Micro-Holographic Data Storage: Materials and Systems

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Research and development progress on micro-holographic data storage is reviewed. Basic concept of micro-holographic storage, and micro-hologram recording and characterizations are presented. Analysis and experimental results are reported to show that threshold behavior of the material is required to enable high-density micro-holographic storage through multiple layers. Key threshold material parameters are discussed and current material performance is reported. Dynamic system that demonstrates recording and readout of multi-layer micro-holographic storage is presented. Research and development areas to enable micro-holographic solution for high-density optical storage are discussed.

Key Words: Micro-holographic data storage, Threshold material, Disc, Multi-layer optical storage, High-density optical storage

1. Introduction

From CD, DVD, to Blu-ray Disc (BD), optical storage has demonstrated continued data capacity improvements. Currently, the disc storage capacity is ~ 50 GB in a dual-layer BD. To achieve higher storage capacity, holographic data storage is considered a promising candidate. Traditional holographic data storage, which is known as page-based holographic storage, uses whole volume of an optical disc to achieve high data capacity.1 A digital bit is represented by a volume hologram distributed through thickness of the media disc. Because of the Bragg condition, many holograms can co-exist sharing the same volume, which provides the high data capacity. Unfortunately, for the same reason, page-based holographic storage has very low tolerance to environmental conditions such as temperature variation and vibrations. Although these issues may be solved by using advanced compensation schemes in the drive,1 it makes the drive quite expensive (as much as $20,000).

Micro-holographic storage3–5 uses a different approach from the page-based holographic storage. Micro-holographic storage is a multi-layer bit-wise storage, which has a lot of similarities to conventional optical storage such as CD, DVD and BD. The data bits are arranged in data tracks in discrete layers. The differences from the conventional storage are: 1. Each data bit is a hologram - a bright and dark fringe pattern. 2. Data layers are recorded in a monolithic light-sensitive material. In multiple-layer BD, different data layers are recorded at different material layers stacked together in the disc. As layer number increases, the complexity of the disc manufacturing increases and yield on disc manufacturing decreases geometrically, which is probably the main hurdle to commercialize multi-layer BD solution. Compared with page-based holographic storage, the hologram in micro-holographic storage is localized to the focal region of the laser beam instead of distributed through the depth of the disc; therefore, it has much better tolerance to environmental conditions and thus makes the drive economical. In addition, because of the great similarity to conventional optical storage methods, micro-holographic drive can leverage on many technologies developed for BD and is expected to be low-cost.

In this paper, we first present experimental characterization and estimation of diffraction efficiency of a micro-hologram. We then discuss material requirements for multi-layer micro-holographic storage and report state of the art material development. Following that, demonstrations of multi-layer micro-holographic storage in a dynamic tester are presented. Finally, we close with discussions on a few aspects related to a micro-holographic drive for a future product.

2. Single-bit Micro-hologram Characterization

Basic characterization of micro-hologram recording and readout is done in a static micro-holographic system. Several groups constructed such systems over the past few years.3–4,6,7 With these systems, feasibility of recording micro-holograms in existing holographic materials was demonstrated. In addition, this type of system has proven to be an effective tool for material performance characterization as well. Static test system developed by GE group is shown in Fig. 1. The system uses a pulsed Q-switched laser as the light source for recording and readout, and was designed to operate at either 532 nm, or 405 nm. Both configurations utilized laser pulses with energies < 1 μJ, pulse duration of ~ 5 ns, and rep...
etition rate of 200 Hz, which allowed to achieve high light intensity (100 s to 1000 s of MW/cm$^2$) even with low numerical aperture (NA) focusing optics (NA ~ 0.2-0.4).

For micro-hologram recording, the beam was split into two beams (signal and reference) of equal power that were steered and focused into the recording sample in counter-propagating directions. The front and back objective lenses focus the two recording beams into the bulk of the sample and are positioned such that the two focal spots overlap. Polarizations of the two beams are matched to create an interference pattern of bright and dark intensity fringes in the beams’ focal volume, which is subsequently imprinted into the holographic material as a micro-hologram, a high and low refractive index fringe pattern. The recording is performed at a NA of 0.16 (at 405 nm) that results in a beam focal volume ~ 1.6 × 1.6 × 11 μm.

Readout was performed with a single beam of reduced power to minimize overwriting. The focused readout beam is partially reflected backward when positioned on a micro-hologram recorded in the material. After passing through the quarter-wave plate twice, the beam changes its polarization to be reflected by the polarizing beam splitter toward the detector. The detector is equipped with a pinhole for a confocal detection that allows discrimination of the micro-hologram signal from interfering signals such as reflections from holograms in adjacent layers or reflections from the sample surface.

The sample was mounted on a precision 3D translation stage. Upon readout, the sample is translated to characterize the spatial profile of the hologram. Figure 2 shows an example of micro-hologram response curves as functions of hologram displacement from the beam center. One-, two-, and three-dimensional arrays of micro-holograms can be recorded to assess scattering in the material and evaluate cross-talk between adjacent micro-holograms (Fig. 3).

Characterization of the material response involves variation of the recording and readout beam conditions such as the recording fluence, intensity of both recording and readout light, NA, exposure time, etc. The observed reflectivity of a micro-hologram at various recording conditions can be related to material parameters discussed in Section 3.
Diffraction efficiency as a function of the refractive index profile can be calculated using the Born approximation approach. However, important scaling dependencies can be understood from simple treatment of a micro-hologram as a plane-wave grating of finite thickness \( L \), refractive index modulation amplitude \( \delta n \), and recording wavelength \( \lambda \): 
\[
\eta = (\pi \delta n L \lambda)^2
\]
where \( L \) is defined by the recording beam geometry: 
\[
L = 2\Delta n/\pi NA^2
\]
As can be seen, the diffraction efficiency scales as \( 1/NA^2 \), resulting in a significantly lower reflectivity at a higher \( NA \) required to achieve higher density data storage.

3. Materials for multi-layer micro-holographic storage

Materials with linear response that is independent of the intensity of optical irradiation have been commonly used in page-based holography due to their ability to reproduce intensity patterns of overlapping data pages. However, to preserve the data after the recording, a mechanism that terminates sensitivity of the material is needed. An example is a photochemical fixing process that disables the photo-induced refractive index change. This step follows a completed recording of a spatially localized block of data.

In the multi-layer micro-holographic approach, the recording conditions differ significantly. A micro-holographic data mark in a virtual layer is accessed with a focused laser beam, which necessarily exposes the holographic material above and below the virtual layer of interest (Fig. 4). After recording a complete layer of data, the entire thickness of the disk has been exposed to the same fluence and each bit volume receives equal energy \( E \). When \( N \) layers of data are recorded, the amount of energy received by each bit is \( N \times E \), while only \( E \) was used to create a useful interference pattern for each data mark, utilizing refractive index \( \Delta n = \Delta n_{max}/N \). Therefore, to maintain a desired micro-hologram reflectivity, the index capacity \( \Delta n_{max} \) would have to increase as \( N \), making it prohibitively high for any practically relevant numbers of layers.

For multi-layer micro-holographic storage, a threshold material is needed. In a threshold material, sensitivity of the material is a function of the recording light intensity. It is close to zero at low intensities (below the threshold), and large at higher intensities (above the threshold), as shown in Fig. 5 (a). During recording with a high power beam, material operates in the high-sensitivity mode; during readout or under ambient light exposure, the intensity is below the threshold and the material remains inert. Figure 5 (b) shows a measured dependence of diffraction efficiency on recording intensities at a fixed fluence. Although the recording energy per bit was the same, the resulting diffraction efficiency dramatically increased at the high intensity exposures, demonstrating intensity threshold.

Figure 6 presents a static experiment that mimics multi-layer recording in linear and threshold materials. A single micro-hologram was recorded in a sample (marked 1 in Fig. 6 (a)) and its reflectivity profile was scanned along the depth direction. Further, two more micro-holograms were recorded (2 and 2’ in Fig. 6 (a)) above and below the original one, and the reflectivity profile scans were repeated. As seen from Fig. 6 (b), in a linear material the first-written micro-hologram is reduced with each subsequent recording in its surrounding. In contrast, in a threshold material (Fig. 6 (c)), after recording the adjacent micro-holograms (2 and 2’), and even 8 more above and below (3 and 3’), the response of the original micro-hologram was not significantly affected. This comparison clearly illustrates the advantage of a threshold recording mechanism.

Requirements on the threshold material performance are largely driven by the system parameters of a future holographic drive (Table 1). Main performance characteristics of a threshold material are 1) Refractive index change capacity (dynamic range), which limits the micro-hologram reflectiv-
Table 1 Essential system and material parameters (assumes media absorbance 0.3).

<table>
<thead>
<tr>
<th>System parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>NA</td>
<td>0.85</td>
</tr>
<tr>
<td>Laser power (on disc) (mW)</td>
<td>300</td>
</tr>
<tr>
<td>Recording time (ns)</td>
<td>3.5</td>
</tr>
<tr>
<td>Reflectivity</td>
<td>0.1 %</td>
</tr>
<tr>
<td>Energy/bit (nJ)</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Material parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Refractive index change</td>
<td>0.02</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>0.04</td>
</tr>
<tr>
<td>Threshold intensity (MW/cm²)</td>
<td>200</td>
</tr>
</tbody>
</table>

GE threshold holographic materials evolved through several generations. In May 2009, we reported 405 nm threshold material with large refractive index change of ~ 0.1, which is sufficient to achieve hologram reflectivity of ~ 0.1-1% at NA ~ 0.85 to support storage capacity of 0.5 TB in a φ120 mm disc, material sensitivity was ~ 4 × 10⁻⁴ cm²/J and the threshold intensity was ~ 200 MW/cm². We continue working on further material improvements to meet the requirements for a commercial product.

4. Dynamic System

A dynamic system is needed to demonstrate capabilities of recording data to a holographic disc medium in real time. Schematic of the GE dynamic test system is shown in Fig. 7. Recording media used for dynamic testing was based on a linear thermoplastic holographic material optimized for the 532 nm wavelength. A continuous wave (CW) 532 nm single-longitudinal-mode laser with an electro-optic light modulator was used as the light source for recording and readout. In the dynamic tester, data marks are recorded into a continuously rotating holographic disc. Rotation of the disc results in a significant non-repetitive variations in the beam position, therefore calling for a dynamic position compensation mechanism. To access the data for readout after recording, a high degree of beam positioning repeatability is needed. This was achieved through an embedded reference layer in the disc, which acted as a guide for the radial and axial beam positioning.
A two-wavelength configuration was used for repeatable beam positioning on a data layer. A 532 nm data beam was used to record and read holographic patterns; a 658 nm tracking beam generated error signals used in positioning control for the data beam to stay on a pre-determined trajectory (Fig. 7). The two beams were decoupled with dichroic optical components. The tracking and data beams share the moving optical element of the system (objective lens L3), so that the run-out compensation of the tracking beam results in compensation of the data beam run-out.

The error signals are generated using well-known approaches from the traditional optical disc storage area. Both axial (focusing error - FE) and radial (tracking error - TE) positioning errors are extracted from the optical signals received by four segments of a quadrant detector. The focusing error is generated using the astigmatic technique, which utilizes an elliptical beam spot on the detector whose shape changes with the axial displacement of the focal spot in the disc. The tracking error is generated from the push-pull signal that arises from the interference between the specular-reflected beam and ±1-order diffracted beams. Both focusing and tracking error signals are represented by a S-shaped curve that crosses zero at the optimal beam position.

Recording process is conceptually similar to that in a static tester. For a rotating disc, the overlap of two recording beam spots must be dynamically maintained at all times during the recording, therefore the positioning of the back beam focal spot is controlled through another (three-axis) servo control loop via positioning of the back objective lens (L4) along the axial and radial directions, and a galvanometer mirror for tangential displacement. Generation of the positioning error is performed using one of the data beams that passes through both objective lens assemblies, and is collected on another quadrant detector. FE generation is identical to that used with the tracking beam. The radial and tangential follow errors are computed as combinations of quadrant signals.

The optical system was designed to operate at the numerical aperture (NA) of 0.4 with wavefront error better than 0.05, and had capability of arbitrary depth selection from 0.1 to 0.5 mm into the disc.

Signal focusing and control was done using a dSPACE real-time rapid control prototyping system. Optical signals from the quadrant detectors were filtered through a set of programmable low-pass filters (5 kHz cut-off). The band accommodated the spectrum of the disc movement at 120 RPM. Signal variations due to the light modulation lie outside the band to reduce interference of the data stream with the servo operation.

Using the described dynamic test system, recording of periodic waveforms as well as 17PP/NRZI run-length limited data was demonstrated. A preliminary demonstration of waveform recording in up to 5 layers was performed. Fig. 8 shows...
monotone waveform readout from 5 different layers recorded at 5 different carrier frequencies. The layer spacing was 30 \( \mu \text{m} \), and recorded region spanned over ~0.5 mm along the disc radius. An example waveform of a 17PP data is shown in Fig. 9. Recording was done over hundreds of tracks, after which the depth was changed by 30 \( \mu \text{m} \) and the second layer of data was recorded. The average raw bit error rate (BER) was estimated to be 0.1 to 1 \% immediately after recording. Adding another layer significantly deteriorated the previously recorded data due to the erase effect in the linear material, as discussed in Section 3.

5. Discussions and Conclusions

To achieve TeraByte storage from micro-holographic approach, data layer number needs to be ~30-40, which is significantly larger than current BD. Larger layer number will require signal level to be lower. SONY calculated from SNR perspective that transmittance of each layer should be greater than 98 \% (i.e., diffraction efficiency smaller than 2 \%) for large layer numbers.\(^{(16)}\) Due to scattering loss and absorption of disc material, signal level from multi-layer micro-hologram can be even smaller. Reflectivity \((R)\) from the bottom data layer, assuming 50 \% data filling density in each layer, can be calculated as:

\[
R = DE \cdot X^{2(\text{N} - 1)} \\
X = (1 - DE \cdot 0.5) \cdot e^{-2.3 \cdot A/N}
\]

Where \(N\) is layer number; \(DE\) is diffraction efficiency from a micro-hologram; \(A\) is disc absorbance. Figure 10 shows that signal will be less than 1 \% for a 40 data layer case. Reduced signal level may require improvement on signal detection in the drive system.

As described in Section 4, the currently demonstrated dynamic test system relies on a single reference layer for beam positioning on the data tracks in multiple layers. With increased NA in a higher capacity system, this implementation becomes more challenging as the tilting and other deformations of the disc result in an uncompensated run-out of the data beam from the hologram data track. Generating error signals directly from the reflected data beam would be the most natural and efficient. We demonstrated feasibility of error signal generation from the data beam reflected from a micro-hologram in a static experiment. More recently, SONY demonstrated tracking from data layer in a dynamic test system.\(^{(19)}\) Compared with conventional groove tracking method, the readout signals acquired with tracking from the data marks resulted in a significant improvement in the envelope of the modulated signal.

Replication process in micro-holographic storage brings new research and development challenges and opportunities. Injection molding process can be used to produce monolithic micro-holographic discs. However, since the data bit is a fringe pattern in micro-holographic storage, an optical replication process has to be developed to put content or format in a disc.

In summary, micro-holographic storage is promising as a high capacity, low cost optical storage candidate. Dynamic recording and readout of micro-holographic storage has been demonstrated. To achieve multiple data layers, threshold material is required and has to meet a set of performance parameters. Threshold material has been developed and currently is under performance improvements. While micro-holographic drive can leverage on many technologies developed for BD, improvements or modifications on signal detection, servo schemes, and others may be required or beneficial. In addition, replication for micro-holographic storage is completely different from conventional replication solution and needs to be developed.

References


