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Multiplexed phase–conjugate holographic storage using an intermediate buffer hologram

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1. ABSTRACT

Volume holographic storage combines fast, parallel readout (because each hologram stores a large data page) with high density (because many holograms are multiplexed within the same volume). Phase-conjugate readout has been proposed as a way to eliminate the precision optics that recent demonstrations have relied upon to image the pixels of the input spatial light modulator (SLM) onto those of the output detector array. However, hologram multiplexing with the phase-conjugate approach requires multiple pairs of phase-conjugate beams, which are extremely difficult to create and maintain.

We have developed a two–step recording process which combines the advantages of phase–conjugate holography with the simplicity of using the same multiplexed reference beam for recording and readout [1]. The data–bearing object beam first passes completely through a long storage crystal, and is then temporarily stored in a second holographic storage material. This "buffer" hologram is immediately read with a phase–conjugate reference beam, reconstructing a phase–conjugate object beam which travels back into the storage crystal. This new object beam can now be recorded, and then later reconstructed, with a multiplexed reference beam at any of the spatial storage locations. We describe the advantages and limitations of this technique, the materials requirements for the buffer hologram, and describe a test platform designed to implement this technique.

Keywords: phase–conjugate readout, volume holographic data storage

2. INTRODUCTION

In volume holographic data storage, data are input and output as 2–D pages of bright and dark pixels. These data pages, which can carry as many as one million bits of data [2], are stored as holograms in a thick photosensitive material. With appropriate multiplexing techniques, the interference fringes from many different pages can be superimposed in the same volume. Upon readout, the volume nature of the holograms suppresses undesired pages through Bragg–mismatch. This combination of multiplexing and parallel readout allows holographic data storage to provide both high storage density and fast readout speed.

In order to retrieve data with low bit–error–rate (BER), the system must be able to clearly distinguish between bright and dark pixels. However, optical energy intended for a given detector pixel tends to spread to neighboring pixels, either through diffraction or aberrations in the optical imaging system. When pushing the holographic system to high density, the volume dedicated to a 'stack' of superimposed holograms must shrink, making diffraction unavoidable. Aberrations can be minimized by careful design of the imaging path: from input spatial light modulator (SLM), through a small volume of the holographic storage material, and onto the output pixel array (such as a CCD detector). The need for both high density and excellent imaging 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.

3. PHASE–CONJUGATE READOUT

Several authors have proposed to bypass these problems by using phase–conjugate readout of the volume

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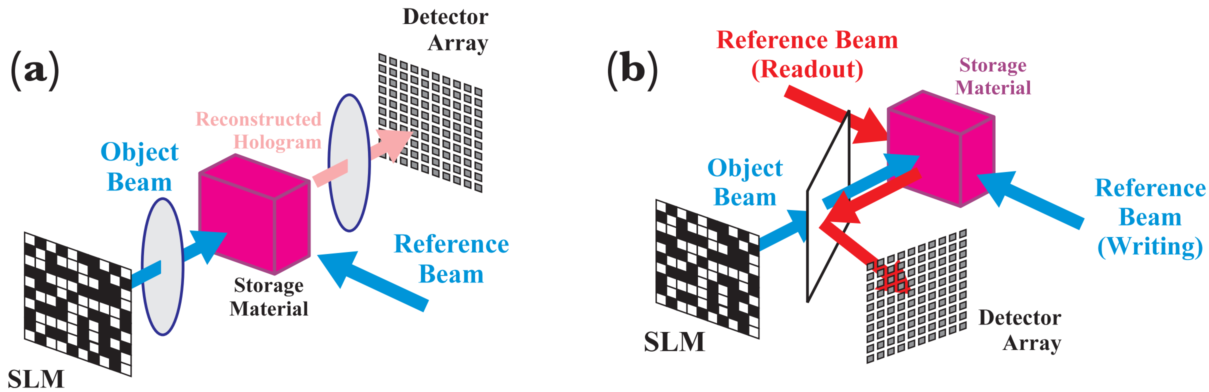

Figure 1: Holographic data storage systems: (a) conventional, and (b) using phase–conjugate readout.

holograms [3–6]. After recording the object beam 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 wavefront then retraces the path of the incoming object beam, canceling out any accumulated phase errors. This should allow data pages to be retrieved with high fidelity with a low–performance lens, from storage materials fabricated as multimode fibers [3, 4], or even with no lens at all [5, 6] for an extremely compact system. However, almost all large–scale holographic demonstrations [7–12] have avoided phase–conjugate readout in favor of precision lenses, often custom–made at great expense.

In the next section, we describe the advantages of phase–conjugate readout, as well as the disadvantages that have prevented its widespread use so far.

4. SYSTEMS TRADEOFFS IN PHASE–CONJUGATE READOUT

4.1 ADVANTAGES

The conventional holographic storage system, and the basic phase–conjugate system are compared in Figure 1. In the phase conjugate system, the detector array is moved from the far side of the storage material to the near side, and the reconstructed object beam is deflected away from the SLM and onto the detector with a beamsplitter. The advantages of phase–conjugate readout arise from the relaxation of engineering constraints associated with the imaging of the pixellated data page from SLM to the detector array. These include:

- **Fewer imaging optics**—If the pixel pitch on the SLM and detector array are identical, then the phase–conjugate holographic system does not require any optics at all. If the pixel pitches are not identical, then magnification optics will be required. These optics must be of high-quality, since they will not be retraced twice during the phase–conjugation process. However, the demands on these magnification optics are less stringent than in a conventional holographic storage system—although low aberrations are still required, the effective focal lengths can be larger, and a Fourier plane with large working distance around it is not required.

- **Tolerance to material quality and lens aberrations**—Because the phase–conjugate object beam is reconstructed back along its input path, any phase errors introduced by the common–path optics or the storage material itself will factor out. While this relaxes some constraints on fabrication and surface flatnesses/curvatures, this does not relax any demands on amplitude effects within the storage material such as striations, bulk scattering, or large scratches.

- **Use of a random phase mask**—Random phase masks are useful for spreading the optical energy in the object beam across the Fourier plane to avoid material saturation. In a conventional system, a random phase mask must be carefully aligned with the SLM—in a phase–conjugate system, however, the phase mask can be placed between the beamsplitter and the storage material without the need for careful alignment.

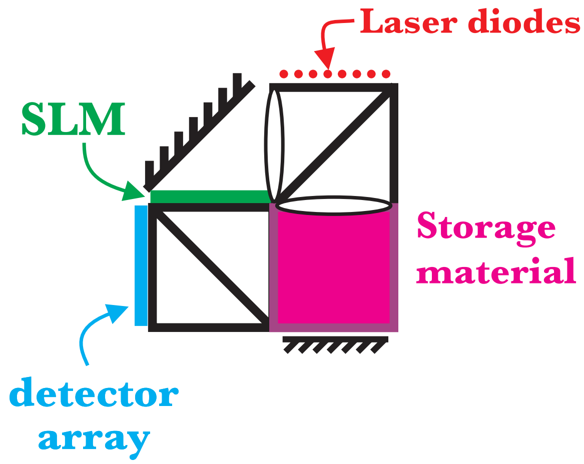

Figure 2: Compact phase–conjugate holographic memory (after Reference [6])

- **Compact system**—The ability to remove all lenses makes it possible to fabricate an extremely compact system. If a read–only platform is to be built, then the beamsplitter in front of the SLM and the detector array can be omitted.

- **Multiple storage locations**—A final advantage of phase–conjugate readout is its ability to reconstruct an object beam that would otherwise be beyond recall. For instance, the small crystal shown in Figure 1(b) can be extended along the direction of the incoming object beam, using total internal reflection to confine the object beam. This idea works best when the material absorption at the readout wavelength is low, as in two–color holographic storage in $LiNbO_3$ [13, 14]. In a conventional system (Figure 1(a)), it would be impossible to expect such a distorted object beam to be recognizable at the detector array at the far end of the crystal. With phase conjugate readout, however, the reconstructed object beam travels back down the crystal, replicating the total internal reflection, and exits the front face ready to be pixel–matched by the detector array. Such a configuration increases the number of stacks which can be accessed under a single laser/SLM/detector, thus increasing capacity manyfold without significantly increasing the cost of the system.

4.2 DISADVANTAGES

Despite these many advantages, phase–conjugate readout has not been implemented in any large–scale holographic storage system. This is because the advantages described above are more than balanced by several serious disadvantages, including:

- **Aligning the detector array and SLM**—In a conventional holographic storage system, one aligns the detector array to the SLM using a transmitted image at low power before recording any holograms. In the phase–conjugate system, it is impossible to know if the two pixel arrays are aligned until a hologram is recorded. This would seem to demand some loss of capacity just to ensure alignment.

- **Switching between writing and reading**—The beamsplitter in the object beam must be either implemented with a mirror or with a polarizing beam–splitter and computer–controlled waveplate. A mirror merely folds the optical system without distorting the reconstructed holograms, but is slow to move. In addition, for liquid–crystal SLMs, a polarizer of some type is required between the SLM and the storage medium (in order to turn the polarization modulation into amplitude modulation). This polarizer reduces the space available for the mirror, and becomes a component which is present in the forward path but not in the return path. In contrast, using a polarizing beamsplitter to direct the reconstructed object beam to the detector array also analyzes the incoming object beam modulated by the SLM. The beamsplitter can be switched to pass the return beam to the detector array by rotating the polarization between the beamsplitter and the storage media. Possible difficulties include the spatial frequency response (acceptance angle) of the polarization rotator and beamsplitter, and phase differences between the two states of the polarization rotator.

- **The phase–conjugation might be imperfect**—Any phase differences between the two reference beams used to store and then retrieve the holograms will either be transferred to the reconstructed object beam, resulting in an imperfectly phase–conjugated object beam, or will result in a loss of efficiency in reconstructing this object beam. The loss of efficiency is accompanied by a broadening of the angular selectivity, which implies the possibility of increased inter–page crosstalk between stored pages. Finally, even if the phase–conjugation is perfect at the time the hologram is recorded, the reference beams may drift out of perfect phase–conjugation, or the return path to the detector array might change (because of temperature changes, or the index changes associated with holograms stored in the material along this path) [15].

- **Multiplexing**—In order to superimpose multiple holograms within the storage material, it is necessary to multiplex by changing the reference beam in some way (typical methods include angle, wavelength, and phase code). In order to implement phase–conjugate readout, it would seem necessary to have many pairs of reference beams, and to maintain their phase–conjugation over long periods of time in order to access the stored holograms.

  This problem alone has been responsible for most of the lack of interest in phase–conjugate readout. One solution to this problem was proposed by Drolet et. al. [6], and is illustrated in Figure 2. In this system, a pair of beamsplitters sandwich the SLM and detector array next to a block of storage media (such as a photorefractive inorganic crystal). By storing and accessing one hologram for each laser diode, this system provides volumetric storage in an extremely compact and robust package. The use of phase–conjugation and the short distances involved allows the system designer to shrink the pixel size of the SLM and detector array [16], increasing the readout rate and storage capacity. The phase–conjugation, however, can only work if the the laser diodes and reflecting mirror are positioned extremely accurately. Other considerations for this geometry include the relatively low power output of currently available vertical–cavity surface–emitting laser diodes, and the system cost given the small amount of storage accessed by each set of expensive components.

5. SEPARATING PHASE–CONJUGATION AND LONG–TERM STORAGE BY USING A BUFFER HOLOGRAM

In this section we describe a two–step recording process which combines the advantages of phase–conjugate holography with the simplicity of using the same multiplexed reference beam for recording and readout. As shown in Figure 3, data to be recorded is modulated onto the object beam (1) with the SLM and focussed into a long storage crystal. The 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 which 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 permits all the same angle–, phase-code–, wavelength–, and spatial–multiplexing approaches used for conventional volume holograms [7, 8].

The buffer hologram technique still requires a pair of phase–conjugate reference beams, although only a single pair which do not need to ever change angle. In Section 6, we discuss methods for producing an accurate pair of phase–conjugate reference beams. In the remainder of this section, we discuss how the buffer hologram technique overcomes or reduces many of the conventional disadvantages of phase–conjugate readout.

5.1 CONVENTIONAL DISADVANTAGES REMOVED

- **Aligning the detector array and SLM**—The detector array can now be aligned to the hologram stored in the buffer material, allowing system alignment without reducing the capacity of the system.

- **Switching between writing and reading**— For the purposes of reasonable recording speed, the buffer hologram needs to have a high efficiency. Therefore the reconstructed phase–conjugate object beam return-

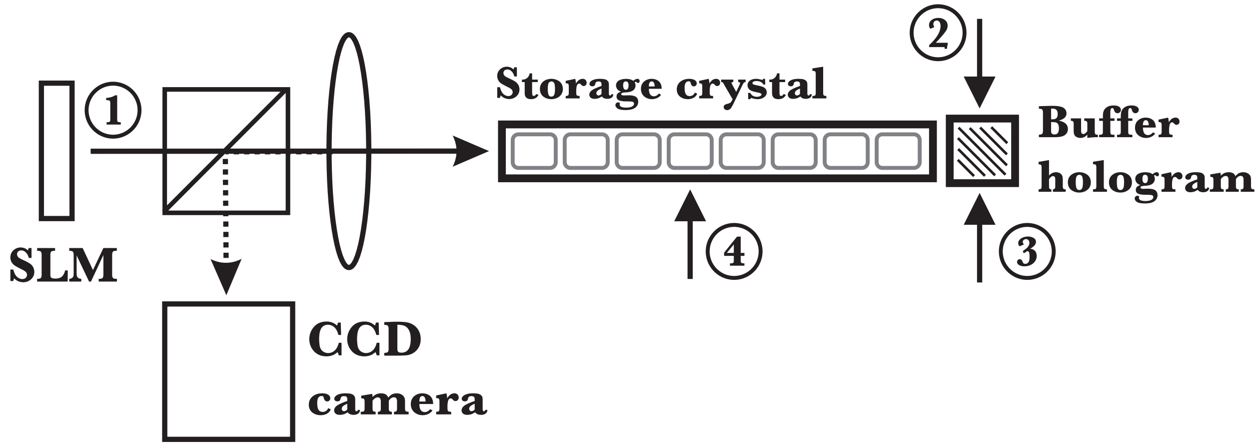

Figure 3: Phase–conjugate holographic storage system using a buffer hologram (after Reference [1])

ing from the buffer hologram towards the SLM will be quite strong. If just a small portion of this beam is deflected through the polarizing beamsplitter to the detector array, the data page can be monitored while the long–term hologram is being recorded.

This allows the use of predistortion [17] while writing the buffer hologram, to improve the signal–to–noise ratio of the data pages before they are transferred into the long–term storage crystal. When recording of holograms is completed, then the polarization of the reconstructed beam coming from the long–term storage crystal towards the beamsplitter can be rotated to allow the weak multiplexed holograms to fully illuminate the detector array.

- **The phase–conjugation might be imperfect**—The buffer hologram allows the use of a phase–conjugate mirror (PCM), as described in the next section. This provides the highly accurate phase–conjugation needed for high capacity data pages, and pushes the disadvantages of the PCM onto the buffer hologram instead of the long–term storage material.
- **Multiplexing**—As described above, any multiplexing technique can be used to store and retrieve holograms into the long–term storage crystal. The buffer hologram serves as a virtual SLM, producing the exact phase–and–amplitude pattern needed to produce a high–fidelity image back at the original SLM plane.

5.2 LIMITATIONS

Conventional single–color recording in $LiNbO_3$ has some undesirable properties as the long–term storage material in a phase–conjugate/buffer hologram system. 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 absorption problems can be solved by using two–color, gated volume holography in $LiNbO_3$ (see Reference [14] and references within). The object and reference beams use long wavelength light (say, red or IR) which the crystal only absorbs 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 that 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, either with electric field or an incoherent erase beam. There are several read–write materials whose strengths and weaknesses fit well here, including photorefractive polymers [18] and bacteriorhodopsin [19].

Since this technique for multiplexed phase–conjugate holograms records two holograms for each stored data page, it would seem to inherently slow down the recording process. However, once the diffraction efficiency of the

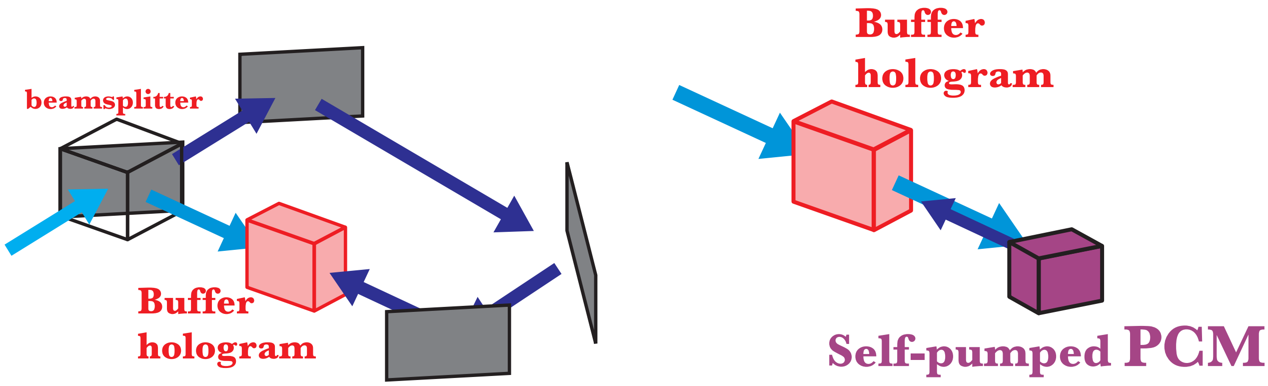

Figure 4: Methods for producing a pair of phase–conjugate reference beams for using a buffer hologram: (a) aligning two counter–propagating beams; (b) using a self–pumped phase–conjugate mirror.

buffer hologram exceeds the power efficiency of the original object beam (typically ∼1–10%), then the recording of the storage hologram is actually accelerated. In addition, by overwriting the previous contents of the buffer hologram with the new data page, neither the buffer material nor its two reference beams ever moves, and a PCM only needs 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 counter–propagating beam. This might have advantages over the self–pumped PCM, for example when implementing the buffer hologram in a wavelength–multiplexed system. In the next section, we discuss these two methods for creating the two phase–conjugate reference beams required.

6. CREATING PHASE–CONJUGATE REFERENCE BEAMS

Two methods have been discussed in the literature to produce pairs of phase–conjugate beams. The first involves carefully aligning two beams to be exactly counter–propagating and to have exactly opposite curvature, typically using a ring interferometer in which the storage medium sits in one arm (Figure 4(a)). The typical choice is to make both plane waves, since it is simple to measure the degree of collimation in the laboratory with an optical flat. The two beams are then aligned in the interferometer until the forward and reverse plane waves passing through the medium result in a minimum number of fringes at the exit of the interferometer. Other choices include aligning one converging and one diverging beam to have a common focus on one side of the storage medium, or using two gaussian beams whose waists coincide at the center of the storage media.

The impulse response of the hologram is the 3–D Fourier Transform of the overlap between the readout reference beam $\mathbf{R}$ and the writing reference beam $\mathbf{W}$ within the storage material. If the two are truly phase–conjugate, then the impulse response is the expected three–dimensional sinc function [20]. One of these dimensions describes the selectivity function (diffraction efficiency as reference beam angle is tuned), and the other two describe the effects of diffraction from the finite exit aperture on the expected output plane wave (which exactly opposes the "stored" object plane wave). If, however, $\mathbf{R} \neq \mathbf{W}^*$, then two effects would be expected: first, the angular (or wavelength) selectivity would be broadened and the diffraction efficiency at Bragg–match reduced. Second, the output point–spread function would be expected to be broadened and possibly shifted in the vertical direction, leading to blurring and shifting of pixels in the detected page (assuming holograms are stored in the Fresnel or Fourier geometry). For holograms stored in a Fresnel plane (near but not at the Fourier plane), this shifting and blurring can vary across the detected image. As a result, portions of a pixellated data page can be pixel–matched, but not the entire page, and overall BER even in the matching portions is poor. This effect was observed when attempting to pixel–match the 320 × 240 data pages described in Reference [15] with two counter–propagating plane waves.

In order to guarantee that the two reference beams $\mathbf{R}$ and $\mathbf{W}$ would be phase–conjugate, it is preferable to use a self–pumped phase–conjugate mirror [21], as shown in (Figure 4(b)). This has the advantage of providing a true phase–conjugate. For instance, we have shown that megapel pages can be stored and retrieved with low BER [22]. However, the phase–conjugate mirror has the disadvantage that the reflectivity of such a PCM is

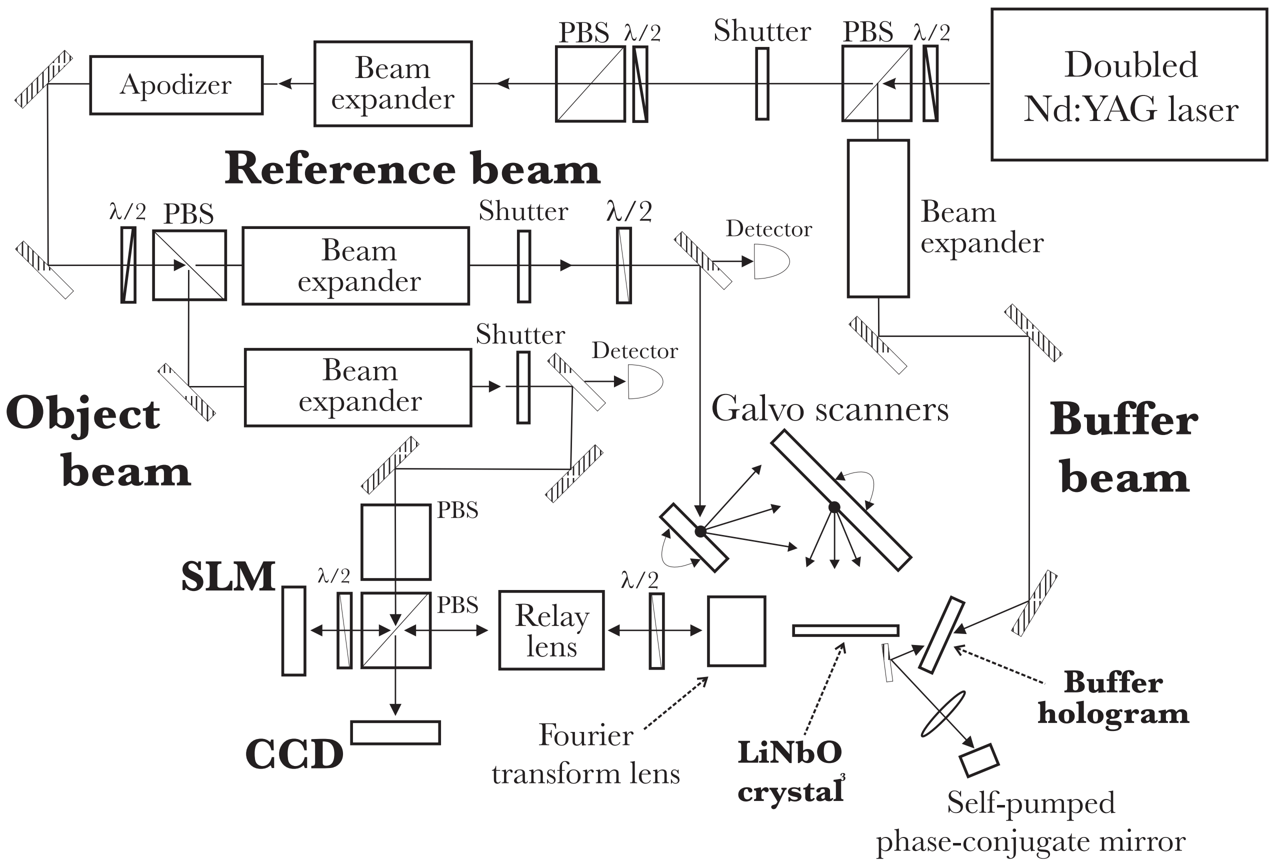

Figure 5: DEMON3 test platform for phase–conjugate multiplexed holographic data storage.

typically $\rho \sim 30\%$. [15]. In addition, in order to obtain the phase–conjugate from the self–pumped PCM, both **R** and **W** must be present in the holographic storage material at some point. If both **R** and **W** are present during recording, then there is a loss in modulation depth, and the possibility of an undesired grating written between the two reference beams. By optimizing the beam intensities, the decreased modulation depth can be seen to reduce diffraction efficiency by a factor of $\rho/(1+\rho) \sim 0.23$. If both **R** and **W** are present in the readout phase instead, then the loss of efficiency in using the conjugate beam to read is simply $\rho \sim 0.3$, and the write beam **W** will reconstruct a strong copy of the forward–propagating object beam in addition to the desired phase–conjugate object beam.

While the PCM appears, by itself, to solve many of the limitations of phase–conjugate readout described above, it could not be used to efficiently multiplex holograms without the buffer hologram. The reason is that every time the reference beam is changed to read or write the next multiplexed hologram, the phase–conjugate reflectivity of the PCM would need to build up, taking > 15 seconds even for 100mW of optical power. With the buffer hologram, the phase–conjugate beams produced by the PCM need only follow slow environmental changes. The one exception to this is if the long–term holograms are accessed via wavelength multiplexing—the slow response of the PCM is then felt even in the buffer hologram system.

7. DEMON3 HARDWARE PLATFORM

We are currently in the process of assembling a test platform called DEMON3, which is designed to evaluate the phase–conjugate/buffer hologram system. The optical layout is shown in Figure 5. A beam from a Coherent DPSS 532nm laser is expanded and split with various beam expansion optics to create three beams: an object beam for illuminating the SLM, a reference beam for conventional spatial– and angle–multiplexing, and a third beam for writing the buffer hologram. The SLM will be a 1024×768 reflective FLC (ferroelectric liquid crystal) device, and the CCD detector a 41Hz Dalsa camera with 1024×1024 pixels. These components were chosen for their identical pixel pitch of 12μm. A 1:1 relay lens delivers the SLM image to the input plane of a short–focal length Fourier tranform lens, which focusses the object beam into the 2×2mm^2 aperture of a long $LiNbO_3$:Fe bar (cut for the 90° geometry). The object beam expands out of the back end of the $LiNbO_3$ onto a thin buffer hologram material, initially to be a photorefractive polymer material. The phase–conjugate reference beam for the buffer hologram will be provided by a self–pumped phase–conjugate mirror in $BaTiO_3$ [1,21]. After the object beam is phase–conjugated, it will be stored in the long $LiNbO_3$ bar with the reference beam. A pair of galvo mirrors provides control over beam position along the bar as well as horizontal incidence angle.

Although we have already shown the phase–conjugate retrieval of megapel pages [22], this platform will allow us to repeat this experiment in the presence of significant total internal reflection of the object beam. We also expect to improve our understanding of the required specifications of the buffer hologram material, and to test the two–mirror spatial–multiplexing approach. The continual absorption of the long bar at 532nm prevents any attempt at high capacity using numerous holographic stacks. However, other planned experiments might include

- spatial multiplexing across the length (2") of the $LiNbO_3$ bar,
- verifying pixel matching with a cheap Fourier transform lens,
- attempting to achieve pixel–matching with a pair of aligned phase–conjugate reference beams, and
- attempting to successfully convey the object beam from one long bar to a second (and then back, without losing beam confinement). This would show that manufacturing limitations on crystal size would not necessarily limit the accessible crystal length in such a phase–conjugate/buffer hologram system.

8. CONCLUSIONS

In conclusion, we have described the systems tradeoffs involved with using phase–conjugate readout in holographic data storage. The use of phase–conjugate readout allows mapping of SLM pixels to detector pixels without custom imaging optics, but has conventionally been impossible to implement in a practical system. A novel holographic storage system was described which 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 allows rapid data input. Transferring the phase–conjugated object beam using two–color gated holography provides non-volatility and large storage capacity. We described two different methods for generating the two phase–conjugate reference beams needed to write and then read a single phase–conjugate hologram. Finally, we described a test platform built to evaluate this concept.

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