Holographic Data Storage

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1. Introduction

Our memory is fickle and fleeting and so through centuries, we have innovated to grow our external memory through writings, paintings, photographs and so on. The digitalization of information storage devices have followed a trend similar to Moore's law - digital space is becoming both cheaper and more abundant every year. At the same time, the digital age has enabled more ways of collecting and analyzing data. This interaction between the supply and demand for storage has led to intense innovation in data storage. However, magnetic data storage drives that currently dominate the commercial data storage market are reaching their physical limits. In this evolution of external memory, Holographic Data Storage (HDS) stands as a strong contender to lead the next generation of data storage.

2. Background

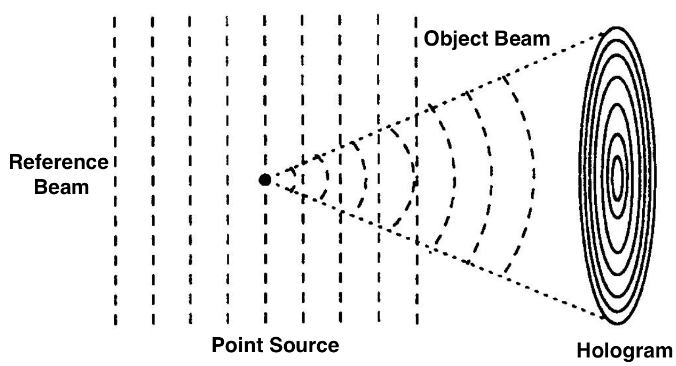

Fig. 1: Hologram of a point source constructed using the interference of a plane wave as a reference beam. The spherical object beam interferes with the reference beam on a holographic media forming the hologram. Source: *laser.physics.sunysb.edu*

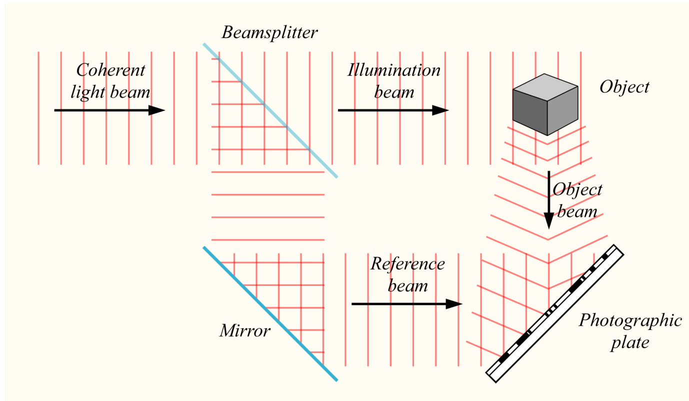

Fig. 2: The process of recording of a hologram. Source: *wikipedia.org*

Holography is the process of capturing and reconstructing optical information of a three-dimensional object. We can think of holography as three-dimensional lens-less photography. To create a hologram we need a coherent light beam, a beam splitter, an object and a photographic medium to record the hologram in. The coherent light beam is generally a laser beam and the photographic materials are commonly photorefractive crystals and photopolymers. In order to understand the process of creating a hologram for a complex object, let us first look at hologram of point sources. A beam from a coherent source, typically a laser, is split into a reference beam and an object beam. The reference beam, depicted as plane waves in Figure 1, is shone on the point object, which leads to the creation of the object beam, represented as spherical waves. The object beam and the reference beam interfere at a holographic medium and the resulting interference pattern is recorded in this photosensitive material. This interference pattern is the hologram for a point source.

Any complicated object is composed of a set of point sources. Similar to a point source, a hologram of any object can be created using the method described above (Figure 2). The image is reconstructed by shining a reconstruction beam on the film that was used to record the hologram, which diffracts the beam such that the viewer sees a virtual image of the original object (Figure. 3).

So far we have considered recording of holograms in thin mediums but optical interferometric information can also be stored in thick volumes. Whether a media is thick or thin is determined by the evaluating Q parameter:

$$Q = \frac{2\pi\lambda L}{n_0 \Lambda^2}, \tag{1}$$

where λ is the wavelength of light, L is the thickness of the recording layer, n_0 is the refractive index of the medium and Λ is the grating period. This media is considered thin if Q $<$ 1 and thick if Q $>$ 1. Holograms recorded in a thick medium are called volume holograms. Volume holograms are specially useful because they allow for more dynamical range - storing of multiple holograms in the same physical location through multiplexing.

Multiplexing is the process of storing multiple holograms in the same physical location by using distinct reference beams that vary in terms of wavelengths, angle of incidence or some

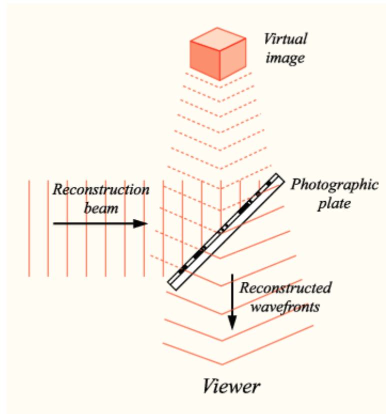

Fig. 3: The process of reconstructing a virtual image of an object using a hologram. . Source: *wikipedia.org*

other optically distinguishable characteristic. To understand multiplexing we must understand diffraction efficiency. Diffraction efficiency of a material is the amount of incident light that is diffracted into the direction of the object beam. For a recorded hologram, the diffraction efficiency of the medium is dependent upon the similarity between the original reference beam and the reconstruction beam. In fact, a slight discrepancy in the wavelength, phase or the angle of the readout beam can lead to zero diffraction efficiency. This sensitivity can be used to store multiple holograms in the same physical location through multiplexing. Given a thick media with a recorded hologram, angular multiplexing is done by changing the angle of reference beam such that diffraction efficiency for the original hologram is zero. This new reference beam can then used to write a new hologram in the same location. Having recorded multiple holograms, these holograms can be read by using the different reference beams that were used to construct them. [4]

3. Application

A HDS device, as the name suggests, stores data as holograms. To do so, digital information, which is in the form of 0s and 1s, needs to be translated into optical data. Given a long string of binary digits, we can convert them into grids of binary data and then assign light and dark regions of the interference pattern to the 0s and 1s. In doing so, we have translated the digital data into a black and white grid. This grid is referred to as a data page and is shown in Figure 4.[3] A page is recorded in a volume hologram using a spatial light modulator (SLM), a device capable of spatially modulating amplitude, phase and polarization of light waves.[2] We can think of an SLM as a grid with thousands of pixels where each pixel can be made dark or light (i.e. each pixel can be switched on and off.) As shown in Figure. 2, a coherent beam is split using a beam splitter and one of the two resulting coherent beams is shone upon the SLM, while the other is reflected. The object beam from the SLM and the reference beam interfere at a thick recording medium hence forming a volume hologram. This hologram can be read by sending the same reference beam through the hologram and focusing the resulting light onto a detector. A charged-coupled device is commonly used as a detector. The original digital grid is reconstructed at the detector, which we can convert to the original information we stored, as shown in Figure 5.

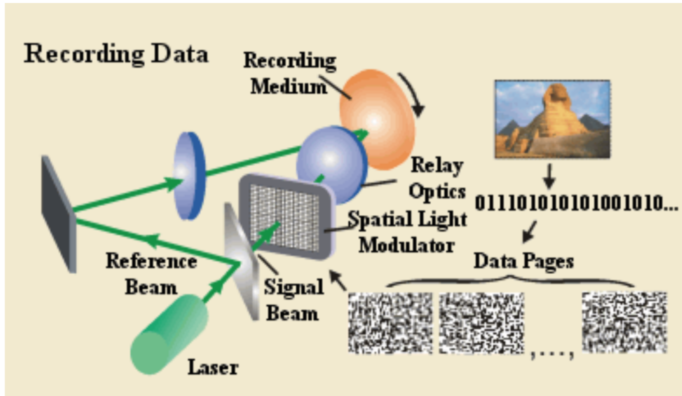

Fig. 4: A detailed description of the process of recording data in a hologram. Source:howstuffworks.com

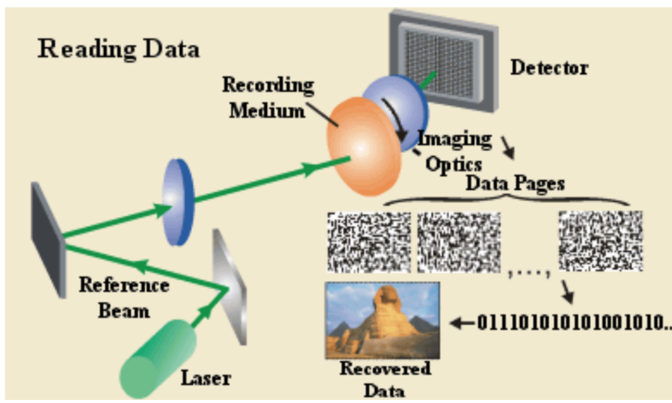

Fig. 5: A detailed description of the process of reading data from a hologram. Source:howstuffworks.com

HDS devices are faster, more capacious, more secure and more durable than the commercially available data storage methods. These characteristics make the HDS ideal for institutions that large amounts store private or sensitive information for long periods of time and require a fast recording and retrieval rate. Government run-institutions, large IT companies, hospitals and media companies are ideal examples of such institutions. In the following paragraphs, we will discuss each of these characteristics in detail.

It has been claimed that the data transfer rate of HDS devices can reach upto 10 Gbit/s which is the fastest data transfer method in the current market. This speed is achieved due to the parallel data recording and readout process used by HDS devices. As described before data read or written as whole pages in a HDS device, which allows for parallel recording or readout. This is considerably faster than the linear data readout processes of magnetic drives. Moreover, as HDS uses optics its speed is much higher than data storage methods that rely solely on electronic circuits.

As shown in Table 1, HDS is much more dense than its commercial alternatives. HDS has immense storage density because through multiplexing multiple holograms can be recorded at the same physical location in a thick medium. Moreover, the holograms are stored throughout the volume of the medium allowing for more storage per volume than currently used optical data storage devices like CD and DVDs, which store data only on the surface. [1] In fact, the storage density of a device can be further increased by implementing multiple multiplexing methods simultaneously. [3]

Currently, the commercial data storage market is dominated by magnetic tapes, optical tapes (for instance CD and DVDs) and flash drives. Magnetic and optical tapes provide archival storage at a rate much cheaper than any other alternatives, while flash-drives have commendably fast data retrieval times. However, neither of the three have both large storage capacity with fast data retrieval time. HDS devices, which have both these qualities, is attractive to consumers who require both high capacity and short data transfer time. [5]

Another benefit of using HDS drives for archival storage is the added security offered by these devices. For a HDS device, the read and write process has many degrees of freedom as we can vary the phase, wavelength, angle and polarization of the reference beam. These degrees of freedom each allow for different ways of encrypting data. For instance, in wave-length code encryption, if someone illegally tries to read the data with a readout beam of wavelength that is different from the reference beam used to record the data then the diffraction efficiency will be zero and no information will be retrieved. This further means that there are as many ways of encryption as there are ways of multiplexing and so we can encrypt different holograms with different encryption techniques.[7]

Longevity is another attractive feature of HDS devices. HDS devices have a lifetime of around 50 years which is considerably more than that of magnetic drives. As shown in Table 1, none of the commercially available data storage methods have such a long life-expectancy. However, being able to save information for 50 years is not the same as being able to retrieve it after 50 years. As hardware and software are updated regularly, some institutions are concerned if their old storage devices would still be able to be read after 50 years. In response to that, companies making HDS are engineering their devices to have backward capability. As HDS itself is a new-born technology, the backward compatibility of the devices in reading decades old data is yet to be concretely established.

With all the amazing features that HDS boasts, the biggest weakness of HDS devices would be their cost - the most recent price for a HDS drive was 18000 dollars. Therefore, the next challenge in front of engineers is to create HDS devices at a much lower cost. Moreover, HDS devices so far rely mainly on angular multiplexing. Exploration of the efficacy of other multiplexing techniques to store holograms is another plausible next step in the development of HDS. [3]

4. Broader Impacts

The dawn of HDS as a commercial storage method would have many economic implications - for the data storage market and for the world as a whole. As certain companies hold patents for development holographic drives, new companies will break the barrier of entry and will come to the forefront. This will lead to transfer of labor, capital and wealth from well-established companies to the newer ones that manufacture HDS devices. Moreover, we might see to a noticeable change in how data is used and stored worldwide - institutions and people alike will be more liberal with generating and storing more data. The effect of this would be similar to the transition from 1.44 MB floppy drives to multi GB blu-rays.

The scenario above however is an optimistic prediction. The reality is that HDS as been the “next big thing” for quite a long time and there is not much reason to believe that HDS will ever dominate and reform data storage. The main source of my pessimism is the rise and fall of InPhase Technologies. With multiple experienced scientists working for it, InPhase Technologies made considerable headway in commercializing HDS devices. The marketing and publicity was very successful and big companies like Nintendo seemed willing to partner with InPhase. However, their products even as advertised were considerably expensive. Moreover, by setting unrealistic goals and through bad capital and labor management, the company eventually went bankrupt in 2011. The fall of InPhase has been noticeable and will be enough to drive potential investors away from HDS. Magnetic hard drives have economy of scale on their side and they are much cheaper than HDS, even though HDS might be more efficient. With high costs and low-investment, HDS cannot realistically compete with magnetic drives. The situation is worsened by emergence of newer competitors. Potential competitors of HDS include 3D optical storage devices that promise to store 1000 TB in a disc similar in size to a DVD and M-Disc that claims to have a life-expectancy of 1000 years. [8]

In conclusion, the advancements in speed, security, storage density and life-expectancy make HDS a great candidate to replace the older and inferior techonologies currently in the market. However, there probably will not be any good news for HDS in the near future because the technology is expensive and there are virtually no investors willing to invest in technology. With older storage methods getting cheaper, and newer storage methods getting more abundant, rise of HDS as the “next big thing” would be fortunate but unrealistic.