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Transient Diffraction Efficiency and the Role of the Deep Center Levels in BaTiO$_3$ Crystal

M. H. Rashid[1], Y. Haque[1], S. K. Das[1], S. M. Sharafuddin[1]
[1]*Department of physics, Shajalal University of Science & Technology, Sylhet, Bangladesh.*
Emails: *yasmeen@sust.edu*, *skdas-phy@sust.edu*

Abstract

The charge transport model has been applied to the photorefractive crystal. Shallow & Deep levels have been accounted for in the formulation of the charge transport equations. It is assumed that the writing beams excite the shallow level charges where as the electrons from the deep level are the ones excited into the conduction band by the reading beam. An appreciable fraction of these electrons recombine with the deep level holes. The electron-hole recombination rate is dependent on the excitation rate of the electrons. This rate is a maximum when the number of electron in the shallow level is equal to the existing hole in the deep centers. The space charge field is directly dependent on the recombination rate. The space charge field is changed by the modulation intensity of the beams. In this study the analytical calculations used to obtain the space charge field is used in the expression of the gain coefficient. The theoretical result for the enhancement factor is seen to be in good agreement with the experimental data.

1. Introduction

The presence of the effect of Optical Phase Conjugation in the field of nonlinear optics becomes important in applications such as optical computing, optical image processing, optical signal processing etc [1-12].

In [13] it was proposed that an erasure of the grating will result in a decrease of the enhancement factor M. In this study this effect has been taken into account in the Transport Model. New and improved rate equations have been incorporated into the mathematical modeling.

Grating formation in a photo-refractive crystal is accompanied by energy redistribution between the two interfering light beams that is due to the phase mismatch between the phase grating, the light grating and the light intensity pattern. The two optical beams have transmitted intensities I_f and I_p and the crystal c axis is chosen so that the probe beam experiences gain. The amplitude gain can be expressed in terms of the exponential gain coefficient. The dominated deep center charge transport model has been introduced for the space charge field to describe the Enhancement Factor M.

2. Theory of Charge Transfer

Qualitative Treatment

In the following, the charge – transport model is shown in fig.1. A deep center C_D and two shallow centers C_{S2} and C_{S1} are present. All centers occur in two different valance states. First the model explains the enhanced diffraction efficiency qualitatively. Second a more quantitative analysis will be given in which the measured dependences are compared with model calculations. Two coherent writing beams (I_f, I_P), for low and continuous light intensities excites electrons from C_{S2} into the conduction band. An appreciable fraction of these electrons recombine with the empty centers C_{S1}. However the concentration of electrons in C_{S2} remains small .Considering photo-excitation cross section of $C_{S2}(S_2)$ is large compared with that of $C_{S1;}$ during writing, C_{S2} is emptied by the light while C_{S1} is appreciably populated. During the time period between one reading beam to the next, the electrons are thermally excited from C_{S1} (for large thermal excitation cross section β_1) and some of them are trapped into C_{S2} and hence the concentration of C_{S2} increases.

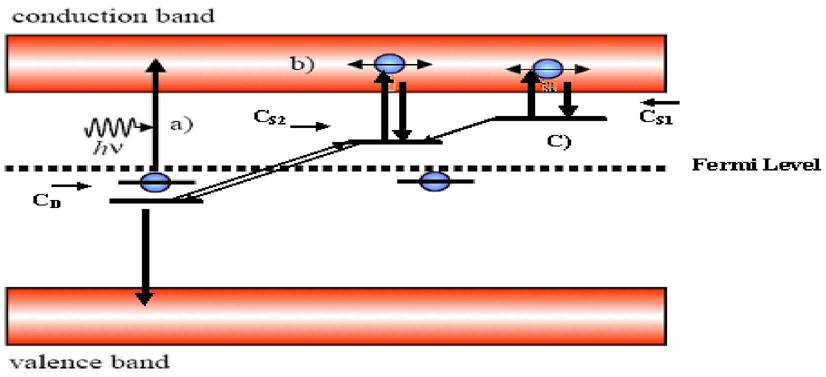

Fig1: Band diagram of the charge transport model. A deep center C_D and two different shallow levels C_{S2} and C_{S1} are present. The arrows indicate possible excitation and recombination of electrons and hole.

These electrons are transferred to the valance band if there is no hole created in the deep level C_D. For holes in the deep level the transfer of electrons from C_{S2} is fractional. An excess number of electrons goes to the conduction band after recombining with the deep centers. The writing beam power is not sufficient to excite the deep level electrons. The reading beam power plays the dominating part on the number of electrons recombining from C_{S2} to C_D. The reading beam (I_b) excites electrons from C_D into the conduction band. An appreciable fraction of these electrons recombine with the empty centers C_{S2} and C_{S1}. During the time period T, these electrons recombine with the deep level holes. The number of these recombining electron rates depends on the excitation rate of the electrons. The rate of electron hole recombination is a maximum when the number of electron in C_{S2}, (due to fixed, thermal excitation cross section β_{s1}, photo excitation cross section S_2 and thermal excitation period such as reading period T) is equal to the holes existing in the deep centers due to the reading beam. For low intensity reading beams, the electron number in C_{S2} is lower than existing holes in C_D and for higher intensity reading beams, the electron number in C_{S2} is higher than the holes existing in C_D.The electron-hole recombination valance point obviously represents the maximum electron conductivity. The reading beam intensity lowering or increasing from the valance point decreases the recombination rate. Decrease of recombination rate (electron-hole), decreases the space charge field.

3. Quantitative Treatment

During the reading, the grating is formatted by the density of electrons in the conduction band. The rate equation becomes:

$$\frac{dN_e}{dt} = -\frac{dN_e}{dI_b}[N_D - q_D N_D^-] + N_e[(N_{S2} - S_2 I_p N_{S2}^-)r_{S2} + (N_{S1} - \beta_{S1} N_{S1}^-)r_{S1}] \qquad (1)$$

N_e is the number of charge carriers in the conduction band, N_D, N_{s2}, and N_{s1} is the number of charge carriers in the deep level and in the shallow levels respectively. N_D^-, N_{s2}^-, and N_{s1}^- represent the number of electrons in the deep and shallow levels respectively. q_D, s_2, β_{s1} here express the quantum excitation rate, the photo-excitation rate at the shallow level S_2 and the thermal excitation rate S_1 respectively. In the equation, r_{s1} and r_{s2} are the charge recombination rates at the shallow levels S_1 and S_2. I_b, I_p & I_f comes from experimental conditions for the reading beam, the probe beam & the forward beam respectively.

$$\frac{dN_e}{dt} = -R\frac{dN_e}{dI_b} + N_e P \qquad (2)$$

Here, $[N_D - q_D N_D^-] = R$ and $[(N_{S2} - S_2 I_p N_{S2}^-)r_{S2} + (N_{S1} - \beta_{S1} N_{S1}^-)r_{S1}] = P$

Using the eigen-function method and applying the boundary conditions: $N_e(0,t) = N_e(I_b,t) = 0$, at t=0, I_0=50 mm/cm^2, we get the solution of equation (2)

$$N_e(I_b,t)=\sum_{n=1}^{n} B_n e^{\frac{P+\lambda_n}{R} I_b} C_n e^{-\lambda t} \tag{3}$$

λ is a constant coming from the variable separation in the eigen-function method.

$B_n=1$, n=1,2,3… and C_n=constant. and applying the boundary condition gives; $N_e(0,t)=N_e(I_b,t)=0$, at t=0, I_0=50 mw/cm^2

Considering the value of n=1, Eq(3)becomes

$$N_e(I_b,t)=500CExp[-(\frac{6.214R}{I_b}-P)t \tag{4}$$

From experimental value $I_b=1.1r_{int}$, time period t=90s , Eq (4) becomes,

$$N_e(I_b,t)=500CExp[-\frac{6.214\times 90}{1.1}\frac{R}{r_{\text{int}}}+90P] \tag{5}$$

Substitute the value of R, P, C respectively as 0.031, $15/r_{int}$, 0.23

The space charge field is defined as

$$E_{sc}=\frac{-ie}{k\varepsilon\varepsilon_0}[N_{S1}^{-}+N_{S2}^{-}+N_e],$$

$$E_{sc}=E_{S0}+\frac{-ie}{k\varepsilon\varepsilon_0}N_e, \qquad \text{here } E_{S0}=\frac{-ie}{k\varepsilon\varepsilon_0}[N_{S1}^{-}+N_{S2}^{-}]$$

$$E_{s0}=-\frac{2\Delta n}{\eta^3{}_0 r_{eff}}=\frac{2\times 4.71\times 10^{-5}}{1.13\times 10^{-8}}, \text{ for BaTiO}_3 \text{ sample [15-17].} \tag{6}$$

where $\eta^3{}_0 r_{eff}=1.13\times 10^{-8}$ m/v [17].

From Eq(5) and Eq(6) the total space charge field E_{sc} can be calculated.

4. Enhancement Factor (M)

$$Enhancementment\ factor\ M=\frac{Maximum\ \text{int}\,ensity\ of\ the\ phase\ conjugate\ beam}{Initial\ \ \text{int}\,ensity\ of\ the\ phase\,conjugate\ beam}$$

$$M=\frac{I_{c,\max}}{I_{c,0}}=\frac{P_{c,\max(at\ certain\ time\ t)}}{P_{c.0(at\ time\ t=0)}}$$

$$M=\frac{I_c(\max)[I_p,I_f,ON]}{I_c(0)} \quad [14]$$

$$=\frac{p_c(t)_{\max}[I_p,I_f,on]}{P_c(0)}$$

Here I_c, I_p and I_f are the intensity of phase conjugate beam, probe and forward pump beam respectively. P_c, P_b, P_p represents their power. In terms of the exponential gain coefficient (Γ') [18, 19]

$$M=\frac{(1+\beta')\exp(\Gamma' d)}{1+\beta'\exp(\Gamma' d)}, \quad \beta'=\frac{P_b}{P_p}(phase\,conjugate\,beam) \text{ [14].}$$

$\Gamma'=kn^3 r_{eff}E_{sc}m$[13] has been measured using the values of $k, n^3 r_{eff}, E_{sc}$ from the previous section and the value of modulation factor ‘m’ from[13].

Using the exponential gain coefficient the Enhancement factor becomes: $M = \dfrac{1 + \dfrac{1}{r_0 A} r_{\text{int}} \exp \Gamma' d}{(1 + \dfrac{1}{r_0 A} r_{\text{int}}) \exp \Gamma' d}$

(7)

d (interacting length) $= 1.2 \times 10^{-3}\, m$[14], Value of A=0.91 , r_0=1.0046 for $BaTiO_3$ crystal[13]

5. Results and Discussion

The diffraction efficiency observed in phase conjugation due to a pulse-reading beam has been investigated in an un-doped $BaTiO_3$ crystal theoretically. From equation (7) the quantitative agreement between the experimental results [14].

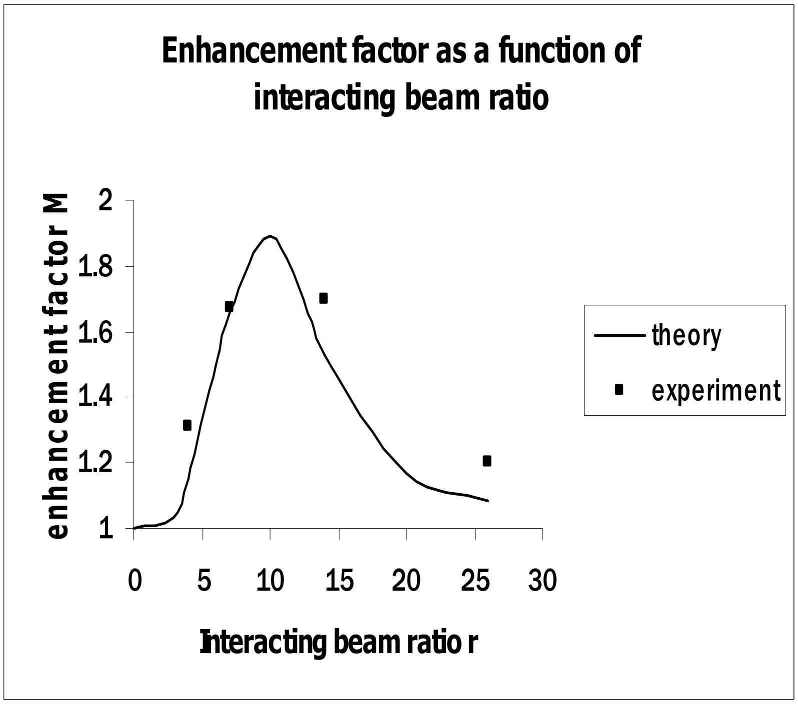

Fig 2: Enhancement factor as a function of interacting beam ratio.

and theory is quite satisfactory. The comparison between the theory and experimental data leads to the conclusion that the dominated deep center model quite satisfactorily describes the enhancement of the switched phase conjugate reflectivity in an un-doped $BaTiO_3$ crystal. It may be of interest to investigate this in doped $BaTiO_3$ crystals where the deep levels are greater in number. This theory suggests that a doped crystal will give rise to a pronounced enhancement of the switched phase conjugate reflectivity.

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