Use of grating in reading multilayer disc to reduce amount of interlayer crosstalk.

Shigeharu Kimura, Tatsuro Ide, Yumiko Anzai, Koichi Watanabe, Toshimichi Shintani, Eriko Tatsu, Hitachi, Ltd. (Japan). [TD05-155]

We proposed a cross-talk reduction method in which a grating was positioned parallel onto the optical axis in an optical return path from multi-layered disc.

Development of a new 9.5mm height ultra-slim super multidrive incorporating a grayscale diffractive optic.

Yosuke Mizuyama, Riccardo Leto, Xinbing Liu, Panasonic Boston Lab. (United States); Shogo Horinouchi, Satoshi Nagata, Eizo Oto, Panasonic Communications Co., Ltd. (Japan) [TD05-156]

We have developed a grayscale technology and were the first in successfully mass-producing a 9.5mm height Ultra Slim Multi Drive incorporating a grayscale diffractive optic.

Recordable multilayer superresolution using discrete-track three-dimensional pit selection.

Soichiro Eto, Hiroyuki Minemura, Yumiko Anzai, Toshimichi Shintani, Hitachi, Ltd. (Japan) [TD05-157]

Discrete-track Three-Dimensional Pit Selection was developed for recordable multilayer super-resolution, where super-resolution effect and high transmittance were confirmed. Perspectives for 500 GB/disc are indicated.

Novel materials for multiwavelength optical recording.

Makarand P. Gore, Charles R. Weirauch, Hewlett-Packard Co. (United States); Jitka Brynjolfssen, Richard Lione, Plasmon Data Systems Ltd. (United Kingdom) [TD05-158]

The paper describes novel materials: an absorber to capture energy in one radiation, and a contrast agent to cause changes at same or another wavelength.

Improvement of reproduced digital-bit-data quality using adaptive optics in holographic data storage.

Tetsuhiko Muroi, Nobuhiro Kinoshita, Norihiko Ishii, Koji Kamijo, Naoki Shimizu, NHK Science & Technical Research Labs. (Japan) [TD05-159]

Adaptive optics can compensate for the distortion in interference fringes caused by shrinkage of a holographic medium and increase the signal-to-noise ratio of the reproduced digital-bit-data.

Compatibility between compact-ROM reader and recording system.

Yukiko Nagasaka, Masayuki Nishikawa, Ryuouhei Kawamura, Akiko Kobayashi, Shinya Yoshida, Yukio Kurata, Sharp Corp. (Japan) [TD05-160]

To produce the holographic data storage system for consumer usage, we develop the compact ROM reader which has high compatibility and wide readout tolerance.

Compact fiber laser for two-photon recording in multilayered optical memory.

Masatoshi Tsuji, Shizuoka Univ. (Japan); Norihiko Nishizawa, Osaka Univ. (Japan); Yoshimasa Kawata, Shizuoka Univ. (Japan) [TD05-161]

We have developed a compact fiber laser for three-dimensional optical memory. We demonstrated the two-photon recording by using the developed fiber laser.

Novel subwavelength pit detection by the photonic nanojet.

Soon-Cheol Kong, Alan V. Sahakian, Allen Taflove, Vadim Backman, Northwestern Univ. (United States) [TD05-162]

We find that nanojet-illuminated pits having lateral dimensions of only 100nm by 150nm yield a 40-dB contrast ratio for optical data storage application.

Collinear phase-lock holography for hologram memories of the next generation.

Hironobu Koga, Hisayuki Noichi, Toyohashi Univ. of Technology (Japan); Hideyoshi Horimai, OPTWARE Corp. (Japan); Pang-Boey Lim, Mitsuteru Inoue, Toyohashi Univ. of Technology (Japan) [TD05-163]

Collinear phase-lock holography using phase-modulated data pages was proposed for holographic multi-level recording.

Magnetic-volumetric holography with magnetic garnet films.

Takamasa Okawa, Hidenobu Takahashi, Pang-Boey Lim, Toyohashi Univ. of Technology (Japan); Hideyoshi Horimai, OPTWARE Corp. (Japan); Mitsuteru Inoue, Toyohashi Univ. of Technology (Japan) [TD05-164]

Fundamental properties of volumetric holography with magnetic garnet films were investigated, so as to examine the potential of media for high density holographic memories.

Optical high-spatial resolution using super-RENS disk system.

Hisaos Hayashi, Tetsuya Sase, Takaya Tanabe, Ibaraki National College of Technology (Japan) [TD05-165]

We have experimentally investigated an optical spatial resolution of the super-RENS disk system. The CNR can be detected at the mark length of 23 nm.

Experimental and analytical study on the dynamic behavior of spinning flexible disk close to rotating rigid wall.

Abdelrasoul M. Gad, Yoon Chul Rhim, Yonsei Univ. (South Korea) [TD05-166]

The behavior of a flexible disk rotating close to fixed, co-rotating, and counter rotating flat-stabilizers in open air is investigated both experimentally and analytically.

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The backflow is experimentally and numerically confirmed to climb the SIL.

Numerical simulations on a stepped solid-immersion lens suggested from the experimental consideration of the backflow, Moon Ho Choi, Seung Hyun Han, Yoon Chul Rhim, Yussei Univ. (South Korea); Jeong Kyo Seo, In Ho Choi, Byung Hoon Min, LG Electronics Inc. (South Korea). . . . . . . . [TD05-171]

The backflow is experimentally and numerically confirmed to climb the SIL along its lateral surface and some modifications are applied to the SIL to prevent particles’ approaches to its top.

Layer stack design of high-density ROM disc for near-field system using solid immersion lens, Kazutoshi Kitano, Atsushi Yamaguchi, Masahiro Miura, Kunihiko Horikawa, Takao Tagiri, Eiji Muramatsu, Shoji Taniguchi, Fumihiko Yokogawa, Pioneer Corp. (Japan). . . . . . . . . . . . [TD05-167]

For high-NA near-field readout system, we have designed, fabricated, and tested the first-surface ROM disc with layer stack optimized by rigorous vector diffraction theory.

Mode-hopping detection technique for external-cavity laser diodes, Yukiko Nagasaka, Shinya Yoshida, Masaki Tanaka, Tetsuo Saeki, Yukio Watanabe, Hiroyuki Oka, Takahiro Miyake, Tetsuo Ueyama, Yukio Kurata, Sharp Corp. (Japan) . . . . [TD05-168]

We propose a mode hopping detection technique for ECLD using a time differential of output voltages of the single element photodiode.

Transition mechanism of WOx available for optical disc by laser irradiation, Keiichiro Yusu, Ryosuke Yamamoto, Masaaki Matsumaru, Naomasa Nakamura, Shinichi Katsuda, Toshiba Corp. (Japan) . . . . [TD05-169]

We investigated the transformation mechanism of WOx used for write-once type optical disc or the heat mode mastering during laser irradiation and observed the change in valence of W atoms after laser irradiation.

Characterization and recording mechanism of Bi-Fe-(N) layer for high-speed write-once optical recording, Hung-Chuan Mai, Tsung-Eong Hsieh, National Chiao Tung Univ. (Taiwan); Shiang-Yao Jeng, Ming-Chien Sun, Prodisc Technology, Inc. (Taiwan) . . . . [TD05-170]

Bi-Fe-(N) layer for high-speed write-once recording was investigated. TEM/EDS characterization revealed that the separation of Bi and Fe-rich phases and grain coarsening in the mark regime are mainly responsible to the recording mechanism.

Numerical simulations on a stepped solid-immersion lens will be discarded.

Posters must be removed at the end of the day after the oral sessions.

Posters not removed by 7:00 pm will be considered unwanted and will be discarded.

Room: Queen’s Ballroom · Tues. 2:00 to 3:30 pm

Session Chairs: Barry H. Schechtman, Information Storage Industry Consortium; Junji Tominaga, National Institute of Advanced Industrial Science and Technology (Japan)

5:15 pm: Near-field rewritable dual-layer recording with SIL system, Masahiro Birukawa, Eichi Ito, Kenji Narumi, Rie Kojima, Noboru Yamada, Matsushita Electric Industrial Co., Ltd. (Japan); Takeshi Mizukuki, Aiyoshi Nakaoki, Osamu Kawakubo, Sony Corp. (Japan). . . . . . . . [TD05-151]

A data capacity of 150GB per 12cm-diameter disc was proved feasible in a near-field recording system with the assistance of PR (12221)/17PP code and LDPC decoding method.

4:45 pm: Near-field rewritable dual-layer recording with SIL system, Masahiro Birukawa, Eichi Ito, Kenji Narumi, Rie Kojima, Noboru Yamada, Matsushita Electric Industrial Co., Ltd. (Japan); Takeshi Mizukuki, Aiyoshi Nakaoki, Osamu Kawakubo, Sony Corp. (Japan). [TD05-152]

Dual-layer rewritable recording with a SIL system was first demonstrated, and overwriting and read-out have been successfully achieved for the both phase change recording layers.
MONDAY
SESSION MPD: Post-deadline Posters

Queen's Ballroom
Mon. 2:00 to 3:30 pm
Use of grating in reading multi-layer disc to reduce amount of interlayer cross-talk

Shigeharu Kimura*, Tatsuro Ide, Yumiko Anzai, Koichi Watanabe, Toshimichi Shintani, and Eriko Tatsu
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ABSTRACT

Cross-talk from adjacent layers is considered to affect the tracking-error signal of conventional optical pickups when a multi-layered disc is read. The tracking-error signal fluctuates and makes carrying out precise tracking difficult. We propose using a grating in the return path in order to reduce the amount of cross-talk. Using a grating with an uneven plane on the optical axis reduces the amount of stray light causing the amount of cross-talk and lets the target light pass through. We show that using a grating with an appropriate pitch prevents diffracted light higher than an order of ±1 from going back to detectors. As the shape and depth of the grating is an important factor for the 0-order light, we chose a deep triangular one. We measured the distribution of the transmitted intensity through the grating as a focused beam position was scanned and found that the grating can reduce the amount of cross-talk.

Keywords: Cross-talk, multi-layer, tracking error, grating, triangular, pitch, depth, BD, disc, pickup

1. INTRODUCTION

A multi-layer Blu-ray Disc (BD) to increase the recording capacity per disc is considered not to have basic technical difficulties for the optical system because the conventional optical pickup for the single/dual layer disc can be used without needing any changes to its basic optical structure to be applicable for the medium. Until recently, BD read-only-memory discs of 100 and 200 GB with 4 and 8 layers, respectively, have been developed and signals from the discs have been read out successfully. [1, 2] However, to effectively use a rewritable multi-layer disc, we need to reduce the fluctuation of the tracking error signal as well as reduce the RF signal deterioration by stray light from other adjacent layers when a pickup uses the differential push-pull method. For a one-beam optical system a technique using a polarization longitudinal slit comprising photonic crystal was implemented and reduced the amount of cross-talk. [3] In this paper we describe and propose the use of an inexpensive way of using a grating that reduces the amount of cross-talk. We also show the preliminary experimental results of the transmission property of the optical device.

2. PROPOSED METHOD

We propose the use of a new method in which a grating reduces stray light from adjacent layers. A schematic of the optical pickup is shown in Fig. 1. A focusing lens, a grating, and a reflector are attached in the return path from a multi-layer disc to a normal pickup. The reflection from the multi-layer disc including the stray light is focused on to the reflector situated at the focal position of the focusing lens. The grating is positioned on the optical axis between the focusing lens and the reflector. This arrangement and the stray light from the adjacent layer farther from the objective than the target layer is shown in Fig. 2. The stray light impinges upon the grating and is not able to return to the focusing lens. On the other hand, since there is a gap between the grating and the reflector, the reflection from the target layer can get through the gap without being obstructed by the grating, return to the focusing lens, and be detected by detectors. Stray light from the layers nearer to the objective also strikes on the grating in the same way as from the farther layer after it has reached the reflector. In this case the stray light cannot go back to the focusing lens either. If the grating effectively prevents the stray light from returning to the focusing lens, the amount of interlayer cross-talk can be reduced.

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3. DESIGN OF GRATING

We used the general grating equation to show that the light diffracted by on-axis grating into the higher orders other than the 0-order cannot return to the focusing lens; if the pitch of the grating is shorten, this light may go beside the lens. The maximum pitches of the gratings in the air and a transparent substrate were calculated for the NA of the focusing lens (Fig. 3). We can thus determine which pitch is appropriate when we choose the focusing lens and the refractive index of the grating substrate. The 0-order light from the grating cannot be reduced by merely changing the pitch. We considered changing the groove depth as another factor for our purpose. We calculated by using the FDTD method the 0-order efficiency of rectangular and triangular gratings that depend on the groove depth and incident angle. The efficiency changes periodically with the groove depth for a rectangular grating, but the triangular grating does not do so for a range of groove depths and incident angles (Fig. 4). Therefore, since the grating on optical axis is irradiated by the incidence of large incidence-angle range in the proposed system, we used the triangular grating.

Fig. 3 Largest grating pitch vs. NA of focusing lens.
A grating pitch shorter than the largest pitch for an NA can prevent the reflection by the adjacent layers returning to the lens.

Fig. 4 Calculated two-dimensional map of 0-order diffraction efficiency in TE wave for a triangular grating. The grating is made of Al and the pitch is 10 λ. Both axes are the groove depth and incidence angle.
4. MEASUREMENT

We measured the transmission power of a focused beam through a grating with an uneven plane that was parallel to the optical axis and with grooves that were perpendicular to the axis. The groove was triangular and the NA of the focusing lens was 0.1. The focused beam position was scanned in the xz-plane and an image of the transmission power distribution was plotted (Fig. 5). The upper line corresponds with the front surface and the lower one with the back surface. When the beam focused on the grating, the transmission power decreased. This means that the grating on the optical axis can reduce the amount of interlayer cross-talk. The simulation of transmission power distribution through a vertical sheet of absolute absorbance is shown in Fig. 6 and shows a distribution similar to the experiment.

![Fig. 5 X-z transmission intensity map of triangular grating device. The focused position was scanned in the device. The grating pitch and depth are 8.9 µm and 6 µm, respectively. The optical thickness is 3 mm.](image1)

![Fig. 6 Simulation of transmission intensity map through absorption sheet in a glass. Sheet is assumed to be absolutely thin and zero in reflectivity. Brightness corresponds with transmission power.](image2)

5. CONCLUSION

We have proposed a way of reducing the amount of interlayer cross-talk and developed a grating device that can be used in the optical pickup. While we hope to further reduce the stray light by the grating, our measurements of the transmission through the grating demonstrate the effectiveness of our method. We aim to further improve the ability of the grating device as well as to integrate it into an optical pickup.

REFERENCES


Development of a New 9.5mm Height Ultra Slim Super Multi Drive Incorporating a Grayscale Diffractive Optic

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1. Introduction
A new 9.5mm height DVD/CD ultra slim super multi drive was developed to compete in the market. We developed a grayscale technology to fabricate a grayscale diffractive optic used in the new drive for focusing with the astigmatic method. The new grayscale diffractive optic brought technical improvement compared to conventional binary optics and realized a cost competitive drive. Technologies used in this new optical drive are reported.

2. The new Ultra Slim Super Multi Drive
A new 9.5mm height DVD/CD Ultra Slim Super Multi Drive was developed with a new technology. The new drive consists of DVD and CD optical system sharing all the optics, three beam gratings, integrated prism, collimator, and objective lens. Fig.1 shows a perspective view of the drive.

The two wavelength laser diode emits a single-mode laser beam at a wavelength of 665nm for DVD or 785nm for CD. The laser beam passes through wavelength selective three beam gratings, integrated prism, collimator and objective lens. The returning beam from the disc comes back to the integrated prism and is reflected by a polarization beam splitter inside the prism. The beam is directed to a grayscale diffractive optic, which is an astigmatic mirror and generates astigmatic aberration. Two sets of quad-detector arrays generate electrical signals to compute the focus error signal and the push-pull signals as it receives the astigmatic beam from the grayscale optic. The differential push pull method and the in-line differential push pull method are used for DVD and CD tracking, respectively. Fig. 2 shows the detail of the integrated prism. Fig. 3 depicts the beam paths around the prism.

Fig. 1: The new Ultra Slim Super Multi Drive.

Fig. 2: Integrated prism with grayscale diffractive astigmatic mirror.
The grayscale diffractive optic is fabricated on a wafer using grayscale photolithography and is covered with reflective coating. The wafer is glued with other wafers with polarization beam splitter over-coated and diced to form the integrated prism, which is a distinct and proprietary element of the Panasonic super slim drives. Grayscale optics drastically improve the diffraction efficiency compared to binary optics. The diffractive astigmatic mirror could have been made with a Fresnel zone plate by binary lithography but the diffraction efficiency is so low that undesired diffraction gives rise to a drive quality problem. The combination of the integrated prism and the embedded grayscale diffractive astigmatic mirror significantly reduces cost compared to optical drives of semi-discrete type in which a separate astigmatic lens and a lens holder are necessary.

![Fig. 3: Beam paths around the integrated prism.](image)

3. The grayscale technology
We were the first in successfully developing a grayscale photolithography using Laser Direct Write (LDW) grayscale mask with mass-production level in quality, namely the yield of production, which mainly depends on the shape error and surface quality, is such that the factory accepts. The LDW grayscale mask is a commercial product of Canyon Materials Inc. (CA, USA). The transmittance of LDW masks changes proportionally to the applied heat.

A focused laser beam can write precise grayscale pattern on LDW mask. Once a grayscale mask is prepared, regular photolithography process follows, i.e., exposure by a stepper, bake, development, and plasma etching are carried out to manufacture the final optic. Fig. 4 shows a microscope picture of an actual grayscale mask pattern of the grayscale diffractive astigmatic mirror, cross sectional profile of the white light interferometer measurement data along the mirror center (dotted line) of the final element, and the shape error from the design. There are some spurious measurement errors at each break point of the mirror due to the discontinuity, which are not counted in the shape error. The RMS shape error being less than 10nm excluding the measurement errors, the agreement of the design and measurement is good enough for mass-production.

![Fig. 4: Grayscale mask (top), design and actual interferometer measurement (middle), shape error (bottom) for the grayscale astigmatic mirror.](image)
The greatest technical improvement in using grayscale optics is its high diffraction efficiency compared to binary optics. We could achieve about 85% diffraction efficiency while conventional binary hologram, which used to be employed in older version of our drives, had only about 32% in diffraction efficiency. This difference made significant increase in signal to noise ratio of the signal processing for focusing and tracking.

Furthermore, one of the advantages of using the LDW mask over other grayscale masks such as HEBS (High Energy Beam Sensitive) mask\textsuperscript{1)}, which is the complementary mask of LDW, and half-tone grayscale mask\textsuperscript{3}) is that the blurring at the break point of the phase jump in a diffractive optical pattern on LDW mask is much less, which is of significant importance for the diffraction efficiency of the final optic. The blurring at the break point on the final optic in case of LDW mask is no more than 1µm in combination with the use of a 5X image reduction stepper. Although this blurring creates about 15% diffraction loss, the associated stray light forms relatively uniform background light as is known\textsuperscript{4}) and it does not give significant negative effect on the signal processing. The HEBS mask and the half-tone grayscale mask cannot achieve this accuracy. It is well known in the scope of scalar diffraction theory that the diffraction efficiency rapidly drops as the blurring increases\textsuperscript{5)}. We can not expect 85% diffraction efficiency with blurring that is beyond 1µm.

Another key technology is an in-house grayscale laser writer system with excellent stability and repeatability. A diode pumped solid state green laser is used for mask writing with about 0.8 ~ 2µm spot size depending on the objective lens. The laser beam is modulated by an Acousto-Optic Modulator (AOM) through a 16-bit D/A converter. Linear air bearing stages are used to translate in 2 axes the LDW mask and are synchronized with the laser trigger signal based on the pattern data. A real time auto-focusing system captures the surface of the mask so that it keeps focusing over large area. Fig. 5 depicts a schematic of the grayscale laser writer. The graylevel being given in up to 65535, the laser writer can write extremely smooth profile of an optic pattern all over the pattern area with real grayscale tone whereas lower graylevel, e.g., 256 levels, often suffers step like profile.

The main features of the system are the following.

1. Stability of laser power : < 1% PV
2. Repeatability of focusing : < ±0.5µm PV
3. Repeatability of stage : < 0.5µm PV

To the best of our knowledge, these specs are not achieved for commercially available laser writers.

4. Conclusion
We have developed a grayscale technology and were the first in successfully mass-producing a 9.5mm height Ultra Slim Super Multi Drive incorporating a grayscale diffractive optic. The technology improved the signal quality by increasing the diffraction efficiency of the diffractive optic and brought significant reduction of cost per drive as a result. Consequently the technology made our optical drives very competitive in terms of technology and cost.

5. References
1) http://www.canyonmaterials.com
Recordable Multilayer Super-Resolution Using Discrete-Track Three-Dimensional Pit Selection

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ABSTRACT

A recordable multilayer super-resolution method (Discrete-Track Three-Dimensional Pit Selection) has been developed. Fundamental super-resolution characteristics were experimentally examined both for a discrete-track (DT) and conventional discs to compare their characteristics. The experimental results show that the DT disc exhibits higher optical resolution and an optical transmittance of 71%, sufficient for multilayer super-resolution. Disc design indicated the possibility of a data capacity of 500 GB/disc.

Keywords: super-resolution optical disc, multilayer optical disc, Three-Dimensional Pit Selection

1. INTRODUCTION

Among the various optical storage techniques developed to realize sub-terabyte data capacity, the super-resolution technique is one of the major candidates because of its compatibility with current techniques such as Blu-ray Disc (BD). Super-resolution is considered to be able to realize a data capacity of 100 GB/layer \([1]\). To achieve larger data capacity, we have developed a multilayer super-resolution technique called the Three-Dimensional Pit Selection (3DPS) method \([2]-[5]\). Its data capacity target is about 500 GB. This is to be realized by embedding super-resolution material in only data pits of a ROM disc to obtain the high optical transmittance of a recording layer. This method, however, is limited to ROM discs. A recordable method is necessary for use in a wider number of applications.

In this paper, we propose a recordable multilayer super-resolution technique that, similar to 3DPS, embeds super-resolution and recording materials in track grooves. The fundamental experimental results for the fabricated disc are reported. The prospects of multilayer discs are also discussed in accordance with the disc design.

2. PROPOSED METHOD AND EXPERIMENTAL CONDITIONS

2.1 Concept of proposed method

Figure 1 shows the proposed disc’s structure. Films on the lands are removed and are embedded only in the track grooves. This configuration enables high optical transmittance and realizes multilayer super-resolution. This is because the land is so transparent that the average transmittance of a recording layer is sufficiently high to meet the requirements for a multilayer disc. The film structure is discretized by the track grooves, so here we call this method discrete-track (DT) 3DPS.

2.2 Experimental conditions

A conventional super-resolution disc (with the films on both lands and grooves continuously) and the DT disc were measured. The DT disc was fabricated by chemical mechanical polishing \([3]\). For the super-resolution material, GeSbTe was used. For the recording material, BaTiO\(_3\), developed by J. Kim et al. \([6]\), was used. The film structures of the conventional disc and the groove region of the DT disc were the same: polycarbonate substrate / dielectric / BaTiO\(_3\) / dielectric / GeSbTe / semi-transparent film / 0.1-mm thick sheet. The track pitch and the groove depth of the substrate were 320 nm and 23 nm, respectively. To compare their super-resolution characteristics, the conventional disc and DT disc were evaluated using an optical disc tester with a laser of 405-nm wavelength and an objective lens of 0.85 numerical aperture.
3. RESULTS AND DISCUSSIONS

3.1 Conventional super-resolution disc

Figure 2 shows the relationship between carrier level and readout power (Pr). Single-tone patterns of the marks with lengths of 137 nm and 99 nm were measured. The carrier level was normalized by Pr. This figure shows that the super-resolution effect was larger than 2.4 mW and the largest effect for 99-nm marks was around 3.4 mW.

Figure 3 shows the relationship between the mark length and the carrier levels for Pr = 0.3 mW and Pr = 3.4 mW. The carrier level for Pr = 0.3 mW decreased with decreasing the mark length. This carrier level was not detected at a mark length less than 124 nm. However, the optical resolution enhancement was observed for the conventional disc, confirming the super-resolution effect. The minimum mark length detectable was 87 nm.

3.2 Discrete-track super-resolution disc

Figure 4(a) shows a photograph of the fabricated DT disc. Homogeneity of polishing was determined using an optical disc tester. Figure 4(b) shows the push-pull and readout signals that confirm this homogeneity.

Figure 5 shows the relationship between the carrier level and Pr where the measurement conditions were the same as those for a conventional disc. This figure shows that the carrier level of the 137-nm mark was nonlinearly increased by Pr=2.4 mW, almost the same as the trend of the conventional disc shown in Fig. 2. The optimum Pr for 99-nm marks was determined to be 3.6 mW. Figure 6 shows the relationship between the mark length and the carrier level of the DT disc for Pr = 0.3 mW and Pr = 3.6 mW, where the minimum mark length detectable in the DT disc was 62 nm.

Optical transmittance of the DT disc, measured using a spectrophotometer, was 71%. This high transmittance indicates the possibility of the multilayer super-resolution disc.

When comparing the data for the conventional and DT discs, two differences can be seen. First, in Figs. 2 and 5, the characteristics for 99-nm marks (below the diffraction limit) are almost the same for both discs, while the super-resolution effect at 137-nm marks (above the diffraction limit) is larger for the conventional disc than for the DT disc. Second, optical resolution enhancement is higher for the DT disc than for the conventional disc. The reasons are not clear yet. To clarify them, we have to investigate the differences between the optical and thermal characteristics and the possibility of differences in the shape and size of the written marks. The optimum power for super-resolution readout is almost the same for both discs, though the DT disc has no light absorption in lands. This indicates that the super-resolution effect results mainly from the heat generated by the center of the optical spot.

3.3 Disc design for multilayer disc

A multilayer DT disc structure was designed to estimate the possible number of layers realized with this method. The design criteria are described elsewhere. The result is that five layers are possible when the average amount of reflected light detected by the detector of a drive is 5% for each layer and that transmittance of the recording layer closest to light incidence is about 80%. This transmittance is about 10% higher than that of the fabricated DT disc. This will be solved by disc design because BaTiO$_3$ recording film is so highly transparent that transmittance of the track region will be increased than the DT disc used in this study. If 100 GB/layer, as indicated by J. Kim et al., is realized for each layer, 500 GB/disc will be possible with a recordable BD-compatible disc.

4. SUMMARY

A discrete-track (DT) Three-Dimensional Pit Selection was developed for a recordable multilayer super-resolution. The experimental results show that the DT disc exhibits higher optical resolution and an optical transmittance of 71%, sufficient for realizing multilayer super-resolution. The disc design indicates the possibility of the data capacity of 500 GB/disc.

REFERENCES


Fig. 1 Structure of discrete-track disc suitable for recordable and multilayer super-resolution. Recording and super-resolution films embedded in grooves.

Fig. 2 Readout power (Pr) vs. Carrier level normalized by Pr.

Fig. 3 Mark length vs. Carrier levels with Pr=0.3 mW and 3.4 mW. Carrier levels normalized by Pr.

Fig. 4 (a) Photograph of DT disc. (b) RF level of polished region.

Fig. 5 Readout power (Pr) vs. Carrier level normalized by Pr.

Fig. 6 Mark length vs. Carrier levels with Pr=0.3 mW and 3.6 mW. Carrier level normalized by Pr.
Novel Materials for Multi-Wavelength Optical Recording

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ABSTRACT

The paper describes novel materials- an absorber to capture energy in one radiation, and a contrast agent to cause changes at same or another wavelength. Materials that produce color-change upon stimulation with light are of great interest due to their applications in optical media and imaging. At this time, no simple, ubiquitous, low cost technology exists that enables data writing in blue laser optical drive media. These contrast changes are tunable to desired wavelengths. For example, blue laser writing, and red laser reading. We have successfully created a commercial DVD disc that can write with a blue laser that can be read by any digital versatile disc (DVD) drive. The technology has significant implications in step towards the convergence to blue, and for the Media On Demand markets. The future for this technology is to become the pervasive industry solution for low-cost writable dye for high density recording. The dyes we have developed not only switch colors, but also alter the electromagnetic behaviors, such as conductivity and optical constants at a molecular level. Therefore many applications using these effects are possible. The Chemistry and Physics of the dye marking is the subject of this presentation.

Keywords: Media, dual wavelength, dye, absorber, contrast former, color former, DVD, BD, High Density

1. INTRODUCTION

Materials that produce color and/or contrast change upon stimulation with radiation are used in optical recording and imaging media and devices. Further, widespread adoption of and rapid advances in technologies relating to optical recording and imaging media have created a desire for greatly increased data storage capacity in such media. Thus, optical storage technology has evolved from the compact disc (CD) and laser disc (LD) to far denser data types such as DVD and blue laser formats such as Blu-ray and high-density DVD (HD-DVD). It is of great interest and benefit to enable novel technologies for such applications.1, 2

2. DUAL WAVELENGHT RECORDING AND MATERIALS

We have invented methods and materials to induce contrast and color change at a selected wavelength, using light source at a different wavelength. The materials consist of two components: 1. an absorber tuned to the marking radiation that may not substantially change, and 2. a color or contrast change component that affects physical or chemical changes readable in another wavelength. The ability to use one wavelength of radiation to effect change in another wavelength is a unique and very powerful tool. The two stage architecture results in two levels of response. The absorber functions to capture the energy and then transfers this to the color/contrast change system. (Figure 1)
In one case the color/contrast system consists of a Leuco dye such as Fluoran Leuco dyes, and a developer such as phenol developer. In a second case, the color/contrast agent consists of a commercial or designer DVD dye. For example, we identified Blue absorbers that effectively combine with conventional (red absorbing) materials used in DVD recording. This is the key innovation required to write with 405nm (Blue Laser), and read with 650nm (Red) Laser. We have named the media Write-Blue:Read-Red (WB-RR).

2.1 Media and Mechanism

The Absorber molecules, such as C.I. Solvent Yellow 93 are homogeneously dispersed in the DVD dye (CIBA IRG1699) layer, and coated on DVD substrates for preparation of the discs. When the disc tracks are digitally exposed to 405nm radiation, energy is captured by the absorber. Energy is instantaneously transferred to the DVD dye, which changes chemical or physical properties. The DVD dye change causes significant $\Delta n$ and $\Delta k$, as measured at normal DVD operating wavelength (650nm) that is readable in standard DVD player as if the dye had been recorded in a standard DVD drive with standard 650nm laser. The discs thus described can be written with a Blue (405nm) laser yielding written data that meet commercial DVD standard industry specification. During the course of this research, we have discovered many absorbers that are compatible with conventional DVD and CD dyes. We are developing these coatings to interact with devices that use Blue Laser Drive Optical Processing Units (OPU’s) such as HD-DVD, Blu-ray and modified DVD drives.

2.2 Performance and Results

In the case where DVD dye is used as contrast agent, we have discovered that WB-RR media provide more than just similar performance to conventional Write Red – Read Red (WR-RR) media. Indeed there are many significant performance advantages. Recording blue laser spot diameter is significantly smaller than standard red spot in conventional DVDR drives. The effect of this is to increase the focused intensity of the laser energy in the dye layer during recording. Relatively lower laser power is needed to record data using 405nm laser compared to 658nm laser. Cross talk (track to track) of recorded data can be reduced. Contrast (modulation) of data recorded with 405nm blue laser is significantly greater than data recorded with 658nm red laser. (Figure2)

![Figure 2](image2.png)

Figure 2 – WB-RR Advantages – Modulation and Laser Power Margin

Read stability of DVD data recorded with Blue 405nm laser is significantly superior to that of DVD data recorded with standard Red 658nm laser. (figure4)

![Figure 4](image4.png)

Figure 4 – Effect of Blue Laser 405nm Recording vs. Red Laser 658nm Recording on Read stability
2.3 Applications to MOD

Blue laser recording of WB-RR DVDR media that exceeds DVDR performance specifications has been achieved. One application that can benefit from this discovery is Media-on-Demand (MOD). The media providers such as movie studios, sports networks and other over IT content providers are looking for secure, copy protected ways to deliver content over the net. The studios have thousands of movies available for digital distribution, but only hundreds in ready to sell media because there is currently no way to assure complete MOD copy protection and compatibility using current systems. Of particular interest for MOD application are discs that appear as close as possible to DVD-ROM after recording. Especially, low Push-Pull and Wobble signals (at 650nm) are desired for good playback compatibility with legacy devices. Because Blue laser recording of WB-RR DVDR media improves performance margins compared to standard DVDR media, this allows window to manipulate groove and coating structures to tune discs specifically for MOD application requirements. For instance it is possible to significantly reduce the Push-pull and Wobble amplitude of WB-RR DVDR media while retaining specification for other key parameters such as Reflectivity, Modulation and Jitter. Parameter optimization is currently in progress. By encrypting a hard key in the WB-RR DVDR media, the content providers can assure complete security and copy protection, without the opportunity for incompatibility.

3. Summary

We have successfully prepared two compositions that were spin coated on optical discs. The discs are exposed to a focused blue ray laser at 405nm, operating at 10mW and 8.4ms⁻¹ (2.4x DVD) speed. The data was recorded on the discs using conventional DVD write strategies. The read back and environmental stability meets or exceeds the standards requirements for commercial DVD media and drives at 658nm. (Figure 5).

Figure 5: Spectra of WB-RR discs showing activity at 405nm and 658nm, and marks obtained thereof

There is currently no commercial dye based solution that offers writing at 405nm and reading at 658nm. WB-RR discs solve this and use it to provide an excellent solution for the MOD application with superior legacy compatibility and encryption hardware key that can activate a software key. The ability to use radiation of one wavelength to change optical properties in another, presents a very powerful tool with many applications. Especially, in many cases the optical change is accompanied by changes in magnetic and electrical properties.

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Improvement of reproduced digital-bit-data quality using adaptive optics in holographic data storage

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ABSTRACT

A holographic medium made of photopolymer shrinks due to photopolymerization, and this shrinkage degrades the reproduced digital-bit-data. Adaptive optics controlled by a genetic algorithm were developed to compensate for the distortion in interference fringes caused by shrinkage of a holographic medium whose thickness was 2 mm and shrinkage ratio was 0.3 %. The adaptive optics increased the signal-to-noise ratio of the reproduced digital-bit-data.

Keywords: holographic data storage, adaptive optics, genetic algorithm, compensation, signal-to-noise ratio

1. INTRODUCTION

Next-generation recording systems might use some form of holographic data storage. Holographic data storage potentially has large capacity and high data-transfer-rate. Photopolymer is a feasible medium since it has a large diffraction efficiency and high stability. However, photopolymer shrinks when holograms are recorded on it. Furthermore, the temperature difference between the recording and reproducing conditions causes the photopolymer medium to shrink or expand [1]. This shrinkage or expansion distorts the interference fringes and decreases the signal-to-noise ratio (SNR) in the reproduced digital-bit-data. The amount of shrinkage is especially large when the photopolymer of the medium is thick in order to obtain a high data recording density. While a medium that does not shrink would be the best solution to these problems, so far, no such medium has been found. Therefore, we tried to use adaptive optics to compensate for the shrinkage of the holographic data storage medium. We previously found that the intensity distribution in a reconstructed image whose pixels are all white could be improved [2]. However, actual hologram data are discrete white and black bit data. In this paper, we show that adaptive optics on a thick hologram medium can be used to increase the SNR of reproduced digital-bit-data.

2. HOLOGRAPHIC DATA STORAGE USING ADAPTIVE OPTICS

Figure 1 shows the optical configuration of our system for holographic data storage using adaptive optics. A laser beam is divided into signal and reference beams by a polarized beam splitter (PBS). The signal beam is spatially modulated by a spatial light modulator (SLM) before it reaches the media. The reference beam reaches the media through a deformable mirror (DM) that controls the wavefront of the beam. The reconstructed beam, which includes the reproduced digital-bit-data, is observed with a CCD camera. The CCD camera and DM are connected to a computer. The CCD camera measures the reproduced digital-bit-data, and the computer controls the DM in order to ensure the reference beam entering the hologram has an optimum wavefront.

We used a genetic algorithm (GA) to obtain an optimum wavefront in the adaptive optics. The parameters of the GA

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were gene, individual, population and fitness. The values of the pins driving the DM were taken to be genes. Each individual is a condition of the DM as determined by genes. The population is a group of \( n \) individuals. Fitness is an evaluation parameter. The objective of the adaptive optics is to obtain reproduced digital-bit-data with a high SNR. Therefore, a simple way is to make SNR the fitness measure. SNR is represented by

\[
SNR = 20 \log \frac{\mu_1 - \mu_0}{\sqrt{\sigma_1^2 + \sigma_0^2}} \tag{1}
\]

where \( \mu_1 \) and \( \mu_0 \) represent the mean of reproduced digital-bit-data “1” and “0”, respectively, and \( \sigma_1 \) and \( \sigma_2 \) are the standard deviations of reproduced digital-bit-data of “1” and “0”, respectively. However, when SNR is used as fitness, the reconstructed image converges on darkness in some cases even though the SNR is high. This is because the standard deviations are dependent on the means of each bit type, respectively, which indicates that there is a correlation between the denominator and numerator in eq. (1). Based on this fact, we employ the coefficient of variation \( c \), which is expressed by

\[
c = \frac{\sigma}{\mu}. \tag{2}
\]

Thus eq. (1) becomes

\[
Fit = \frac{\mu_1 - \mu_0}{\sqrt{c_1^2 + c_0^2}} \tag{3}
\]

where \( c_1 \) and \( c_2 \) represent coefficients of variation of reproduced “1s” and “0s”, respectively. The GA is performed to obtain a maximum \( Fit \).

### 3. IMPROVEMENT OF SNR OF REPRODUCED DIGITAL-BIT-DATA

We made a holographic medium using photopolymer consisting of M-110 and M-1600 (Toagosei) \(^3\). The photopolymer layer whose thickness was 2 mm was sandwiched between two glass plates. The shrinkage ratio was approximately 0.3%, as measured with a plane wave tester \(^4\). This shrinkage ratio could be controlled by varying the pre-exposure time.

Figure 2(a) shows a reproduced digital-bit-data image without compensation. As the medium shrank, interference fringes became distorted. Some areas in the reconstructed image were dark, and digital-bit-data could not be reproduced. To compensate for this phenomenon and to reproduce digital-bit-data with a higher SNR, adaptive optics were employed. Figure 3 shows \( Fit \), which is the maximum value in the same generation, plotted as a function of generation in the GA. \( Fit \) increases from 21.9 before compensation to 27.8 after compensation. Figure 2(b) shows a reproduced

![Fig. 2 Reproduced digital-bit-data image](image-url)
digital-bit-data image with compensation. The dark areas decrease, and the digital-bit-data are clearer than in Fig. 2(a). As the reproduced digital-bit-data is compensated using Fit, we need to calculate SNR using eq. (1). In this calculation, the reconstructed image is divided into blocks, and SNR is calculated in each block because the combination of bright and dark areas in the digital-bit-data image cannot be correctly evaluated. The block SNR for Fig. 2 was calculated by dividing the reconstructed image into 128×128 pixel blocks. The minimum block SNR before compensation was -2.5 dB, which indicates digital-bit-data cannot be obtained, and it increased to 2.0 dB after compensation. Adaptive optics with the GA can thus improve reproduced digital-bit-data quality in a holographic medium with a 2-mm-thick photopolymer layer and shrinkage ratio of 0.3%.

4. CONCLUSIONS

A holographic medium made of photopolymer shrinks due to photopolymerization. The shrinkage becomes especially large when the photopolymer layer is thick in order to obtain a high data recording density. We proposed a method to compensate for medium shrinkage and increase the SNR of reproduced digital-bit-data in a holographic medium. The method increased SNR in the dark areas in an image from a medium with a photopolymer layer thickness of 2 mm and shrinkage ratio of 0.3%, and the minimum SNR increased from -2.5 dB before compensation to 2.0 dB after compensation. This technology can reproduce digital-bit-data in the dark area in an image and increase the SNR of digital-bit-data reproduced from a thick hologram. It is also useful when designing the medium, i.e., a medium has a very large diffraction efficiency but also has shrinkage. However, shrinkage can be compensated by adaptive optics. Shrinkage and expansion caused by temperature changes can also be compensated.

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Compatibility between Compact ROM Reader and Recording System

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Abstract

To produce the holographic data storage system for consumer usage, we develop the compact ROM reader which has high compatibility and wide readout tolerance.

Keywords: holographic memory, compatibility, tolerance

1. Introduction

Holographic data storage (HDS) is a promising technology that can provide very large storage density and high speed. So far, HDS has been developed in various field of technology such as systems, materials, and signal processing. On the other hand, to achieve HDS as consumer products, it is necessary to development in consideration of the compatibility among HDS systems and the reconstructing margin of these systems [1-3].

In this paper, we present experimental results of the compatibility between our compact ROM reader and our angle multiplexing recording system and simulation results of readout tolerance in terms of relative position between the objective lens and the hologram. We successfully obtain the high compatibility among HDS systems and confirm the wide readout tolerance. These results show the possibility for commercialization of HDS technology.

2. Compact ROM reader

The compact ROM reader prototype is shown in Fig. 1(a) with its schematic figure is shown in Fig. 1(b), and specification of that summarized in Table 1. This ROM reader can reconstruct the angle multiplexed holograms. The reference beam reflected at a fixed mirror1 is incident on a surface substrate of a medium at an angle 56°, and then it irradiates holograms from a backside substrate of a medium by reflecting at rotating mirror2, and phase-conjugate signal beams are reconstructed from holograms. By rotating mirror2, the incidence angle of reference beam can be changed. The medium is set on an XY stage with the position adjusted using a focus-position sensor and a tilt sensor. By shifting the XY stage, the spot where the reference beam on the medium is irradiated changes, and the book can be selected. This ROM reader uses the laser source and the objective lens similar to that of the recording system. The laser source is YVO4 laser (λ=532 nm) and the objective lens is commercially used the single aspherical lens.

The positional relation among signal beam, reference beam, and medium in the angle multiplexing recording system is shown in Fig. 2. In this recording system, the signal beam waist is set on the outside of the medium, and the divergent signal wave incident into the medium. Book size on the bottom plane of the medium is 2.49 x 2.72 mm. One book has 70 pages with recording pitch of 0.2°, and the user data capacity per page is 9.5kBytes. Layout of books on the medium is shown in Fig. 3. The recording pitch between two books in the X- and Y- direction (δx, δy) are 650 µm. These shift pitches are decided in consideration of size of the nyquist aperture which is set at a focal plane of the objective lens. In this experiment, we recorded single book with 70 pages per book and 9 books with 10 pages per book.

3. Experimental results

Reconstructed images from the same multiplexed hologram using the recording system and using the ROM reader are shown in Fig. 4(a) and (b), respectively. The intensity distribution on these reconstructed images depends on that of the reference beam, and it is not uniform. This intensity distribution can be removed by optimizing the diameter of the
reference beam and adjusting the irradiation area of the hologram. These reconstructed images have mostly comparable quality, and the raw bit error rate of each image is same level and these values are the first half of $10^{-5}$ order. This result shows the compatibility is maintained between the recording system and the ROM reader.

It is considered that mounting accuracy of the objective lens when the ROM reader is assembled has effect on distortion of the reconstructed image. Therefore, readout tolerance is confirmed from the amount of field curvature and distortion of the image when the relative position between the objective lens and the hologram is changed by the simulation. The simulation result of readout tolerance of shifting in the X- and Z- direction of a medium is shown in Fig. 5(a), (b). The imaging performance of an objective lens decreases as the shift distance of the medium increases. Considering specifications of devices and over sampling rate, the allowance of the deterioration of the imaging performance by the aberration of the objective lens is approximately 10%. From these results, the tolerance of the shifting of the medium is 30 μm. Similarly, the tolerances of the focus- direction shifting and tilting of the medium are 60 μm and 2°, respectively. From the experimental results of error evaluation, it is confirmed that the error rate increases from approximately 40 μm when the medium is shifted in the X- direction. Moreover, we confirmed that each tolerance value is larger than the value of mechanical accuracy of the ROM reader.

4. Conclusion

We develop a compact ROM reader using commercially used objective lens. These results of experimentation and simulation show these systems have a high compatibility and a wide tolerance of reconstruction though there is still room for improvement in the storage density. In the future, we will develop the HDS system that can achieve the high storage density, retaining wide tolerance.

References

Table 1. List of components and their specifications

<table>
<thead>
<tr>
<th>Component</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser</td>
<td>Wavelength: 532 nm</td>
</tr>
<tr>
<td></td>
<td>Output power: 130 mW</td>
</tr>
<tr>
<td>Aperture</td>
<td>Hole size: 600 μm</td>
</tr>
<tr>
<td>Objective lens</td>
<td>Focal length: 4.03 mm</td>
</tr>
<tr>
<td></td>
<td>NA: 0.62</td>
</tr>
<tr>
<td>CCD imager</td>
<td>Area size: 1024 x 768 pixels</td>
</tr>
<tr>
<td></td>
<td>Pixel pitch: 4.65 μm</td>
</tr>
<tr>
<td>Mirror2</td>
<td>Scanning range: ± 7 degree</td>
</tr>
<tr>
<td></td>
<td>Position accuracy: &lt; 0.02 degree</td>
</tr>
<tr>
<td></td>
<td>Interval time of angle changing: 12ms</td>
</tr>
<tr>
<td>X_Y stage</td>
<td>Scanning range in X: 18.7 mm</td>
</tr>
<tr>
<td></td>
<td>Scanning range in Y: 17.55 mm</td>
</tr>
<tr>
<td></td>
<td>Position accuracy in X: 10.0 μm</td>
</tr>
<tr>
<td></td>
<td>Position accuracy in Y: 7.0 μm</td>
</tr>
<tr>
<td></td>
<td>Interval time of book shifting in X: 106ms</td>
</tr>
<tr>
<td></td>
<td>Interval time of book shifting in Y: 151ms</td>
</tr>
<tr>
<td>Medium</td>
<td>Size: (X) 21.4 mm, (Y) 21.0 mm</td>
</tr>
<tr>
<td></td>
<td>Thickness: 2.9 mm</td>
</tr>
<tr>
<td></td>
<td>(include two 0.7mm glass substrate)</td>
</tr>
</tbody>
</table>

Fig. 1. (a) Compact ROM reader prototype, and (b) schematic of ROM reader.
Fig. 2. Geometric positional relationship of a signal beam and a reference beam in a medium.

Fig. 3. Layout of books on a medium.

Fig. 4. Reconstructed image from single book with 70 pages per book: (a) Using recording system; (b) Using ROM reader

Fig. 5. Field curvature and distribution in case a medium is sifted: (a) X-direction; (b) Z-direction
Compact Fiber Laser for Two-Photon Recording in Multilayered Optical Memory

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ABSTRACT

We have developed a compact and high-power mode-locked fiber laser for three-dimensional optical memory. Fiber lasers have potential to be compact and stable light source which can replace bulk solid-state lasers. We demonstrated the two-photon recording by using the developed fiber laser.

Keywords: Fiber laser, three-dimensional optical memory

1. INTRODUCTION

Three-dimensional (3D) optical memory has been developed by many researchers to increase the recording capacity.¹⁻²) The two-photon process is one of the key technologies to realize 3D memories for recording bit data. Ultrashort pulsed lasers are required to generate the two-photon process effectively, because the absorption probability of the two photon process is proportional to a squared peak intensity of pulses.

Ti: sapphire lasers are used as a short-pulse laser for demonstration of two-photon recording. They have many advantages such as high power, high repetition rate, and output of ultrashort pulses. However, they are rather large because they contain many bulk components such as lenses, mirrors, and prisms, and the laser cavity is configured in the rectilinear space. They also require water cooling and they are expensive. As a result, it is difficult to use Ti: sapphire lasers for consumer production.

Fiber lasers that use erbium-doped fiber (EDF) are very promising as ultrashort-pulsed lasers.³) Because a fiber laser oscillates at 1.56 μm, the wavelength range of fiber laser is similar to that of a Ti: sapphire laser by doubling frequency with nonlinear crystals. In fiber lasers, the laser cavity comprises of ring fibers and light is resonated in the fiber cavity. Fiber lasers have advantages in comparison with bulk solid-state lasers. First, a fiber laser is very compact, because the fiber cavity can be bended and the cavity does not require free space. Second, a fiber laser is very stable, because light is confined in the fiber and there is no necessity of water cooling. By splicing each fiber, coupling loss is much reduced and there is no misalignment of the optical system. Finally, the spatial intensity distribution of the output beam shows circular symmetry. Because light is emitted from a single-mode fiber (SMF), the transverse mode of output beam is TEM₀₀.

We have developed a compact erbium-doped fiber laser and succeeded two-photon recording in a photochromic material.

2. OPTICAL SETUP AND DEVELOPMENT RESULT OF FIBER LASER

Figure 1 shows the optical setup of the fiber laser that we developed. The cavity comprised EDF and SMF. EDF has positive dispersion and SMF has negative dispersion at 1.56 μm. Two laser diodes (LDs) were used as the pump laser. The wavelength and average power of each LD were 980 nm and 450 mW, respectively. Pump lights were introduced in a single fiber using a polarization beam combiner (PBC) and coupled into the ring cavity through the wavelength division multiplexing (WDM) coupler. Each fiber was spliced and the splicing loss was negligible. A polarization beam splitter (PBS) operated as the output port.
We measured the spectrum and the average power from the PBS, and the time interval of pulse trains from the monitor coupler. The center wavelength of the spectrum is about 1540 nm. We succeeded in operating with an average power of 109 mW and high-power pulse generation. The time interval of pulse trains was 17.4 ns, and the repetition rate was 57.5 MHz. The pulse energy was calculated as 1.9 nJ from the average power and repetition rate. We also measured the temporal waveform of output pulse. Figure 2 shows the temporal waveform of the output pulse from the PBS. This waveform was the autocorrelation trace and it was monitored using a two-photon absorption-type autocorrelator. The pulse shape was well defined and the pulse width was 2.1 ps. In order to increase the probability of the two-photon process, the pulse width should be decreased.

In order to decrease the pulse width, we performed dispersion compensation. In this study, we used 2.5 m length SMF for dispersion compensation, because SMF is cheap and practical. Since the compression method does not require bulk components such as prisms and a pair of gratings, it should be compact.

We measured the average power and the temporal waveform from the SMF end. The average power at SMF end was 90 mW. Figure 3 shows the temporal waveform of the output pulse after SMF. The autocorrelation trace was composed of three peaks. From the trace, the temporal waveform of the output pulse was presumed to be composed of two peaks. We assumed that each peak in the waveform was of the sech² shape. By the fitting process of autocorrelation of the temporal waveform to the measured waveform shown in Fig. 3, we derived that the pulse width was 93 fs and the peak power was 5.3 kW. From the result, the fiber laser we have developed is a good candidate as a light source of 3D optical memory.

![Fig. 1. Optical setup of developed fiber laser.](image1)

![Fig. 2. Temporal waveform of output pulse from PBS.](image2)

![Fig. 3. Temporal waveform of compressed pulse after SMF.](image3)
3. RECORDING BY DEVELOPED FIBER LASER

We recorded bit data in a photochromic media by using the developed fiber laser. Photochromic material was spiropyran (1,3,3-Trimethylindolino-6'-nitrobenzopyrylospiran) and it was doped in polystyrene thin film. Figure 4 shows the optical setup for recording and reading data. The output pulse from fiber laser was converted into the doubled frequency with a periodically poled lithium niobate (PPLN). After the frequency doubling, the pulse was focused by the objective lens with numerical aperture (NA) of 1.3. The bit data was observed with a CCD camera.

![Fig. 4. Optical setup for (a) recording and (b) observation of bit data.](image)

Figure 5 shows readout image of recorded data. We recorded $3 \times 3$ bit data with the average power of 25.9 mW. 6 dots were clearly recorded, and 3 dots were very weak. We believe the weakness of the 3 dots was due to unevenness of medium. From this result, we may conclude that the output pulse from fiber laser has enough power for two-photon recording. The fiber laser that we have developed was very promising for replacing the other ultrashort pulse laser in multilayered memory.

![Fig. 5. CCD image of dot pattern.](image)

4. CONCLUSIONS

We developed compact and high-power fiber laser and demonstrated two-photon recording bit data with the developed fiber laser. The fiber laser is very promising as a light source of multilayered memory in commercial use.

REFERENCES

Novel Subwavelength Pit Detection by the Photonic Nanojet for Optical Data-Storage Applications

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ABSTRACT
We consider using the photonic nanojet to detect deeply subwavelength pits in a metal substrate for the purpose of high-density optical data storage. Three-dimensional finite-difference time-domain (FDTD) computational solutions of Maxwell’s equations are used to analyze and design the system. We find that nanojet-illuminated pits having lateral dimensions of only $100 \times 150$ nm$^2$ yield a 40-dB contrast ratio.

Keywords: Backscattering, photonic nanojets, optical data storage, finite-difference time-domain, FDTD

1. INTRODUCTION
Dielectric cylinders and spheres under electromagnetic wave illumination generate a narrow, high-intensity beam which has been called the photonic nanojet [1]. The photonic nanojet was initially predicted using numerical modeling [1] and later directly imaged at an optical wavelength [2]. This beam propagates into the background medium from the shadow-side surface of a lossless dielectric cylinder or sphere of radius greater than the illuminating wavelength, $\lambda$. It appears for a wide range of diameters of the cylinder or sphere if the refractive index contrast relative to the surrounding medium is less than about 2:1.

The photonic nanojet propagates with little divergence for several wavelengths into the surrounding medium while maintaining a transverse beamwidth smaller than $\lambda$. In fact, a transverse beamwidth as small as $0.3\lambda$ has been reported [3]. The present research was motivated by a key nanojet phenomenon — namely, inserting a tiny ($\sim \lambda/100$ diameter) particle within the nanojet perturbs the backscattered power of the cylinder or sphere emitting the nanojet by an amount that is comparable to the total backscattered power of the cylinder or sphere.

In this paper, for a practical realization, we apply the finite-difference time-domain (FDTD) computational solution of Maxwell’s equations [4] to study the photonic nanojet’s sensitivity to the presence of a small pit in a metal substrate. Ratios of the backscattered power with and without the pit are computed. Based upon these results, we propose a method to use the photonic nanojet to read high-density optical data.

2. PROPOSED SCHEME AND RESULTS
Previous dimensionally scaled experiments at a microwave frequency (30 GHz) showed the detectivity of the backscattered signal from a deeply subwavelength pit structure using the photonic nanojet [5]. In this paper, we report three-dimensional FDTD computational simulations in order to investigate the potential use of the nanojet to detect similar pits in an optical data-storage disk. Figure 1 illustrates the present proposed configuration. A 2-\textmu m diameter polystyrene microsphere of refractive index $n=1.59$ is assumed to be 60 nm above the optical data-storage medium, which is composed of a grooved metal plate covered by a 500-nm thick dielectric layer of polymethyl methacrylate (PMMA). The PMMA thickness is optimized to yield the maximum detectability of a pit in the metal substrate.

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In Figure 1, the three-dimensional FDTD model employs a uniform Cartesian grid of 10-nm spatial resolution with perfectly matched layer absorbing outer grid boundaries. The metal plate is treated as a perfect electric conductor. An $x$-polarized, modulated Gaussian impulsive plane wave propagating in the $+z$-direction is assumed. Near-field and far-field data within the spectral range of interest are obtained via discrete Fourier transformation of the transient response generated by the impulsive incident wave.

Figure 2 graphs the ratio of the FDTD-computed backscattered far-field power with no pit present to the computed backscattered far-field power with the pit present as a function of the nanojet wavelength. This “no-pit/pit” power ratio is generally positive because the pit scatters the incident nanojet and reduces the power retroreflected to the microsphere. From Fig. 2, with a lateral ($x$-$y$-plane) pit area of $100 \times 150$ nm$^2$, we observe for a pit depth of 80 nm an extremely large no-pit/pit power ratio exceeding 40 dB near $\lambda = 396.1$ nm. As the pit depth increases, the wavelength where the peak occurs increases, but the opposite behavior is observed for the pit width in Fig. 2(b). Various power ratios are obtained by the FDTD simulations according to different pit depths and widths. This property may permit the use of pit-depth modulation and/or pit-width modulation to increase the data-storage capacity or retrieval speed for a given substrate area.

For practical implementation of the photonic nanojet technology, an ultralow refractive index aerogel could be used to mount the dielectric microsphere without impacting the characteristics of the nanojet.

### 3. DISCUSSION AND CONCLUSIONS

We have computationally modeled a photonic nanojet technique to optically sense a deeply subwavelength pit structure in a metal substrate for purposes of high-density data storage. We implemented 3-D FDTD computational solutions of Maxwell’s equations to design the photonic nanojet and pit configuration. The monotonic power ratios achieved using the photonic nanojet suggest the possibility of encoding several data bits at each pit according to its depth and width.
Fig. 2. FDTD-calculated far-field no-pit/pit power ratio as a function of the wavelength. (a) The lateral dimensions of the pit are 150 × 100 nm. (b) The pit length is 150 nm and the pit depth is 80 nm.

REFERENCES


Collinear phase-lock holography
for hologram memories of the next generation
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ABSTRACT
Collinear phase-lock holography using phase-modulated data pages was proposed for holographic multi-level recording. Collinear phase-lock holography is phase-to-amplitude conversion method which applied real-time holographic interferometry to collinear holography. This method is based on phase interference between signal beam and phase-lock beam which passes common path of signal beam. And over sampling phase shifting interferometry was also proposed in order to detect phase-modulated data pages directly. In this method, phase-lock beam is divided in four areas and each area has phase data of 0, $\pi/2$, $\pi$, and $3\pi/2$, respectively. Phase data is calculated from $\arctan \left( \frac{(i_3-i_1)}{(i_0-i_2)} \right)$, where $i_0$, $i_1$, $i_2$, and $i_3$ are intensity of interferogram at each area. The feasibility of the proposed methods was experimentally demonstrated. As the results, phase-modulated data was retrieved as amplitude-modulated data with collinear phase-lock method and phase-data was retrieved with over sampling phase shifting interferometry method.

Keywords: Collinear holography, multi-level recording, phase-modulated data page, phase shifting interferometry.

1. INTRODUCTION
Hologram memory has a potential for realizing a high data transfer rate and a large data capacity due to the processing two-dimensional data pages and the multiplexing holograms. Multi-level recording is one of the methods which elevate both a data transfer rate and a data capacity. In the past, multi-level recording using gray-scale data page was proposed. But, a data transfer rate and a data capacity were increased only 30% [1]. Then a new holographic multi-level recording method is proposed. In this method, multi-level phase-modulated data page is used instead of gray-scale data page. The use of phase-modulated page data has a lot of merit for hologram memory. For example, the use of phase-modulated data pages provides uniform Fourier plane [2] that allows one to make efficient use of the material dynamic range. In this paper, collinear phase-lock holography is proposed for holographic multi-level recording.

2. COLLINEAR PHASE-LOCK HOLOGRAMY
Several methods have been proposed for the phase-to-amplitude conversion of phase-modulated data pages [3, 4]. Collinear phase-lock holography is the method which applied real-time holographic interferometry to collinear holography [5]. The recording process of collinear phase-lock holography is similar to that of collinear holography except for recording data pages. In collinear phase-lock holography, phase-modulated data pages which are generated by spatial light phase modulator are used. In the retrieving process of collinear phase-lock holography, reference beam and phase-lock beam are illuminated. Phase-lock beam has uniform amplitude and phase and passes common path of signal beam. Then phase interference of signal beam and phase-lock beam is carried out in order to convert phase-modulated data pages to amplitude-modulated data pages. Using collinear technology, it is easy to control the phase difference between signal beam and phase-lock beam with a spatial light phase modulator.

3. OVER SAMPLING PHASE SHIFTING INTERFEROMETRY
Collinear phase-lock holography is the method to obtain phase-modulated data pages as amplitude-modulated data pages. To obtain phase-modulated data directly, over sampling phase shifting interferometry (PSI) is also introduced. PSI is the well-known method to measure phase difference between object and reference with high accuracy. In over sampling PSI method, phase-lock beam is divided in four areas, and each area is given phase shift of 0, $\pi/2$, $\pi$, and $3\pi/2$, respectively. So, obtained image has four values $i_0$, $i_1$, $i_2$, and $i_3$, respectively. Phase data $\phi$ can be calculated from $\arctan \left( \frac{(i_3-i_1)}{(i_0-i_2)} \right)$. 

\[ \phi = \arctan \left( \frac{(i_3-i_1)}{(i_0-i_2)} \right) \]
[(i_3-i_1) / (i_0-i_2)]. Although it is necessary to readout several times per data page to obtain the phase data in conventional PSI method, the phase data was obtained only once readout with over sampling PSI method. Therefore, it is thought that this technique is very effective at the view of data transfer rate.

4. EXPERIMENTS AND RESULTS

Figure 1 shows experimental setup for collinear phase-lock holography. Spatial light phase modulator and spatial light amplitude modulator were used to control the phase and the amplitude of light, respectively. As for SLM1, digital micro-mirror device (DMD) was used to generate signal beam and phase-lock beam. Amplitude mask (AM) was also used to generate reference beam. As for SLM2, parallel aligned liquid crystal (PAL)-SLM was used to modulate the phase of each beam. By using half wave plate (HWP) 2 and polarization beam splitter (PBS) 2, amplitude ratio of signal beam (phase-lock beam) and reference beam was controlled property for recording and retrieving.

As a verification of collinear phase-lock holography, phase-modulated data was recorded and retrieved. Fig. 2 (a) shows image of recorded phase data. Black area and white area indicate phase data of 0 and \( \pi \), respectively. Fig. 2(b) shows reconstructed image with conventional reconstruction technique of collinear holography. Fig. 2 (c) and (d) show reconstructed image with phase-lock beam whose phase data are 0 and \( \pi \), respectively. Phase-modulated data was clearly retrieved as amplitude-modulated data with phase-lock beam. And contrast of amplitude-modulated data was inversed when phase data of phase-lock beam was inversed. Thus, phase-modulated data was retrieved by phase interference.

Over sampling PSI method was also demonstrated. At first, uniform phase data \( \phi_{REC} \) was recorded. Then, phase data was reconstructed with phase-lock beam which is divided in four areas and each area has phase data of 0, \( \pi/2 \), \( \pi \), 3\( \pi/2 \).

Fig. 3 (a) shows retrieved image with over sampling PSI method. Phase data \( \phi_{RET} \) was calculated by this interferogram. Fig. 3 (b) shows retrieved phase data with over sampling PSI method. Retrieved phase data has correlation with recorded phase data. Therefore, principle of over sampling PSI method was confirmed.

Fig. 1. Optical setup for collinear phase-lock holography. HWP, half wave plate; PBS, polarization beam splitter; BE, beam expander; A, aperture; D, diffuser; AM, amplitude mask; SLM, spatial light modulator; BS, beam splitter; L, lens; P, polarizer; DBS, dichroic beam splitter; QWP, quarter wave plate; PD, photo detector; LD, laser diode.

Fig. 2. (a) Recorded phase data, (b) reconstructed image with reference beam, (c) reconstructed image with reference beam and phase-lock beam which has phase data of \( \pi \), (d) reconstructed image with reference beam and phase-lock beam which has phase data of 0.
5. CONCLUSIONS

Collinear phase-lock holography which uses phase-modulated data pages was demonstrated. As the result, phase-modulated data page was reconstructed as amplitude-modulated data page. Furthermore, over-sampling phase shifting interferometry was proposed and demonstrated. Consequently, phase-data was retrieved from interferogram directly. Therefore, the feasibility of these methods was confirmed experimentally. These techniques are aimed for holographic multi-level recording. Experimental results about multi-level recording will be reported at the conference.

REFERENCES

Magnetic volumetric holography with magnetic garnet films

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ABSTRACT

Fundamental properties of volumetric holography with magnetic garnet films were investigated, so as to examine the potential of media for high density holographic memories. When the garnet film thickness was 3.75 $\mu$m, the maximum diffraction efficiency of 0.26 \% was obtained from the magnetic fringes by utilizing 2-axis holography. This value is approximately 50 times higher than that of the case when 70 nm thick amorphous TbFe film was used as a recoding material, suggesting that the volumetric effect for enhancing the diffraction efficiency is remarkable. In fact, the maximum diffraction efficiency was obtained when the Bragg matching condition is satisfied between the recording and retrieving systems. Collinear holography was also used to test the performance of the magnetic volumetric holography. Unfavorably, resultant retrieved images were noisy and weak. Thermal diffusion, which results in unclear magnetic fringes, was likely to be responsible.

Keywords: magnetic holography, rewritable holographic memory, magnetic garnet film, 2-axis holography, collinear holography

1. INTRODUCTION

Recently, renewed interest in holographic memories has arisen due to its potential for high density optical memories. It is true that the appearance of good photopolymer materials as their recording media has also assisted the development of volumetric holography. Unfortunately, however, the photopolymer materials possess several issues for hologram memories. For instance, their thermal expansion is one of the key issues because, at different temperatures, the recorded media are read with multi-wavelength laser source. Media cartridge providing optical shading is also troublesome, because conventional CD or DVD does not require such a cartridge.

We here studied fundamental properties of volumetric holography with magnetic garnet films (ferromagnetic transparent films), so as to examine the potential of media for holographic recording. This is because the inorganic oxide films do not possess the difficulties as hologram media the photopolymer materials have. Moreover, the use of magnetic material provide us the possibility of erasing the recorded information by applying a magnetic field.

To our knowledge, studies on magnetic hologram were achieved so far by utilizing metal MnBi film \cite{1} or amorphous TbFe film \cite{2} for transmission mode recording. In order to maintain the transmitted light intensity, thicknesses of these metal films are generally very thin, and hence thin holograms were only recorded and examined so far. Contrary to these cases, we here used transparent rather thick magnetic garnet films so as to enable the formation of thick (or volumetric) holograms and examined their fundamental performance for volumetric holography.

2. SAMPLE PREPARATION

As holographic recording material, magnetic garnet films were deposited onto SGGG substrates by RF-magnetron sputtering using Bi$_{1.5}$Y$_{1}$Dy$_{1}$Fe$_{3.8}$Al$_{1.2}$O$_{x}$ target. The deposited films was subjected to rapid thermal annealing at 750 $^\circ$C for 10 minutes in air for crystallization. Figure 1 shows the Faraday rotation angle and transmissivity as a function of sample thicknesses at wavelength 532 nm. The magnetic garnet film showed perpendicular magnetization and the Curie temperature was about 170$^\circ$C.
3. **MAGNETIC HOLOGRAPHIC RECORDING**

For holographic recording, 2-axis and collinear holography methods were used. Illustration of the optical setup is shown in Fig. 2. YAG pulse laser (532 nm) was used as the laser light source, while He-Ne laser (633 nm) was used for focusing.

3.1 **2-axis holography**

Figure 3(a) shows the polarized microscope image of magnetic fringes formed by the 2-axis system. As clearly seen in the figure, magnetic fringes (black and white stripes correspond to regions where the direction of magnetization (up and down) differs) whose periodicity is approximately 1 µm were formed. This periodicity coincides with the theoretical value which was determined from the incident angle of two optical beams. It is interesting that, as shown in Fig. 3 (b), the magnetic fringes disappear by applying a magnetic field perpendicular to the film plane. Figure 4 shows the diffraction efficiency from magnetic fringes versus recording energy density for magnetic garnet films for different film thicknesses ranging from 1.25 µm to 6.18 µm, where the spatial frequency was 1000 line pairs/mm. From this figure, minimum recording energy density for writing the magnetic fringes was evaluated to be about 30 mL/cm², the value of which is almost equivalent to the case of photopolymer materials. It was also confirmed experimentally that the spatial frequency exceeding 1500 line pairs/mm was formable. Figure 5 shows the film thickness dependence of the diffraction efficiency, where the recording was achieved at about 100 mL/cm². In general, the thicker the thickness of film sample, the higher the diffraction efficiency. When the film thickness was \( t = 3.75 \) µm, the diffraction efficiency reached at 0.26 %, whose value is approximately 50 times larger than that of the case when amorphous TbFe film \( (t=70 \) nm) was used [2]. When \( t = 6.18 \) µm, however, the diffraction efficiency was reduced to one third of the value when \( t = 3.75 \) µm, indicating that the thermal diffusion is presumably responsible for this. It is interesting that, as shown in Fig. 6, the diffraction efficiency clearly showed the angle selectivity of hologram (when incident angle of retrieving light tilted to 25°, the diffraction efficiency was reduced to one third compared to the case of normal incident of light), indicating that the diffraction occurred due to Bragg matching although magnetic fringes does not contribute a large difference in reflection coefficient.

3.2 **Collinear holography**

Collinear holography is one of the most promising methods for ultra-high density volumetric optical storage system, for its simple optical pick up [4]. In addition to the case of 2-axis holography, we here examined the performance of magnetic holography in collinear system. Figure 7 (a) shows original pixel image of DMD, while Fig. 7 (b) shows the reconstructed image. As seen in Fig. 7 (b), reconstructed image in the collinear system can be seen showing that the magnetic holograms are able to form in the system. The image quality is, however, rather noisy and weak, which does not meet the requirement for memories. This is presumably due to the thermal diffusion which prevents the formation of magnetic fringes corresponding to the collinear interference pattern in film. To avoid this, high speed laser system might be useful.

4. **CONCLUSION**

Magnetic volumetric holograms were examined with magnetic garnet films which are transparent ferromagnetic films enabling the formation of volumetric hologram. The experimental results showed that the use of garnet films was effective for enhancing the diffraction efficiency, whose maximum value reached to about 50 times larger that of the case of amorphous TbFe alloy film. This infers that the magnetic garnet film might be a good candidate as hologram media, where magnetic erasing of fringes are also attractive. The study showed that the reconstructed images from the collinear holography was rather poor. This is presumably due to the thermal diffusion preventing the formation of magnetic fringes corresponding to the collinear interference pattern in film. To avoid this, further experimental investigation is now under way. The work has been supported in part as the super optical information memory project from the Ministry of Education, Culture, Science and Sports of Japan.

**REFERENCES**

Fig. 1 Transmissivity $T$ and Faraday rotation angle $\theta_F$ as a function of sample thicknesses.

Fig. 2 Optical setup for holographic recording by 2-axis and collinear holography methods.

Fig. 3 (a) Magnetic grating image, and (b) after erasing with a magnetic field applied perpendicular to the film plane.

Fig. 4 Diffraction efficiency vs. recording energy density.

Fig. 5 Diffraction efficiency vs. sample thicknesses.

Fig. 6 Angle selectivity of holograms.

Fig. 7 Collinear holography: (a) Original DMD pattern and (b) reconstructed image from the magnetic hologram.
Optical high spatial resolution using Super-RENS Disk system

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1. Introduction

In conventional optical disk systems, information bits are recorded and read with a laser beam focused to a small spot on the recording layer of the optical disk. The data capacity of the Blu-ray disk is 27 GB, which is mainly determined by the diffraction-limited spot size. However, there is no room to minimize the spot size dramatically. Therefore, a new record and retrieve system is required to realize one Terra-Byte (TB) optical disk for the data storage hierarchy requested by ICT society.

An optical super-resolution near-field structure (Super-RENS) disk system is one of the promising methods for achieving this because the spot is sharpened to much less than the diffraction-limited size. Various Super-RENS disk systems have been investigated to realize high density recording. However, the spatial resolution of 25 nm for realizing one TB disk is uncommon in the optical disk system.

In this paper, several Super-RENS disks with changing AgInSbTe (AIST) mask layer are prepared and evaluated their spatial resolution experimentally.

2. Disk preparations and measurements

Figure 1 shows our basic structure of Super-RENS disk with a PtOx recording layer and an AgInSbTe (AIST) mask layer. On a polycarbonate substrate of 1.1 mm, a reflective layer of 40 nm, first dielectric layer of 20 nm, a mask layer, second dielectric layer of 30 nm, a recording layer of 4 nm and third dielectric layer of 110 nm were RF sputtered continuously. The thickness of the AIST mask layer was changed from 6.5 nm to 18.6 nm. The PtOx recording layer was prepared by using the sputtering with a pure Pt target and the gas mixture of argon and

![Fig.1. Basic structure of Super-RENS disk.](image-url)
oxygen. The gas flow ratio of argon and oxygen for the sputtering was about 1:3. These disks were prepared by using a FR magnetron sputtering equipment at the National Institute of Advanced Industrial Science and Technology (AIST) under Prof. Tominaga’s supervision.

A cover layer of 100 µm and the disk were bonded with the UV–sensitive adhesive using a vacuum bonding equipment donated by the New Energy and Industrial Technology Development Organization (NEDO).

In order to evaluate the recording characteristics of the disk, a Blu-ray disk drive tester with the laser wavelength of 405 nm and the lens NA of 0.85 was used. The measuring conditions for the disks were linear velocity of 4.92 m/s.

3. Results and discussions

Figure 2 shows a readout power dependence of a carrier to noise ratio (CNR). Marks of 100 nm in length were recorded at recording powers from 4 mW to 5.5 mW using a recording frequency of 24.6 MHz. The mark length is less than the resolution limit expressed as \( \lambda / (4NA) \) which is equal to 120 nm. As increasing a readout power, the CNR is suddenly increased at 2.1 mW and reached 46 dB at the readout power of 2.6 mW. This disk has a wide margin of readout power.

Figure 3 shows a recording power dependence of the CNR. The CNR of more than 45 dB was able to obtain above 5 mW at mark length of 100 nm. The CNR of more than 40 dB was able to get at 5.5 mW at mark length of 70 nm. The CNR of more than 30 dB was able to obtain at 6 mW at mark length of 40 nm.

Figure 4 shows the thickness of AIST mask layer dependence of a maximum CNR
value. As increasing the thickness of AIST mask layer, the CNR is increased at the mark lengths of 100 nm and 70 nm. However, at the mark length of 40 nm the CNR shows complicated correlation with the thickness of AIST layer. Signals reading from the mark length of 30 nm can be only obtained at the AIST layer thicknesses of 10 nm and 18.6 nm.

Figure 5 shows the readout power dependence of the CNR. Here, recording mark lengths were 70 nm, 40 nm, and 30 nm. The recording power was 6.0 mW. As increasing a readout power, the CNR was suddenly increased at 2.1 mW at every mark lengths of 70 nm, 40 nm and 30 nm. From Figs. 1 and 5, the super-RENS shows steady dependence of readout power at any mark length.

Figure 6 shows the mark length dependence of the maximum CNR value at the AIST mask layer thickness of 18.6 nm. The CNR monotonously dropped with decreasing mark length and the CNR can be detected at the mark length of 23 nm. This means a λ/18 spatial resolution can be obtained experimentally and the recording capacity of 1.2 TB per disk can be estimated.

4. Conclusions
We have experimentally investigated the recording characteristcics of the Super-RENS disk with changing the thickness of the AIST mask layer. The Super-RENS disk with a mask layer of 18.6 nm can record and readout small mark length of 23 nm which is far beyond the diffraction limit. This spatial resolution has a prospect for the optical disk with over one TB capacity.

Reference
Experimental and Analytical Study on the Dynamic Behavior of Spinning Flexible Disk close to Rotating Rigid Wall
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ABSTRACT
The behavior of a flexible disk rotating close to fixed, co-rotating, and counter rotating flat-stabilizers in open air is investigated both experimentally and analytically. An experimental test-rig is designed to investigate the effects of the rotation speed, the initial gap height and the inlet-hole size on the flexible disk displacement and vibration amplitude with the different stabilizers. The experimental results show that the flexible disk rotating close to a co-rotating stabilizer possesses the largest displacement and vibration amplitude relative to the three types of stabilizer.

Keywords: Experimental and analytical study, flexible disk, rotating rigid wall

1. INTRODUCTION
The drastic increase in the quantity of computer data calls for high-speed and reliable devices based on flexible disks. For such devices, the transverse vibrations of the disk, at high rotation speeds, must be negligibly small. So, it is important to investigate the optimal design for flexible disk system since it is a good candidate for compact as well as high-capacity data storage means. Several studies have been carried out for the investigation of the dynamic behavior of a flexible disk rotating close to a rigid wall both analytically and experimentally such as Pelech and Shapiro [1] who used an optical method to measure the gap between a Mylar membrane and rigid flat wall. They found that, for a given inlet flow rate, the position of the disk relative to the plate is, over its outer portion, essentially independent of the position of the clamping hub and the disk spacing can be controlled by controlling the flow rate at the inlet side. D’Angelo and Mote [2] carried out thorough experiments on a thin steel disk rotating inside an enclosure; as a result they concluded that the disk spinning at high supercritical rotation speed in a fluid becomes unstable by traveling wave aeroelastic flutter. The self-excited vibrations of a flexible disk rotating in air were investigated by Yasuda et al. [3] and they found that the vibrations of the disk in air propagate as forward and backward traveling waves; the forward traveling wave always decays while the backward traveling wave can become of a self-excited nature at rotational speeds higher than certain value. Also, Huang and Mote [4] investigated the instability mechanisms in the coupled fluid-disk system analytically and they concluded that the maximum rotation speed of a stable disk vibration is bounded above by the onset speed of rotating damping instability. However, earlier studies did not consider the effects of fluid centrifugal force, fluid inertia forces and fluid coriolis force on the fluid-disk behavior. These forces should be considered when investigating the dynamics of spinning flexible disks rotating at high speeds. Also, previous studies focused their analyses as well as their experiments on a flexible disk rotating close to a fixed wall and no attempt was made to investigate the dynamics of the fluid-disk system when the flexible disk is rotating close to a rigid co-rotating or counter-rotating wall. The reason for introducing the rotating stabilizer in the present study is to reduce the speed of the rotating damping relative to the disk speed and thereby increasing the critical speed of rotating damping instability allowing the flexible disk to rotate stably at reasonably high speeds.

2. NUMERICAL METHOD
The air flow in the gap between the flexible disk and the rigid wall is modeled using Navier-Stokes and continuity equations while the flexible disk is modeled using linear plate theory. The flow equations are discretized using cell-centered finite volume method (FVM) on a uniformly staggered grid. The velocities at cell boundaries are approximated using the UPWIND differencing scheme. The discretized flow equations are solved with the SIMPLE algorithm using the ADI method with TDMA. The spatial terms in the disk equation are discretized using second order finite difference method while the temporal derivative is integrated using fourth-order Runge-Kutta scheme.

3. EXPERIMENTAL SET-UP
An experimental test-rig is designed to measure the effects of rotation speed, inlet-hole radius, and initial gap height on the flexible disk displacement and its vibration amplitude.
As the stabilizer design should consider its main functions (co-rotating, counter-rotating, or fixed relative to the rotating flexible disk), the experimental test-rig is composed of two parts; the lower part is the stabilizer assembly while the upper part is the flexible disk assembly. The test-rig is assembled and the experiments are carried out on a vibration isolation table as shown in Fig.1. Three spacers are used with inlet-hole diameters of 26, 31 and 36 mm to give radial clearances of 0.5, 3 and 5.5 mm, respectively. The flexible disk assembly is attached to a system of microstages (x, y, and z directions) in order to assure the concentricity of the flexible and glass disks and to control the initial gap height. The flexible disk displacement and its vibration amplitude is measured using laser displacement sensor (Keyence, LK-G10). The disk displacement is measured at five points in the radial direction (r = 41, 46, 50, 54, and 58 mm) and at three different angles in the circumferential direction. Throughout the present experiments, a polycarbonate flexible disk clamped at its inner radius \( r_c = 12.5 \) mm and free at the outer radius \( r_o = 60 \) mm, is used. Also, the disk thickness, disk-material density, modulus of elasticity, and Poisson's ratio are 95 \( \mu \)m, 1200 kg/m\(^3\), 2.5 GPa, and 0.23, respectively. One side of the flexible disk, that faces the stabilizer, is coated with a very thin silver film (60 nm thickness).

### 4. EXPERIMENTAL RESULTS AND DISCUSSIONS

Comparisons of the flexible disk behavior with fixed, counter rotating and co-rotating stabilizers at inlet-hole radii of 13, 15.5 and 18 are given in Fig. 2. It can be noticed that the flexible disk displacement with counter rotating stabilizer is the smallest relative to that with fixed and co-rotating stabilizers and the difference between the flexible disk displacements with the three kinds of stabilizer becomes more pronounced as the inlet-hole radius increases. Also, it is clear that the vibration amplitude of the flexible disk rotating close to co-rotating stabilizer is the highest among the three kinds of stabilizer and the vibration amplitude of the disk decreases with the increase of the inlet-hole radius. A comparison between the experimental and numerical flexible disk displacements with different stabilizers is shown in Fig.3. The figure shows clearly that the experimental results agree well with the numerically obtained results at the investigated region of the flexible disk. The small slope of the disk near the outer edge may be attributed to the large centrifugal forces acting on the disk material at this region which acts to flatten the disk while the effect of the negative pressure forces at this region is almost negligible. Also, the experimental results show that the peak-to-peak vibration amplitude of the flexible disk decreases with the decrease of the initial gap height or with the increase of the rotation speed.

### 5. CONCLUSIONS

The following conclusions can be drawn out from the present work:

1) The flexible disk displacement with counter rotating stabilizer is the smallest relative to the other types of stabilizer.
2) The vibration amplitude of the flexible disk decreases with the decrease of the initial gap height for the different stabilizers while the vibration amplitude of the flexible disk rotating close to co-rotating stabilizer is the highest among the three kinds of stabilizers.
3) The peak-to-peak vibration amplitude of the flexible disk decreases with the decrease of the initial gap height or with the increase of the rotation speed.

4) Narrow as well as wide inlets are not good candidates for the proper design of flexible disk systems rotation close to fixed or counter rotating stabilizers.

5) The numerical results are in good agreement with the experimental results.

Fig. 2: Comparison between the flexible disk behavior with fixed, counter rotating and co-rotating stabilizer, (7200 rpm, initial gap = 300 μm). (a) Flexible disk displacement. (b) Peak-to-peak vibration amplitude.

Inlet-hole radius = 13 mm
Inlet-hole radius = 15.5 mm
Inlet-hole radius = 18 mm

Fig. 3: Comparison between experimental and numerical results through the flexible disk displacement. (7200 rpm, initial gap = 200 μm, inlet-hole radius = 13 mm)

REFERENCES

TUESDAY
SESSION TPD: Post-deadline Posters

Queen's Ballroom
Tues. 2:00 to 3:30 pm
Layer Stack Design of High Density ROM Disc for Near-Field System using Solid Immersion Lens

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1. Introduction
Recently, near-field systems using solid immersion lens (SIL) have been expected to be a technology for the future large capacity data storage. The first surface type of ROM disc is suitable to realize high data density with the extremely high-NA system and also relatively easier to be manufactured. In last ISOM, we reported some measurement results of first surface ROM discs with SIL-equipped playback tester of NA 1.84 [1]. The performance, however, was not sufficient regardless of high-NA. In this study, we have first investigated a layer stack of ROM disc based on rigorous vector diffraction theory, and then fabricated polycarbonate ROM discs of 75 GB and 100 GB capacity with layer stacks. The evaluation results with the test discs in the near-field system of NA 2.0 and 2.26 will be presented.

2. Theoretical design of layer stack structures
Figure 1 shows a schematic cross-sectional view of stacked disc model with reflective and dielectric layers on the substrate. In near-field systems, evanescent waves arise at the bottom of SIL from the high-NA incident light. They can be coupled with the top surface layer of the disc when the air gap between SIL and the disc is about less than wavelength. The high-NA incident beam illuminated on subwavelength structures has a chance of inducing the excitation of guided modes and surface plasmon polaritons [2]. The stacked layer structure that includes high index material and metallic layers can support these surface modes. The complicated interactions between surface modes and layer structures cause anomalous variations in the angular spectrum of the reflected beam. Figure 2 shows an example of the pupil pattern when the beam spot is on the center of the space and pit. We can observe a dark annulus in the patterns that seems to be caused by the excitation of surface modes. The excitation of guided modes and surface plasmon polaritons is affected by the pitch, depth and duty cycle of the periodic structures. In addition, these phenomena intensively depend on the incident polarization. Accordingly, the rigorous vector diffraction theory is required to optimize the pit structure exactly in consideration of the surface effects and the polarization dependence.

![Fig. 1 Cross-sectional view of layer stack](image1)

![Fig. 2 Simulated pupil patterns when beam spot is on the center of (a) space and (b) pit](image2)

In this study, we adopt a rigorous coupled wave analysis (RCWA) method to numerically analyze the readout signal. The refractive index of SIL, wavelength, and effective NA used in the following calculation
are 2.38, 405 nm, and 2.26, respectively. The incident beam onto the disc is in circularly polarized. The reflective layer has a thickness of 25 nm and a refractive index of 0.33+2.5i. Figure 3 shows the simulated 8T modulated amplitudes of readout signal in dependence on pit depth for Type I and II models when the dielectric layer thickness changes. In Type I model, the refractive index of the dielectric layer is chosen to be 1.8. In Type II model, we additionally inserted the high-index dielectric layer (n = 2.3), as surface plasmon control layer (SPCL), underneath the top dielectric layer (n = 1.8). We can obtain the large modulated amplitude when the pit depth is around 50 nm with the dielectric layer thickness (t_D) of 75 nm for Type I. For Type II case, large modulation can be obtained with the similar pit depth in the thickness range of 25 to 50 nm. The gap error signals calculated for Type II is presented in Figure 4. Since the moderate curve is preferable for gap servo systems, the layer thickness was chosen to be 25 nm for Type II design. In order to estimate MTF characteristics, the spatial frequency response of reflectivity contrast was calculated with one-dimensional grating model. Figure 5 shows the contrast characteristics in both cases of Type I (t_D = 75 nm) and Type II (t_D = 25 nm). We confirmed that higher resolution can be realized for higher index scheme. The improvement of the modulation and resolution can be expected for the disc that has appropriate thickness of SPCL.

3. Experimental Setup
We have fabricated actual ROM discs based on the simulation results. The polycarbonate substrate was replicated by molding on the stamper mastered with electron beam recording (EBR). And subsequently it was stacked with the reflective layer of Ag alloy, the top dielectric layer of SiN (n = 1.8) and SPCL of high-index dielectric material (n = 2.3) by sputtering, according to the design of Type I and II. The top SiN layer plays a role in surface protection. These test discs have a track pitch of 185 nm and minimum pit length of 85 nm for 75 GB, track pitch of 160 nm and minimum pit length of 75 nm for 100 GB. The
modulation code for the discs is RLL (1, 7). To perform high-NA readout experiments, we have fabricated SIL assembly of NA 2.0 and NA 2.26 whose appearance is shown in Figure 6. It is composed of super-hemispherical SIL made of KTO (NTT-AT, n = 2.38) and objective lens. The wavefront aberration of the assembly is analyzed with the interferometer system in Twyman-Green configuration. Figure 7 shows the optical layout of our near-field readout system. The assembled lens is mounted on the conventional 2-axis actuator for the air gap and tracking control. Differential Phase Detection (DPD) tracking method is used for ROM discs.

4. Measurement results
We have evaluated the designed test discs with NA 2.0 system. The observed eye patterns of 75 GB and 100 GB ROM disc are shown in Figure 8 and 9, respectively. As compared with Type I disc, the jitter value of Type II disc using a limit equalizer was successfully improved to be 5.8% for 75 GB and 6.8% for 100 GB. 2T/8T resolution has also increased to 0.23 for 75 GB and 0.12 for 100 GB.

5. Conclusion
We have investigated the layer stack structures of first surface ROM disc with SPCL. By means of the EBR mastering and conventional replication process, we have fabricated the polycarbonate ROM discs. Consequently, we achieved significant improvements for 75 GB and 100 GB disc with the optimized layer stack. Further investigation and optimization of the layer structure will lead to the realization of higher capacity disc.

References
Mode hopping detection technique for external cavity laser diodes

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ABSTRACT

We propose a mode hopping detection technique for ECLD using a time differential of output voltages of the single element photodiode. By scanning the drive current of laser diode, we could obtain clear mode detection signals. The result indicates this technique is useful to maintain a stable single mode operation of ECLDs

Keywords: Extra Cavity Laser diode, Holographic Memory

1. INTRODUCTION

In recent years, there has been considerable interest in holographic memory because of their high density recordings beyond 500GB/in² [1, 2]. Holographic memory system records information as three dimensional interference patterns, the system requires the light source to operate in a single longitudinal mode. External cavity laser diodes (ECLDs) are attractive candidate for the light sources of the system, because of their wavelength tunability, advantages in down sizing and possibilities for price reduction compared to the other lasers. However, ECLDs suffer from the mode hopping of laser diode which is caused by drift of a laser driving current and ambient temperature. When the mode hopping occurs, ECLDs oscillate in multiple longitudinal modes which decrease a contrast of interference patterns leading to waste of the media dynamic range. In order to avoid the mode hopping, a mode hopping detection method using a multi-segmented photodiode has been proposed [3]. In this method, high assembling accuracy is required to align the interval of fringe patterns with line spaces of the photodiode.

In this paper, a mode hopping detection technique using a time differential of electrical output of a single element photodiode is proposed. We detected rapid fluctuations of electric voltage caused by the mode hopping and successfully determined the drive current value to avoid multiple modes operation.

2. OPTICAL CONFIGURATION

The schematic of the optical setup and the photograph of the blue external cavity laser diode are shown in Fig. 1 (a), (b), respectively. Littrow arrangement was used in the setup to shorten the external cavity length and keep a single longitudinal mode operation stable. The diffraction grating and the mirror were mounted on the same rotor to hold the direction of output beam constant when wavelength was changed [3]. The rotor was turned by SIDM (smooth impact drive mechanism) on the magnet joint. The absolute wavelength was controlled by using the rotation angle of the rotor measured by the tilt sensor.

The light beam emitted from the blue laser diode was collimated by the collimation lens (f = 10mm) and diffracted by the grating (grating resolution: 3600 /mm). The first order diffraction beam passed through collimation lens again and returns to the facet of the blue laser diode. The facet of the laser diode was coated with antireflection layers whose reflectivity was 0.25 %. The 0th order diffracted beam was reflected by the mirror and passed through the wedge prism and became the output light beam.

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The light beam reflected at the incident surface and the exit surface of the wedge prism, the angle of which is 0.05 degree, entered the photodiode and formed interference patterns on the detector of the photodiode. The photodiode had a single segment detector whose width was designed to be the half cycle of the fringe pattern (124 µm). Because we detect a mode hopping by using time-differential value of output voltage of the single segmented photodiode, we can assemble the setup without aligning fringe patterns to the segment of the detector precisely and also the allowed angular tolerance of the wedge prism is relatively large.

The first order diffraction efficiency of the grating was designed to be 20% to balance the stability of the extra cavity mode and the output power. The thermo sensor and the Peltier module were attached on the laser holder to control temperature of the laser stem.

3. MODE HOPPING DETECTION METHOD AND EXPERIMENTAL RESULTS

As the wavelength shifts with increasing the drive current, fringe patterns shifts gradually on the photo detector and the output signal voltage varies sinusoidally. When the mode hopping is occurred, the fringe patterns fluctuate rapidly and the deviation value of output voltage becomes large and we can determine the value of the drive current where the mode hopping occurs.

Figure 2 shows the control flow of the mode hopping detection method. The drive current \( I_{LD} \) is scanned at a rate of 1mA/s and the output signal voltage \( V_{PD} \) of the photodiode is measured at an interval of 0.1ms. In the next step, the operation mode detection signal \( S_M \) is obtained by processing \( V_{PD} \) using the following equation.

\[
S_M = \frac{d(V_{PD})}{dt}
\]

The \( S_M \) is compared with a threshold value \( S_{th} \) and if \( S_M \) is larger than \( S_{th} \), current state is judged as the multiple modes operation and the drive current value is memorized in \( I_n \). After the scanning the drive current, a pair of \( I_n \) and \( I_{n+1} \) which have the largest value of \( |I_{n+1} - I_n| \) is searched and the intermediate value \( (I_n + I_{n+1})/2 \) is set as the new drive current. By taking these procedures, the mode hopping is actively avoided and the single longitudinal mode operation can be maintained.

Figure 3 shows the experimental output signal voltage \( V_{PD} \) and the operation mode detection signal \( S_M \), when the drive current was increased from 60 mA to 120 mA at the rate of 1 mA/s. With increasing the drive current, \( V_{PD} \) changed gradually. When the mode hopping occurred, the fringe pattern fluctuated rapidly and the time differential of \( V_{PD} \) became large. Figure 4 shows the relations between the \( S_M \) and wavelength when the drive current was increased. With increasing the drive current, the wavelength changed in a saw tooth-shaped and the clear mode detection signals were obtained where ECLD operated in multiple modes. This result shows that the proposed technique is usable for the mode hopping detection.

4. CONCLUSION

We proposed the mode hopping detection technique for ECLD using a time differential of output voltages of the single element photodiode. By scanning the drive current of laser diode, we could obtain the clear mode detection signal, which indicates this technique is useful to maintain the single mode operation of the ECLDs.

REFERENCES

Fig. 1 (a) Schematic of optical setup and (b) photograph of the ECLD.

**Flowchart of the single mode detection.**

- **START**
- Start drive current \( I_{LD} \) scanning @1mA/s
- Acquire electrical output signal \( V_{PD} \) of the photodiode @ repetition rate of 100ms
- Calculate mode detection signal; \( S_M = \frac{\frac{d}{dt} (V_{PD}/\eta)}{dt} \)
- **Yes**
- Record the Drive current value as \( I_n \) (n=1-k)
- End of the \( I_{LD} \) scanning?
  - **Yes**
  - Search a pair \( I_x \) and \( I_{x+1} \) which have the longest interval in the group of \( I_n \) (n=1-k)
  - **No**
  - **END**

**Mode detection signal and Wavelength v.s. drive current**

**Time derivation of the photodiode’s output signal against the laser diode drive current variation**

**Fig. 2 Flowchart of the single mode detection.**

**Fig. 3 Time differential of the photodiode’s output signal**
Transition mechanism of WOx available for optical disc by laser irradiation

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ABSTRACT

WOx thin films are one of the candidates as the recording layer of write-once type optical disc and the inorganic photo-resist material used for heat mode mastering. We have investigated the transformation mechanism of WOx during laser irradiation. As a result, we observed the significant change in volume of WOx film and the change in valence of W atoms after laser irradiation. We also consider from various analysis that the solubility of WOx film in alkali solution might depend on the oxidized degree and crystallinity.

Keywords: WOx, heat mode mastering, transformation, AFM, TEM, XRD, XPS, optical disc

1. INTRODUCTION

Heat Mode Mastering (HMM) [1] has gotten a lot of attention as a candidate of the advanced mastering system. Phase change materials epitomized by GeSbTe and SbTe, and transition metal oxides epitomized by WOx [2] have been investigated by various research institutes as promising candidates of the inorganic photo-resist materials used for HMM. As for the former, it was reported in the paper [3] that the crystal state of the phase change material was etched faster by alkali solution than the amorphous state. The difference of etching rate between crystal and amorphous is applicable for the observation method of recorded marks in phase-change optical discs and the optical discs with three-dimensional pit selection suggested in the paper [4] as well as HMM. As for the latter, it was shown in the report [2] that WOx film was available for HMM as so called negative-type photo-resist material. The negative-type means that the transformed micro region of WOx film by laser irradiation remains and the other region is dissolved by the alkali development. WOx was also reported to be applicable for the optical disc as a recording layer of the write-once media [5]. It was considered that the recording mechanism of WOx as a recording layer came from the expansion of exposed micro region by laser. Few papers, however, have discussed about the transition mechanism of WOx by laser irradiation resulting in etching mechanism by alkali solution. We have paid much attention to solve this issue. WOx film is analyzed by several analytical and observing instruments like XRD (X-Ray Diffraction), XPS (X-ray Photoelectron Spectroscopy), AFM (Atomic Force Microscopy), and TEM (Transmission Electron Microscope) to understand transition mechanism by laser irradiation in this paper.

2. EXPERIMENTS

WOx films were deposited on Si wafers, Si chips and glass chips. Each sample was prepared under the conditions listed in Table 1. Some film structures on the substrate were chosen depending on the target of use. The samples consisting of WOx layer with the thickness of 25 nm on the glass chip were chosen for the optical analysis. The samples consisting of Si buffer layer with 70-nm thickness on a Si wafer and chips, on which WOx layer was deposited with over 50 nm were used for the structural analysis. Si buffer layers were inserted between the substrate and the WOx film in some samples to enhance the sensitivity of exposure. WOx films on Si wafers were exposed by the continuous laser under the condition listed in Table 2. The reflectivity from the surface of WOx film after exposure was monitored and the change in the reflectivity was considered to mean that the exposed region transformed. WOx films after exposure were developed in
an alkali solution. The composition and the binding state of atoms in a WO\(_x\) film on a Si chip were measured by XPS. The structure of WO\(_x\) film on Si chip was also measured by XRD, AFM and TEM before and after exposure. The optical constants of as-deposited WO\(_x\) films on glass chips were measured by spectroscopic ellipsometer.

<table>
<thead>
<tr>
<th>Film</th>
<th>WO(_2)</th>
<th>WO(_3)</th>
<th>Si</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target</td>
<td>WO(_2)</td>
<td>WO(_3)</td>
<td>Si</td>
</tr>
<tr>
<td>Sputtering method</td>
<td>DC magnetron</td>
<td>RF magnetron</td>
<td>DC magnetron</td>
</tr>
<tr>
<td>Ar gas pressure</td>
<td>0.2 – 1.0 Pa</td>
<td>0.2 – 1.0 Pa</td>
<td>0.2 Pa</td>
</tr>
<tr>
<td>Substrate rotation</td>
<td>50 rpm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Base pressure</td>
<td>&lt; 1.0 x (10^{-3}) Pa</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2. Exposing condition for WO\(_x\) film.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>405 nm</td>
</tr>
<tr>
<td>Lens NA</td>
<td>0.85</td>
</tr>
<tr>
<td>Power</td>
<td>&lt; 10 mW</td>
</tr>
<tr>
<td>Linear velocity</td>
<td>6.61 m/s</td>
</tr>
<tr>
<td>Pitch</td>
<td>0.4 (\mu)m</td>
</tr>
</tbody>
</table>

3. RESULTS & DISCUSSION

3.1 Microstructure in WO\(_x\) film

Structural analyses of both WO\(_2\) and WO\(_3\) films were carried out by using XRD, XPS, TEM and AFM. Structural change of WO\(_3\) and WO\(_2\) films on Si buffer layers by laser exposure were shown in Fig. 2, respectively. We can not see any changes in XRD pattern of WO\(_3\) film between exposed and unexposed samples as shown in Fig. 2 (a). At the same time, there was no peak that can be assigned to various WO\(_x\) crystal systems. We only, however, see a few bumps corresponding to WO\(_3\) crystal at the diffraction angles from 20 deg. to 40 deg. On the other hand, WO\(_2\) film unexposed to the laser showed a bump around 38 deg. corresponding to WO\(_2\) crystal system. The bump slightly shifted to lower angle after exposure. WO\(_2\) film after exposure also showed another bump at around 25 deg. corresponding to WO\(_2\) crystal system. From the above results, it was found that the crystallization in WO\(_2\) film was accelerated after exposure, while remarkable crystallization did not occur in WO\(_3\) film before and after exposure. The O/W atomic ratio in each film was measured by XPS. The O/W ratio was 2.91 for WO\(_3\) film and 2.06 for WO\(_2\) film.
Fig. 2. XRD patterns from (a) WO₃, in which red lines represent peaks from standard WO₃ powder sample and (b) WO₂ films, in which blue and green lines represent peaks from standard WO₂ powder sample.

We also carried out morphological observation by AFM and TEM for both WO₃ and WO₂ films same as used for the above measurements. Fig. 3 shows AFM images of the surface of WO₃ and WO₂ films after exposure. Changes in reproduced signal of 25% and 22% were monitored just after exposed with 3.5 mW for WO₃ and 6.0 mW for WO₂, respectively. Optimized power for each film we chose was the lowest power showing the maximum change in reproduced signal. It means that WO₁ film is more sensitive than WO₂ film because the optimized power for WO₃ is lower than that for WO₂. It was found from Fig. 3 (a) and (b) that the exposed parts of the both films were swelled and the swelled part of WO₂ film was higher than that of WO₃ film, although the change in reproduced signal from exposed part of WO₂ was lower than that of WO₃. From Fig. 3 (c), characteristic morphology, which had a dimple on the top of bump, was observed while simple patterned surface was observed in Fig. 3 (d). Height of the bump was measured as 30 nm for WO₃ and 50 nm for WO₂.

Fig. 3. AFM images of (a) WO₃ film exposed by laser with 3.5 mW and (b) WO₂ film exposed by laser with 6.0 mW. Section profiles corresponding to (a) and (b) are represented in (c) and (d), respectively. Scale is different from the vertical axes and horizontal axes in (c) and (d).
We also observed cross-sectional images of both films by TEM as shown in Fig. 4. Both films showed that swelled parts appeared by exposure and particularly WO$_2$ film showed big tumor than WO$_3$ film. White and gray parts of the exposed region in the both films mean low density and unevenness. Electron Diffraction analysis done at the same time revealed that exposed part of WO$_2$ film had higher ordering than that of WO$_3$. This is qualitatively consistent with the results of XRD measurement. The above results also agreed with the results reported in the paper [2].

![Fig. 4. TEM images of (a) WO$_3$ film exposed by laser with 3.5 mW and (b) WO$_2$ film exposed by laser with 6.0 mW.](image)

### 3.2 Development

Both films were developed in inorganic alkali solution for 5 minutes after exposure. As for WO$_3$ film, exposed part was perfectly dissolved in the solution and unexposed part slightly dissolved, which resulted in the developing depth of less than 60 nm corresponding to the thickness of WO$_3$ film left. On the other hand, exposed part of WO$_2$ film was also perfectly dissolved in the solution, while unexposed part was not dissolved at all, which created the groove with the depth of 75 nm. The above results considerably differ from that in the paper [2], in which unexposed part is dissolved in the alkali solution while exposed part remains, although the composition of WO$_x$ is unknown and their deposition condition would differ from that in this paper. It is considered that the solubility of WO$_x$ film against the alkali solution strongly depends on its oxidized degree and the crystallinity.

### 4. CONCLUSIONS

We have investigated the mechanism of transformation for two types of WO$_x$ films by laser irradiation. It was found by XRD measurement that WO$_2$ films showed the tendency of slight crystallization by laser irradiation, while WO$_3$ did not show any significant change of the structure. AFM observation revealed that exposed parts of both WO$_2$ and WO$_3$ films were deformed and bumps were created the height of which were 30 nm for WO$_3$ and 50 nm for WO$_2$. TEM observation revealed that these bumps of both films had low density and high atomic order. Exposed parts of both films were dissolved by alkali solution, although unexposed part of WO$_2$ was not dissolved. Unexposed part of WO$_3$ was also dissolved by alkali solution in our study. We consider from various analysis that the solubility of WO$_x$ film in alkali solution might depend on the oxidized degree and crystallinity.

### REFERENCES

Characterization and Recording Mechanism of Bi-Fe-(N) Layer for High-Speed Write-Once Optical Recording

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Abstract

Bi-Fe-(N) layer for high-speed write-once recording was investigated. TEM/EDS characterization revealed that the separation of Bi and Fe-rich phases and grain coarsening in the mark regime are mainly responsible to the recording mechanism.

Keywords: high-speed write-once recording, Bi-Fe-(N) layer.

1. Introduction

Materials for high-speed write-once optical recording are still under developed. Inorganic materials for high-speed recording including bi-layer such as Cu/Si [1-2], Ge/Au [3], and Bi-Ge nitrides [4] have been reported. However, their applicability to high-speed recording utilizing blue-ray hardware and relationship between microstructure and recording mechanisms required further investigation. Pervious studied on Bi-Fe-(N) layer demonstrated its feasibility to write-once optical recording using blue laser [5]. This study further investigates the signal and microstructure characteristics of disk containing Bi-Fe-(N) layers at the high-speed condition. Experimental results illustrate that the separation of Bi and Fe-rich phases in the mark comprises of the major recording mechanism of disk sample.

2. Experimental

As depicted in Fig. 1, the four-layered disk samples constituted by the pre-grooved PC substrate (0.6 mm), lower ZnS-SiO₂ dielectric layer, Bi-Fe-(N) recording layer, upper ZnS-SiO₂ dielectric layer and Ag reflection layer were prepared. The Bi-Fe-(N) recording layer was deposited by the sputtering of Bi-Fe alloy target under the Ar/N₂ gas flow. After the deposition of Ag layer, another 0.6-mm PC substrate was attached on to complete the disk sample preparation. The disk samples were then sent to a dynamic tester (ODU-1000, PULSTEC) equipped with a 405-nm laser diode and a numerical aperture (NA) of 0.65 to evaluate their optimum write power (Pw), modulations and signal properties. The characterization was performed at clock frequency = 64.8 to 139.6 MHz, linear speed = 6.61 to 13.22 m/sec and the track pitch = 0.4 µm. The microstructures of the recording marks were examined by a transmission electron microscope (TEM, Jeol FX-II 2010) equipped with an energy dispersive spectrometer (EDS, Link ISIS 300).

3. Results and Discussion

The disk samples evaluated in this work possess a high to low recording polarity. The disk structure was optimized in order to achieve the highest reflectivity for high-speed recording. It was found that thickness reduction of Bi-Fe-(N) layer and thickness increment of upper ZnS-SiO₂ dielectric layer results in the increment of reflectivity of disk samples. According to this finding, we iterated the disk sample preparation by fine tuning the thicknesses of Bi-Fe-(N) layer and upper ZnS-SiO₂ dielectric layer of the disk samples so as to obtain the highest reflectivity. It is noted that the increase of reflectivity may cause the increase of Pw. However, via the optimization of write strategy, the recording sensitivity could effectively be improved.

Figure 2(a) shows the TEM images of random signal marks written at the optimized Pw = 7.1 mW for 1X recording speed. Corresponding eye pattern read directly from oscilloscope is presented in Fig. 2(b). As revealed by dynamic test, the maximum PRSNR of 26.7 dB, the minimum sbER of 7.4×10⁻⁸ and modulations of 0.7 were achieved, exceeding the requirements of HD-DVD Specifications [6]. It clearly illustrates that the random signals could be written perfectly in our optical disk.

The image of random signal marks written in optical disk at optimized Pw = 9.1 mW for 2X recording speed and the corresponding eye pattern are presented in Figs. 3(a) and 3(b), respectively. The signal properties, i.e., maximum PRSNR of 23.8 dB, the minimum sbER of 2.2×10⁻⁷ and modulations of 0.7, exceeding the requirements of HD-DVD Specifications [7] were also obtained. Figure 3(a) illustrates that at 2X recording speed, the seashell-like signal marks possess a rather sharp edge. The implies the good sensitivity of disk samples containing Bi-Fe-(N) layer at low Pw for high-speed recording.
As shown by TEM images in Figs. 2(a) and 3(a), the irregular grey and black phases comprised of the seashell-like signal marks regardless of the recording speeds. Though the grain sizes of grey and black phases become comparatively small at the edges of marks, all marks with various recording lengths remain intact. Selected area electron diffraction (SAED) patterns taken from the non-mark and mark areas both exhibit the vague ring patterns, indicating and recording layer remains amorphous and there is no recrystallization during laser recording. Figure 4(a) specifies the locations of EDS analysis on a short T mark and the analytical results is presented in Figs. 4(b). It can be readily seen that the grey and black phases correspond to the Fe-rich and Bi-rich solid solution phases. Non-uniform distribution of Bi and Fe elements in the mark region shown in Fig 4(b) indicates the distinct element separation in the Bi-Fe-(N) recording layer due to laser irradiation. Accordingly, the optical property change of Bi-Fe-(N) layer required for the satisfactory signal properties is mainly resulted from the element separation as well as the grain size change in mark area. Above analytical results on microstructure and phase constitution clearly demonstrate a distinct recording mechanism in contrast to amorphous-to-crystalline phase transition reported in the studies relating to conventional optical disks.

4. Conclusions

We demonstrate the feasibility of Bi-Fe-(N) layer as the recording media in high-speed write-once optical recording. For the disk sample with optimized layer structure and write strategy, the PRSNR of 23.8, the sBER of 2.2×10^{-7}, and modulations of 0.7 were achieved at P_w = 9.1 mW at 2X recording speed. The optical property change required for the satisfactory signal properties is hence resulted from the element separation and grain size change in Bi-Fe-(N) layer, rather than the amorphous-to-crystalline structure change as observed in conventional optical disks. Experimental results clearly illustrated that the Bi-Fe-(N) is a promising material for next-generation high-speed write-once optical recording.

5. Acknowledgements

This work was supported by the National Science Council of the Republic of China under contract NSC96-2221-E-009-010. Dynamic test supplied by Prodisc Technology Inc., Taiwan, is also deeply acknowledged.

6. References


Figure 1 Cross-sectional structures of Bi-Fe-(N) recording layer for write-once optical disk.
Figure 2 (a) TEM micrograph of random signal marks at optimized $P_w = 7.1$ mW and 1X recording speed (b) the corresponding eye pattern read from oscilloscope.

Figure 3 (a) TEM micrograph of random signal marks at optimized $P_w = 9.1$ mW for 2X recording speed (b) the corresponding eye pattern read from oscilloscope.

Figure 4 (a) The locations of EDS analysis on a short T mark and (b) the variations of chemical compositions deduced from the EDS analysis in the mark and its vicinity shown in (a).
Numerical Simulations on a Stepped Solid Immersion Lens Suggested from the Experimental Consideration of the Backflow

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1. Introduction

Near field recording (NFR) technology has issued and developed for higher storage capacity and data transfer rate before some decades. However, this innovative optical storage technology was hard to be adopted promptly, since the researchers found some theoretical constraints that make the NFR technology performable in commercial products. One of the most critical constraints is extremely short distance between the disk surface and an objective lens. This short gap, an equivalent to the distance between the head and the flatter surface in a hard disk drive, brings control and contamination problems of the lens.

The contamination problem was first treated in the research of Ishimoto et al. They experimentally showed deposition of some particles have floated in the drive and the conical solid immersion lens (SIL) is more reliable to the contamination than the navel one. Park et al. followed simulating the air flow field numerically using the finite volume method (FVM) and then tried to change the path lines of contamination particles heading for the SIL by using an asymmetric lens and obstacles in front of the SIL. Unlike most researchers who neglect the gap between the medium and the lens, Higgs III and Terrell simultaneously calculated air field and tracks of particles floating in the air near the conical SIL including the gap flow. Their simulation results showed that most particles delivered by the main flow would not enter into the gap between the SIL and the medium. Choi et al. suggested another possibility of contamination. They showed backflow at the back of the SIL in numerical and experimental results. They considered it as a source of remaining contaminants, and tried to reduce the pressure difference between the SIL top and its bottom.

In this study, the backflow, a key factor of remaining contaminants, is experimentally and numerically confirmed to climb the SIL along its lateral surface, not just horizontally come back to the SIL. And some modifications are applied to the SIL geometry to prevent particles’ approaches to the SIL top.

2. Experimental setup

Experimental setup is same as that of Choi et al. except a use of mirror to see the flow field near the SIL along the lateral view. The mirror is coated with enhanced aluminum to catch small scattering from the particles and installed with an angle of 45 degrees with respect to the laser beam as shown in Fig. 1 so that we can see flow field on a symmetric plane of the SIL whose normal vector is parallel to the x axis. And the mirror is at the place where it changes the flow field near the SIL little, and at the same time, it does not make the length of light path from the subject to the objective lens of a microscope system exceed the focal length of the objective lens.

We seed the smoke of mineral oil whose particle size is 0.5μm in diameter. And the lines where the velocities of the particles are taken are shown in Fig. 2.

3. Numerical Model

We made the numerical model which includes mirror and 20μm gap between the disk and the SIL following the same procedure as Choi et al.. Semi implicit method for pressure linked equations (SIMPLE) algorithm is used to couple pressure and velocity, and 1st order upwind scheme is used to discretize the momentum equation. And the standard k-ԑ model is selected for turbulent simulation.
4. The Comparison of Results from Experiments and Numerical Simulations

As shown in Fig. 3, the backflow climbs the lateral surface of the SIL not just turn back horizontally. And we can find the y velocities in experimental result are similar to those in numerical result along the specified lines as shown in Fig. 4. The backflow exists only up to 26 % of the gap between the disk and the lateral surface of the SIL.

5. Modifications of the SIL Geometry

We have known from the experiment that the backflow climbs the lateral surface of the SIL and that exists very slightly from the SIL. Furthermore it is not efficient way to change the shape of lens holder to reduce the pressure difference between the SIL top and the bottom of the SIL. Thus, it is worth while trying the stepped SIL to generate vortexes on every step and detach the backflow from it. We made the SIL divided into sixteen equal heights (each step is 18.75\,\mu m in height) and attach steps on the lateral surface of the SIL and calculated flow field. As we expected, vortexes on steps pull the backflow from the SIL and additionally, the pressure difference is remarkably reduced as shown in Fig. 5. However, such tiny steps are hard to be manufactured as intended. Instead, we suggested a SIL which has single step, and calculated the flow field around it with various step positions and heights.

6. Numerical Results of the Modified SIL

First, the effect of position is tested. Based on the stepped SIL, the single – stepped model, p02, is taken as the reference model whose step is on the fifteenth floor in the stepped SIL. And model p01 has a step over 6.25\,\mu m high from that of p02, and model p03, p04, and p05 have each own step which is 6.25\,\mu m lower than that of previous one. As shown in Fig. 6, the pressure change was obtained along the marked line segments. Since the line segments jump pathlines, the more pressure difference will block the particles in the backflow climbing the step. And the particles may empty into the detached backflow. Hence we choose the p03 model for its large pressure difference and enough distance of 25\,\mu m from the top of the SIL.

Second, various height of a step are tried for p03 model instead of 6.25\,\mu m; models with steps of 8\,\mu m, 10\,\mu m, 12\,\mu m, 14\,\mu m, and 16\,\mu m in height are named as h01, h02, h03, h04, and h05 respectively. Figure 7 shows model h01 has the largest pressure gradient along the radial direction at the step position.

7. Conclusion

We confirmed that backflow climbs the SIL and that very close to the lateral surface of it from the experimental and numerical results. Thus we suggest a SIL has single step around its surface to block the particles and wash them away from the SIL. Among various positions and heights of a step, one whose height is 8\,\mu m and distance from the SIL top is 25\,\mu m shows the largest pressure gradient. This single stepped SIL is expected to prevent particles from approaching the top of the SIL.

References

Fig. 1 Mirror and schematic view of experimental setup

Fig. 2 Area and positions where particle motions are taken: position 1, position 2, position 3,
position 4, and position 5 have distance of 210\(\mu\)m, 300\(\mu\)m, 420\(\mu\)m, and 500\(\mu\)m respectively from the SIL top.

Fig. 3 Lateral view of velocity field rear the SIL: (a) experimental result, (b) numerical result

Fig. 4 Comparison of \(y\) velocities from experimental and numerical results: The results are obtained on the (a) position 1, (b) position 2, (c) position 3, and (d) position 4.

Fig. 5 Velocity and pressure of original and stepped model: (a) velocity distribution at the back of the original model, (b) velocity distribution at the back of the stepped model, (c) pressure distribution on the original model, and (d) pressure distribution on the stepped model

Fig. 6 Pressure change near steps of each model and position where it is obtained: (a) lines where pressure change is obtained, (b) pressure change along the entire lines, and (c) pressure change near steps of each model.

Fig. 7 Pressure gradient in radial component at steps of each model
THURSDAY
SESSION ThD: Oral Post-deadline Papers

Monarchy Ballroom
Thurs. 4:30 to 5:30 pm
109 Gbit/in² recording on a near-field optical disc using the PR (12221)/17PP code and LDPC decoding

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1. INTRODUCTION

For near-field optical recording we have proposed a super-hemisphere solid immersion lens (SIL) with a numerical aperture (NA) of 1.84 \cite{1}. This NA realizes an areal recording density 4.5 times of the Blu-Ray disc whose NA is 0.85 - 80.7 Gbit/in² with a bit error rate of 4.5×10⁻⁵ \cite{1}. On the other hand, in order to improve recording density, several approaches in signal processing have been also examined \cite{2-4}. Miyauch et al. \cite{2} have demonstrated that a novel trellis decoding technique for the 17PP code is effective for increasing the recording density of Blu-Ray disc. Ohkubo et al. proposed a new LDPC-coded PR17PP system \cite{4}. They showed that their system would make it possible to increase the recording capacity of the Blu-Ray disc up to 36GB. This article is a brief report on the improvement in the recording capacity of our near-field optical disc system brought about by applying the LDPC-coded PR17PP system.

2. EXPERIMENTAL METHOD

Figure 1 is a block diagram of our experimental setup consisting of the recording system, the equalizer board and the LDPC system \cite{5}. The equalizer board was designed so that the readout signal is processed through either the PR-(1221) or PR-(12221) code. The second-order adaptive Volterra filter proposed by Kajiwara et al. \cite{6} was implemented in the adaptive equalizer for the purpose of compensating for the large amplitude asymmetry. After being equalized through the selected PR channel, the readout signal is decoded by the LDPC system. To measure the bit error rate, a series of data of about 300k bits is fed into and analyzed by the LDPC system. The objective lens was an SIL of 1.84 NA and the medium was a phase-change disc of the GeSbTe alloy. We optimized the write-strategy at each recording density by minimizing the Sequenced Amplitude Margin Quasi-Error estimation (SAMQES) value \cite{7}.

Fig. 1. Block diagram of proposed near-field recording system, equalizer board and LDPC system.

3. RESULTS AND DISCUSSION

We examined the efficiency of the two PR classes, i.e. PR-(1221) and PR-(12221). The SAMQES value was measured at different linear recording densities ranging from 72.0 Gbit/in² to 100.8 Gbit/in². To take into the effect of the inter-track crosstalk, random data was recorded on three consecutive tracks and the data on the center track...
was read out and examined. The results in Fig. 2 show that PR-(12221) is more effective than PR-(1221) in the density region larger than 80 Gbit/in².

![Graph showing comparison of PR classes at different recording densities.](image)

**Fig. 2.** Comparison of the PR classes at different recording densities.

Thus, we decided to use the PR-(12221) class and the Volterra equalizer to estimate the upper limit of the recording density. To change the recording density we adjusted the linear velocity, keeping the channel clock constant at 66MHz. The laser power and the write-strategy pattern were optimized for each recording density. We evaluated the decoding performance of the PRML and LDPC codes, observing the bit error rate of the decoded signals. The results are shown in Fig.3. In both cases, we saw that a recording density higher than 100 Gbit/in² is feasible. However, when the LDPC was employed for decoding, no error was observed at an areal density below 109 Gbit/in².

![Graph showing dependence of bit error rate on areal recording density.](image)

**Fig. 3.** Dependence of the bit error rate on the areal recording density.

Next, using the LDPC code, we measured the recording power tolerance at the areal density of 109 Gbit/in², keeping the ratio of between the peak power and the bottom power constant. In Fig.4, the x axis is the ratio of each peak power to a reference peak power that was determined arbitrarily. We obtained the power tolerance of ±8.1%.

![Graph showing recording power tolerance.](image)

4. **CONCLUSION**

The signal properties were examined at the recording densities higher than 100 Gbit/in² in our near-field optical recording system. The LDPC-coded PR17PP system raised the recording density by around 35% compared with the previous results[^1]. The recording power tolerance was ±8.1% at a recording density of 109 Gbit/in². We conclude...
that the upper limit of the recording density is 109 Gbit/in², which is equivalent to 151 GB for a 12cm-diameter disc, assuming the same redundancy as that of the Blu-ray disc format.

Fig. 4. Recording power tolerance of a phase-change disc at an areal density of 109 Gbit/in².

ACKNOWLEDGEMENT

The authors thank their colleagues for their technical assistance and invaluable pieces of advice. This work was only made possible by elaborate and sophisticated technical elements established by Mr. Kobayashi, Mr. Shiraishi and Mr. Miyauchi. Finally, the authors express their gratitude to Mr. Yamamoto for his constant and warm encouragement.

REFERENCES

Near-field Rewritable Dual-layer Recording with SIL System

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ABSTRACT

Dual-layer rewritable recording with a SIL (Solid Immersion Lens) system was first demonstrated. The refractive index of the SIL was 2.068 and the laser wavelength was 405 nm. Newly developed optical disk medium has two phase-change recording layers, L0 and L1, separated by an only 3 µm thick resin layer having the refractive index of 1.5. The disk surface was coated with the same resin of 1 µm in the thickness for protection. Two optical heads that were different in the SIL thickness and the distance between the objective lens and the SIL were used separately for L0 and L1 in order to minimize the spherical aberrations for each layer. Successive overwriting and read-out were successfully achieved for both layers. The promising recording capacity will be 180 GB by increasing the refractive index to 1.8.

Keywords: Near field recording, Dual-layer, SIL, Phase-change, Rewritable

1. INTRODUCTION

Near-field optical recording using a SIL (Solid Immersion Lens) system is a potential candidate for the next generation optical disks aiming, for example, at 3D or 4K2K contents in the near future. By utilizing the large numerical aperture (NA) of the SIL, five times or more recording density as compared with the conventional Blu-ray Disc systems (25GB/\(\phi 120\text{mm}\)) is promising. Here, it is becoming important whether the SIL technology will be applicable to the multi-layer recording. Unless it is possible, the recording capacity may remain as high as around one and half GB. Reportedly, some simulation results suggested the possibility of multi-layer recording with SIL systems\textsuperscript{1); however, no actual experimental demonstration has been reported yet in fact. In the present work, we first demonstrated the near-field dual-layer recording using the set of SIL and a rewritable phase-change optical disk. We newly developed a phase-change optical disk and SIL systems optimized for the disk structure. In this paper, we describe the structure of the optical disk, construction of the SIL system, and read/write experimental results using them.

2. PREPARATION

2.1 Dual layer media for SIL systems

Figure 1 shows the schematic diagram of the rewritable dual-layer phase-change optical disk optimized for the SIL recording. The film stacks of the two layers are designed basically after the Panasonic 50 GB BD-RE media\textsuperscript{2-3). As seen in the figure, the substrate-side and the beam-incident-side (cover layer-side) recording layers are taken to be L0 and L1, respectively. The large different points from the BD are the thicknesses of the intermediate and the cover layers. In order to minimize the influence to the optical transferring, each layer was set as thin as possible: 3 µm and 1 µm, respectively. They were formed by spin coating method using the same UV-resin for the BD (refractive index n=1.5). The NA of the SIL system was limited by the refractive index of these layers and the NA in this system is estimated remaining around 1.4. The resin layer with low refractive index (1.5) will limit the transferring of the laser beam from the SIL (n=2.068) to the recording layers.

2.2 SIL optical head for dual layer recording

The refractive index of the SIL was 2.068 (@405 nm in wavelength), and the optical head structure was the same as the previous paper.\textsuperscript{5) However, the spherical aberration became a serious issue especially in the case of multi-layer recording using a high NA system. Since we were not ready yet for the spherical aberration compensation mechanism, two optical heads were provided for the dual-layer optical disk, one for L0 and the other for L1, in this experiment. Each head was

TD05-152 (1)
adjusted to minimize the spherical aberration by arranging the SIL thickness and the distance between the objective lens and the SIL. The schematic diagram and the measured results of the aberration for the dual layer disk are shown in Fig. 2. As seen in the figure, the spherical aberration is negligibly small.

![Diagram of the experimental dual-layer disk for the SIL system](image1)

**Fig. 1** Schematic layer structure of the experimental dual-layer disk for the SIL system

![Diagram of the arrangement of two optical heads and interference fringe patterns on the SIL](image2)

**Fig. 2** Schematic diagram of the arrangement of two optical heads and interference fringe patterns on the SIL

### 3. READ/WRITE DEMONSTRATION

The read/write test has been performed with the gap distance of 30 nm and the linear velocity of 3.08 m/s. The channel clock frequency was fixed to 66 MHz and the modulation code of 1/7 RLL was adopted. The dependence of each C/N for L1 (a) and L0 (b) is shown in Fig. 3. In the figures, each curve shows the recording result after 10-cycle overwriting. The recording power defines the incident power on the SIL system in this case; therefore, the incident power on the media is estimated to be half of the recording power because of the air gap. The erasing ratio of 9T signal overwritten by 2T signal for L1 (a) and L0 (b) are shown in Fig. 4. As interpreted from the sufficiently large erasing ratios, overwriting was successfully achieved for either of L1 and L0.

Figure 5 shows the signal eyepatterns for L1 (a) and L0 (b). The recording, erasing and read-out powers were 18 mW, 6 mW and 0.4 mW for L1, and 15 mW, 5 mW and 0.5 mW for L0, respectively. As can be seen in the figure, clear eye patterns are obtained for both recording layers. Here, the 10-time overwrite jitter of L1 is 10.9%, and that of L0 is 10.7%. As shown here, overwriting and read-out have been demonstrated successfully for the both recording layers. These results tell us that the film stacks applied for the dual-layered BD structure are essentially applicable to the near field optical recording using the SIL system. The recording capacity in this experiment corresponded to only 135GB since the effective NA remained around 1.4. But it is promising to increase the capacity just by increasing the refractive index of the resin for the intermediate and the cover layers. For example, the capacity will increase to 180 GB if the present resin could be replaced by new resin with the refractive index of 1.8.

### 4. CONCLUSION

Near-field recording combining the multi-layer technologies and the SIL system was first actually demonstrated using the BD-like phase-change optical disk and the two optical heads. Since the refractive index of the resin layer is still low (1.5), the achieved recording density is corresponding to only 135GB. However, this work is just the promising first step willing to achieve a higher density optical disk. By developing the new resin with higher refractive index, the expected capacity will be close to half terabyte/φ120mm. As a solution of the next generation optical disk, the multi-layer SIL recording will be a promising candidate that is available for all of ROM/R/RE systems.
REFERENCES


Fig. 3 Recording power dependence of C/N for L1 (a) and for L0 (b)

Fig. 4 Erasing power dependence of erasing ratio for L1 (a) and L0 (b)

Figure 5 Eyepattern of 1-7 random signal from L1 (a) and L0 (b)
Bit-Error-Rate Evaluation of Energy-Gap-Induced Super Resolution (EG-SR) ROM Disc with Dual Layer Structure

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Abstract
We measured bit error rate (bER) of a dual-layer 80 GB energy-gap-induced super-resolution (EG-SR) read-only-memory (ROM) disc with a zinc oxide (ZnO) film using a partial response maximum likelihood (PRML) detection method. The experimental capacity of each layer was 40 GB in a 120 mm diameter. Titanium (Ti) was adopted as a material of the reflective film in the L1 layer in order to reduce the loss of light which reaches the L0 layer, and the material of a reflective film in the L0 layer was Tantalum (Ta) which we already reported. BER better than a criterion \((3 \times 10^{-4})\) was obtained with a readout power of about 2 mW in both layers. Practically available characteristics including readout power margin and readout cyclability were also confirmed in the dual-layer 80 GB EG-SR ROM disc.

Keywords: super-resolution, dual-layer, ROM disc, zinc oxide, bER

1. INTRODUCTION

Energy-Gap-induced Super-Resolution (EG-SR) technique using a zinc oxide (ZnO) film has been proposed as a promising technique to obtain an areal density higher than that of current commercial Blu-ray Disc (BD). We already reported that EG-SR read-only-memory (ROM) discs with dual layer structure showed practical carrier-to-noise ratio (CNR) at a pit length smaller than the optical resolution limit.\(^1\)\(^-\)\(^4\) We also reported that a 40 GB EG-SR ROM disc with a tantalum (Ta) reflective film shows good bER in a BD optics using a partial response maximum likelihood (PRML) detection method and that practically available characteristics are obtained.\(^5\)

In this paper, we describe that titanium (Ti) was effective as a reflective film for the L1 layer rather than Ta, and that the readout power margin and the readout cyclability in both the L0 and the L1 layers of the dual-layer EG-SR ROM disc are satisfactory for practical use.

2. EXPERIMENT

Figure 1 shows the dual-layer EG-SR ROM disc structure in this study. A ZnO film was used as an EG-SR film for both of the L0 and the L1 layers. A Ta film was utilized as a reflective film for the L0 layer and a Ti film was utilized as a reflective film for the L1 layer. The thickness of each film in the L0 layer was controlled in order to achieve good bER characteristics. Meanwhile, the thickness of each film in the L1 layer was controlled in order to achieve a good balance between good bER characteristics in the L1 layer and high transmittance of the L1 layer which has much effect on bER characteristics in the L0 layer. All of these films were deposited by a sputtering method.

A plastic ROM substrate was utilized. And UV resin was used for the space layer, and a random pit pattern was formed on it by photo polymerization. A Polycarbonate/Pressure Sensitive Adhesive (PC/PSA) sheet was employed as a cover layer which was supplied by LINTEC Corporation.

Table 1 shows bER measurement conditions. A BD optical pickup with a 405-nm-wavelength laser and a 0.85-numerical-aperture objective lens was utilized. The optical resolution limit was about 120 nm. The experimental minimum mark length was 94 nm, which is smaller than the optical resolution limit. The modulation code was 1-7 PP. The experimental capacity in each layer corresponded to 40 GB in a 120 mm diameter, thus the total capacity was 80 GB. The track pitch of 0.32 µm was the same as that of commercial 25 GB BD discs.
In this study, we utilized a non-adaptive PR(1,2,2,2,1)ML with d-constraint to evaluate bER. The criterion for bER was set to $3.0 \times 10^{-4}$, which corresponds to a threshold bER for practical use in the conventional optical disc storage field.

3. RESULTS AND DISCUSSION

3.1 Ti reflective film in L1 layer

To design dual layer structure optical discs, reflective film thickness in the L1 layer is important. A reflective film in the L1 layer needs to have high transmittance from the viewpoint of readout sensitivity of the L0 layer. On the other hand, a reflective film has a role of heat source for an EG-SR disc, so in order to obtain good bER characteristics, it requires a certain amount of thickness. From these viewpoints, we selected Ti as more suitable material for a reflective film in the L1 layer than Ta which had been already reported in ref. 5 as a reflective film showing good bER characteristics.

Figure 2 indicates the readout power dependence of two single-layer EG-SR ROM discs. One of them has a ZnO EG-SR film and a Ti reflective film (ZnO/Ti disc), and another has a ZnO EG-SR film and a Ta reflective film (ZnO/Ta disc). The thicknesses of a reflective film and ZnO EG-SR film were the same between these two discs, and they were 7 nm and 60 nm, respectively. As shown in Figure 2, Ti and Ta reflective films showed almost the same good bER characteristics. We also measured the transmittance at 405 nm wavelength between Ti and Ta films which have the same 7 nm thickness. Transmittances of these films on glass substrate were measured with spectrometer. The transmittances of a Ti film and a Ta film were 45 % and 33 %, respectively. A Ti film has higher transmittance than a Ta film. From those results, we adopted a Ti reflective film for L1 layer.

3.2 Readout power characteristics of EG-SR ROM disc with dual-layer structure

Figure 3 shows the results of readout power dependence of bER in the dual-layer EG-SR ROM disc. The gray dashed-dotted line means the threshold value of bER for practical use. We obtained better bERs than the threshold value in both the L0 and the L1 layers with about 2 mW readout power by adopting a Ti reflective film in the L1 layer. And practically available readout power margin was also obtained. The readout power margin in L0 layer was from 1.6 mW to over 3.6 mW, more than ±1.0 mW, and that in the L1 layer was from 2.2 mW to over 3.6 mW, more than ±0.7 mW.

3.3 Readout cyclability

Figure 4 shows readout cyclability of the dual-layer EG-SR ROM disc. In this measurement, a 2.0 mW and 2.6 mW readout laser beams were continuously irradiated on the L0 and the L1 layers, respectively. We confirmed the bERs in both the layers remained under the threshold until ten to the fifth readout cycles.

4. CONCLUSION

We evaluated readout power margin and readout cyclability of the dual-layer 80 GB EG-SR ROM disc using the PRML detection method in the BD system. The experimental capacity of each layer was 40 GB in a 120 mm diameter and the total experimental capacity was 80 GB. We obtained bERs better than the criterion at the readout power of about 2 mW, practical readout power margin (more than ±0.7 mW), and good readout cyclability (ten to the fifth cycles), in both layers.

REFERENCES

Fig. 1. Dual-layer EG-SR ROM disc structure.

Table 1. Measurement conditions.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tr>
<td>Wavelength (nm)</td>
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<td>Numerical aperture</td>
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<td>Linear velocity (m/s)</td>
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<tr>
<td>Minimum mark length (nm)</td>
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<td>Track pitch (µm)</td>
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<tr>
<td>Data detection method</td>
<td>PR(1,2,2,1,2)ML with d constraint (non-adaptive)</td>
</tr>
</tbody>
</table>

Fig. 2. Readout power dependence of single-layer EG-SR ROM discs, ZnO/Ti disc and ZnO/Ta disc.

Fig. 3. Readout power dependence of bER in the dual-layer EG-SR ROM disc.

Fig. 4. Readout cyclability dependence of dual-layer EG-SR ROM disc.
Tunable External Cavity Blue Laser Diode for Holographic Data Storage

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Abstract: InPhase and Nichia have developed a tunable external cavity blue laser diode (ECLD) for holographic data storage (HDS). Our initial data indicate that the lifetime of the tunable ECLD is approximately 5000 hours with 6 nm wavelength range and 45 mW output power at 25 deg. C ambient temperature.

1. Introduction
In the Holographic Data Storage (HDS) drive at InPhase Technologies, the holographic media exhibits a temperature dependence that can be compensated by tuning the wavelength of the laser light source in the drive. InPhase Technologies and Nichia Corporation have co-developed a tunable ECLD that performs reliably under practical conditions for the InPhase HDS drive. In this paper, we report on the performance and reliability of the tunable ECLD.

2. Features
2.1. Optical system configurations
The tunable ECLD, shown in Figure 1, consists of a laser diode, optics, a stepper motor, sensors, and a FPGA. Figure 2 shows the schematic diagram of the tunable ECLD. The laser cavity consists of an anti-reflection coated laser diode, a lens to collimate the laser light and a transmission grating that creates the external cavity and acts as the output coupler. The stepper motor adjusts the ECLD wavelength by rotating the grating. After the grating, anamorphic prisms convert the elliptical beam from the cavity into a symmetrical beam.

We designed the ECLD to maximize output power, single-mode tuning range and pointing stability. The Littrow configuration of the cavity, combined with a transmission grating, enables high output power with stable beam pointing. The location for the axis of rotation of the grating minimizes the number of cavity mode hops. The collimation lens is highly achromatized to insure broad wavelength tuning range.

2.2. Sensors
The ECLD is monitored and controlled by internal sensors and an on-board FPGA. The sensors measure the wavelength, the longitudinal mode and the output power of the ECLD.

2.2.1 Mode sensor
We use a portion of the output from the cavity for monitoring the power and mode of the laser. The mode sensor consists of a beamsplitter, an optical wedge and a linear sensor array as shown in Figure 2. Figure 3 shows a detailed schematic of the mode sensor. A part of the incident light is reflected at the first surface of the beamsplitter. The reflected beam is incident on the wedge, which creates two overlapping reflections from the first and second surface of the wedge. The wedge creates a spatially-varying phase between the reflections. After transmission through the beamsplitter, the wedge reflections interfere to create a linear fringe pattern that is detected by the linear array.
In this configuration, single-mode light creates a fringe pattern with high contrast and multi-mode light creates a fringe pattern with low contrast. Using a Fabry Perot etalon, we verified a strong correlation between the number of laser modes and the contrast ratio of the fringes. Further, we correlated the fringe contrast to the signal-to-noise ratio of holograms in the HDS drive. When the contrast ratio falls below 0.55, the hologram SNR falls below a critical threshold and the holograms must be rewritten. Data from the linear array is processed by the FPGA to calculate the fringe contrast ratio.

2.2.2 Power Sensor
The light transmitted through the mode sensor is incident on a photodiode (Fig. 2). The light detected by this photodiode is proportional to the output of the ECLD. During ECLD assembly we calibrate the photocurrent from the power sensing photodiode to an external power meter. The ECLD stores the power sensor calibration in its internal memory. The FPGA recalls the calibration to read the ECLD power.

2.2.3 Wavelength sensor
In the ECLD, the grating angle determines the wavelength of the laser. The wavelength sensor measures the wavelength by detecting the linear position of the end of the grating mount, which is calibrated to wavelength. Figure 4 shows the wavelength sensing system. The sensor consists of an LED, mounted to the underside of the grating mount, and a PSD (position sensitive detector) mounted to the mechanical base plate. The LED light is incident on the PSD, which generates a signal that is proportional to the position of LED light. During ECLD assembly, the LED position is calibrated to an external wavelength meter. The calibration coefficients are stored in the memory of the ECLD, which the FPGA can recall for future wavelength measurements. The accuracy of the wavelength sensor is +/- 0.07 nm.

3. Characteristics
3.1. Optical Power and tuning range
Figure 5 shows the output power versus LD forward current of a tunable ECLD. The threshold current at 405 nm is 38 mA. The output power at 405 nm is 55 mW at 90 mA. Figure 6 shows the output power versus wavelength at 90 mA LD forward current. The maximum output power is 53 mW at 405.7 nm. The minimum wavelength, where the ECLD remains in a single longitudinal mode, is 400.3 nm and the maximum wavelength is 410 nm. The tuning range of the ECLD is 9.7 nm. If we require the minimum output power to be 35 mW, then the tuning range is 8 nm. Because the central wavelength of the ECLDs may vary (from unit-to-unit) by +/- 1 nm, the tuning range is estimated to be 6 nm.
3.2. Probability of single-mode operation

The laser must operate in a nearly pure, single longitudinal mode ("single-mode") to generate strong holograms in our HDS drive. However, the ECLD cavity is not free of mode hops and single-mode behavior is not guaranteed for all tuning parameters. We use the mode sensor to detect when the laser is multi-mode, and then adjust the LD current, ECLD wavelength, or both to return the ECLD to single-mode operation. The required wavelength is determined by the temperature of the holographic media in the HDS. Therefore, usually LD current is changed to keep the laser single-mode. Figure 7 shows a map of the contrast ratio of the mode sensor versus current and wavelength. In these data we step the current by 0.2mA and the wavelength by 0.2nm. As mentioned above, when the contrast exceeds 0.55, the laser is sufficiently coherent to produce good holograms in our HDS drive. The white area in Fig. 7 corresponds to more single-mode operation, while the black areas correspond to more multi-mode operation. Figure 8 also shows the distribution of contrast ratios in a histogram. For reliable operation, the HDS drive requires that the laser is single-mode over 80% of the wavelength and current tuning space. From the data in Fig. 7 and 8, we calculate that the laser is single-mode in 94% of the tunable range of LD currents and wavelengths.

4. Lifetime

4.1. Lifetime of AR coated LD

Figure 9 shows the result of the life test of ECLDs under automatic power control at 45 mW, 25 deg.C ambient temperature. The life test was performed with ECLDs in the configuration shown in Figure 1. The criterion for end-of-life is that the LD forward current and voltage increase by 30% from their initial values. At 1000 hours we confirmed that the ECLDs show single-mode tuning with characteristics similar to the start of the test. Based on data from the first 1000 hrs, we estimate the ECLD lifetime is approximately 5000 hrs. In the future, we plan to test a new, more efficient laser diode for the ECLD. The new laser diode may increase the ECLD lifetime and create more total output power.

5. Conclusion

InPhase Technologies and Nichia Corp. have developed a tunable external cavity blue laser diode that has 45mW output power and 6 nm of wavelength tuning range. From the first 1000 hours of life test data, we estimate the ECLD life time is approximately 5000 hours.

6. References


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