



Research Proposal

Optimization of Angular Multiplexing for Holographic Data Storage

A Study of Holographic Data Storage for Efficient Commercial Use

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1 Introduction

Holographic data storage involves storing many two-dimensional images inside a certain volume filled with photopolymer by slightly tilting the reference beam. It presents a good alternative to hard drives, as it offers both high capacity and access rates. One of the main techniques this is achieved by is angular multiplexing. Conventional angular multiplexing involves a Mach–Zehnder interferometer, although there are other setups including the CGH technique.

This project will try to optimize angular multiplexing to maximize the amount of data storage included. We will try to include the maximal amount of different angles with data uploaded while still being able to accurately retrieve each stored image. As the angular separation between holograms decreases, more holograms can be stored within the same material. However, if the angles become too close together, interference and crosstalk between neighboring holograms can make it difficult to recover the original data. Therefore, our project is meant to find the right balance between the two.

1.1 Intellectual Merit

This project will improve the current methods of holographic data storage by using angular multiplexing to increase storage capacity. This will potentially lead to an improved set up for holographic data storage that is more financially and spatially efficient. This would allow holographic data storage to be used more often in commercial settings.

1.2 Broader Impact

In this day and age, it is important to be able to store large amounts of data without taking up a large amount of space. Holographic data storage can store incredibly large amounts of data compared to cloud storage. Our research would increase the storage capacity of holographic data storage by optimizing angular multiplexing methods. This method could be used in future encoding of holographic data storage to improve data capacity.

2 Background and Prior Work

Holographic data storage records information within the volume of a material instead of just on the surface. A signal beam, carrying a two-dimensional data page, interferes with a reference beam inside the recording material. This interference creates a pattern that changes the refractive index of the material. Later, the stored data can be retrieved by shining the same reference beam onto the material. Because a whole page of data can be recorded and read at once, holographic storage offers the possibility of high storage capacity and fast data access. [1]

One way to boost this capacity is by using angular multiplexing. Instead of having a single hologram stored in a given spot, many holograms are written in the same volume, each with a slightly different angle of the reference beam. Hoshizawa et al. built a system using multiplexing that was designed for 2 TB of storage and 1 Gbit/s transfer speed. They achieved a recording density of 2.4 Tbit/in² [2]. This shows that angular multiplexing can significantly increase how much data fits in a space. The key to separating these holograms lies in Bragg selectivity. For a volume hologram, the Bragg condition is given by

$$2n\Lambda \sin(\theta_B) = m\lambda, \tag{1}$$

where n is the refractive index of the material, Λ is the spacing between the grating planes, θ_B is the Bragg angle, λ is the wavelength of light, and m is the diffraction order. When the reference beam matches this condition, the hologram is reconstructed efficiently. If the reference beam is off the Bragg angle, the diffraction efficiency drops. This allows different holograms recorded at different angles to be read separately. If the angles are too close, the Bragg-selectivity ranges overlap, causing crosstalk and errors in the retrieved data. [2]

Various optical setups have been used for multiplexing. Most systems keep the signal and reference beams separate. Yoneda et al. showed a different approach: a common-path method, where the signal and reference beams are the same, using a computer-generated hologram to produce both beams. They successfully retrieved four data pages this way. [3] Other studies have also looked at increasing storage by using properties of light such as amplitude, phase, and polarization to encode data [4].

Project Need / Research Gap. Previous work shows that angular multiplexing can greatly increase storage density. However, the actual usable angular spacing depends on the setup, the laser wavelength, the recording material, and how much error is acceptable in reconstruction. Our project will measure experimentally how close the angles of the reference beams can be while still recovering each data page accurately. We will use this angular separation to calculate the maximum storage capacity possible with our system.

3 Research Goals

The research aims to understand how angular spacing influences data storage and retrieval. All outcomes will be documented, whether reducing the separation leads to higher storage capacity, causes reconstruction errors that are too large, or has no noticeable impact.

Goal 1— Establish a Baseline Holographic Recording and Retrieval Setup

Question / Objective: Determine whether individual two-dimensional data pages can be reliably recorded in and reconstructed from the selected photopolymer using the proposed setup.

Approach: Use the ultraviolet laser, beam splitter, spatial light modulator, reference beam, and photopolymer to record individual data pages before attempting angular multiplexing. Reconstruct each page using the reference-beam angle and compare the retrieved image with the original data page.

Measurement / Output: Measurements of reconstruction accuracy, image quality, and repeatability for recorded holograms.

Success Criterion: This goal is complete when multiple individual data pages can be recorded and reconstructed well enough to provide a baseline for comparison with multiplexed recordings.

Goal 2— Determine the Minimum Usable Angular Separation

Question / Objective: Determine how closely two or more holograms can be spaced in reference-beam angle while still allowing each data page to be accurately retrieved.

Approach: Record data pages in the same region of the photopolymer while changing the reference-beam angle with the servo-controlled mirror. Begin with large angular separations and gradually decrease the spacing. The Bragg selectivity condition will be used to estimate the range of angles that should be tested. Each stored page will then be reconstructed at its reference angle.

Measurement / Output: Reconstruction accuracy and image quality as functions of separation, along with measurements of crosstalk between neighboring holograms.

Success Criterion: This goal is complete when the smallest angular separation that still meets a predefined reconstruction-accuracy threshold has been identified and reproduced across multiple trials.

Goal 3— Determine the Maximum Practical Storage Capacity

Question / Objective: Determine how much information can be stored within one recording region using the measured angular separation.

Approach: Use the minimum angular separation to estimate and experimentally test the maximum number of distinct holograms that can be multiplexed across the available reference-beam angular range. Record more data pages until reconstruction quality falls below the selected accuracy threshold.

Measurement / Output: The maximum number of retrievable holograms, total number of stored pixels, estimated number of stored bytes, and reconstruction accuracy as the number of multiplexed pages increases.

Success Criterion: This goal is complete when a maximum practical number of multiplexed recordings has been determined and converted into an estimated storage capacity for the experimental setup.

4 Proposed Methods and Research Design

Our experimental setup will use an ultraviolet laser source. An ultraviolet laser will be optimal for the purposes of this project as the lower wavelength allows for increased storage capacity. The laser beam will then be sent through a beam splitter to create a reference beam and a signal beam.[5]

The reference beam will then be directed towards a mirror. The mirror will be mounted to a servo that will control the change in angle between recordings. The change in angle between each recording will be determined using the Bragg selectivity condition.

Similarly, the signal beam will be directed to a spatial light modulator (SLM). The SLM will encode a 2D data package in the signal beam through amplitude modulation and phase shifting.

Both beams will both be directed towards a photo-polymer where the data will be stored. The beams will create a unique interference pattern that will be stored within the photo-polymer.[3]

Once we have recorded using as many angles as we can we will calculate the total amount of data stored at that location. We will find this value by multiplying the total number of angles used by the number of pixels in each data package, then converting that into bytes.

Methods may change. These procedures describe the current experimental design. If any unexpected constraint arises, the method will be revised, and the change, reason, and effect will be

documented.

5 Expected Results and Data Analysis

The expected results of this study depends on the thickness of the photo-polymer that is used. The greater the thickness the more angles can be used for the reference beam, therefore the more data can be stored.

The photo-polymer used would impact the storage capacity. Materials with higher refractive indexes result in higher minimum change in angle, therefore reducing storage capacity.

The ultraviolet laser we plan on using should lead to a higher storage capacity. In the Bragg capacity a smaller wavelength results in a smaller minimum change in angle, leading to a higher storage capacity.

Previous studies have achieved capacities of approximately 2 terabytes. [2] We estimate that we will achieve results of equal or higher capacity proportional to our photo-polymer thickness.

6 Feasibility and Resources

This project needs access to an ultraviolet laser, beam splitter, mirrors, a spatial light modulator, photopolymer recording material, and a camera or detector to capture the reconstructed data pages. A servo-controlled mirror will also be needed to make small and repeatable changes to the angle of the reference beam. A computer will be used to control the SLM and servo and to analyze the accuracy of the reconstructed images.

The main limitation of the experiment will be the precision of the angular adjustments. If the servo-controlled mirror cannot move in small enough increments, it may limit how closely spaced the holograms can be tested. The photopolymer must also be compatible with the laser wavelength and capable of storing multiple holograms without too much degradation.

7 Safety and Risk Considerations

This project involves ultraviolet lasers, so accidental exposure to the laser beam or the reflected light can be dangerous. Therefore, the proper safety precautions should be taken. In addition, the optical components will be set up securely in order to reduce risk of them shifting during experimentation, and the photopolymer will be handled according to safety guidelines.

8 Potential Pitfalls and Alternative Strategies

Challenge 1

The photo-polymer materials with lower refractive indices may be more expensive than other materials. Not being able to use these photo polymers would reduced our storage capacity.

Solution: If we are not able to procure an ideal photo-polymer we could use more commercially available holographic film. Using this method we could generalize our results by determining the proportional volume and refractive index and predicting results that would occur with more ideal storage material.

Challenge 2

The reference beam angle may not be able to have as small increments as we would need. This would result in fewer recordings in a specific recording and reduce overall storage capacity.

Solution: If the servos currently available at TJHSST do not have a capacity to increment at small angles we could purchase a more precise servo made for industrial use. If we are not able to purchase these specialized servos we could adjust the set up to instead include a motor that is able to move over small increments.

9 Research Timeline

Milestone 1: Late October: Complete All Theoretical Calculations

Task — What will you do? Finalize necessary theoretical background required for project implementation. Complete all necessary calculations using material specifications

Objective — What measurable result should this work produce? Determine the minimum change in angle feasible for this project based on laser wavelength, thickness of material and refractive index of material.

Goal — What larger research capability or milestone does this establish? Completes initial planning before beginning experimental implementation.

Milestone 2: Mid-December: Complete Experimental Setup

Task — What will you do? Implement experimental setup using all components of the experiment.

Objective — What measurable result should this work produce? Complete experimental set up including all components necessary for both the reference beam and signal beam.

Goal — What larger research capability or milestone does this establish? Finalize experimental setup before starting to record data using angular multiplexing.

Milestone 3: Mid-March: Determine Final Storage Capacity

Task — What will you do? Calculate total holographic data storage capacity based on all iterations using multiple photo polymer materials.

Objective — What measurable result should this work produce? Determine a maximum data capacity based on our experimental.

Goal — What larger research capability or milestone does this establish? Finalize all experimental results before beginning analysis to determine significance.

Milestone 4: Early May: Final Analysis and Research Product

Task — What will you do? Complete all statistical comparisons to determine significance. Create concise presentation and poster describing study and results.

Objective — What measurable result should this work produce? Determine significance of study based on results for storage capacity compared to results of previous studies.

Goal — What larger research capability or milestone does this establish? Completes overall project with a final result of significance.

10 Group Responsibilities

Avishi Anurag

Primary responsibility for the computer-operated and math-based methodology, such as programming and operating the spatial light modulator (SLM), calculating the angular spacing used during testing and analyzing the storage capacity of the holograms.

Zoya Moloo

Primary responsibility for the servos and optical hardware, including setting up the mirrors, lasers, beam splitters, and photopolymers while also ensuring everything is built stably.

Both students

Both students will jointly set up and test the system, retrieve the holograms, analyze experimental data, document results, follow laboratory safety features and write up an analysis.

References

- [1] J. C. et. al, *Can holographic optical storage displace hard disk drives?*, (2024) <https://pmc.ncbi.nlm.nih.gov/articles/PMC11189537/> (visited on 2024).

What did this work do? This article compares holographic optical storage with hard disk drives and looks at whether holographic storage could eventually be used for cloud data. The researchers tested iron-doped lithium niobate crystals and studied how writing and reading holograms affects stored data over time.

Why is it relevant? This is relevant to our project because it gives an example of a working holographic storage system and shows some of the challenges that appear when many holograms are stored in the same material. It also discusses how storage density and repeated reading can affect the quality of the stored data.

How will we use it? We will use this article to understand what can cause stored holograms to weaken or become harder to read. This will help us think about how many holograms we can store using angular multiplexing while still being able to clearly recover the original data.

- [2] K. F. Taku Hoshizawa Ken-ichi Shimada and Y. Tada, “Practical angular-multiplexing holographic data storage system with 2 terabyte capacity and 1 gigabyte transfer rate”, *Japanese Journal of Applied Physics* **55**, 10.7567/JJAP.55.09SA06 (2016).

What did this work do? This article uses run-length limited modulation to optimize the recoding density of holographic data storage. It also includes a method to improve the efficiency of reading holographic data.

Why is it relevant? This article describes the process of increasing the data capacity of holographic data storage which directly aligns with our goal of increasing storage density by maximizing the potential reference beam angles used for angular multiplexing.

How will we use it? This study provides formulas for disk capacity, which we could use to maximize the disk capacity in our research. We could also use their method of run-length limited modulation to reduce the volume taken up by each recording and therefore increase the total number of recordings.

- [3] N. Y. et. al, “Common-path angular-multiplexing holographic data storage based on computer-generated holography”, *Optics Letters* **46**, 2920–2923 (2021).

What did this work do? This paper proposes a method of holographic data encrypting that reduces the necessary equipment by using computer generated holography to simultaneously reconstruct the signal and reference beams.

Why is it relevant? The methods and findings of this paper are relevant to our project because they propose a unique holographic encryption technique that needs further refinement to increase recording density.

How will we use it? Our project would apply the method of angular multiplexing used in this study to minimize the equipment required and work to optimize the data storage capacity of this technique of holographic data storage.

- [4] R. C. et. al, “Encoding and decoding of multidimensional optical field modulation in holographic data storage”, *Optica* **13**, 591–601 (2026).

What did this work do? This article explains how holographic data storage can store more information by using several properties of light at the same time, including amplitude, phase, and polarization. The researchers developed a method for encoding and decoding information using these different properties in one holographic storage system.

Why is it relevant? This is relevant to our project because we are also studying ways to increase the amount of information that can be stored holographically. It shows that storage capacity can be improved by changing more than just the position or angle of the light beam.

How will we use it? We will use this article to better understand how different properties of light can be controlled in a holographic storage setup. It may also help us think about possible ways to increase the amount of data stored in our system beyond only using angular multiplexing.

- [5] Microsoft, *Project hsd: holographic storage device for the cloud*, (2026) <https://www.microsoft.com/en-us/research/project/hsd/how-does-holographic-storage-work/> (visited on 2026).

What did this work do? This online article by Microsoft research department describes how holographic data storage works as well as their plan to develop holographic data storage for the cloud.

Why is it relevant? This is relevant to our project because it describes a holographic encryption set up using angular multiplexing similar to the set up we hope to achieve.

How will we use it? We will apply this information when creating our own set up for holographic data encryption by using a similar method of changing the angle of the reference beam to maximize data storage.