Journal of the Indian Institute of Science
A Multidisciplinary Reviews Journal
ISSN: 0970-4140 Coden-JIISAD

Holographic Imaging: Information Recording and Retrieval

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Abstract | Classical holography has paved the way for synergies between communication theory and optics towards the development of volume holographic memories. Digital information can be encoded, modulated and stored as an optical interference pattern called a 'hologram' within a photosensitive material. The recording density is fundamentally linked to the material properties, strength of the hologram and the underlying noise statistics during information recording and retrieval. In this paper, a system level overview of a volume holographic memory is provided. Various sub-systems such as recording physics, media/optical components and coding/signal processing methods are discussed, and the viability of such memories as an archival storage alternative is assessed. New research problems of theoretical and practical interest relating to quantum holography are discussed.

Keywords: *holographic imaging, volume holographic memories, three-dimensional storage.*

1 Introduction

The continued need for high end data storage devices has led to technological advancements in traditional areas of magnetic storage, optical storage, flash memories as well as emerging technologies such as phase change memories. The driving force behind these technologies is the need for devices with high storage capacities (>1 Tb/in^2), fast data access rates (read out speeds in excess of 5 Gb/s) and provably high reliability (decode failure rates below 10^{-12}). Along with these fundamental constraints, the memory module comprising recording sub system, media, servo and signal processing circuitry must be packaged well within a very large scale integrated (VLSI) chip meeting additional requirements on power and area to eventually reduce the cost per bit for commercial viability.

Optical recording systems have evolved from CDs, DVDs to multi-layered Blu-ray disks. The capacity of commercially available disks has not gone beyond 400 Gb. Fundamental limitations in diffraction efficiency has been a major setback for optical disk storage technology in competing with magnetic storage that continues to evolve beyond areal densities of 750 Gb/in^2 with simultaneous reduction in cost per bit.

Holographic storage is a potential optical technology to go beyond the capacity of current optical disks. It is possible to achieve capacities beyond 1 Tb/cm^3.[1–3] In a holographic system, digital information is replicated as an optical interference pattern and stored within a photo sensitive material. Unlike magnetic disks, retrieval of information can be done in parallel, thereby offering massive parallel read out speeds. Since laser beams have no inertia, significantly high read/write speeds can be achieved within optical systems compared to their magnetic counterparts that need mechanical actuators for servo and positioning.

In this paper, we describe the basic ingredients of a holographic imaging system from a storage perspective. In Section II, the physics behind classical holography is discussed along with recording techniques, materials and optical components. In Section III, we discuss the channel model of a holographic memory system and highlight coding and signal processing approaches for overcoming noise and interference in these channels. We also present a comparison of the holographic memory

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system and the magnetic recording system. In Section IV, we survey recent advances on quantum holography and present several fundamental research issues of interest to information storage.

2 Holographic Recording

Digital holographic storage involves holographic imaging, recording techniques, medium characteristics and readout methods towards data recovery. The origin of holographic imaging dates back to studies in x-ray crystallography pioneered by Wolfke and Bragg[4–5] who saw the need in retaining both amplitude and phase information from scattered optical waves to determine crystal structures accurately. Gabor invented the holographic imaging technique to obtain increased resolution in electronic microscopy.[5–6] Thus, the concept of information storage is naturally embedded within holography.

2.1 *Holographic principle*

Figure 1 shows the basic principle behind holography. Digital data from a point source is imposed on a spherical optical wave front called the object beam. A plane wave (non converging/diverging wave), called the 'reference beam', coherently interferes with the object beam forming a grated interference pattern which is replicated as a physical/chemical change within a photo sensitive medium. This is called a hologram. The reference beam or its phase conjugated version can later be used to retrieve the object beam in the original direction or in time reserved direction from the stored interference pattern. Digital data can be eventually reconstructed from the received wave with high fidelity rates (i.e. low probability of reconstruction error).

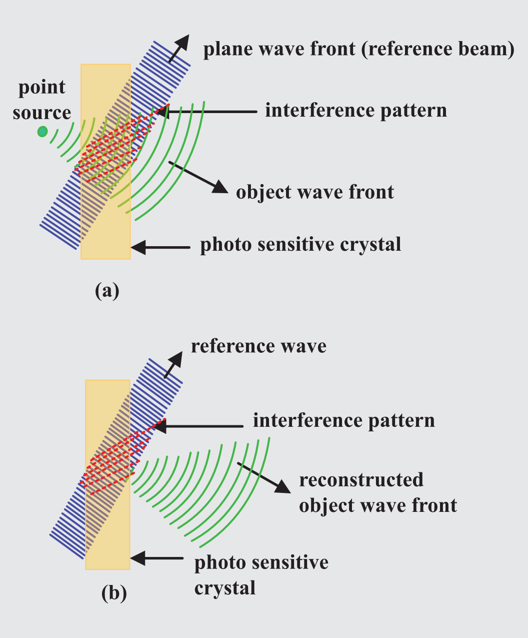


Figure 1: Recording and reading a binary hologram. (a) During recording, the spherical wave front from a point source interferes with a reference beam. The resulting interference pattern changes the refractive index of a photosensitive medium. (b) During retrieval, the medium is excited with the original reference beam. The diffracted beam resulting from coherent interference of the reference beam with the stored hologram can used to reconstruct the single bit.

The holographic medium can be a photopolymer, an inorganic photo refractive crystal or an ordinary photographic film.[7]

There are several well investigated holographic imaging methods such as the Fourier hologram, image hologram, Fraunhofer hologram, etc.[5] In some cases it may be desired that the reconstructed images be shift invariant to in-plane translations of a hologram. Such holograms are called Fourier holograms, and can be realized using a lens placed equidistant between the object and the recording medium or without a lens by keeping the object and the reference beam in the same reference plane. Other applications require sharp image luminance. This can be done using image holograms where a lens is used to project the real image of the object in the same position of a hologram. For example, in applications where microscopic particles have to be imaged in the far-field, it is desired that the light from the conjugated image be spread out over a large area so that the primary image can be enhanced. This technique constitutes the Fraunhofer hologram. All these holographic imaging methods look for enhanced signal information. Thus, retaining amplitude and phase from the scattered optical waves is a common theme.

Apart from high resolution imaging, holography is also used in many scientific applications such as interferometry, memory devices, image de-blurring, fast associative optical search engine over large data warehouses, (search pattern is embedded in the reference beam to ensure highest correlation in the diffracted object beam) etc.

In succeeding sections, we will focus our attention on the application of holography for information storage.

2.2 *Recording schemes*

Unlike conventional recording schemes such as magnetic recording/flash memories where data is assigned a particular location on the medium, in holographic storage, data can be distributed throughout the volume of the medium, and hence this memory is termed 'volumetric storage' technology. The direction and spacing of the fringes/gratings ensures that the reconstructed optical wave arriving at the detector during retrieval corresponds to the incident readout beam.

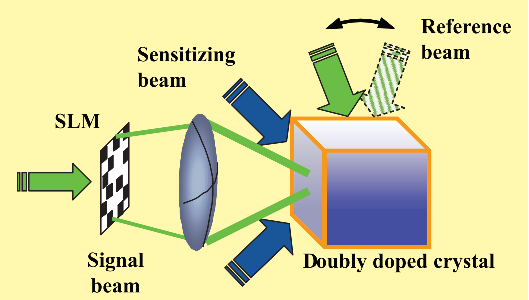
Figure 2 shows the schematic of two different holographic recording schemes. Both the recording schemes require a spatial light modulator (SLM) which is essentially a pixelated grid of optical shutters for modulating digital data.

There are two main practical recording schemes: angle multiplexing[8–9] and localized holography.[10]

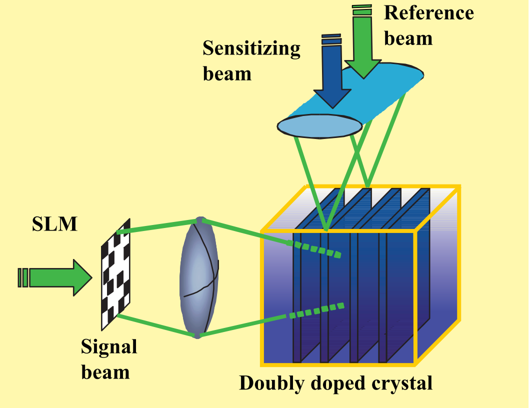
In both the recording schemes, digital data is modulated using an SLM that controls the intensity of light entering the pixels. The object beam is made to coherently interfere with a reference beam to form a grated interference pattern.

1. In angle multiplexing, by varying the angle of the reference beam, different holograms can be recorded within the volume of the material as shown in Figure 2(a). The conditions for the appearance of the reconstructed object beam depend on the thickness of the holographic material. For thin films, the readout beam can slightly differ in the angle from the reference beam and still produce the reconstructed object beam. In thick materials, the reconstructed beam will appear when the readout beam is nearly identical to the original reference beam wave vector. This condition is called Bragg matching. The number of holograms that can be multiplexed within the volume are limited since only those holograms that are Bragg matched exhibit higher readout powers. This condition is called Bragg's selectivity and is more predominant for reference and object beams lying within the same reference plane. The accumulated phase error between the propagating wavefronts from front and rear portions of the 3-D hologram increases for angles deviating from Bragg's condition.

   Angle multiplexed scheme is 'non-localized' since all the holograms are distributed within the volume of the holographic material. The term diffraction efficiency[3] is related to the amount of energy in the readout signal and is inversely proportional to the square of the number of holograms recorded within the medium. One of the main drawbacks of this scheme is destructive read out due to charge re-excitation i.e., it is not possible to selectively erasure a hologram without disturbing others. It must be noted that one can similarly multiplex holograms using wavelengths[11–12] from a tunable laser keeping the angle fixed. This is practically more difficult than the angle multiplexing scheme.
2. The invention of two-center recording[13] (and in general gated holography)[14] allows for a new way of looking at the holographic data storage system. The fact that holograms can be recorded and/or erased only in places where a sensitizing beam exists, allows for the important concept of 'localized' holographic recording similar to DVDs. Sensitizing beams act as gates for selective erasure of holograms within specified slices of the medium. In localized holographic recording, each hologram is recorded within a thin slice typically about a 20 μm over a recording medium using 90-deg geometry as shown in Figure 2(b). The diffraction efficiency in this case is inversely related to the number of holograms.[15] Localized holography is most suitable for memory applications with fewer holograms but with higher diffraction efficiencies compared to the conventional angle-multiplexed scheme.



(a) Angle Multiplexing



(b) Localized Recording

Figure 2: Holographic recording schemes:[16] Angle multiplexing and localized holography. (a) In angle multiplexing, different holograms share the volume of the holographic medium. (b) In localized recording, each hologram is stored in a specific slice within the holographic material.

In order to increase the storage capacity without altering the recording physics or the medium, (i.e., selective writing, reading, and erasure), one can use M-ary (or gray-scale) recording[16] for localized holography since higher diffraction efficiencies can be efficiently utilized to optimize the storage capacity.

2.3 *Holographic memory configurations*

The holographic memory system comprises of the holographic material, several optical components such as lenses, beam splitters, mirrors, collimators, etc., as part of the imaging sub-system along with the coding and signal processing architectures to ensure data is recovered with high fidelity.

Figures 3(a) and (b) show two different volume holographic memory systems employing angle multiplexed recording and localized holography respectively.

2.3.1 Angle multiplexed holographic memory: In this scheme a 4F lens configuration[3] is normally used. During recording, the digital data is modulated using a laser source such as a Krypton laser (676 nm). This forms the object beam. A reference beam is derived from the same laser source using a beam splitter. The object beam coherently interferes and gets recorded as a hologram in a doubly doped crystal such as $LiNbO_3$:Fe:Mn. Waveplates are used for controlling the amount of polarization along with a beam steering system for changing the reference angle.

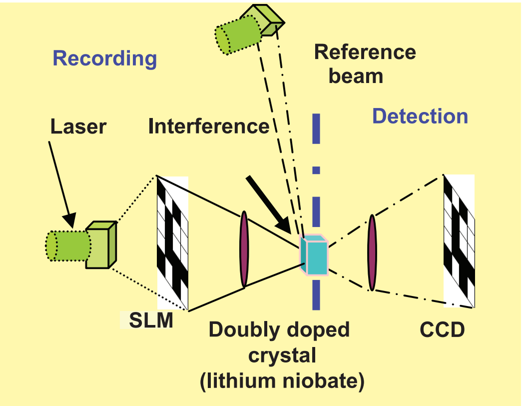


Figure 3(a): A volume holographic memory[1,17] using angle multiplexing and 4F configuration. Digital data is modulated through the SLM, focused through the first lens and made to interfere coherently with a reference beam. The grated pattern is stored within a photo refractive material crystal such as $LiNbO_3$. During detection, a reference beam at the original reference angle interferes with stored pattern; the reconstructed object beam is projected onto a CCD array for decoding the bits.

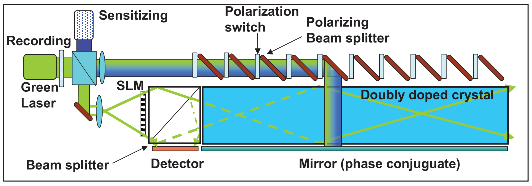


Figure 3(b): Holographic memory using localized recording.[18,19] Two recording beams and a sensitizing beam are used. The recording beam and sensitizing beam are focused through a cylindrical lens to focus on a thin slice of the doubly doped crystal. The beam splitter splits the recording beam into an object and a reference beam. The object beam goes through the SLM and interferes with the reference beam and is recorded as a hologram using the sensitizing beam at the desired slice that can be selected from a switching array.

Read-out is performed by the reference beam, which results in reflection from the bottom mirror to send the phase conjugate of the signal beam towards the detector as shown above.

2.3.2 Localized holographic memory: Figure 3(b) shows the localized holographic memory set up. The two recording beams are at 532 nm (green) and the sensitizing beam is at approximately 404 nm. The reference (green) beam and the sensitizing (blue) beam are focused via a cylindrical lens into a thin beam to illuminate over a thin slice of the crystal. The signal beam goes through the SLM to encode the data pages. The desired slice of the holographic material can be selected using a polarizing switch and each hologram can recorded using a sensitizing beam. Read-out is performed by the reference beam, which results in reflection from the bottom mirror to send the phase conjugated signal beam to the detector as shown in Figure 3(b).

2.3.3 Media: The holographic medium is a central piece in the storage system. The selection of the medium is important depending on the storage application such as write-once read many (WORM), non-volatile read-write (NVRW), etc. For WORM applications, the physical change in the medium must be irreversible. Typically, organic materials such as photopolymers and photochromatic materials are used for this application.[2,3,7] In photopolymer materials, small monomer chains polymerize and form long molecular chains in response to optical illumination. Alternatively, photochromatic/direct-write materials such as polymethylmethacrylate, phenanthraquinone that change their refractive index or respond to local changes in absorption can be used. Both these materials can have high sensitivity, which may be baneful when some of the material can be partially exposed to nearby recording locations. Media shrinkage, scattering, excessive absorption, and dynamic range are some fundamental issues in media fabrication. Media shrinkage and rapid variations to brightness lead to distortions in the reconstructed image at the CCD that can be compensated via signal processing. Using techniques such as peristrophic beam rotation, spherical and randomly speckled reference beams, the dynamic range can be improved.[2,7]

For read-write applications, photorefractive crystals are generally used. The crystals are typically a centimeter cube thick. Examples include lithium niobate, barium titanate, strontium barium niobate with dopants such as Fe, Mn etc.[3] Other media include photorefractive polymers,[20–21] deep levels associated with donor atoms in semiconductor materials (DX-center)[22] and bio proteins such as bacteriorhodopsin.[23] Photorefractive polymers respond quickly to optical illumination, but they tend to have short dark life times. Also, large electric fields are needed to realize electro-optic effects i.e., build the necessary space charge field for altering the local refractive index in the medium. Photoexcited charges persist in the conduction band of the semiconductor material resulting in strong phase-holograms, but are prone to thermal excitation, leading to volatility. Photo-refractive crystals transport and trap charge carriers via diffusion and drifts. Selective erasure can be done by rearranging the trapped charges. However, the process of selective re-excitation can lead to erasures in normal read outs.

In order to make the medium resistant to erasures during readouts for NVRW, various thermal and electronic fixing procedures over portions of the volume of the material have been adopted. A rather naïve approach is periodic duplication and rewriting of the data pages. This procedure leads to poor data fidelity rates due to frequent material re-use. Gated recording[14] over a doubly doped crystal is the best way to realize NVRW. The gated beam is present only during recording and switched off during readout. The recorded fringes are still Bragg-matched to the readout wavelength. A dopant such as Mn creates a deep trap near the middle of the band gap while Fe creates a shallow trap near the valence band. The recorded hologram does not suffer from erasures during readouts since it resides in the deep trap where gating occurs. The shallower trap provides an intermediate level where trapped charges can persist longer in the dark.

3 Volume Holographic Memories: A Communication-Theoretic View

From a communication-theoretic perspective, the entire process of encoding digital information, recording as a hologram and retrieving it at the CCD is an instance of a noisy communication channel. The ultimate aim is to recover stored data with high fidelity rates. In order to develop coding and signal processing techniques for mitigating signal artifacts, we need to build realistic channel models that capture the physical behavior of the system and are mathematically tractable. Simplifications such as linear approximations and stationarity can be done to channel modeling towards the development of practical algorithms. We need to strike a balance between modeling sophistication for accuracy vs. ease of use.

3.1 *Channel model*

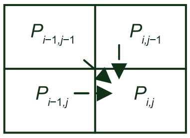
Several authors have considered various channel models[24–26] for holographic recording. These include an analog model with a complex carrier,[24] transmission model for dominant optical scattering,[25] a discrete magnitude-squared model[26] etc. We consider a 2-D ISI channel model with optical scattering. Let vector $\vec{x}$ denote the transmitted signal. Let the received signal at the CCD be $\vec{y}$. The channel can be abstracted as the conditional probability density function (pdf) $p(\vec{y}\,|\,\vec{x})$ with underlying random noise vector $\vec{n}$ that corrupts the transmitted signal. Without any optical scattering, electronic noise at the CCD detector $\vec{n}$ is characterized by a Gaussian distribution. When the noise is dominated by optical scattering, the received signal $\vec{r}$ is a vector addition of the signal amplitude and a resultant noise phasor. At the CCD, the magnitude of the received intensity $y = |\vec{r}|^2$ is recorded, and characterized by a Rician pdf given by[16,25]

$$y = \frac{r}{\sigma^2}\exp\left(-\frac{r^2+x^2}{2\sigma^2}\right)\mathrm{I}_0\left(\frac{rx}{\sigma^2}\right), \tag{1}$$

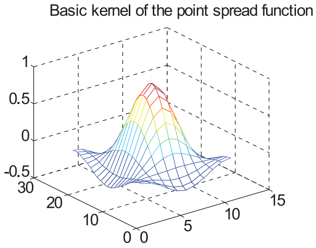
where, $y = |\vec{y}|$, $r = |\vec{r}|$, $x = |\vec{x}|$, I_0 is the zeroth-order modified Bessel function of the first kind and σ^2 is the noise variance.

Due to finite aperture length and dimensions of the holographic material, the resulting signal suffers from 2-D spatial interference. Figure 4(a) shows the schematic of a 1st order 2-D ISI model.

The spacing of the SLM pixels Γ determines the spatial sampling rate. Let g_{SLM} denote the linear fill factor of the SLM. If λ is the source wavelength and f is the focal length of the lens, the Nyquist



(a) 1st order 2-D ISI



(b) 2-D ISI

Figure 4: (a) A 1st order 2-D spatial ISI model. (b) Basic kernel of the point spread function due to finite aperture and material dimensions.

aperture length is given by $A_N = \lambda f/\Gamma$. If A^2 is the area of the square aperture, the 2-D spatial impulse response is determined by the convolution of the space invariant impulse response and the square pixel shape as

$$h(x,y) = c^2 \int_{-0.5g_{SLM}}^{0.5g_{SLM}} \int_{-0.5g_{SLM}}^{0.5g_{SLM}} \operatorname{sinc}\left[\frac{A}{A_N}(x-x')\right] \times \operatorname{sinc}\left[\frac{A}{A_N}(y-y')\right] dx'dy', \qquad (2)$$

where the constant 'c' ensures unit energy in the impulse response. Figure 4(b) shows the shape of such a 2-D impulse response.

Let g_{CCD} denote the linear fill factor of the CCD. The received signal at location (i,j) is the total received intensity $y_{i,j}$ integrated over the CCD area belonging to pixel $p_{i,j}$. This intensity includes a self-term, a non-linear contribution from neighboring pixels and noise $w(i,j)$ governed by the following equation

$$y(i,j) = \int_{-0.5g_{CCD}}^{0.5g_{CCD}} \int_{-0.5g_{CCD}}^{0.5g_{CCD}} r^2(x,y)\,dxdy + w(i,j).$$
$$r(x,y) = \sqrt{p_{i,j}}\,h(x-i,\,y-j) + \sum_{m,n:m\neq i,n\neq j} \sqrt{p_{m,n}}\,h(x-m,\,n-y). \qquad (3)$$

The pixel values can be gray coded i.e., taking one of the M-ary levels from the set $\{0, 1, \ldots, M-1\}$.

The signal-to-noise ratio (SNR) is defined as the ratio of the average received signal power to the average noise power, and serves as a meaningful metric to study the bit error probability for these systems.

It must be noted that SNR is intimately related to the diffraction efficiency of the holographic system. Recording more holograms implies low SNR. Incorporating more M-ary levels implies admitting higher levels of crosstalk, making signal detection a difficult problem.

In the physical sense, SNR is linked to (a) the material constant (M/#) (b) the number of stored holograms (P) and (c) the noise variance σ^2. With an appropriate channel model, we can estimate the capacity for the holographic channel C_{holo} that depends on SNR and serves as an upper bound on the maximum encoding rate R_{holo} for reliable storage and retrieval.

2.3.4 Information storage density: We would like to comment on the maximum theoretical bound for information storage density purely based on the physical constraints.[7] Each reconstructed object beam of wavelength λ goes through the square aperture of area A. Diffraction effects determine the resolvability of two fringes that are less than $\lambda/\sqrt{A}$ apart. Also, fringe spacings get averaged over a media of thickness d. The minimum fringe spacing for resolvability is λ/d. Thus, over a material of volume $V = Ad$, we can multiplex d/λ holographic pages with A/λ^2 pixels per page, implying maximum storage density $D_{\max} \le 1/\lambda^3$. Evaluating the maximum storage density for a green laser with wavelength $\lambda = 532$ nm, we get $D_{\max} \sim 1$ Tbyte/cm^3. Unfortunately due to noise, interference and various signal distortions, we cannot achieve such high densities.

For a given SNR that depends on the material, signal strength and noise sources, the information storage density is given by

$$D = R_{\text{holo}} PB, \qquad (4)$$

where, P is the number of recorded holograms, and B is the number of pixels per holographic page. There is a tradeoff in choosing P, the number of M-levels consistent with rate R_{holo} and the recording mechanism for maximizing the information storage density.

Experimental studies have demonstrated 400 b/μm^2[2,27] storage densities using binary recording. Under similar conditions, using 2-D ISI channel modeling, the predicted lower bound to the storage density[16] is around 231 bits/μm^2. Thus, channel modeling is an important step to understand the nominal physical behavior and estimate realistic information storage densities. Advanced coding and signal processing methods are guided by realistic channel models and information-theoretical tools.

3.2 *Coding and signal processing*

The received signal from the CCD suffers from distortion, spatial interference and noise due to media effects such as shrinkage and limitations in the imaging optics. These have to be appropriately processed in order to retrieve the digital data to the end user. Thus, signal processing and coding techniques are an integral part of the holographic memory system and form the read channel architecture.

The goal of this read channel sub-system is to ensure reliable detection and decoding of digital data. Under nominal conditions, very high reliability rates of the order 10^{-12} and below are expected for storage channels. This is because we do not have any re-transmissions in storage unlike other communication channels such as the wireless channel.

Figure 5 shows the schematic of read channel architecture for holographic storage.

Digital data is modulated by means of a modulation code. The modulation code for holography serves two purposes:

- It helps shape digital data via multi-level amplitude modulation if there is sufficient SNR in the medium to support this.
- It constrains digital data and shapes the power spectral density of the data patterns to better match channel spectral properties. For example, it is desirable that a dark pixel '0' is not surrounded by brighter pixels since the bright pixels may completely dominate the dark pixel due to spatial interference. A constraint of this type is called the no isolated bit (nib) constraint.

Figures 6(a) and (b) show examples of 2-D multi-level modulation constraints such as the (nib) constraint[28] and the balanced array constraint respectively. The (nib) constraint avoids blurring of certain pixels due to neighboring pixel interactions. The use of balanced array constraints limits the diffracted power per page.

M-ary modulation without any constraints carries an information rate of $\log_2(M)$ bits. Since constrained M-ary modulation codes forbid certain data patterns to occur, the rate of a multi-level constrained modulation code is strictly less than $\log_2(M)$. The design of such 2-D efficient constrained modulation codes[28–30] is a challenging task and is an active area of research in coding theory.

Error control coding[31] (ECC) is an important aspect in channel engineering. The holographic channel is prone to random and burst errors resulting from noise and interference. Also, holographic channels exhibit different error rates over a holographic page.[32] Error rates towards the edges are higher than those at the center. This requires design of error correcting codes and interleavers suited for these requirements.

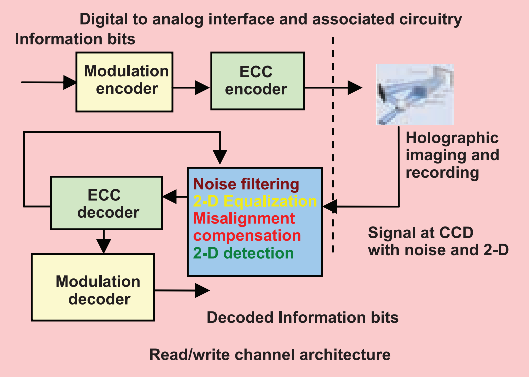
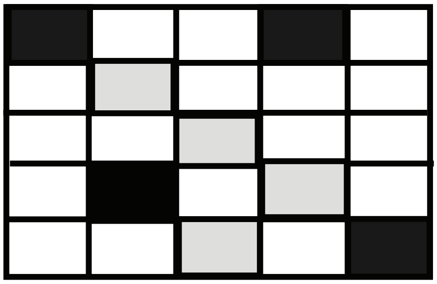
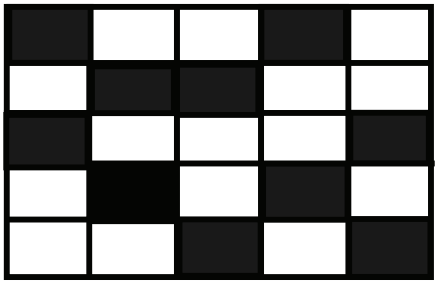


Figure 5: Schematic of a read write channel. Digital data goes through modulation and error control encoding in reverse concatenation form before being optically modulated and stored as a hologram. The reconstructed object beam after necessary optics is projected on a CCD array for processing by a read channel circuitry. The read back signal goes through 2-D signal processing circuits before being decoded via an ECC decoder and a modulation decoder.



(a) 3-ary no isolated bit constraint over a 3 × 3 neighborhood.



(b) Binary balanced dark and gray pixels.

Figure 6: Modulation constraints for a hologram. (a) A dark/gray pixel does not have all bright pixels surrounding it and vice versa within a 3 × 3 neighborhood. (b) The grid has the same number of dark and bright pixels across every row and column.

A simple coding architecture is shown in Figure 7 for illustration purposes. One might wonder why we would prefer to have a modulation encoder preceded by an error correcting encoder and not the other way since it is intuitive to have a modulation encoder after ECC to shape the data. Modulation codes are typically prone to error propagation. Thus, it is better to decode using an ECC first and then do modulation decoding than the reverse way. The coding scheme with modulation followed by ECC is called reverse order coding (ROC)[33] and is typically the preferred coding architecture in most storage systems.

If R_1 and R_2 denote the code rates of the modulation code and the ECC, the overall coding rate $\sim R_1R_2 \leq R_{\text{holo}} < C_{\text{holo}}$. So far we discussed the coding aspects in holographic systems. Signal processing is an integral part of the storage system.

Due to material shrinkages and imperfect imaging, the signal received at the CCD is not an exact replica of the transmitted signal. We need to process the analog signal and overcome the effects of distortion, noise and spatial interference. Also, CCD and SLM arrays may not be perfectly aligned. In such cases 2-D lateral and rotational misalignments along with scaling may be pronounced.[27,34,35]

Signal artifacts must be carefully compensated via signal processing. Channel equalization techniques[26] such as the minimum mean square based estimation (MMSE) and adaptive equalization are popular, but they are not optimal in the maximum *a-posteriori* probability (MAP) decision rule sense i.e., to yield low bit error rates. Two-dimensional signal detection for holography is a challenging task. Techniques based on adaptive thresholding, two-dimensional decision feedback techniques[36] and image over sampling methods[37] have been investigated. These methods are not efficient from performance point of view but are of low-complexity and quite pragmatic. Signal detection based on 2-D maximum likelihood (ML) and maximum a-posteriori probability (MAP) rule is NP-complete. Developing near optimal 2-D signal detection techniques have been a subject of active research investigation. Techniques based on multi-row and column separable 2-D detection,[38] 2-D belief propagation based techniques have been studied in the past.[39] The separable 2-D detector is not effective from performance stand point as some channels are not separable. 2-D belief propagation detection methods suffer from high complexity. An iterative zig-zag scanning based 2-D detection algorithm[40] has been recently developed. A computationally efficient algorithm using local feedback structures with near optimal 2-D MAP performance was also recently developed.[41–42] This method is attractive from implementation stand point of view as well as providing near optimal performance. One can configure the detection architecture to meet the desired performance albeit with higher complexity. Since holographic readout is parallel, signal processing algorithms and architectures exhibiting high degree of parallelism are preferred. This ensures that the read channel circuitry is not a bottleneck in sustaining the readout throughput rates. We need detection architectures that enable parallel signal processing.

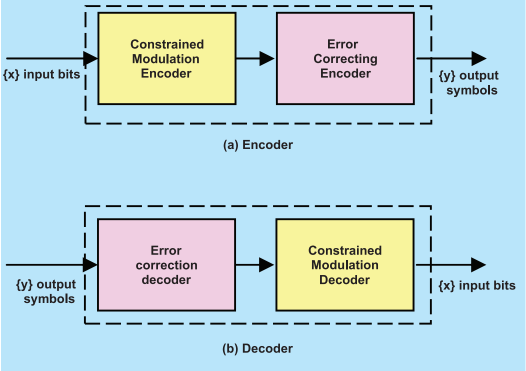


Figure 7: Schematic of the reverse order coding architecture. (a) Digital data in bits goes through a constrained modulation encoder followed by an error correcting code. (b) The decoding is just an inverse of the encoding process.

3.3 *Holographic memory vs. magnetic disk*

Though holography was already well studied by 1960s, interest in holographic storage was rekindled during early 1990s with the development of SLMs, CCDs and single spatial mode high power lasers with long coherence lengths. Significant research progress is on-going over nearly two decades from 1990 at various academic research groups at Caltech, Stanford, Georgia Tech, etc., and also at IBM, Bell Labs, Optware, Rockwell and spinoffs such as In Phase technologies and Aprilis.[3]

Optical holographic memories seem to be a promising technology since they can offer high volumetric density storage and massively parallel data transfer rates. However, there are several technological challenges for holographic memories to be a viable storage alternative. We need rapidly tunable, high powered pulsed lasers that can work in the visible region. High end lasers are costly. Other components such as servo focus, angle steering systems and the opto-electronic package have to be robust to sustain mechanical and other physical perturbations when packaged together within an integrated optical chip. Non-volatility is a core issue in the context of recording and media design. Gated recording over doubly doped inorganic materials is a promising direction. However, issues such as thermal and electronic fixing[3] need more validation to ensure that the medium can be made ready for mass production.

Today's magnetic disks working on perpendicular recording technology have perfected head and media designs ensuring recorded magnetic data stays long enough when powered off. Also today's commercial disks have high densities ~750 Gb/in^2. Though magnetic discs are slow in terms of read access times (typically milli-seconds), the overall magnetic storage system has orders of magnitude reduced cost per bit making it still highly competitive as a storage technology. Holographic storage needs to mature from lab demonstration towards a truly archival storage solution with further innovations in media, recording, system stability and data recovery techniques.

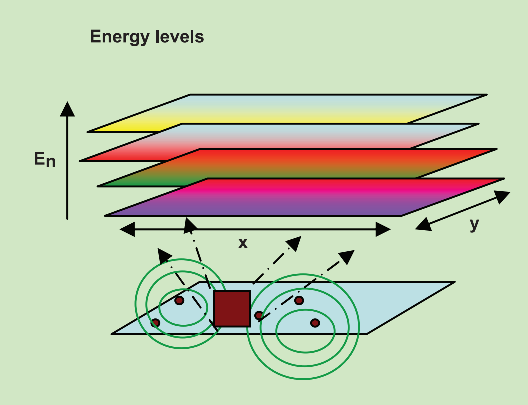


Figure 8: Schematic of quantum holographic recording.[43] Information is encoded in electron waves on a metal surface using electronic holograms from spatially arranged gas molecules. The information is localized in two spatial dimensions and an energy level, and can be retrieved via a scanning tunneling microscope.

4 Quantum Holography

In a recent pioneering work, the concept of classical holography has been extended to the quantum case based on an experimental demonstration at Stanford.[43] Using quantum holographic technique, it is possible to store information at Fermi wavelengths by localizing electron waves within energy-space regions. The information densities are around 20 bits/nm^2.

In the quantum holography set up, electrons from the tip of a scanning tunneling microscope[44–45] (STM) tunnel across a gap, typically a few tens of nano-meters wide, to a metal surface on the other side where CO molecules are placed. Assuming elastic collisions between 2-D electron waves and the molecules arranged on the surface, the direct electron wave coming from the tip can interfere constructively or destructively with the scattered returning waves. This causes interference patterns that can be seen in the STM images. Any inelastic electron collisions move to the bulk space. Changes in the bias voltage can lead to changes in the interference pattern so that two completely different information patterns can be share in the same spatial region. Thus, information can be projected into two degrees of spatial freedom and one degree of energy freedom through quantum interference similar to classical holographic techniques discussed in Section IIB. Retrieval is complementary to the storing procedure. The data is read out by mapping the energy-resolved density of states.

Given the extreme physical conditions like low temperatures and high pressures for conducting this experiment, it is a rather daunting task building such a quantum holographic storage device for encoding and decoding classical information through quantum means.

What is really intriguing is the fact that it is possible to image at sub-wavelengths of electrons or the smallest separation between the molecules and still demonstrate storage and retrieval at such nanoscopic scales.

The key components of quantum systems are entanglement and coherent superposition. It would be interesting to study quantum storage systems from an information theoretical point of view. With the demonstration of experimental quantum holography, there are plenty of unaddressed open questions. For example, what are the ultimate limits for information density at quantum scales? What are the error models for these systems? How can we realize coding methods around such systems?

5 Conclusions and Perspectives

Holography is a discipline by itself. Classical optical holography finds applications in 3-D imaging, interferometers, associative search, data storage and many others. The concept of information storage is fundamentally embedded in holography. There have been significant advances over the last two decades in areas of recording physics, media design and high resolution imaging components towards the demonstration of high capacity optical storage. However, significant research needs to be done to enable holographic storage as a next generation optical storage device and break the stagnation in today's CD and DVD technologies.

Hard disk drives (HDD) still dominate the storage market, and new technologies such as shingled writing, heat assisted magnetic recording, bit patterned media are expected to get past the 1 Tb/in^2 density barrier. Over the last few years, solid state storage drives (SSD) have steadily progressed in capacity and cost effectiveness. Hybrid drives comprising HDD and SSD are envisioned to be the storage devices on most computers and hand held devices.

Given advancements in other storage technology areas, research on holographic storage needs to pace up in all levels of system science and technology, such as media, recording, channels and other components to carefully balance all these to the 'right' system design point and overcoming today's limitations. The work on quantum holography is a major leap in the demonstration of quantum interference, localization and retrieval at nanoscopic bit densities. Crossing beyond the barriers of classical physics, quantum information processing systems will play a major role in the future. Research within system science and engineering would need to gear up both theoretically and experimentally in these emerging areas.

Acknowledgments

The author would like to acknowledge his former colleagues Drs. Momtahan and Karbaschi and Prof. Adibi from Georgia Tech for fruitful collaborations and insights into holographic data storage during 2002–2006. The author is thankful to Dr. Aravind Nayak for helpful comments on an earlier version of this paper.

Received 25 December 2012.

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