*Progress In Electromagnetics Research Letters, Vol. 2, 115–123, 2008*

# HOLOGRAPHIC FEMTOSECOND LASER PROCESSING AND THREE-DIMENSIONAL RECORDING IN BIOLOGICAL TISSUES

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**Abstract**—Data recording on biological tissues and prostheses with femtosecond laser processing for personal identification is demonstrated. The target materials are human fingernails (fingernail memory) and dental prostheses (dental memory). Because they have unexpected movements and individual three-dimensional shapes, the processing system is required an adaptive focusing and high-throughput recording capability. The adaptive focusing is performed with a target surface detection. The high throughput is realized by parallel laser processing based on a computer-generated hologram displayed on a spatial light modulator. Two-dimensional and three-dimensional parallel laser processing of glass is demonstrated.

## 1. INTRODUCTION

Femotsecond lasers are powerful tools for micro- and nano-structuring of transparent materials because they can process with high spatial resolution resulting from multiple photon absorption, and reduced thermal damage due to the ultra-short interaction time between the laser pulse and the material, as well as various physical phenomena caused by the ultra-high intensity of the laser pulse. The high three-dimensional (3-D) spatial resolution requires a precise control of the focus position. Femtosecond laser processing with an axial focus position control is commercially available at present. To realize data recording on biological tissues and prostheses for personal identification [1–4], a femtosecond laser processing system with a lateral focus position control in addition with the axial focus position control is developed [5] because the biological tissues and the prostheses

have unexpected movements and individual three-dimensional shapes. Another approach of processing of biological tissue is to develop femtosecond laser processing system with a high-throughput. The high-throughput is realized by parallel laser processing based on a computer-generated hologram (CGH) displayed on a liquid crystal spatial light modulator (LCSLM). This is called as holographic femtosecond laser processing [6–10]. The use of a LCSLM enables to perform an arbitrary and variable patterning.

In this paper, we demonstrate the data recordings in fingernail (fingernail memory) and dental prostheses (dental memory). We also demonstrate two-dimensional and three-dimensional parallel laser processing of glass using the holographic femtosecond laser processing.

## 2. FINGERNAIL MEMORY

Our goal is to realize optical memory in a human fingernail for highly secure data transportation that does not suffer from problems such as theft, forgery, or loss of recording media. In this section, we demonstrate to record a 3-D arranged bit data inside fingernail by a femtosecond laser pulse and demonstrate the fluorescence readout.

An optical system for recording is composed of an amplified femtosecond laser system and an optical microscope. The femtosecond laser system is composed of a mode-locked Ti : sapphire laser (Spectra Physics, Tsunami) pumped by a diode-pumped solid-state cw green laser (Spectra Physics, Millenia), and a multikilohertz pulsed Ti : sapphire regenerative amplifier (Spectra Physics, Spitfire) pumped by a diode-pumped, Q-switched Nd : YLF laser (Spectra Physics, Merlin). The femtosecond laser system generates pulses with a central wavelength of 800 nm and a pulse width of ∼150 fs. The optical microscope system having a 40× objective lens (OL) (numerical aperture (NA) = 0.55) has a computer-controlled three-axis motorized stage. The read out of the bit data is performed with an ordinary fluorescence microscope.

Figure 1 shows transmission-illumination microscope observations of three bit layers recorded inside a human fingernail. These bit arrays were recorded with $E_p = 0.49\,\mu$J at the depths of (a) $Z = 40\,\mu$m, (b) $60\,\mu$m, and (c) $80\,\mu$m. The bit spacing was $5\,\mu$m in the transverse direction and $20\,\mu$m in the axial direction, the corresponding recording density was $2\,\mathrm{Gbit/cm^3}$.

In investigating a suitable readout method of the recorded bit data inside a human fingernail, we discovered increased fluorescence at the structural changes formed in the fingernail compared with the auto-fluorescence of the fingernail [3]. Figure 2 shows the fluorescence

readout observed with a fluorescence microscope. Each bit layer was read out without crosstalk. The increased fluorescent effect had been continued over 180 days, which is the time a fingernail is replaced by growing in about 6 months.

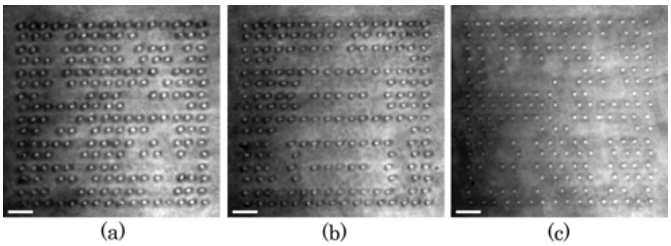


**Figure 1.** Three bit planes at (a) $Z = 40\,\mu$m, (b) $60\,\mu$m, and (c) $80\,\mu$m. The scale bar indicates $10\,\mu$m.

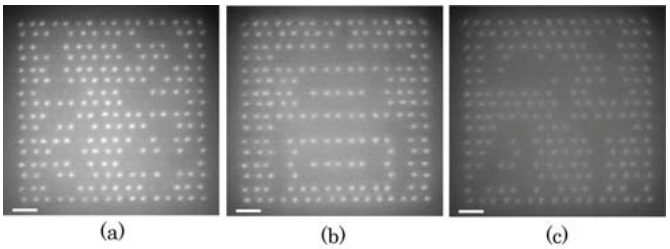


**Figure 2.** Fluorescence images of three bit planes at (a) $Z = 40\,\mu$m, (b) $60\,\mu$m, and (c) $80\,\mu$m.

## 3. DENTAL MEMORY

In mass natural disasters such as earthquakes and tsunamis, personal identification of victims is an important problem. Forensic dentistry and fingerprints have been used for personal identification. These methods, however, require a lot of time and are expensive when identifying a large number of victims, because they involve comparing personal information about the victim with pre-registered information. If information for identifying the victim could be obtained from the victim himself, the time and cost involved could be substantially reduced.

As a method for realizing this scheme, we proposed to record personal information on a dental prosthesis. Dental prostheses are

good information storage media because it is resistant to thermal and putrefactive changes. The method has some advantages, including ease of data access, low risk of theft of the recorded information, and high data storage capacity. Furthermore, combining the method with forensic dentistry could improve the accuracy of personal identification, as well as reducing the time required.

Figure 3 shows the experimental setup composed of an amplified femtosecond laser and a confocal surface detection system. The processing was performed by single pulse irradiation. The confocal optical system consisting of a laser diode ($\lambda = 650\,\mathrm{nm}$), a $20\times$ OL (NA = 0.40), a pinhole, and a photodetector was used to control the focus position of the femtosecond laser pulses. Samples are made of a Au-Ag-Pd dental alloy (Castwel MC®, GC, Tokyo, Japan). The processed structures were observed with a scanning electron microscope (SEM; S-4700, Hitachi).

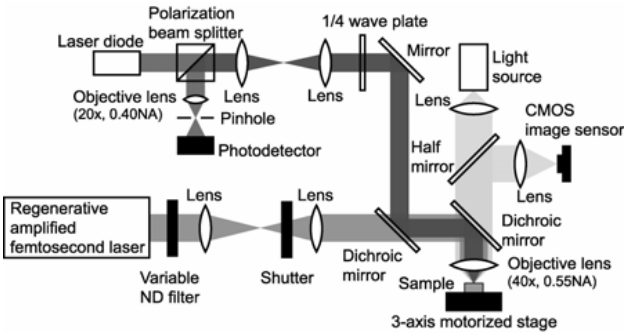


**Figure 3.** Experimental setup.

Figure 4 shows the SEM images of two-dimensional data recorded on the alloy plate surface without and with surface detection. Femtosecond laser pulses with an energy of $0.06\,\mu\mathrm{J}$ were irradiated at 2 Hz. Around the upper left area where the processing was started with manual correction of the focus position, the structures were ablated depressions surrounded with melted and scattered debris. Around the lower right area where the processing ended, the surface morphologies processed without and with the surface detection were quite different. When the surface detection was used, the morphologies of the processed areas were the same ablated structures over a wide area and a wide axial range. The spacing between the recording points was $2.0\,\mu\mathrm{m}$, resulting in a recording density of $250\,\mathrm{kbit/mm^2}$.

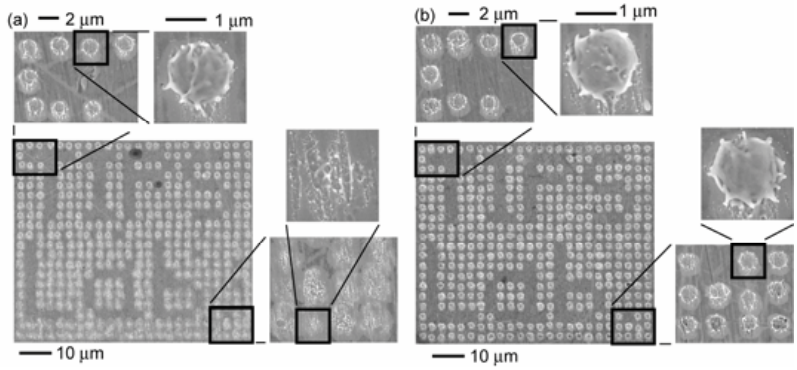


**Figure 4.** SEM images of the recording data on sample surface (a) without and (b) with the surface detection.

## 4. HOLOGRAPHIC FEMTOSECOND LASER PROCESSING

Holographic femtosecond laser processing is classified three types according to a positional relationship between a hologram and a target. (1) When the target is put on the image plane of the hologram, the irradiation beam is divided to multiple-beams by a diffractive beam splitter, which is a kind of holograms. The diffractive beams form the interference pattern on the target through a 4f-imaging optical system. An advantage of this method is suitable for processing of a periodic structure to a large area. (2) When the target is put on the Fourier plane of the hologram, the Fourier transform hologram is used [6, 9, 10]. The hologram with a high quality is designed with a low computational cost by optimization techniques. The reconstructed diffraction has little dependence on an undesired beam intensity distribution. (3) When the target is put on the Fresnel plane of the hologram [7, 8], the Fresnel transform hologram is used. Because the femtosecond laser processing is based on the multiphoton process, the 0th-order beam doesn't contribute to the processing. The Fresnel transform hologram enable us to perform a three-dimensional processing without any mechanical movements.

Figure 5 shows the experimental setup of the holographic femtosecond laser processing system using a Fourier hologram. The system mainly consisted of an amplified femtosecond laser system and an LCSLM (Hamamatsu Photonics, PPM). The collimated laser pulse was diffracted by the CGH displayed on the LCSLM to form a processing pattern at the plane P. The 0-th order light was obstructed

at plane P. The processing pattern was reduced with Lens 4 and a $60 \times$ OL (NA $= 0.85$) and was applied to a sample. The processing was performed with single-pulse irradiation. A halogen lamp (HL) and a charge-coupled device (CCD) image sensor were used to observe the processing. The sample was an ordinary glass microscope cover slip (Matsunami), subjected to ultrasonic cleaning in ethanol and pure water.

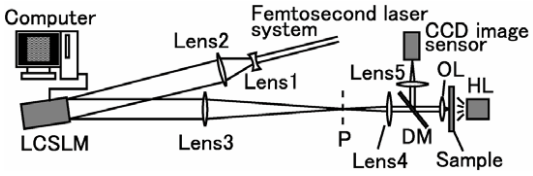


**Figure 5.** Experimental setup.

Figure 6 shows the results of 3-D processing using three CGHs without an axial translation of the sample. The processing for each CGH performed with single-pulse irradiation. Figure 6(a) shows the CGHs designed to generate 12, 12, and 8 diffraction peaks, and having focal lengths of 1800, 2000, and 2400 mm, respectively. Figure 6(b) shows the optical reconstructions of the CGHs. The respective uniformities $U$ were 92%, 93%, and 83%, and the diffraction efficiencies $\eta$ were 73%, 71%, and 68%. The uniformity is defined as $U = I_{\min}/I_{\max}$, where $I_{\min}$ and $I_{\max}$ are the minimum and maximum peak intensities, respectively. In the transmitted optical microscope observation of the fabricated area, when the axial positions were 9, 17, and 30 $\mu$m inside the glass from the sample surface was focused, the structures were observed as the dark spots, as shown in Figure 6(c). The irradiation energies were 7.3, 7.0, and 6.9 $\mu$J, respectively.

Figure 7 shows the results of 3-D processing with a single pulse. Figure 7(a) shows CGH designed to generate 32 diffraction peaks, and having focal lengths of 1800, 2000, and 2400 mm, respectively. Figure 7(b) shows the optical reconstructions of the CGH. The respective uniformities $U$ were 89%, 88%, and 83%. The total diffraction efficiency $\eta$ was 68%.The upper three images in Figure 7(c) show the transmitted optical microscope observation of the fabrication area, when the axial positions were 7, 18, and 29 $\mu$m was focused, the structures were observed as the dark spots. The irradiation energy was 18 $\mu$J.

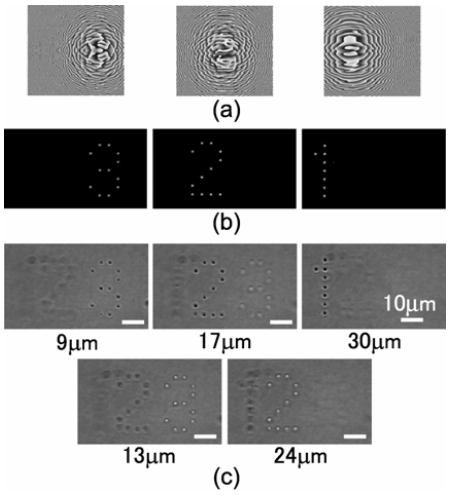


**Figure 6.** (a) Three CGHs having focal lengths of 1800, 2000, and 2400 mm, (b) optical reconstructions of the CGHs, (c) and microscope images of 3-D fabrications.

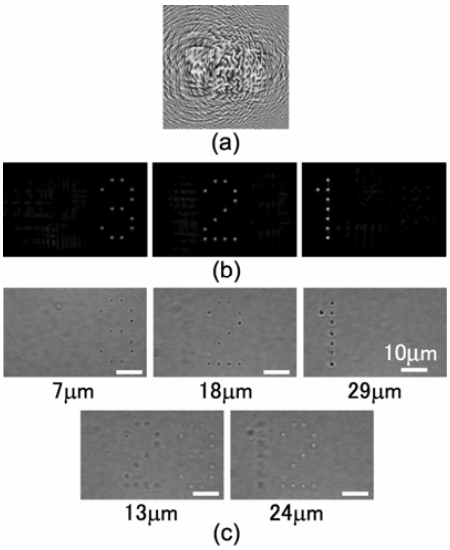


**Figure 7.** (a) A CGH having focal lengths of 1800, 2000, and 2400 mm, (b) optical reconstructions of the CGH, and (c) microscope images of 3-D fabrication.

## 5. CONCLUSIONS

We have demonstrated the fingernail memory. The data recording is implemented with a focused femtosecond laser pulse and the readout is performed with an increased fluorescence intensity. Three bit planes read out with little cross-talk with the fluorescence readout. We have also data recording on a dental prosthesis for personal identification using a femtosecond laser processing system with a surface detection function. We have demonstrated holographic femtosecond laser processing with three-dimensional parallelism. The next stage of our study is to integrate the focus control technique and holographic technique.

## ACKNOWLEDGMENT

This work was supported by the Venture Business Incubation Laboratory of The University of Tokushima, The Murata Science Foundation, The Asahi Glass Foundation, Research for Promoting Technological Seeds program of the Japan Science and Technology Agency, and a Grant-in-Aid for Scientific Research (B) from the Ministry of Education, Culture, Sports, Science, Japan.

## REFERENCES

1. Takita, A., M. Watanabe, H. Yamamoto, S. Matsuo, H. Misawa, Y. Hayasaki, and N. Nishida, "Optical bit recording in a human fingernail," *Jpn. J. Appl. Phys.*, Vol. 43, No. 1, 168–171, 2004.
2. Hayasaki, Y., H. Takagi, A. Takita, H. Yamamoto, N. Nishida, and H. Misawa, "Processing structures on human fingernail surface by a focused near-infrared femtosecond laser pulse," *Jpn. J. Appl. Phys.*, Vol. 43, No. 12, 8089–8093, 2004.
3. Takita, A., H. Yamamoto, Y. Hayasaki, N. Nishida, and H. Misawa, "Three-dimensional optical memory using a human fingernail," *Optics Express*, Vol. 13, No. 12, 4560–4567, 2005.
4. Ichikawa, T., Y. Hayasaki, K. Fujita, K. Nagano, M. Murata, T. Kawano, and J. R. Chen, "Femtosecond pulse laser-oriented recording on dental prostheses," *Dental Materials J.*, Vol. 25, No. 4, 733–736, 2006.
5. Takita, A., Y. Hayasaki, and N. Nishida, "Femtosecond laser processing system with target tracking feature," *Journal of Laser Micro/Nanoengineering*, Vol. 1, No. 3, 288–291, 2006.

6. Hayasaki, Y., T. Sugimoto, A. Takita, and N. Nishida, "Variable holographic femtosecond laser processing by use of spatial light modulator," *Appl. Phys. Lett.*, Vol. 87, No. 3, 031101, 2005.
7. Hasegawa, S., Y. Hayasaki, and N. Nishida, "Holographic femtosecond laser processing with multiplexed phase Fresnel lenses," *Opt. Lett.*, Vol. 31, No. 11, 1705–1707, 2006.
8. Hasegawa, S. and Y. Hayasaki, "Holographic femtosecond laser processing with multiplexed phase fresnel lenses displayed on the liquid crystal spatial light modulator," *Opt. Rev.*, Vol. 14, No. 4, 208–213, 2007.
9. Takahashi, H., S. Hasegawa, and Y. Hayasaki, "Holographic femtosecond laser processing using optimal-rotation-angle method with compensation of spatial frequency response of liquid crystal spatial light modulator," *Appl. Opt.*, Vol. 46, No. 23, 5917–5923, 2007.
10. Chaen, K., H. Takahashi, S. Hasegawa, and Y. Hayasaki, "Display method with compensation of the spatial frequency response of a liquid crystal spatial light modulator for holographic femtosecond laser processing," *Opt. Commun.*, Vol. 280, No. 1, 165–172, 2007.