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Application of interference microscopy to the study of hologram build-up in $LiNbO_3$ crystals

István Bányász *, Gábor Mandula

Department of Crystal Physics, Research Institute of Solid State Physics and Optics of the Hungarian Academy of Sciences, P.O. Box 49, H-1525 Budapest, Hungary

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ABSTRACT

Interference microscopy was applied to direct microscopic observation of temporal evolution of phase holograms in $LiNbO_3$:Fe photorefractive crystals. First a hologram was recorded in the sample, and diffraction efficiency was monitored during hologram build-up using inactinic laser light. Thus kinetics of hologram build-up could be determined. The initial hologram was erased using white light. Then a series of write-erase cycles were performed with increasing exposure times. Holograms were observed by interference microscope after each exposure. The time elapsed between the exposure and the microscopic observation was negligible compared to the relaxation time of the hologram. The obtained temporal evolution of the grating profile gives a deeper insight into the physical mechanism of hologram formation in photorefractive materials than simple diffraction efficiency measurements. A congruently grown sample of $LiNbO_3$ doped with 10^{-3} mol/mol Fe in melting was studied by this method. Sample thickness was set to 300 μm to allow correct microscopic observation. Plane-wave holograms were recorded in the samples using an Ar–ion laser at $\lambda = 488.0$ nm of grating constants of 3, 6.5 and 8.8 μm.

1. Introduction

Since its discovery in 1966, the photorefractive effect has been studied extensively by several methods in various materials and has turned out to play a key role in modern optical technologies like photonics [1]. The holograms or simple gratings created by the effect have been experimentally studied mainly by measuring its diffraction efficiency or by reconstructing the recorded hologram. Relatively few papers report microscopic investigation of photorefractive gratings. In 1988, Matull and Rupp investigated thermally fixed holograms in copper doped lithium niobate crystals by microphotometric method, and measured not only the intensity but also the phase distribution of the light intensity pattern at the exit face of the crystal [2,3]. Brody and Garvin [4] developed a real-time laser holographic microscope using a photorefractive hologram and digital signal processing in 1990. Poumellec et al. [5] reported an ultraviolet light induced densification during Bragg grating inscription in Ge:SiO_2 using interferometric microscopy in 1995. In the following year, Grabar et al. published their three-dimensional investigation of domain structures of uniaxial ferroelectrics by applying photorefractive grating and polarization microscope [6]. In 1997, Douay et al. reported the monitoring of the build-up of photorefractive grating in PZG glass thin film both by He–Ne laser and interferometric microscope [7]. By using both optical and scanning electron microscope, Cipparrone et al. showed that the basic mechanism of the optical storage effect in dye-doped polymer dispersed liquid crystals is the photorefractive effect [8]. Atomic force microscopy was used for the direct study of charge grating at the surface of $LiNbO_3$ crystal by Soergel et al. [9]. Zhao et al. studied waveguide structures recorded in $LiNbO_3$:Fe, KNSBN:Ce and SBN:Cr crystals using digital holography with a Mach-Zehnder interferometer and a CCD camera [10]. de Angelis et al. adapted digital holography to the study of static holographic gratings recorded in iron doped lithium niobate [11].

However, no work on microscopic study of the build-up of two-wave mixing volume gratings of high spatial frequency in a photorefractive crystal has been reported so far. In the present article we report a quasi in-situ investigation of the build-up of photorefractive gratings in $LiNbO_3$:Fe.

Systematic study of phase gratings fabricated via ion-implantation in glass both with interference- and phase-contrast microscopy was performed by one of the authors of the present article

* Corresponding author. Tel.: +36 702988539, +36 13922222x1732; fax: +36 13922215.
E-mail address: banyasz@sunserv.kfki.hu (I. Bányász).

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and his co-workers [12,13]. In those experiments the highest spatial frequency of the implanted gratings was 250 lp/mm. Semi-physically developed phase holograms in Agfa 8E75HD emulsion were also studied by him using phase- contrast microscopy [14]. It was proved that phase-contrast microscopy could be used for the quantitative determination of the refractive index modulation in holographic phase gratings [15,16]. The above results made us hope that these standard microscopic techniques of phase object visualization could be suitable for studying high spatial frequency photorefractive gratings, too.

2. Experimental

2.1. Recording the holograms

For the investigation, we used an iron doped as grown lithium niobate sample. The crystal was grown by the Czochralski method with iron content of 10^{-3} molar ratio in the melt, using suprapur lithium carbonate (from Merck) and grade LN Nb_2O_5 materials (from H.C. Starck). The dimensions of the sample were $5 \times 0.3 \times 4\ mm^3$ in order of the crystallographic axes *a*, *b* and *c*, where *c* is the polar axis. The edges of the sample were short-circuited by silver paste. For recording the grating, we used standard two-wave mixing set-up with extraordinarily (horizontally) polarized recording beams, and with different angles of incidence. The set-up was similar than we used for thermal fixing experiments [17] or to investigate the effect of thermal neutron absorption to the decay of the photorefractive grating in $LiNbO_3$:Fe [18]. The wavelength of the recording beams was 488.0 nm, produced by an argon ion laser and a space filtering beam expander. The input intensities were adjusted using gray filters. We used an expanded and space-filtered laser beam of a He–Ne laser as a reading beam with intensity less than 0.01 mW/cm^2. The reading beam was adjusted into the Bragg angle of the grating using precision rotary and translating stage. The sample holder was mounted on a computer controlled precision rotary stage. After each microscopic measurement, we checked the diffraction efficiency by optimising the position of the rotary stage, reading beam and photodiodes both at the transmitted and the refracted beams. The signal of the photodiodes was measured using lock-in technique, and the sensitivity was increased by applying interference filters for 632.8 nm (Fig. 1).

In order to monitor the right value of the diffraction efficiency during recording, before each recording we recorded a new grating only for fine adjustments of the set-up. After the fine adjustment, we erased the grating by a fibre-optic 150 W tungsten halogen lamp for 20 min, and waited for at least 8 min for thermal equilibrium of the sample and the sample holder. After recording, we checked once again the diffraction efficiency by rotating the stage.

2.2. Microscopic study of the holograms

After terminating holographic recording, the photorefractive crystal was taken to the microscopy laboratory, and microphotographs of the holographic gratings were taken with a **Zeiss Peraval** microscope. That microscope can be used both as an interference- and a phase-contrast one, and there is a third option, the so-called interference phase-contrast (interphako), where optical path differences throughout the phase microobjects show up in different interference colours. After having checked all three methods, we opted for using interference microscopy. Phase-contrast microscopy (using high-power microscope objective) can resolve fine holographic gratings recorded in thick photorefractive crystals. However, in case of the routinely used thick (of some mm) samples, precise orientation of the sample with respect to the microscopic illumination becomes crucial. Small angular maladjustments can result in reduced phase-contrast. Furthermore, one has to take into account all the factors reducing the real phase-contrast, namely: modulation transfer function (MTF) of the microscope objective and that of each element (e.g. CCD camera) of the recording set-up. That is why we finally chose interference microscopy for the present experiments. In interference microscopy optical path differences are visualised as deformations of an equidistant parallel interference fringe system, consequently interference photomicrographs are much less susceptible to changes caused by the recording system.

2.3. Results of diffraction efficiency measurements

Recording and study of six series of holograms, in the same $LiNbO_3$:Fe sample, are presented in this article. Holograms of three

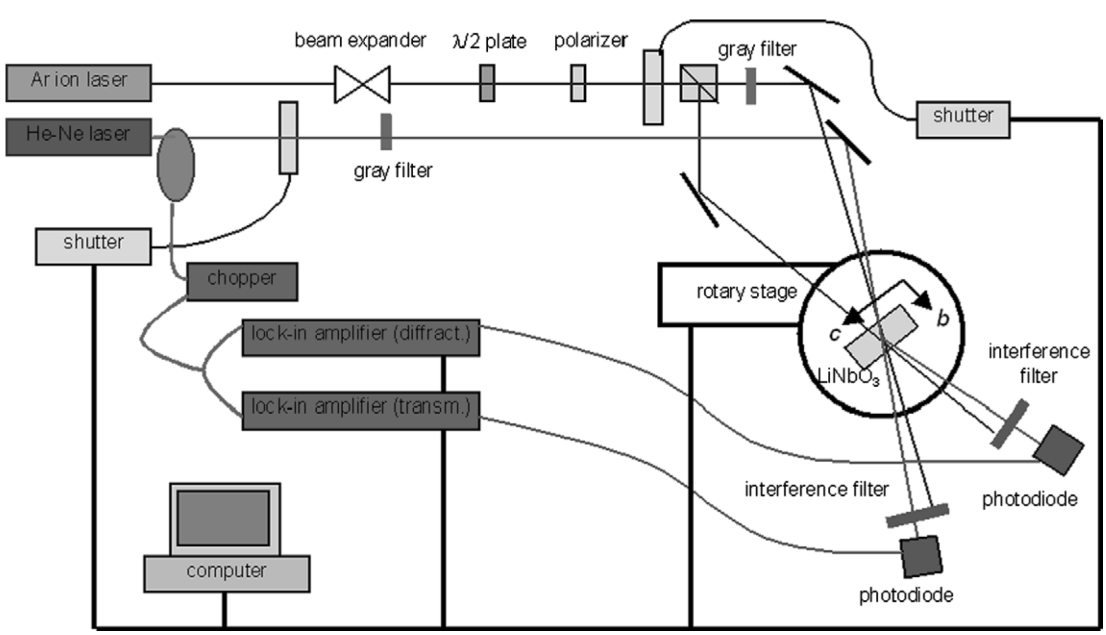

Fig. 1. The set-up for hologram recording in a photorefractive crystal.