ELectronics EXpress

A digital-data-preservation system featuring LED-light computer tomography

Takao Watanabe[a], Toshimichi Shintani, Kazuo Ono, and Toshiyuki Mine

Central Research Laboratory, Hitachi, Ltd., Kokubunji, Tokyo 185–8601, Japan

a) *takao.watanabe.yh@hitachi.com*

Abstract: A fundamental study on a digital-data-preservation system featuring a LED-light computer tomography (CT) was successfully performed. With this system, $17 \times 17 \times 17$-bit test data (recorded by femtosecond laser in a 5-mm-thick, flat synthetic fused silica sample) is extracted from 27 projections at different angles. The results of annealing tests at 973 K (700°C) and 1173 K (900°C) imply that the system has the potential for achieving archival lifetime of over one-hundred-thousand years at room temperature. The storage density could be as large as 16.6 Mbytes/cm^3 if bit pitch is minimized to 10 μm.

Keywords: data preservation, computer tomography, femtosecond laser, synthetic fused silica

Classification: Storage technology

References

[1] M. Shefter and A. Maltz, "The Digital Dilemma," Second printing, *The Science and Technology Council of Academy of Motion Picture Arts and Sciences*, CA, Feb. 2008. [Online] http://www.oscars.org/sciencetechnology/council/projects/digitaldilemma/index.html

[2] Y. Yuxiang, N. Miura, S. Imai, H. Ochi, and T. Kuroda, "Digital Rosetta Stone: A Sealed Permanent Memory with Inductive-Coupling Power and Data Link," *2009 Symp. VLSI Circuits*, Kyoto, Japan, pp. 26–27, June 2009.

[3] K. M. Daivis, K. Miura, N. Sugimoto, and K. Hirao, "Writing waveguides in glass with a femtosecond laser," *Opt. Lett.*, vol. 21, no. 21, pp. 1729–1731, Nov. 1996.

[4] J. Qiu, K. Miura, and K. Hirao, "Three-Dimensional Optical Memory Using Glasses as a Recording Medium through a Multi-Photon Absorption Process," *Jpn. J. Appl. Phys.*, vol. 37, pp. 2263–2266, April 1998.

[5] A. C. Kak, "Reconstruction," *Digital Picture Processing*, Second Edition, ed. W. Rheinboldt, vol. 1, pp. 353–430, Academic Press Inc., Orlando, 1982.

[6] B. Kemper, S. Stürwald, C. Remmersmann, P. Langehanenberg, and G. V. Bally "Characterisation of light emitting diodes (LEDs) for application in digital holographic microscopy for inspection of micro and nanostructured surfaces," *Opt. Lasers Eng.*, vol. 46, no. 7, pp. 499–507, July 2008.

DOI: 10.1587/elex.6.1569
Received September 02, 2009
Accepted October 09, 2009
Published November 25, 2009

1 Introduction

In recent years, most data has been created in digital format. However, the lifetime of current digital storage is much shorter than that of ancient records (such as cuneiform characters written on a clay board)—which have already been preserved for 5,000 years. The limited lifetime of digital storage provides problems, such as data migration, for permanent preservation [1]. Even if the lifetime of data becomes longer as technology progresses (for example, [2]), reconstruction of driver hardware as well as precise control of ambient storage conditions will be major problems. An innovative digital-storage system for preserving historically important data resources is therefore indispensable. The system should provide data with an extremely long archival lifetime (namely, at least ten thousand years) with a thermally and chemically stable storage material and a simple, easily reconstructible driver.

In the present study, a promising candidate for such a digital-storage system was investigated. That is, LED-light computer tomography (CT) was developed and combined with microscopic modification in solid materials by femtosecond laser [3, 4].

2 LED-light computer tomography

Figure 1 (a) show the experimental system for LED-light CT, which can take a "parallel-projection image" of a sample at different angles. This system consists of a parallel-lighting unit, a sample holder, a post optical unit, and a 2 k × 2 k-pixel, 16-bit monochrome cooled CCD camera with a wide-band color filter. The parallel-lighting unit (which consists of a white LED-light, a pin hole, and a collimator lens) provides parallel light to the sample. The low-power visible light from the LED is useful for avoiding damage to the stored data. The angle between the parallel light beam and the sample can be changed by rotating the sample holder. It should be noted that no high-speed sample rotation is necessary (like a conventional optical driver); only setting it at different angles is necessary.

The post optical unit (which consists of two lenses and a pinhole forming a telecentric optical system) is placed between the sample and the cooled CCD camera. Image magnification, which was set to ×2.5, can be set by changing the ratio of the focal length of the two lenses. The 16-bit cooled CCD camera can take a two-dimensional projection of a sample at a resolution of 2048 × 2048 pixels, each with 65,536 gradations (16-bit depth). A 400–500-nm, wide-band-pass color filter attached in front of the CCD camera reduces chromatic aberration of the lens and sample.

Test data were recorded in 30 × 30 × 5-mm, non-doped synthetic fused silica as 17 × 17 × 17 bits in a 1.6-mm^3 volume at the center of the sample by microscopic refraction-index modification with a femtosecond laser by Namiki Precision Jewel Co., Ltd.. A 50-μm cubic volume with a pitch of 100 μm expresses a data bit as 1 if the refraction index is slightly modified or 0 if it is unmodified.

The parallel beam projections enable simple image processing for the de-

DOI: 10.1587/elex.6.1569
Received September 02, 2009
Accepted October 09, 2009
Published November 25, 2009

IEICE Electronics Express, Vol.6, No.22, 1569–1575

veloped CT compared with fan- or cone-beam projections for X-ray CT [5]. However, the use of visible light produces inherent problems. That is, diffused light in the recorded area significantly degrades the contrast of a projected image, and the refraction that occurs at the surface of the flat sample causes one-dimensional resizing in the x-axis direction of the projected images. This diffused-light problem is solved by placing a telecentric optical system between the sample and the cooled CCD camera.

The system removes light diffused by the recorded dots inside the sample so that a projection image is formed at the CCD camera only by parallel light. The one-dimensional resizing of the projected image is corrected after adjusting the shift of the projected image by using an alignment pattern recorded inside the sample. The image shift is mainly due to setting error of the center of the sample in relation to the axis of rotation in the sample holder. Figure 1 (b) schematically explains the one-dimensional resizing in the x-axis direction, where P_j and P_{ccd} are respectively the desired parallel-beam projection image and the projection image taken by the CCD camera. The one-dimensional resizing factor, m (i.e., (X-width of P_{ccd})/(X-width of P_j)), see Fig. 1 (b), can be corrected by image processing based on the following equation,

$$m = \cos\theta_a / \cos\theta_i \tag{1}$$

where θ_i and θ_a are rotational angle of the inside of the sample and that of the outside of the sample (in air). The relationship between angles θ_i and θ_a with refraction index, n, is expressed by Snell's law as

$$n = \sin\theta_a / \sin\theta_i \tag{2}$$

Once a set of corrected projection images is prepared, cross-sectional im-

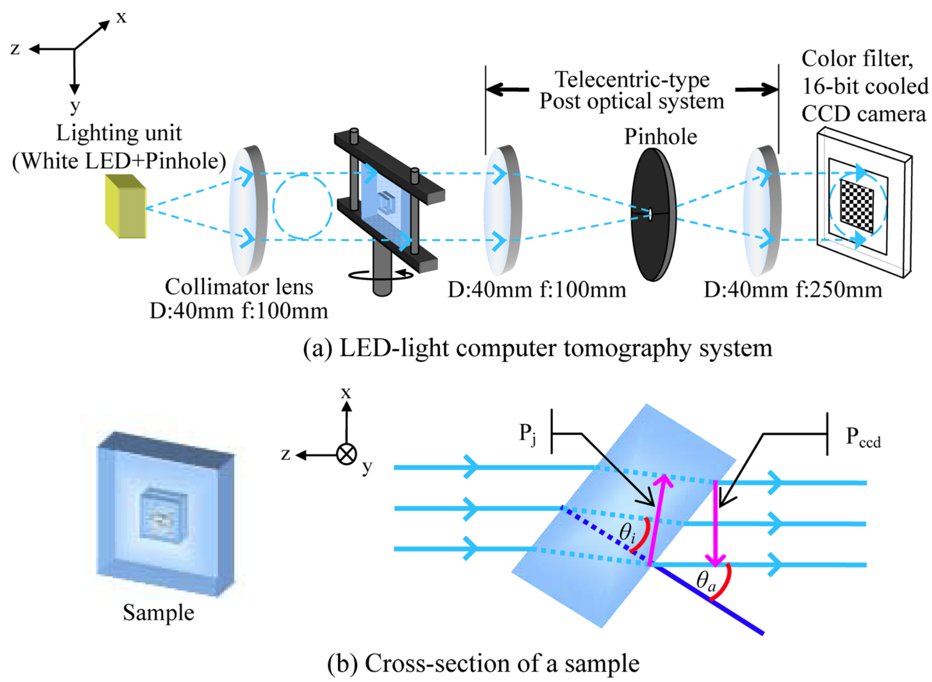

Fig. 1. Experimental equipment for LED-light CT

© IEICE 2009
DOI: 10.1587/elex.6.1569
Received September 02, 2009
Accepted October 09, 2009
Published November 25, 2009

IEICE Electronics Express, Vol.6, No.22, 1569–1575

ages of any layer (on the x-z plane) at different y-axis values can be reconstructed simply by applying a logarithmic transformation and an inverse Radon transformation (filtered back projection).

Figure 2 shows examples of reconstructed cross-sectional images on two different layers calculated from 27 projection images of a $17 \times 17 \times 17$-bit synthetic-fused-silica sample. Angle θ_a is set according to Eq. (2) so that internal angle θ_i is changed from -39 to $+39$ degrees in steps of three degrees. The projection images (P_{ccd}), the writing patterns, and the images reconstructed by the proposed CT are shown in the figure.

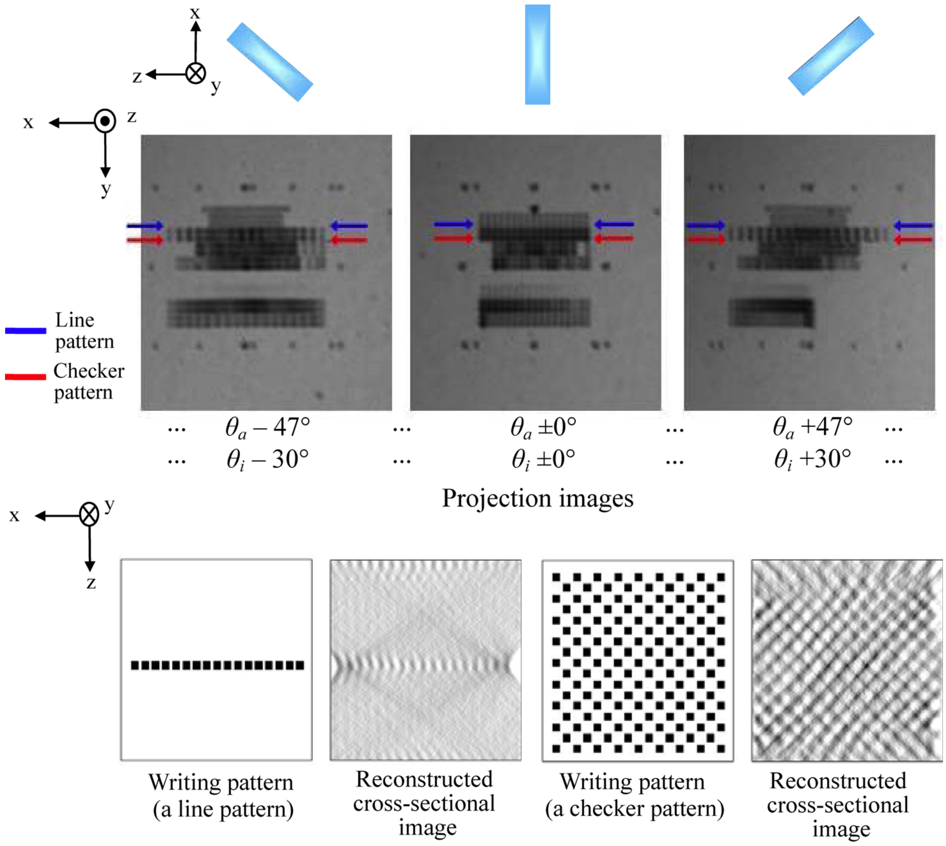

Fig. 2. Examples of writing patterns and their reconstructed images

3 Potential of lifetime and storage density

The archival lifetime of data stored by the developed system was examined by estimating the time, τ, when bit contrast on the projection image (at $\theta_a = 0$) is degraded by 1 dB. (Although there may be a room for discussion on the definition of the lifetime, the above definition is used in this paper.) It should be noted that the measured signal of bit contrast versus noise is 30.3 dB. Under the assumption that the Arrhenius equation holds, τ is expressed as

$$\tau = A \exp\left(E_a/kT\right) \tag{3}$$

DOI: 10.1587/elex.6.1569
Received September 02, 2009
Accepted October 09, 2009
Published November 25, 2009

where A, E_a, k, and T are an arbitary constant, activation energy, Boltzmann's constant, and absolute temperature, respectively. From Eq. (3), activation energy and archival lifetime at a given temperature can be expressed in terms of archival lifetimes τ_1 and τ_2 at temperatures T_1 and T_2 as

$$E_a = \left\{ k \frac{\ln(\tau_1/\tau_2)}{1/T_1 - 1/T_2} \right\} \tag{4}$$

and

$$\tau = \tau_1 \exp\left\{ \left(\frac{E_a}{k} \right) \left(\frac{1}{T} - \frac{1}{T_1} \right) \right\} \tag{5}$$

Archival lifetime at room temperature is derived from Eqs. (4) and (5) with parameters obtained from annealing experiments on a sample at 973 K (700°C) and 1173 K (900°C).

As shown by the Arrhenius plot in Fig. 3, archival lifetime at 300 K (27°C) is obtained from τ_1, 0.74 hours, at T_1, 973 K (700°C), and τ_2, 0.15 hours, at T_2, 1173 K (900°C), as 9.75×10^8 hours (111,000 years). If 3-dB degradation is allowed, the lifetime becomes as long as 2.79×10^{12} hours (319-million years), where τ_1, 3.53 hour, at T_1, 973 K (700°C), and τ_2, 0.44 hour, at T_2, 1173 K (900°C).

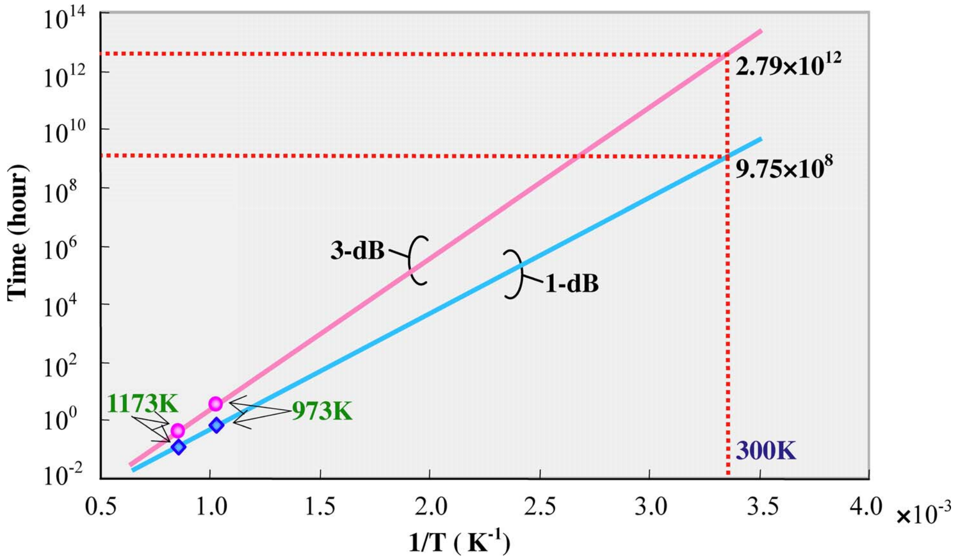

Fig. 3. Arrhenius plot for 1-dB and 3-dB degradation of bit contrast of projection image

The potential of storage density was examined next. The size of a bit recorded by focused femtosecond laser could be smaller, namely, 400 nm [4], so adjacent bit pitch can be minimized to 800 nm if the mechanical stage allows such precision. The use of bit space smaller than the coherent length of LED light, however, will deteriorate projection images by interference of the scattered light at the adjacent bits. The bit pitch (bit size + bit space) will be restricted around 10 μm since the coherent length of LED light is in the range of a few micrometers [6]. Numbers of layers enabled by the CT compensates above restriction.

DOI: 10.1587/elex.6.1569
Received September 02, 2009
Accepted October 09, 2009
Published November 25, 2009

The maximum number of layers can be estimated as follows. The contrast of a projected image of bits, $C(n)$, is expressed as $I(1-t^n)$, where I, t, and n are the signal intensity of a pixel when the LED light goes through the storage material directly, the attenuation rate with a single modified area (bit '1'), and the number of '1' bits along the z-axis. Contrast, $C(n)$, increases as n increases, while the difference in the contrast, $\Delta(n)$, which is expressed as $C(n) - C(n-1)$, decreases. The minimum value of the difference of the contrast, $\Delta_{\min}$, is

$$\begin{aligned} \Delta_{\min} &= \Delta\left(n\_\max\right) \\ &= C\left(n\_\max\right) - \left(n\_\max - 1\right) \\ &= I\left(t^{(n\_\max-1)} - t^{n\_\max}\right) \end{aligned} \tag{6}$$

where $n\_\max$ (the value of n when all the bits are '1') equals the number of layers. While the value of the noise of the contrast, $N(n\_\max)$, is

$$\begin{aligned} N\left(n\_\max\right) &= C\left(n\_\max\right)/r \\ &= I\left(1 - t^{n\_\max}\right)/r \end{aligned} \tag{7}$$

where r is the signal-to-noise ratio of the total system. From Eqs. (6) and (7), $n\_\max$, which satisfies $\Delta_{\min} > N(n\_\max)$, is derived as

$$n\_\max < \frac{-\ln(r/t - r + 1)}{\ln(t)} \tag{8}$$

In Eq. (8), $n\_\max$ approaches its upper limit, r, as t approaches one. According to measurement, t can be approximately expressed as $e^{-0.008d}$, where d (μm) is the thickness of a '1' bit. Therefore, as far as r is constant, thinner d gives larger $n\_\max$. For example, a number of layers of 26 is derived from Eq. (8) under the assumption of d of $1\,\mu$m ($t = 0.99$) and r of 29.2, which corresponds to 29.3 dB ($= 20 \log 29.2$), which is 1 dB (aging degradation) lower than the signal-to-noise ratio of the experimental system. Note that d of $1\,\mu$m and t of 0.99 are both acceptable for laser modification [4] and detection of single-bit contrast by using a 16-bit, cooled CCD camera.

The resultant storage density is 16.6 Mbyte/cm^3, when 26 layers of 1024×1024 bits are stored with a 10-μm pitch inside a $14 \times 14 \times 1$-mm media. The storage density is not the first priority, but increase of the signal to noise ratio, r, of the CT system is one of our future challenges.

4 Summary

A fundamental experiment on LED-light computer tomography—which enables extraction of three-dimensional data recorded by femtosecond laser deep inside flat-shaped samples—was successfully performed. The potential of this technology for practical and permanent archival lifetime and a simple optical driver strongly imply that it is a promising candidate for permanent digital preservation of important human data resources such as works of art and public archives.

DOI: 10.1587/elex.6.1569
Received September 02, 2009
Accepted October 09, 2009
Published November 25, 2009

IEICE Electronics Express, Vol.6, No.22, 1569–1575

Acknowledgments

The authors wish to express their thanks for the tutorials on current issues regarding digital data preservation by former Deputy Librarian of the National Diet Library A. Yasue and Prof. Em. of Tokyo University of Agr. & Techn. R. Oye and on Archive technology using current optical disks by Prof. Em. of Teikyo Heisei University K. Tanaka. They also wish to express their thanks to T. Odaka and K. Harusawa for their helpful support.

DOI: 10.1587/elex.6.1569
Received September 02, 2009
Accepted October 09, 2009
Published November 25, 2009