Simple Near-Field Optical Recording Using Bent Cantilever Probes

Jeongyong Kim, Ki Bong Song, Kang-Ho Park, Hyo Won Lee, and Eunkyoung Kim

This paper describes our high-density near-field optical recording using bent cantilever fiber probes installed in an atomic force microscope. We conducted a near-field reading of nano-scale hole patterns with a 100 nm spatial resolution and a 25 µm/s scan speed; this implies a capability of a data reading density of 60 Gb/in^2 with a 0.25 kbps data transfer rate. In addition, we investigated re-writable near-field recording on photochromic diarylethene films. We successfully recorded erasable memory bits having a minimum width of 600 nm in a writing time as short as 30 ms. We found that using a cantilever probe simplifies the setup and operation of the near-field optical recording system and may offer multifunctional recording capabilities.

I. INTRODUCTION

Optical data storage media, such as compact discs and digital versatile discs (DVD), have two advantages: they have a high area density and are cost efficient. Recently, the data density of optical storage devices has increased vastly, up to a few Gb/in^2 in DVD technology. However, as the required data storage continues to increase, the recording density of optical media is fundamentally limited by the diffraction of light. This situation demands alternative optical storage techniques. The effort to surpass the diffraction limit and achieve ultra high data density has been extensively investigated [1]-[3]. Especially, near-field scanning optical microscopy (NSOM) offers a high spatial resolution of a few tenths of the laser wavelength [3], [4], and thus promises to be a good candidate for the next-generation optical storage technique. Many studies have actively investigated conventional materials, such as phase change materials and organic materials, as recording media for near-field recording [5]-[8]. The advantages of organic materials are low cost, easy fabrication of homogeneous films, high resolution, and sensitivity [9].

One of the drawbacks of near-field recording techniques is the complexity of NSOM systems where the probe must be within about 10 nm of the recording media. This is accomplished in most NSOM systems by using a sophisticated shear-force detection system to regulate the gap between the probe and the medium. Some studies suggested using cantilever style probes as an alternative gap control mechanism [10], [11]. These probes are normal NSOM probes that are tapered optical fibers having sub-wavelength optical apertures, the only difference being that they are bent near the tip to operate as a cantilever probe. Since these probes can operate just like normal atomic force microscope (AFM) probes, they

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offer several advantages over gap control by shear force detection. The cantilever probe has a much lower spring constant, typically less than 1 nN/m; suffers less chance of damage; offers better manageability; and is thus suitable for the high-speed scanning operation required for storage applications. The cantilever can operate in various image modes implying that the cantilever probe offers various writing/reading modes, not limited to the photon mode [10], [11]. For instance, applying an electrical or heat pulse to the media can generate memory bits, and the memory bits can be optically read out [12]. The higher efficiency of heat or current delivery over light transmission in the writing probe can reduce the writing time and may expand the scope of near-field recording media mechanisms.

For our investigation, we constructed a simple near-field recording system using a bent cantilever optical probe installed in an AFM. We successfully carried out near-field recording (writing/reading) of nano-scale hole patterns as a read only memory (ROM) type application and used photochromic materials as re-writable recording media demonstrating the clear feasibility of the practical applications of our system.

II. NEAR-FIELD RECORDING SETUP

We modified a commercial AFM (PSIA, CP-Research) to carry out the near-field recording. Figure 1 shows the layout of our near-field recording system. We installed bent cantilever fiber probes (Nanonics) in place of the AFM probes and used them as near-field recording probes. In most cases, commercial bent near-field probes are directly compatible with AFMs because the ridge of bent cantilever probes is polished for optimized beam reflection [10], [11]. However in our AFM, the direction of the laser beam for sensing the cantilever deflection was perpendicular to the fiber probe stem (the laser beam comes from the side), and the beam reflected off the probe ridge diffracted rather than focused on the position sensitive detector of the AFM. To correct this situation, we fabricated (100×100×15 μm) micro-mirrors and attached them to the ridge of the cantilever probes to improve the shape of the reflected beam. By doing this, the laser light reflected from the micro-mirror on the cantilever probe edge was focused and thus provided an intensity and sensitivity comparable to those of ordinary AFM probes. As a result, sharp mechanical resonance peaks ranging from 80 to100 kHz with a quality factor over 50 were routinely obtained even with a micro-mirror attached; this shows that our bent near-field probe is capable of both contact and non-contact mode imaging, i.e., operating just like ordinary AFM probes. To minimize damage to the probe in our experiment, we used the non-

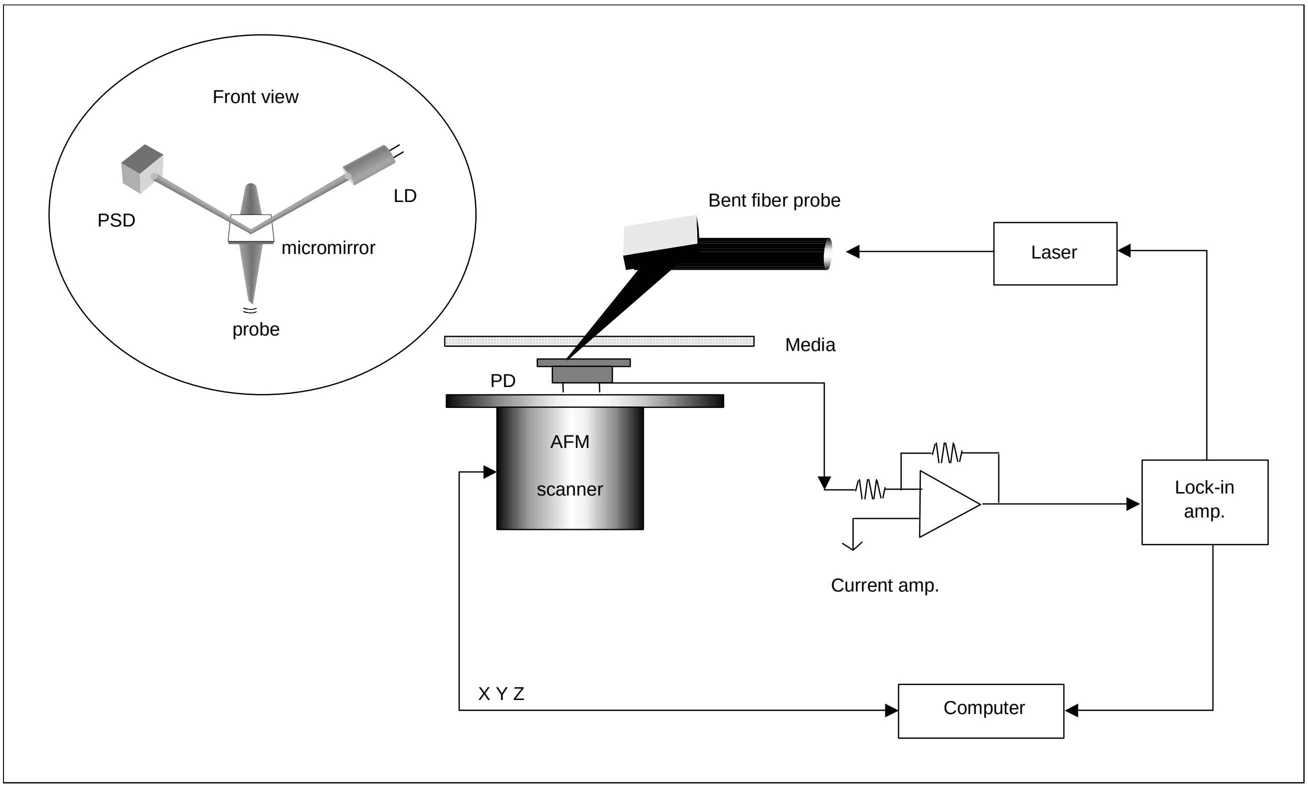


Fig. 1. Experimental layout of the near-field optical recording system using a bent cantilever fiber probe. The inset shows the optical path of the deflection sensing laser and arrangement of the micromirror.

contact (AC) mode for gap control by vertically vibrating the probe and monitoring the vibration amplitude.

We launched the laser light into the other end of the fiber and detected the light transmitted through the sample by placing a small (4 mm×4 mm) planar silicon photodetector under the recording media [13]. That way, the light detection system was quite simplified; it eliminated the use of collection optics or a high sensitivity avalanche photodiode while still allowing the use of the transmission mode, the most efficient light collection mode in NSOM. This is advantageous for the desired practical use in data storage devices. We did not use a filter to prevent a portion of the deflected laser beam from reaching the photodetector [13]. Although some DC signals were introduced, a lock-in detection system successfully eliminated the DC component of the signal.

III. RESULTS AND DISCUSSION

The low throughput of near-field optical probes has been problematic in data writing, while in data reading, a high-speed data transfer rate (up to a few Mbps) has been achieved [14]. This suggests that the read only memory (ROM) is most feasible for near-field recording systems. Since the nanometric bit size can be written by nano-imprint techniques [15], the maximum data density of ROM media is likely to be determined by the spot size of the reading laser light. To evaluate the applicability of our near-field recording system to ROM media, we conducted near-field readings of fabricated nano-bit patterns.

Figure 2 shows the near-field images of nano-hole patterns fabricated by electron-beam lithography. The sample is a gold film having a series of 200 nm deep holes arranged in a regular manner, as shown in the topography images (b, d). The laser wavelength used for the near-field reading was 635 nm from a laser diode. The film was prepared on a glass substrate to use the NSOM transmission mode; when the NSOM probe was above and between the holes, transmission was maximized and minimized, respectively. High-resolution near-field optical transmission images (a, c) and the corresponding topography images (b, d) were simultaneously obtained. Optical transmission images revealed a hexagon array of holes observed as bright spots having spacing of 1 µm. Figure 3 shows the near-field optical transmission image of another nano-hole pattern. The sample has a 500 nm spaced hole pattern with a hole diameter of only 200 nm. The cross-section of the intensity profile shows the high spatial resolution of our recording system, which is estimated to be about 100 nm from the distance between 90% and 10% of peak intensity as shown in Fig. 4(b).

The noise level of our near-field optical reading system is 40 pA with a 2 µA/V setting in the current amplifier. Our recording probe has a light throughput of 10^{-6}, and without damaging the probe coating it was able to deliver a maximum of 10 nW out of a laser input power of 5 mW. Assuming a responsivity of the photodiode of 0.5 A/W, this signal corresponds to about a 100:1 signal-to-noise ratio (SNR). The experimentally observed SNR was around 20:1, which is high enough for simple data reading with ROM media. We attribute the additional loss of the SNR to stray light from the probe. Because the typical scan speed was 25 µm/s and the observed spatial resolution of the optical image was 100 nm, a data transfer rate of 0.25 kbps should be achievable with our system.

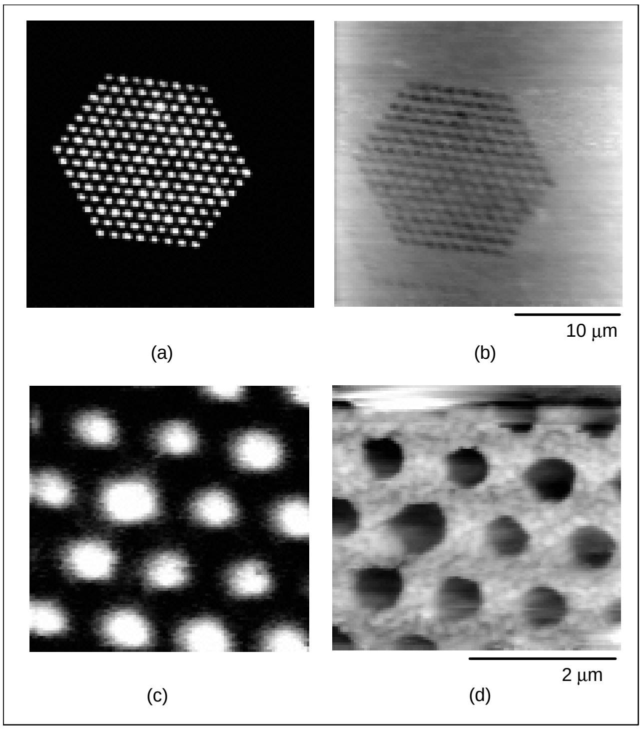


Fig. 2. Near-field images of hexagonal nano-hole patterns: (a) is an optical transmission image; (b) is the corresponding topography image; (c) and (d) are zoom-in images. The hexagonal hole pattern is well reproduced showing a 100 nm spatial resolution.

Next, we used photochromic materials for the re-writable near-field recording media. Diarylethene-based photochromic materials have been extensively studied as re-writable organic recording materials [9]. We used acetyl substituted diarylethene (DABTF6) as the photochromic material because of its high thermal stability plus its high photochromic efficiency in solid matter. In addition, DABTF6 is one of the few diarylethenes that can be processed to an optically transparent film with sub-micron thickness by simple vacuum deposition. DABTF6 was synthesized from 2,3-bis(2-methylbenzo[b]thiophene-3-yl) hexafluorocyclopentene (BTF6) in one step. The colorless vacuum-deposited diarylethene film turned a deep red hue

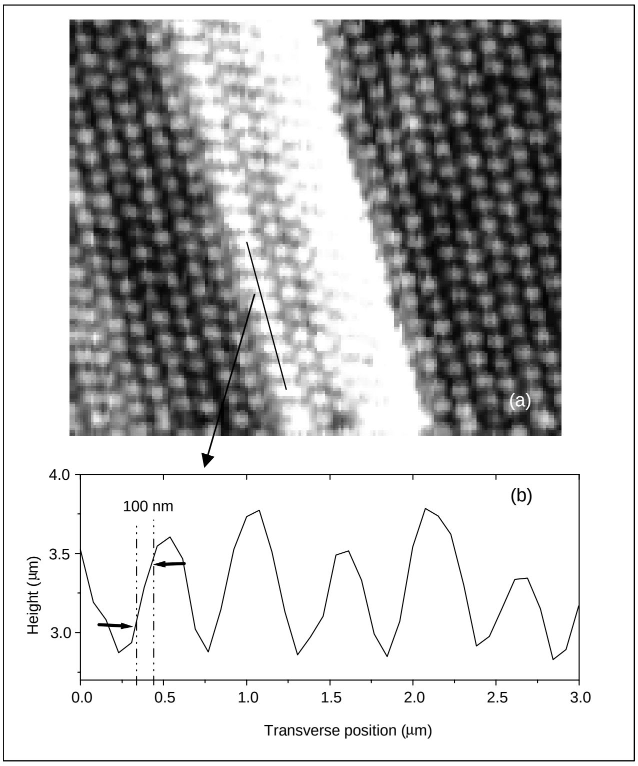


Fig. 3. (a) Near-field optical image of the array of holes. The diameter of the holes is 200 nm and the spacing is 500 nm. (b) the cross-sectional profile of the transmitted light intensity. The spatial resolution of our NSOM is estimated to be 100 nm.

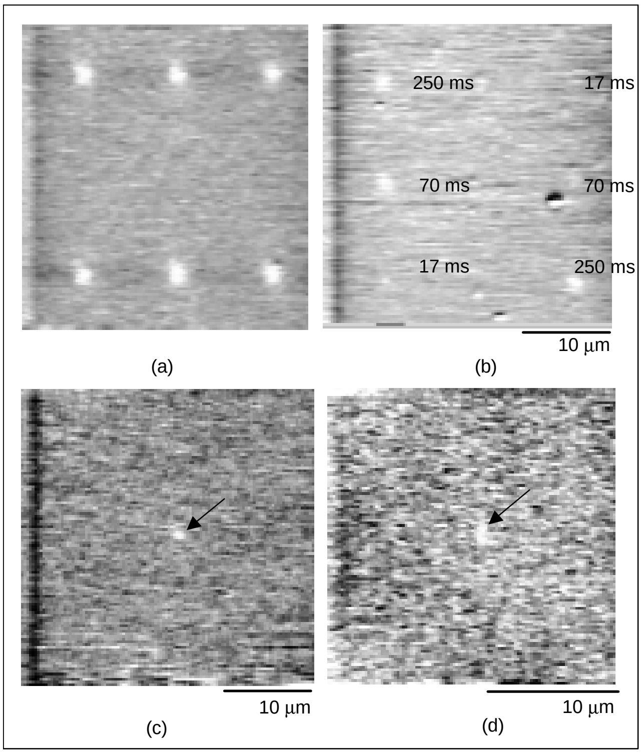


Fig. 4. Near-field optical transmission images of recorded marks on photochromic diarylethene films: (a) writing time is 1 second for each mark recorded on sample I; (b) shows a dependence on writing (exposure) time (sample I). Note that the contrast decreases with shorter writing times. With a 17 ms writing time, the memory bit is not discernible; (c) shows a mark recorded with the shortest writing time achieved, 30 ms, at the center of the image (indicated by an arrow) (sample I); (d) displays the smallest bit width of 600 nm at the center of the image (indicated by an arrow)(sample II).

when it was exposed to UV light. In the UV spectrum, a new band characteristic of a closed isomer appeared upon excitation with a UV light; the band disappeared immediately on exposure to visible light. The coloring and bleaching process was repeatable, thus confirming the re-writability of the films. We prepared two films, samples I and II, with a thickness of 659 nm and 360 nm, respectively. The optical density (OD) difference between the colored and bleached states of the two samples was 0.11 and 0.08 at a wavelength of 514 nm for samples I and II, respectively.

The sample films were colored by UV excitation before the near-field recording. Near-field writing and reading were done using the 514 nm line of an Argon ion laser. When writing, the probe stayed at each marking position for 1 second with 0.5 mW of laser light coupled into the fiber. The whole area was then scanned to get a transmission image with 0.3 mW of laser input power to avoid bleaching while reading. Figure 4(a) shows the near-field optical images of typical marks recorded on sample I. Each line scan took 1 second for the best image, which consisted of 128 lines. Distinct formation of memory bits with a 1 µm bit diameter was clearly observed as bright spots. We were able to totally erase these marks by converting the whole area by scanning the area with a laser input power of 0.4mW. Figure 4(b) displays the dependence of mark formation on writing time. The mark heights were 60, 90, and 200 mV out of a 5 V full scale for 17, 70, and 250 ms marks, respectively, which indicates that writing time determines the mark height and hence the SNR. The bit size was about 1 µm in all marks, showing no clear dependence of bit size on the writing time. The shortest writing time achieved was 30 ms (Fig. 4(c)). Sample II, having a 350 nm thickness, was also used in the experiment with the same recording procedure. Due to the lower OD of sample II, the recorded mark at the center of the image (indicated with an arrow) is barely noticeable (Fig. 4(d)). The bit size was estimated to be about 600 nm, smaller than in sample I, due to the smaller film thickness.

The observed mark-diameter of 600 nm is rather large for high-density near-field recording. For our near-field recording system to be a practical re-writable recording tool, further reduction of the bit size and the writing time is essential. The observed large bit size is attributed to two factors: the aperture size of our near-field recording probe and the thickness of the media used in the experiment. We created a probe whose aperture size was about 300 nm because a probe having an aperture size of 100 nm or less generated too small a laser power to give an adequate SNR. In the case of sample I, the OD at 514 nm was 0.11, which corresponds to a 23% transmission difference. The bent near-field probe used for the photochromic recording had a throughput of 10^{-3}, transmitting about 300 nW. With this level of laser power, the contrast obtained in the experiment was only around 10% while the noise level was about 3% and the SNR only 3:1. Thus, a laser power of 300 nW appeared to be marginal for writing discernible recording marks and any less laser power would result in non-discernible marks. Here, we can see that to be able to use a probe with a smaller aperture, it is essential to increase the throughput of the probe. Media thickness is also a factor in determining the bit size, because the light emanating from a near-field probe diverges and the spatial width of the excited volume of the media film sharply increases with film thickness. This is clearly seen when we compare the 1 μm mark size recorded on sample I having a 659 nm thickness to the reduced mark size of 600 nm on sample II having a 360 nm film thickness. However reducing the film thickness also leads to a smaller OD difference between colored and transparent states. We used samples with a minimum thickness of 300 nm to provide a high enough OD.

We found that the intensity of the marks is dependent upon the writing time: a shorter writing time needs more laser power. However, the 0.5 mW laser power used to achieve a 30 ms writing time is the maximum power that the metal coating of the fiber tip can tolerate without being damaged. Again, a higher throughput aperture probe is the solution for achieving shorter writing times as well as smaller bit sizes.

IV. CONCLUSION

We carried out a simple near-field optical recording using a bent cantilever fiber probe installed on an AFM. Nano-bit ROM samples were imaged with the near-field recording system with a 100 nm spatial resolution; this implies a capability of a data reading density of 60 Gbits/in^2 with a 0.25 kbps level data transfer rate. We used vacuum-deposited acetyl-substituted diarylethene derivatives as re-writable near-field recording materials. We successfully recorded erasable recording marks featuring a minimum 600 nm bit width and a writing time as short as 30 ms. Despite the simplicity of the system, near-field recording using bent optical fiber probes appears to have significant feasibility for practical application if improvement of the light throughput of the near field probes is achieved.

REFERENCES

[1] E. Betzig, J.K. Trautman, R. Wolfe, E.M. Gyorgy, P.L. Finn, M.H. Kryder, and C.H. Chang, "Near-Field Magneto-Optic and High Density Data Storage," *Appl. Phys. Lett*., vol. 61, 1992, pp. 142-144.

[2] B.D. Terris, H.J. Mamin, and D. Rugar, "Near-Field Optical Data Storage," *Appl. Phys. Lett*., vol. 68, 1996, pp. 141-143.

[3] J. Kim, J.T. Boyd, H.E. Jackson, and K.D. Choquette, "Near-Field Spectroscopy of Selectively Oxidized Vertical Cavity Surface emitting Lasers," *Appl. Phys. Lett*., vol. 76, no. 5, 2000, pp. 526-528.

[4] W.C. Liu, C.Y. Wen, K.H. Chen, W.C. Lin, D.P. Tsai, "Near-Field Images of the AgO/sub x/-type Super-Resolution Near-Field Structure," *Appl. Phys. Lett*., vol. 78, no. 6, 2001, pp. 685-687.

[5] S. Hosaka, T. Shintani, M. Miyamoto, A. Hirotsune, M. Terao, M. Yoshida, K. Fujita, and S. Kämmer, "Nanometer-Sized Phase-Change Recording Using a Scanning Near-Field Optical Microscope with a Laser Diode," *Jpn. J. Appl. Phys*., vol. 35, 1996, pp. 443-447.

[6] M.R. Kim, J.H. Park, and W. Jhe, "Near-Filed Optical Recording by Reflection-Mode Near-Field Scanning Optical Microscope: Submicron-Sized Marks and their Thermodynamic Stability," *Jpn. J. Appl. Phys*., vol. 39, 2000, pp. 984-985.

[7] M. Hamano and M. Irie, "Rewritable Near-Field Optical Recording on Photochromic Thin Films," *Jpn. J. Appl. Phys*., vol. 35, 1996, pp. 1764-1767.

[8] M. Irie, H.I. Ishida, and T. Tsujioka, "Rewritable Near-Field Optical Recording on Photochromic Perinaphthothioindigo Thin Films: Readout by Fluorescence," *Jpn. J. Appl. Phys*., vol. 38, 1999, pp. 6114-6117.

[9] M. Irie, "Photochromism: Memories and Switches-Introduction," *Chem. Rev*., vol. 100, 2000, pp. 1685-1716.

[10] K. Lieberman, A. Lewis, G. Fish, S. Shalom, T.M. Jovin, A. Schaper, and S.R. Cohen, "Multifunctional, Micropipette Based Force Cantilevers for Scanned Probe Microscopy," *Appl. Phys. Lett*., vol. 65, 1994, pp. 648-650.

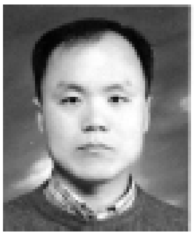
[11] K. Nakajima, H. Muramastu, N. Chiba, T. Ataka, and M. Fujihira, "Optical Processing by Scanning Near-Field Optical/Atomic Force Microscopy," *Thin Solid films*, vol. 273, 1996, pp. 327-330.

[12] J. Kim, K.B. Song, and K.H. Park, "Near-Field Optical Readout Combined with Atomic Force Probe Writing," to be published in *Jpn. J. Appl. Phys*., vol. 41, 2002, pp. 1903-1904.

[13] W. Fann, "Simple Transmission Mode Near-Field Optical Microscope," *Rev. Sci. Instum*. vol. 66, 1995, pp. 271-272.

[14] F. Issiki, K. Ito, K. Etoh, and S. Hosaka, "1.5-Mbit/s Direct Readout of Line-and-Space Patterns Using a Scanning Near-Field Optical Microscopy Probe Slider with Air-bearing Control," *Appl. Phys. Lett*., vol. 76, 2000, pp. 804-806.

[15] T. Iida and M. Katsumura, "Progress of High Density Mastering Using Electron Beam Recorder," *ISOM 2001 Technical digest*, 2001, pp. 66-67.



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