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Dependence of the refractive index grating in photorefractive barium titanate on intensity

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Abstract

The interference pattern of light waves creates a refractive index modulation in photorefractive media. This process is relatively well described by the theory (Kukhtarev equations) but deviations are found. Therefore, experimental methods are used in order to characterise the processes. The influence of the absolute intensity as well as of the intensity ratio of the interfering waves on the refractive index modulation are studied in a two-wave mixing arrangement. Especially for the dependence on the absolute intensity the interesting relation $\Delta n = f(I_{abs}) \sim I_{abs}^{\alpha}$ was found that is not predicted by the theory. Nevertheless, this experimental approximation can be used in calculations in order to minimise the error.

Refractive index gratings can be created in photorefractive media via an intensity distribution built by interference of two waves. The strength or modulation of such a grating is influenced by the intensity of the writing beams, by their absolute intensity as well as by their intensity ratio. The theory (band transport model, Kukhtarev equations) yields the following expression for the space charge field E_{sc} that is created inside the medium after a sufficient time [1]:

$$E_{\mathrm{sc}} = -\,m\,\xi(K)\,\frac{k_{\mathrm{B}}T}{q}\,\frac{K}{1+\left(\frac{K}{k_0}\right)^2}\,\sin\left(\vec{k}\vec{r}\right) \qquad (1)$$

where m is the modulation of the intensity distribution ($m \ll 1$), ξ describes the influence of positive charge carriers, k_B is the Boltzmann constant, T is the temperature, q is the unit charge, $\vec{k}$ is the vector of the intensity grating, $K = |\vec{k}|$, $k_0 = \sqrt{4\pi N q^2/\epsilon k_\mathrm{B} T}$, N is the effective density of photorefractive charge carriers, and $\epsilon = (\vec{k}\,\overline{\overline{\varepsilon}}\,\vec{k})/K^2$. An important point of this equation is that E_sc is direct proportional to the modulation m (visibility) of the intensity distribution (valid for $m \ll 1$) and that E_sc does not depend on the absolute intensity I_abs. The diffraction efficiency η at the grating can be derived for the Bragg case from

$$\eta \sim \sin^2\left(\frac{\pi\,\Delta n\,d}{\lambda\cos\theta}\right) \approx \left(\frac{\pi\,\Delta n\,d}{\lambda\cos\theta}\right)^2 \sim \Delta n^2 \sim E_\mathrm{sc}^2 \sim m^2 \tag{2}$$

where Δn is the refractive index modulation, d is the thickness of the grating, λ is the wavelength, θ is the angle between the writing beams, and E_sc is the amplitude of the space charge field, to be proportional to m^2. The relations $\eta = f(m)$ and $\Delta n = f(m)$ should be verified first.

For this purpose the experimental arrangement shown in figure 1 was used. The grating is written by two beams with intensities I_1 and I_2 of an

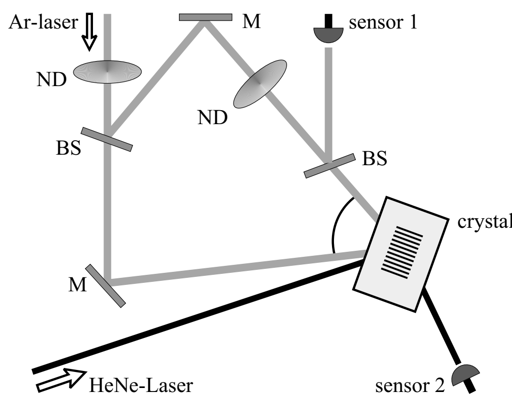

Figure 1: Experimental arrangement. ND are variable neutral density filters, M are mirrors, BS are beam splitters, and the sensors are power meters.

Ar^+-laser (514 nm), where the absolute intensity ($I_\mathrm{abs} = I_1 + I_2$) as well as the intensity ratio of the beams in the $BaTiO_3$ crystal can be controlled by neutral density filters. The grating is read by a probe beam from a HeNe-laser (633 nm) fulfilling the Bragg condition. An interaction between the beams is avoided by using two mutually incoherent lasers. The homogeneous illumination of the crystal by the probe beam effects the erasure of the refractive index grating or at least the decrease of the modulation of the grating. In order to avoid a distortion of the results of the measurement the probe beam was switched off during the write process. Then we measured the intensity of the diffracted part of the probe beam after switching on this beam. Figure 2 shows a typical temporal course. The peak value of the intensity

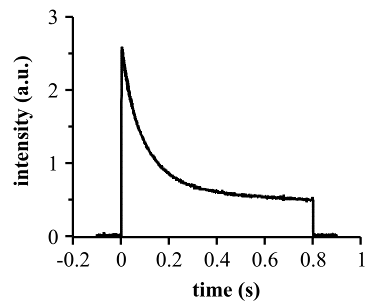

Figure 2: Temporal course of the intensity of the diffracted probe beam.

for $t = 0$, when the grating is undistorted, was noted. The modulation m of the intensity distribution, $m = 2\sqrt{I_1 I_2}/(I_1 + I_2)$, of the writing beams is varied, whereas the total intensity I_{abs} is kept constant. The results are shown in figure 3. The left diagram shows the diffraction efficiency η as a

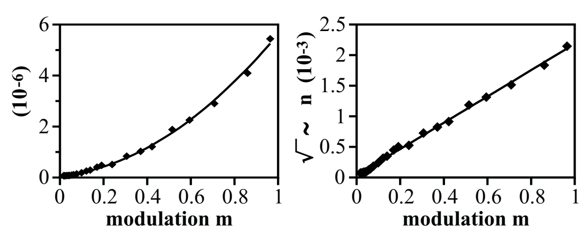

Figure 3: Influence of the modulation of the intensity distribution on the diffraction efficiency and on the refractive index modulation.

function of the parameter m. A parabolic curve fits well to the measured values. The relation shown by equation (2) is confirmed. The right diagram leads to the same result. Here, the modulation of the refractive index Δn as a function of the modulation m is shown. The linear dependence is obvious. Astonishingly, the dependencies are not only valid for small modulations m, as required to derive equation (1), but for all the range of m between zero and unity. Efforts to explain this result have been done in [2,3] by using perturbation analysis and taking higher harmonics into account.

In the following, the influence of the total intensity I_{abs} on the refractive index modulation Δn and the diffraction efficiency η is studied (figure 4). The intensity I_{abs} was varied over five orders of magnitude, between $50\,\text{nW/mm}^2$ and $30\,\text{mW/mm}^2$ (we worked with unexpanded laser beams).

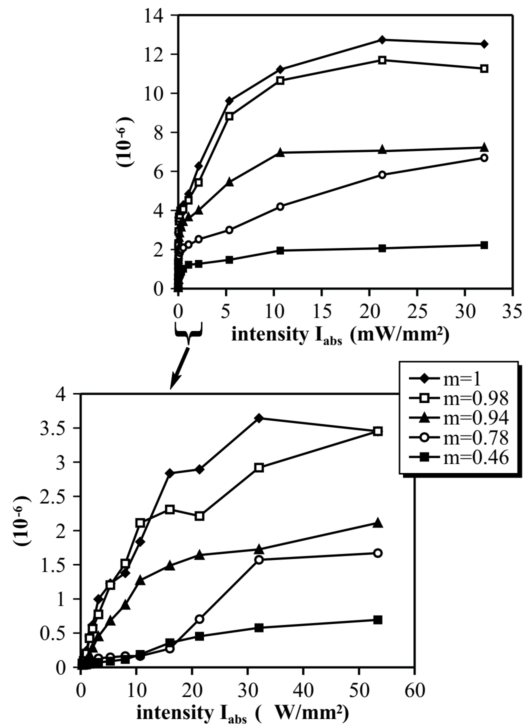

Figure 4: Influence of the absolute intensity I_{abs} on the diffraction efficiency η.

The relation is measured for various values of the modulation m that is used as a parameter varying between different graphs. The diffraction efficiency increases with increasing intensity. Because of the large intensity range, a logarithmic representation is shown in figure 5, where Δn is calculated from η using equation (2). The theory (Kukhtarev) does not explain the measured

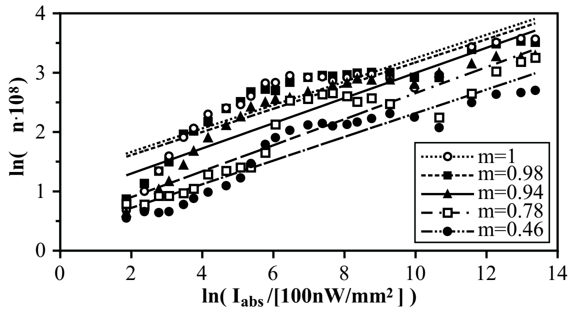

Figure 5: Influence of the absolute intensity $I_{\rm abs}$ on the refractive index modulation Δn (logarithmic representation).

relation between Δn and $I_{\rm abs}$. Therefore, it thoroughly seems to be appropriate to fit the measured points (figure 5) by linear functions in order to get a first rough approximation. Using $\ln(\Delta n) \sim \ln(I_{\rm abs})$ we get

$$\Delta n \sim I_{\rm abs}^{\alpha} \tag{3}$$

where the value of α was determined to be 0.20 ($\pm$0.01). This function describes the physical relation but cannot be explained by the theory up to now. Other obviously possible functions (e.g. exponential) gave no satisfactory results.

Efforts have been done in the literature [4–6] to partially explain the influence of the intensity in certain ranges [7,8] but no fully suitable models exist [9–12]. The inclusion of the dark conduction [12–15], of two centres [12], of the photovoltaic effect [16], of quadratic recombination [9], and of shallow traps [17–19] seems to be promising.

Nevertheless, the error in any further calculation based on intensity dependencies is much smaller if the approximation according equation (3) is used than if the dependence is ignored at all. Moreover, figure 6 makes clear that the deviation between approximation and real values is not too important and that the description by the derived function is rather good.

In conclusion, we have studied the dependence of the refractive index modulation with two-wave mixing in a photorefractive medium on the modulation and on the intensity. For the modulation we could confirm the relation known from the literature and predicted by the theory. We observed a strong dependence on the absolute intensity and could describe this mathematically.

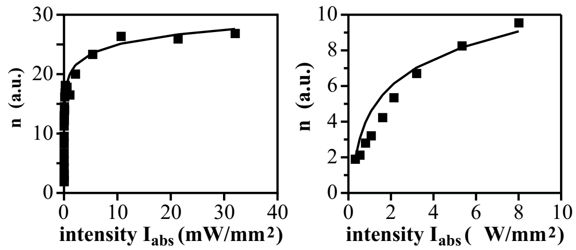

Figure 6: Fit of the derived function $\Delta n \sim I_{\text{abs}}^{\alpha}$ to the measured values shown in figure 4 for $m = 0.94$.

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