Three-dimensional optical data storage using a solid immersion lens to focus a femtosecond laser pulse

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A solid immersion lens (SIL) has been applied to the writing and reading of three-dimensional optical data storage in transparent materials. Using a SIL with n=1.516 to focus a 150-fs, 800-nm Ti:sapphire laser, the 5-layer reading and writing of data are achieved in fused silica and polyethylene methacrylate at a density of 1.1×10^{12} b/cm^3. Some advantages of the employment of SIL have been discussed.

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The need to store the large quantities of data has led to considerable research into high-density memory. For optical memory, the density is ultimately limited by the diffraction of electromagnetic waves. For higher density memory, the techniques for exceeding the optical diffraction limit in high resolution have been developed recently. Up to the present, there have been two different approaches to improve optical resolution below the limits dictated by diffraction. The first approach takes advantages of the nanometer aperture of a near-field scanning optical microscope probe and high numerical aperture (NA) of a solid immersion lens (SIL), while the second approach is based on the nonlinear absorption of light by a dielectric exposed to an intense electromagnetic field[1−4]. In contrast with near-field optics, the latter is famous for its space-selection which makes it become a great excitement over the development of techniques for photolithographic nanometer-scale device fabrication in three dimensions. On the other hand, further increases in storage density require the use of the third dimension. Femtosecond laser induced plasma ablation in transparent materials, which produces a submicrometer micro-explosion, provides a powerful way to realize three-dimensional (3D) optical storage[5−7].

In this paper, the combination of high aperture of SIL and spatial selection of nonlinear absorption induced by femtosecond laser pulse is applied in 3D high-density optical storage. A SIL with n = 1.516 is positioned under a 0.55NA microcopy objective to focus a 150-fs, 800-nm Ti:sapphire laser, a 250-nm optical spot size is obtained inside fused silica. The 5-layer reading and writing of data are achieved with 2.5-μm separation between two neighboring layers and 600-nm separation between two neighboring bits. Accordingly, 1.1-Tb/cm^3 storage density is demonstrated in this way. To our knowledge, it is the highest writing density in fused silica with a single femtosecond laser pulse. In addition, some advantages and characteristics of the employment of SIL are discussed.

A schematic of the experimental apparatus is presented in Fig. 1. Excitation was provided by a home-built chirped pulse amplified Ti:sapphire laser system (λ = 800 nm, linearly polarized) whose light first passed through a spatial light filter (10-μm pinhole) in order to improve the laser beam quality and enlarge its diameter[8,9]. After being reflected from a dichroic mirror (the 800-nm dichroic mirror permits light from a light emitting diode (LED) (λ=405 nm) that illuminates the sample to pass through so that the focus position can be monitored in real time), the beam was focused into SIL by a NA=0.55 objective lens with 13-mm working distance to provide a 600-nm diffraction limited spot. The pulse duration was 150 fs, and the pulse energy was 150 nJ. The refractive index of SIL is 1.516. So the focusing system provides a NA of 0.85. Fused silica was prepared in cubic shape with six optical surfaces to allow the laser-matter interaction zone to be observed from different orthogonal directions. A computer controlled three-axis translation stage (100-nm resolution at X direction, 125 nm at Y direction, and 7 nm at Z direction) is used to move the sample between two pulses. A charge-coupled device (CCD) camera, attached to a conventional phase-contrast optical microscope, was used to observe the sample after ablation.

The chirped pulse amplified Ti:sapphire laser system consists of a femtosecond mode-locked seed, a regenerative amplifier, and a two-grating compressor. Pumped by a pulsed Nd:YLF laser (1.3 W, 1 kHz), the system outputs 2.1-ps, 140-μJ maximum pulse energy without compressor. With the two-grating compressor at 7.4-mm distance, it outputs 140-fs pulse at zero group

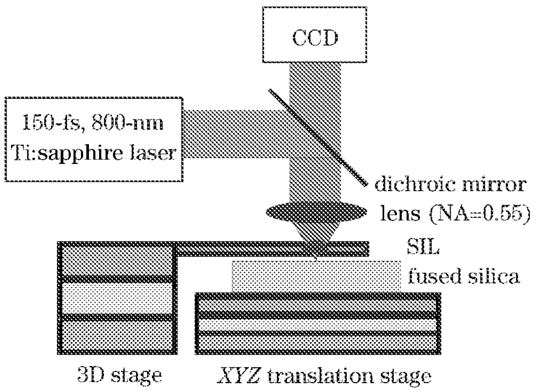

Fig. 1. Schematic of the experimental setup.

velocity dispersion (GVD) region with a pulse energy of 20 μJ. However, the pulse will be stretched when it passes through spatial light filter, attenuator, and focusing objective. In order to obtain minimum pulse width inside the recording sample, we put the two gratings at 8-mm distance to make sure that there is zero dispersion inside the sample.

Nano-machining experiments were performed at pulse energies in the range of 90 – 150 nJ. A two-step attenuation scheme was used to accurately control the pulse energy. 10% of the transmitted laser beam from the beam splitter was further attenuated using a polarizer as analyzer. In comparison with our previous experimental setup, the neutral attenuator is discarded. The Gaussian laser beam becomes a non-circular beam when it is through tunable neutral attenuator, which deteriorates seriously the quality for lithography. We expect these two improvements to achieve higher spatial resolution.

Commercially available SIL is made of K9 optical glass (refractive index n=1.516) with a diameter of 1.5 mm. The manual 3D stage connects with the holder of the SIL through a cantilever taken from a hard disk. So the SIL is not movable in X-Y plane, and movable along Z axis (optical axis of the system). The laser beam was aligned to the middle of the SIL by imaging its surface in monitor with ± 2 μm error. Fused silica (GJS1) and polyethylene methacrylate (PMMA) were used as recording materials in the experiments.

Figure 2 presents an optical image of bits written on the surface of PMMA by a single pulse focused by a NA=0.55 objective lens with 13-mm working distance and the SIL. All experiments on PMMA were conducted at pulse energies in the range of 30 – 100 nJ. When the energy is above 80 nJ, it will lead to the damage or pollution of SIL on the surface. And with the energy below 40 nJ, the induced bits are beyond our system resolution (240 nm) and thus too faint to be distinguished. However we believe that there are bits on the PMMA surface even with 30-nJ irradiation energy. The bits shown in Fig. 2 are viewed parallel to the 50-nJ, 150-fs excitation pulse. Each bit is separated by 1 μm from its nearest neighbors.

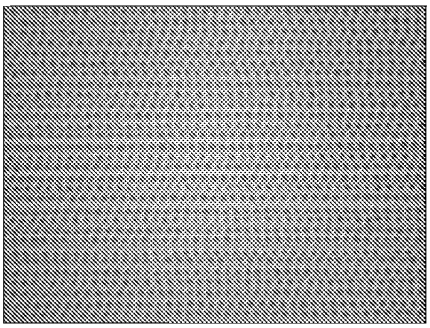

Fig. 2. Optical image of bits written inside PMMA by a single pulse focused by a NA=0.55 objective lens and SIL. The bits are viewed parallel to the excitation pulse.

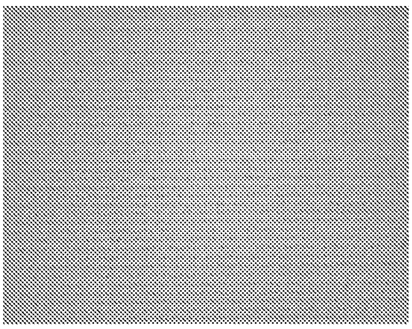

Fig. 3. Optical image of bits written inside fused silica by a single pulse focused by a NA=0.65 objective lens and SIL. Bits are viewed parallel to the excitation pulse. Each bit is separated by 600 nm from its nearest neighbors. Nonlinearity in the step motor is the reason that the bits are not perfectly aligned.

Different from the bits on the surface of a PMMA bulk, the bits shown in Fig. 3 are inside fused silica, and are viewed by the writing optical system with illumination of 405-nm LED. The laser damage thresholds of SIL and recording materials are mainly considered. In our recording system, the laser damage thresholds of PMMA, SIL (K9 optical glass), and fused silica are 30, 80, and 100 nJ, respectively. The writing on the surface of fused silica leads to damage of the SIL. So we move the SIL 60 μm near to the long working distance objective (accordingly, the focus of this system just move 15 μm) and write the bit arrays in an area of 200×200 μm^2. The side view of the five layers of written data is shown in Fig. 4, which is observed by conventional phase-contrast optical microscope with illumination of a white light. A separation of 600 nm between two bits cannot been distinguished in longitude by this microscope.

It is well known that the wavelength inside SIL is reduced by the high index of the glass, leading to a reduction in the diffraction limited spot size. In addition, the incident rays are refracted at the sphere's surface, leading to a further reduction in spot size. Hemispherical SIL serves to increase the NA of the optical system by n, where n is the index of refraction of the lens materials in near field[1,2]. In our experiment, however, propagating wave rather than evanescent waves is used to write inside fused silica. The NA of the system changes with the off-focus distance (h) and the SIL displacement (d), and the schematic is shown in Fig. 5. So the numerical aperture of the focusing system $\text{NA} = n_{\text{sample}} \sin[\arcsin(\frac{d \sin\theta}{r}) - \arcsin(\frac{d \sin\theta}{nr}) + \arcsin(\sin\theta)]$, where n_{sample} is the refractive index of the recording sample, n=1.516 is the index of the SIL material, r=0.75 mm is the radius of the SIL, $\sin\theta$=0.55 is the NA of the objective in air. The curve in Fig. 6 is the dependence of the NA of the focusing system on displacement of the SIL/sample. It is clear that

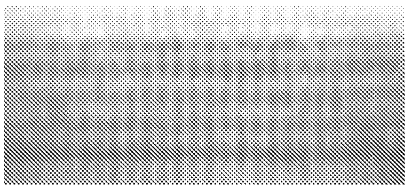

Fig. 4. The side view of a 5-layer storage viewed perpendicular to the excitation pulse, and observed by conventional phase-contrast optical microscope with illumination of a white light. In-plane bit separation is 600 nm and the layer separation is 2.5 μm.

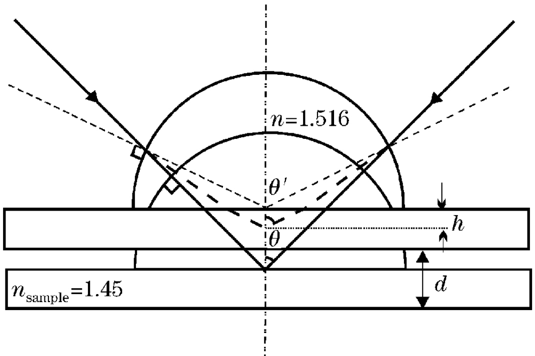

Fig. 5. Schematic of the dependence NA of the system on the off-focus distance (h) and SIL displacement (d).

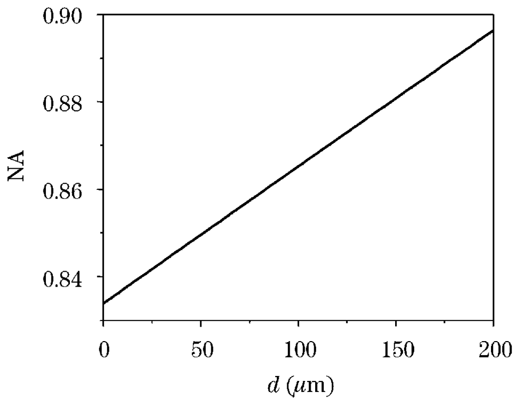

Fig. 6. The dependence of NA on the SIL displacement (d).

the NA of this system increases with the increase of the SIL displacement. It is profitable to write in three dimensions since the threshold of optical damage grows with the increase of the writing depth, because the intensity of point expansion function decreases with the writing depth.

Besides the NA of the system, the focus of the system (off-focus distance) changes with SIL displacement. Based on geometrical optics, an approximate relationship can be expressed as $h = 0.25d$, so a displacement of 60 μm for the recording sample and SIL just brings an off-focus distance of 15 μm. After recording one layer, we move the fused silica 15 μm near to the objective. So the separation of two layers is 2.5 μm, which is in agreement with the experimental results shown in Fig. 4.

In contrast with traditional microscopy objective, the employment of SIL can increase effectively spatial resolution and remain diffraction limited near the SIL/object interface[10]. Especially, there is no air layer between the SIL and recording material. So it is easy to keep higher NA (NA>1) during data writing in three dimensions. This can also be achieved by use of liquid immersion lens. However, its evaporation and instability make it unpopular. On the other hand, under the same NA, the reflection loss at air/recording material interface is bigger than that at SIL/recording material interface due to the fact that the incidence angle on the recording materials from air is bigger than that from SIL. So utility efficiency of energy with SIL is higher than traditional objective. Without the SIL, the damage threshold of fused silica with same laser parameters is 150 nJ, and the maximum recording density is 0.063 Tb/cm^3 ($1.5\times1.5\times7$ μm^3 bulk). In our previous experiment, 0.85NA objective with 400-nJ pulse energy has achieved a density of 0.5 Tb/cm^3 ($1 \times 1 \times 2$ μm^3 bulk)[7].

In conclusion, the generation of a high density plasma in a small region allows a high optical storage density. In this paper, we have demonstrated the writing of bits in three dimensions in fused silica and PMMA at a density of 1.1 Tb/cm^3 using a chirped amplified femtosecond laser. Data can be read out with high contrast using either a conventional phase-contrast microscope and a CCD camera or a transmission confocal microscope. By employing SIL with the higher refractive index material so as to increase the NA and reduce the interaction time between the laser and plasma (by ensuring that the beam intensity remains a little above the optical breakdown threshold), it should be possible to obtain data storage densities of hundreds of Tb/cm^3.

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