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Investigation of Pit Formation in Laser-Irradiated Multilayer Thin Films by Using Optical Coherence Tomography

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We propose a novel application of optical coherence tomography (OCT) to monitor pit formation in laser-irradiated optical storage materials. A multilayer optical storage recordable compact disk is composed of multiple layers, each of different structure. The disks were irradiated with a Q-Switched Nd:YAG laser with an energy of 373 mJ. Post-irradiated disks were evaluated by using OCT, and the images were compared with those obtained by using optical microscopy. Our results indicate that OCT can be a useful instrument for investigating pit formation in multilayer optical storage disks and might also provide information on ways to optimize optical memory technology.

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Keywords: Optical coherence tomography (OCT), Multilayer optical storage material, Pit formation

I. INTRODUCTION

Recently, as compact semiconductor lasers have been developed, optical memory technology, such as optical disks and holography, have attracted great attention. Many studies have evaluated several optical materials, such as photo-polymers, photo-resisters, and synthetic materials containing inorganic substances and metals [1, 2]. Thus, a method to investigate the optical characteristics of these new materials is essential. Moreover, non-invasive imaging might also be helpful in determining the optimal laser parameters, including the wavelength, energy, and pulse duration. Although significant efforts have been devoted to optimizing the pit formation process, to date, an optimal method has not been developed.

Optical coherence tomography (OCT) is a new modality to perform cross-sectional imaging [3, 4]. OCT is very attractive because it offers high-resolution, real-time, and non-invasive imaging. OCT has been extensively used for high-resolution imaging in the fields of medicine and biophotonics [3–5]. Non-medical applications of OCT, such as optical data storage, materials investigation, and microfluidic devices, have also been reported [6–8]. Usually, OCT images of highly scattering or reflecting materials are difficult to acquire due to the limited penetration depth (2 – 3 mm) of the probe

beam. Many material defects, however, originate at the surface or at the subsurface boundaries between different substances, making OCT an ideal instrument for surface inspection and quality control. For transparent or translucent materials such as plastic or polymer composites, defect imaging using OCT at greater depths is also feasible [6,7].

In this research, we used OCT to monitor pit formation in laser-irradiated multilayer optical storage media. After Q-Switched Nd:YAG laser irradiation, structural changes in the storage material were examined by using OCT. Results were used to explain the mechanism of pit formation and were correlated with those obtained by using optical microscopy.

II. METHODOLOGY AND SAMPLE PREPARATION

The structure of a conventional multilayered optical storage material is like that of a recordable compact disk, which is usually composed of 4 – 5 layers. The bottom layer is the substrate layer and is composed of polycarbonate with a thickness of ~ 1.2 mm. The second layer is the recording dye layer, which is an organic layer coated by dye with a thickness of 100 – 300 nm. This layer is removed after laser irradiation for recording. The third layer is the reflective layer containing metals,

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such as Ag, Au, Al, and reflects the laser beam. The top layer is the protective layer and contains a UV-cured resin. The semiconductor laser beam passes through the substrate layer and is focused onto the “groove” of the substrate/dye layer interface of the rotating CD-R. Depending on the input laser’s energy, thermal deformation of the dye layer may occur at the groove, thus generating binary signals on the dye layer from the difference between the “pit” (thermally deformed groove) and the “land” of the substrate/dye layer interface [9,10]. Laser spot marking generally involves three physical processes: optical absorption of the irradiated laser beam, heat flow, and mass motion [11–13]. The interaction of these processes initiated by a high-intensity beam results in the formation of small pits. Absorbed optical energy melts the dye and induces heat flow. As a result, the center of the irradiated spot collapses, and a “pit” and “rim” are created on the material surface.

Our objective was to evaluate laser marking of an optical storage material that contained a recording layer with dye. The individual layers of the storage material were separated in order to study the optical characteristics of each substance as in Fig. 1. All layers, except for the protective layer, were produced separately. The method to fabricate a multilayered storage material follows the

typical manufacturing process of a CD/CD-ROM. First, the substrate polycarbonate layer is made by injection molding after engraving the groove and land; a vacuum oven is then used to dry the cyanine (cyanine solution 14 + quencher 2.5) or Cu-phthalocyanine (Cl⁻ replacement) after spin coating. Then, Ag is vacuum-deposited for 25 s by using a sputtering method. Fig. 2 shows the surface images of a fabricated multilayered disk imaged by SEM (scanning electron microscopy). In Fig. 2, the groove and the land are clearly distinguished by the different materials and structures, shown as wave shapes in Fig. 1, with a very uniform distribution.

III. EXPERIMENT

In our experiment, a Nd:YAG laser is used to irradiate the fabricated storage material. The Nd:YAG laser, which has a linearly polarized beam with a 3-mm diameter, is magnified and changed to a circularly polarized beam by using a $\lambda/4$ plate. The laser beam is launched into a beam splitter and separated into two paths. One path is directed toward the photodetector to monitor the intensity, the other towards the targeted disk. The direction of the irradiation beam is controlled by using an x - y position-controllable mirror coated with ZeSe in order to keep the focal point on the surface of the storage material. The irradiated beam is collimated, and its focal distance is fixed at 225 mm. A power meter was used to monitor the energy of the irradiated beam deposited in the sample.

After laser irradiation, the optical storage material was imaged by using OCT. A schematic of the OCT system is shown in Fig. 3. A low coherent light source was coupled into the 2×2 fiber coupler and split into two paths. One beam was directed toward the disk and the other to a reference mirror. The light source had an output power of 10 mW at a central wavelength of 1310 nm with a bandwidth of 70 nm. A visible (633 nm) aiming beam was used to find the exact imaging position on the optical

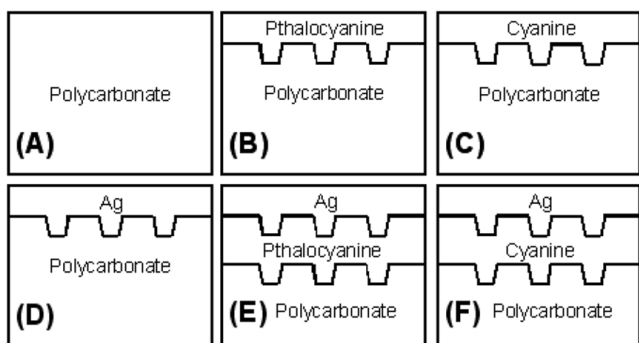


Fig. 1. Structures of the fabricated samples; the laser pulse is coming from the bottom.

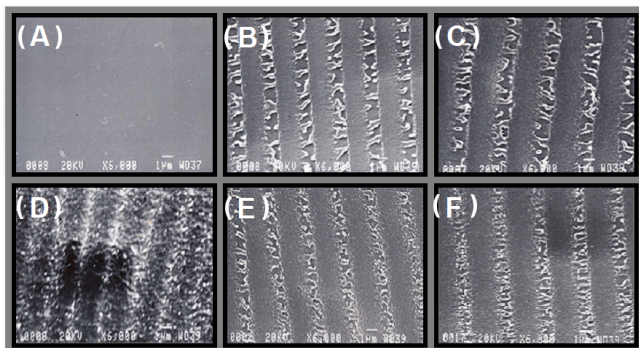


Fig. 2. Surface images of samples using the SEM ($\times 6,000$): (A) polycarbonate, (B) polycarbonate + pththalocyanine, (C) polycarbonate + cyanine, (D) polycarbonate + Ag, (E) polycarbonate + pththalocyanine + Ag, and (F) polycarbonate + cyanine + Ag.

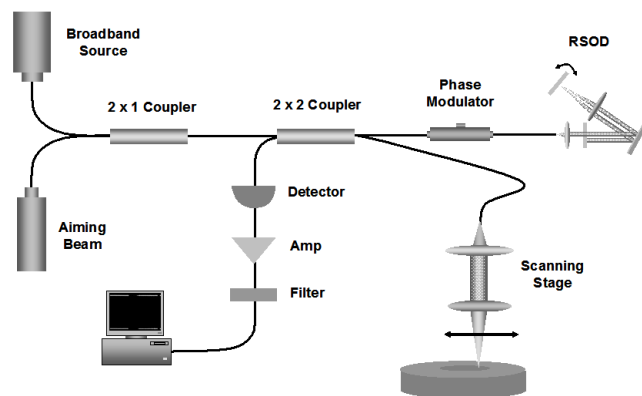


Fig. 3. Schematic of the OCT imaging system. RSOD is a rapid-scanning optical delay.

storage material. In the reference arm, a rapid-scanning optical delay line was used that employed a grating to control the phase and group delays separately so that no phase modulation would be generated when the group delay was scanned [14–16]. The phase modulation was generated through an electro-optic phase modulator that produced a carrier frequency. The axial line-scanning rate was 400 Hz, and the modulation frequency of the phase modulator was 500 kHz. Beams reflected from the two arms of the interferometer were recombined in the fiber coupler and detected on a photodetector. The detected optical-interference fringe-intensity signals were band-pass filtered at the carrier frequency. Resultant signals were then digitized with an analog-digital converter and transferred to a computer where the structural image was generated. The lateral and the axial resolutions of the reconstructed image were both $10\ \mu\text{m}$.

IV. RESULTS AND DISCUSSION

Fig. 4 presents OCT images of the optical storage material used in our experiment. Images were obtained after scanning from the inside to the outside of the optical storage material. In the images, the upper lines represent reflection from the substrate layer, and the bottom lines represent reflection from the reflective layer. In the area of the substrate layer without any coated material, the line is clear; with the protective layer, the substrate layer is not. In the reflective layer coated with Ag, high reflection is imaged, and a thick line is shown in the recording layer coated with dye, albeit clearer than the reflection layer. The image changes by layer because the reflection coefficient is different for each layer and thickness.

In Fig. 5, images from OCT and optical microscopy, showing pit formation, are presented. A prepared disk with different layers was irradiated using a Q-switched Nd:YAG laser with an energy of 373 mJ on $80\text{-}\mu\text{m}$ spot sizes. Spot-marking images on the substrate layer are shown in Fig. 5(A). Polycarbonate was melted out in the microscopy image, and a back area between two white

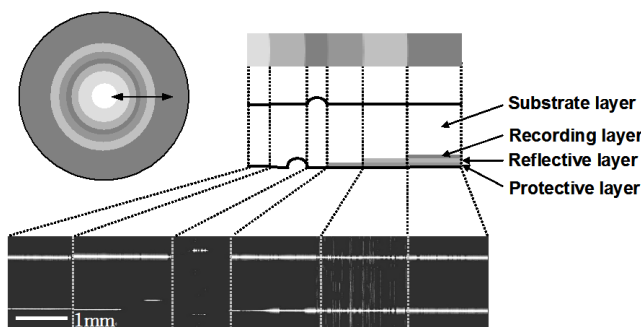


Fig. 4. OCT images of a multilayer optical storage recordable compact disk. The OCT image size is $6.0 \times 1.5\ \text{mm}^2$ with $10\ \mu\text{m}/\text{pixel}$.

lines is clearly apparent in the OCT image due to less reflection. Compared with the lower white lines of the other OCT images, the one in Fig. 5(A) appears thinner, because the reflection coefficient of the substrate layer is much less than those of the other dye layers, such as the recording and the reflective layers. Figures 5(B)–5(C) present spot marking on the substrate layer coated with dye. The dye in the recording layer and the polycarbonate of the substrate layer were melted out and separated at the same time. The small spot, which appears in the center of the upper line, was caused by chemical changes and thermal transformation of the dye. The non-uniform image gap of the lower line-component changed while polycarbonate was melted. When the thicknesses of the lower lines were compared, the cyanine dye was determined as having a higher reflection coefficient than the phthalocyanine. On the substrate layer deposited with Ag, only polycarbonate was melted and separated, with less melting of Ag [Fig. 5 (D)]. Because Ag has a high melting point, it didn't melt after laser irradiation, and the minimal effect is seen as a thin line in the center of the upper line of the OCT image. This correlated very well with the microscopy spot images that were severely distorted. The non-uniform image gap in the lower line is caused by component changes as the temperature-sensitive polycarbonate layer changed after laser irradiation and indicates that the reflection coefficient decreased.

A thickness increase in the lower line means that the reflection coefficient of Ag is much higher than those of polycarbonate and dye. Fig. 5 (E) and (F) show the

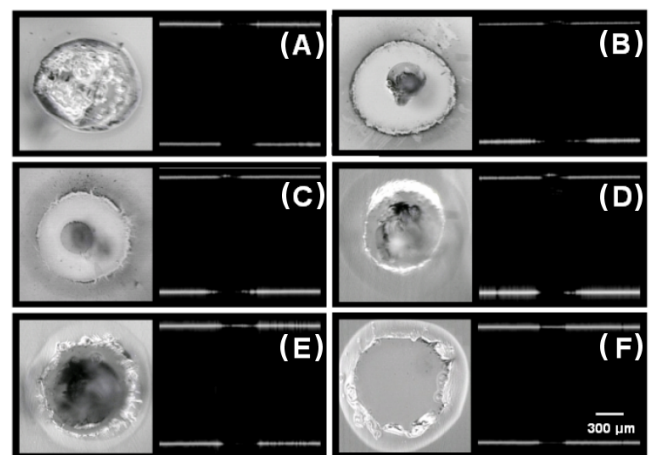


Fig. 5. Comparison of optical microscopic and OCT images of post-laser-irradiated multilayer optical storage media: (A) substrate layer (polycarbonate), (B) substrate layer (polycarbonate) + recording layer (phthalocyanine), (C) substrate layer (polycarbonate) + recording layer (cyanine), (D) substrate layer (polycarbonate) + reflective layer (Ag), (E) substrate layer (polycarbonate) + recording layer (phthalocyanine) + reflecting layer (Ag), and (F) substrate layer (polycarbonate) + recording layer (cyanine) + reflecting layer (Ag).

spot-marking formation on the recording layer deposited on top of the reflective layer. OCT images show thinner and clearer lower lines from the dye coating when compared to those from the Ag-reflective coating shown in Fig. 5(D). Thin upper lines at the center of the spot marking were also observed in the OCT images in Figs. 5(E) and (F) because the laser irradiation did not affect the Ag-reflective layer while it melted the dye layers. The inconsistency of the upper line in Fig. 5(E) resulted from remaining the dispersion of pthalocyanine dye that had survived melting and the polycarbonate heat transfer processes from laser irradiation. On the contrary, the OCT image in Fig. 5(F) shows a complete upper line because an efficient interaction between the cyanine dye and the laser irradiation leads to complete decomposition of the dye, leaving the Ag-layer intact. The differences in the clarities of the upper lines illustrate that cyanine dye is more sensitive to laser irradiation than pthalocyanine dye, thus resulting in complete chemical decomposition.

V. CONCLUSIONS

We have shown that spot marking, including pit formation, in multilayered optical storage material can be explained by using OCT and microscopy. The interaction between the optical storage material and light was clearly explained by using a top-view image with a cross-sectional view. Using OCT and microscopy images, we evaluated the process of spot marking and the different reactions by structure and material. In particular, changes in the recording and the reflective layers were monitored by OCT, which provided valuable information for understanding the recording mechanism in optical storage material after laser irradiation. Our results suggest that OCT has the potential to be a powerful method for evaluating spot-marking post-laser irradiation. This work focused on a multilayer optical storage materials, but the results should also be directly and broadly applicable to other material areas for evaluating the optical characteristics and changes of materials.

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