

# Two-color holographic recording in a single-doped photorefractive LiNbO<sub>3</sub> crystal

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**Abstract.** We recorded a hologram in a photorefractive LiNbO<sub>3</sub>:Fe crystal with a two-color recording technique in transmission geometry. The holographic recording involves a light with wavelength 633 nm for interference, and a light with wavelength 532 nm for exciting. The short wavelength light excites more charges so that the holographic recording is affected, and the storage capacity ( $M$ -number) and the sensitivity vary accordingly. We found that the optimized intensity ratio of the interference lights and the exciting light is between 50 and 60. In the optimized conditions, the  $M$  number and the sensitivity are enhanced by 43 and 35%, respectively. Because the crystal we used is a typical iron-doped LiNbO<sub>3</sub> crystal and the short wavelength exciting light source is inexpensive now, the proposed method is easy to be achieved in most holographic systems. © 2009 Society of Photo-Optical Instrumentation Engineers. [DOI: 10.1117/1.3095915]

Subject terms: two-color recording; lithium niobate; holographic storage;  $M$ -number; sensitivity.

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## 1 Introduction

Volume holograms are capitalized in optical tomography,<sup>1</sup> holographic data storage<sup>2</sup> and optical communication<sup>3</sup> due to its wavelength and wavefront selectivity. Although in the last decade, various photopolymers have been invented for volume holography, photorefractive LiNbO<sub>3</sub> crystals are still widely studied because they are rewritable, do not shrink during exposure, and are easy to be grown thicker. However, there are still some shortcomings in the LiNbO<sub>3</sub> crystals. Higher storage capacity and higher recording speed are expected in holographic data storage. In most practical applications, nonvolatile recording is also required. Accordingly, various fixing methods, such as thermal fixing,<sup>4,5</sup> electrical fixing,<sup>6</sup> and two-center fixing,<sup>7</sup> are proposed. Most of them, however, are still impractical in a commercial system because of their complicated processes or low diffraction efficiency. On the other hand, some novel materials, such as periodic poled LiNbO<sub>3</sub>,<sup>8,9</sup> stoichiometric LiNbO<sub>3</sub>,<sup>10,11</sup> and doubly doped LiNbO<sub>3</sub>,<sup>7,12</sup> have been proposed to improve the holographic abilities of crystals. Although there are specific advantages by using these novel

materials, the global holographic properties of these materials are always worse than those of general iron-doped LiNbO<sub>3</sub>. In this letter, we propose another simple method to record holographic gratings in a nominally iron-doped LiNbO<sub>3</sub> crystal. In our demonstration, the storage capacity and sensitivity are remarkably improved by the proposed method. Because the proposed method only requires an additional low-coherence, short-wavelength light source for exciting, it is easy to be achieved in most of present holographic systems.

## 2 Experimental Setup

The setup for two-color holographic recording is shown schematically in Fig. 1. We used a He–Ne laser with wavelength 633 nm as the light source for interference. The laser beam was collimated and divided into two, the signal beam and the reference beam, by a polarizing beamsplitter. The two beams with polarization state normal to the tabletop crossed each other to form an interference fringe pattern in a photorefractive LiNbO<sub>3</sub>:Fe crystal. The size of the crystal to be used is 10 × 10 × 2 mm<sup>3</sup>, and the doping concentration is 0.1%. The optic axis ( $c$ -axis) of the crystal is parallel to the tabletop, as shown in Fig. 1. Thus, the interference beams are ordinarily polarized in the crystal. Finally, a diode-pumped solid state (DPSS) laser with wavelength 532 nm was used for carrier exciting. The exciting laser beam was also collimated to illuminate the crystal surface uniformly.

In the recording process of two-color holographic recording, the shutter (SH) in Fig. 1 was opened so that both the signal beam and the reference beam reached the crystal to interfere. In the crystal plane, the intensity of each interference beam is 15 mW/cm<sup>2</sup>, and the intensity of the exciting light beam varied from 0.2 to 2 mW/cm<sup>2</sup> in different attempts. During the recording, the diffracted light power was measured by a photodetector at intervals of 1 min. It is noted that the shutter in Fig. 1 was closed as the photodetector was taking data for avoiding the disturbance of directly transmitting signal light. In the retrieving process, the shutter was always closed, and the intensity of the reference beam doubled to simulate the illumination due to another recording. Finally, we also performed one-color holographic recording in the same geometry by a single He–Ne laser and by a single DPSS laser, respectively, for comparison. The total intensity of He–Ne laser and DPSS laser are respectively 30 and 2.9 mW/cm<sup>2</sup>.

## 3 Experimental Results

After the relationship between diffraction efficiency and the recording (retrieving) time was obtained, the corresponding holographic parameters were found as well.  $M$  number ( $M$ ) is a parameter that is directly relative to the storage capacity of a holographic system.<sup>13</sup> The system with larger  $M$  will record more holograms with the same diffraction efficiency or will record the same number of holograms with higher diffraction efficiency.  $M$  can be easily found by<sup>2,13</sup>

$$M = \frac{d\sqrt{\eta}}{dt} \Big|_{t \rightarrow 0} \tau_e, \quad (1)$$

where  $\eta$  is the diffraction efficiency being function of recording time,  $t$ ;  $\tau_e$  is the erasing time constant, which is

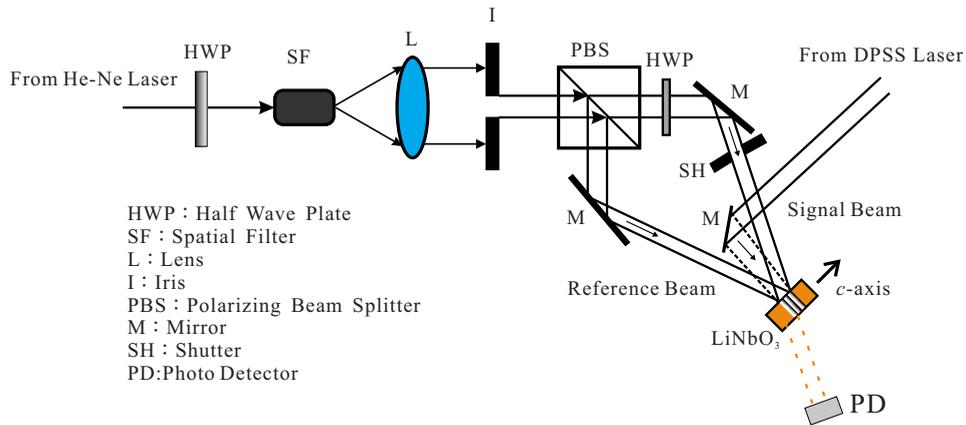


Fig. 1 Schematic of experimental setup for two-color recording.

defined as the time at which the diffraction efficiency drops to  $1/e^2$  of its initial value, and the first quantity in the right side of Eq. (1) can be directly obtained by calculating  $\sqrt{\eta}/t$  at the moment of the first measurement. The resultant curve of  $M$  in various exciting light intensity is shown in Fig. 2. Here  $I_R$  denotes the total intensity of the signal beam plus the reference beam, and  $I_E$  denotes the intensity of the exciting beam. It is found from Fig. 2 that too much or too little exciting light will result in a declining  $M$ , and the maximum  $M$  ( $M=9.0$ ) is achieved at  $I_R/I_E \approx 60$ . Compared to the  $M$  in one-color recording ( $M=6.3$ ), the  $M$  is enhanced by 43%.

Besides  $M$ , sensitivity ( $S$ ) is also an important parameter that reflects the energy requirement for a holographic system. A system with higher sensitivity will record a hologram faster, which is expected in most applications. Sensitivity can be found by<sup>2</sup>

$$S = \left. \frac{d\sqrt{\eta}}{dt} \right|_{t \rightarrow 0} \frac{1}{I_0 L}, \quad (2)$$

where  $L$  is the effective thickness of the holographic material and  $I_0$  is the total illuminating intensity (i.e.,  $I_R + I_E$ ). The sensitivity at different  $I_R/I_E$  ratios is shown in Fig. 3.

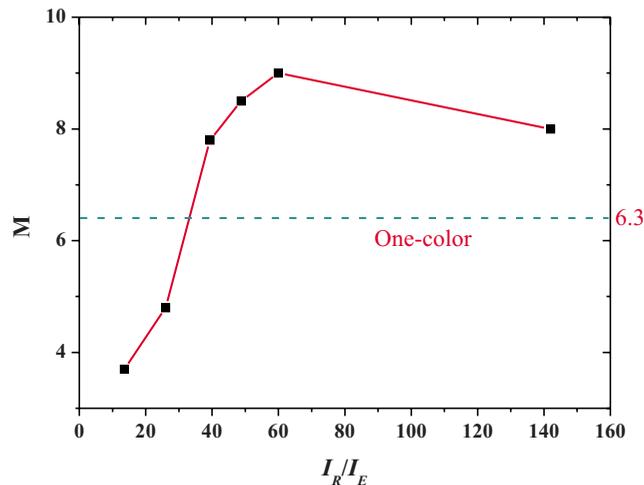


Fig. 2 Relationship of  $M$  and  $I_R/I_E$  ratio.

Similar to the relationship of  $M$  and  $I_R/I_E$ , the maximum sensitivity ( $S=0.42$  cm/J) is at  $I_R/I_E \approx 50$ , and it is 35% enhanced by comparing to the sensitivity in one-color recording by a He-Ne laser ( $S=0.31$  cm/J).

#### 4 Discussion

Although two light sources are involved in the proposed two-color holographic recording, it differs from the two-center nonvolatile recording because no nonvolatile effect has been observed. To interpret the experimental results, charge migration and interference visibility should be taken into account. For general one-color holographic recording in a photorefractive LiNbO<sub>3</sub> crystal, charges are excited from impurity levels due to doping by the interference light. These excited charges move in the conduction band via diffusion and photovoltaic effect, and are trapped some time later. In quasi-steady state, the charges being resident in the dark region of the crystal are more than those in the bright region. Finally, the space-charge field due to nonuniform space charges results in a modulation of the refractive index via Pockels effect. In two-color holographic recording, the whole process is similar except for the additional exciting light. The exciting light excites more charges from the impurity levels in the first step of photorefractive effect.

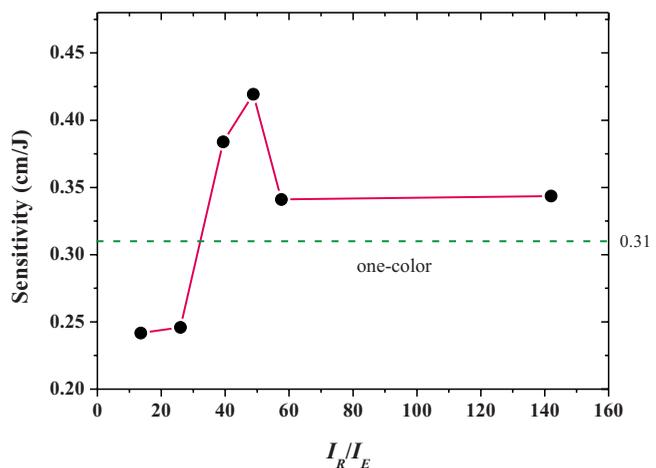


Fig. 3 Relationship of  $S$  and  $I_R/I_E$  ratio.

**Table 1** Performance characteristics of one- and two-color recordings.

	Max. $\eta$ (%)	$\tau_e$ (s)	$M$	$S$ (cm/J)
Two-color recording ( $I_R/I_E \approx 50$ )	23	$4.1 \times 10^3$	8.5	0.42
One-color recording (He-Ne)	19	$3.3 \times 10^3$	6.3	0.31
One-color recording (DPSS)	6.0	$1.3 \times 10^4$	6.1	0.79

Therefore, either the formation speed or the dynamic range of the photorefractive gratings becomes larger. In our demonstration, the absorption coefficients of the crystal at 633 and 532 nm are 0.786 and 5.96 cm<sup>-1</sup>, respectively. Thus, there is a substantial difference between the exciting efficiencies of the two wavelengths. This helpful effect can be easily found, as shown in the right side of experimental curves in Figs. 2 and 3 ( $I_R/I_E > 40$ ). On the other hand, the exciting light is uniform so that it cannot help to generate nonuniform distribution of charges. Thus, the grating strength as well as the fringe visibility will deteriorate if too much exciting light is added. This effect is the reason for the drooping of  $M$  in the left side in Figs. 2 and 3 ( $I_R/I_E < 40$ ).

In addition to above mechanisms, the exciting light is also associated with the effect of incoherent erasure. In previous research, it was found that suitable incoherent light or ordinary light will help the formation of phase grating in a BaTiO<sub>3</sub> crystal.<sup>14,15</sup> It is reasoned that the incoherent light will suppress the fanning light (the source of optical noise) so that the principal gratings form without disturbance. In our experiment, the exciting light and the interference light are mutually incoherent. Thus, the exciting light will suppress the fanning light due to the interference light. This effect will affect the crystal performance in steady state, resulting in better maximum diffraction efficiency. However, the effect should not be the only mechanism in two-color recording because it cannot enhance the sensitivity, which only relates to the transient response in the beginning of recording.

For comparison, we listed the performance characteristics of two and one-color recordings in Table 1. Because the holographic performance of photorefractive crystals depends on the illuminating intensity, the total intensity for one-color recording is similar to that used in two-color recording, as described in Section 2. According to Table 1, all the performance characteristics of two-color recording are better than those of one-color recording by He-Ne laser. On the other hand, the performance characteristics of two-color recording are generally better than those of one-color recording by DPSS laser because the intensity of the DPSS laser is low. However, the sensitivity of the latter is about 1.5 times higher than that of the former, which reflects the high absorption coefficient at 532 nm. Finally, in either one- or two-color recording, the performance characteris-

tics depend on the intensity of interference light. Therefore, the enhancement effect achieved by applying two-color recording will become insignificant in saturation interference intensity.

### Conclusion

In summary, we proposed a two-color holographic recording method to improve the holographic properties of a single-doped LiNbO<sub>3</sub> crystal. In our demonstrations, a light with wavelength 633 nm is used for interference and a light with wavelength 532 nm is used for exciting. In the optimized intensity ratio, the  $M$  and the sensitivity are enhanced by 43 and 35%, respectively. Because the crystal we used is a typical iron-doped LiNbO<sub>3</sub> crystal, the proposed method is easy to be achieved in most holographic systems. Moreover, an exciting light source in two-color recording can be low power and low coherence, such as an inexpensive light-emitting diode. Therefore, the proposed method provides a good balance between the system performance and the cost.

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