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Photorefractive properties of periodically poled $LiNbO_3$

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ABSTRACT

We study theoretically the photorefractive response of periodically poled $LiNbO_3$ crystals with dominating photovoltaic transport. Strong suppression of the photorefractive effects at low spatial frequencies (in comparison with the single-domain case) and preservation of these effects for short fringe spacings are shown. We also describe a new kind of photorefractive wave coupling, which is forbidden for single domain crystals. It is characterized by wave propagation angles, dependent on the domain inversion period, and by a large gain factor.

SUMMARY

Introduction

Over the last few years poling techniques based on the use of electric-field pulses have allowed to fabricate high quality periodically poled ferroelectrics (PPF) [1, 2, 3, 4]. The period of such structures ranges from a few to several tens of μm and the number of periods can reach a few thousands. So far, the main interest for PPF, and especially for periodically poled lithium niobate (PPLN), was associated with the effect of quasi-phase-matched frequency conversion. Recently, the observation of unusual light-induced scattering [5] produced a real interest to PPLN as a new photorefractive material [6, 7]. In this paper we summarize the results of our theoretical studies on the photorefractive properties of PPLN.

Model

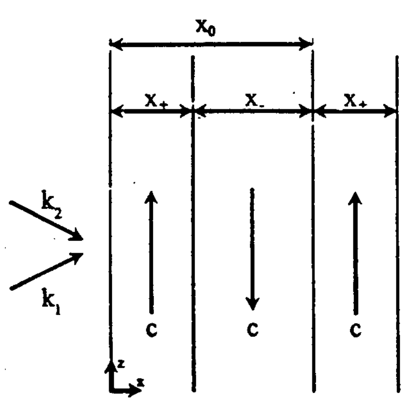

Figure 1: *Geometrical scheme of PPLN.*

The medium in consideration, consisting of periodically inverted domains, is drawn in Fig. 1. The sizes of opposite domains (in general different) are x_+ and x_-, and the period of the structure is $x_0 = x_+ + x_-$. The fringes of the interference light pattern, produced by a pair of light waves of the same polarization with wave vectors $\vec{k}_1$, $\vec{k}_2$, are perpendicular (or near perpendicular) to the polar $\vec{c}$- axis. The main mechanism of charge separation is the photovoltaic effect [8]. No voltage is applied to the illuminated region.

To characterize the photorefractive response, one should find the spatial distribution of the light-induced refractive index, $\delta n(x, z)$, and its Fourier spectrum.

Qualitative considerations

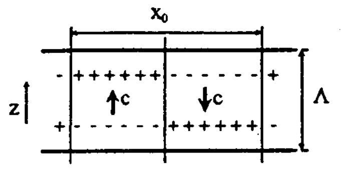

Figure 2: *Scheme of the photovoltaic charge separation for a symmetric domain structure.*

If the fringe spacing Λ is much less than the period x_0, the space-charge field $\vec{E}$ inside each domain corresponds to the single domain case, see Fig. 2. This means that the edge effects are negligible, $E_z \gg E_x$, and $E_z(x)$ changes periodically its sign because of the domain inversion. Further we notice that the sign of the linear electrooptic coefficient, r, is also correlated with the direction of the $\vec{c}$-axis. In other words, the dependence $\delta n(x,z)$ in the limit $\Lambda \ll x_0$ is everywhere nearly the same as for the single domain case. The role of the transient regions between opposite domains, where E_z and δn are close to zero, is of minor importance.

In the opposite limit, $\Lambda \gg x_0$, the space-charge field is strongly reduced because of a quick alternation of positive and negative photoinduced charges, see Fig. 2. Consequently, the optical damage associated with large-scale variation of δn has to be strongly reduced.

Photorefractive response

The nonlinear variation of the refractive index can be written as $\delta n = -n^3 r E_z/2$, where n is the non-perturbed refractive index. The space-charge field $\vec{E}$ can be found using the continuity equation, $(\vec{\nabla} \cdot \delta\vec{j}) = 0$, where $\delta\vec{j}$ is the spatially oscillating part of the current density,

$$\delta\vec{j} = \beta\,\vec{z}\,\delta J + \kappa\, I_0\, \vec{E} \quad (1)$$

Here β is the relevant photovoltaic coefficient, κ the specific photoconductivity, $\vec{z}$ the Cartesian unit vector, $I_0 = |A_1|^2 + |A_2|^2$ and $\delta I = A_1 A_2^* \exp(i\vec{K}\cdot\vec{r}) + c.c.$ are the uniform and the spatially modulated part of the light intensity, respectively, $\vec{K}$ is the light grating vector, and $A_{1,2}$ are the amplitudes of the light waves. The sign of β (as well as the sign of r) is opposite in opposite domains. The ratio $|\beta|/\kappa$ gives simply the value of the photovoltaic field, E_{pv}.

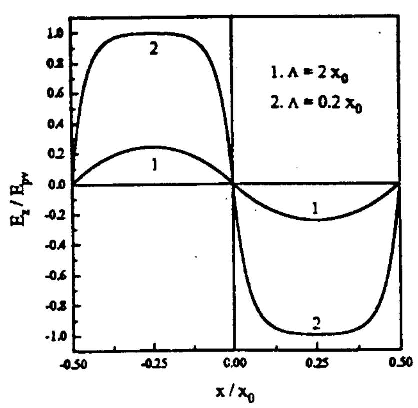

Figure 3: *Dependence $E_z(x)$ for a symmetric domain structure.*

Fig. 3 illustrates our calculations of the space-charge field for the case $K_x = 0, x_\pm = x_0/2$. One can see that the photorefractive response is strongly reduced already for $\Lambda = 2x_0$. On the other hand, the role of the edge effects remains substantial even for $\Lambda = 0.2x_0$.

In the general case, when $K_x \neq 0$, the photorefractive response may be represented in the form

$$\delta n = -\frac{n^3\,|r|}{2}\,\frac{A_1 A_2^*}{I_0}\,e^{i\vec{K}\cdot\vec{r}} \sum_{s=-\infty}^{\infty} E_{\vec{K}}^{(s)}\, e^{2\pi i s x/x_0} + c.c.\,. \quad (2)$$

The periodicity of PPLN manifests itself (a) in modifying the fundamental harmonic, $E_{\vec{K}}^{(0)}$, in comparison with the single-domain case and (b) in producing side spatial harmonics with $s \neq 0$.

It is important that $E_{\vec{K}}^{(0)}$ is a real quantity regardless of the ratio x_0/Λ and of the relation between K_x and K_z. This means that the fundamental component remains π-shifted with respect to the light fringes. Fig. 4 shows the dependence $E_K^{(0)}(x_0/\Lambda)$ for the case $x_\pm = x_0/2, K_x = 0$. The effect of reduction for $x_0 < \Lambda$ and the transition to the short fringe-spacing limit for $\Lambda < 0.3x_0$ are clearly seen.

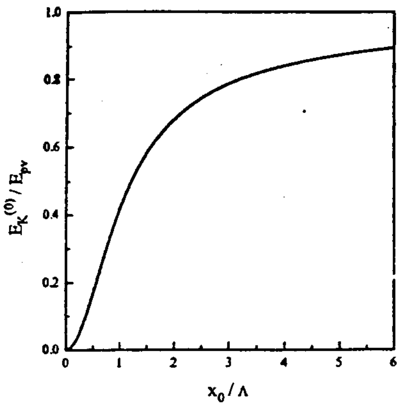

Figure 4: *Dependence of $E_K^{(0)}$ on the ratio (x_0/Λ) for $x_\pm = x_0$.*

The amplitude $E_K^{(0)}$ is directly related to the Bragg diffraction efficiency of the recorded grating, $\eta = \sin^2(glE_{\vec{K}}^{(0)}/2E_{pv})$, where l is the thickness of the sample and $g = \pi n^3|r|E_{pv}/\lambda$ the coupling constant. The transition region, $\Lambda \approx x_0$, corresponds usually to a pump half-angle of several degrees.

Regarding the side harmonics, the case $K_x \ll K$ constitutes our main interest. In this case

$$E_K^{(s)} \simeq \frac{2E_{pv}}{\pi(is + x_0/\Lambda)} e^{-isx_+/x_0} \cos(s\pi x_+/x_0) . \qquad (3')$$

This quantity is complex and its phase depends on the ratio x_+/x_0. Only even harmonics are present in the case $x_\pm = x_0/2$.

Parametric coupling

The presence of the side harmonics in the Fourier spectrum of δn makes possible new schemes for the photorefractive wave coupling. Let the wave vectors of the pump wave $(\vec{k}_p)$ and of the two side waves $(\vec{k}_1, \vec{k}_2)$ meet the phase-matching condition shown in Fig. 5. Direct amplification of the side beams is forbidden here, because the fundamental gratings produced by wave pairs $\vec{k}_1, \vec{k}_p$ and $\vec{k}_p, \vec{k}_2$ are both π-shifted with respect to the light fringes. However the s^{th} harmonic induced by the pair $\vec{k}_1, \vec{k}_p$ coincides in spatial frequency with the fundamental harmonic of the pair $\vec{k}_p, \vec{k}_2$. Similarly, Fig. 5 shows that the $-s^{th}$ harmonic from the pair $\vec{k}_p, \vec{k}_2$ has the spatial frequency $\vec{k}_1 - \vec{k}_p$. Since the additional contributions to the amplitudes, $E_{\vec{k}_1 - \vec{k}_p}$ and $E_{\vec{k}_p - \vec{k}_2}$ are complex, the energy transfer to the side beams becomes allowed.

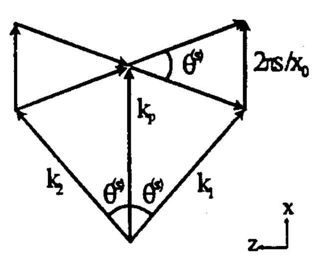

Figure 5: *Wave vector diagram for parametric wave coupling in PPF.*

The angle of synchronism, $\theta^{(s)}$, calculated from Fig. 5, is given by $\sin\theta^{(s)} \simeq (s\lambda/nx_0)^{1/2}$. The exponential gain coefficient, Γ_s, is calculated to be

$$\Gamma^s = (4g\theta^{(s)}/\pi s)\,|\cos(\pi s x_+/x_0)| . \qquad (4)$$

Its value depends on the ratio x_+/x_0 and may easily exceed 10 cm^{-1} for typical parameters of $LiNbO_3$:Fe.

The use of the described coupling mechanism has allowed us to explain the main regularities of self-organized light-induced scattering in PPLN [5, 7].

Conclusions

Periodically poled ferroelectrics are promising photorefractive materials. On one hand, the domain inversion allows to reduce strongly the optical damage. On the other hand, the photorefractive properties appear in the range of high spatial frequencies. A new kind of photorefractive beam coupling is possible in PPF. The phase-matching conditions for this coupling include not only the light wave vectors but also the grating vector of the periodic structure. Further experiments are needed in this new photorefractive research area.

Acknowledgments

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