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Pixel–matched phase–conjugate readout for holographic data storage

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1. ABSTRACT

We demonstrate one-to-one pixel–matching of phase–conjugate digital volume holographic data storage, with data pages as large as a megapel (1024 × 1024 pixels). A self–pumped phase–conjugate mirror in $BaTiO_3$ is used to provide a phase–conjugate reference beam, which reconstructs the data–bearing object beam from a $LiNbO_3$:Fe crystal using the 90° geometry. The systems tradeoffs of phase–conjugate readout are described, and two methods of generating phase–conjugate reference beams are described and compared.

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 [1], 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 holograms [2–5]. 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 [2, 3], or even with no lens at all [4, 5] for an extremely compact system. However, most researchers have relied on visual quality of retrieved images or detection of isolated fine structure in resolution targets as proof that phase–conjugate retrieval provides high image fidelity.

In this paper, we discuss some of the advantages and disadvantages of phase–conjugate readout, and report successful pixel–matching of digital holographic data pages, both through a phase aberrator and with data pages containing 1 million pixels. Pixel–matching, where each of the spatial light modulator (SLM) pixels is mapped directly onto a single detector pixel, is an extremely sensitive measure of imaging fidelity. Any errors in rotation, focus, x-y registration, magnification, or residual aberrations will rapidly increase the measured bit-error-rate (BER) for the data page.

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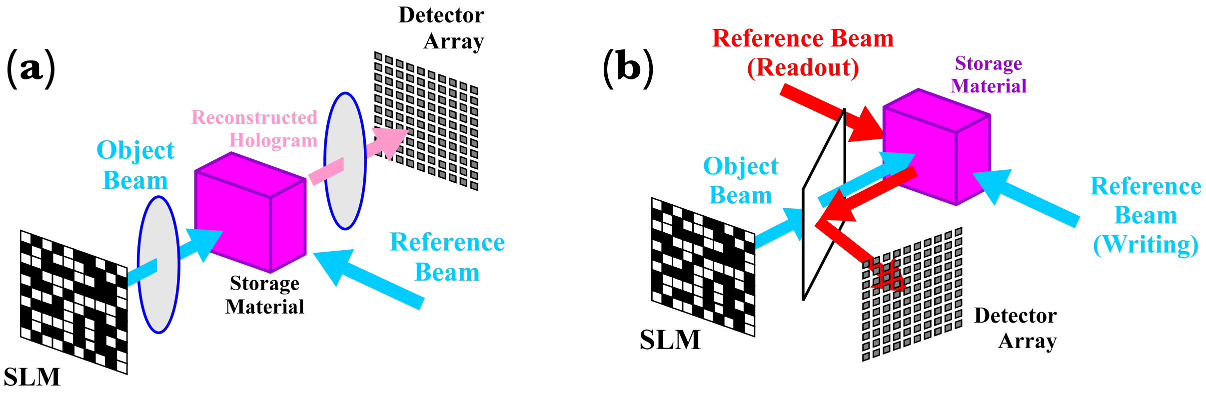

Figure 1: Holographic data storage systems: (a) conventional, and (b) using phase–conjugate readout.

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. The detector array, which normally sits on the far side of the storage, is brought 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

- **Less 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. However, the demands on these 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**—Because the phase–conjugate object beam is reconstructed back along its input path, any phase errors introduced by the storage material itself will factor out. While this relaxes some constraints on fabrication and surface flatnesses, this does not relax any demands on amplitude effects within the storage material such as striations or bulk scattering.

- **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 contrast, in a phase–conjugate system the phase mask can be placed between the beamsplitter and the storage material without the need for careful alignment.

- **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 used to direct the reconstructions to the detector array can also 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 $LiNbO_3$ [6,7]. 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

Balancing these advantages are several disadvantages, which include:

- **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 voltage–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**—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).
- **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.

Although this latter problem would appear to be a show–stopper for phase–conjugate readout, we believe that a solution is in the works. In this paper, however, we concentrate on the fidelity of the phase–conjugation: in the next section, we discuss methods for creating two phase–conjugate reference beams. In the remainder of the paper, we show experimental results using one of these methods and demonstrate pixel–matching of phase–conjugate holograms.

4.3 CREATING PHASE–CONJUGATE REFERENCE BEAMS

Two methods have been discussed in the literature to demonstrate phase–conjugate readout of holographic data storage. 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. 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 [8]. 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 is exactly what we observed when attempting to pixel–match the 320 × 240 data pages described in Section 6 with two counter–propagating plane waves.

In order to guarantee that the two reference beams **R** and **W** would be phase–conjugate, we decided to use a self–pumped phase–conjugate mirror (PCM) [9]. This has the advantage of providing a true phase–conjugate, but has the disadvantage that the reflectivity of such a PCM is typically $\rho \sim 30\%$. 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. A final factor to consider with the PCM is that, when the reference beam is changed to read or write the next multiplexed hologram, the phase–conjugate reflectivity of the PCM must build up, taking > 15 seconds even for 100mW of optical power.

As above, while these drawbacks would *seem* to be showstoppers, we are not particularly worried about them here. Instead, in the remainder of the paper, we verify that the fidelity of the phase–conjugate mirror is sufficient to reconstruct a high–fidelity object beam, as measured by pixel–matching onto the detector array.

5. PHASE–CONJUGATE PIXEL–MATCHING THROUGH AN ABERRATOR

We first demonstrated pixel–matched phase–conjugate readout using the experimental apparatus shown in Figure 2. Not shown is the Ar^+ laser (514.5nm), the polarizing beamsplitter separating object and reference beams, and 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 [10], from the Epson SLM to the input image plane in Figure 2 (18μm pixel-to-pixel spacing). This object beam was imaged by a f/1.4 Nikon camera lens (f=50mm) placed ~145mm away into a .02% Fe–doped $\mathrm{LiNbO_3}$ crystal ($8\times15\times15\mathrm{mm}^3$, $\alpha \sim 0.8\mathrm{cm}^{-1}$). The second image plane within the crystal was $5\times3.8\mathrm{mm}^2$ and contained 600μW of power for a typical half–ON encoded data page.

The $\mathrm{LiNbO_3}$ crystal was cut for the 90° geometry (**c**–axis horizontal, at 45° to the faces). A lens (f=100mm) was used to collect the 8.5mm diameter **R** beam into a 2mm diameter spot on the $5\times6\times8\mathrm{mm}^3$ nominally–undoped $\mathrm{BaTiO_3}$ crystal. The **c**–axis of the $\mathrm{BaTiO_3}$ crystal was horizontal and parallel to the $6\times8\mathrm{mm}^2$ entrance face, creating the necessary conditions for a cat–conjugator [9]. **R** was horizontally polarized (ordinary) at the $\mathrm{LiNbO_3}$ crystal, and vertically polarized (extraordinary) at the self–pumped PCM. The system was used with 70mW in beam **R** before the $\mathrm{LiNb0_3}$ (37mW after). The PCM reflectivity saturated at ~27% within 20–30 seconds, providing a phase–conjugate reference **W** of 10mW. The orientation of the **c**–axis of the $\mathrm{LiNbO_3}$ (from lower left to upper right in Figure 2) was roughly orthogonal to the grating vector between **R** and the **Object** beam, making the hologram between **W** and the **Object** beam much stronger despite the 7:1 difference in incident power.

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 $\mathrm{LiNbO_3}$ crystal mount and the Nikon lens. Beam **R** was first directed through the crystal for ~1 minute to establish the phase–conjugate reference beam **W**. Then a data page was displayed on the SLM, imaged with the DEMON optics to the intermediate image plane, and directed into $\mathrm{LiNbO_3}$ crystal as the **Object** beam for 45 seconds. After sliding the mirror on the far side of the Nikon lens into the return path, the hologram was reconstructed by **R**, and the data page detected pixel-to-pixel by a Pulnix TM6701AN CCD camera (640×480 pixels on 9μm centers, alternate rows and columns are ignored [10]). The image was brought to focus and registered by moving the CCD; magnification (and rotation) were optimized upon system

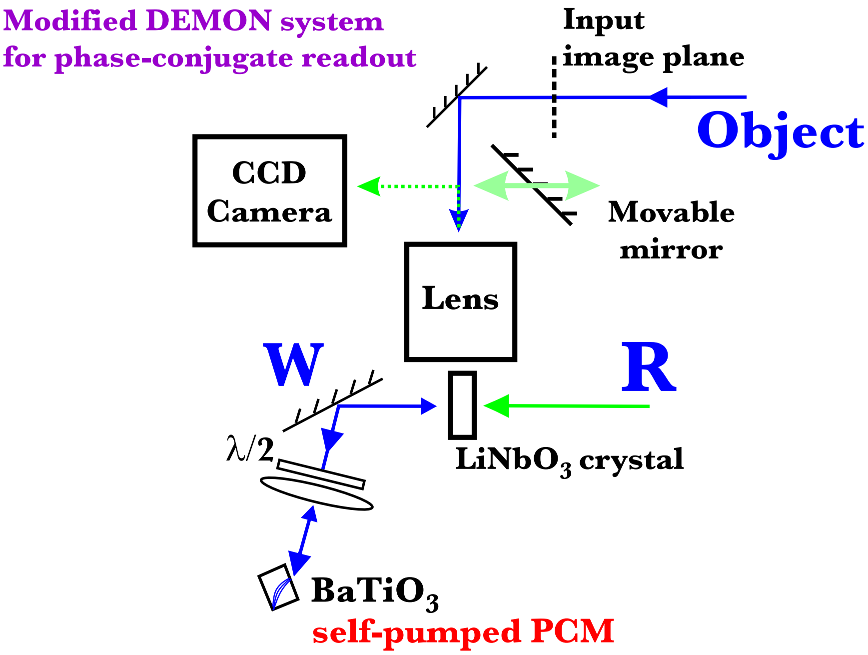

Figure 2: Modified DEMON platform, used to implement pixel–matched phase–conjugate readout of data pages containing 320 × 240 pixels.

setup with the DEMON optics (and SLM rotation). Removing and replacing the movable mirror typically resulted in a misregistration of 5–10 CCD pixels.

Figure 3(a) shows a portion of the pixel–matched data page recorded and then reconstructed with high fidelity through the phase distorter. Figure 3(b) shows the same portion of the data page when the same hologram is reconstructed without the phase distorter in place. In Figure 3(c), the phase distorter was replaced (imperfectly), resulting in roughly the same optical path length between $LiNbO_3$ and detector array but a different phase distribution. This shows that the poor fidelity of Figure 3(b) was partly due to the change in phase distortion (thickness variations of the plastic lid), and partly due to defocus (average thickness). Finally, in Figure 3(d), a second hologram was recorded and reconstructed without the phase distorter, showing excellent fidelity again.

6. PHASE–CONJUGATE PIXEL–MATCHED MEGAPEL

In this section, we describe successful pixel–matching of '1 megapel' holograms, containing 1024 × 1024 pixels on 9mum centers, read out with a phase–conjugate reference beam. In 1997, we achieved pixel–matching for 1 megapel holograms using the custom imaging optics on our 'PRISM' teststand [1]. Here we use the same teststand with the imaging optics removed to implement phase–conjugate pixel–matching over a 1 megapel data page. As we show here, phase–conjugation allows a 30–fold increase in areal density per hologram over the results of Reference [1].

Figure 4 shows a simplified diagram of the Prism tester. The custom lenses, which form a 4–F system to image the SLM (chrome-on-glass mask) onto the scientific CCD camera, were removed. The vertically–polarized object beam was focussed by a lens (f = 175mm) before the SLM through the megapel mask (9 μm pixels with 25% areal fill factor) onto a mirror (diameter 2in) placed halfway between the SLM and CCD. After deflection by this mirror, the object beam was collected by a Nikon f/1.4 lens, forming an image plane of the mask. Here a $8 \times 15 \times 15$ mm^3 $LiNbO_3$ crystal was placed, doped with .02% Fe and cut for the 90° geometry. The reference beam was a plane wave of elliptical cross–section, 3mm wide by 15mm tall. After passing through the crystal, the reference beam polarization was rotated from vertical to horizontal, and a lens (f=100mm) was used to collect the beam into a 1.5mm × 8mm spot on the $5 \times 6 \times 8$mm^3 nominally–undoped $BaTiO_3$ crystal. The c–axis of the $BaTiO_3$ crystal was horizontal and parallel to the 6×8mm^2 entrance face, creating the necessary conditions for a cat–conjugator [9]. The c–axis of the $LiNbO_3$ was oriented such that the return beam from the cat–conjugator wrote the hologram, and the strong incoming beam was used for readout with the $BaTiO_3$ crystal blocked and the center mirror was turned 90°.

Figure 5 shows a histogram of detected pixel values after the camera position and rotation was optimized. With

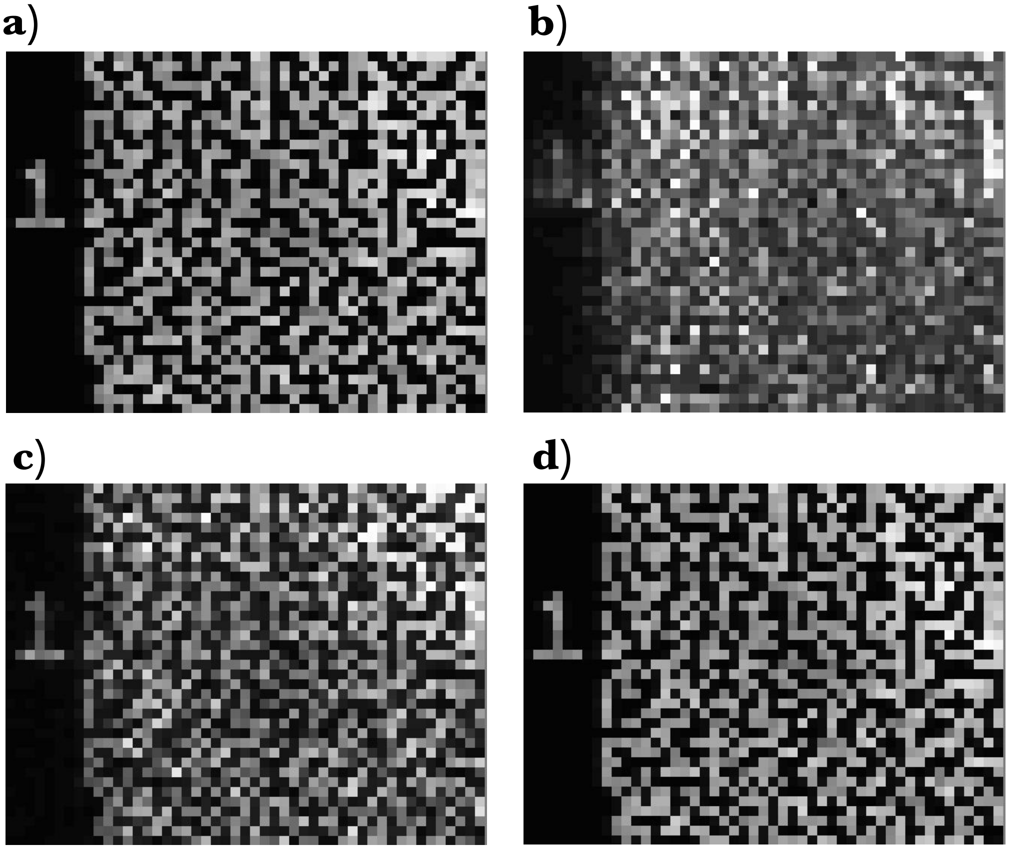

Figure 3: Modified DEMON platform, used to implement pixel–matched phase–conjugate readout of data pages containing 320 × 240 pixels.

a single global threshold, there were 477 errors (BER $\sim 5 \times 10^{-4}$) The experiment was repeated with a square aperture of 2.4mm on a side placed in the object beam at the $LiNbO_3$ crystal, resulting in 670 errors. Even with the large spacing between SLM and CCD, this is already an areal density of 0.18 bits per μm^2 per hologram. In contrast, in Reference [1], the entire clear aperture of 14 × 14 mm^2 and the custom optics were needed to produce low BER.

7. CONCLUSIONS

In conclusion, we have described some of the systems tradeoffs involved with using phase–conjugate readout in holographic data storage. We have described two different methods for generating the two phase–conjugate reference beams needed to write and then read a single phase–conjugate hologram. Finally, pixel–matching of digital holographic data pages was demonstrated in the presence of a phase aberrator, and with data pages of 1024 × 1024 pixels. The use of phase–conjugate readout allows mapping of SLM pixels to detector pixels without custom imaging optics, and for the megapel provides an improvement in areal density (at the entrance aperture of the storage material) of more than 30.

8. REFERENCES

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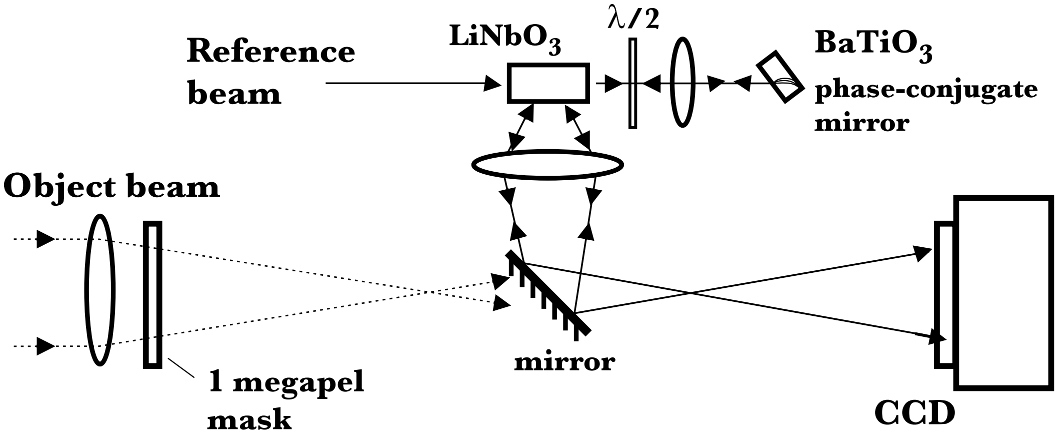

Figure 4: Modified IBM Prism test-stand, used to implement pixel–matched phase–conjugate readout of data pages containing 1024 × 1024 pixels.

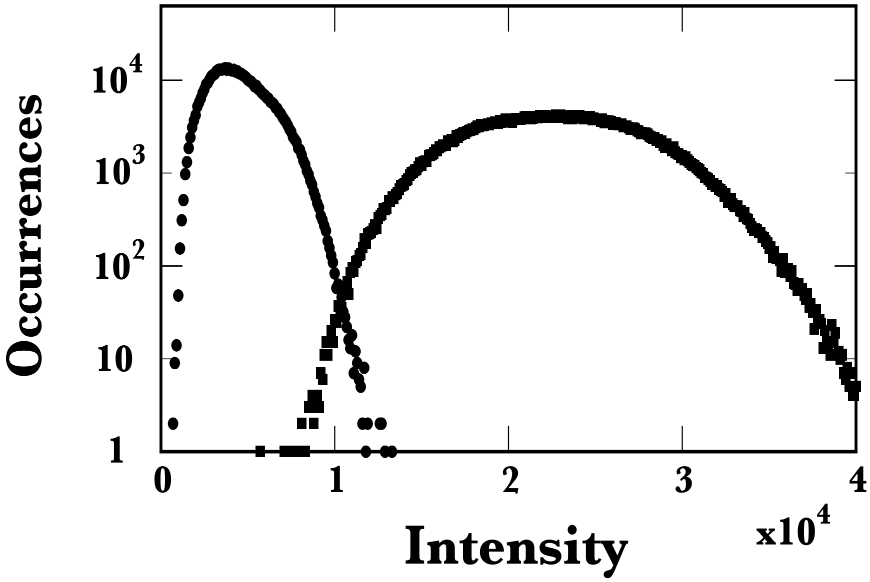

Figure 5: Histogram of received data values for data page, containing 477 errors with a single global treshold (BER $\sim 5 \times 10^{-4}$)

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