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Multilayer Recording and Dynamic Performance of Volumetric Two-Photon-Absorbing Fluorescent Al_2O_3 Media

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Multilayer recording in volumetric two-photon absorbing fluorescent Al_2O_3:C,Mg media is reported. Dynamic random mark-length recording and readout in a single crystalline disk was performed at rotation speed up to 3600 rpm and linear velocity of 14 m/s. Clear eye diagrams were obtained at data clock from 0.32 to 6.5 MHz. Monotones with carrier-to-noise ratio (CNR) from 22 to 45 dB were demonstrated at different data rates. [DOI: 10.1143/JJAP.46.3902]

KEYWORDS: optical data storage, recording materials, volume memories, aluminum oxide, two-photon absorption, confocal detection

1. Introduction

Volumetric bit-wise technology has a real chance to achieve terabyte capacity per disk and at the same time promises back compatibility with current compact disk technologies such as compact disc, digital versatile disc, and Blu-ray Disc (CD/DVD/BD), and much simpler and more reliable drive in comparison with digital holography. There are two types of homogenous media being investigated for bit-wise recording: (a) reflective type volumetric media where writing process causes local change of refraction index[1,2] and (b) fluorescent photochromic media where electronic or structural transformation caused by non-linear two-photon absorbing (2PA) changes the yield of fluorescence.[3,4] It is important to emphasize that physical layers in this approach are not fabricated during manufacturing of the media but rather recorded into otherwise uniform storage material.

Homogeneous volumetric media and incoherent fluorescent readout eliminate the difficulties associated with diffracting and scattering of laser light in reflection-type multilayer data storage. Organic photochromic materials that are probably cheaper to manufacture have significant issues with environmental stability, oxidation and photo-bleaching. The physics of recording in organic photochromic media is usually based on so-called "simultaneous" two-photon absorbing that has a low probability of transition through a virtual (non-existing energy level) in the electronic molecular structure. Because of extremely low cross-section of the simultaneous 2PA process recording requires high (0.1–10 GW/cm^2) recording power densities from pulsed femtosecond or picosecond lasers which are difficult to modulate with data.

Non-linearity of the optical absorption process is required to produce transformation in the volume of the data storage media. 2PA is one of these non-linear processes that can be used in practice. The strong laser power dependence of 2PA and a highly focused laser beam produce high irradiance in a spatially localized volume of the media (see Fig. 1) and assure that photo-induced electronic transformation takes place only in the vicinity of the focal spot. Because of strong optical non-linearity of the media no phototransformation should take place outside of the focus spot.

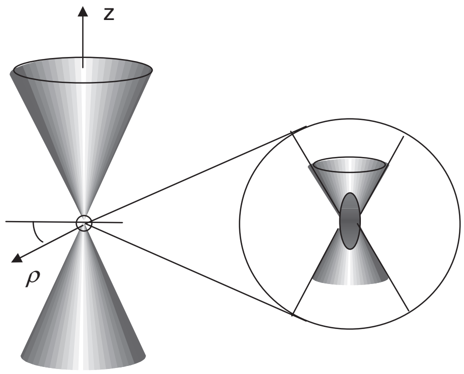

Fig. 1. Confinement of a single bit as a result of laser-induced two-photon absorption and photochromic transformation in the focus of a high NA objective lens.

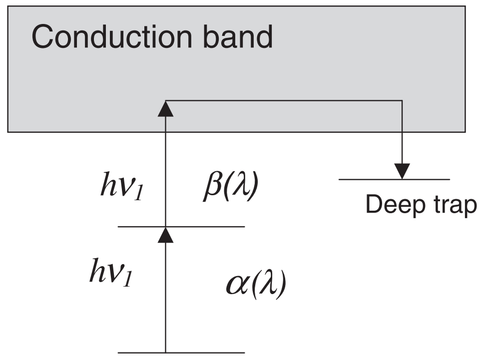

Fig. 2. Write process in Al_2O_3:C,Mg crystal utilizing sequential two-photon absorption and photo-ionization through real excited state.

Inorganic aluminum oxide single crystal media (Al_2O_3:C,Mg) developed at Landauer for bit-wise recording[5–11] has a very important fundamental advantage in comparison with all organic materials suggested so far. The Al_2O_3 crystal is a wide-gap dielectric ($E_g = 9.5$ eV) with electronic defects having ground and excited states localized deeply within the energy gap. Due to this very important feature of Al_2O_3, data can be recorded and erased using "sequential" or step-wise 2PA (see Fig. 2, and refs. 9 and 11) and later read non-destructively multiple times using laser induced fluorescence that results from linear or 1PA process. Both 2PA for recording and 1PA for reading are utilized in demonstrations

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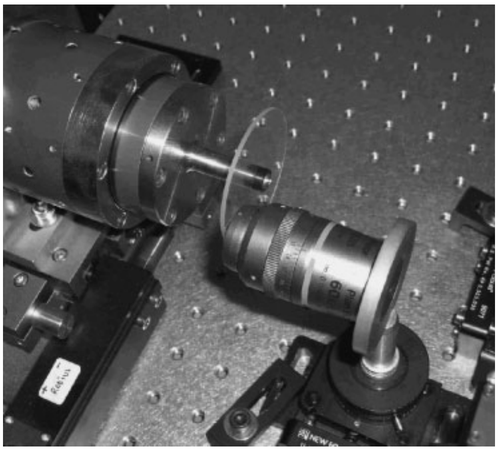

Fig. 3. Al_2O_3:C,Mg disk on a spin-stand with air-bearing spindle and 0.85NA lens having spherical aberration correction capability.

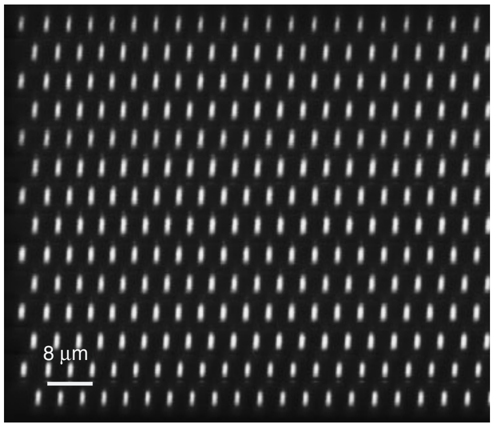

Fig. 4. Fourteen layers of data recorded in aluminum oxide medium and read using static tester. The surface of the disk is at the bottom of the image.

of one-bit confocal and holographic applications. It is important to reemphasize that instead of simultaneous two-photon absorption process having low cross-section and requiring expensive high peak power lasers Al_2O_3:C,Mg media employs high probability sequential 2PA that allows one to use a low peak power blue laser diode for recording and a red laser diode for non-destructive readout. The new material is attractive for a wide variety of storage applications because of extremely high temperature stability of the recorded data (up to 600 °C), mechanical hardness, chemical and environmental stability of aluminum oxide crystals known also in the optical industry as sapphire. Al_2O_3 crystal has extremely rigid crystal structure and does not experience shrinkage or thermally induced deformation. Crystal growth technology of sapphire is relatively well established and sapphire wafers can be polished to high optical quality and flatness. Preliminary performance characteristics of the Al_2O_3:C,Mg media obtained with static and dynamic testers were presented at ODS-2003 in Vancouver,[5,6] at ISOM-2003 in Nara,[7] at ODS-2004 in Monterey,[8] and ISOM/ODS-2005 in Honolulu.[9]

For this study the latest modification of Al_2O_3:C,Mg disk with high concentration of light absorbing color centers was used. The goal of this paper is demonstration of multilayer and dynamic mark-length recording at high data rate that were previously restricted by the relatively low intensity of fluorescence.

2. Experimental Procedure

An experimental optical setup that combines static and dynamic testing systems was constructed at Landauer to obtain a set of parameters needed for a feasibility study of a new optical disk (Fig. 3) and was described elsewhere.[7] Both the "write" and "read" beams are produced by modulated cw laser diodes. The recording process is performed with 405 nm laser diode producing a 8 mW at the back pupil of the objective lens. Reading the data is performed through the same lens by scanning the media with a 635 nm red laser diode (6 mW) in conditions of 1PA without photo-ionization of the color centers. Near IR (750 nm) fluorescence was detected in confocal geometry using avalanche photodiode (APD) from Hamamatsu 5460-01 (100 kHz bandwidth) or faster module 5460 (10 MHz). The optics of our current tester allows for spherical aberration compensation at a maximum depth of only 140 μm. Further improvements of the system are underway.

One of the main advantages of a homogeneous Al_2O_3:C,Mg volumetric media is a low light absorption, scattering and reflection per one layer that should make it possible to record more than 200 layers of data with DVD density per layer with minimum adjustment of recording laser power. In a proposed configuration a single crystalline disk has a standard for CD/DVD 1.2 mm of thickness with both sides accessible for data recording. Our latest disks are 60 mm in diameter and have 12 cm^{-1} of optical absorption coefficient at the peak of 435 nm band and 6 cm^{-1} of absorption at 405 nm that correspond to 70% transmission at 0.6 mm of media depth.

3. Multilayer Recording of Fluorescent Marks in Aluminum Oxide Media

Figure 4 shows 14 layers of data recorded with the constant laser power with no degradation of fluorescence signal amplitude with the depth of recording. Figure 5 depicts the magnified image of the same bits. The images were obtained using a static tester developed at Landauer and described previously.[7] The recording was performed with 15 nJ of energy per bit using 405 nm laser diode. The data was recorded with bigger intersymbol and interlayer spacing of 4 and 10 μm respectively for better visibility. In actual recording the tracks and layers can be spaced much tighter and 20 layers of data spaced by 7 μm were easily produced.

4. Random Mark-Length Recording and Reading Using Dynamic Tester

For the first time we demonstrate dynamic mark-length recording in aluminum oxide fluorescence media. An example of fluorescence images obtained from the dynamic tester with air-spindle rotating at 120 and 2400 rpm is presented in Figs. 6 and 7. The random marks were generated by modulating the driver of the 405 nm laser diode with an arbitrary wavefront generator with the mark and space length from 2T to 11T. Linear velocity during recording was 0.32 or 0.64 m/s and was restricted by the

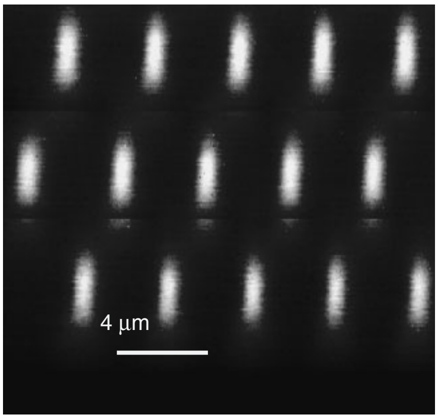

Fig. 5. Magnified image of fluorescent marks. Readout is performed in Z-direction (along the optical axis of the objective lens).

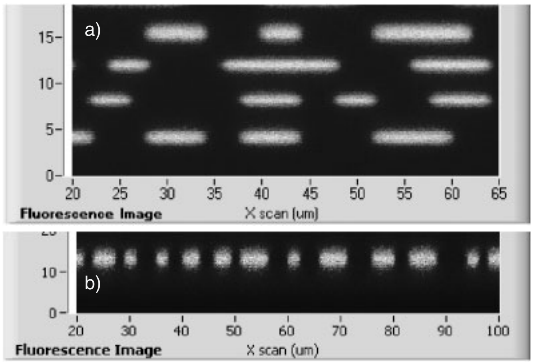

Fig. 6. Fluorescent images of multiple tracks recorded with random (2T–11T) mark length and read at 120 rpm of disk rotation and 0.35 m/s of linear velocity: a) image obtained in radial scanning direction with 0.1 μm per revolution of scan increment; b) axial cross section of one of the tracks with axial (Z) increment of 0.2 μm.

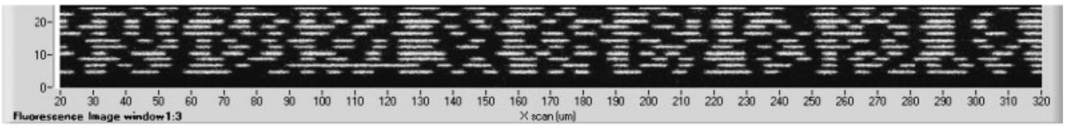

Fig. 7. Fluorescent images of multiple tracks recorded with random mark-length and read at 2400 rpm of disk rotation and 7 m/s of linear velocity (clock 3.5 MHz).

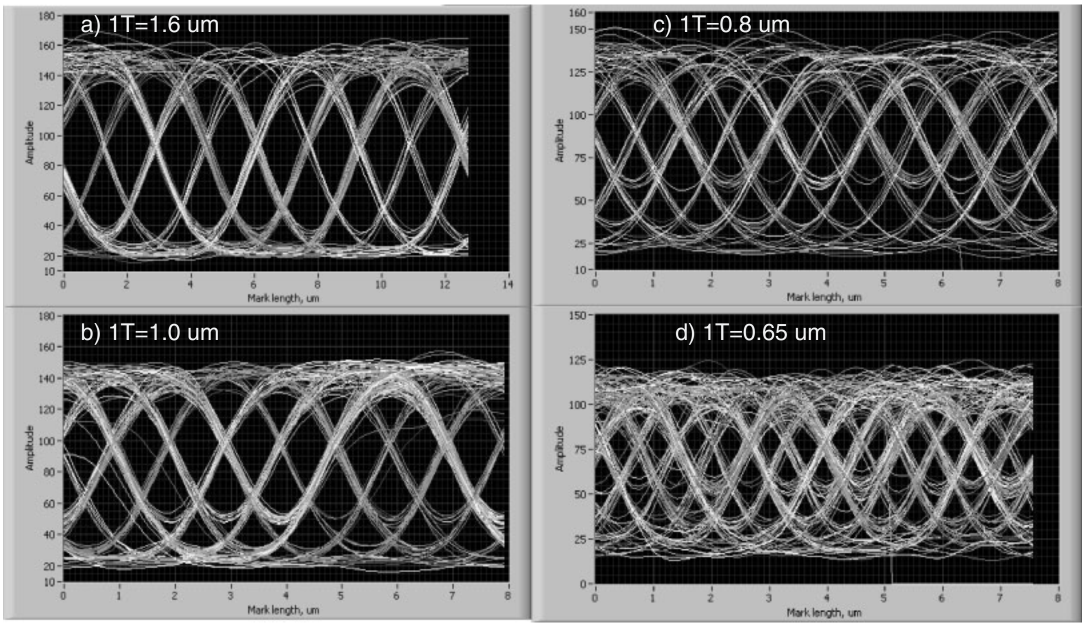

Fig. 8. Effect of bit spacing on eye diagram. Recording and reading was performed at 240 rpm and linear velocity 0.65 m/s. Spacing for changed from (a) 1T = 1.6 μm, (b) 1T = 1.0 μm, (c) 1T = 0.8 μm, to (d) 1T = 0.65 μm.

available power of 405 nm laser light and maximum update rate of a DAQ board used for waveform generation. Readout was performed with the APD and transimpedance amplifier having 10 MHz bandwidth. During readout the linear velocity of the media was changed from 0.32 to 6.5 m/s and the data clock from 0.32 to 6.5 MHz. Image on Fig. 6(a) was obtained at 240 rpm in radial scanning direction of 0.1 μm per revolution of scan increment, whereas Fig. 6(b) illustrates an axial cross section of one of the tracks with an axial (Z) increment of 0.2 μm. Figure 7 depicts the same multiple tracks imaged in dynamics at 2400 rpm and linear velocity of 7 m/s and still having a good contrast.

5. Effect of Mark Spacing

Figure 8 demonstrates eye diagrams of a RF signal obtained from the output of the amplifier at different intersymbol spacing ranging from 1.3 to 0.65 μm. The data was obtained at the same 240 rpm and 0.65 m/s of linear velocity.

6. Dependence on Rotation Speed and Linear Velocity

Figures 9 demonstrate eye diagrams of an RF signal obtained from the same recording performed with minimum mark length of 2 μm and intersymbol increment of 1 μm at

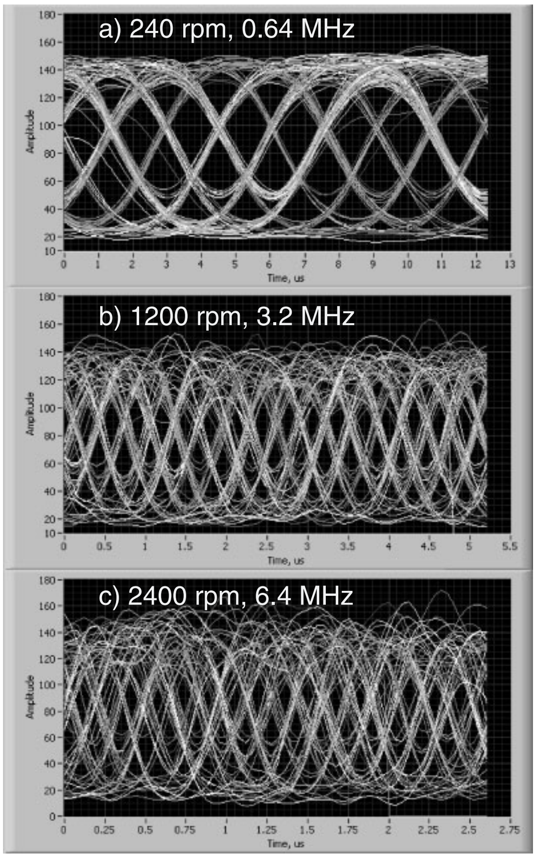

Fig. 9. Eye diagram obtained from the same recording at different disk rotation speeds (linear velocities): (a) 240 rpm, 0.64 m/s, 0.64 MHz clock; (b) 1200 rpm, 3.2 m/s, 3.2 MHz clock, and (c) 2400 rpm, 6.4 m/s, 6.4 MHz clock.

different rotation speeds of the disk corresponding to a clock frequency range from 0.65 to 6.5 MHz. Relatively clear eye diagrams were obtained. We believe that further improvement will be achieved through increase of color center concentration and uniformity of crystal properties.

7. Recording of Monotone and Evaluation of Carrier-to-Noise Ratio

Figures 10 and 11 provide some data on the modulation depth of 40% for the RF signal of the monotone recorded with minimum mark and space length equal to 1 µm. At 240 rpm, with media linear velocity of 0.65 m/s and clock frequency 0.32 MHz, the obtained carrier-to-noise ratio (CNR) was 45 dB. CNR reduces to 33 dB at 2400 rpm and data rate of 2.6 Mbit/s. At 4800 rpm and 6.5 MHz clock the CNR drops down to about 20–25 dB.

8. Conclusions

New reusable inexpensive volumetric data storage medium made of aluminum oxide single crystal with high concentration of color centers and high yield of fluorescence was tested in static and dynamic conditions. Recording was perfromed with compact 405 nm cw blue laser diode and low laser energy per recorded bit (1–100 nJ). Nondestructive readout was done via 1-photon absorption and laser induced

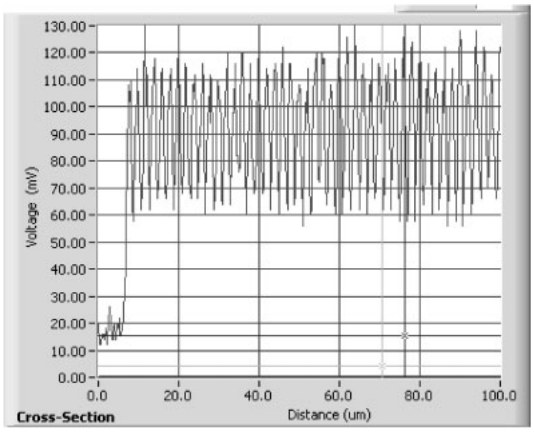

Fig. 10. RF signal of bits having 1 µm mark length and 1 µm spacing recorded at 240 rpm and linear velocity of 0.64 m/s.

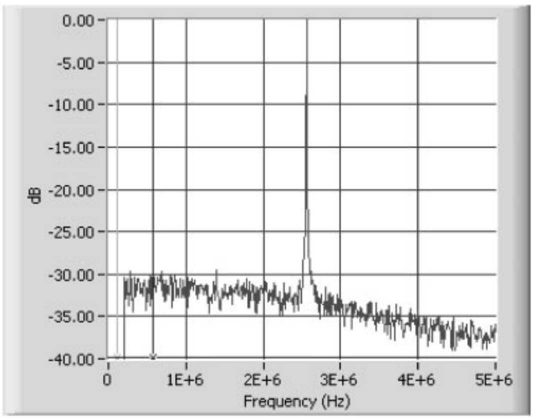

Fig. 11. Spectral power density and CNR = 33 dB of a monotone readout at 2400 rpm of disk rotation and 2.6 Mbit/s. Bandwidth resolution is at 10 kHz.

fluorescence. Multilayer recording with 14 and 20 non-overlapping layers of data were recorded and read in the bulk of the media with the same laser power and without significant bit intensity degradation. Random mark-length recording and open eye-diagram was successfully demonstrated with data rate of up to 6.5 Mbit/s. Monotone of data marks was read at 2.6 Mbit/s with CNR close to 33 dB.

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