha I_o t}.\tag{7}$$

The photorefractive sensitivity is a useful figure of merit because it tells us how well a material uses a given amount of optical energy. Alternatively, it allows comparison of crystals with different absorption coefficients on an equal basis. The refractive index change Δn can be given by

$$\Delta n = \Delta n_{ss} (1 - e^{-t/\tau}),\tag{8}$$

where a stationary index grating is assumed. For $t \ll \tau$,

$$\Delta n = \Delta n_{ss} t / \tau.\tag{9}$$

Since τ is inversely proportional to αI_o , then

$$S \propto \Delta n_{ss} \frac{E_o + i(E_d + E_q)}{E_o + (E_d + E_\mu)}, \quad (10)$$

where $E_\mu = \gamma N_A / (\mu K) = \text{drift field}$.

Clearly a large steady-state index change is preferred. Moreover, large mobilities and long recombination rates are generally desirable because these properties allow the carriers to diffuse or drift longer distances before they recombine, thereby reducing the drift field E_μ . In either case the photorefractive sensitivity is increased.

3. SUMMARY OF MATERIAL PARAMETERS AND FIGURES OF MERIT FOR PHOTOREFRACTIVE CRYSTALS

Table 1 summarizes the material parameters of interest for BaTiO₃, SBN, and BSKNN along with other photorefractive crystals, while in Table 2 the corresponding figures of merit are given. Included is the wavelength range in which the crystals are known to be photorefractive.

As expected, the ferroelectric crystals BaTiO₃, SBN:60, SBN:75, BSKNN, LiNbO₃, and KNbO₃ exhibit the largest photorefractive effect due to their large n_{eff}^3 values. Although n_{eff}^3/ϵ is approximately equal in all the materials, the former term apparently is more important for determining the steady state refractive index change. However, the non-ferroelectric crystals BSO, GaAs, and InP:Fe are significantly faster than the ferroelectrics. Owing primarily to their larger mobilities and their generally favorable transport properties, these materials have photorefractive response times 2 to 3 orders of magnitude smaller than those of the ferroelectric crystals.

Table 1. Material Parameters of Select Photorefractive Crystals

Crystal	$n_i^3 r_{ij}$ (pm/V)	$n_i^3 r_{ij} / \epsilon_j$ (pm/V)	μ (cm ² /Vsec)	γ_R (cm ³ /sec)
BaTiO ₃	11300	4.9	0.5	5×10^{-8}
SBN:60	5100	5.8	0.5	5×10^{-8}
SBN:75	17000	5.0	0.5	5×10^{-8}
BSKNN	4600	13.2	---	---
LiNbO ₃ ^(10,12-15)	320	11.0	0.8	---
KNbO ₃ ⁽¹⁶⁻¹⁹⁾	690	14.0	0.5	---
BSO ^(20,21)	82	1.8	0.03	2×10^{-11}
GaAs ^(22,23)	43	3.3	5800.0	---
InP ⁽²⁴⁾	52	4.1	>5000.0	---

Table 2. Figures of Merit of Select Photorefractive Crystals
($E_0 = 0$ V/cm)

Crystal	Wavelength Range (μm)	Δn_{ss}	τ for 1W/cm ² , λ	S (cm ³ /J)
BaTiO ₃	0.4-1.1	4.8×10^{-5}	50msec, 0.5μm	2.4×10^{-4}
SBN:60	0.4-0.85	3.2×10^{-5}	120msec, 0.5μm	5.3×10^{-3}
Ce-doped SBN:60	0.04-0.85	9.6×10^{-5}	80 msec, 0.5μm	6.0×10^{-4}
Ce-doped SBN:75	0.4-0.85	4.0×10^{-5}	150msec, 0.5μm	3.0×10^{-4}
Ce-doped BSKNN	0.4-0.85	4.0×10^{-5}	200msec, 0.5μm	2.0×10^{-4}
LiNbO ₃ ^(10,12-15)	0.4-0.7	$10^{-5} - 10^{-3}$	> 1sec	$5 \times 10^{-6} - 5 \times 10^{-5}$
KNbO ₃ ⁽¹⁶⁻¹⁹⁾	0.4-0.7	5.0×10^{-5}	<100msec, 0.05μm	1.7×10^{-4}
BSO ⁽²⁵⁻²⁷⁾	0.4-0.7	5.0×10^{-6}	< 1msec, 0.05μm	3×10^{-3}
GaAs ^(22,23)	0.8-1.8	6.4×10^{-6}	80μsec, 1.06μm	5.0×10^{-2}
InP:Fe ⁽²⁴⁾	0.85-1.3	0.2×10^{-6}	<100μsec, 1.06μm	$>2 \times 10^{-3}$

Since the photorefractive sensitivity is proportional to $\Delta n_{ss}/\tau$, these differences in the values of Δn_{ss} and τ between the nonferroelectrics and the ferroelectrics essentially cancel, and large values of S are, therefore, possible with either type of crystal. It is interesting to note that the photorefractive sensitivity of SBN:60 is reduced by the addition of cerium, although such a doped crystal exhibits improved

values of Δn_{ss} and τ . This implies that not all of the optical absorption in the cerium-doped SBN:60 crystal contributes to the photorefractive effect.

Finally, the wavelength ranges given in Table 2 indicate that the photorefractive effect in the oxides is observed only with visible or very near infrared radiation. At longer wavelengths only the semiconductors such as GaAs and InP are known to be photorefractive.

4. ACKNOWLEDGMENTS

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