Developing characteristics of Thermally Fixed holograms in $Fe:LiNbO_3$

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ABSTRACT

Thermal-fixing holographic storage in photorefractive crystals is an effective nonvolatile storage technique for stabilizing holograms against the optical erasure. The developing characteristics of fixed holograms in iron-doped lithium niobate dominate their final diffraction efficiencies after developing, provided that the ionic compensation in the fixing stage is nearly complete. Developing kinetics of fixed holograms under homogeneous illumination is studied. The effect of developing light intensity on developing efficiency has been demonstrated experimentally. The fixed holograms with the same initial recording grating strength are developed under illumination of the different light intensities, such as 200mW/cm^2, 400mW/cm^2, 600mW/cm^2, and 800mW/cm^2, respectively. The fixed holograms with the different initial recording grating strengths are developed under illumination of the same light intensities as well. The overdeveloping characteristics of fixed holograms are described. The developing efficiency of the hologram with a given initial recording grating strength is found to depend on the intensity of developing light. These features can be explained with the joint effect of the resulting space-charge holographic field of the fixed hologram and the photovoltaic field under homogeneous illumination.

Key words: volume holographic storage, developing, diffraction efficiency, thermal fixing efficiency, developing efficiency.

1. INTRODUCTION

Volume holographic storage technique, which is able to store multiple holograms within a small volume of a storage material and to retrieve data pages with thousands of bits in parallel, provides an attractive combination of high density and fast speed. Photorefractive crystals (e.g. $Fe:LiNbO_3$) have been considered as one of the most important materials owing to their wider dynamic range and being able to be reused. According to the charge excitation and transport mechanism, the electronic charges constitute holograms in photorefractive crystals to store some desired optical information. But, the above-mentioned mechanism similarly causes optical erasure to stored holograms under readout illumination or further homogenous illumination. Thermal fixing technique is an effective method for obtaining stable holograms in photorefractive crystals by forming ionic replica of initial holographic gratings. Many authors have investigated the fixing and developing process of holographic gratings in $LiNbO_3$ extensively[1-4], and recent progresses in

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the thermal-fixing technique for multiplexed holograms provide us a promising practical method for achieving high-density, high fidelity, and non-volatile holographic storage[5-6]. Therefore, the higher diffraction efficiency of fixed holograms is desired for increasing non-volatile storage density of optical memories as well as for other different applications of stable volume holograms.

A complete thermal fixing procedure includes two steps i.e., fixing and developing. In fixing stage, the ions in crystals move to form an ionic grating that compensates the electronic grating at elevated temperature 120℃~140℃, and then the diffraction efficiency of the resulting grating decays nearly zero at the end of this stage. In developing stage after cooling crystals to room temperature, the diffraction efficiency of the resulting grating is recovered partially under homogeneous illumination, owing to only the electronic grating suffering optical erasure but the ionic grating not. The final developed grating is the ion-dominant resulting grating, composed of the remaining part of the electronic grating and ionic one. Since the recorded electronic gratings always can be fully compensated by the ionic gratings at fixing stage, the thermal-fixing efficiency actually represents available developing efficiency of the fixed holograms. Therefore, developing characteristics of fixed gratings directly affect on diffraction efficiency of the fixed holographic gratings, and then the storage density of multiplexed holograms.

Some optimal developing conditions, such as doping level, oxidation-state of the crystal, grating spacing and applied field, have been investigated theoretically as well as experimentally[7-8]. The holograms developed by coherent light usually suffer from self-enhancement, Bragg-angle shift, selective angel broadening and scattering noise increasing[7]. However, The influence of homogeneous developing light intensity and the initial recording grating strength of holograms has not been reported yet.

In this paper, we present a detailed experimental study on the developing process. Developing kinetics of fixed holograms under homogeneous illumination are investigated. The effect of developing light intensity on developing efficiency has been demonstrated experimentally. Developing of the fixed holograms, with the different initial recording grating strengths, are characterized as well. The overdeveloping characteristics of fixed holograms are described.

2. THEORETICAL FORMULA

A thermal fixing procedure of only including recording, fixing and developing steps, no matter how many holograms to be multiplexed. In its revealing process, ionic gratings screened in part by trapped electrons are unable to be fully revealed, even though they completely replicate electronic holograms in the fixing process. Therefore, the ionic holograms are partially readout after a sufficient developing process.

The thermal fixing efficiency η_F of holograms is commonly defined as $\eta_F = \eta_i / \eta_e$ [5], where η_i is diffraction efficiency of the developed ionic gratings, and η_e is diffraction efficiency of the electronic gratings before fixing, nearly equal to that of initial recorded holograms. Although η_F is the complicated function of parameters both of storage material and optical system, it can be measured experimentally.

Assuming that the electronic gratings are fully compensated by the ion gratings after heating (which is always valid as there is no measurable diffraction from the fixed holograms before developing), the final diffraction efficiency of fixed holograms is dependent on the developing effect, and the thermal-fixing efficiency actually represents available developing efficiency of the fixed holograms. Thus, the developing efficiency η_D can be expressed as

$$\eta_D = \eta_F = \frac{\eta_i}{\eta_e} \tag{1}$$

3. EXPERIMENT

3.1 Experiment system

The experimental set-up is shown in Fig. 1. A defocused-Fourier transform holographic system and conventional 90-degree recording geometry are used in the experiment. The translation platform of the angular-dimension multiplexing system can realize reference light scanning in horizontal direction. The crystal of 0.03% Fe-doped $LiNbO_3$ with dimensions of 1cm×1cm×1cm is mounted on a reposition plate for off-line thermal fixing.

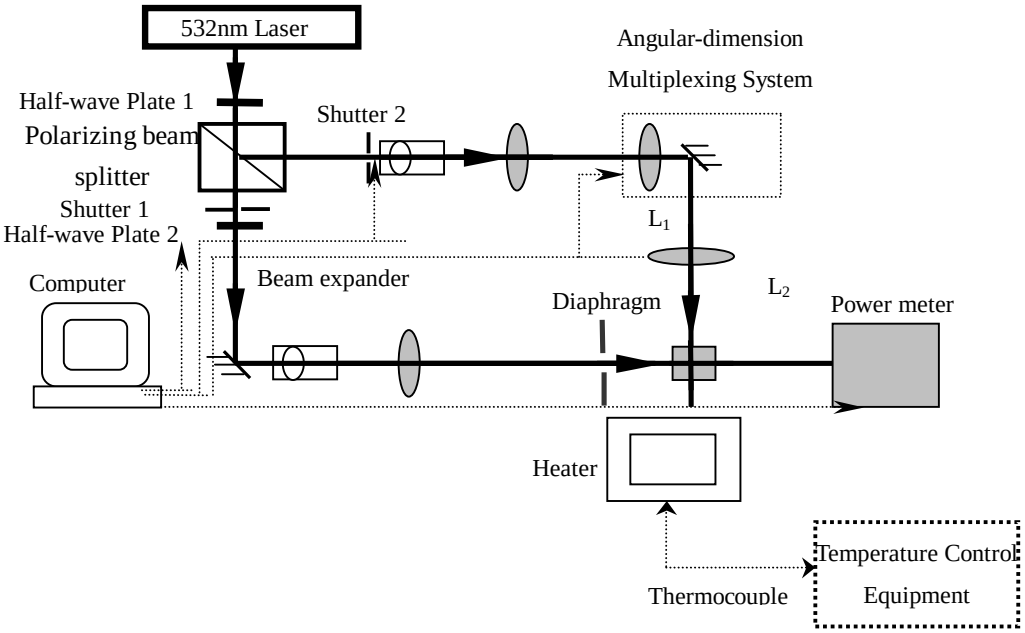

Fig. 1 Experimental setup for thermal fixing

In our experiment system, coherent light from the 532nm laser was separated into two beams by the beam splitting prism. Half-wave plate 1 was used to adjust the light intensity proportion of object and reference beams, and half-wave plate 2 was used to transfer the *p*-polarization of the object beam to *s*-polarization, since the reference beam is *s*-polarized. The recording and readout of gratings was controlled by a computer through DA/AD conversion interface, wherein shutter 1 and shutter 2 was controlled to ON/OFF the beam, power meter was controlled to gather diffraction power of gratings, angle-dimension multiplexing system (translation resolution is 0.06μm, corresponding to the rotation resolution of reference light 0.7μrad, and scanning range of reference light is 14°) was controlled to change the incidence angle of the reference light, so that the angle-multiplexing and scanning readout can be accomplished.

The heating device for thermal fixing is an off-line compact heater. Temperature control with a precision of ±0.1℃ was achieved by a Eurothem 818 Temperature Controller/Programmer. A thermocouple was used in measuring the

temperature continuously. With this system the holograms could be thermally fixed after recording.

In our experiments, both the reference and object beams for recording holographic gratings are s-polarized. The light-spot size of object beam is 6mm and its total light power is 10mW. The size of light spot of reference light is 8mm and the total power is 17mW. The total intensity of recording beams is 68mW/cm^2, and the intensity ratio of the recording beams is nearly 1:1. One holographic grating was recorded at a certain position of the crystal. After the recording, the crystal was put into the heater to rise the temperature to 140℃ rapidly and keep the temperature for 10-15 minutes, so that the grating was fixed. Then, after cooling the crystal down to the room temperature and repositioning it, the recorded grating was developed under homogenous illumination of non-coherent light. In the developing process, the diffraction of the fixed grating, i.e. the developed ion grating, was readout with the original reference beam at equal-time intervals. After finishing one entire developing process, the crystal was put into the heater and its temperature was elevated to 210℃, in which the grating was be erased owing to the ions and electrons was redistributed into initial uniform distribution.

3.2 Experimental results

3.2.1 Developing with different intensities

We implement a whole thermal fixing procedure of a single holographic grating for four times. In every procedure, the grating is recorded up to diffraction power of 4.70×10^{-5} W, corresponding to diffraction efficiencies 0.28%, and each fixed grating is illuminated with different light intensities, such as 200 mW/cm^2, 400 mW/cm^2, 600 mW/cm^2 and 800 mW/cm^2, respectively.

The developing kinetics of fixed holograms under homogeneous illumination of the different developing intensities is shown in Fig. 2. Curves a, b, c, and d show that developing efficiencies, related to the different developing intensities, all can rise to the peak value after certain illumination time, and then reach a stable level with a slow oscillation. The higher the developing light intensity, the shorter the time spent for reaching peak developing efficiency is.

The thermal fixing efficiency of gratings versus the intensity of developing light is shown in Fig. 3. In all cases, the optimum developing intensity for the grating of initially diffraction efficiency 0.28% is about 400 mW/cm^2, which achieve the maximum developing efficiency 12.35% after developing for 70 minutes.

Similarly as above experiment, the initial recording power of the gratings is 2.70×10^{-4} W, corresponding to diffraction efficiency 1.61%. The fixed gratings are illuminated with different light intensities 200 mW/cm^2, 400 mW/cm^2, 600 mW/cm^2, 800 mW/cm^2, and 1000 mW/cm^2, respectively.

Curves a, b, c, and d of the developing efficiency versus developing time in Fig. 4 also indicate similar feature of developing kinetics as shown in Fig. 2. Each curve of developing efficiency always rises to the peak value after certain illumination time, and then gradually reaches to a stable level with a slow oscillation. The higher the developing light intensity, the shorter the time spent for reaching peak developing efficiency is.

Figure 5 shows the thermal fixing efficiency of gratings versus intensity of developing light. In all cases, the optimum developing intensity for the grating of initially diffraction efficiency 1.61% is about 800 mW/cm^2, which achieve the maximum developing efficiency 20.71% after developing for about 20 minutes.

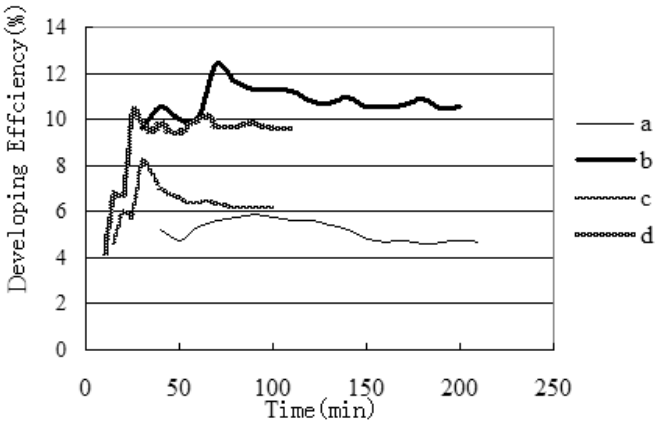

Fig.2 Developing efficiency of grating versus developing time. The intensity of developing light of sequences a, b, c and d is 200mW/cm^2, 400mW/cm^2, 600mW/cm^2, and 800mW/cm^2, respectively.

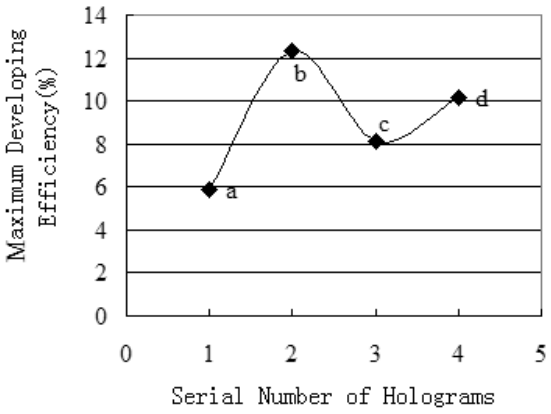

Fig.3 Maximum developing efficiency of gratings versus intensity of developing light.

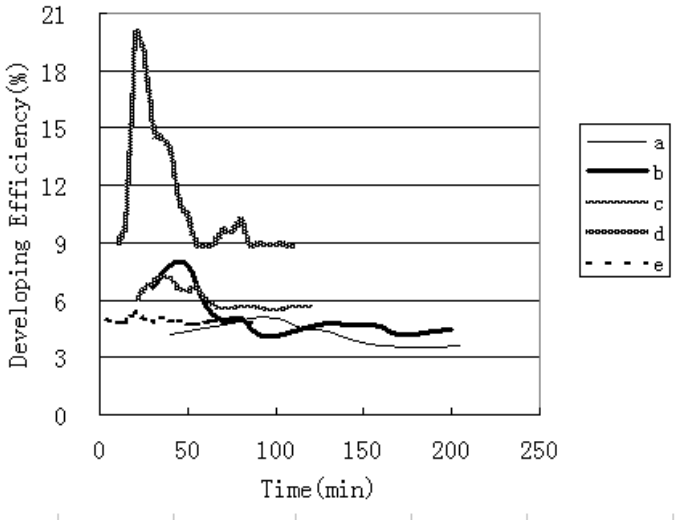

Fig. 4 Developing efficiency of grating versus developing time. The intensity of developing light of sequences a, b, c, d and e is 200mW/cm^2, 400mW/cm^2, 600mW/cm^2, 800mW/cm^2 and 1000mW/cm^2, respectively.

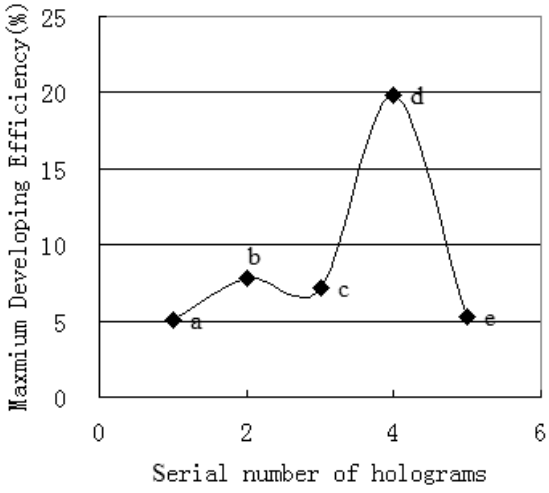

Fig.5 Maximum developing efficiency of gratings versus intensity of developing light.

3.2.2 Developing for the different initial gratings strengths

Five gratings are individually recorded to different strengths, corresponding diffraction power 2.08×10^{-5} W, 4.72×10^{-5} W, 7.65×10^{-5} W, 2.40×10^{-4} W and 6.52×10^{-4} W, respectively. After fixing, the gratings of different initial grating strengths are developed under homogeneous illumination of light intensity 400 mW/cm^2, respectively.

Fig. 6 shows the developing efficiency versus developing time. We can see from curves in Fig. 6 that developing light of 400 mW/cm^2 can optimally develop the grating of diffraction power 4.72×10^{-5} W, i.e. achieving the maximum peak and stable developing efficiencies for the grating b in comparison with other gratings. The maximum developing efficiency is 12.35% reached after developing for about 70 minutes. Fig. 7 shows the dependence of thermal fixing efficiency on the initial recorded grating strengths of different gratings.

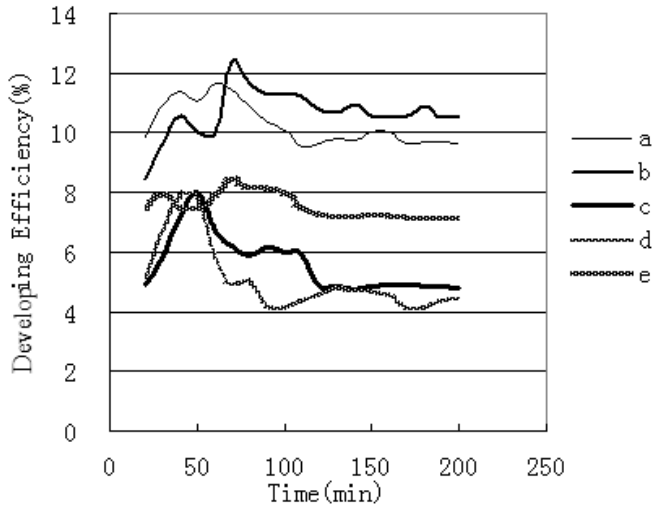

Fig.6 Developing efficiency of grating versus developing time. The intensity of gratings a, b, c, d and e is 2.08×10^{-5}W, 4.72×10^{-5}W, 7.65×10^{-5}W, 2.40×10^{-4}W and 6.52×10^{-4}W, respectively.

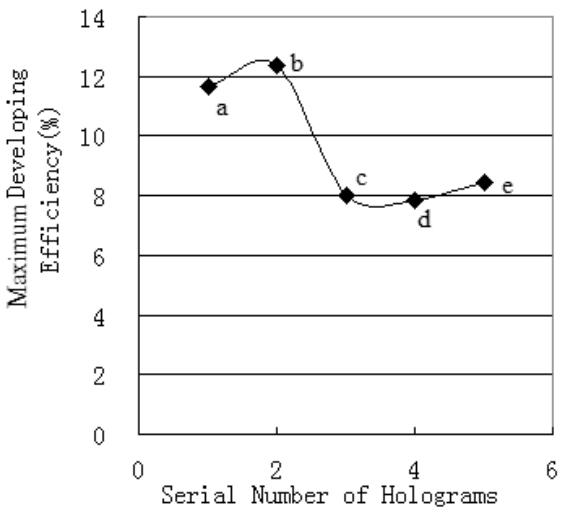

Fig.7 Maximum developing efficiency versus intensity of gratings.

Another five gratings are individually recorded to different strengths, corresponding diffraction power 4.87×10^{-5} W, 7.78×10^{-5} W, 2.39×10^{-4} W, 6.54×10^{-4} W and 1.10×10^{-3} W, respectively. After fixing, the gratings of different initial grating strengths are developed under homogeneous illumination of light intensity 800 mW/cm^2, respectively.

Similarly, Fig. 8 shows the developing efficiency versus developing time, and Fig. 9 shows the dependence of thermal fixing efficiency on the initial recorded grating strengths of different gratings. The developing curves indicate that the grating c of diffraction power 2.39×10^{-4} W is developed to the maximum peak developing efficiency of 20.71%, compared with other gratings, with developing light of 800 mW/cm^2. But the maximum stable developing efficiency is achieved for the grating b.

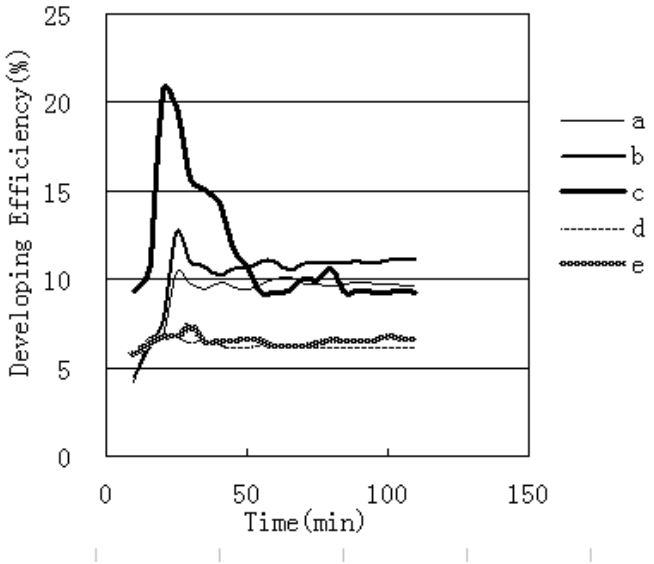

Fig.8 Developing efficiency of grating versus developing time. The intensity of gratings a, b, c, d and e is 4.87×10^{-5}W, 7.78×10^{-5}W, 2.39×10^{-4}W, 6.54×10^{-4}W and 1.10×10^{-3}W, respectively.

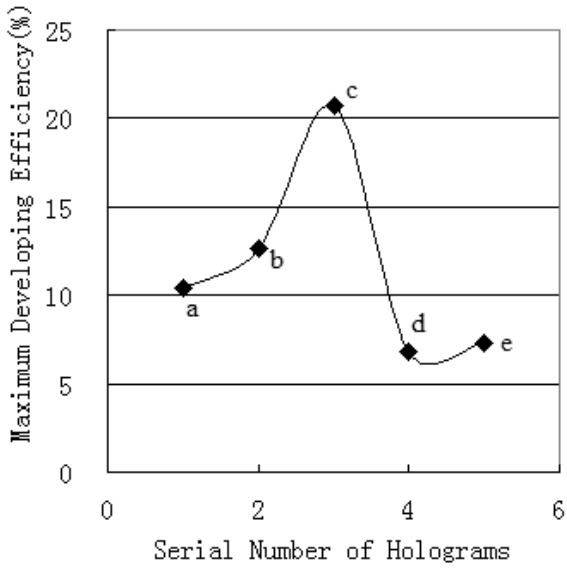

Fig.9 Maximum developing efficiency versus intensity of gratings.

3.2.3 Developing with a recording light

The recording light of sequential holograms in batch fixing scheme will develop the holograms that have been recording in the crystal[6]. We recorded the multiplexed gratings to simulate the process. A holographic grating was recorded at certain position of the crystal, of which the diffraction power is 2.27×10^{-5} W. The grating was thermally fixed off-line and then reposition the crystal to its primary position. The second grating was recorded at another position of the crystal with the same recording intensity. The diffraction power of the first recorded grating was detected with a power meter during the second continuous recording at intervals of equal time. The curve in Fig. 10 shows the developing kinetics of fixed holograms under illumination of recording light.

In comparison with the fixed grating illuminated with 400 mW/cm^2, the developing efficiency of fixed grating with the recording light is much greater. The maximum developing efficiency is up to 68.72%.

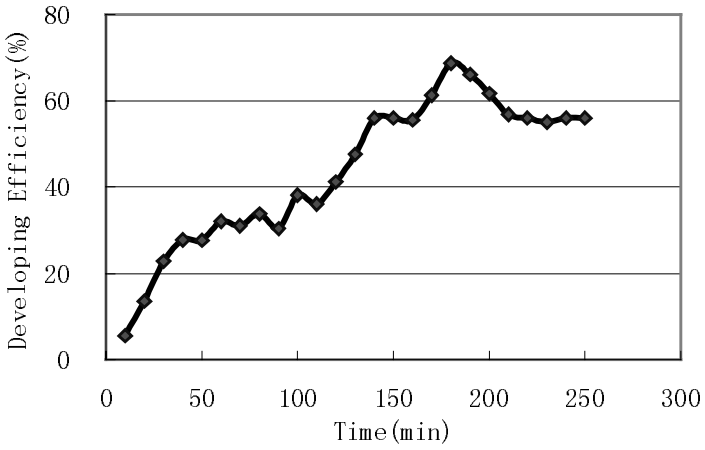

Fig. 10 Developing efficiency of grating versus developing time.

4. DISCUSSION AND CONCLUSIONS

According to the above results, the ionic grating will compensate the electric grating after thermal fixing and developing light erases the electronic grating that is sensitive to light. The final developed grating is the ion-dominant resulting grating, composed of the remaining part of the electronic grating and ionic one.

At first stage of developing, the space-charge field of ion gratings, E_i, is small, which leads to weak bound strength to electrons. But, in compared to E_i, the photovoltaic field, E_p, proportional to illumination intensity I, is much greater. As a result, optical erasure of electrons dominates as the charges photo-excited from trapped electrons redistribute under homogeneous illumination. With keeping on developing, the developing efficiency of the fixed grating can reach the peak value, and then is gradually to reach a constant level., which indicate a balance between the bound force that ironic gratings field acting on the electron, and the uniform redistribution of photo-excited electrons that is caused by a photovoltaic field.

By comparing the experimental results of same grating amplitude but different developing light intensities, we can see that the higher the developing light intensity, the shorter the time spent for reaching peak developing efficiency is. The developing efficiency of the fixed grating of the given initially diffraction efficiency can achieve optimum peak and stable values with the optimal developing intensity, e.g. for the gratings of the initial recording power 2.70×10^{-4} W, with the optimal developing intensity of 400 mW/cm^2, the maximum developing efficiency 12.35% is achieved after developing for 70 minutes.

The experimental results also indicate that the optimum developing light intensity and developing time vary with different grating amplitude. For gratings that are recorded to high amplitude, high thermal-fixing efficiency can be achieved in short time by adopting stronger beams (800 mW/cm^2) for developing. However, for gratings that are recorded at lower amplitude, high thermal-fixing efficiency can be achieved in long time with weaker developing light (400 mW/cm^2).

At the steady state, multiplexing of holograms in the same photorefractive crystal are illuminated with the initial

recording beams so that the electronic grating is erased much more greatly and nearly full ionic grating amplitude is revealed which has a much higher amplitude than that achieved with uniform developing. Meanwhile, similar developed amplitudes can be obtained over a much shorter illumination time with the recording light than with the incoherent illumination. Then, developing with recording light may be used to enhance the relative weights of one given or several holograms with regard to the others that are not affected. The detailed analysis of this as well as other possible application should be the objective of additional future work.

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REFERENCES

1. D. L. Staebler, W. J. Burke, W. Phillips, and J. J. Amodei, "Multiple storage and erasure of fixed holograms in Fe-doped $LiNbO_3$", Appl. Phys. Lett., **26**, (182-184), 1975.
2. M. Carrascosa and F. Agulló-López, "Theoretical modeling of the fixing and developing of holographic gratings in $LiNbO_3$", J. Opt. Soc. Am. B **7**, (2317-2322), 1990.
3. A. Yariv, S. S. Orlov, and G. A. Rakuljic, "Holographic storage dynamics in lithium niobate: theory and experiment", J. Opt. Soc. Am. B **13**, (2513-2523), 1996.
4. J. F. Heanue, M. C. Bashaw, A. J. Daiber, R. Snyder, and L. Hesselink, "Digital holographic storage system incorporating thermal fixing in lithium niobate", Opt. Lett., **21**, (1615-1617), 1996.
5. Xin An, D. Psaltis, and Geoffrey W. Burr, "Thermal fixing of 10000 holograms in $LiNbO_3$: Fe", Appl. Opt., **38**, (386-393), 1999.
6. Z. Jiang, G. Meng, G. Liu and S. Tao, "A study on batch method of thermal fixing for multiplexed holographic recordings", MRS Symp. Proc. **674**, pp. V3.3.1-6, 2001.
7. M. Carrascosa and F. Agulló-López, "Optimization of the developing stage for fixed gratings in $LiNbO_3$", Opt. Commun, **126**, (240-246), 1996.
8. Eva M. de Miguel, Josefa Limeres, Mercedes Carrascosa, and Luis Arizmendi, "Study of developing thermal fixed holograms in lithium niobate", J. Opt. Soc. Am. B **17** (1140~1146), 2000.