# Large amplitude photocurrent in photo-emf experiments in pure and doped absorbing photorefractive crystals

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## ABSTRACT

We report a mathematical formulation that successfully describes the holographic photocurrent produced in photo-emf experiments, with large oscillation amplitudes, in strongly absorbing photorefractive materials. The large amplitude produces a sensible enhancement of the photocurrent signal and in this way facilitates measurements. Accounting for bulk light absorption of the sample is essential in order to adequately describe the experiment. We measure pure and doped photorefractive $Bi_{12}TiO_{20}$ (BTO) crystals and show that these data are in excellent agreemnt with theory. From data fitting we are able to determine some material's parameters.
**Keywords:** *Photorefractives, Photoconductors, Photo-emf, Nonlinear optical materials*

## 1. INTRODUCTION

The holographic photocurrent in photo-emf experiments were already reported [1, 2, 3] to characterize some photorefractive materials. The influence of bulk light absorption was also reported before [4] but for large modulation frequencies only. Some experiments using pattern-of-fringes vibration of large amplitude were already published [1, 2, 3, 5] but rather rough approximations were used. In this paper we report an accurate formulation for the holographic photocurrent density, for bulk absorbing materials, including the case of large amplitudes and for any frequency of the vibrating pattern of fringes .

## 2. THEORY AND EXPERIMENT

Let us assume a pattern of fringes sinusoidally oscillating with (angular) frequency $\Omega$ and phase amplitude $\Delta$ along the coordinate $x$ (parallel to the gratingvector $\vec{K}$) as described by

$$I = I_0 + (I_0/2)[m(t)\, e^{iKx} + m(t)^*\, e^{-iKx}]; \qquad m(t) = |m|\, e^{i\phi}\, e^{iK\Delta \sin \Omega t} = |m|\, e^{i\phi} \sum_{l=-\infty}^{+\infty} J_l(K\Delta)\, e^{il\Omega t} \quad (1)$$

where $m(t)$ is the complex fringes modulation coefficient, $\phi$ is the phase shift of the fringes and $J_l()$ is the ordinary Bessel function of order $l$. It is possible to show that, in the absence of externally applied electric field and for $|m| \ll 1$, the current density along the $\vec{K}$ direction can be written as

$$j(t) = \frac{j^0}{2} + \frac{j^\Omega}{2} e^{i\Omega t} + \frac{j^{2\Omega}}{2} e^{i2\Omega t} + ... + cc \quad (2)$$

where the first harmonic term in $\Omega$ is

$$j^\Omega = -\frac{\sigma_0 |m|^2 J_1(K\Delta) E_D \cos\phi}{(1+K^2 l_s^2)(1+K^2 L_D^2)} \left[ \frac{J_0(K\Delta)\Omega\tau_{sc}}{1+i\Omega\tau_{sc}} + \frac{J_2(K\Delta)3\Omega\tau_{sc}}{(1-i\Omega\tau_{sc})(1+i2\Omega\tau_{sc})} \right] \quad \text{with} \quad \tau_{sc} = \frac{\epsilon\epsilon_o}{\sigma_0} \frac{1+K^2 L_D^2}{1+K^2 l_s^2} \quad (3)$$

where $L_D$ and $l_s$ are the diffusion and Debye screening legths, respectively, $\epsilon$ is the dielectric constant, $\varepsilon_0$ is the electric pemittivity of vacuum and $\sigma_0$ is the photoconductivity. A similar calculation leads to an expression for the second harmonic term that, for the present $\phi = 0$ condition, is zero: $j^{2\Omega} = 0$. The Eq.(3) however is somewhat different from those reported in the literature [1] for large $\Delta$. Light absorption effects cannot be neglected in most photorefractive materials and were actually analysed before [4] but for the $\Omega\tau_{sc} \gg 1$ limit only. In this paper we are dealing with the whole range for $\Omega$ so that we need to consider the effect of absorption on the holographic response time, besides its obvious effect on the photoconductivity: The irradiance decreases exponentially along the sample's thickness coordinate $z$ so that irradiance-dependent quantities like photoconductivity and holographic response time do also vary along $z$, respectively as $\sigma_0(z) = \sigma_0(0)\, e^{-\alpha z}$ and $\tau_{sc}(z) = \tau_{sc}(0)\, e^{\alpha z}$, where $\sigma_0(0)$ and $\tau_{sc}(0)$ are the values at the input plane inside the sample and $\alpha$ is the effective absorption coefficient. The expression for $j^\Omega$ in Eqs.(3) is therefore also dependent on $z$, because of its

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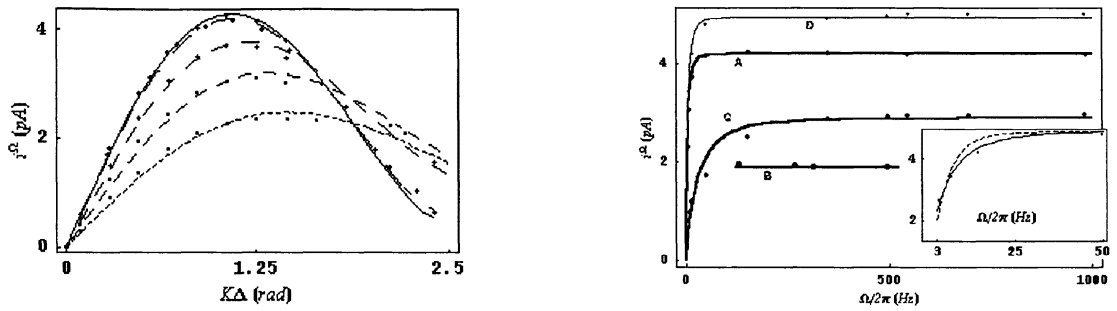


Figure 1: **Left picture:** $|i^{\Omega}|$ data (spots) as a function of $K\Delta$ with the best fit (curves) to theory, from $\Omega/2\pi = 980$ Hz (thickest continuous) through 546Hz, 349Hz, 152Hz, 49.7Hz, 14.7Hz and 6.9Hz, to 3.5Hz (thinest dashed). **Right picture:** $|i^{\Omega}|$ data (spots) ploted as a function of $\Omega/2\pi$, for $K\Delta = 1.1$ rad: for BTO (curves **A** and **B** for different irradiances), for BTO:Ce (curve **C**) and for BTO:Pb (curve **D**). The continuous curves are their respective best fit. The inset is an enlarged detail of BTO:Pb data with the best fit curve with (continuous) and without (dashed) considering bulk absorption.

dependendence on $\sigma_0(z)$ and $\tau_{sc}(z)$, and should be rather written as $j^{\Omega}(z)$ in order to explicitely indicate this dependence. The experimentally measured photocurrent value is

$$i^{\Omega} = H \int_0^d j^{\Omega}(z)\mathrm{d}z \tag{4}$$

where $H$ is the heigth and $d$ is the thickness of the sample. The experiment is carried out using a conventional setup where a sinusoidal pattern of fringes is projected onto the (110) crystallographic plane of the BTO sample, with its [001]-axis perpendicular to the plane of incidence and to $\vec{K}$. The angle between the interfering beams (in air) is $51^{o}$ and the wavelength is $\lambda = 0.5145\mu m$. A piezoelectric supported mirror (PZT), placed in one of the interfering beams, is used to produce the phase modulation. The modulus of the first harmonic amplitude $|i^{\Omega}|$ in Eq.(4) is measured as a function of $K\Delta$ for different fixed values of $\Omega$ and plotted (spots) in the left picture in Fig.1, where the curves are the best fit to theory. Values of $|i^{\Omega}|$ were computed for all available values of $\Omega$, at a fixed $K\Delta = 1.1$ rad and plotted (spots) in the right picture in Fig.1 as a function of $\Omega/2\pi$, for pure BTO and for doped BTO samples. From these fittings some material's parameters like $l_s$, and $\sigma(0)/(I(0)(1+K^2L_D^2))$ were obtained that are self-consistent and in agrement with the available data in the literature. The inset in the right of Fig.1 shows a detailed partial view of the fit of data for BTO:Pb with and without considering bulk absorption, respectively: The latter shows a much poorer fitting and the resulting parameters are considerable different.

## 3. CONCLUSIONS

We have shown the interest of using a large modulation amplitude for the phase modulation in the experiment, in order to considerably improve the size of the signal. We report an accurate theoretical formulation for this large-amplitude operation condition and draw the attention to the misleading use of some approximations. We have also shown the importance of taking into account the bulk light absorption in these materials. The excellent theoretical fit to experimental data strongly supports our model and shows the possibilities of this technique.

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