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Non-volatile volume holograms in bismuth tellurite crystals

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Abstract
We investigate the durability of volume holograms in bismuth tellurite crystals, Bi_2TeO_5. This material enables self-fixing of holograms during the recording process rendering any further fixing technique unnecessary. Therefore the material overcomes the vulnerability of holograms which is a typical inconvenient property of inorganic storage crystals. The quality reduction of reconstructed analogue and digital data pages under permanent read-out is studied. In terms of digital page-oriented storage, the change of the bit error rate is investigated. For comparison, all experiments are also performed on iron doped lithium niobate crystals, $LiNbO_3$:Fe.

Keywords: Volume holographic data storage, bismuth tellurite, non-volatile holograms

1. Introduction

Volume holographic memories have been widely investigated during the last decade and have demonstrated their advantages in terms of storage capacity and fast read-out speed (e.g. [1]). These features are achieved by multiplexing several holograms in one location in the storage material (e.g. by angular, wavelength or phase-code multiplexing) and by the parallelism of the storage process (e.g. [2–4]). However, volume holographic storage systems still suffer from the lack of an appropriate memory material. Such a material has to fulfil a series of property requirements; e.g. it should possess high sensitivity, good optical quality and a large dynamic range while being cheap and robust and preventing data loss due to hologram volatility. Various types of storage material have been proposed such as photorefractive inorganic crystals, polymers and doped glasses (e.g. [1]). Today, photorefractive $LiNbO_3$ crystals still provide the best optical quality, while cheaper polymers possess a much higher dynamical range [5–7]. The major disadvantage of $LiNbO_3$ is the vulnerability of the holograms which necessitates use of a special recording scheme (sequential or incremental recording) when multiplexing several holograms in one storage location [8].

In photorefractive materials the interference pattern of the two writing beams is stored as a local modulation of the refractive index. The optical interference pattern raises charge carriers into the conduction band where they redistribute. Therefore it produces an internal space charge field which yields local changes of the refractive index. In inorganic photorefractive crystals such as $LiNbO_3$ the photovoltaic effect is crucial for this process. However, in order to avoid data loss some additional fixing technique has to be applied. These fixing techniques require elaborate system technologies and are partially applied after the recording process. Most well known is thermal fixing, where at high temperatures the space charge field leads to a redistribution of ions [9]. Since these ions are immobile at room temperature their pattern cannot be erased after cooling the storage material again. This technique is either applied simultaneously with or after hologram recording [10]. Another approach is electrical fixing, where the space charge field is copied into ferroelectric domains by applying large external electric fields [11]. This domain pattern is then also resistant against subsequent illumination. A more practical and all-optical approach can be realized using doubly, Fe and Mn, doped, photochromic $LiNbO_3$ [12]. For recording holograms the material has to be illuminated with sensitizing ultraviolet light additionally to the writing beams at red wavelengths. The part of the hologram which is stored in the deep Mn traps is insensitive to illumination with the red light, so the read-out is non-volatile.

Here we present a completely different approach in which the storage material is illuminated just by the writing beams; no special fixing, requiring further system technology for heating, providing electric fields or additional ultraviolet light, is applied. Therefore this approach is more convenient and due to its straightforward implementation it is attractive for applications.

It is a typical feature of fixed storage crystals that the diffraction efficiency of the written holograms suffers a rapid decay in the first minutes of permanent illumination. In thermally fixed crystals or when fixing in doubly doped $LiNbO_3$ this drop is caused by an erasure of the extant electric grating. Then after bleaching, the remaining fraction stays mainly constant over a long time period (cf e.g. [10, 12]). In electrically fixed crystals a similar effect occurs, yielding different time constants of the grating decay [13]. In Bi_2TeO_5 the diffraction efficiency of written holograms undergoes three different phases [14, 15]. In the first ≈10 s a rapid decay takes place erasing charge carriers in shallower traps, followed by a slower decay over several minutes corresponding to an erasure of charge carriers in deeper traps. In the third phase the signal remains to a large extent unchanged and subsequent permanent read-out is non-volatile. The diffraction efficiency of the long-living signal is approximately 10% of the initial one directly after the storage process. The origin of that long-term stability has not been identified unambiguously. Most probably the effect is related to the large structural oxygen deficiency (17%) in Bi_2TeO_5 crystals. The photorefractive space charge field probably gives rise to an oxygen ion transfer, which tends to compensate the field. Thereby the electro-optically induced refractive index modulation is converted into an electrically neutral modulation of the spatial oxygen distribution [15]. The experimentally observable slight enhancement of the hologram contrast during sequential read-out supports this model.

2. Experimental set-up

The Bi_2TeO_5 and $LiNbO_3$:Fe crystals used in our experiments were grown by the diameter-controlled Czochralski technique. The technical details of the growth and preparation of the undoped Bi_2TeO_5 samples are described in [16]. The congruently grown $LiNbO_3$:Fe crystals are iron doped with a dopant concentration of 10^{-3} Fe-ions/$LiNbO_3$ mole. After growth the Fe^{3+}/Fe^{2+} ratio was adjusted by oxidative and reductive treatments [17]. All samples were x-ray oriented, (45°-) cut and polished. The typical sample dimensions were $6 \times 6 \times 7$ mm^3. No specific coating was applied to the optical surfaces.

For performing the experiments a simple holographic set-up in the 90° configuration was used. Figure 1 shows a sketch of the relevant components. The beam of a frequency doubled Nd:YAG laser ($\lambda = 532$ nm, cw) is split into a reference and a signal beam. In the signal arm a two-dimensional amplitude pattern is imprinted on the signal wave by a test pattern or

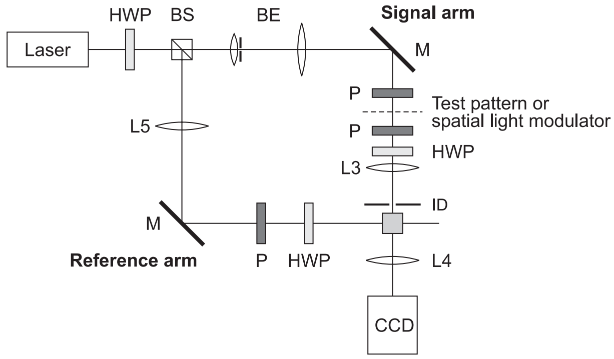

Figure 1. The experimental set-up in the 90° configuration for recording single holograms (BS = polarizing beam splitter; HWP = half-wave plate; BE = beam expander including spatial filter; M = mirrors; L3–5 = lenses (3, 4: imaging data page; L5: imaging beam waist); ID = iris diaphragm; P = polarizers).

a liquid crystal display. The two waves are then interfering in the storage crystals where the crossing angle is 90°. The overlapping volume of the two beams is about $1 \times 1 \times 1$ mm^3. A high resolution CCD camera is used to detect the reconstructed holograms.

The holograms are written in the different materials in such a way that the modulation depth and the diffraction efficiency of the holograms are the same in each case before beginning the read-out process. In order to achieve this condition the beam intensities had to be adapted. For writing holograms in $LiNbO_3$:Fe, beam intensities of 0.4–0.8 W cm^{-2} and 0.03–0.08 W cm^{-2} were used for the reference and the signal wave, respectively. In the less absorptive Bi_2TeO_5 crystals the beam intensities were adjusted to 4.0–5.5 W cm^{-2} and 0.4–0.6 W cm^{-2}. The writing time was in both cases in the range of 1.5–2.0 min.

3. Results

For a first qualitative investigation holograms of an analogue test pattern were recorded. Figure 2 shows the reconstructed holograms after different durations of permanent read-out where the reference beam intensity was 0.4 W cm^{-2}. In order to allow study of the signal decay for a longer time period while not changing the camera's exposure time, a slight overexposure of the holograms reconstructed at $t = 0$ (i.e. at the end of the storage process) was tolerated. This procedure is reasonable since it was carefully ensured that the diffraction efficiencies of the holograms and the amount of overexposure were the same in each case. It is clearly discernible that the holograms in $LiNbO_3$:Fe fade away quickly and are no longer detectable after around 10 min of permanent read-out. In comparison the visibility of the reconstructed holograms in Bi_2TeO_5 is still reliable even after several hours of permanent illumination. The resolution was equal to that in $LiNbO_3$ and remained constant over the read-out period.

A quantitative evaluation of the signal decay can be performed by analysing the bit error rate (BER) performance of reconstructed digital data pages. The BER is defined as the ratio of incorrect reconstructed bits to the total number N of reconstructed bits in the limit of N going to infinity [18]. In

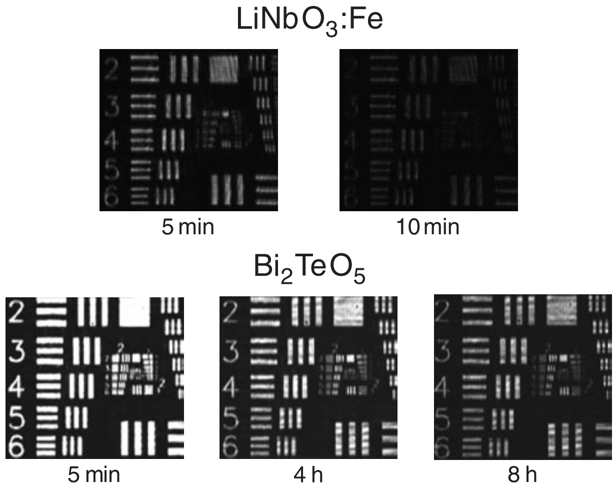

Figure 2. Reconstructed holograms of an analogue test pattern illustrate the decrease of diffraction efficiency after different times of permanent read-out in $LiNbO_3$:Fe (upper row) and Bi_2TeO_5 (lower row).

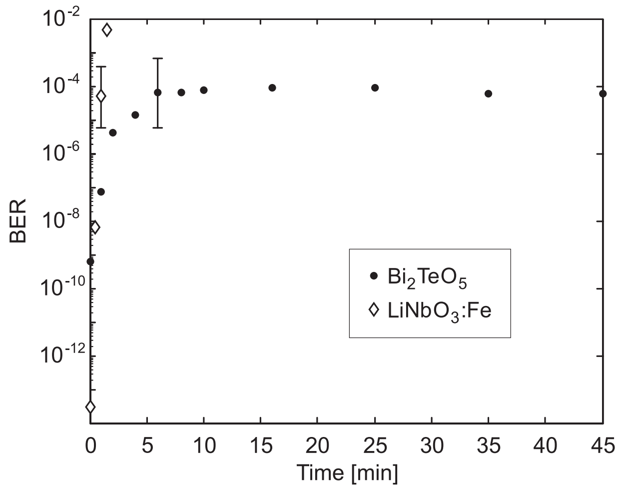

Figure 3. The BER of modulation encoded, singly stored digital data pages after different times of permanent read-out in $LiNbO_3$:Fe (rhombi) and Bi_2TeO_5 (circles). The error bars indicate the ambiguity of the calculated BERs due to the fitting process. They have been drawn in the region of interest where the BER of Bi_2TeO_5 remains constant.

order to increase the reliable observation range the data were encoded by a differential modulation code [19].

Figure 3 shows the characteristics of the BER performance under permanent read-out of digital data pages stored in $LiNbO_3$:Fe and Bi_2TeO_5. The initial BER of pages stored in $LiNbO_3$:Fe was in this experiment less than 10^{-13}. In the first 2–3 min of permanent read-out the BER degraded to values above 10^{-2} and the holograms were completely erased after 10 min at most. The intensity of the reference beam was for the whole experiment adjusted to 0.5 W cm^{-2}. The data pages stored in Bi_2TeO_5 yielded under the same conditions an initial BER of 10^{-9}, which is around four orders of magnitude higher than for $LiNbO_3$:Fe. This worse performance is mainly caused by light scattering due to defects and internal cleavage surfaces inside the BiTeO samples used in the experiments. The effect can be clearly seen in figure 4 which shows magnified detail of a reconstructed digital data page stored in $LiNbO_3$:Fe and Bi_2TeO_5.

However, the BER then grows continuously and the three different phases of signal decay can be verified. After 5–10 min of permanent read-out the BER remains almost unchanged at slightly less than 10^{-4}. Keeping in mind that only single data pages have been stored and modulation coding was applied this resultant BER seems to be rather poor. Actually in this experiment the comparison to the reference material $LiNbO_3$:Fe was the matter of particular interest and not the absolute value of the BER. In the present state the raw BER when storing in $LiNbO_3$:Fe was about 10^{-3}. Therefore, for a better BER performance especially for the fixed fraction of the holograms the imaging system should be optimized; also further error reduction schemes could be implemented.

4. Conclusions

We have presented a first quantitative investigation of non-volatile volume holographic data storage in Bi_2TeO_5 crystals. The implementation of this self-fixing technique is straightforward since no additional system technology is required. Up to now the quality of reconstructed data pages

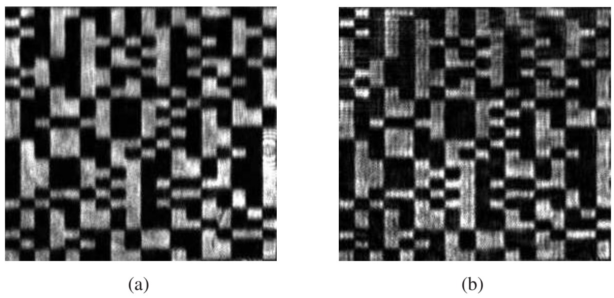

Figure 4. Details of reconstructed digital data pages stored in $LiNbO_3$:Fe (a) and Bi_2TeO_5 (b) demonstrating the different optical qualities of the storage crystals used.

has suffered from light scattering. This is mainly a problem of crystal growth; solutions which seem to be of minor complexity are currently being investigated. Thereby a large improvement in the BER can be expected. A more demanding task is the enhancement of the material's sensitivity which includes also the careful implementation of dopants. However, the constant BER performance of data pages reconstructed from self-fixed holograms in undoped Bi_2TeO_5 is remarkable.

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