Bull. Soc. Photogr. Imag. Japan. (2016) Vol. 26 No. 1: 10–13

Original Paper

Digital Silica Photography with Future Readability and Fire Resistance

Takao Watanabe, Ryo Imai, Shigeki Mori, Toshiyuki Mine, Toshimichi Shintani, and Koichi Watanabe

Abstract: We proposed a concept of 'digital silica photography' for long-term preservation. It stores digital photographic data with decode-free analog images inside a fused-silica plate using a femtosecond pulse laser. The digital data are written so as to be able to read out using a normal camera in order to guarantee future readability. The decode-free analog images will explain digital contents and reading method in the distant future. As a feasibility demonstration, photographic data of Ukiyo-e (Japanese woodblock prints) were recorded at 290 μm under the surface of a fused-silica plate with a density of 1,693 dpi. The decode-free analog image was made by a 1-bit error-diffusion dithering method. The digital data were successfully read out from a single-shot picture taken by a 24-M pixel camera with a macro lens. We also showed the potential of fire resistance through an annealing test at 1,000°C.

Key words: Fused silica, Digital photography, Preservation, Future readability, Fire resistance

1. Introduction

In recent years, almost all photographic data are born-digital and inherently preserved in digital-storage media. Migration of photographic data from traditional media to digital ones is also underway. Digital photography has an advantage that cannot be provided by traditional analog formats. For example, it enables worldwide concurrent access via internet. However, curators and archivists feel anxiety about the digital photography due to following three concerns in long-term preservation. The first concern is about archival lifetime of digital media. Traditional photographic films with a base of polyester having silver-gelatin are expected to have a lifetime over 500 years when they are processed appropriately and preserved at low temperature and humidity[1]. Data retention of digital media has been improved, but they seem not to have exceeded that of photographic films. For example, recent magnetic tapes whose thermal stability has been improved [2] are expected to have retention time of over 30 years [3], and optical discs(type 'R') can retain data for 100-200 years [4]. The second concern is about data migration. Execution of data migration in short period of time is fairly costly [5] and increases the risk of data loss. Even if digital media have a long lifetime, another risk in data migration still exists. For example, if reading equipment is not be reconstructed in the future then data migration cannot be performed. The third concern is lack of durability against change of storage condition. For the long period of preservation, it is difficult to preserve storage media under precise control of temperature and humidity. In addition, storage media probably suffer from conflagration in the long period of time. All the existing recording media as well as newly proposed 'bit on film' [6)7] have no resistance against fire.

Recording digital data inside fused silica utilizing non-linear effects induced by a femtosecond laser [8-17] is one of the promising solutions to solve concerns described above. Fused silica is expected to have long lifetime without precise control of archiving environment since it is chemically stable. In addition, it has high resistance against fire since its softening temperature is approximately 1,700°C and coefficient of thermal expansion is as small as 5.8×10^{-7} /K [18]. In this work, we proposed digital silica photography that records photographic data both with future readability and fire resistance. Table 1 shows comparison of this work with our previous work [17]. In

Table 1. Comparison of this work with our previous work.

	Our previous work	This work
Feature	High density	Simple reading system
Test data	Text data	Photographic data
Medium	Fused silica	Fused silica
Pitch of dots	2.3 μm (11,043 dpi)	15 μm (1,693 dpi)
Number of recording layers	100	1
Reading system	Microscope with transmitted illumination	Macro lens with reflected illumination
Laser used for writing	Femtosecond laser with regenerative amplifier	Femtosecond laser without regenerative amplifier

Received: 18th, February 2016; Accepted: 7th, June 2016

Center for Technology Innovation - Electronics, Research & Development Group, Hitachi, Ltd.
Kokubunji, Tokyo 185-8601, Japan
e-mail: takao.watanabe.yh@hitachi.com

our previous work, we used text data and succeeded making the one-hundred recording layer sample with a dot pitch of 2.3 μm. In order to achieve the high density we used a microscope for reading and a high energy femtosecond laser for recording. In this work, we used single layer and a dot pitch of 15 μm to simplify the reading system. We verified that the photographic data can be read out using a commercially available macro lens.

2. Setup of systems and making of digital data for writing

Figure 1 shows the concept of proposed 'digital silica photography'. A decode-free analog image is recorded with digital photographic data in fused silica. The decode-free analog image is made by a 1-bit error-diffusion dithering method * in order to show the contents of digital photography. Other information such as how to decode the digital data can be recorded in the same way by using illustrations and fonts. In this feasibility demonstration, we recorded decode-free analog images and full-color digital data in different fused-silica plates, but both data can be recorded inside the same fused-silica plate as shown in the figure.

Figure 2 shows schematic diagram of our writing system to generate dots inside a fused silica plate. Writing was performed by a femtosecond laser whose center wavelength, pulse width, and repetition rate of the output beam were 780 nm, 190 fs, and 76 MHz, respectively. The objective lens with the numerical aperture of 0.85 tightly focuses the laser beam inside a fused-silica plate. As a result, nonlinear absorption creates a micro void-like structure inside a fused-silica plate. The micro void-like structure is used for both a decode-free analog image and digital data. For digital data, the micro void-like structure corresponds to bit one. And the area without a micro void-like structure corresponds to bit zero.

Figure 3 is the reading system for digital data. The 24-Mpixel camera with a 60-mm macro lens was used to take a picture of the recording area where a binary-bitmap pattern of multi-blocks of two-dimensional barcode was recorded. The LED lamp was used for reflected illumination. The picture taken by the camera was transferred to a notebook PC for decoding.

Figure 4 explains the sequence of making data for recording a full-color photograph with description sentences. In the first step, a binary file of a full-color image was transformed into characters expressing hexadecimal numbers (00 to FF). In the second step, the long character line was divided into set of shorter character lines and header characters are attached for each divided line. The header characters were used to connect the divided character lines and also

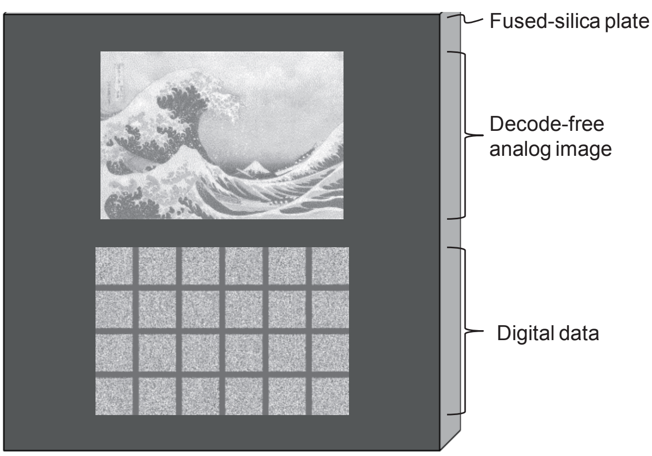


Fig. 1. Concept of digital silica photography.

*1-bit error-diffusion dithering method: An image processing method that converts a n-bit grayscale image into a 1 bit(black and white)image so that the density of black dots in the converted image approximates the original gray level.

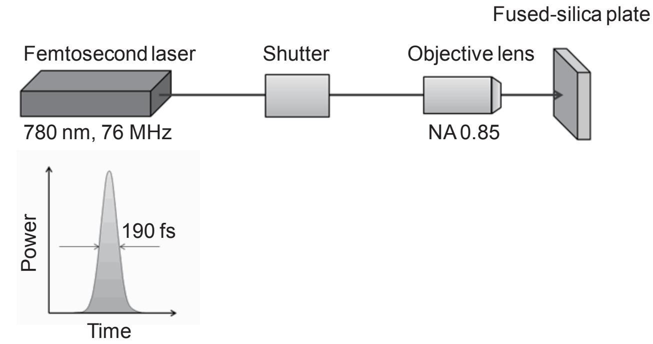


Fig. 2. Schematic diagram of the writing system.

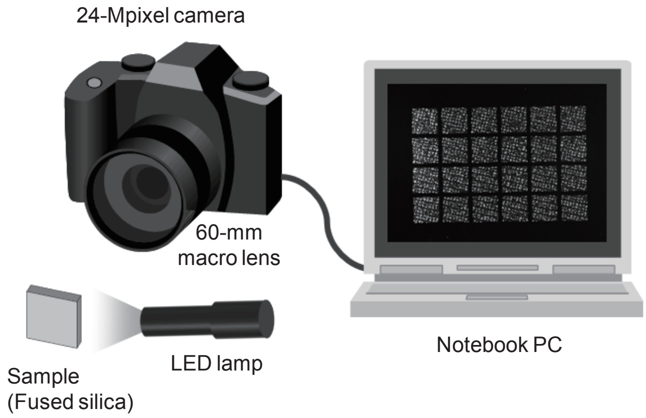


Fig. 3. Reading system for digital data.

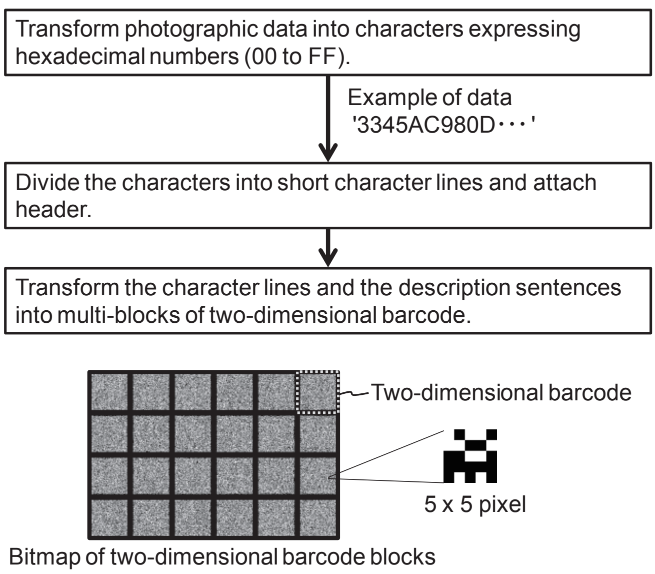


Fig. 4. Sequence of making data for writing.

to reconstruct the full-color image. In the final step, the set of character lines and the description sentences were transformed into multi-blocks of two-dimensional barcode. Then, the blocks were arranged into a rectangular area to make a bitmap image for recording. In this experiment, we used QR Code that is the one of the most popular two-dimensional barcode (QR Code is registered trademark of DENSO WAVE INCORPORATED).

3. Experiments for feasibility demonstration

Table 2 summarizes specification of samples used in experiments. The size of a sample was 20 × 20 × 2 mm. An area of 12 × 8 mm that was located 290 μm under the surface was used for recording. Recording pitch of dots (the micro void-like structures) was set to be 15 μm for the use of a macro lens in the reading procedure. The resultant recording density was 1,693 dpi.

A microscopic image of recorded dots is shown in Fig. 5. Total reflection at the surface of the micro void-like structure may contribute the bright area of each dot. Diameter of the bright area in a dot is about 1.4 μm. At the beginning of reading experiments, we determined the best F number of the macro lens for decoding digital data. Figure 6 shows the relationship between the F number and bit-error rate (bER). Smaller F number provides higher resolution since smaller F number provides larger numerical aperture. On the other hand, large F number provides higher periphery quality. The tradeoff determines the best F number. The figure shows the F number of 8 was the best value for our experiments.

Figure 7 shows decode results of full-color images and their description sentences. An optical magnification of ×1.6 was used for taking a picture of a sample. For each sample, 23 blocks and one block of two-dimensional barcode were used for encoding the photographic image and the sentences. All data were successfully decoded. The bERs of the sample 1, 2, and 3 were 0.04%, 0.05%, and 0.18% which were calculated using all data in the recording area. The bit errors were corrected by ECC (Error-Correcting Code) in decoding procedure of the two-dimensional barcode. The recording time was 7,458 seconds (about 2 hours) for the sample 2. The value was restricted not by the time for making a dot, but by the scanning speed of the XY stage, which was not optimized in this experiment. In order to check whether or not recorded data have fire resistance, we annealed the sample 1 at 1,000°C for 2 hours in an annealing oven with air of one atmosphere. The photographic data and the description sentences were read out correctly. The bER calculated using all of the data in the recording area showed no degradation after the annealing.

Figure 8 shows the result of a decode-free analog image. Black-

Table 2. Specification of samples used in experiments.

Material	Synthetic fused silica
Size	20 × 20 × 2 mm
Recording area	12 × 8 mm
Depth of recording area	290 μm
Pitch of dots	15 μm
Recording density	1,693 dpi

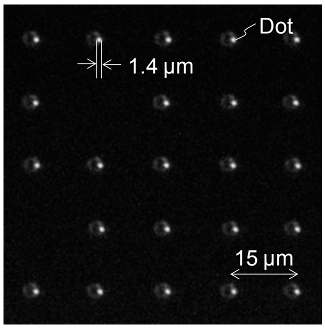


Fig. 5. A microscopic image of recorded dots.

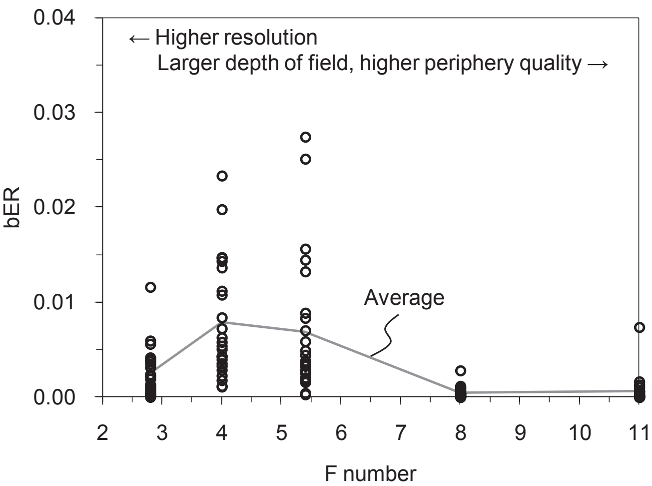
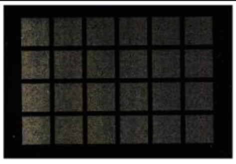
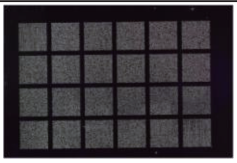
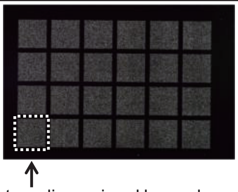


Fig. 6. Relationship between the F number and bit-error rate (bER)

and-white image for recording was made by the 1-bit error-diffusion dithering method from an 8-bit, monochrome-photographic image. The size of recording area was about 12 × 8 mm, and other recording conditions were also set to be the same as the ones used for digital-data recording. Gradation of the original image was expressed by the error-diffusion dithering method as shown in Fig. 8 (a) without using gray-level pixels. The image shown in Fig. 8 (a) was correctly recorded as shown in Fig. 8 (b), though vertical stripes due to uneven size of dots were observed in the background.

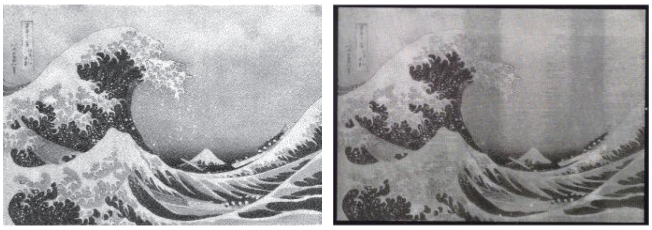
4. Conclusion

We propose digital silica photography that records photographic data with sentences in digital format inside a fused-silica plate using a femtosecond laser. It can also record decode-free analog image that will be indispensable to know the contents and method for decoding in distant future. As a feasibility demonstration, decode-free analog image and full-color digital data of Ukiyo-e were written inside a fused-silica plates. The digital data were read out using a commercially available camera with a macro lens just like making a photographic copy of a 35-mm slide. The simple reading procedure of digital data enables reconstruction of reading tools in the future. We confirmed the recorded data were read out after 1,000°C annealing without degradation. It implies that the data have fire resistance and stability for change of storage condition.

Sample number	Camera image of a sample	Read out image *1	Read out sentences	bER *2
1		 330 x 232 pixel	This is an ukiyo-e (Japanese woodblock print) titled “Kanagawa-Oki Nami-Ura” by Katsushika Hokusai, a collection of the Hiraki Ukiyo-e Foundation. …	0.04%
2		 340 x 224 pixel	This is an ukiyo-e (Japanese woodblock print) titled “Yui: Satta Peak, from the series of Fifty-three Stations of the Tokaido Road” by Utagawa Hiroshige, a collection of the Hiraki Ukiyo-e …	0.05%
3	 two-dimensional barcode	 235 x 350 pixel	This is an ukiyo-e (Japanese woodblock print) titled "Suruga Province: Miho Pine Grove, from the series of Famous Places in the Sixty-odd Provinces" by Utagawa Hiroshige, a collection of the Hiraki Ukiyo-e Foundation. …	0.18%

*1 The use of image data is allowed by the Hiraki Ukiyo-e Foundation.
*2 Error bits are corrected in decoding procedure.

Fig. 7. Decode results of full-color images and their description sentences.



(a) Bitmap data used for recoding (b) Picture of the image recorded inside fused silica

Fig. 8. The result of decode-free analog image.

Acknowledgements

The authors wish to express their thanks to Hiraki Ukiyo-e Foundation for the use of the data of Ukiyo-e collections. They also wish to express the thanks to T. Azuma, T. Morioka, and Dr. J. Tanaka of Hitachi, Ltd. for their helpful support, and to Prof. K. Miura, Associate Prof. Y. Shimotsuma of Kyoto University for the tutorials on their related works [10)12)].

References

1) ISO 18901.
2) M. L. Watson, R. A. Beard, S. M. Keintz, and T. W. Feebeck, “Investigation of Thermal Demagnetization Effects in Data Recorded on Advanced Barium Ferrite Recording Media”, IEEE Trans. Magn., **44**(**11**), 3568-3571 (2008).
3) http://www.fujifilm.com/news/n100910.html
4) Fred R. Byers, “Care and Handling of CDs and DVDs: A Guide for Librarians and Archivists”, Report 121, Council on Library and Information Resources, Washington, DC, 2003, Chapter 4.
5) M. Shefter and A. Maltz, “The Digital Dilemma”, Second printing, The Science and Technology Council of Academy of Motion Picture Arts and Sciences, CA (2008).
6) P. Fornaro and R. Gschwind, “Monolith - migrationless long term digital storage: A method to overcome technological obsolescence in audio visual archives”, Proc. JTS2010., Oslo, Norway (2010).
7) A. Seino, “Long-term Preservation of Digital Data Utilizing Film”, J. Soc. Photogr. Sci. Tech. Jpn., **75**(**1**), 22-27 (2012)[in Japanese].
8) E. N. Glezer, M. Milosavljevic, L. Huang, R. J. Finlay, T.-H. Her, J. P. Callan, and E. Mazur, “Three-dimensional optical storage inside transparent materials”, Opt. Lett., **21**(**24**), 2023-2025 (1996).
9) M. Watanabe, H. Sun, S. Juodkazis, T. Takahashi, S. Matsuo, Y. Suzuki, J. Nishii, and H. Misawa, “Three-dimensional optical data storage in vitreous silica”, Jpn. J. Appl. Phys. 2, Lett., **37**(**12B**), L1527-L1530 (1998).
10) Y. Shimotsuma, P. G. Kazansky, J. Qiu, and K. Hirao, “Self-organized nanogratings in glass irradiated by ultrashort light pulses”, Phys. Rev. Lett., **91**(**24**), 247405 (2003).
11) T. Watanabe, T. Shintani, K. Ono, and T. Mine, “A digital-data-preservation system featuring LED-light computer tomography”, IEICE Electron. Express, **6**(**22**), 1569-1575 (2009).
12) Y. Shimotsuma, M. Sakakura, P. G. Kazansky, M. Beresna, J. Qiu, K. Miura, and K. Hirao, “Ultrafast manipulation of self-assembled form birefringence in glass”, Adv. Mater., **22**, 4039-4043 (2010).
13) M. Shiozawa, T. Watanabe, E. Tatsu, M. Umeda, T. Mine, Y. Shimotsuma, M. Sakakura, M. Nakabayashi, K. Miura, and K. Watanabe, “Simultaneous multi-bit recording in fused silica for permanent storage”, Jpn. J. Appl. Phys., **52**, 09LA01 (2013).
14) T. Watanabe, M. Shiozawa, E. Tatsu, S. Kimura, M. Umeda, T. Mine, Y. Shimotsuma, M. Sakakura, M. Nakabayashi, K. Miura, and K. Watanabe, “A driveless read system for permanently recorded data in fused silica”, Jpn. J. Appl. Phys., **52**, 09LA02 (2013).
15) M. Shiozawa, T. Watanabe, E. Tatsu, M. Umeda, T. Mine, Y. Shimotsuma, M. Sakakura, M. Nakabayashi, K. Miura, and K. Watanabe, “Simultaneous multi-bit recording and driveless reading for permanent storage in fused silica”, J. Laser Micro/ Nanoengineering, **9**(**1**), 1-4 (2014).
16) J. Zhang, M. Gecevicius, M. Beresna, and P. G. Kazansky, “Seemingly unlimited lifetime data storage in nanostructured glass”, Phys. Rev. Lett., **112**, 033901 (2014).
17) R. Imai, M. Shiozawa, T. Shintani, T. Watanabe, S. Mori, Y. Shimotsuma, M. Sakakura, K. Miura and K. Watanabe, “100-Layer recording in fused silica for semi permanent data storage”, Jpn. J. Appl. Phys., **54**, 09MC02 (2015).
18) http://www.tqgj.co.jp/english/silicaglass/mechanical.html