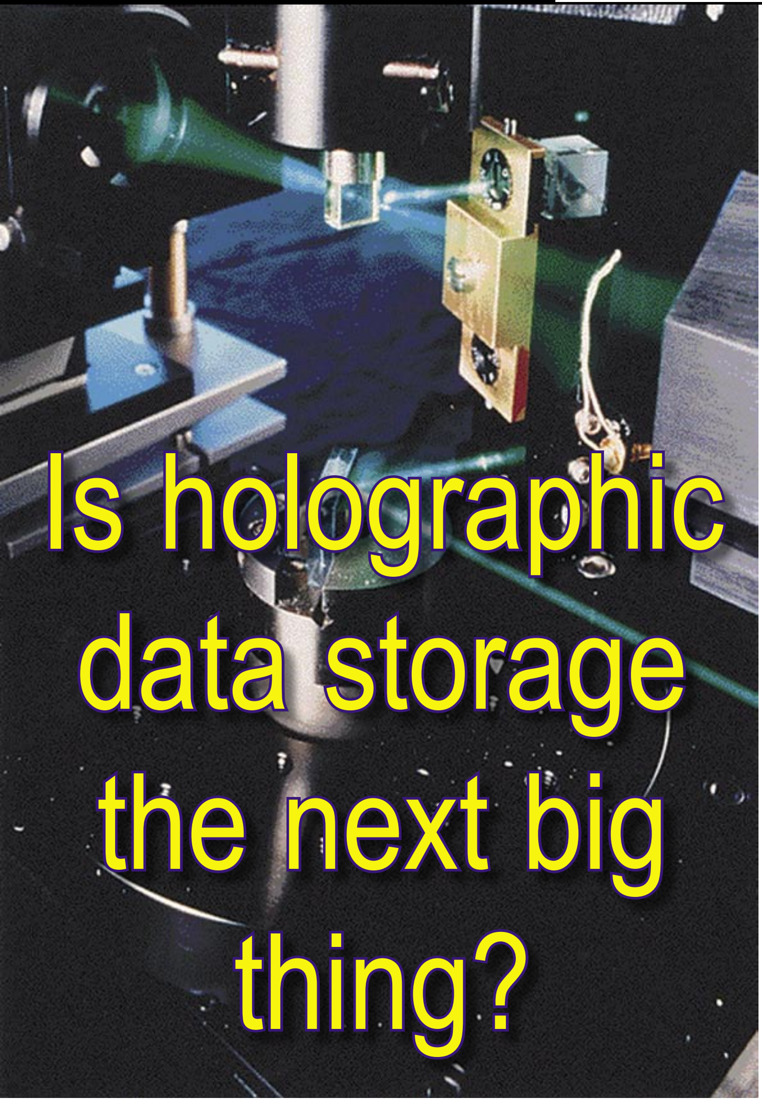


Is holographic data storage the next big thing?

In the era of the Internet and the DVRs expansion in the CCTV market, massive amounts of information are stored. Current storage capacities seems to never be sufficient. Hard disk manufacturers are now considering vertical magnetic particles in order to achieve even higher storage density per square millimetre. There is strong evidence, however, that these surface-storage technologies are approaching fundamental limits that may be difficult to overcome; the ever-smaller data storage regions become less thermally stable and harder to access. New technologies are needed. It seems that Superman's idea of crystal Holographic data storage is one of the most promising.

This article is courtesy of physicsweb.org.

An intriguing approach for the next generation of data-storage systems uses optical holography to store information throughout the three-dimensional volume of a material. And by superimposing many holograms within the same volume of the recording medium, it should be possible to achieve far greater storage densities than current technologies can offer.

Although holography was conceived in the late 1940s, it was not considered a potential storage technology until the development of the laser in the 1960s. The rapid development of holography for displaying 3-D images led to the realization that holograms could potentially store data at a volumetric density of one bit per cubic wavelength.

Given a typical laser wavelength of around 500 nm, this density corresponds to 10^{12} bits (1 terabit) per cubic centimetre or more.

In holographic storage, data are transferred to and from the storage material as 2-D images composed of thousands of pixels, each of which represents a single bit of information. Since an entire "page" of data can be retrieved by a photodetector at the same time, rather than bit-by-bit, the holographic scheme promises fast read-out rates as well as high storage densities. If a thousand holograms, each containing a million pixels, could be retrieved every second, then the output data rate would reach 1 gigabit per second (1 Gb/s). In comparison, a DVD optical-disk player reads data 100 times slower. Despite this attractive potential, however, research into holographic data storage all but died out in the mid-1970s due to the lack of suitable devices that could transfer 2-D pixelated images.

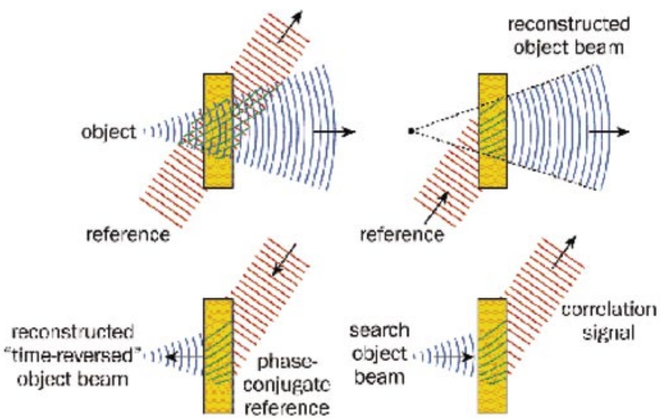


Illustration of Holographic storage of a single data bit. The spherical wave from a single pixel (the object shown in blue) interferes with a coherent plane wave (red) in the reference beam. The resulting interference pattern (green) changes the refractive properties of the photo-sensitive medium (yellow).

Interest in volume-holographic data storage was rekindled in the early 1990s by the availability of charge coupled devices (CCD), semiconductor detectors, small liquid-crystal panels and other devices that can display and detect 2-D pages of data. The wide availability of these devices was made possible by the commercial success of hand-held camcorders, digital cameras and video projectors.

With these components at their disposal, researchers have begun to demonstrate the potential of holographic storage and have shown that data can be stored at densities equivalent to 390 bits per square micron. This density exceeds the storage capabilities of DVD disks by a factor of almost 20, and of magnetic disks by a factor of five.

Holography basics

A hologram is a recording of the optical interference pattern that forms at the intersection of two coherent optical beams. Typically, light from a laser is split into two paths called the object and reference paths. The beam that propagates along the object path carries the information while the reference beam is used to record and read out the hologram. A plane wave is commonly used as the reference beam because it is simple to reproduce at a later stage.

To make the hologram, the reference and object beams are made to overlap on a photosensitive medium, such as a photopolymer or an inorganic crystal, where the resulting optical interference pattern creates chemical and/or physical changes. As a result, a replica of the interference pattern is stored as a change in the absorption, refractive index or thickness of the media.

The pattern contains information about both the amplitude and the phase of the two light beams. This means that when the recording is illuminated by the read-out beam, some of the light is diffracted to "reconstruct" a weak copy of the object beam. If the object beam originally came from a 3-D object, then the reconstructed hologram makes the 3-D object reappear.

If the hologram material is thin - as it is on many credit cards - the read-out beam can differ in angle or wavelength from the reference beam that was used to record the image and the scene will still appear. However, if the hologram is recorded in a thick material, the reconstructed object beam will only appear when the read-out beam is almost identical to the original reference beam.

Since the diffracted wavefront accumulates energy from throughout the thickness of the storage material, a small change in either the wavelength or angle of the read-out beam generates enough destructive interference to make the hologram effectively disappear.

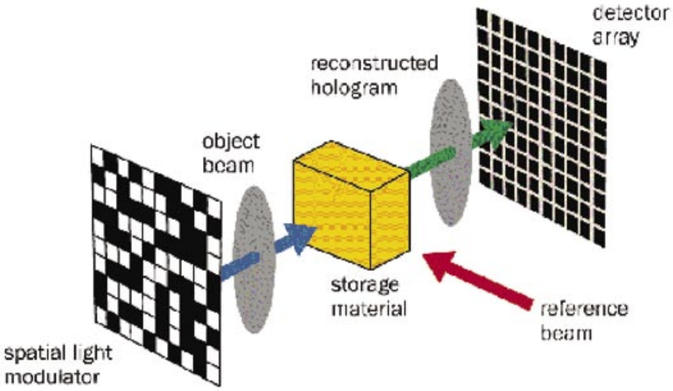
The sensitivity of the holographic reconstruction to changes in wavelength and angle increases with the material thickness, which means that the laser and read-out optics need to be stable and give repeatable results. However, destructive interference also opens up a tremendous opportunity: a small storage volume can now store multiple superimposed holograms, each one distributed throughout the entire volume. The destructive interference allows each of these stored holograms to be independently accessed with its original reference beam.

Several different techniques have been developed to define a set of suitable reference beams by, for example, slightly changing the angle, wavelength or phase of the original light beam. Using so-called angle multiplexing, as many as 10 000 holograms have been stored in a 1 cm^3 volume.

Storing and retrieving digital data

To use volume holography as a storage technology, digital data must be imprinted onto the object beam for recording and then retrieved from the reconstructed object beam during read out.

The device for putting data into the system is called a spatial light modulator (SLM) - a planar array consisting of thousands of pixels. Each pixel is an independent microscopic shutter that can either block or pass light using liquid-crystal or micro-mirror technology. Liquid-crystal panels with 1000 x 1000 pixels and micro-mirror arrays with 1000 x 800 elements are commercially available due to the success of computer-driven projection displays. The pixels in both types of device can be refreshed over 1000 times per second, allowing holographic data-storage systems to reach input data rates of 1 Gb/s - assuming that the laser power and material sensitivities permit.



Data are imprinted onto the object beam by shining the light through a pixelated device called a spatial light modulator. The reference beam overlaps with the object beam on the storage material, where the interference pattern is stored as a change in absorption, refractive index or thickness of the medium. A pair of lenses image the data through the storage material onto a pixelated detector array, such as a charge coupled device (CCD).

The data are read using an array of detector pixels, such as a CCD camera or a semiconductor sensor. The object beam often passes through a set of lenses that image the SLM pixel pattern onto the output pixel array. To maximize the storage density, the hologram is usually recorded where the object beam is tightly focused.

When the hologram is reconstructed by the reference beam, a weak copy of the original object beam continues along the imaging path to the camera, where the optical output can be detected and converted to digital data.

The speed of a storage device is described by the read-out rate (in bits per second) and the latency, or time delay, between asking for and receiving a particular bit of data. To access holographically stored data, the correct reference beam must be directed to the appropriate spot within the storage media. The hologram is then reconstructed and the optical signals processed and decoded to extract the desired digital data.

The read-out rate is often dictated by the camera integration time: the reference beam reconstructs a hologram until a sufficient number of photons accumulate to differentiate bright and dark pixels. A frequently mentioned goal is an integration time of about 1 millisecond, which implies that 1000 pages of data can be retrieved per second. If there are 1 million pixels per data page and each pixel stores one bit, then the read-out rate is 1 gigabit per second. This goal requires high laser power (at least 1 W), a high-quality storage material and a detector that has a million pixels and can be read out at high “frame rates”.

Noise

Noise can arise in a holographic storage system from a number of sources, including poor imaging of the data pattern onto the detector, optical scatter, cross-talk between multiplexed holograms, spatial brightness variations and electronic detector noise. The fundamental trade-off between the levels of signal and noise is a consequence of the finite dynamic range of the storage material. As the number of holograms or the read-out rate increases, the amount of power diffracted towards the detector array decreases, reducing the signal-to-noise ratio and increasing the number of incorrect bits.

Experiments show that an expensive short-focal-length lens system and a storage material with high optical quality are needed to combine high density storage with excellent imaging capabilities. Moreover, the optical system must be corrected for all aberrations,

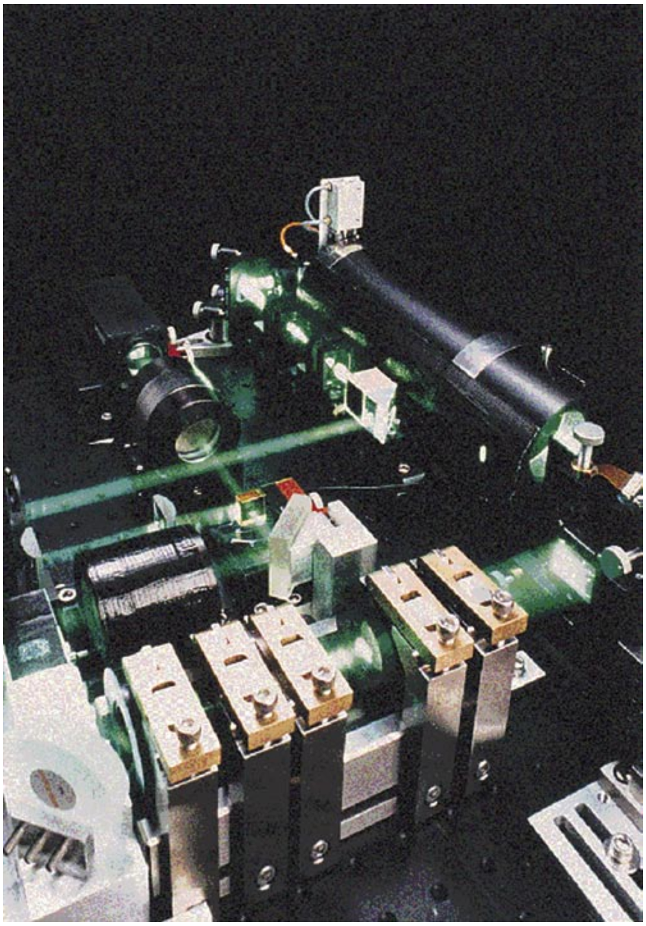
Holographic search speed

Holographic data storage has the unique ability to locate similar features stored within a crystal instantly. A data pattern projected into a crystal from the top searches thousands of stored holograms in parallel. The holograms diffract the incoming light out of the side of the crystal, with the brightest outgoing beams identifying the address of the data that most closely resemble the input pattern. This parallel search capability is an inherent property of holographic data storage and allows a database to be searched by content.

A fast, erasable holographic memory could provide sub-millisecond access to information and support terabytes of data with read-out rates in excess of 1 gigabit per second. Suitable applications might include “video on demand,” large Web servers and, certainly, fast search of a surveillance footage.

Holography could provide a unique hardware device for searching databases rapidly. This device might offer 1000 searches through more than 1 million database records per second, supporting applications such as data-mining, surveillance image search, fingerprint or iris-print databases and bio-informatics.

Write-once 3-D disks could support more than 100 gigabytes per disk, each 120 mm in diameter. Blocks of data 100 megabytes in size could be accessed in 10-100 milliseconds and could perhaps be read out at rates of 500 Mb/s. Suitable applications might include the archiving of data that require permanent storage yet rapid access, such as medical information and surveillance recording. There are initial indications that some write-once materials could possibly be made reversible, leading to erasable 3-D disks.



With a conventional memory or data-storage device, a user must supply an address at which the desired data is located. In volume-holographic data storage, this implies that the data - which were once imprinted on an “object” beam and stored within the volume - can be read out later by illuminating the volume with the correct “addressing” reference beam.

If the patterns that make up these pages correspond to the various data fields of a database, and if each stored page represents a data record, then this optical-correlation process can be used to simultaneously compare the entire database against the search argument. This parallelism gives content-addressable holographic data storage an inherent speed advantage over a conventional serial search through large databases, in particular. For example, it would take a conventional software-based search 40 seconds to go through one million records each containing 1 kilobyte of data. In comparison, an appropriately designed holographic system built using off-the-shelf components could search the same records in about 30 ms - over 1200 times faster. Custom-built hardware could reduce this search time to 1 ms or less.

Holographic storage is an emerging candidate for the next generation of data-storage systems. It could potentially lead to new devices, including fast, erasable holographic memory, write-once 3-D disks, pre-recorded 3-D disks and holographic “content-addressable” database machines .

It may well be that the crystals we have seen in the Superman comics and movies will actually become our "crystal clear" reality. [•]

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