Molecular Crystals and Liquid Crystals

Enhancement of the Coupling Gain in GaAs-Liquid Crystal Hybrid Devices

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In this work the evanescent space-charge field generated in semi-insulating GaAs semi-conductor substrates was used to reorient the liquid crystals molecules sandwiched between them to study the energy exchange in two-wave mixing experiments. We show that the two-beam coupling gain coefficient in hybrid devices is enhanced by a factor of ~36 as compared to GaAs alone. The photorefractive gain coefficient reported here is the largest ever reported in semiconductors without the need of space-charge enhancing techniques such as externally applied fields or running gratings.

Keywords: GaAs; hybrid; liquid crystals; photorefractive

Introduction

The photorefractive effect has been studied extensively over the last 30–40 years in inorganic photoconducting electro-optic crystals. The photorefractive effect consists on the refractive index change produced by a space-charge field generated by photo-induced charge transport. An important consequence of the photorefractive effect is the $\pi/2$ spatial phase shift between the intensity pattern and the refractive index grating. Thus, in a two-wave mixing configuration, unidirectional energy transfer is observed allowing exponential amplification ($\sim e^{\Gamma d}$, where Γ is the gain coefficient and d is the material thickness) of a weak signal beam [1]. Typical values for Γ in inorganic materials lie in the range of 1–200 cm^{-1}. One of the limiting factors of the relative low value of Γ is the small modulation in refractive index ($\Delta n \approx 10^{-4}$) achieved in these crystals. This limitation can be compensated by using relative thick crystals (0.5–1 cm). A large number of applications have been proposed and demonstrated using the photorefractive effect: beam amplification, image processing, phase conjugation, Bragg gratings, tunable narrow band filters, ultrasound detection and so on [1]. However, to our knowledge, no commercial applications are available in the market, owing mainly to the high cost of the inorganic crystals (several thousands of dollars) and the lack of reproducibility of their photorefractive properties. Thus cheap, easy to fabricate and reproducible materials are needed to develop commercial applications of the photorefractive effect.

One of such materials are liquid crystals (LC). LC are materials with large anisotropy over a large spectral range and are easily polarized by small electric fields. By using

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photorefractive-like effect, gain coefficients as large as $\Gamma \sim 2900$ cm^{-1} has been demonstrated on dye-doped liquid crystal cells [2, 3]. In order to enhance the molecular reorientation of pure LC, a photo-generated space-charge field in photorefractive [4] or organic photoconducting layers [5] was used yielding Γ values as large as ~ 3700 cm^{-1}. These gain coefficients are two orders of magnitude higher than those typically reported in solid inorganic crystals mainly because the large refractive index modulation (typically ≈ 0.2) of LC. One disadvantage of these devices is the need of application of large electric fields to reach such high gain coefficients and the limited spatial resolution. Recently, it was demonstrated that the use of photorefractive substrates dispense the use of large external applied fields yet providing large Γ values [6–10]. Although the use of photorefractive substrates in hybrid liquid crystal devices represents a major step towards high gain materials without the need of external fields, other material options must be sought since photorefractive materials are expensive and difficult to growth.

Semiconducting materials are well known photorefractive materials offering many advantages over ferroelectric materials: (1) fast response time owing to the large charge carrier mobility (typically on the microsecond time scale), (2) sensitivity in the near infrared spectral region (0.7–1.5 μm), (3) comparative low cost, and (4) high optical quality due to its extensive use in the electronic industry. In addition, photorefractive sensitivity is two-three orders of magnitude larger than photorefractive ferroelectrics. Although their electro-optic coefficient is too small for energy exchange, this is not important for us since we will be interested on the $\pi/2$ phase-shifted space-charge field to reorient the LC molecules. An excellent review of the photorefractive properties of semiconductor materials can be found in Ref. [11]. Of the wide variety of semiconductors, GaAs is quite attractive due to its high quality and low price. The first report of two beam coupling gain in GaAs was done by Marvin Klein obtaining $\Gamma \sim 0.4$ cm^{-1} in absence of applied field [12]. This work attracted a lot of attention to semiconductor materials because its near infrared sensitivity translate to compatibility with cheap light sources and optical communications devices. Since then, many reports have been published using different enhancing techniques such as applied fields and moving gratings obtaining gain coefficient as large as 7 cm^{-1} [13]. More recently, a liquid crystal hybrid device based on CdTe semiconductor has been employed and a gain coefficient of 16 cm^{-1} was obtained [14].

In this work, we demonstrate that the two-beam coupling gain coefficient in hybrid GaAs/5CB liquid crystals can be increased by a factor of ~ 36 as compared to pure GaAs without enhancing techniques, obtaining the largest gain coefficient semiconductor based hybrid devices.

Experimental Details

We used semi-insulating, $(100 \pm 5°)$-cut GaAs undoped wafers from AXT Company. The wafer's thickness is 590 μm and 10 cm diameter with both sides polished. We used semi-insulating GaAs because exhibits relatively low dark conductivity which prevents compensation of the light-induced grating by dark charge carriers. It must be pointed out that the (100)-cut is not a holographic one, i.e., the two-beam coupling gain coefficient is zero but even a small misorientations may lead to gain coefficient as large as 0.13 cm^{-1} [15] due to nonzero effective electro-optic coefficient. This fact is very important since we will be interested on the evanescent space-charge field produced in the photoconductive substrates as aligning mechanism of liquid crystal molecules and not in the photorefractive effect itself.
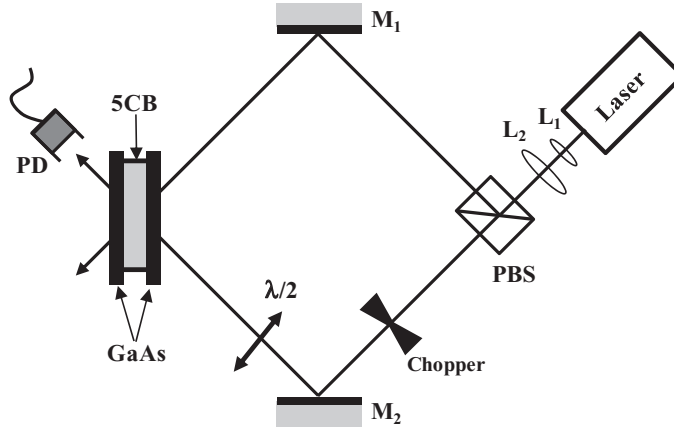
Figure 1. Experimental set up. Lenses L_1 and L_2 expand the near-infrared laser beam ($\lambda = 1.064 \mu$m), which is divided in two by 99:1 polarizing beam splitter (PBS). Both beams are redirected to the sample by mirrors M_1 and M_2. The $\lambda/2$ waveplate rotates the probe beam polarization to optimize the interference pattern contrast.

A PVA aligning layer is deposited on a 2×1.5 cm^2 GaAs crystal cut from a wafer, unidirectionally rubbed, filled in by capillarity with 5CB liquid crystals and sealed with an epoxic glue. Cells of different thickness were fabricated. The LC pretilt was measured as $\sim 8°$. The cells were assembled such that the pretilt angle sign is opposite on both substrates since this configuration optimizes the flexoelectric effect [9]. We did not notice a significant change on the pretilt angle on the crystallographic orientation but a more careful study is necessary.

For the two-wave mixing experiments, a pair of beams from a Nd:YAG laser ($\lambda = 1064$ nm) are made to interfere on the front surface of the device (see Fig. 1). Lenses L_1 and L_2 expand the near-infrared laser beam ($\lambda = 1.064 \mu$m) to about 8 mm diameter, and divided in two by 99:1 polarizing beam splitter (PBS). Both beams are redirected to the sample by mirrors M_1 and M_2. The $\lambda/2$ waveplate rotates the probe beam polarization to optimize the interference pattern contrast. The gain coefficient dependence on the grating spacing was obtained by changing the angle between the interfering beams. In order to measure the gain coefficient, a photodetector, connected to a lock-in amplifier, was placed on the path of the transmitted weak beam and its intensity was measured when the pump beam is absent (I_{off}) or present (I_{on}). The gain coefficient was determined by using the undepleted pump approximation $\Gamma = (1/d)\log(I_{on}/I_{off})$ where d is the sample thickness (1203 μm). The probe beam was chopped at 150 Hz and the chopper triggers the locking-in amplifier.

Results

Prior to cell assembling, the gain coefficient of each substrate was determined by using the setup of Fig. 1 at a fixed grating spacing Λ of ~ 1 μm. The crystal was rotated along the normal of the crystal to optimize TBC gain coefficient and the direction of energy transfer was determined and marked on the substrate. The gain coefficient is quite small as expected for this crystal cut. Then a device with two GaAs substrates separated by 23 μm spacers and filled with index-matching oil (n = 1.5, close to the refractive index of the liquid crystal to
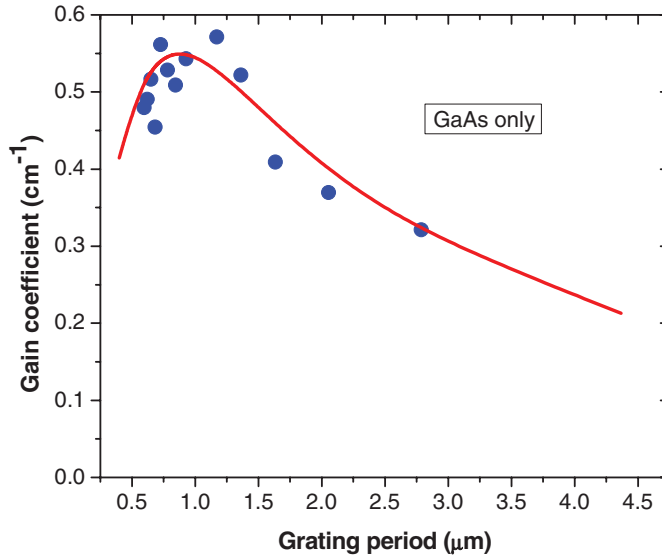
Figure 2. Two-beam coupling gain coefficient of two substrates of GaAs separated by 23 μm space filled in with index-matching oil (n = 1.5). The continuous line is fit to a one-impurity photorefractive model in absence of applied field. Maximum gain coefficient is about 0.55 cm^{-1}.

minimize Fresnel losses) was made. The gain coefficient direction of both GaAs substrates was the same. The net gain coefficient of the oil-filled device is ~0.55 cm^{-1} as shown in Fig. 2. On the same figure, a fit to the Γ value predicted by the one-impurity center model in absence of applied field is shown with the Debye length Λ_{Debye}~0.9 μm and effective trap density of ~10^{-16} cm^{-3}, consistent with previous results. Note that the gain coefficient value is about 3 times higher than that reported in the literature for single crystals [11]. This may be explained by small misalignments in crystal cut and sample orientation in the experimental set up as reported in Ref. [15]. These measurements are important in order to determine the gain coefficient of the hybrid device alone.

In general, LC molecules are sensitive to the sign of the electric field which means that a grating with twice the period of the interference pattern should be recorded and therefore no coupling between the beams should take place. As it was demonstrated earlier, in order to break the symmetry of the LC a pretilt is need it [7–9]. The pretilt will give rise to flexoelectric effect. Thus, coupling between the beams in hybrids devices occurs and it is expected to be enhanced by the large anisotropy of the LC.

Figure 3 shows the gain coefficient vs grating period in samples of different thickness. Three features are remarkably: (i) an enhancement factor of almost 36 in Γ in the thinnest device (23 μm) is observed and it decreases as the thickness of the sample increases. This behavior is consistent with results obtained in ferroelectric photorefractive-LC devices [8,16]; (ii) the gain coefficient is negative for small grating period with crossover at grating spacing of ~0.7 μm; and (iii) Debye's length moves towards larger grating spacing (~1.2 μm) as compared to that of the pure GaAs (~0.9 μm) and it seems to be independent of the sample thickness as also pointed out in Ref. [16]. In inorganic photorefractives, the increase on the gain coefficient (as a result of a larger effective trap density) is accompanied by a decrease of the Debye's length, the opposite tendency is observed in our results. Clearly, the standard photorefractive model cannot by applied to hybrid devices. Recently,
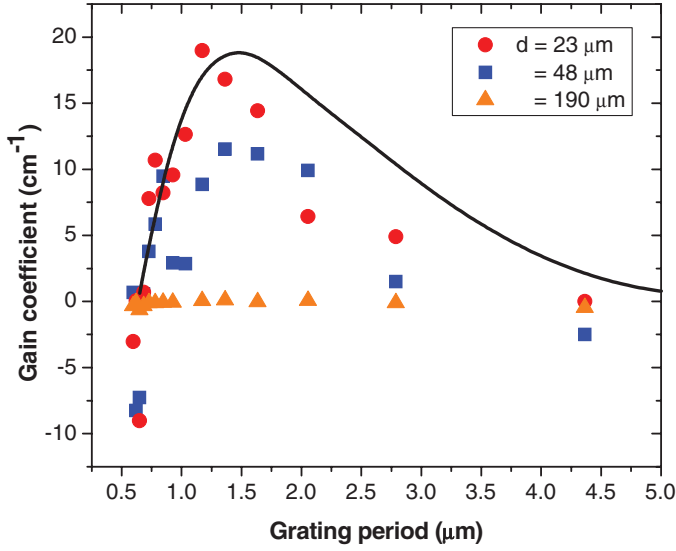
Figure 3. Two beam coupling gain coefficient for GaAs-5CB hybrid devices for several thicknesses. Solid line is a fit to the model proposed in Ref. [16] (see text for details).

Reshetnyak et al. proposed a comprehensive model to explain beam coupling in hybrid photorefractive liquid crystals [16]. In this model, the energy exchange is explained in terms of a nonlinear coupling between the space-charge field and the flexoelectricity of the LC. In previous works, it was assumed that the coupling of space-charge field and flexoelectricity follows a linear relationship; however, a cubic dependence is more compatible with experimental results. The solid line in Fig. 3 represents a fit to the gain coefficient given by [16]

$$\Gamma \approx r\, I\,(K)\, H_{\text{flexo}}\,(K)\left[E_{sc}\,(K) + \mu\,(L)\, K^2 E_{sc}^3\right] \tag{1}$$

where r is an adimensional parameter, I is a factor describing the beam interference, H_{flexo} accounts for the flexoelectricity, E_{sc} is the bulk space-charge field, K is the grating vector ($K = 2\pi/\Lambda$, Λ the grating spacing) and $\mu\,(L)$ is a factor that depends on the thickness of the liquid crystal film. The fitting was performed for the thinnest device (for $\Lambda \geq 0.7\ \mu$m) showing that this semi-quantitative model explains most of the observed features reported in this work. It must be point out that the fit is quite good for the small grating period but fails in the large grating spacing as reported in Ref. [16]. Although this is model is quite comprehensive there is still to work to be done to fully describe energy exchange in liquid crystal based hybrid devices.

Conclusions

In this work the evanescent space-charge field (due by photoinduced charge separation) generated in semi-insulating semiconductor materials was employed to reorient liquid crystals molecules sandwiched between them. We have shown that the two-beam coupling gain coefficient in hybrid devices is enhanced by a factor of ∼36 as compared to GaAs alone. The experimental results can be described reasonably well with nonlinear coupling between the flexoelectricity and the space-charge field. The photorefractive gain coefficient

reported here is the largest ever reported in semiconductors without the need of space-charge enhancing techniques such as externally applied fields or running gratings.

Acknowledgments

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