A Practical Method of Suppressing Photovoltaic Noise in Fe: LiNbO₃

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ABSTRACT

A practical method of suppressing photovoltaic noise in photorefractive iron doped lithium niobate crystals (Fe: LiNbO₃) is proposed, in which the surfaces of the crystal are coated with transparent electric-conductive material (In₂O₃ doped stannum, ITO) forcing the crystal to operate in a short-circuit mode. In order to assess the validity of this method, the loss of signal-to-noise ratio (LSNR) was used to evaluate the quality of images formed directly through uncoated and ITO-coated crystals respectively. Several iron doped lithium niobate crystals were measured. The main experimental results showed that the scattering noise decreased obviously in the ITO-coated crystals, suggesting that the short-circuit operation suppressed photovoltaic noise effectively. Furthermore, it is found that the dynamic range ($M#$) of the crystals increased after they were coated with ITO. The results of experiments on multiple hologram recordings in the uncoated and ITO-coated Fe: LiNbO₃ crystal verified the improvement of $M#$ well.

Key Words: Holographic storage, Photorefractive crystal, Photovoltaic effect, Scattering noise, Short-circuit mode, Dynamic range

1. INTRODUCTION

Comparing with the traditional magnetic storage and two-dimension optical storage, volume holographic storage has the advantages of high density, large capacity and high data transfer rate owing to its three-dimensional nature and the page-oriented data access. This makes volume holographic storage more potential to become the next-generation mass storage technique [1]. The utility of holographic storage technology depends on several key factors, such as properties of storage media, performances of optical elements and so on. Among them, the storage media plays an important role.

Iron doped lithium niobate crystals are widely used recording materials for volume holographic storage. Large-scale holographic storage, reported by many authors in recent years, mostly stored data pages in iron doped lithium niobate crystals [2~4]. However, the photorefractive lithium niobate crystals exhibit a pronounced photovoltaic effect that results
from the unidirectional motion of the charge carriers excited by illumination to the crystals [5]. If the crystals are in open-circuit condition during holographic recording, both an inhomogeneous (space-charge) electric field owing to photorefractive effect and a homogeneous electric field resulting from bulk photovoltaic effect will be created in these crystals [6, 7]. The presence of the bulk photovoltaic electric field will build up noise gratings additional to desired holographic signal gratings, and in turn, cause scattering noise. The existence of the photovoltaic noise results in the degradation of quality in retrieved images. Theoretical analysis has shown that the photovoltaic noise can be effectively suppressed if the crystals are operating in a short-circuit mode, and some method (e.g. one involving in wet process of the crystal) was proposed [8].

In this paper, a practical method for short-circuit operation without need of any wet process is proposed. The surfaces of the crystal were coated with transparent electric-conductive material (In$_2$O$_3$ doped stannum, ITO). In order to assess the validity of this method, the loss of signal-to-noise ratio (LSNR) [9] was used to evaluate the quality of images formed directly through uncoated and ITO-coated crystals respectively. Several iron doped lithium niobate crystals were measured. The experimental results showed that the scattering noise decreased obviously after the crystals were coated with ITO, suggesting that the short-circuit operation suppressed photovoltaic noise effectively. Furthermore, the holographic time constants of the crystal samples were measured in order to investigate the effect of photovoltaic electric field on the holographic properties of the crystals. We found that the dynamic range (M#) of the crystals increased after they were coated with ITO. Since both low noise and high dynamic range are in favor of multiplexed holographic storage, it is expected that higher density storage with better image quality could be achieved in short-circuit operation of crystals. The experiments on multiple hologram recordings in a Fe: LiNbO$_3$ crystal before and after ITO coated were carried out and verified this expectation.

2. PHOTOVOLTAIC NOISE

In photorefractive lithium niobate crystals, photovoltaic effect is one of the main mechanisms of charge transfer, together with diffusion resulting from the gradient of charge carrier concentration and drift resulting from external electric field. The photovoltaic effect is a kind of transfer of charge carriers along the crystal axis when light radiation acts upon such a photorefractive crystal [10]. In other words, the photoexcited charge carrier (electrons) will move along the crystal axis under illumination by light. After reaching the border of illuminated region they are captured by deep traps and stay there motionless. On the other hand there appears a lack of electrons at opposite side of illuminated region. As a result, a quasi-stationary (homogeneous) electric field, directed along optical axis of the crystal, appears in that region. This field changes the refractive index of the crystal via electro-optical effect.

The change of refractive index brings appearance of a negative lens in the crystal. Having passed such a lens the exciting light will spread a bit in the plane containing the optical axis of the crystal, resulting in the appearance of scattering lights. Under laser beam illumination, such scattering lights together with those resulting from the defects in crystal exists, and are mutually coherent with the laser radiation. This interaction will result in refractive index gratings (phase holograms). Both the initial beam (laser radiation) and the scattering light are automatically Bragg matched to
this grating, and self-diffraction occurs. The diffraction of this hologram will reestablish the initial scattering lights. In that way photoinduced light scattering appears and grows \(^9,10\). In the case of the short-circuit condition, the quasistationary (homogeneous) electric field is nominally zero, which is equivalent to remove the primary source of scattering lights, thus suppressing the photovoltaic noise to some extent.

3. SOME HOLOGRAPHIC PERFORMANCES OF CRYSTALS

Massive holographic storage with high-fidelity image retrieval requires material that has perfect performance: large dynamic range (M#), good image fidelity, sensitive to the writing wavelength \(^{12}\). Several parameters have been introduced in previous reported research work in order to describe the holographic performance of photorefractive crystals and holographic storage systems. In this section the holographic performance parameters of the crystals, mainly the loss of signal-to-noise ratio (LSNR), dynamic range and sensitivity, are described.

The fidelity of a holographic data page (image) is normally specified by the signal-to-noise ratio (SNR) that is defined as

\[
SNR = \frac{I_1 - I_0}{\sigma_1 - \sigma_0},
\]

where \(I_1\) and \(I_0\) is the average value of bright and dark pixels, respectively, \(\sigma_1\) and \(\sigma_0\) is the corresponding standard variation. The loss of signal-to-noise ratio (LSNR) was introduced for characterizing the degradation of image fidelity due to the scattering noise (containing photovoltaic noise) \(^9\),

\[
LSNR = 10\times\log\left(\frac{SNR_0}{SNR_f}\right),
\]

where \(SNR_0\) is the signal-to-noise ratio of the original image that was obtained through a “clean” crystal (all gratings previously recorded in the crystal are thermally erased) inserted in a noisy optical imaging system, whereas \(SNR_f\) is the signal-to-noise ratio of the same image obtained through the same system after the scattering in the crystal reaches saturation. The lower the LSNR of a crystal, the better the image fidelity it may provide.

The dynamic range (M#) of the photorefractive storage material was introduced as a parameter for characterizing holographic memory systems, which is a function of many variables and can be expressed as the following equation \(^{11}\):

\[
M# = \frac{\tau_w \pi \Delta n_{sat} d}{\tau_w \lambda \cos \theta},
\]

where \(\tau_w\) and \(\tau_e\) is the writing and erasure time constant respectively, \(\Delta n_{sat}\) is the saturated modulation of refractive index, \(d\) is the thickness of the crystal, \(\theta\) is the incident angle of laser beam and \(\lambda\) is the wavelength of laser beam.
If M holograms are multiplexed in the same volume, the final equalized diffraction efficiency will be 

\[ \eta = \left( \frac{M^\#}{M} \right)^2, \quad (3.4) \]

where \( A_0 \) is the saturation grating strength. Equation (3.4) suggests that in multiplexing holograms with prescribed diffraction efficiency \( \eta \), increasing the \( M^\# \) results in increasing the number of holograms that can be multiplexed \( (M) \), thus the capacity of holographic storage system increases.

Another important parameter of the material is sensitivity \( (S) \), which determines the recording speed. The larger the sensitivity, the faster we can record the hologram with a fixed recording intensity. From the single-hologram recording we can calculate the sensitivity using

\[ S = \frac{d\sqrt{\eta}}{dt \mid_{t = 0}} / dI_w, \quad (3.5) \]

where \( \eta \) is the diffraction efficiency obtained under Bragg condition, \( I_w \) is the total writing intensity.

The parameters mentioned in the above equations (3.1) ~ (3.5) form the fundamental of our investigation on the holographic performances of the material. In the following, we adopt the short-circuit operation of the crystal to suppress photovoltaic electric field, and to investigate the effect of the homogeneous photovoltaic electric field on the holographic performances of the material.

4. METHOD OF COATING ITO ON THE SURFACES OF THE CRYSTALS

The ITO material (Indium Tin Oxide) has excellent photoelectric performance (such as high optical transmittance, and high electric conductivity). In our experiments, we adopted the method of vaporizing ITO in vacuum to coat the film on the surfaces of the crystal. The material of the transparent electric film is the admixture of In\(_2\)O\(_3\) and SnO\(_2\) and the concentration ratio of the two components is 9:1. The crystal was placed into the vacuum container and heated up to a high temperature of about 150ºC. At the same time, oxygen was inflated into the container incessantly in order to create In\(_2\)O\(_3\) and SnO\(_2\) as much as possible resulting in excellent photoelectric performance of ITO coating.

The performance of ITO coating can be optimized by controlling the vaporizing speed and time. Furthermore, the thickness of ITO coating is a key factor that affects the electric performance and optical transmittance. Thus we worked out the optimal thickness of the film in advance according to the wavelength of the laser, the refractive indices of both the photorefractive crystal and the ITO film. During the process of coating, the thickness of the film was measured in real-time through the special optical set-up to ensure the desired thickness could be achieved.
The temperature of ITO vaporizing is another important parameter, which affects greatly the photoelectric performance of ITO coating. If the vaporizing temperature is higher, the resistance of ITO coating will be lower, and so will the transmittance. The ideal vaporizing temperature of ITO powder is above 200°C. However, the temperature of vaporizing ITO does not achieve this ideal value due to the limitations in our equipment. Therefore, after the crystal was coated with ITO, it was annealed again at an appropriate temperature in order to improve the electric performance and the transmittance.

In holographic storage systems using photorefractive crystals different recording geometries require different orientation of crystal. The reflection geometry requires that the c-axis is perpendicular to the entrance surfaces. The transmission and 90-degree geometry requires the c-axis being parallel and at 45° to the entrance surfaces respectively. Several Fe: LiNbO₃ samples for reflection, 90-degree and transmission geometry were selected to coat ITO. Before and after these crystals are coated with ITO, the short-circuit resistance of the sample between surfaces perpendicular to the c-axis was measured using a multimeter. The transmittance of the Fe: LiNbO₃ samples in both open-circuit and short-circuit and resistances in short-circuit mode are given in Table1.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>1#</th>
<th>2#</th>
<th>3#</th>
<th>4#</th>
<th>5#</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recording Geometry</td>
<td>Reflection</td>
<td>90-degree</td>
<td>Transmission</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Component (LiNbO₃)</td>
<td>Fe:0.03wt%</td>
<td>Fe:0.08wt%</td>
<td>Fe:0.12wt%</td>
<td>Fe:0.08wt%</td>
<td>Fe:0.08wt%, Zn: 6mol%</td>
</tr>
<tr>
<td>Transmittance (%) open-circuit</td>
<td>34</td>
<td>67</td>
<td>59</td>
<td>36</td>
<td>64</td>
</tr>
<tr>
<td>short-circuit</td>
<td>40</td>
<td>71</td>
<td>64</td>
<td>46</td>
<td>66</td>
</tr>
<tr>
<td>Resistance (KΩ) short-circuit</td>
<td>2.0</td>
<td>2.0</td>
<td>3.0</td>
<td>2.0</td>
<td>1.5</td>
</tr>
</tbody>
</table>

The resistance of the crystal surfaces in short-circuit condition has been reduce to a relatively small value comparing with the nearly infinite resistance in open-circuit condition. The transmittance of the crystals has been improved a little. Both the improvement of transmittance and the electric conductivity would be advantageous to our following experiments.

5. EXPERIMENTS AND EXPERIMENTAL RESULTS

We conducted experiments to investigate the effect of scattering noise resulting from photovoltaic (homogeneous) electric field on the data fidelity of images formed directly through crystals without ITO coating using a traditional Fourier transform holography system. A coherent beam with total power 2mW, which act as the signal beam in holographic recording, illuminate the crystal for 300 seconds. The $SNR_0$ and $SNR_f$ of an image, formed directly through the crystal, which was inserted near the spectrum plane, were measured before and after the long-time illumination of the crystal by the signal beam. By using this method, several crystals were measured. The recording configurations
under investigation included transmission, reflection, and 90-degree geometry. After the crystal samples are coated with ITO, the same measurements were repeated in the same experimental conditions.

The *LSNR* of crystal samples was calculated according to the *SNR₀* and *SNRᵣ* measured in experiments when the crystals operating in open-circuit and short-circuit mode respectively. The experimental results are shown in Table2.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>1#</th>
<th>2#</th>
<th>3#</th>
<th>4#</th>
<th>5#</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recording Geometry</td>
<td>Reflection</td>
<td>90-degree</td>
<td>Transmission</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Doping concentration</td>
<td>Fe: 0.03wt%</td>
<td>Fe: 0.08wt%</td>
<td>Fe: 0.12wt%</td>
<td>Fe: 0.08wt%</td>
<td>Fe: 0.08wt%</td>
</tr>
<tr>
<td>LSNR (dB)</td>
<td>Open-circuit</td>
<td>8.0</td>
<td>5.0</td>
<td>13.3</td>
<td>8.7</td>
</tr>
<tr>
<td>Short-circuit</td>
<td>3.5</td>
<td>3.4</td>
<td>3.6</td>
<td>5.0</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Based on most of the experimental results, we can see that the photovoltaic noise was suppressed to some extent when the crystals were operated in a short-circuit mode though the resistance was not zero. The effective suppression of photovoltaic noise also embodied in the improvement of image qualities. The comparison of image quality was showed in Fig.1. and Fig.2.

![Fig.1. Image formed through crystal 1# without ITO coating (a) before and (b) after the crystal being exposed to an coherent beam for 300 seconds (LSNR=8.0 dB)](image1.png)

![Fig.2. Image formed through crystal 1# with ITO coating (a) before and (b) after the crystal being exposed to an coherent beam for 300 seconds (LSNR=3.5dB)](image2.png)
In order to investigate the influence of the photovoltaic electric field on the holographic performance of photorefractive Fe: LiNbO$_3$ crystal, the key holographic parameters were measured in the open-circuit and short-circuit operation of the Fe: LiNbO$_3$ crystal respectively. Typical experimental results are given in Table 3.

Table 3. Holographic parameters of Fe: LiNbO$_3$ crystals in the open-circuit and short-circuit mode respectively

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>1#</th>
<th>3#</th>
<th>6#</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Recording Geometry</strong></td>
<td>Reflection</td>
<td>90-degree</td>
<td></td>
</tr>
<tr>
<td><strong>Doping concentration</strong></td>
<td>Fe:0.03wt%</td>
<td>Fe:0.12wt%</td>
<td>Fe:0.03wt%</td>
</tr>
<tr>
<td><strong>Status</strong></td>
<td>ITO-uncoated</td>
<td>ITO-coated</td>
<td>ITO-uncoated</td>
</tr>
<tr>
<td>$\Delta n_{sat}$ $(10^{-5})$</td>
<td>0.8</td>
<td>1.2</td>
<td>3.2</td>
</tr>
<tr>
<td>Sensitivity: $S$ $(10^{-2}$ cm / mW)</td>
<td>3.0</td>
<td>1.1</td>
<td>4.4</td>
</tr>
<tr>
<td>Writing time constant $\tau_W$ (s)</td>
<td>90</td>
<td>280</td>
<td>265</td>
</tr>
<tr>
<td>Erasure time constant $\tau_E$ (s)</td>
<td>1100</td>
<td>2600</td>
<td>1150</td>
</tr>
<tr>
<td>Dynamic Range (M#)</td>
<td>2.7</td>
<td>3.0</td>
<td>1.9</td>
</tr>
</tbody>
</table>

The experimental results showed that the saturation index modulation is more or less increased by the ITO coating, accordingly, the sensitivity reduced to some extent. The most exciting result is that the dynamic range of crystal increased by the ITO coating. From Table 3 one can see that both the writing and erasure time constants increased in short-circuit operation and the latter increased much more, which contributes a lot to the improvement of the dynamic range (M#).

Furthermore, the experiments of multiplexing holograms with the appropriate exposure schedule were carried out using crystal No.6. With the approximately equal final diffraction efficiency (1.3E-5), the number of multiplexed holograms increased from 200 in open-circuit operation to 300 in short-circuit operation of the Fe: LiNbO$_3$ crystal. The result has also validated the improvement of M# well.

6. CONCLUSIONS

The short-circuit operation of photorefractive crystals by means of coating transparent electric film (ITO) on the surfaces of the crystal is a more practical and effective method for suppressing the harmful effect of photovoltaic electric field on holographic storage. The experimental results showed that the method could effectively suppress the photovoltaic noise, thus improve the quality of read-out holograms. At the same time, the holographic performance, especially the dynamic range (M#) of the crystal improved by the ITO coating. Since both low noise and high dynamic range are in favor of multiplexed holographic storage, it is expected that higher density large-capacity storage with better image quality could be achieved in short-circuit operating mode of the crystals.
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