Localized holographic recording in doubly doped lithium niobate

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Received September 14, 1999

Persistent holograms are recorded locally with red light in a $LiNbO_3$ crystal doped with Mg and Fe. Selective erasure is realized by use of a focused UV sensitizing light. We demonstrate the recording of 50 localized images as well as selective erasure in a 4 mm × 4 mm × 4 mm crystal. A comparison of the total recording time for M holograms obtained with the conventional distributed-volume recording and the localized methods is presented. © 2000 Optical Society of America

OCIS codes: 090.7330, 210.0210, 210.4680.

In holographic data storage,[1] pages of information overlap in the volume of the recording medium. Coherent erasure of a particular page also erases all the other pages stored in the same volume, owing to destructive readout of holograms in photorefractive crystals such as $LiNbO_3$:Fe. Recently, nondestructive readout has been demonstrated in doubly doped $LiNbO_3$.[2] When holograms are multiplexed in such crystals,[3] the erasure of a single page of information requires that sensitizing light be present, causing the erasure of all the other pages of information stored in the same volume. In this Letter we propose holographic recording of localized holograms in doubly doped $LiNbO_3$. This method can be applied to any other material that produces nonvolatile readout.[4–6] The method can be considered the holographic analog of the three-dimensional optical two-photon memories architecture.[7,8] We experimentally demonstrate recording of 50 localized holograms in doubly doped $LiNbO_3$ and selective erasure. These localized holograms can be erased and refreshed selectively without influencing adjacent holograms. We show that the total recording time for this method is shorter than the total recording time of the distributed-volume recording method.

We perform experiments with a congruent 90°-cut $LiNbO_3$ crystal doped with 0.075-wt. % Fe_2O_3 and 0.015-wt. % MnO. Figure 1 depicts the experimental setup. We use a frequency-doubled femtosecond laser as a sensitizing light source (wavelength, 405 nm) and a 15-mW He–Ne laser for generation of coherent red light (wavelength, 633 nm; ordinary polarization). We recorded a plane-wave hologram, using two red beams that interfere in a 90° geometry crystal illuminated by the sensitizing light. The hologram that we obtain with the pulsed sensitizing beam is less persistent than the cw sensitization reported in Ref. 2. When it is read out with only the red reference beam, the hologram is erased with a time constant that is only three times the writing time constant. The ratio reported in Ref. 2 with cw sensitization is of the order of 10^4.

An intensity transmission mask is imaged by a 4-f system onto a CCD camera. The reference beam is focused by an 8-cm cylindrical focal lens. The UV beam copropagates with the red reference beam. The lateral extension ($1/e^2$ value) of both focused beams inside the crystal is 40 μm. The signal diameter is 1.5 mm inside the crystal (Fresnel region). The crystal is mounted on a computer-controlled translation stage. At each spatial location, the crystal is presensitized with the focused UV beam for 10 s. We use an exposure schedule for the recording of 50 holograms because of the nonpersistence of holograms, as explained above. The holograms are recorded with the red beams for 4.5 min on average (reference, 720 μW; signal, 120 μW; UV, 100 μW). Multiple holograms are recorded by translation of the crystal between exposures. A center-to-center separation of 80 μm, which is equal to twice the lateral extension of the red and the UV beams, is used between spatial locations. The experimental result is shown in Fig. 2(a). Each peak in the plot results from the diffraction efficiency of a localized hologram as the crystal is translated in the direction perpendicular to the reference beam. As shown in Fig. 2(b), hologram 25 is selectively erased by continuous illumination with UV light. The detector is then replaced by a camera, and an example of a reconstructed image is shown in Fig. 2(a). We do not

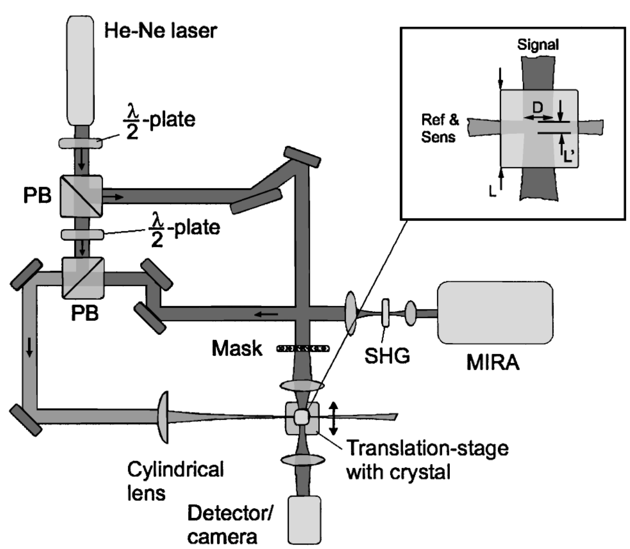

Fig. 1. Recording setup for the 50-hologram experiment. The camera CCD and detector are interchangeable. $\lambda/2$-plate, half-wave plate; PB's, polarizing beam splitters; SHG, second-harmonic generator; MIRA, femtosecond laser.

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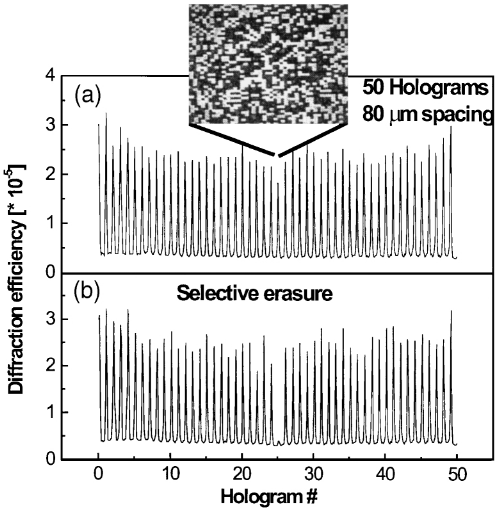

Fig. 2. (a) 50 images recorded in a $LiNbO_3$:Fe, Mn crystal. Each peak corresponds to the diffraction efficiency of a hologram stored at a different spatial location. (b) Hologram 25 is selectively erased by continuous illumination with UV and red reference light.

measure the fidelity of the reconstruction quantitatively. This experiment demonstrates that holograms can be recorded locally in $LiNbO_3$:Fe, Mn crystal, permitting selective noncoherent erasure.

In the following analysis we compare the total recording time of M holograms by use of conventional distributed-volume holographic recording in doubly doped $LiNbO_3$ (Ref. 3) and localized recording in the same crystal described above. In the analysis we calculate the recording time required for the same final diffraction efficiency for the two methods. The total power for recording is fixed and equal for both recording methods, so that the comparison will be fair, since the results derived in this Letter scale identically with total power for both methods. The power is divided equally in the reference and the signal beams for distributed recording because it optimizes the recording speed. We keep the reference and the signal power equal in the case of localized recording for the same reason.

For distributed-volume hologram recording, an exposure schedule is necessary to obtain equalized diffraction efficiency for M holograms. The square root of the final diffraction efficiency is equal to[9]

$$\begin{aligned}\sqrt{\eta} &= CA_0\left[1 - \exp\left(-\frac{t_M}{\tau_w}\right)\right] \\ &\simeq C\,\frac{A_0}{\tau_w}\,t_M \\ &= C\,\frac{M_\#}{(\tau_e/t_1) + M - 1}\,, \end{aligned} \tag{1}$$

where M is the number of holograms; $M_\# = A_0\tau_e/\tau_w$ is the M-number parameter; A_0 is the square root of the saturation diffraction efficiency after red erasure; τ_w and τ_e are the writing- and erasure-time constants, respectively; t_1 is the recording time of the initial hologram; and $t_M = \tau_e/[(\tau_e/t_1) + M - 1]$ is the recording time of the last hologram. Equation (1) differs from the equation in Ref. 9 by a factor C, which is the square root of the ratio between the signal and reference beam area in the crystal, $C = \sqrt{A_s/A_r}$. It is introduced here because we are concerned with the diffraction efficiency expressed as a power ratio and not as an intensity ratio. The total recording time for M distributed-volume holograms is equal to

$$T_{\text{tot}} = \tau_e \ln[1 + (M - 1)(t_1/\tau_e)]. \tag{2}$$

For the localized method the total recording time for M holograms is simply

$$T_{\text{tot}}' = Mt_s', \tag{3}$$

where t_s' is the time needed to record one hologram. In the following relations the primed variables correspond to the localized recording. The square root of the diffraction efficiency of one localized hologram recorded for time t_s' is equal to $\sqrt{\eta'} \simeq C\sqrt{M}\,(A_0'/\tau_w')t_s'$, where $t_s' \ll \tau_w'$. The extra factor $\sqrt{M}$ comes from the fact that the area of the reference beam has been reduced by M ($L/M = L'$; see the inset of Fig. 1). Since A_0' is proportional to modulation depth $m' = \sqrt{I_r'I_s}/I_r' + I_s$ and interaction length L', and $\tau_w' \propto \frac{1}{I_r' + I_s}$,[10] the recording slope S' for the localized recording is equal to

$$\begin{aligned} S' &= C\sqrt{M}\,\frac{A_0'}{\tau_w'} = C\sqrt{M}\,\frac{A_0}{\tau_w}\,\frac{1}{M}\sqrt{\frac{I_r'I_s'}{I_rI_s}} \\ &= C\,\frac{A_0}{\tau_w} = S\,. \end{aligned} \tag{4}$$

Since $S = C(A_0/\tau_w)$ is the recording slope for the distributed-volume recording, Eq. (4) shows that as long as $t_s' \ll \tau_w'$ the ratio between the recording slopes is independent of L'. We experimentally verify this result by measuring the recording slope of the square root of the diffraction efficiency (computed as a power ratio) for different interaction lengths L', keeping the power in the reference and the signal beams constant. For $L' = 40\ \mu$m to 3.5 mm, we observe a decrease of 20% in recording slope, which we attribute to experimental errors owing to the difficulty of overlapping the UV and the red reference beams in the crystal for small lateral extension. We use the result of Eq. (4) to compare the recording speed of the localized and the distributed-volume recording. The final diffraction efficiencies for the two cases are

$$\begin{aligned}\sqrt{\eta'} &= C(A_0/\tau_w)t_s' \\ \sqrt{\eta} &= C(A_0/\tau_w)t_M\,. \end{aligned} \tag{5}$$

Equations (5) show that the total recording time of the localized hologram method is shorter than that of the distributed-volume method, since t_M is the shortest recording time of the exposure schedule. This result, however, is valid only if holograms are recorded in the linear region of the recording curve. We have to be careful because the localized-recording time constant τ_w' becomes, when we use $(\tau_w'/\tau_w) = (I_r + I_s)/(I_r' + I_s)$,

$$\tau_w' = \tau_w\,\frac{I_r + I_s}{MI_r + I_s} = \tau_w\,\frac{2}{M + 1} \simeq \frac{\tau_e}{M}\,, \tag{6}$$

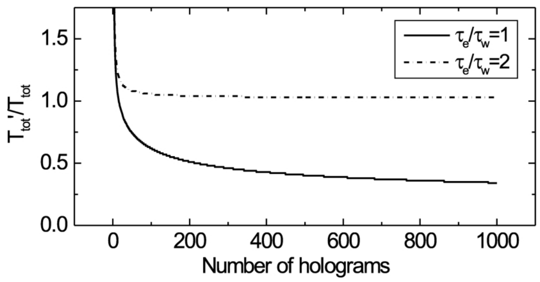

Fig. 3. Ratio of total recording time between the localized and the distributed-volume methods as a function of the number of holograms needed to record for two different values of the ratio τ_e/τ_w and $t_1 = \tau_e/20$.

where I_r and I_s are the reference and the signal intensity, respectively. We set $I_r = I_s$ in Eq. (6) because, for distributed-volume recording, the recording beams have similar area and equal power. Experimentally, τ_e is roughly equal to τ_w in doubly doped $LiNbO_3$ as a result of constant sensitizing illumination in the crystal volume throughout the recording process of the M holograms.[3] This is different with localized recording, since the sensitizing light is localized and does not erase previous holograms. Thus, from Eq. (6), the last recording time of the exposure schedule for the distributed-volume recording ($\simeq \tau_e/M$) is of the same order as the writing-time constant of the localized holograms, and therefore they are being recorded in the nonlinear region. The total recording time of the localized recording has to be computed by use of the exact form of the recording curve:

$$\sqrt{\eta'} = C(A_0/\tau_w)\tau_w'[1 - \exp(-t_s'/\tau_w')] = C(A_0/\tau_w)t_M\,. \tag{7}$$

By substituting Eq. (6) into Eq. (7) and solving for t_s', we can obtain the total recording time:

$$T_{\text{tot}}' = Mt_s' = \frac{-2M}{M+1}\tau_w \ln\left[1 - \frac{\tau_e}{\tau_w}\frac{M+1}{2(\frac{\tau_e}{t_1} + M - 1)}\right].$$

The total recording time for the distributed-volume method is given by Eq. (2). We note that the ratio of T_{tot}' and T_{tot} depends on the ratio of time constants τ_e/τ_w, the number of holograms M, and the initial recording time t_1 of the exposure schedule. A practical value for t_1 is taken as $\tau_e/20$. Figure 3 shows the ratio of total recording times for both methods, T_{tot}' and T_{tot}, versus the number of holograms for two values of τ_e/τ_w. One can see from Fig. 3 that for $\tau_e/\tau_w = 1$ the total recording time of the localized method can be shorter than the total recording time of volume holograms for M longer than 10 holograms. As the ratio τ_e/τ_w increases, this advantage of the localized recording method quickly vanishes. There exists a ratio τ_e/τ_w above which the localized holograms cannot reach the diffraction efficiency obtained with distributed-volume holograms independently of the exposure time allotted. For $M = 1000$ and $t_1 = \tau_e/20$, this threshold ratio is equal to 2.1.

Another basis for comparison of the two methods is in terms of storage density. We first consider the experiment described in this Letter. Fifty localized holograms with equal diffraction efficiency of 2×10^{-5} were recorded. The effective $M_\#^{\text{loc}}$ of the localized method is equal to $M\sqrt{2 \times 10^{-5}} = 0.22$. If we use the same crystal for distributed volume recording (with $M = 50$), we can compute $M_\#$ by use of a single plane-wave hologram recording in the same crystal. Assuming equal recording and erasing time constants (see discussion above), we found that $M_\#^{\text{vol}} = 0.18$. This result suggests that 50 holograms for both methods can be recorded in the same volume with approximately the same diffraction efficiency. We need to know how this result scales with M. The maximum number of localized holograms that can be stored in a given crystal thickness is limited by the diffraction of the focused sensitizing beam. Let a typical spot size for a high-bandwidth signal beam recorded in the Fourier plane be $\simeq$3 mm. This translates to an optimal focusing of 15 μm ($1/e^2$ value) for the sensitizing beam and thus a center-to-center spacing of 30 μm. Therefore, if we assume a crystal thickness of 1 cm, 330 localized holograms can be recorded with a diffraction efficiency equal to 2×10^{-5}. Comparatively, the diffraction efficiency of 330 holograms stored with the distributed-volume method would be equal to $\eta = (M_\#^{\text{vol}}/330)^2 = 1.9 \times 10^{-6}$. The larger final diffraction for the localized recording comes at the expense of a longer recording time, since in this case each hologram would have to be recorded in the nonlinear region.

We thank Wenhai Liu and Ali Adibi for valuable discussions about this Letter. This research was supported by the U.S. Air Force Rome Laboratory and by a Jet Propulsion Laboratory research Hybrid Technology Multithreading project. C. Moser's e-mail address is moser@sunoptics.caltech.edu.

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