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Selective page-addressable fixing of volume holograms in $Sr_{0.75}Ba_{0.25}Nb_2O_6$ crystals

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We demonstrate selective fixing of volume holograms in photorefractive media. Each holographic page may be fixed individually and overwritten without destroying the other fixed pages. We present experimental results describing this process in Cr-doped $Sr_{0.75}Ba_{0.25}Nb_2O_6$ at room temperature, with hologram lifetimes exceeding 100 days during continuous readout with an intense beam (1 W/cm^2).

Permanent storage of volume holograms in photorefractive media, or fixing, was first demonstrated in $LiNbO_3$ (Ref. 1) by use of a thermal fixing process. The physical mechanism responsible for the fixed grating is believed to be ionic compensation of the electronic space-charge grating during a thermal development cycle[2] or space-charge-induced local ferroelectric domain reversal.[3] Permanent fixing was soon thereafter reported in $Sr_{0.75}Ba_{0.25}Nb_2O_6$ (SBN:75) by applying an electrical fixing pulse to bias the hologram about the coercive field[4] or photoinduced ferroelectric domain nucleation on cooling from the paraelectric phase.[5] Recent research on electrical fixing[6] and fixing based on screening[7] has been reported for SBN. The electrical fixing technique was also applied to $BaTiO_3$.[8] In addition, fixing has been reported in $Bi_{12}TiO_{20}$,[9] $Bi_{12}SiO_{20}$,[10] and $KTa_{1-x}Nb_xO_3$.[11]

The common characteristic of these earlier fixing studies is a single development stage during which time all the space-charge holograms are simultaneously fixed. After the development process, the holographic memory is unable to be updated selectively; that is, to update a single holographic page of data, one must rewrite the entire memory. For applications such as a random access memory, the ability to update existing fixed holograms selectively is highly desirable. While selective erasure and overwriting of dynamic holograms have been reported in the literature,[12] we believe that this is the first demonstration of selective overwriting of fixed holograms. Recently[13] we presented experimental results of electric-field multiplexing, including two holograms individually fixed in SBN:75. In this Letter we describe this selective page-addressable fixing technique. We present data on the holographic diffraction efficiency during the reading and writing process and demonstrate the selective overwriting of a single fixed hologram that does not destroy adjacent fixed holograms that share the same volume.

The crystals used in this experiment are SBN:75 single crystals, 6 mm × 6 mm × 6 mm, grown at the Rockwell International Science Center. Sample A has facets cut perpendicularly to the principal axes, whereas the axes of sample B are rotated 45° about the y axis in the $x-c$ plane. The crystals are poled by application of a dc electric field of 5 kV/cm while they are uniformly heated to 80 °C in a high-dielectric-strength oil bath. With the field on, the samples are cooled at a rate of 0.5 °C/min to 25 °C. The poling field is then removed. Note that the 45° cut of sample B makes the task of poling difficult; hence the diffraction efficiencies for this sample are very small.

The experimental setup is depicted in Fig. 1. During the writing process, A_1 and A_2 are the signal and reference beams, respectively. During the coherent reconstruction with A_2, B_1 and B_2 are the reconstructed signal and remnant reference beams, respectively. Since the holograms are sufficiently weak, we have defined the diffraction efficiency as B_1/B_2, to include reflection and absorption losses (absorption coefficient 1.9 cm^{-1}). We also adopt a conventional definition of the term fixed; that is, the

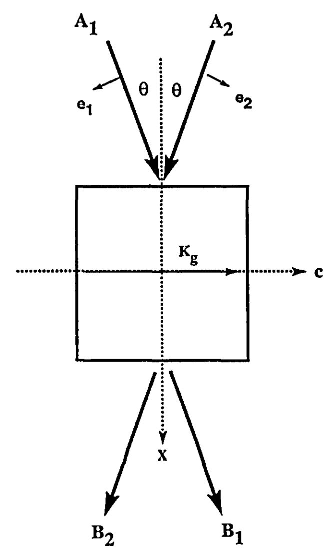

Fig. 1. Typical experimental setup.

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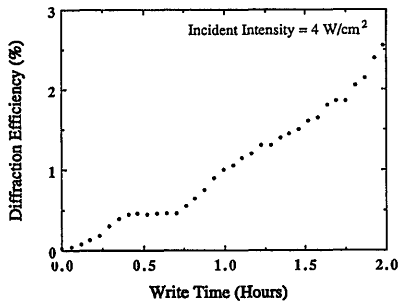

Fig. 2. Diffraction efficiency of the fixed hologram during an extended writing process, illustrating the monotonic increase in diffraction efficiency (sample A).

lifetime of the fixed hologram is several orders of magnitude longer than that of the dynamic hologram. The transmission holograms are written in the image plane at 488 nm, with equal angles of incidence ($\theta = 16°$). The following experiments have all been performed at or near room temperature (25–30 °C) in the ferroelectric phase.

The selective page-addressable fixing process occurs simultaneously with the dynamic hologram writing process; no thermal development cycle or electrical fixing pulse is required. However, increases in incident intensity, in temperature (while well below $T_c = 56\,°C$), or in write time all tend to enhance the diffraction efficiency of the fixed hologram. The hologram diffraction comprises a dynamic component, with a characteristically fast response time, and a fixed component, with a much slower response and a lifetime that is several orders of magnitude larger than that of the dynamic grating. This dependence of relaxation rate on exposure level was first reported by Thaxter and Kestigian,[14] who measured a fixed component with a lifetime of several minutes. We obtain a significant fixed component by simply writing holograms with an incident intensity greater than 1 W/cm^2 for a duration of 2 min or more, or an exposure level of 100 J/cm^2. For a total intensity of the signal and reference beams of 100 mW/cm^2, only a significant dynamic grating is present. As the intensity is increased to 4 W/cm^2, the hologram diffraction efficiency monotonically increases with an extremely slow response time (several orders of magnitude larger than the dynamic grating). In fact, the diffraction efficiency grows by a factor of 25 from the initial value of 0.1% during a writing process of 2 h, surpassing the diffraction efficiency of the dynamic hologram alone (Fig. 2). While it is exceedingly difficult to maintain stability of the interference pattern during these long write times, the diffraction efficiency was found to increase for approximately 20 h until saturation occurred at a maximum diffraction efficiency of 3%.

Thus the hologram written at a higher exposure level is automatically fixed during the writing stage. Figure 3 (sample B) shows that the dynamic hologram disappears completely after only 7 s. The diffraction efficiency of the fixed hologram decays for 40 s and then settles into steady state. This behavior is contrary to early fixing techniques, in which the diffraction efficiency initially grows during readout, since the reconstruction with uniform illumination depletes the dynamic grating and leaves behind only the uncompensated ionic grating. In contrast, the development stage in this selective fixing technique occurs simultaneously with the writing or exposure stage.

The inset of Fig. 3 (sample A) illustrates the long-term decay of a fixed hologram written at room temperature with total intensity of 4 W/cm^2 for 1 h. The diffraction efficiency decreases by a factor of 3

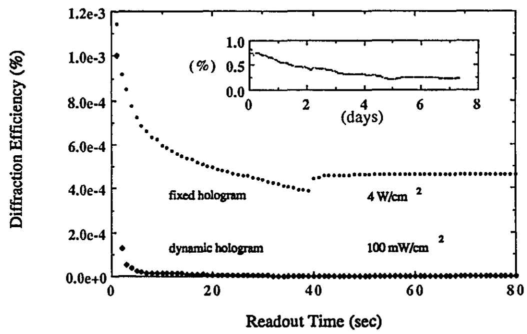

Fig. 3. Comparison of the time response of the dynamic (written and read out with a low-intensity beam of 100 mW/cm^2) and fixed (written and read out with a high-intensity beam of 4 W/cm^2) readout processes (sample B). The inset shows the diffraction efficiency of the fixed hologram during an extended readout process under intense illumination (sample A).

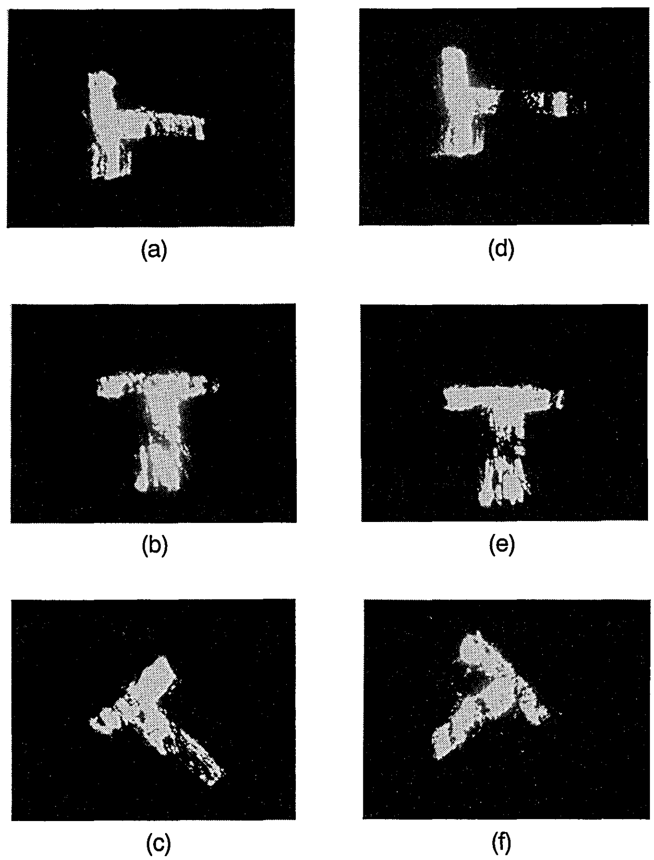

Fig. 4. Selective overwriting of a single angle-multiplexed volume hologram: Hologram (c) is overwritten with (f), leaving (a) and (b) slightly degraded as (d) and (e) (sample A).

during the initial 4 days of readout and then reaches a steady-state value. The hologram was continuously reconstructed with an intense beam of 1 W/cm^2 with a beam diameter of 2 mm. Extrapolating this curve, we estimate that the hologram will survive at least several hundred days during continuous readout. The lifetime is further enhanced for readout with a plane wave, as this will prevent accumulation of space-charge fields that is due to the intensity gradient in the radial direction for a focused reference beam. A fixed page written for 15 min has been monitored intermittently for over 1 month without any degradation in image quality.

A significant advantage of this fixing technique is the ability to address an individual page and selectively overwrite the hologram only at that location. Figure 4 shows the selective overwriting of one of three fixed angle-multiplexed holograms, each hologram separated from the next by $\Delta\theta = 0.01°$. Note that because the Bragg peaks of these holograms are thermally broadened (no thermal stabilization during writing), the minimum angular separation between adjacent holograms is a factor of 10 larger than the theoretical limit of 0.001° in this configuration. Initially, the three holograms, labeled (a)–(c), were written with 4 W/cm^2 for 30 min each. Hologram (c) was then overwritten by hologram (f) for 20 min, during which time the diffraction efficiency of the remaining two fixed holograms, (d) and (e), decayed by approximately a factor of 2. The three holograms remained fixed following the overwriting procedure. Fundamentally, for a writing process in which multiple volume holograms share the same volume, each time a hologram is overwritten the diffraction efficiencies of the remaining holograms sharing the same volume are diminished. Thus even though this fixing technique is selective in the sense that fixed holograms at a particular address (wavelength, field, and angle) may be overwritten completely, holograms at other addresses are slightly degraded. We expect that proper scheduling during the selective overwriting process will minimize the degradation of adjacent fixed holograms.

We present the following evidence that demonstrates that the fixing mechanism is local ferroelectric domain reversal: (1) In an electro-optic amplitude-modulation measurement, the half-wave voltage V_π increased by a factor of 10 following the hologram-writing process, because the fixed hologram periodically polarizes the crystal. By applying a field equal to the coercive field (~1.2–1.6 kV/cm) for 1 s, the crystal is partially repoled as the half-wave voltage decreases by a factor of 3. (2) In some configurations the fixed grating displays a large second spatial harmonic because the index modulation is proportional to the square of the dielectric polarization. (3) The motion of domains under applied dc electric fields is apparent during coherent reconstruction of the hologram, and the hologram can be erased by uniformly illuminating and applying a field larger than the coercive field. (4) Photorefractive response is diminished locally in regions where many holograms have been written, because the effective electro-optic coefficient is reduced. (5) Domain gratings are revealed by a microphotometric method[15] and erased by applying large fields.

In summary, fixing and writing occur simultaneously during exposure levels of at least 100 J/cm^2. This technique is identical to the method of writing dynamic space-charge gratings, except that the fixed hologram exhibits an extremely large read/write time asymmetry. This method has three primary advantages: (1) holograms are individually written and fixed, (2) the process is automatic, and (3) fixing occurs at room temperature. As a consequence, this technique is well suited for applications requiring an updatable ensemble of gratings, such as a holographic random access memory.

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