Three-dimensional optical storage in fused silica using modulated femtosecond pulses

Qing Liu (刘 青)[1,2], Guanghua Cheng (程光华)[1], Yishan Wang (王屹山)[1],
Zhao Cheng (程 昭)[1], Wei Zhao (赵 卫)[1], and Guofu Chen (陈国夫)[1]

[1] *State Key Laboratory of Transient Optics and Technology, Xi'an Institute of Optics and Precision Mechanics,*
Chinese Academy of Sciences, Xi'an 710068

[2] *College of Physics & Electrical Information, Ningxia University, Yinchuan 750021*

Received November 4, 2003

Three-dimensional bitwise optical recording with a density of 500 Gb/cm^3 in fused silica using a Ti:sapphire femtosecond laser modulated by binary digits is demonstrated. Laser pulses modulation is realized by modulating two circuits of trigger pulses signal which are used to control laser pulses trapping and switching out from cavity, respectively. Bits are optically readout in both a parallel reading (phase-contrast) and a serial reading (confocal-type) methods. The method for modulating laser pulses can also be used in all of pulsed laser systems which operate in cavity-dumping configuration.

OCIS codes: 210.4680, 320.7090.

The rapid advances in the generation and amplification of ultrashort laser pulses have opened up many new possibilities in laser-matter interaction and materials processing. Three-dimensional (3D) optical data storage offers the potential for very large recording capacity. A number of recent papers reported bitwise binary 3D optical storage in transparent materials[1−5]. Femtosecond laser which is tightly focused in the bulk of transparent materials induces permanent structural damage in the focal region of the sample, a sub-micrometer micro-explosion bit is generated in which the difference of refraction index presents a striking contrast with respect to the original material. This phenomenon provides a potential way to realize 3D optical storage with advantages of long storage life and temperature stability (up to ~ 1100 °C), which are the key considerations for data archiving[6].

For realizing 3D optical storage or information processing using femtosecond laser pulses, it is necessary to modulate series of laser pulses by digital signal. In this paper, we report a handy way for modulating femtosecond pulses with digital signal, and demonstrate the writing and readout of binary digital information. A Ti:sapphire femtosecond laser pulse is magnified in the cavity, and the Pockels cell acts as a trapper and a cavity-dumper for pulses. An amplified pulse is switched out from cavity when gain is depleted. Laser pulses are modulated by modulating two circuits of transistor-transistor logic (TTL) which control laser pulses to be injected into and dumped out from the cavity. Using the modulated laser pulses, we recorded 3D high-density optical data in fused silica with a density of 500 Gb/cm^3. Through a charge coupled device (CCD) attached to an objective (parallel reading) and confocal scheme (serial reading), multilayer array of damage bits corresponding to recorded binary digital information is observed.

In order to record binary digital information in transparent materials using femtosecond laser pulses, it is necessary to modulate the laser pulses before it is injected into transparent materials. We achieved modulating laser pulses from a Ti:sapphire chirped-pulse regenerative amplification system, including a Pockels cell Driver DR85-A and a Pockles cell assemblies series 700 system (MEDOX Electro-Optics, USA). A seed pulse is injected and trapped in the regenerative amplifier by the combination of a polarizer and the Pockels cell. The Pockels cell acts as a dumper as well. The trapping and switching-out of laser pulses is controlled respectively by two synchronized high voltage (TTL trigger signal) with fine adjusted delay. One of the trigger signals is used to trap seed pulses, and causes a seed pulse to be injected into the regenerative amplifier. Another signal switches the amplified pulses out of the cavity when gain is depleted[7]. Laser pulses modulation is realized by modulating the two sequences of TTL trigger pulses (or one of them) injected into Pockels cell with desired digital signal. The modulated laser pulse is dumped only when gain is depleted and the binary bit to be recorded is "1". Thus the binary digital information has been carried in laser pulses sequence. There are many mature methods in which TTL signals can be modulated by digital signal.

Light beam carrying binary digital information passes through a spatial light filter (a 10-μm pinhole) to improve laser beam quality and enlarge its diameter firstly. A microscope objective (40× magnification, numerical aperture (NA) 0.65) focuses the laser beam in bulk of a fused silica specimen that has been prepared in cubic shape with four optical surfaces to allow the laser-matter interaction zone to be observed from different orthogonal directions. Fused silica sample is placed on a three-axis translation stage (100-nm resolution) controlled by a computer. The translation stage moves regularly, so bits are recorded successively in the fused silica specimen, row-by-row and layer-by-layer, each bit induced by a single pulse. Laser pulses are produced by Ti:sapphire femtosecond laser with pulse duration 200 fs, wavelength 800 nm, and repetition frequency 1 kHz[8].

Figure 1 shows the image of bits induced by a serial of laser pulses modulated by different 8 bits circulating binary digital. The energy of each single pulse inducing the storage dot is 1 μJ. The results of measurement (Figs. 1(a)–(d): bits observed parallel to excitation pulses; Fig.

1(e): bits observed orthogonal to the excitation pulses) with different binary digital signals are obtained by a CCD camera attached to a phase-contrary optical microscope. These pictures prove that laser pulses are modulated properly. The disorder of pits between lines observed in the figures is because of the continuous writing of a number of bits in different lines, which does not affect the reading and identifying of the recorded bits. Figure 1(e) shows optical image of bits that were observed orthogonal to the excitation pulse modulated by "11111111" signal with 7-μm inter-plane spacing.

We recorded the farthest layer from the excitation source at first, thus the recorded bits do not affect subsequence bits to be recorded, and the sizes of the bits recorded in different layers are uniform. With the NA = 0.65 objective, bits over 60 layers are recorded with 2-μm in-plane bit spacing and 7-μm inter-plane spacing, as shown in Fig. 1, corresponding to a memory density of 3.6×10^{10} bit/cm^3. The area of the material with refractive index change is ~ 400 nm in diameter and ~ 3 μm in depth.

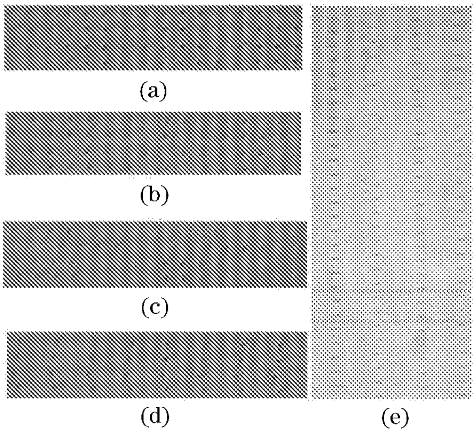

Fig. 1. Optical image of array of bits induced by laser pulses modulated by different 8-bit digital signals in fused silica. Light is focused by a NA = 0.65 objective. In-plane bit spacing is 2 μm and the layer spacing is 7 μm. (a)–(d): Bits observed parallel to excitation pulse modulated by "11111111" (a), "10101111" (b), "00001111" (c), and "01010101" (d) signals; (e): bits observed orthogonal to the excitation pulse modulated by "11111111" signal.

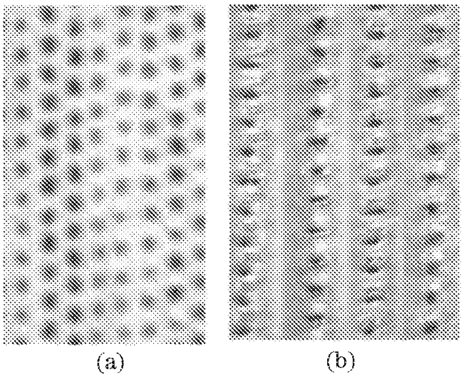

Fig. 2. Optical image of bits array written inside fused silica, observed parallel to the 400-nJ, 200-fs excitation pulse. Light is focused by a NA = 0.85 objective. In-plane bit spacing is 1 μm and the layer spacing is 2 μm. (a) Bits observed parallel to the excitation; (b) bits observed orthogonal to the excitation pulse.

In order to further increase the memory density, a higher NA (0.85) objective lens (with shorter focal depth) is employed. The energy of a single pulse inducing storage dots decreases to 400 nJ, thus the dimension of the dots can be decreased (< 300 nm). Figure 2 shows the optical image of dots with 1-μm in-plane bit spacing and 2-μm inter-plane spacing, corresponding to a density of 500 Gb/cm^3.

We demonstrated the retrieval of the recorded data in two different ways: parallel reading using a CCD attached to a 40× (0.65-NA) objective and serial reading using confocal-type scheme.

A CCD attached to a 40× (0.65-NA) objective is used to obtain page-wise recorded images. A computer processes and identifies the collected image information, achieving retrieval of the recorded binary digital signal. The amount of bits recorded in one block (page) is determined by the characteristics of the microscope, the imaging area of CCD, and in-plane bit spacing (areal storage density). According to our experiment device (a CCD with 768×576 resolution and 9×9 μm^2 cell size), data of 153×115 bits can be retrieved from one block. In order to retrieve recorded data exactly, it is necessary to ensure that a dot recorded in sample was covered by at least four (2×2) pixels. Choosing an objective with appropriate NA (finite focal depth), so that the reading of bits recorded in one layer cannot be disturbed by that of bits in other layers, and it is easy to find the position of a desired recording layer by computer automotive identifying.

Figure 3 shows the image of a single row of bits and profile of transmitted intensity on bits in a row. The profile is the average brightness of all pixels on the same column between the two denoted lines. Line error of the step motor is responsible for the variations in peak contrast. The full-width at half-maximum of the profile is the size of a bit, and the minimal contrast is 67% of the maximum. The storage density will be increased at least 40%, if we use 8 – 14 coding (eight to fourteen modulation).

Figure 4(a) shows a serial readout system using transmission confocal-type readout scheme. Fused silica was placed on a three-axis rotational stage (PI Inc.). Binary data were written in a homocentric spiral curve.

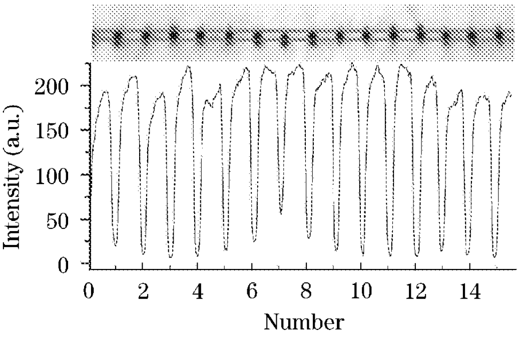

Fig. 3. Parallel reading of data through a phase-contrast microscope. The upper part of the figure shows the signal recorded by a single row of the CCD camera with the two lines denoting the edges of the row. The pits being imaged are shown in the bottom portion. High contrast is evident even for those bits not perfectly centered.

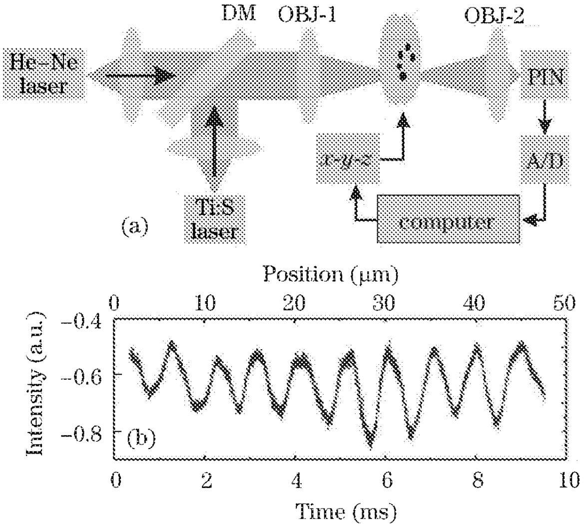

Fig. 4. (a) Schematic of a transmission confocal system for recorded data readout of the 3D optical memory. Data are first recorded by a femtosecond (Ti:S) laser pulse, which is focused on the sample by a high-power objective lens (OBJ-1). Light from a He-Ne laser is collimated, and after passing through a dichroic mirror (DM) it is focused by the same objective lens (OBJ-1) onto the sample surface. A second objective lens (OBJ-2) is used to focus the transmitted light on to a photodiode (PIN), whose output is converted to digital form (A/D), and stored in a computer. (b) Readout sample of data through the above system performed by scanning (x-y-z) the sample at velocity of 5 mm/s.

A beam of He-Ne laser (632.8 nm) is focused into the sample by a 0.65-NA objective (OBJ-1), and another 0.45-NA objective (OBJ-2) is used to collect the light. A PIN photoelectronic detector is used to detect the transmitted optical signal[8]. According to the intensity of transmitted light, the recorded bits can be identified. The intensity of transmitted light decreases dramatically when the He-Ne laser beam is focused at recorded bit. Figure 4(b) presents a sample result of bits data readout using this system. This way of serial readout is similar to the reading of the conventional compact disk (CD). However, a transmitted light is used here rather than reflected light. This method might be one of the most promising ways of 3D high-density memory.

The mechanism of optically induced structural change in bulk materials is not very clear, but some key principles are understandable. For large bandgap transparent materials and pulses shorter than a few picoseconds, the laser intensity in the tightly focused focal volume in the sample can become high enough to ionize electrons from valence band to conduction band by multiphoton ionization, tunneling ionization and avalanche ionization. Electrons in the conduction band are heated by the laser pulse much faster than they can be cooled by phonon emission. The electron density grows through avalanche ionization until the plasma frequency approaches the frequency of the incident laser radiation. This high density plasma strongly absorbs laser energy by free carrier absorption. After the laser pulse is gone, energy is transferred from the electrons to the lattice, and so the energy deposition occurs inside the material. After the plasma recombines, the remaining energy in the material is in the form of thermal energy. At high laser energy, hot electrons and ions may explosively expand out of the focal volume into the surrounding material. This explosive expansion leaves a void or a less dense central region surrounded by a denser halo[9]. This permanent void forming in bulk materials allows a high optical storage density.

In this paper, we propose a way to modulate laser pusles by binary digital signal, and demonstrate the writing of 3D data at density up to 500 Gb/cm^3 in fused silica using a chirped amplified femtosecond laser. Data can be parallel retrieved at high contrast using a CCD imaging system, and also can be serial retrieved by a transmission confocal microscope. We can improve storage density further by suitable coding (such as $8-14$ coding).

This work was supported by the National Natural Science Foundation of China (No. 60078004) and the research foundation of the Chinese Academy of Sciences (No. 40001043). Q. Liu's e-mail address is nxlq@163.com.

References

1. E. N. Glezer, M. Millsavljevic, L. Huang, R. J. Finlay, T.-H. Her, J. P. Callan, and E. Mazur, Opt. Lett. **21,** 2023 (1996).
2. J. Chan, T. Huser, S. H. Risbud, and D. M. Krol, Opt. Lett. **26,** 1726 (2001).
3. D. von der Linde and H. Schuler, J. Opt. Soc. Am. B **13,** 216 (1996).
4. D. L. Wang, C. D. Li, L. Luo, H. Yang, and Q. H. Gong, Chin. Phys. Lett. **18,** 65 (2001).
5. D. Homoelle, S. Wielandy, and A. L. Gaeta, Opt. Lett. **24,** 1311 (1999).
6. A. M. Strellsov and N. F. Borrelli, J. Opt. Soc. Am. B **19,** 2496 (2002).
7. X. Liu, D. Du, and G. Mourou, IEEE J. Quantum Electron. **33,** 1706 (1997).
8. G. H. Chen, Y. Wang, J. D. White, Q. Liu, W. Zhao, and G. F. Chen, J. Appl. Phys. **94,** 1304 (2003).
9. C. B. Schaffer, A. Brodeur, and E. Mazur, Meas. Sci. Technol. **12,** 1784 (2001).