The Pixel Size Limit for A Holographic Memory System

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ABSTRACT

Compact holographic memory architecture with phase conjugate readout and diffraction suppression by internal reflection is investigated. The pixel size requirement for a competitive system is determined. The bandwidth of the holographic recording in $LiNbO_3$ is broad enough to support the pixel size requirement by theoretical calculation and experimental measurement. Holograms of 1 μm^2 pixel size binary data are recorded and reconstructed with this system. The pixel size limit, signal noise ratio (SNR) and the storage density for holographic recording in photorefractive crystals are discussed.

Keywords: Holographic memory, pixel size, bandwidth, phase conjugate

1. INTRODUCTION

With the development of the personal computer and the internet over the last few decades, people are able to store, retrieve and process more and more information easier and faster. All these benefits inspire the requirement of faster, smaller and cheaper data storage technology. Semiconductor and magnetic storage have been and will continue to be the driving forces for memory technology development. The semiconductor and the hard drive industries have continued delivering larger memory capacity with lower price by increasing aerial storage density. Today with the advanced giant magneto resistor (GMR) head, the magnetic disk has reached 14 Gbits/inch^2, or 22 bits/μm^2 [1]. The semiconductor industry has maintained an average 10.5% per year reduction rate in the feature size throughout its history and is projected to reach 25 bits/μm^2 in 2006 [2].

Holographic memory system is a potential competitive storage technology with the advantages of larger storage density and lower cost than the DRAM technology, and shorter page-wise access time than the bit-wise magnetic storage. With a photorefractive crystal sitting on top of a silicon chip, pages of data are stored in and retrieved from the crystal as holographic images. The silicon device with detector array works as the interface to transform the holograms into electronic signal, with similar microelectronics as the DRAM technology, which leads to the same data-accessing rate. With the advantage of large number of holograms and the sacrifice of smaller aerial density per page, we expect to store more data in a holographic memory system than a traditional DRAM with comparable silicon area and price. Therefore the pixel size of the SLM and detector array and the number of data pages in a holographic memory system determine the volume density and the cost per megabyte, which are essential for building a commercial competitive system comparing with the mature DRAM technology.

We consider the simple phase-conjugate holographic memory module as shown in figure 1. M pages of N by N binary pixels, which gives a capacity of MN^2 bits are recorded in a crystal of volume $(Nb)^3$, where b is the dimension of the pixel size in spatial light modulator (SLM) and the pixel matched detector array. The cost of the system is dominated by the silicon devices, which is proportional to the silicon area $(Nb)^2$. Therefore, the cost per megabyte of the system will be proportional to $\frac{b^2}{M}$, and the volume density $\propto$ $\frac{M}{b^3 N}$. With larger M/b^2, the system has larger storage density and lower cost.

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The number of multiplexed pages M is principally limited by the dynamic range of the material M/#, the sensitivity and integration time of the detector, and the limited photon budget during reconstruction. The diffraction efficiency of each page with N^2 bits is $\left(\frac{M/\#}{M}\right)^2$, and the diffraction efficiency for each bit will be $\frac{(M/\#)^2}{M \cdot C}$, where the storage capacity $C=MN^2$ bits. Increasing M will decrease the photon budget for each bit, increase the requirement for the detector sensitivity and the laser power, and complicate the multiplexing techniques. To increase the ratio M/b^2, it is preferred to scale down the pixel dimension b.

In the following sections, we discuss the criteria for the pixel size to have a holographic memory system competitive with DRAM technology and the limiting factors for the pixel size in a holographic memory system. In section 4, we present our experiment results, and draw the conclusion to the challenge to the technologies on implementing a competitive holographic memory system.

2. COMPETITIVE PIXEL SIZE

To study the competitive requirement of the holographic memory system, we consider the simple holographic memory model in figure 1, which consists of an SLM and a pixel matched detector array, a cubic photorefractive medium and some optical elements. The holograms can be angle-multiplex with a laser diode array, or wavelength multiplexed with a tunable laser. Comparing with the DRAM of the same silicon area, we consider the cost of the holographic system consists of the silicon electronic fabrication plus a same amount for the SLM and other optical elements. Therefore, the cost per bit ratio of the holographic memory to the DRAM is $\frac{2b^2D}{M}$, where the DRAM aerial density D is 25bits/μm^2 as projected. To be commercially competitive, we expect to have the cost one order of lower than the DRAM technology. For storage of M=1000 pages of data, this criteria leads to the pixel dimension $b < 1.5$ µm.

The number of pages M is estimated to be 1000 for a practical memory system. Consider a holographic storage capacity C=100 Gbits in a photorefractive crystal of dynamic range M/10, and a 0.5 µm laser of power 0.5 W. The diffraction efficiency for each bit is $10^{-9}/M$. For M=1000, this means 1 photon/µs for each bit during reconstruction. Larger M will only increase the requirement of the detector sensitivity and the laser power, and induce larger noise-signal ratio. If the pixel size b increases by a factor of 2, M has to increase by factor of 4 to keep the storage density. Therefore it is crucial to keep the pixel size b down.

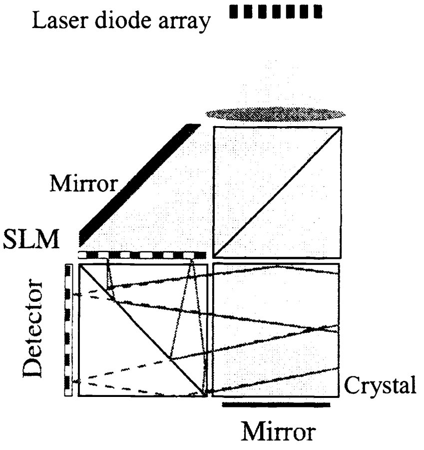


Figure 1. The compact phase-conjugate holographic memory module.

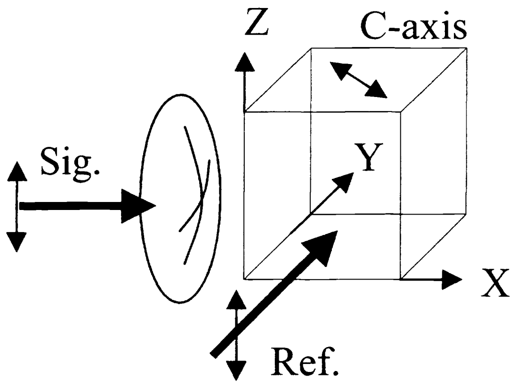


Figure 2. The 90 degree recording structure.

3. THE LIMITS FOR PIXEL SIZE IN A HOLOGRPAHIC MEMORY SYSTEM

To achieve pixel size b< 1.5 μm, we have to study the factors that limit the smallest size for the holographic pixels to be recorded and reconstructed. They are the diffraction limit, the resolution of the imaging system, the recording bandwidth of the material and the physical fabrication of the detector and SLM.

1. The diffraction limit

Due to the light diffraction, as the pixel size decreases, the system volume and the lens aperture have to be increased to contain the main lobe of the diffraction pattern from the SLM. This in turn increases the system volume. It has been shown [3,4] that to maximize the whole system volume density, the pixel size has an optimal value from 2 to 6 μm depending on the system architecture.

For the phase-conjugate readout architecture, the diffraction limit can be overcome. The recording medium can be used as a waveguide to contain all the signal diffraction lobes within the recording medium. The internal reflected signal beams are recorded and can be reconstructed constructively by the phase conjugate readout.

2. The resolution of the imaging system

For an either image plane or Fourier plane holographic system, the imaging system resolution determines the smallest physical size of the each pixel that can be resolve with acceptable SNR. For pixels with dimension b<1.5μm, the imaging lens F/# has to be smaller than 1.5. With the added requirement of pixel matching between the SLM and detector array, such imaging systems increase the cost of the holographic system.

For the phase conjugate readout architecture, the imaging system is removed due to the self-focusing of the phase conjugate signal. It decreases the system volume and increases the cost efficiency, and more importantly removes the resolution limits for the pixel size.

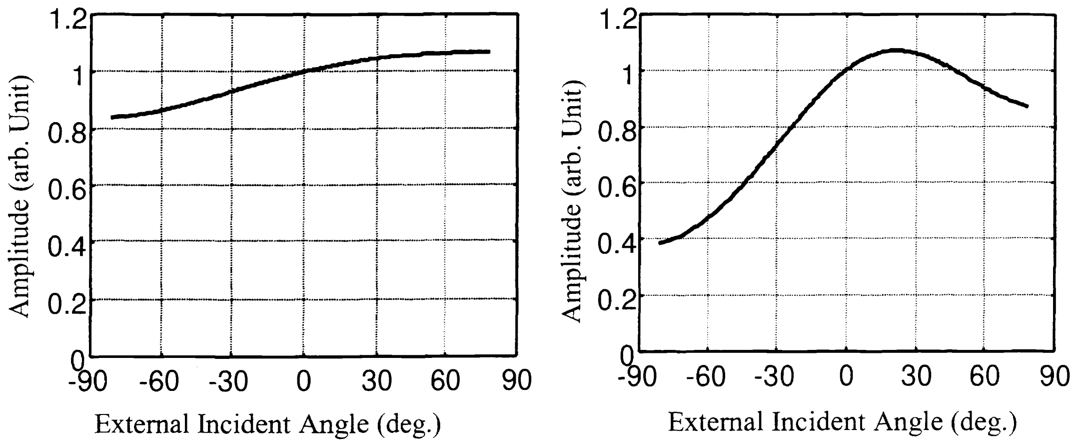
3. The recording bandwidth of the photorefractive crystal

The pixel size of the SLM determines the spatial frequency range of the signal beams. Due to the angle dependent recording efficiency in the crystal, the bandwidth of the recording medium determines the maximum spatial frequency, or the minimum feature size that can be recorded and reconstructed.

We investigated the angle dependent recording efficiency [5] in the 90-degree geometry for $LiNbO_3$, as shown in figure 2. The crystal is cut along 45 degree with c-axis along direction (1, -1, 0). The signal beam comes into the crystal with wave vector (k_x, k_y, k_z), where $k_x^2+k_y^2+k_z^2= k_0^2 =(2\pi/\lambda)^2$, and polarization along $\left(-\frac{k_x k_z}{k_0\sqrt{k_x^2+k_y^2}}, -\frac{k_y k_z}{k_0\sqrt{k_x^2+k_y^2}}, \frac{\sqrt{k_x^2+k_y^2}}{k_0}\right)$. The reference beam comes into the crystal with wave vector (0, k_0, 0) and polarization (0, 0, 1).

Due to the signal spatial frequency k_y, the grating vector will be tilted relative to the c-axis and the grating period is different as the signal beam rotates in the X-Y plane while the polarization direction keeps the same as the reference along the (0, 0, 1) direction. This leads to different recorded grating strength due to the strong photovoltaic effect and different grating periods, and consequently various reconstruction efficiencies. Figure 3 (a) shows the result of the reconstruction efficiencies as a function of the signal spatial frequency k_y as k_z=0.

As for various signal spatial frequency k_z, in addition to the tilting of the grating vector and the grating period, the polarization of the signal will not keep the same as the reference beam, which will decrease the modulation depth and the effective photorefractive coefficients. This leads to non-symmetric recorded grating strength and different reconstruction efficiencies as a function of signal spatial frequency k_z, as shown in figure 3 (b) for k_y=0. The theoretical simulation result indicates that the bandwidth of the recording medium is very broad and can record the spatial frequency as broad as pixel size of submicron with wavelength 0.5 μm.



(a) (b)

Figure 3. The holographic recording and reconstruction amplitudes in 90-degree geometry as a function of the signal incident angle: (a) in the signal-reference plane; (b) out of the signal-reference plane.

4. The physical fabrication of the SLM and the detector array

The current commercial SLM and detector array have the feature size as small as 5 μm, which is much larger than the competitive pixel size 1 μm required for a holographic memory. One solution is the use of an imaging system to scale down the image when recording into the medium, and to magnify the reconstructed signal from the crystal. However, this sacrifices the simplicity, cost efficiency and feasibility of the holographic memory system.

The instinctive solution and technical challenge is to develop SLM and pixel matched detector array with pixel size down to 1 μm. By theoretical simulation on liquid crystal (LC), it is shown that the LC SLM has contrast ratio of 21:1 to 7:1 as the pixel size scaling down to 1 μm [6]. Another potential alternative is to fabricate micro-mirror array on silicon directly. As to the detector, the main concerns for small sensor cells are the sensitivity and the noise level, which is opt to future studies.

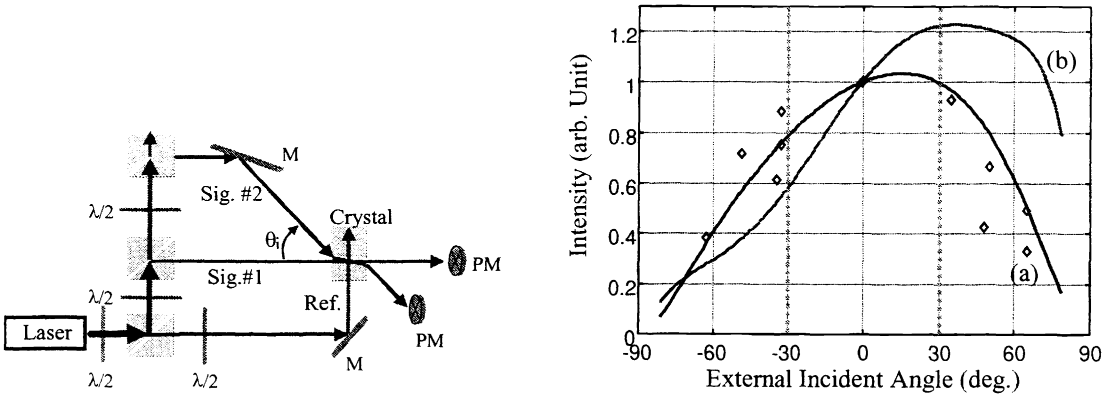
4. EXPERIMENTAL RESULTS

In the following, we present the experiment results of measuring the recording and reconstruction bandwidth of $LiNbO_3$ in 90 degree geometry, and the demonstration of recording and the phase conjugate reconstruction small pixels down to 1x1 μm^2.

1. The recording and reconstruction bandwidth in the signal-reference plane

With a $LiNbO_3$ crystal in 90-degree geometry as shown in figure 4 (1), we have the reference beam and two-signal beam with different incident angle into the crystal during recording. The normal incident signal beam #1 is used as reference. The intensity of the signal beam #2 is adjusted to have same intensity inside the crystal as the signal beam #1. The two signal beams are recorded and reconstructed at the same time. The reconstructed intensity ratio of signal beam #2 relative to signal beam #1 is measured as a function of the signal #2 incident angle.

The experiment results are shown in figure 4 (2). Also shown are the theoretical simulation of the recording and reconstruction efficiency as functions of the signal spatial frequency k_y, k_z with consideration of both the angle dependent recording and reconstruction and the interface reflection losses. The experiment results are consistent with the simulation function of spatial frequency k_y in the plane of signal and reference beams. Again it confirms the width bandwidth to be able to record feature sizes as small as 1 μm.



(1)

(2)

Figure 4: (1) Experiment setup for measurement of the angle dependent holographic recording and reconstruction efficiencies. M: mirror, PM: power meter, λ/2: half wavelength plate. (2): (a) the measurement data and the theoretical calculations of holographic efficiency in the signal reference plane; (b) the theoretical calculations of the holographic efficiency out of signal reference plane. The signal angle range -30 to 30 degree shows the bandwidth requirement for 1 μm pixel size.

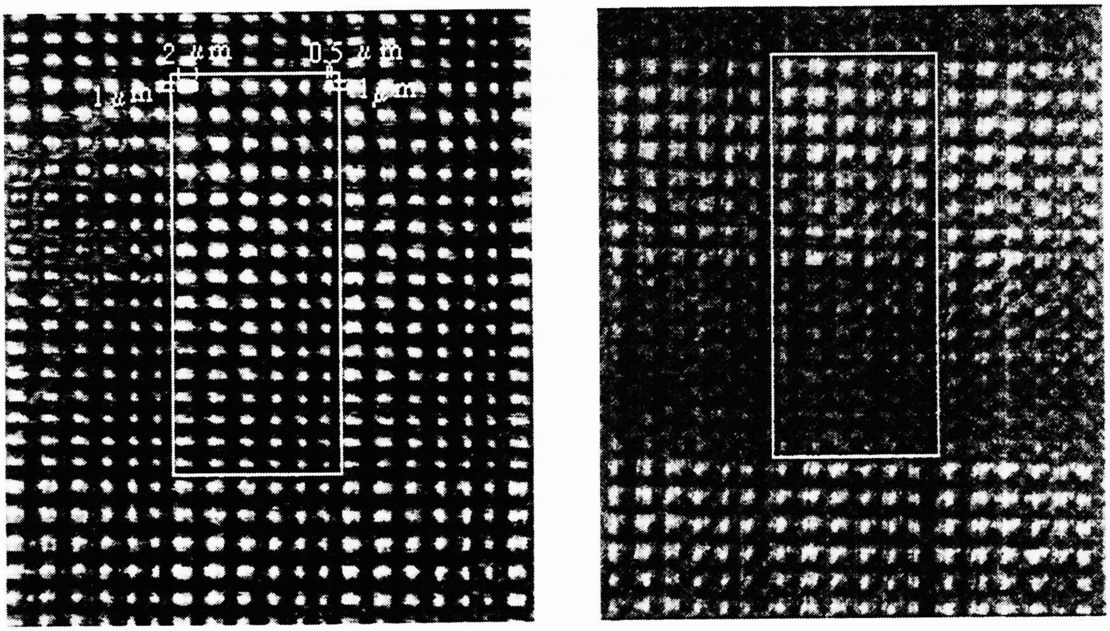
2. The recording and reconstruction of the sub-micron feature sizes.

A photo mask with various feature sizes from 2x1 μm^2 down to 0.3x0.3 μm^2 is used to record holograms in the $LiNbO_3$ crystal as shown in figure 5 (a). The phase conjugate reconstruction as shown in figure 5 (b) illustrates that the feature sizes from 2x1 down to around 0.7x0.7 μm can be recovered distinguishably. This confirms the bandwidth effect of the crystal recording.

Photo masks of 1x1 μm^2 random binary pixels are used to record holograms with $LiNbO_3$ in the 90-degree geometry. The SNR=4.8 is measured for the phase conjugate reconstruction, and the bit-error-rate (BER) is estimated as 7×10^{-5} by assuming Gaussian noise as shown in figure 6.

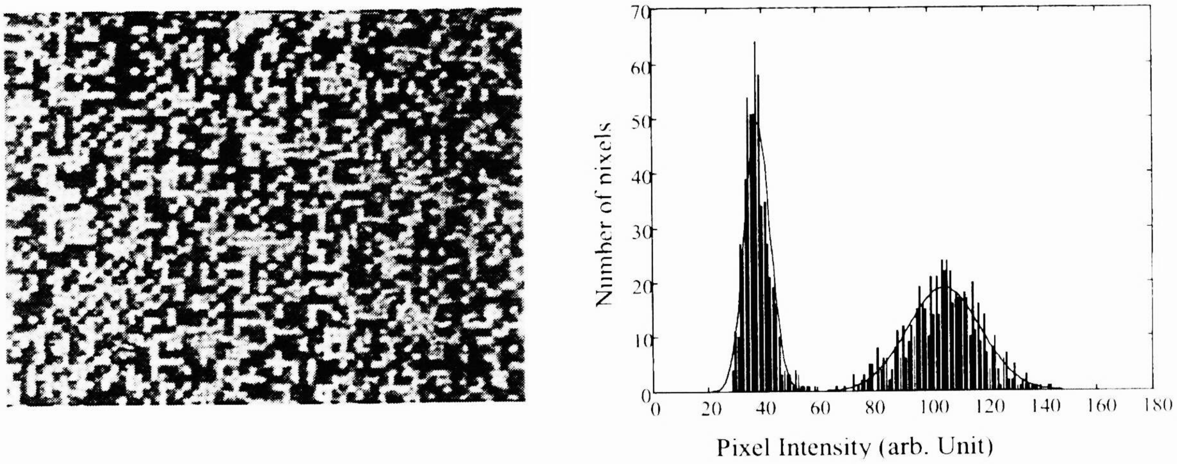
5. CONCLUSION

In this paper, we explain the importance of scaling the pixel size down to 1x1 μm^2 for a holographic memory system to be competitive with the other main storage techniques. The limiting factors for the pixel size in a holographic memory system are investigated. With phase conjugate readout, the pixel size is primarily determined by the holographic bandwidth of the recording medium. The phase conjugate reconstruction is demonstrated to be essential for utilizing the broad bandwidth of the recording medium and reducing the volume and cost of the system. The technical challenge of developing the high density SLM and the detector array will the determine factor to implement a commercial competitive holographic memory system.



(a) (b)

Figure 5. (a) The direct image of a resolution photo mask with pixels from 2x1 μm^2 down to 0.3x0.3 μm^2. (b) The phase conjugate reconstruction of the photo mask holograms.



(a) (b)

Figure 6. (a) The phase conjugate reconstruction of 1x1 μm^2 random data mask holograms. (b) The histogram of the reconstruction pixel intensities, which gives SNR=4.8, and BER=7x10^{-5}.

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