# The Next Generation of Optical Data Storage—Holography

By Lisa Dhar and Edwin Hortelano

The storage and use of digital data is ubiquitous in modern day life. Applications as far ranging as the distribution of content, digital video, interactive multimedia, small personal data storage devices, archiving of valuable digital assets, and downloading over high-speed networks are continually pushing the capabilities of current storage technologies. Of current technologies, optical data storage has had an especially compelling value proposition due to its ability to provide random access to data, rapid replication of content, and the removability of the recording media. However, traditional optical storage technologies are facing growing difficulties in providing the ever increasing storage densities and data transfer rates required by the wide range of applications. These difficulties have triggered a search for the next generation of optical technologies. The most promising is holographic data storage.



## Introduction

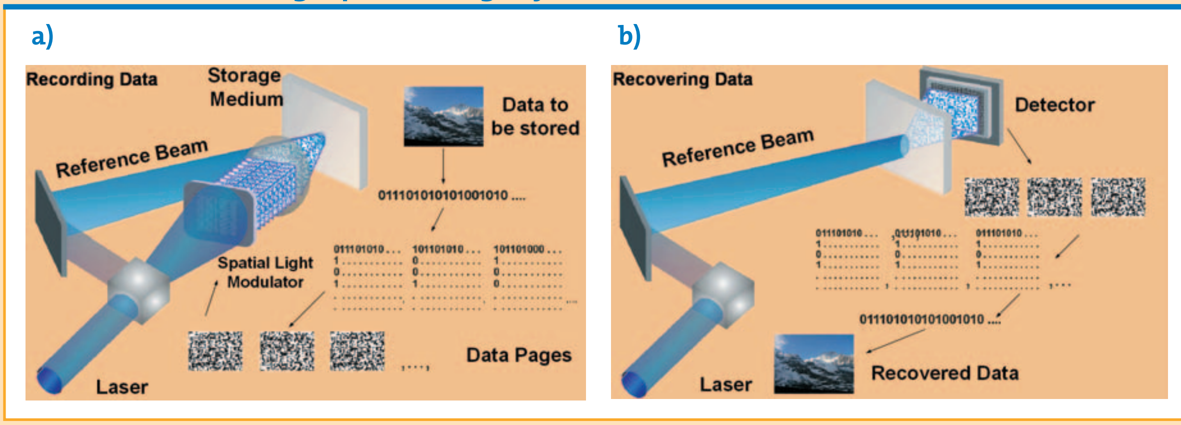
Holographic storage enables storage densities that can surpass those of traditional recording because it goes beyond the two-dimensional approaches of conventional storage technologies to write data in three dimensions. In addition, unlike conventional technologies, which record and recover digital data bit by bit, holography has the ability to read and write millions of bits of data with a single flash of light, enabling data transfer rates of billions of bits per second.

In this article, the underlying principles of holographic storage will be reviewed and one of the enabling advances, the development of high-performance holographic recording materials, will be described. In addition, an overview of the commercialization of holographic data storage will be given.

Figure 1 shows a schematic of a holographic storage system. In holographic storage, light from a coherent laser source is split into two beams—signal and reference beams. These two beams overlap through the volume of a recording medium. The overlapped beams produce an optical interference pattern, which contains information about each beam and is

## FIGURE 1

### Schematics of a holographic storage system




*a) Recording process in holographic storage b) Readout process in holographic storage*

typically imaged as a modulation in the refractive index of the storage medium. The data to be stored are digitized into a stream of 1s and 0s. Here, the 1s and 0s are grouped into arrays or pages, which are then sent electronically to a spatial-light modulator, a device that sits in the path of the signal beam. This device is composed of an array of pixels where each pixel can either block or transmit light passing through it. The signal light beam is therefore modulated with an array of bits with the transmitted signal light resembling a checkerboard pattern with bright and dark squares representing the 1s and 0s.

The data are read out by diffracting the reference beam off of the recorded hologram. The data page is regenerated and captured by an array detector where each pixel of the detector corresponds to a pixel on the spatial light modulator. The data are read off of the detector, allowing the data to be reconstructed. This parallel recording and readout of a million bits at a time enables the rapid data-transfer rates of holographic storage.

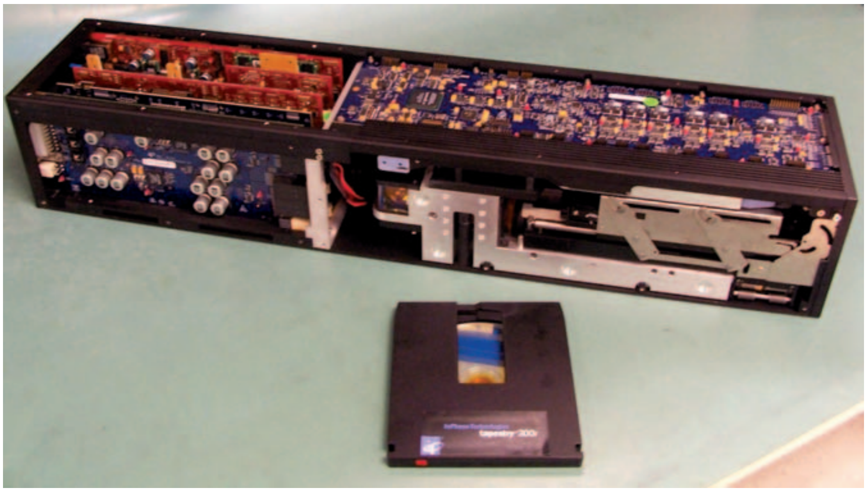
Information stored by the two overlapping light beams possesses a unique volume address provided by the reference beam. Subsequent data pages can be stored in the same volume by altering some aspect of the reference beam, such as its incidence angle, its wavelength, or its phase profile. Individual data pages are then read back independently from the multiplexed set by simply applying the same reference beam used during recording. This ability to multiplex or superimpose throughout the volume yields the enormous storage-density capabilities of holographic storage.

## Challenges

One of the long-standing challenges in the development of holographic storage systems has been the availability of suitable recording media. Holographic media must satisfy stringent criteria, including high-dynamic range and photosensitivity, dimensional stability, readout durability, optical clarity and flatness, shelf life and archival stability. In addition, the material must be manufacturable to enable a commercial system. Many candidate materials, such as lithium niobate, photorefractive polymers, and photochromic materials, addressed a subset of the criteria, but failed to satisfy all. InPhase Technologies has invented high-performance holographic recording materials based on a novel class of photopolymer systems. The material exhibits the performance required for the commercialization of holographic storage.

## How Holography Works

The material is composed of two independently polymerizable systems—one system, the majority component, reacts to form a 3-D crosslinked polymer matrix in the presence of the second photopolymerizable monomer system. The photopolymerizable monomer is the imaging component, as it reacts only during holographic recording. During holographic recording, the optical interference pattern initiates a pattern of polymerization in the photopolymerizable system that mimics the optical interference pattern. Polymerization occurs in the light intensity maxima of the interference pattern while no polymerization occurs in the nulls. This patterned polymerization sets up a concentration gradient in the unreacted species. Unpolymerized species diffuses from the nulls to the maxima of the interference pattern to equalize its concentration in the recording area, creating a refractive



*Holographic recording system.*

difference between the refractive indices of the photopolymerizable component and the matrix.

Using a "two-chemistry" strategy produces high-performance recording media as a result of several important attributes. The matrix is formed in-situ, which allows thick and optically flat formats to be formed. The 3-D crosslinked nature of the polymer matrix creates a mechanically robust and stable medium. The matrix and photopolymerizable monomer system are chosen to be compatible in order to yield media with low levels of light scatter. The independence of the matrix and monomer systems avoids cross reactions between the two that can dilute the dynamic range due to premature polymerization of the imaging component.

## Recent Developments

Recently, InPhase formed a partnership with Bayer MaterialScience to further optimize and to establish the manufacturability of the "two-chemistry" recording materials. A series of statistically designed experiments were used to refine the components of the chemical system to simultaneously optimize parameters such as the thermal cure time of the matrix, the photosensitivity and the dynamic range. The optimization was performed within the boundaries of the required mechanical and environmental properties of the material. Further statistical studies were used to validate the robustness of the formulation to typical variations seen in the raw components of the material formulation. As a result, commercial quantities of the necessary raw materials are provided without lot selection or other costly measures to reduce variation in the raw materials.

With these materials, a holographic recordable drive system targeted for the data archiving market has been developed. The first generation system provides 300 gigabytes per disk of user capacity with recording and readout rates of 160 megabits per second with 250 msec average seek times. The 300 gigabyte drive system is the first entry in a family of products. Second and third generations will provide 800 and 1,600 gigabytes of capacity and 640 megabits per second and 960 megabits per second transfer rates respectively with each drive providing backward read capabilities.

InPhase Technologies has recently reached many important milestones toward the commercialization of its drive-media systems. In October 2005, a prototype unit of these systems was provided to Turner Network Television to evaluate the role of holographic storage in its storage-broadcast systems. Turner used the unit to become the world's first network to broadcast content originating on holographic storage. A promotion for the National Basketball Association was stored on the holographic system, migrated to Turner's servers and aired on its network for several days. In March 2006, the highest data density of any commercially available storage technology was demonstrated, recording and recovering 515 gigabits of data per square inch. In April 2006, InPhase received the 2006 Presidential Emerging Technology Award for its utilization of UV-cured materials in holography at the 2006 RadTech Technology Conference and Expo in Chicago, Ill. In October 2006, at the InterBEE conference in Tokyo, a public demonstration was given on this commercial drive system, which included all drive subsystems such as the auto load/unload mechanics, servo system, holographic read/write head, data channel and electronics. The drive recorded and read out video clips provided by Turner Entertainment Networks. In September 2007, the drive system was demonstrated within a video editing environment at the International Broadcaster's Convention in Amsterdam.

## Summary

With its capabilities and roadmap, holographic data storage can be used in applications ranging from data archiving and data capture to editing in the professional space, to content distribution and to small, mobile form factor storage in the consumer space. ◗

*—Lisa Dhar, Ph.D., is vice president of Media Development, InPhase Technologies, Longmont, Colo. Edwin Hortelano, Ph.D., is director of UV and Waterborne Technology Platforms, Bayer MaterialScience LLC, Pittsburgh, Penn.*