Sensitivity variation in two-center holographic recording

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An experimental study of variation of sensitivity with recording and sensitizing intensities in two-center recording is presented. The experimental results are in good agreement with the theoretical predictions. It is shown experimentally, for what is to our knowledge the first time, that the sensitivity is a function of the ratio of recording to sensitizing intensities and not the absolute intensities. Also, the ratio of recording to sensitizing intensities should be small to obtain high sensitivity values. We also report the highest sensitivity ($S=0.15$ cm/J) that has been achieved to date for a $LiNbO_3$:Fe:Mn crystal. © 2005 Optical Society of America

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Recently proposed doubly doped lithium niobate crystals, such as $LiNbO_3$:Fe:Mn, make possible persistent holographic storage using two-center holographic recording.[1] In this technique, a volume hologram is recorded using two interfering coherent recording beams in the presence of a sensitizing beam with shorter wavelength.[1] When this hologram is read by one of the recording beams, an initial drop in the diffraction efficiency is observed, after which the hologram persists against further readout. Since the initial demonstration of two-center recording,[1] there have been several reports on improving the performance measures of this technique.[2–4] The primary performance measures of interest are the dynamic range parameter (or $M/\#$),[5] which defines the number of holograms that can be multiplexed in a given crystal, and the sensitivity (S),[6] which defines the recording speed. Despite extensive research on the properties and improvement of the $M/\#$ in two-center recording, there have been only a few reports (especially experimental ones) on the properties of the sensitivity in this technique.[4,7,8] For example, we recently performed a theoretical global optimization of $M/\#$ and S in two-center recording,[4] in which we showed theoretically that the sensitivity depends on the ratio of the total recording and sensitizing intensities (I_{rec} and I_{sen}, respectively) and not on the absolute intensities. A similar variation of the $M/\#$ was reported earlier.[2] In this Letter we report, for what is to our knowledge the first time, a detailed experimental study of the role of recording and sensitizing intensities in two-center recording. We show that the sensitivity depends on only the intensity ratio (i.e., I_{rec}/I_{sen}) and not on the individual intensities as predicted theoretically.[4]

All experiments reported in this Letter were performed using a software-based stabilized recording system, shown in Fig. 1, to reduce unwanted vibrations and external noises during recording. The stabilized holographic setup is based on Mach–Zehnder interferometry and is independent of the crystal itself. The light from a CW solid-state laser at wavelength $\lambda=532$ nm was spatially filtered, expanded, and split into two beams. Half-wave plates (W1 and W2) were used to provide two beams with the same polarization and intensity. The split beams were then expanded to twice their original diameter to encompass both the crystal and the beam splitter. A piezo-driven mirror was placed in the path of the signal beam. A nonpolarizing beam splitter was placed at the point of intersection of the recording beams for interfering them and a photodetector (PD_{stab}) placed in the reference beam path was adjusted to detect the interference of the two beams. The recording doubly doped crystal was placed on top of the nonpolarizing beam splitter (Fig. 1). The c axis of the crystal was parallel with the grating vector. Another photodetector (PD_{diff}) was aligned in the direction of the signal beam for monitoring the diffracted intensity. A UV laser beam (wavelength 404 nm) was used to sensitize the crystal. The shutters were also used to control the recording and readout processes.

The stabilization principle of this setup is rather straightforward: an arbitrary set point, corresponding to an arbitrary phase between the interfering beams, is chosen. The fringe movement monitored by

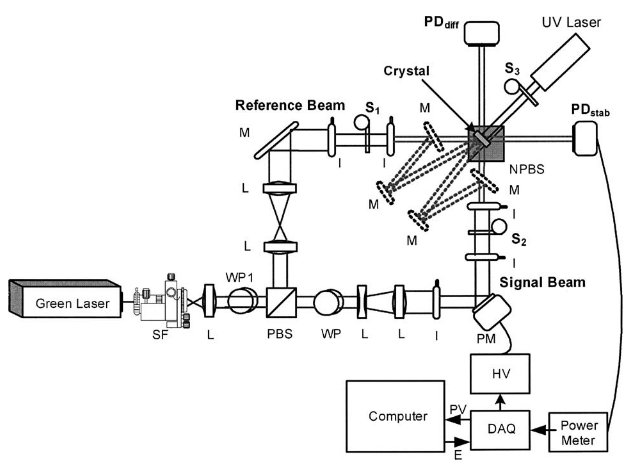

Fig. 1. Experimental setup for stabilized two-center recording. DAQ, data acquisition card; HV, high-voltage amplifier; I, iris; L, lens; M, mirror; NPBS, nonpolarizing beam splitter; PBS, polarizing beam splitter; PD, power detector; PM, piezo mirror; S, shutter; SF, spatial filter; WP: half-wave plate.

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PD_{stab} is sent into a powermeter whose analog output was acquired by the computer via a data acquisition card. The reading value from the PD_{stab} photodetector is subtracted from the set point to produce an error signal that is passed into two proportional, integral, and derivative (PID) controllers that are in series to compensate for the poles and zeros of the unstable system and to make a closed-loop stable system. The processed error is then passed to the piezo-driven mirror, which is used to compensate for the phase perturbation in the fringe pattern. The PID gains are carefully set to obtain a good stability. The software part of the system is completely implemented using LabVIEW. Using this system, we were able to achieve the stability better than $\lambda/20$ (at recording wavelength $\lambda = 532$ nm) for intervals of at least 2 h.

Based on the theoretical optimization,[4] a congruently grown $LiNbO_3$:Fe:Mn crystal with 0.15 wt.% Fe_2O_3 and 0.02 wt.% MnO was obtained from Deltronics Crystals to experimentally investigate the variation of sensitivity in two-center recording. The sample used in all the experiments was an x-cut 2 mm thick crystal. The crystal was put in oxygen atmosphere at 1070 °C for 48 h. All the holograms were recorded in symmetric transmission geometry using ordinary polarization for the recording beams. The angle between each beam and the normal to the crystal (outside the crystal) was $\theta = 45°$. Figure 2 shows a typical reading and readout curve for this crystal with $I_{rec} = 50$ mW/cm^2 and $I_{sen} = 18$ mW/cm^2. The hologram was recorded for 20 min. After recording, the hologram was under the illumination of a Bragg-mismatched beam with 25 mW/cm^2 intensity for 80 min. The persistence factor (β) is defined as $\beta = \sqrt{\eta_2}/\sqrt{\eta_1}$, with η_1 and η_2 being the diffraction efficiency at the end of recording and that at the end of the initial drop during readout, respectively. Diffraction efficiency is measured as the ratio of the diffracted intensity to the incident reading intensity.

To study the properties of the sensitivity in two-center recording, different holograms were recorded using different sets of recording and sensitizing intensities. Before any experiment, the crystal was illuminated by the UV beam to erase the existing holograms. Since the sensitivity is measured only at the beginning of the recording, it is essential to have the electron concentration at both traps at the steady-state value before recording.[4] Therefore, before we measured the sensitivity, a hologram was recorded to saturation for at least 1 h using the sensitizing beam and two recording beams (shown by the dashed lines in Fig. 1), which are Bragg mismatched with the desired hologram. The intensities of such recording and sensitizing beams were equal to those used for sensitivity measurement. This process ensures that steady-state electron concentrations are obtained in Fe and Mn traps of the crystal before recording the desired hologram to have a reliable measurement of sensitivity. Then the desired hologram is recorded using the desired reference and signal beams (as shown in Fig. 1) for at least 3 min, and the diffraction efficiency is monitored in 30 s intervals. After each recording, the hologram was illuminated by the two Bragg-mismatched beams (shown by the dashed lines in Fig. 1) and the sensitizing beam for at least 30 min to erase the previous hologram before recording the next desired hologram while the average electron concentrations in the two traps were kept constant. For each set of recording and sensitizing intensities, the same experiment was repeated at least four times, and the recording time in the fourth experiment was chosen to be long enough to make sure the hologram reached saturation. The hologram was then illuminated using one of the Bragg-mismatched beams to partially erase the hologram and to find the persistent diffraction efficiency (η_2 in Fig. 2). The sensitivity (S) was then calculated as[7]

$$S = \frac{1}{I_{rec}L} \times \left. \frac{d\sqrt{\eta}}{dt} \right|_{t=0}, \tag{1}$$

where η, t, I_{rec}, and L represent the diffraction efficiency, time, total recording intensity (sum of the intensities of the two recording beams), and crystal thickness, respectively. The persistent sensitivity (S') in two-center recording is defined as $S' = S\beta$, with β being the persistent factor defined earlier.[7] The values of S and S' were calculated for all four experiments and then averaged to find the sensitivity for each set of intensities.

Figure 3 shows the variation of S with the recording intensity when the ratio of the recording and sensitizing intensities is kept constant at $I_{rec}/I_{sen} = 3.1$. As can be seen from Fig. 3, the sensitivity is almost constant for a fixed intensity ratio. It should be noted that only S is shown in Fig. 3. We know that the saturated and the persistent hologram strengths are functions of the intensity ratio (I_{rec}/I_{sen}).[2,4] Therefore, persistent factor β and persistent sensitivity S' are functions of I_{rec}/I_{sen} and not the absolute intensities. This is exactly in agreement with the theoretical results obtained in Ref. 4. Therefore, to obtain the complete variation of sensitivity with respect to recording and sensitizing intensities, we only need to find S (or S') as a function of I_{rec}/I_{sen}.

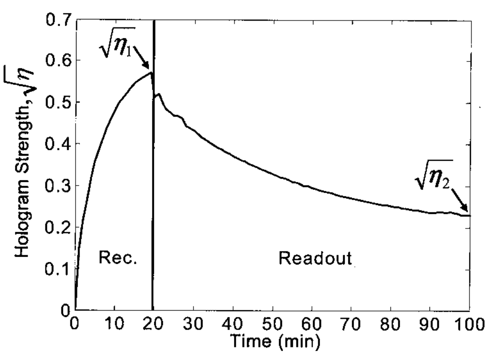

Fig. 2. Typical reading and readout curve for the $LiNbO_3$:Fe:Mn crystal described in the text with $I_{rec} = 50$ mW/cm^2 and $I_{sen} = 18$ mW/cm^2. The hologram was recorded for 20 min. Then the hologram was under the illumination of a Bragg-mismatched beam with 25 mW/cm^2 intensity for 80 min.

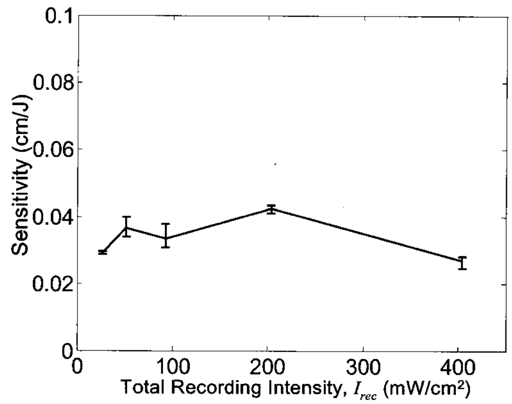

Fig. 3. Sensitivity (S) in two-center recording as a function of total recording intensity (I_{rec}) while the recording to sensitizing intensity ratio is fixed at $I_{\mathrm{rec}}/I_{\mathrm{sen}}=3.1$. The properties of the recording material are described in the text.

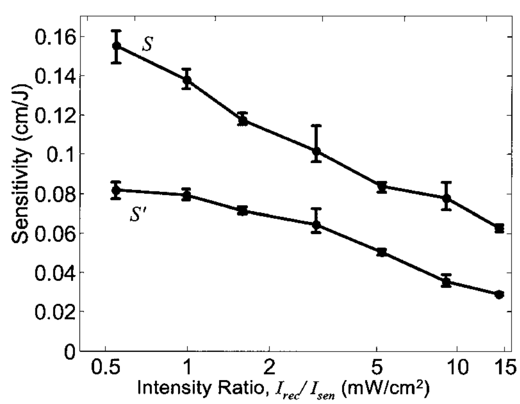

Fig. 4. Sensitivity (S) and persistent sensitivity (S') in two-center recording as functions of the ratio of recording to sensitizing intensities ($I_{\mathrm{rec}}/I_{\mathrm{sen}}$) with $I_{\mathrm{sen}}=36\ \mathrm{mW/cm^2}$ for the $\mathrm{LiNbO_3{:}Fe{:}Mn}$ crystal described in the text. The persistent sensitivity (S') is equal to βS.

The variation of S with $I_{\mathrm{rec}}/I_{\mathrm{sen}}$ for a fixed $I_{\mathrm{sen}}=36\ \mathrm{mW/cm^2}$ is shown in Fig. 4. From Fig. 4 it is clear that S decreases as the intensity ratio increases as we had theoretically predicted in Ref. 4. Another important result is that the maximum value of $S=0.15\ \mathrm{cm/J}$, is obtained with the intensity ratio of $I_{\mathrm{rec}}/I_{\mathrm{sen}}=0.54$. This suggests that to achieve high sensitivity we need to use a sensitizing beam with higher intensity than the recording intensities. At $I_{\mathrm{rec}}/I_{\mathrm{sen}}=0.54$ (which results in the highest value of $S=0.15\ \mathrm{cm/J}$), we measured $M/\#=0.08\ \mathrm{mm^{-1}}$. As is known from theoretical analysis, the maximum value of S and the maximum value of $M/\#$ cannot be obtained in the same crystal, as the design conditions for the two maxima are considerably different.[4]

The variation of persistent sensitivity (S') with $I_{\mathrm{rec}}/I_{\mathrm{sen}}$ is also shown in Fig. 4. As is clear from this figure, although smaller intensity ratios result in higher values of S, the persistent sensitivity (S') reaches its maximum value of 0.08 cm/J around an intensity ratio of 0.54. A further decrease of the intensity ratio will result in a reduction of S'. On the other hand, for high intensity ratios, the difference between S and S' becomes smaller because of larger values of β at higher $I_{\mathrm{rec}}/I_{\mathrm{sen}}$. The variation of S' with $I_{\mathrm{rec}}/I_{\mathrm{sen}}$ is also in good agreement with our theoretical results.[4] Note that the thickness of the crystal used in our experiments was 2 mm. Because of high absorption of the crystal (we measured $\alpha=15\ \mathrm{cm^{-1}}$ at $\lambda=404\ \mathrm{nm}$), the sensitizing beam intensity has a strong variation over the crystal thickness. Thus, the contributions of different slices of the crystal to the sensitivity are different, and only a small portion of the crystal can observe the optimum value of $I_{\mathrm{rec}}/I_{\mathrm{sen}}$.[4] Using a thinner crystal or sensitizing from both sides of the crystal, we can obtain higher values for sensitivity ($S\approx 0.3\ \mathrm{cm/J}$). Nevertheless, $S=0.15\ \mathrm{cm/J}$ is to our knowledge the highest sensitivity that has been reported to date for a $\mathrm{LiNbO_3{:}Fe{:}Mn}$ crystal.

In conclusion, we showed here complete experimental variation of sensitivity in two-center recording as a function of recording and sensitizing intensities. The results are in good agreement with the theoretical predictions. Our results show that the sensitivity in two-center recording is a function of the ratio of the recording to sensitizing intensities and not the absolute intensities. Also, in recording at 532 nm wavelength and sensitizing at 404 nm wavelength, using high-intensity UV sources is a key element for fast recording in doubly doped crystals. We also demonstrated $S=0.15\ \mathrm{cm/J}$ for a 2 mm thick $\mathrm{LiNbO_3{:}Fe{:}Mn}$ crystal, which is believed to be the highest sensitivity reported to date.

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