Potential for Volumetric Bit-Wise Optical Data Storage in Space Applications

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ABSTRACT

Volumetric bit-wise optical memory is a revolutionary storage technology that has exciting possibilities for use in space applications. Primary benefits include lower cost (tens of dollars/Gbit), low risk, and an order of magnitude smaller size and mass than other memory technologies. A recently completed research project focused on evaluating this type of memory for space use. Our accomplishments increased the TRL level from TRL 3 to TRL 4 with an engineering model that, although it used many new technology ideas and new volumetric media, was mostly constructed from off-the-shelf components. The engineering model included new servo technology that allowed focusing through a homogeneous storage medium with one beam, while implementing position control from a second beam focused on reference tracks. We investigated the practical limits of the capacity for this type of memory, and we concluded that the effective surface density of bit-wise volumetric memory can reach nearly 3 Tb/in^2 with an advanced optical system. That is, a disk with only a 2-square inch surface area can hold nearly one terabyte of data. However, engineering challenges still exist for this technology, and we have made progress in several key areas. For example, one of our projects investigated a novel way to use multiple laser beams to increase the data rate. In addition, developments outside our laboratory have indicated improved media performance and additional alternatives for system configurations. Media configurations other than a spinning disk may be more appropriate for this technology, especially in ground-based applications. One new configuration is a cylindrical medium where the optical system fits inside the cylinder.

I. INTRODUCTION

Instead of recording only on a plane, bits in a volumetric storage device are stored throughout the volume of the material in multiple planes. The volumetric storage element has dimensions of the writing/reading laser wavelength. With a wavelength of 650 nm, an effective surface density of over three terabits per square inch (3 Tbits/in^2) is possible.

We are investigating and characterizing a volumetric optical memory device based on a class of light-absorbing (photochromic) compounds that when exposed to laser light absorb photons two at a time and trigger chemical and physical changes (such as fluorescence) with micrometer-sized resolution in three dimensions.

Our activities aim at enabling the Earth Science Enterprise (ESE) to integrate large global data sets involving space based observation systems. With many space and ground-based sensors, ESE must acquire, process, and deliver huge volumes of data. These remote sensing and related data will help solve problems such as global change, environmental monitoring, agricultural inventory, etc.[1] The amount of data to be collected and processed per satellite runs into terabytes.

Development of adaptive, high capacity, high data rate optical storage for space vehicles can set an infusion path by establishing a realistic on-board storage platform for such data organization technologies as feature extraction and data prioritization for transmission. The impact of establishing reliable ultra high capacity storage can also significantly influence development of hierarchical data segments and reduction in data volume for downlink. Terabyte capacity on-board optical storage is an ideal platform on which generations of data products for direct distribution to users can be made possible.

Recent interest in volumetric memories has also been shown by other laboratories. For example, Call/Recall, Inc., has shown encouraging results from recording experiments with high-numerical aperture objective lenses that increase the effective surface data density and dramatically reduce the laser power requirements.[2] A research group at the University of California, Irvine, has demonstrated an erasable two-molecular-component photochromic memory.[3] In addition, Landauer, Inc., has shown stable recording in a sapphire-based material.[4] With parallel readout beams, high data rate retrieval is also achieved.[5]

Our last report discusses development of the Advanced Engineering Model (AEM) for volumetric optical storage.[6] The following sections provide a snapshot of our current research progress, which includes refinement of the AEM and considerations for different media and system configurations. Section 2 provides background on the photochromic process. Section 3 describes recent progress with the AEM, which includes refinement of the master/slave servo system. Section 4 describes considerations for alternate media and system configurations. Section 5 details considerations for achieving 3.3 Tb/in^2 effective surface density. Section 6 summarizes our conclusions.

II. BACKGROUND ON THE PHOTOCHROMIC PROCESS

With a tightly focused laser beam, the photochromic process is initiated and controlled within micrometer-size spaces. A data mark is written within the volume only at points of sufficiently high irradiance.[7,8,9] At these points, two-photon absorption occurs, resulting in a bond dissociation. Thus, the molecular structure is changed into a new, 'written', molecule with a different absorption and emission spectrum, as shown in Fig. 1. To "read" the information written within the volume, the approach exploits the fact that the written form absorbs at longer wavelengths than the unwritten form. As shown on the right side of Fig. 1, excitation of written molecules is followed by fluorescence at ~660 nm, which returns the molecule to its ground state. The presence or absence of this fluorescence is detected and classified as a physical '1' or '0' for the stored data mark. Since the decay lifetime is ~5 nanoseconds and the concentration of molecules is high, it is possible to excite the written molecules many times in a single read cycle and increase the total light collected at the detector.

The advantage of a 2-photon absorption process is based upon its ability to selectively excite molecules inside a volume without populating molecules on the surface of the device. This may be achieved because the laser photons have less energy than the energy gap between the ground state and first allowed electronic level. Therefore, photons propagate through the medium without being absorbed by a one-photon process. However, in the vicinity of the laser beam focus, the intensity is high enough so that two photons can combine to excite carriers across the energy gap. The transition probability of a 2-photon absorption process partly depends upon the temporal and spatial confinement of the photons of the recording laser irradiance, so lasers emitting high peak power in short pulses, i.e. picosecond and sub-picosecond pulses, are used.

The recording material is dispersed in a polymer host, which can then be shaped to produce disks with integrated structures for alignment and mounting. This project uses various media configurations. For example, AEM development uses 75 mm radius by 5mm thick PMMA disks with homogeneously dispersed storage materials.

III. THE ADVANCED ENGINEERING MODEL

The Advanced Engineering Model (AEM) is a sophisticated test stand for characterizing volumetric media and testing design concepts for space applications.[6] The AEM allows for both reading and writing bits in two-photon volumetric media, and it applies a novel tracking system to solve the problem of tracking inside homogeneous volumetric media. The basic concept of the AEM servo is shown in Fig. 2. It is configured with mostly off-the-shelf optical components. The tracking beam and the write/read beams are combined through a single actuator. Using adjustable compensation optics, the write/read beam is focused to different layers in the two-photon disk. The two-photon disk is mounted rigidly to a master grooved disk, *e.g.* a commercial compact disc (CD), so that both disks rotate together on a common axis. A closed-loop servo system is coupled to the CD, the "master disk", and a particular track is followed. When track lock is achieved, the tracking beam accurately follows a reference groove as the disk spins. If a position error is sensed by the electronics, the objective lens position is changed with the actuator to correct the error. Since the write/read beam is slaved to the actuator, its focus point inside the medium follows the same correction path. The write/read beam thus traces a path inside the medium that replicates the track followed by the master servo loop. With this system, any positioning errors in the disk pair as it rotates (repeatable or non-repeatable) are tracked by the master feedback system. Since the medium and the master disk are rigidly fixed together and have corresponding position errors, the position of the laser spot in the two-photon disk is well controlled. A separate control moves the write/read beam focus by constant amounts, in order to define multiple depths within the medium. This servo method should help overcome difficulties discovered in temperature stability with the polymer host.[10]

Figure 3 shows a schematic diagram of the AEM. The collimating laser diode module contains the 638 nm laser diode that is used for reading and track following. Output light of the module is circularly polarized. The writing laser is a miniature Q-switched diode pumped 532 nm cavity, which exhibits a footprint only a few times larger than the 638 nm laser diode. Its output is linearly polarized in the plane of the schematic. The particular configuration shown in Fig. 3 is an efficient combination for the different beams, which are now described in detail.

The transmitted beam is sent through polarization beam splitter 1 (PBS1) and used as the tracking beam. The transmitted beam is linearly polarized in the plane of the schematic. Relay lenses 1 and 2 are used to project an image of the diode module output into the pupil of the objective lens (OL), in order to avoid Fresnel diffraction rings. This beam transmits through PBS2 with high efficiency. The angled mirror and dichroic mirror combination are necessary for detecting the fluorescent data pattern, and will be discussed in a following paragraph. The tracking beam is focused onto the disk by a 0.6 NA molded bi-aspheric objective lens. As shown in the detail of Fig. 3, the tracking beam is focused onto the grooves of the CD. The reflected light from the groves is directed back through the same components to the laser diode module, where tracking and focus sensors produce error signals for the closed-loop servo electronics.

The reflected beam from PBS1 is used as the readout beam. It is polarized perpendicularly to the plane of the schematic, and it contains about half of the power emitted from the laser module. After reflection from PBS3, the readout beam passes through a phase compensator and a group of focus shifting lenses. The phase compensator is necessary to improve the quality of the focus beam as it is focused through the recording medium. The focus shifting lenses form a simple, unity magnification Keplerian telescope, and, when the first lens element is shifted along its axis, the modified conjugate incident on the OL forces a focus shift of the readout beam in the recording medium. Relay lens 3 and relay lens 2 project an image of the focus-shifting lens into the pupil of the OL. Note that the tracking beam and the readout beam are orthogonally polarized.

The fluorescence from the data marks inside the medium is detected with a photomultiplier tube (PMT) behind the dichroic mirror. An angled mirror is used to present a small angle of incidence to the dichroic mirror, because the surface figure of dichroic mirrors purchased for this study were not adequate for reflection at larger angles of incidence. That is, they introduced too much astigmatism due to slight curvatures in the filter glass.

The writing beam passes through PBS3 and follows through the same components as the readout laser. Due to chromatic dispersion of the lenses, the focus shift lens must be adjusted with a slightly different offset than that used for the readout beam.

In fabricating the disk pair, the first step is to prepare the CD-R. The label, protective layer and reflective coating of a commercial phthalocyanine disk is removed, which leaves the track structure and the dye. It is necessary to leave the dye, because the dye provides a small amount of reflection to the tracking laser beam. The relationship between the properties of the dye and the wavelengths of interest are shown in Fig. 4. The dye absorption extends from about 550 nm to 820 nm, with a peak at around 730 nm. The write laser beam at 532 nm passes through the dye without significant absorption or reflection. The 638 tracking and readout laser beams exhibit absorption and reflection, although some amount of reflection is necessary in order to have enough light at the detectors of the laser module for reliable servo error detection. The dye worked much more reliably than a simple metallic coating or a custom thin film coating. The loss in transmitted power of the readout beam is not significant, because the required readout power in the medium is only a few mW. The loss of fluorescent data light is more significant, but, with the fluorescent peak at 670 nm, as shown in Fig. 1, the phthalocyanine dye is a good compromise. After removing the unwanted layers, the two-photon storage disk is bonded to the groove side of the CD-R with epoxy. The thickness of the epoxy layer is approximately 100 µm.

The degree to which the slave readout beam holds focus and track relative to the master tracking beam is shown in the diffraction pattern of Fig. 5, where the pupil image of the reflected slave beam is shown. The pattern results from zero and +/- first diffracted orders overlapping in the pupil. Since the slave beam is slightly out of focus with respect to the grooves, straight-line fringes are observed in the overlap regions. The pattern is similar to those observed in lateral shearing interferometers that are used to test the quality of optical systems.[11] If the number of fringes change in the overlap regions, the slave beam defocus is changed with respect to the tracks, which implies that the depth of the slave beam is changed inside the medium. If the fringes move left or right in the overlap regions, the slave beam is translated horizontally with respect to the reference track, and the slave beam cannot follow data-track runout correctly. If the pattern is stable as the disk spins, the slave beam is correctly registered to the master beam, and the slave beam is expected to correctly follow the data marks inside the storage material. Experiments indicate that the AEM shows a stable pattern for small salve-beam depths within the storage medium.

The deviation of the laser beam from perfection is typically specified with a wavefront aberration plot, where any deviation from a straight, horizontal line must be corrected. Figure 6 shows the wavefront aberration plot for the write laser as it is focused through 300 microns of media thickness. The 'w' shape of the curve is indicative of spherical aberration. Notice that magnitudes and shapes of the curves do not change significantly as the beam focuses into the medium. Thus, a static compensator is sufficient for correcting the wavefront in this focus range.

A phase compensator corrects for the aberration shown in Fig. 6. Two types of compensators are tested. The first compensator is made from a simple, low-resolution gray-scale photoresist technique. The transmission mask shown in Fig. 7(a) is imaged into positive photoresist. The photoresist is developed, and the resulting surface relief profile of the photoresist is the inverse shape of the wavefront aberration shown in Fig. 6. The maximum amount of compensation, as measured on a LADITE interferometer, is 0.5 waves, as shown in Fig. 8(b), which is good match for the required correction. The second compensator is a liquid crystal device consisting of three annular rings, as shown in Fig. 8(a). Each ring exhibits a different phase shift, depending on the voltage potential across it. The best result is obtained when 3Vp-p is applied to this device. The maximum amount of compensation is 0.27 waves, as shown in Fig. 8(b), which is slightly more than half of the necessary compensation.

A solid model of the test laboratory AEM configuration is shown in Fig. 9. The construction uses commercial box-and-rail technology, and occupies approximately 824 in^3. The miniaturized model, which is presently in the fabrication stage, occupies only 8 in^3.

IV. ALTERNATE MEDIA CONFIGURATIONS

Several alternatives to a homogeneous rotating disk may be preferable in certain applications. For example, as the device volume reduces, cylindrical media display an advantage with respect to total storage area. Calculations indicate that a one-inch length and 8 mm diameter cylinder exhibits more surface area for recording than an 8 mm diameter six-disk system.[12] For optical storage media, one might envision a system like that shown in Fig. 10, where a hand-held instrument uses a cylindrical storage medium. Data are recorded on the inside of the removable cylinder, and the optical head is fixed to the instrument. The optical head rotates to read data. The media cylinder is stationary. When a volumetric storage medium is used for the cylinder, the total storage capacity increases dramatically, with terabytes of data in a single cylinder. Alternatively, an optical card could be fabricated with no moving parts.[13]

V. CONSIDERATIONS FOR REACHING 3.3 Tbits/in^2 IN SPACE APPLICATIONS

In our previous report, we showed systems analysis that indicates over 3 Tbits/in^2 effective surface density is possible in two-photon volumetric media. This section briefly discusses possible system configurations that could achieve ultra-high density.

A primary consideration to the ultimate storage density is the maximum number of layers in the disk. The maximum number of layers is decreased if there is significant absorption at each recording layer, as is experienced with multiple-layer versions of third-generation (Blu-Ray) optical disks. If laser power is limited to 100 mW at 405 nm and the threshold power for writing data marks is 5 mW/μm^2, the relationship between the maximum number of layers and the transmission τ of each layer is shown in Fig. 11. Interestingly, there is not a dramatic difference between the far-field system (NA = 0.6) and the near-field system (NA = 1.2) with respect to the maximum number of layers. For $\tau = 0.6$, which is a very high value for third-generation technology, the maximum number of layers is around N = 10. At 25 GBytes/layer, the effective surface density is 0.13Tbits/in^2, which is well below the target density of 3 Tbits/in^2 for two-photon media. The reason two-photon media can exhibit higher effective surface density is because the transmission of each layer exceeds 99%. Extensions of third-generation optical disks require nearly an order of magnitude greater capacity per layer in order to obtain even 1 Tb/in^2. Therefore, some form of homogeneous volumetric storage medium is required.

If two-photon media are used in space applications, a good combination is sapphire media described in Reference 4 with optical systems described in Reference 6. The sapphire media are attractive, because they are robust and can provide stable surfaces over which to actuate a near-field lens system. (For example, stable near-field optical recording was recently demonstrated with a NA = 1.9 near-field system.[14]) Also, the sapphire media are bulk-erasable, stable to high temperatures and can be written with commercially available laser diodes. Near-field recording in two-photon media was also recently demonstrated with a dramatic reduction in laser power required for writing, as described in Reference 2.

A sapphire two-photon cylinder that is 30 mm in diameter and 20 mm high is a reasonable form factor for space use. When combined with a NA = 1.2 optical system and a 405 nm laser beam, the system should exhibit a storage capacity of over 1 TByte with only 100 layers. If the layer spacing is 2 µm, the total thickness of the cylinder is only 200 µm. The entire optical and mechanical system can fit inside the cylinder.

Of course, commercial applications of this technology do not require the robust nature of the sapphire media, and other system configurations are possible. In addition, the sapphire media is most likely more expensive than a photochromic medium dispersed in plastic. In all two-photon media, the data rate during writing can be very high, but the data rate during readout is much lower. Therefore, new techniques for increasing the readout data rate with multiple beams must be developed.[15]

VI. SUMMARY AND CONCLUSIONS

In summary, a laboratory test stand called the Advanced Engineering Model (AEM) is described in detail, which has the purpose of characterizing volumetric media and testing design concepts for space applications. In this report, volumetric two-photon media is used. A servo mechanism for the AEM is investigated that uses one laser beam to provide a reference position signal as the disk rotates, while a second laser beam scans data patterns inside the two-photon medium. This master/slave servo concept uses a commercial CD for the reference surface. The footprint of the AEM is approximately 824 in^3, and a miniaturized version is introduced that occupies only 8 in^3. The AEM uses a compensator to improve the quality of the focused beam inside the two-photon medium. Initially, the highest-performance compensator is a simple photoresist pattern, but investigation with dynamic liquid crystal compensators is continuing. Alternate media configurations are briefly described, including a fixed cylindrical medium geometry that surrounds a rotating optical head. It is shown that extensions of third-generation optical disks, which include the Blu-Ray format, will have great difficulty in reaching effective surface densities over 1 Tbit/in^2. Instead, some form of homogeneous volumetric storage medium is required. A small erasable volumetric system is proposed, which uses a thin sapphire cylinder that is 30 mm in diameter, 20 mm high and holds 1 TB of user data. The optical system is encapsulated inside the cylinder.

ACKNOWLEDGEMENTS

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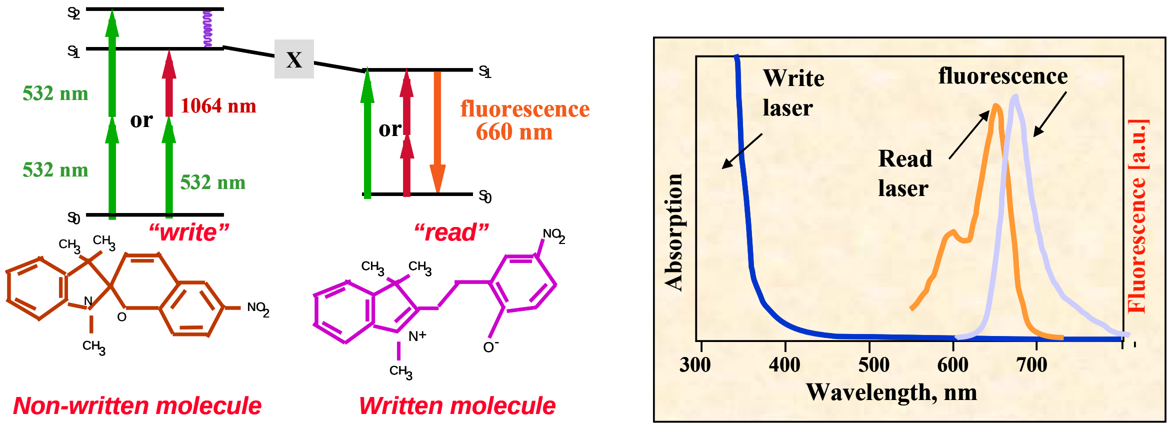


Figure 1. A physical description of what happens when two-photon absorption occurs. The left figure is the energy-level diagram and molecular structure of unwritten and written forms, showing fluorescence. The right figure is the absorption spectra and fluorescence spectrum of the unwritten and written forms of the material

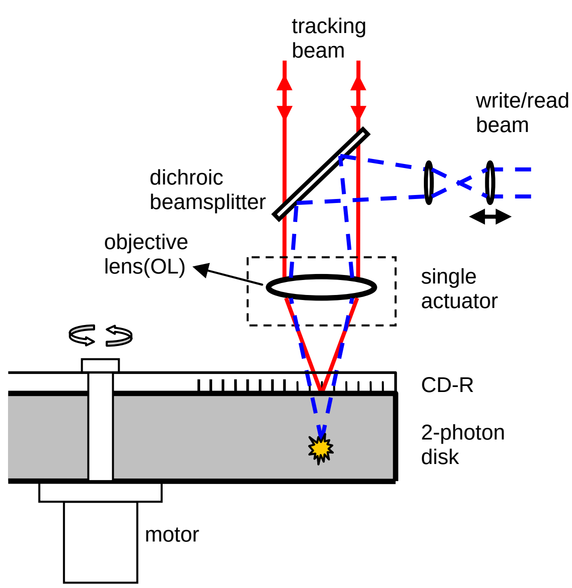


Figure 2. The master/slave servo combines the tracking beam and the write/read beams into a single path.

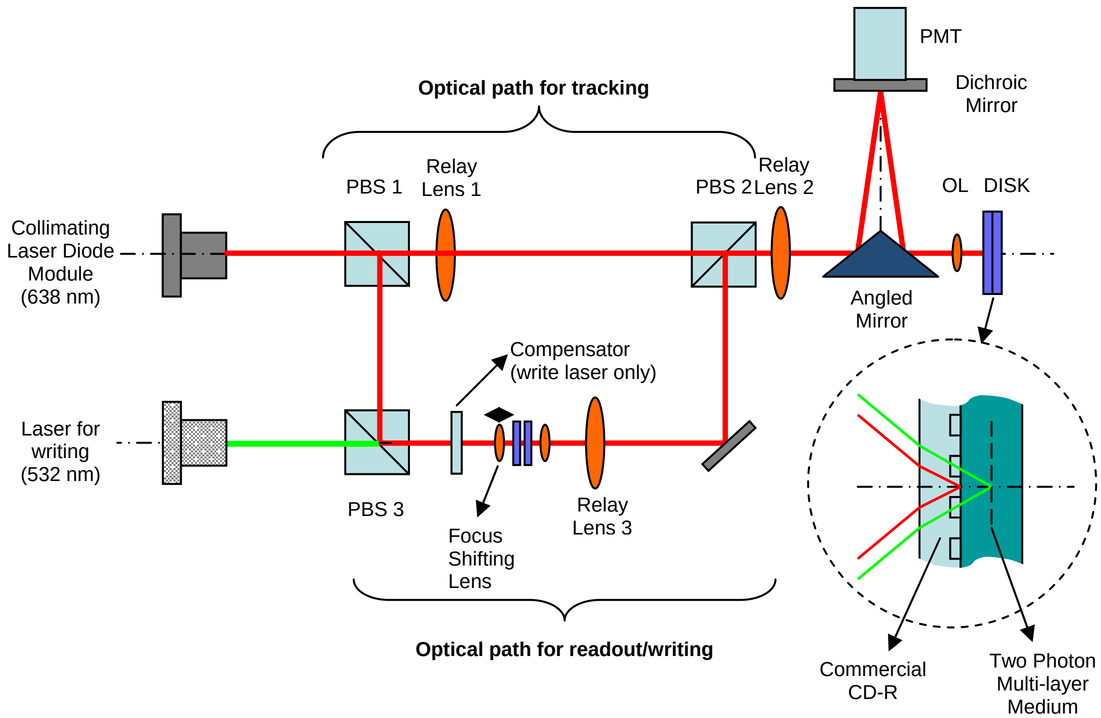


Figure 3. Schematic diagram of the AEM

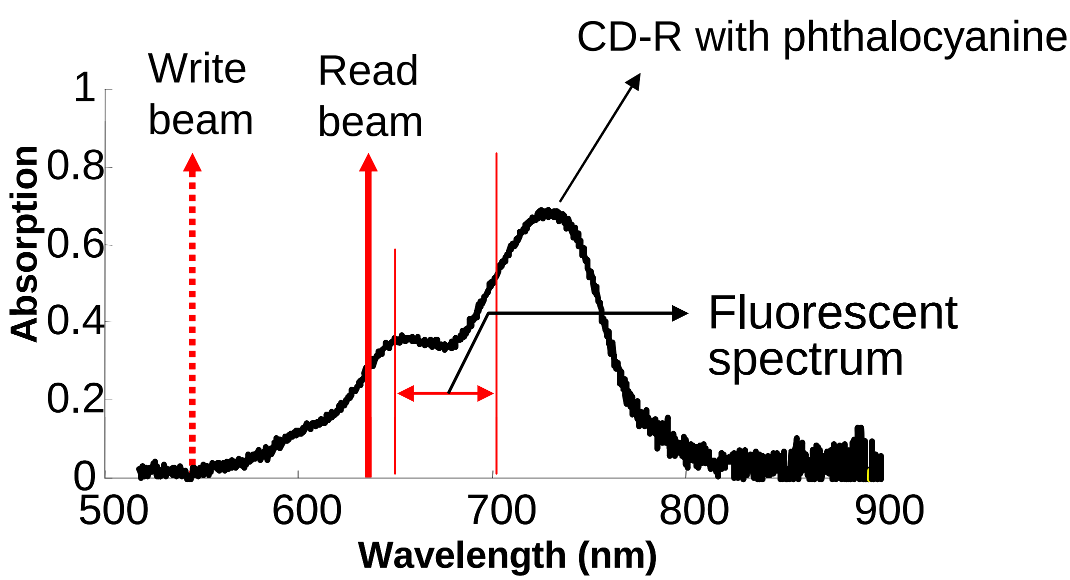


Figure 4 Absorption spectrum of CD-R with phthalocyanine

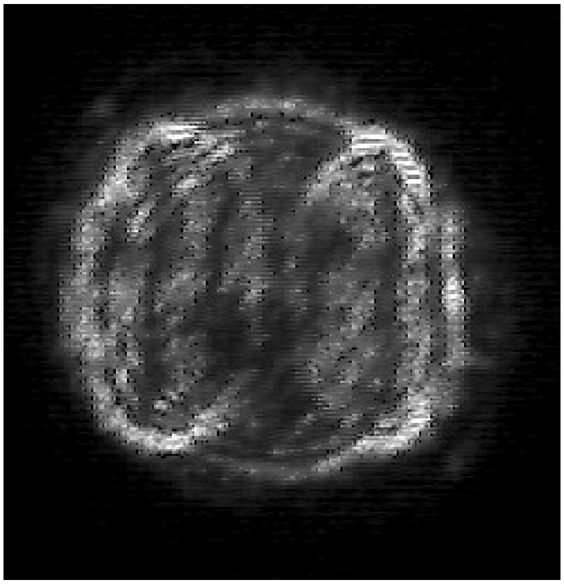


Figure 5 Diffraction pattern of the slave beam from CD-R data layer.

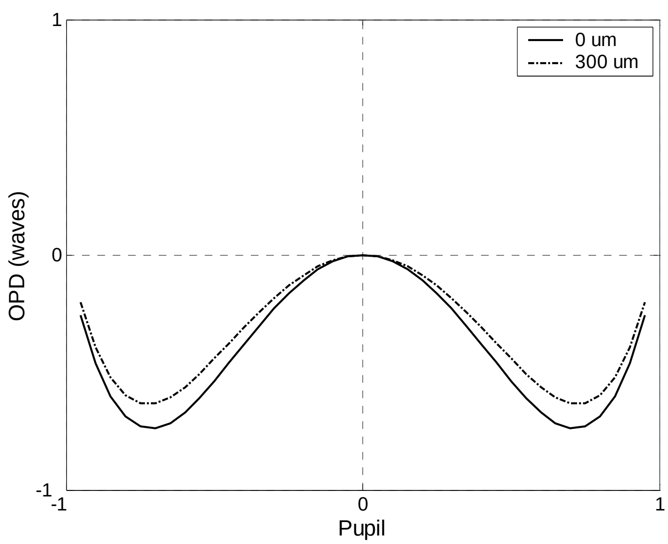
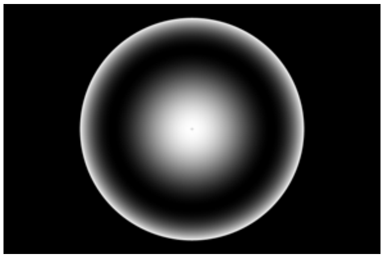
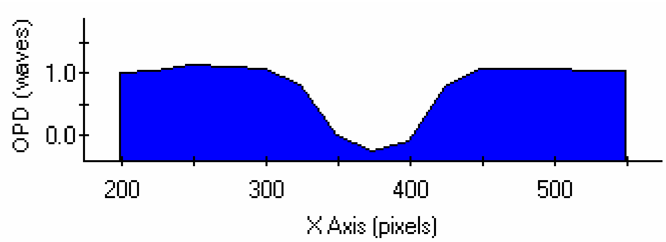


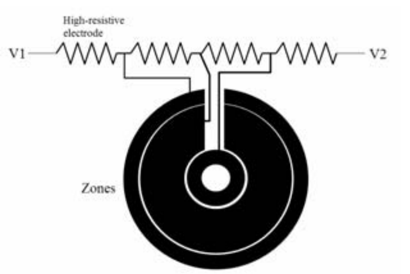
Figure 6. OPD plot for the write laser beam as it is focused to CD-R data surface(solid line) and 300 μm of media thickness (dashed line) in the absence of any compensator.

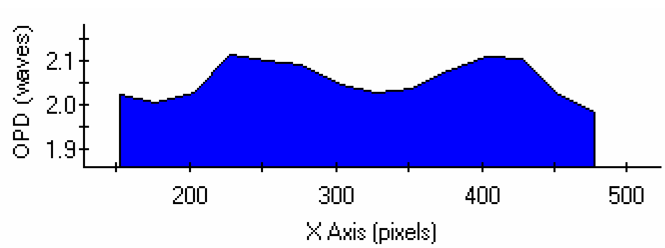




(a) **(b)**

Figure 7 Photoresist compensator:
(a) transmissive gray-scale mask, (b) OPD profile of the developed photoresist





(a) **(b)**

Figure 8 Liquid crystal compensator: (a) schematic diagram, (b) OPD profile of the compensator

Figure 9 Comparison of AEMs. The miniaturized model occupies only 8 in^3.

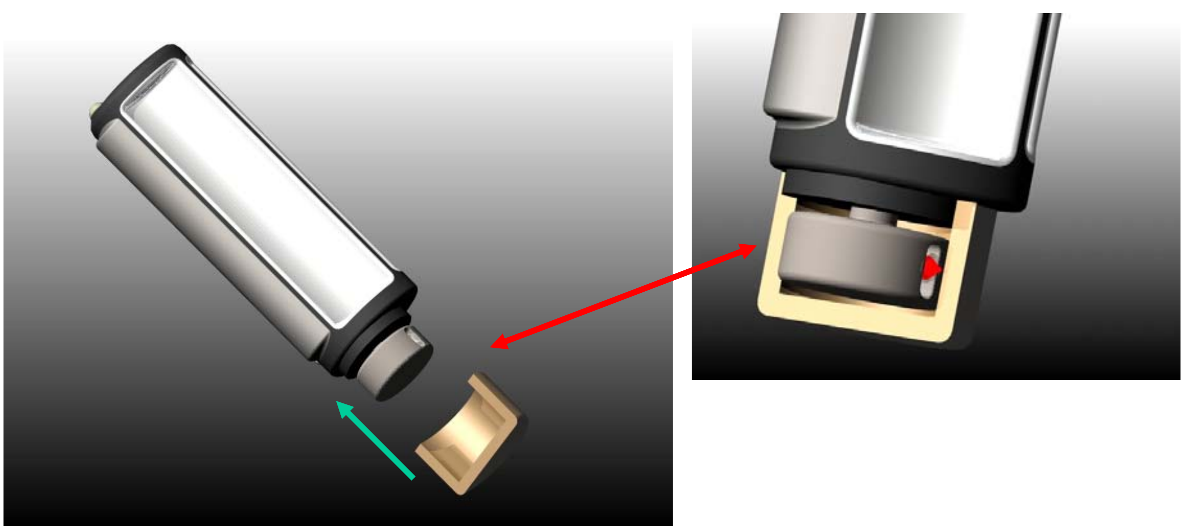


Figure 10 Low-power 1TB memory module that uses stationary cylindrical media and a rotating head. The memory unit is attached to a hand-held instrument in the shape of a larger cylinder.

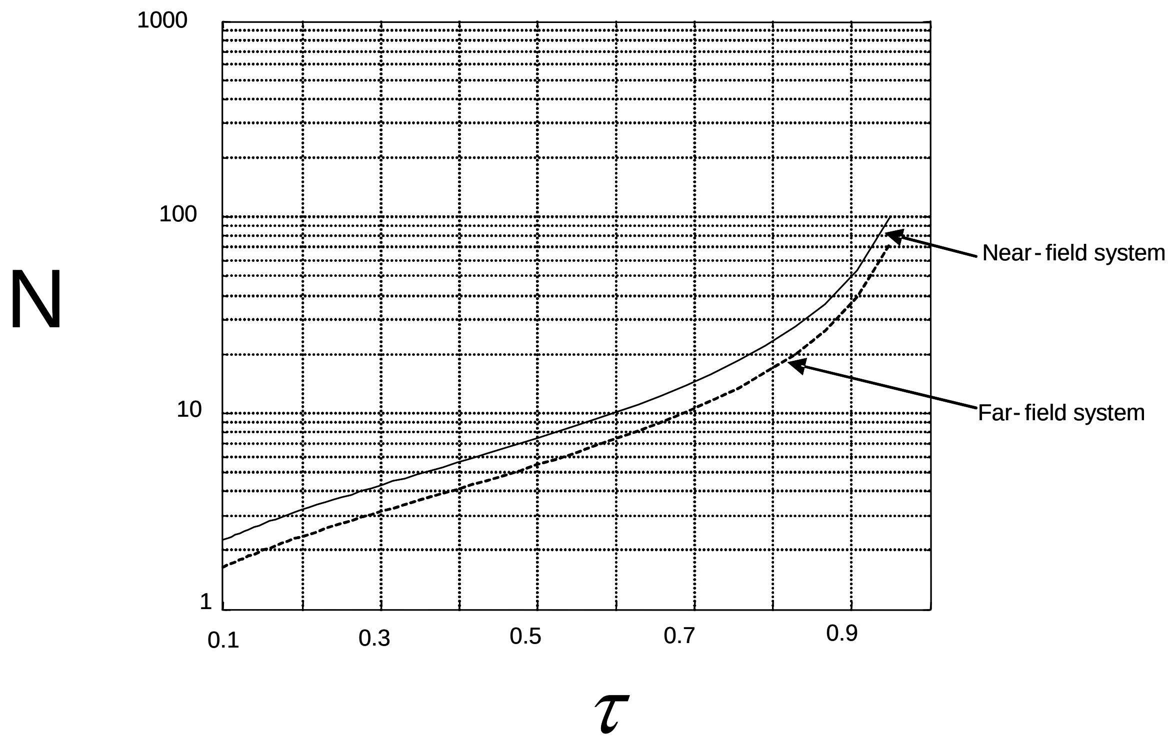


Figure 11. Number of layers N is limited by the transmission τ of each layer