Multiplexing Nonvolatile Holograms in $LiNbO_3$:Cu:Ce Crystals *

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A practical experimental system for two-centre recording by angular multiplexing and 90° geometry is designed with red and blue light. The erasure mechanism of lithium niobate crystals doubly doped with copper and cerium for two-centre recording is discussed and a modified decremental recording schedule for angular multiplexing is proposed subsequently. Finally, 50 nonvolatile holograms with almost the same diffraction efficiency are recorded.

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The two-centre holographic recording in doubly doped lithium niobate has been demonstrated recently by Buse *et al.*,[1] which exhibits nonvolatile readout and brings up some novel concepts for conventional holographic recording technologies. Combining the nonvolatile recording method with the conventional holographic recording system using angular multiplexing is one of the major problems in the practical realization of holographic read-write memories with high performances. The related experiments in $LiNbO_3$:Fe:Mn have been discussed.[2] It has also been reported that $LiNbO_3$:Cu:Ce crystals have the capacity of nonvolatile holographic recording with high persistent diffraction efficiency and weak light-induced scattering.[3,4] In this Letter, we propose and experimentally demonstrate the two-centre recording for angular multiplexing holograms in $LiNbO_3$:Cu:Ce crystals with equal diffraction efficiencies.

The lithium niobate crystal doubly doped with Cu and Ce is acquired from Nankai University in Tianjin, China, which is grown from the melt of congruent composition using the conventional Czochralski method. The starting materials are prepared by mixing small amount of Li_2CO_3 and Nb_2O_5 powders at a congruent ratio of Li:Nb = 48.6:51.4 (mol%). Cu ions and Ce ions are added into the melts with the concentration of 0.01 mol% and 0.085 wt.%, respectively. As is well known, the modest treatment of oxidation and reduction can change the valence state of the doped ions and distribution of other defects, thus can affect the photorefractive effect of the crystal. In our experiment, the sample is oxidized so that initially nearly all Ce traps are empty and a portion of the Cu traps are filled. In the two-centre holographic recording, Cu and Ce act as the deep and shallow centres, respectively. Illumination with light of short-wavelength for sensitization or gating will excite electrons from Cu centres to the conduction band. Some of these electrons can be trapped by Ce centres, which makes the holographic recording with longer-wavelength light feasible. The final holograms are recorded in the Cu traps, and therefore are not erased during the readout using the recording light with long wavelength.

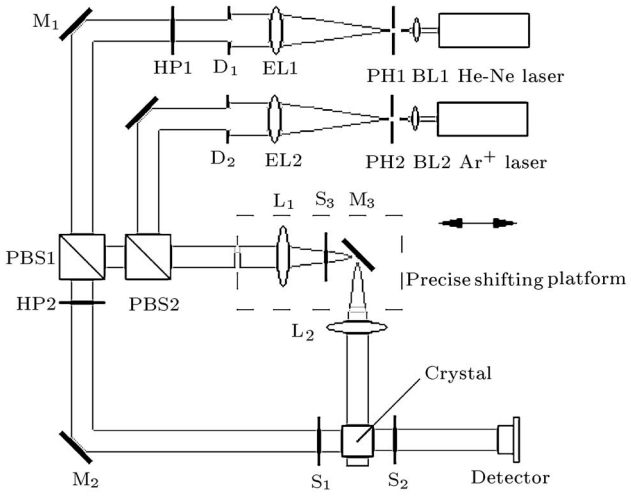


Fig. 1. Experimental set-up for the two-centre recording by angular multiplexing. BL1: microscopic lens, PH1: pinhole, EL1: beam-expanding lens, D1 and D2: diaphragms, HP1 and HP2: half-wave plates, PBS1 and PBS2: polarized beam-splitting prisms, L1 and L2: lenses, M1–M3: reflecting mirrors, S1–S3: shutters.

The experimental set-up designed for two-centre recording by angular multiplexing and 90° geometry in the $LiNbO_3$:Cu:Ce crystal is shown in Fig. 1. The linear polarized light generated from an He–Ne laser ($\lambda = 632.8$ nm) is expanded, filtered and collimated by a microscope lens BL1, a pinhole PH1, a beam-expanding lens EL1, and a diaphragm D_1. Passing through a half-wave plate HP1 and a polarized beam-splitting prism PBS1, the light is divided into two parts as a reference beam and an object beam. A proper power distribution between the reference beam and the object beam can be implemented by rotating the plate HP1. The half-wave plate HP2 is used to adjust the object-beam polarization. A scanning mechanism for spherical reference beam is used to control the incidence angle of the reference beam before it projects on the crystal, which is composed of lens L1 and L2, reflecting mirror M3, and a precise shifting platform.

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Moving the precise shifting platform to change the incidence angle of the reference beam and replacing the input image at the same time, we can record angular multiplexing holograms in the crystal. An Ar^+ laser ($\lambda = 488$ nm) is used to realize sensitization, whose light passes through BL2, PH2, EL2 and D2, and then is incorporated with the reference beam by the PBS2. The three shutters S1, S2, and S3 are used to perform the experiments automatically by the corresponding software.

In the two-centre holographic recording, the erasure process should be discussed under two different conditions. During the angular multiplexing recording, the previous holograms are erased by both blue and red beams when the subsequent holograms are recorded. During the readout by red beam after multiple holograms are recorded, there is a partially erasure, then the further readout will be nonvolatile. We performed the related experiments to compare the two readout processes with and without an illuminating blue beam, the typical curves are shown in Fig. 2. The experimental results prove the theoretical analysis. The recording curve can be approximated by monoexponential formula with τ_r representing the recording time constant. During the angular multiplexing recording, the proper erasure curve is the one that descends faster, whose mechanism is composed of two different erasure processes of blue and red beams. This erasure curve is fitted by multi-exponential formula, and the largest time constant is used for the candidate of the erasure time constant τ_e.

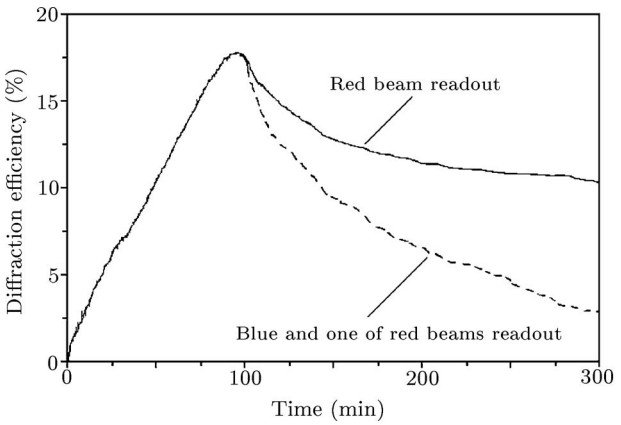


Fig. 2. The curves to compare the two readout processes with and without illuminating blue beam.

As mentioned above, we can use the conventional recording schedule,[5] in which the definition of erasure time constant is modified. Therefore, the dynamic range M can be determined by

$$M = (\beta A_0/\tau_r)\tau_e. \qquad (1)$$

where $(\beta A_0)^2$ represents the remaining persistent diffraction efficiency after readout for a long time with only red beam, which can be measured experimentally.

In our angular multiplexing recording system, the angular separation of the holograms is tested by the scanning mechanism for the reference beam, and the average angle between the main lobes of two adjacent holograms is 0.028°. We chose $\theta = 0.28°$ as the angular separation between consecutive holograms.

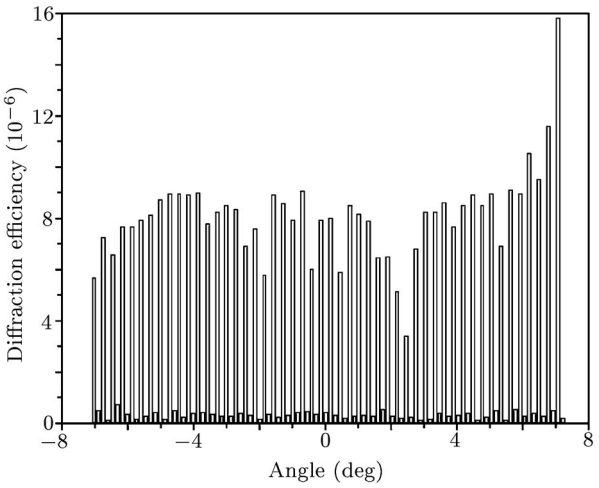


Fig. 3. Diffraction efficiency versus angle for 50 nonvolatile holograms.

To obtain multiple holograms with equal diffraction efficiency, a proper recording schedule must be employed. For the case in which the crystal is singly doped, there is a well-known decremental recording schedule[5]

$$t_i = \frac{t_1}{1 + (i-1)/\gamma}, \qquad (2)$$

where $\gamma = \tau_e/\tau_r$. The proper recording and erasure time constants for two-centre holographic recording can be deduced from Fig. 2 as $\tau_r = 3387 \pm 16$ s, $\tau_e = 4092 \pm 19$ s. When $t_1 = 1800$ s, we multiplied 50 two-centre nonvolatile holograms. Figure 3 shows the diffraction efficiency versus angle for these 50 holograms. Based on Eq. (1), we calculate that $M = 0.1476$. When the number of holograms $N = 50$, the expected diffraction efficiency of each nonvolatile hologram is $\eta = (M/N)^2 = 0.8327 \times 10^{-6}$, which agrees with our experimental results.

In summary, we have designed a practical experimental system for two-centre recording by angular multiplexing and 90° geometry. Moreover, 50 nonvolatile holograms are recorded in a $LiNbO_3$:Cu:Ce crystal with almost the same diffraction efficiency.

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