Capacity of a 3-D multi-layer optical data storage system

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ABSTRACT
Storage capacity of a 3-D multi-layer optical data storage system is analyzed. Theoretical analysis of recorded bit size and cross-talk are presented and experimentally verified.
Keywords: multi-layer data storage, two-photon recording, cross-talk, capacity, photochromic optical memory, fluorescent readout

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Introduction

A high capacity 3-D multi-layer optical data storage system is being developed at Call/Recall, Inc. A single beam 2-photon recording technique is used to record data tracks and layers within a monolithic thick plastic disk[1,2]. The recorded bits emit broadband fluorescence when excited by a laser beam within the absorption band of the written molecule (Figure 1). The recorded volume has no noticeable index change in the visible spectrum. The recorded bits are non-reflective for the readout beam and recording beam. These properties allow the recording and readout beams to access multiple layers in parallel[3,4,5]. The capacity of the 2-photon 3-D multi-layer optical data storage system is influenced by the recorded bit volume, track pitch and layer separation.

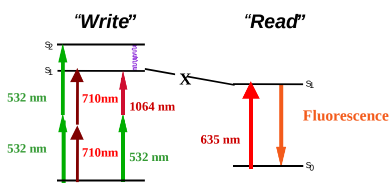

Figure 1 Two-photon fluorescence media recording and readout

Call/Recall, Inc has developed a series of 2-photon recording materials using photochromic fluorescence compounds, that are well suited for 3-D optical memory. A high power laser pulse is required for 2-photon recording due to the low cross-section absorption. Experimentally, a 532nm Nd:Vanadate laser having a pulse width 6.5pSec and repetition rate of 27MHz is used. A 1Mb/s recording rate is achieved with average power of 1.5W and peak power of 10KW. A frequency doubled Ti:Sapphire laser of 460nm is also used having pulse width of 200fSec, repetition rate 76MHz and average power of 0.4mW resulting in a slower recording rate. For readout, a 635nm CW laser diode operating at 0.3mW is used. When the recording laser beam is focused inside the media, the photochromic compounds are excited by the sum of 2-photon energy localized around the focus, then the excited material transforms into a new stable written form. Because of the two-photon response and the irradiance distribution of the focusing beam, recording takes place only within a small volume around the focus of the laser beam. The structure of the recording and readout system is shown as Figure 2.[3]

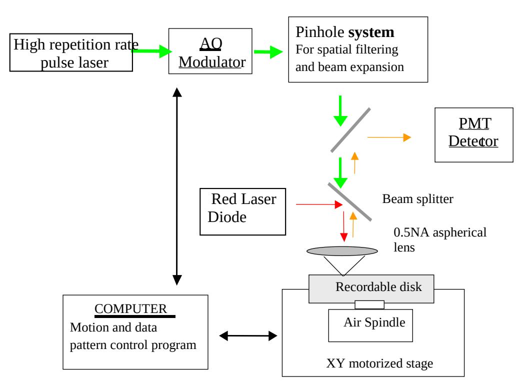

Figure 2 Single-beam two-photon recording system diagram

Recorded bit size

In the recording, the excited molecular distribution can be simply considered to be proportional to the square of the irradiance distribution of the recording laser beam. The recorded bit shape is modeled as:

$$P(x,y,z) = \alpha \times I^2(x,y,z) \qquad (1)$$

α, a constant, is different from one type of molecule to another. $I(x,y,z)$ is the laser beam irradiance. At focus, the laser is Gaussian-shaped, giving:

$$I(x,y,z) = \frac{I_0}{\omega_0^2[1+(\frac{\lambda z}{n\pi\omega_0^2})^2]} \exp\{\frac{-2(x^2+y^2)}{\omega_0^2[1+(\frac{\lambda z}{n\pi\omega_0^2})^2]}\} \qquad (2)$$

where, I_0 is the peak irradiance, $\omega_0 \approx 0.61\lambda/NA$ is the radius of beam waist, λ is the wavelength and NA is the numerical aperture. An OPTISCAN[6] simulation shows the irradiance squared, I^2, distribution of a λ=460nm, NA=0.5 system to have bit dimensions of 0.7*0.7*10μm^3 as shown in Figure 3(a). Figure 3(b) is the image of a real experimental recorded bit

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obtained with an Olympus fluorescence confocal microscope having dimensions of 0.7*0.7*10μm^3. It is recorded with 460nm laser and 0.5NA objective lens. The simulation result matches the recording result. From the bit shape model, we know that the recorded bit size depends on the wavelength and the NA. Figure 3(c) shows the experimental recorded bit with the 532nm laser and 0.5NA objective lens and the bit size is about 1.2*1.2*14μm^3 as expected. Figure 3(d) is the recorded bit with the 532nm laser and 0.75NA objective lens and the bit size is about 0.7*0.7*5μm^3 as expected.

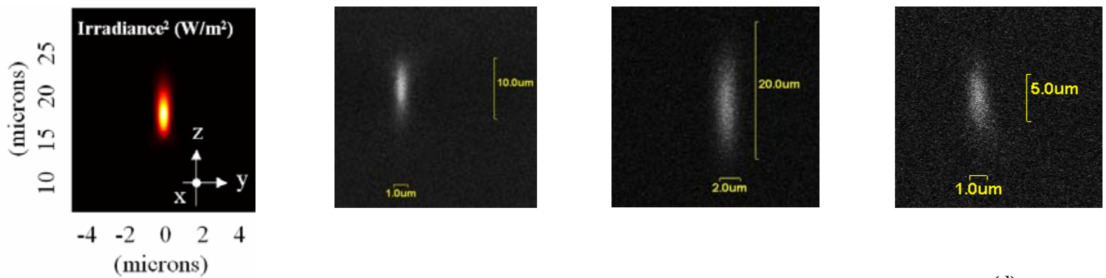

Figure 3 (a) Simulation bit shape: wavelength: 460nm, NA:0.5; (b) Recorded bit: wavelength: 460nm, NA: 0.5; (c) Recorded bit: wavelength: 532nm, NA: 0.5; (d) Recorded bit: wavelength: 532nm, NA: 0.75

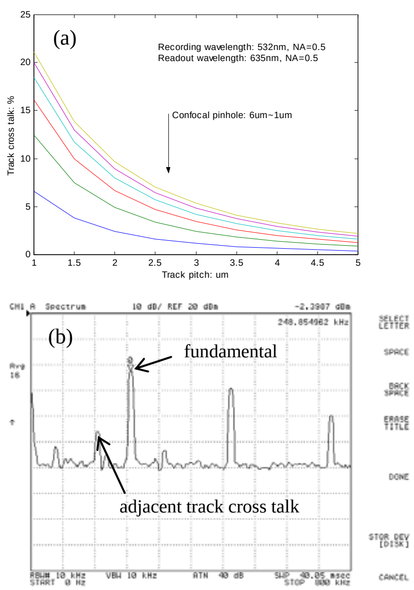

Figure 4 (a) Simulation of the tracks cross talk: recording λ=532nm, NA=0.5; readout λ=635nm, NA=0.5; (b) Experimental result.

Track pitch and areal capacity

The fluorescence generated inside the disk is proportional to the convolution of the recorded bits volume and the illumination beam. The excited fluorescence is incoherent and broadband, $\Delta\lambda \approx 40$nm, with the central wavelength around 680nm. The resolution of the readout system is related to the diameter of the illumination airy disk as well as the recorded bit dimensions, as cross talk from adjacent tracks and layers may cause errors. A confocal pinhole helps to decrease cross talk.[3] Figure 4(a) shows simulation results of cross talk between adjacent tracks in a 1X optical magnification system as a function of confocal pinhole size. Figure 4(b) is an experimental result with the 532nm and 0.5NA system. Different single tone patterns are recoded on adjacent tracks at a track pitch of 3μm. A 15μm pinhole is used in readout with a system magnification of 2.5X, corresponding to a 6μm pinhole in a 1X magnification system. The simulation and experimental results show that the cross talk is about 5% (-26dB).

The total areal capacity is expressed as:

$$C_{areal} = \frac{\pi(r_{max}^2 - r_{min}^2)}{l_{bit} \times w_{pitch}} \qquad (3)$$

r_{max}, r_{min} are max and min recording radius of the disk, l_{bit} is the bit length and w_{pitch} is the track pitch. The areal per layer capacity of 5.25” 2-photon disk is approximately 0.7GB with 1.5μm track pitch.

Layer separation and volume capacity

In a 3-D multi-layer optical data storage system, layer separation is another factor that influences the volume capacity. From analysis and experiments, the depth of the focus of the recording beam affects the length of the recorded bits and will influence the layer separation: the shorter the depth of the focus, the smaller the layer separation. A confocal pinhole also helps to decrease the adjacent layer cross talk. Figure 5(a) shows the simulated relationship between the NA of the recording objective lens and the layer separation, where the cross talk from the adjacent layer is set at 5%. Figure 5(b) is the experimental result. The cross talk from the adjacent layer is ~5% (-26dB). The recording condition is: 532nm laser with 0.5NA objective lens, layer separation of 30μm and track pitch of 3μm. For readout, there is a 4X optical magnification, a DOE to achromatize the fluorescence[4] and a 5μm pinhole placed before the detector.

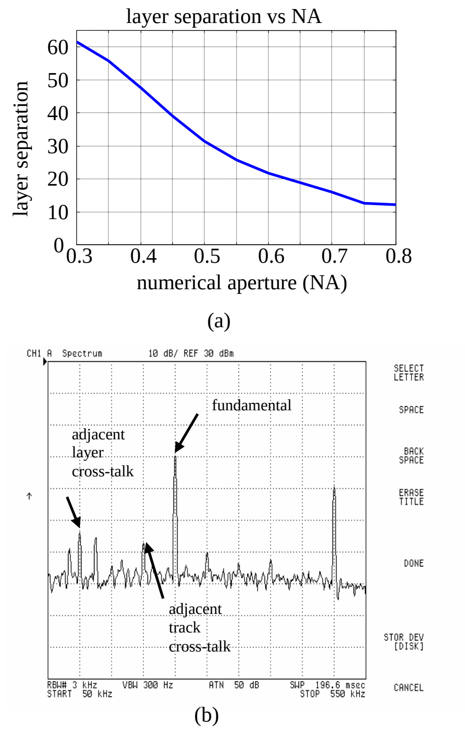

Figure 5 (a) Layer separation vs. NA
(b) Experiment result

The number of layers that can be recorded is expressed as:

$$N_{layer} = \frac{T_{disk}}{S_{layer}} \quad (4)$$

T_{disk} is the thickness of the disc; S_{layer} is the layer separation. The volume capacity of a 2-photon 3-D optical data storage disk is:

$$C_{total} = C_{areal} * N_{layer} \quad (5)$$

For a 5.25" diameter 3mm thick disk, the capacity could be 70GB. In the experiments, a Hamamatsu R4900-02 PMT is used to detect the fluorescence. A custom designed CMOS 2-D detector array will be available soon for 2-D parallel readout experiments. This detector has nW sensitivity and MHz frame rate. The 2-D Detector layout architecture is carefully designed to increase the signal quality and decrease cross talk. A 3-D coding scheme will further decrease the cross talk.[7] By using these techniques, 140GB capacity is possible for a 5.25" diameter 3mm thick disk. Currently, a 1.5μm track pitch and 15μm layer separation is being tested.

NA influences the capacity more than the recording wavelength. A high NA objective lens reduces the track pitch and layer separation. The working distance of the high NA lens should also be considered, as it will affect the total number of recorded layers. For example: an Olympus MplanApo 1.4NA oil immersion lens could record 0.4*0.4*2μm^3 bits, the working distance of this lens is 80μm, therefore, only 40 layers can be recorded with an estimated volume capacity of 249GB. In order to increase the volume capacity, a tradeoff between high NA and working distance needs to be considered

Summary

The data capacity of a 2-photon 3-D multi-layer optical data storage system is analyzed based on the simulation and experiments. By controlling the cross talk between tracks and layers, the capacity of a 5.25" diameter 3mm thick disk could be 140GB.

Acknowledgements

The authors would like to thank, Alexander Dvornikov, and Carlos Caponera for their contributions. This effort was supported as part of the Fast Readout Optical Storage Technology (FROST) program, sponsored by the Defense Advanced Research Projects Agency (DARPA) and administered by the Air Force Research Laboratory (AFRL) under agreement F30602-98-C-0226. AFRL sponsorship under agreements F30602-95-C-0168 and F30602-98-C-0240 is also gratefully acknowledged. The US government is authorized to reproduce and distribute reprints for governmental purposes notwithstanding any copyright annotation thereon.

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