Multiplexed phase-conjugate holographic data storage with a buffer hologram

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We describe and demonstrate a volume holographic storage system in which a phase-conjugate object beam is reconstructed by the same reference beam that was used for recording. An intermediate hologram is used as a temporary buffer, recorded with its own reference beam and the data-bearing object beam. Reading this buffer hologram with the phase conjugate of its reference beam reconstructs the phase conjugate of the object beam, which can then be recorded into the desired volume hologram for long-term storage. This method combines the immunity to lens aberrations provided by phase-conjugate readout with the simplicity of using the same multiplexed reference beam for both recording and readout. Only a single pair of phase-conjugate reference beams is required. Experimental results are shown with a single $LiNbO_3$:Fe crystal used as both buffer and storage holograms and a self-pumped phase-conjugate mirror in $BaTiO_3$ that provides the pair of phase-conjugate reference beams. © 2000 Optical Society of America

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Volume holographic data storage is a topic of much recent interest[1–3] because it provides both high storage density and fast readout speed. Each hologram stores thousands of bits of data, encoded as two-dimensional data pages of bright and dark pixels. Multiple holograms are superimposed within a common volume and accessed independently with a suitable multiplexing technique. To achieve a low bit-error rate (BER) data pages must be carefully imaged from an input pixel array or a spatial light modulator (SLM), through a small volume of the holographic storage material, and onto an output pixel array (such as a CCD detector). This requires a short-focal-length lens system corrected for all aberrations (especially distortion) over a large field as well as a storage material of high optical quality.

Several authors have proposed bypassing this problem by using phase-conjugate readout of the volume holograms.[4–7] After the object beam is recorded from the SLM with a reference beam, the hologram is reconstructed with a phase-conjugate (time-reversed copy) of the original reference beam. The diffracted wave front then retraces the path of the incoming object beam, canceling out any accumulated phase errors. This procedure allows data pages to be retrieved with high fidelity with a low-performance lens, from storage materials fabricated as multimode fibers,[4,5] or even with no lens at all[6,7] for an extremely compact system.

The drawback to the phase-conjugate approach has been the need to multiplex holograms, requiring many matching pairs of phase-conjugate reference beams. If each pair is simply two carefully aligned counterpropagating beams, any deviation from a plane wave front or misalignment of wave vectors will be transferred to the reconstructed object beam. In addition, for angle multiplexing, both of these counterpropagating beams must also have beam steering. A self-pumped phase-conjugate mirror[8] (PCM) could be used to create a true phase-conjugate reference beam. However, for each new reference angle or wavelength the system would have to wait while the PCM reflectivity built up, decreasing either readout or recording speed. In addition, the presence of the third beam decreases modulation depth, reducing storage capacity.

In this Letter we describe a two-step recording process that combines the advantages of phase-conjugate holography with the simplicity of using the same multiplexed reference beam for recording and readout. As shown in Fig. 1, data to be recorded are modulated onto beam ① with the SLM and focused into a long storage crystal. This object beam travels down the crystal, confined by total internal reflection, and passes into a buffer crystal, where it interferes with beam ② and records a hologram. This hologram is then immediately read with beam ③, the phase conjugate of beam ②, reconstructing a phase-conjugate object beam that travels back into the storage crystal. This new object beam can now be recorded, and then later reconstructed, with beam ④ at one of the storage locations. This procedure permits all the same angle-, phase-code-, wavelength-, and spatial-multiplexing approaches that have been used for conventional volume holograms.[1,3]

We demonstrated this two-step recording procedure by using the experimental apparatus shown in Fig. 2.

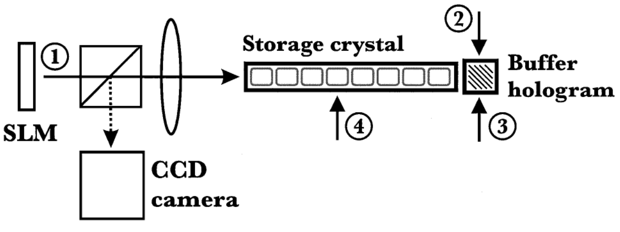

Fig. 1. Holographic system for multiplexing phase-conjugate holograms. A temporary buffer hologram is recorded by an object beam containing the data from SLM ① and a reference beam ②. This hologram is illuminated with phase-conjugate beam ③, reconstructing the phase conjugate of the original object beam, which is then stored permanently with spatial- and angle-multiplexed reference beam ④.

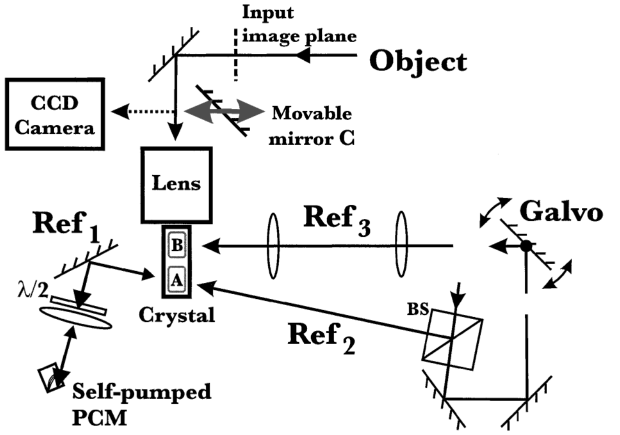

Fig. 2. Experimental setup for recording phase-conjugate holograms. A self-pumped PCM provides a pair of reference beams: Ref$_1$ is used to record the object beam in a temporary hologram (A); Ref$_2$, to read out its phase conjugate and record it in the storage hologram (B) with Ref$_3$.

Not shown are an Ar$^+$ laser (514.5 nm), the polarizing beam splitter that separates object and reference beams, and the collimation optics for each. In the object beam, a field of 320 × 240 pixels was demagnified by the zoom lens and custom 4-F optics from the DEMON holographic demonstration platform,[9] from the Epson SLM to the input image plane in Fig. 2 (18-μm pixel-to-pixel spacing). This object beam was then imaged by an $f/1.4$ Nikon camera lens ($f = 50$ mm) placed ~145 mm away into a 0.02% Fe-doped LiNbO$_3$ crystal (8 mm × 15 mm × 15 mm, $\alpha \sim 0.8$ cm^{-1}, c axis horizontal, at 45° to the faces). The second image plane, located at the letter A in Fig. 2 (no internal reflection), was 5 mm × 3.8 mm and contained 600 μW of power for a typical half-ON encoded data page.

A lens ($f = 100$ mm) was used to collect the 8.5-mm-diameter beam Ref$_2$ into a 2-mm-diameter spot on the 5 mm × 6 mm × 8 mm nominally undoped BaTiO$_3$ crystal (c axis horizontal) used as a self-pumped PCM.[8] Beam Ref$_2$ was horizontally polarized (ordinary) at the LiNbO$_3$ crystal and vertically polarized (extraordinary) at the self-pumped PCM. The system was used with 70 mW of power in beam Ref$_2$ before the LiNbO$_3$ crystal (37 mW after it). The PCM reflectivity saturated at ~27% within 20–30 s, providing a phase-conjugate reference Ref$_1$ of 10 mW. The LiNbO$_3$ was aligned such that the c axis suppressed the hologram between Ref$_2$ and the object beam.

To prove that this apparatus phase-conjugated the object beam, we recorded a hologram with a phase distorter (the plastic lid from a small box) wedged between the LiNbO$_3$ crystal mount and the Nikon lens. First beam Ref$_2$ was directed through the crystal for ~1 min to establish phase-conjugate reference beam Ref$_1$. Then a data page was displayed on the SLM, imaged with the DEMON optics to the intermediate image plane, and directed into the LiNbO$_3$ crystal as the object beam for 45 s. After mirror C on the far side of the Nikon lens was slid into the return path, the hologram was reconstructed by Ref$_2$, and the data page was detected pixel to pixel by a Pulnix TM6701AN CCD camera (640 × 480 pixels on 9-μm centers; alternate rows and columns were ignored[9]). We brought the image to focus and registered it by moving the CCD; magnification and rotation were optimized on system setup. Removing and replacing mirror C typically resulted in a misregistration of 5–10 CCD pixels. Figure 3 shows a portion of the pixel-matched data page, recorded and then reconstructed with high fidelity through the phase distorter.

To implement the transfer of this phase-conjugated object wave into a multiplexed stack of holograms we directed a third beam, Ref$_3$, into the front part of the crystal. Ref$_3$, containing 82 mW of power, was deflected by a galvo-mounted mirror into a cylindrical 2:1 telescope, resulting in a narrowed elliptical beam. After the buffer hologram was recorded at A with Ref$_1$ and the object beam for 45 s, both Ref$_2$ and Ref$_3$ illuminated the crystal for 45 s. Figure 4(a) shows the histogram of pixel values for a data page reconstructed from buffer hologram A; Fig. 4(b) shows the same data page after it was transferred to storage hologram B. Despite the broader intensity distributions in Fig. 4(b), the similarity in BER (extrapolated for a 6-bits-from-8-pixels demodulation decoder[9]) indicates that the local signal variations within code blocks are equally small for both holograms.

By changing the angle of Ref$_2$ and Ref$_3$, and rebuilding the phase-conjugate Ref$_1$, we could record a second data page into the buffer hologram and then transfer it into the stack of stored holograms at B. Four different data pages were multiplexed in this way, spaced by 0.02°. As expected, when the CCD was reregistered to one of these holograms, the other holograms were also registered and accessible simply by rotation of the galvo mirror.

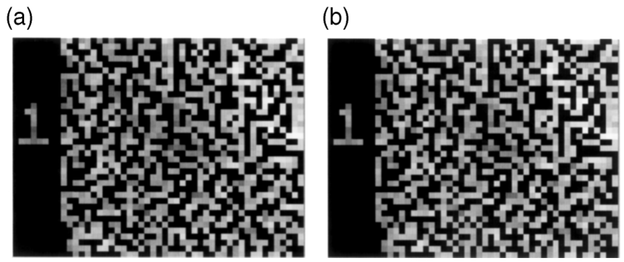

Fig. 3. Small sections of retrieved phase-conjugate holographic data pages. Page (a) was recorded and reconstructed through a phase distorter; page (b), without the phase distorter.

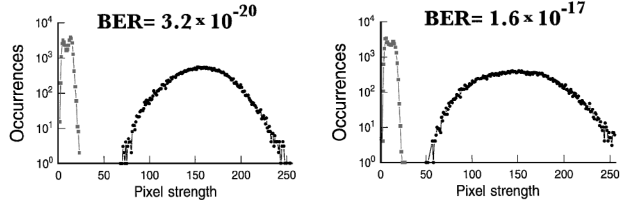

Fig. 4. Histogram of detected signal values for a pixel-matched data page, recalled (a) from the buffer hologram and then (b) after transfer into the storage hologram. η represents hologram diffraction efficiency.

Conventional single-color recording in $LiNbO_3$ has some undesirable properties for implementing the system shown in Fig. 1. These holograms erase during readout exposure, requiring a separate fixing operation. Increases in absorption would speed recording but limit the length of the storage crystal and thus the number of storage locations. Both the volatility and the absorption problems can be solved by use of two-color, gated volume holography in $LiNbO_3$ (see Ref. 10 and references therein). The object and reference beams use long-wavelength light (say, red or IR), which the crystal absorbs only in the presence of short-wavelength gating light (green). The storage crystal can then be made extremely long, the gating light used to activate storage locations, and stored holograms read out without erasure.

The buffer hologram also requires a material with high sensitivity, so each new data page completely and rapidly overwrites the previous one. However, dynamic range for multiple holograms, dark-storage lifetime, hologram thickness, and optical quality are less important and could be traded off during material optimization for more sensitivity (although low scattering and uniform spatial frequency response would still be needed). Erasure of the buffer hologram is preferably induced externally, with either an electric field or an incoherent erase beam. There are several read–write materials, including photorefractive polymers[11] and bacteriorhodopsin,[12] whose strengths and weaknesses fit well here.

As this technique for multiplexed phase-conjugate holograms records two holograms for each stored data page, it would seem inherently to slow down the recording process. However, once the diffraction efficiency of the buffer hologram exceeds the power efficiency of the original object beam (typically by 1–10%), the recording of the storage hologram is actually accelerated. In addition, as a result of overwriting the previous contents of the buffer hologram with the new data page, neither the buffer material nor its two reference beams ever move, and the PCM needs only to adapt to slow alignment drifts. Alternatively, the single phase-conjugate reference beam needed for the buffer hologram could be generated by careful alignment of a counterpropagating beam. This arrangement might have advantages over the self-pumped PCM, for example, in implementing the buffer hologram in a wavelength-multiplexed system.

In conclusion, we have described a novel holographic storage system that combines the advantages of phase conjugation with the multiplexing simplicity of recording and reading holograms with the same reference beam. A buffer hologram and a single pair of phase-conjugate reference beams serve to phase conjugate the object beam. Recording this buffer hologram in a highly sensitive but poorly retentive material such as a photorefractive polymer or bacteriorhodopsin permits rapid data input. Transferring the phase-conjugated object beam by two-color gated holography provides nonvolatility and large storage capacity. We implemented this idea with one-color $LiNbO_3$ as both the buffer and the storage holograms. High fidelity reconstruction of data pages onto a pixel-matched detector array was demonstrated, both through a phase distorter and after transfer of the phase-conjugated object beam into a stack of multiplexed holograms.

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