

# Three dimensional holographic microfabrication by single femtosecond laser pulse

MASAHIRO YAMAJI\*, HAYATO KAWASHIMA, JUN'ICHI SUZUKI, SHUHEI TANAKA

*Nanoglass Research Laboratory, New Glass Forum, 5-9-1 Tokodai, Tsukuba, Ibaraki 300-2635, Japan*

We have developed a new 3D microfabrication method, which uses only a single femtosecond laser pulse. The phase distribution of the pulse is controlled by a computer generated hologram, and a complicated 3D microstructure is fabricated simultaneously. In this paper, two sample 3D microstructures are shown: the first one consists of 24 dot elements of same shape, and the second one has two different shapes, namely 22 dot elements and one line element. The light irradiance distribution control is the key of this method, and indispensable especially for fabricating elements of different shapes simultaneously.

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## 1. Introduction

For the fabrication of various optical and other devices such as waveguides, MEMS and microfluid, a new 3D (three dimensional) microfabrication method at low cost is desired. Up to now, the laser direct-writing method has been used for such fabrication inside transparent materials [1-5]: dot shaped elements are fabricated one by one, and line shaped elements are fabricated with moving the sample parallel to the line. It means that the method takes a lot of time and inefficient in energy, because huge amount of pulses are needed for the fabrication, though one femtosecond laser pulse has usually enough energy to fabricate several hundreds of dot elements. Hence we have developed a new 3D microfabrication method. It uses only one femtosecond laser pulse for the fabrication of complicated 3D microstructure inside transparent materials. Therefore, it realizes both fast fabrication and high energy efficiency, which yields cost reduction for the bulk production of various micro devices. In this paper, two sample 3D microstructures fabricated by this method are shown. They prove that this method can fabricate complicated 3D microstructure simultaneously even though it has different shapes of elements.

## 2. Experimental details

The schematic diagram of the optical system used for this holographic 3D microfabrication method is shown in fig.1. The amplified Ti: Sapphire femtosecond pulse laser (Femtolasers / FEMTOPOWER compact PRO) of 800nm in wavelength and 8mm in diameter is used as the light source. The pulse duration and fluence are able to vary in

the range of 26-735 fs and 10-600  $\mu\text{J}/\text{pulse}$ , respectively. The repetition rate is 1kHz, which is low enough that all thermal and mechanical relaxation processes are completed before the subsequent pulse comes.

This femtosecond laser pulse penetrates through a glass CGH (computer generated hologram), which is a phase distribution pattern encoded on an optically polished silica glass plate (Shin-Etsu Chemical Co., VIOSIL) of 1mm thickness. Two CGH patterns are also shown in fig.1. CGH-A images 24 dot elements arrayed as spiral and CGH-B images line element parallel to the optical axis and 22 dot elements arrayed as spiral. The shapes of these CGHs are circular of 8mm in diameter in order to use all energy of the incident pulse. The CGHs used in this report are binary phase hologram. It means that the phase distribution is controlled by the difference of CGH glass plate thickness, and all pixels on the CGH are divided in two levels; etched area and non-etched area. The etching depth is equal to a  $\pi$  phase shift. Assuming ambient air, the depth becomes 870nm [5]. The white pixel in the CGH pattern means dry etched area by electron beam lithography and reactive ion etching. Because this dry etching technique is well-established in semiconductor manufacturing process for many years, CGHs are able to be fabricated with high accuracy. The pixel size is 20 $\mu\text{m}$  square and its sidewall roughness is less than 50nm, which is small enough to prevent significant degradation of the diffractive efficiency.

The 3D structure formed by the CGH is demagnified to 1/67 by an M20 objective lens (the numerical aperture value = 0.46) in order to increase the photon density enough for the multi photon absorption. The intended microstructure is processed inside optically polished fused silica glass (ES: Tosoh Quartz Corp.). The

Fresnel-Kirchhoff diffractive integral is used to calculate the CGH pattern.

### 3. Results and discussion

#### 3.1 3D microfabrication

Fig.1 shows the first sample 3D microstructure “spiral dot array” fabricated by using CGH-A. The left side of this figure is the design model and the right side is the 7000 magnified microscopic view. This microstructure consists of 24 dot elements on 24 different layers. From this figure, it is found that all elements are well fabricated uniformly at the intended positions; the diameter of the spiral is  $52\mu\text{m}$  and the interlayer distance is  $2\mu\text{m}$ . Because an objective lens is used in the optical system, the magnification ratio varies with the distance from the focal point of the objective lens. Therefore, in order that the spiral’s diameter and the interlayer distance may be constant, the distance of each layer from the focal point of the objective lens must be considered at the designing phase.

This spiral dot array is fabricated by a laser pulse of  $180\mu\text{J}$ . The processible threshold is far smaller than this value, but the strong laser pulse is used here so that all elements become clearly visible by the microscope. Even

smaller elements than the diffraction limit may be processible when the power of the laser pulse is set to just above the threshold.

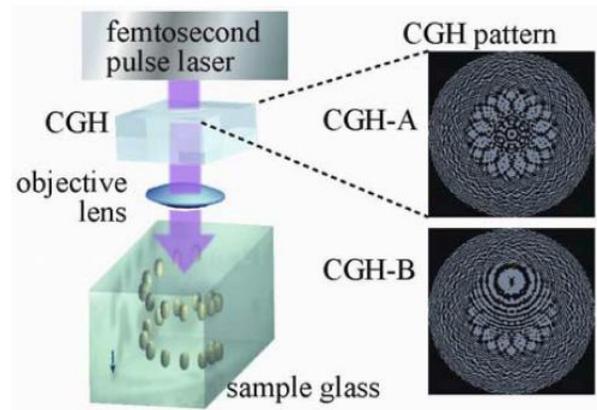


Fig. 1. A schematic diagram of the optical setup of holographic 3D microfabrication method. The CGH patterns used in this report are also shown in right side. CGH-A images spiral dot array of 24 dot elements, and CGH-B images line and spiral. White pixel means the dry-etched area by electron beam lithography and reactive ion etching.

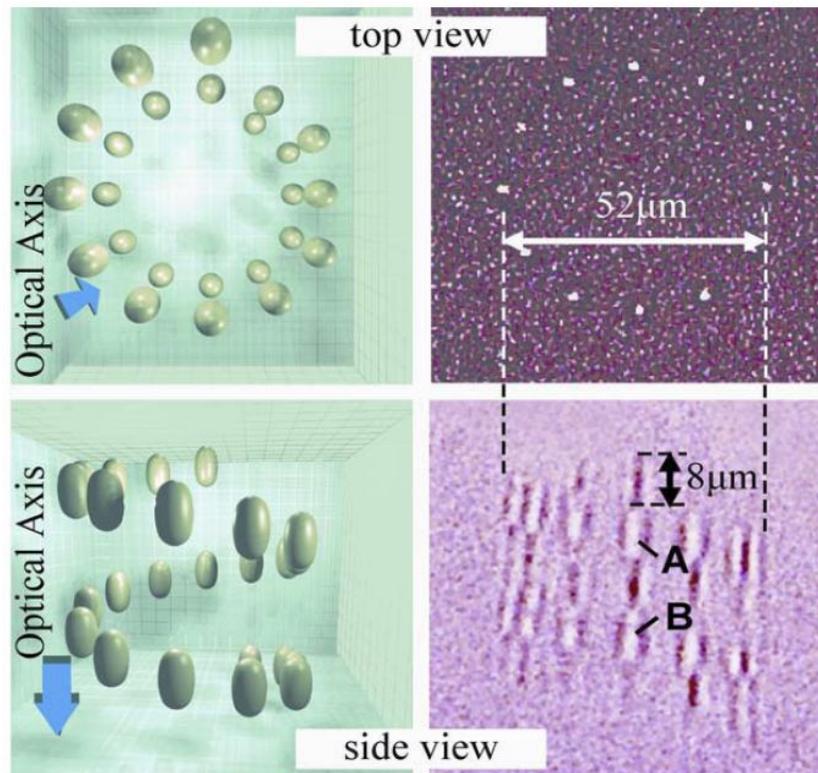


Fig. 2. The designed images (left) and 7000 magnification microscopic views (right) of 3D spiral dot array. The direction of the optical axis is shown by an arrow. The fabricated 3D spiral has diameter of  $47\mu\text{m}$ , and each element has length of  $8\mu\text{m}$ . Element B is processed even though it locates just under element A, which proves high flexibility in designing 3D structure in this method.

The novelty of this result is that elements are able to be processed without restriction of other elements' relative position, even though they are shaded by other elements (e.g. element B is shaded by element A), which makes it possible to design arbitrary 3D microstructures. This is because the change caused by the interaction between the femtosecond laser pulse and the material is thought to occur at the time order of picoseconds though the pulse goes through the fabrication area within several hundreds femtosecond. Hence such refractive index changes caused by the pulse does not affect the pulse itself.

### 3.2 Light intensity control

Thus far, it was very difficult to process elements homogeneously at different depths. Though several groups tried fabricating 3D structures by this holographic 3D microfabrication method, these were limited to 3 different depths [6-8]. This limitation of designing is mainly attributed to the photon density variance along the optical axis, which is caused by the following two reasons. The first reason is the attenuation of the spherical wave. Though the laser pulse is a plane wave and has an extremely low beam spread angle, it becomes numerous spherical waves after penetrating through the phase CGH, and they attenuate as a function of distance from the CGH. Therefore, the longer the focal length, the lower the photon density of each spherical wave becomes. It means that the photon density at the fabrication area also becomes lower. The second reason is the focusing property of the objective lens; the photon density of the processed area depends on the numerical aperture value and the distance from the focal point of the objective lens. If the photon density is inhomogeneous, elements at lower density cannot be fabricated. And even if all elements can be fabricated, the structural change becomes different, and the change is categorized into three change types [2]; isotropic refractive index change, birefringent change, and microvoid.

These have each own threshold, therefore, it is very important to control the light irradiance distribution so that the light intensity is between the threshold of refractive index change and birefringent change, at the whole fabrication area if the refractive index changed elements are needed.

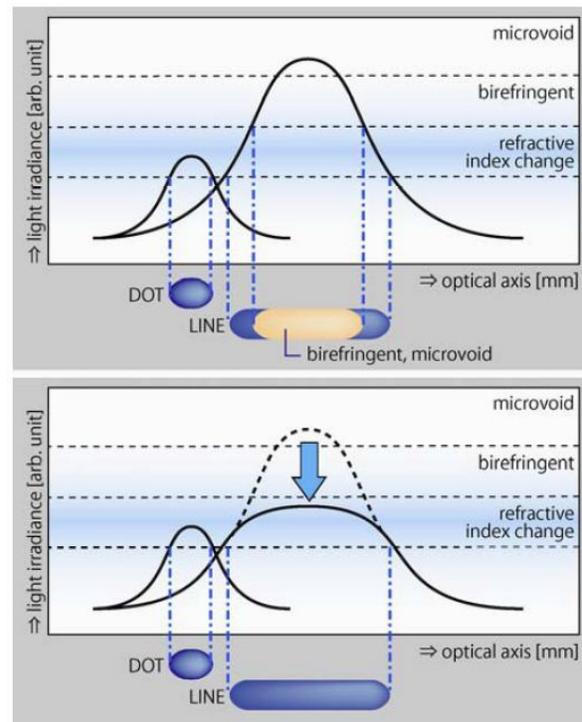


Fig. 3. The schematic diagram to explain how to control the light irradiance distribution; (top) the line is made by increasing whole intensity distribution, which may yields birefringent change or microvoid at the center of the line; (down) the line is made by controlling the shape of the light irradiance distribution. All intensities of the fabrication area are between the thresholds of refractive index change and birefringent change.

This light irradiance distribution control is even more difficult if the element has a certain length. Although the line element parallel to the optical axis can be fabricated by increasing the intensity [9], the center of the line may form birefringent change or microvoid as shown in fig.3. Hence it is important to control not only the peak height but also the shape of the light irradiance distribution.

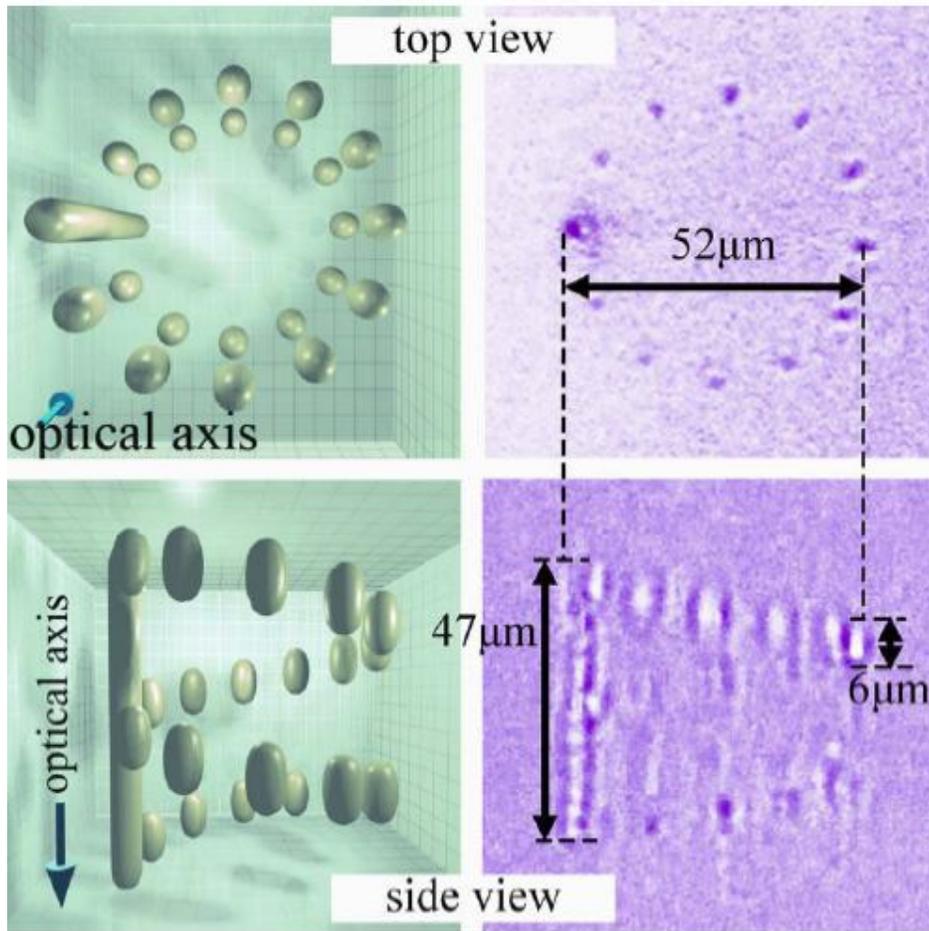


Fig. 4. The designed images (left) and 7000 magnification microscopic views (right) of line and spiral. The direction of the optical axis is shown by an arrow. The fabricated 3D spiral has diameter of  $52\mu\text{m}$ , and lengths of dot and line are  $6\mu\text{m}$  and  $47\mu\text{m}$ , respectively.

By taking this factor into account, CGH-B in fig.1 was designed. This CGH images a line parallel to the optical axis and 22 dot elements arrayed as spiral. The left side of fig.4 shows the design model of the microstructure and the right side shows 7000 magnified microscopic view of the fabrication inside the silica glass sample. From this figure, it is found that all dots and a line are successfully fabricated, and proved that the light irradiance distribution control technique is useful for fabrication of complicated 3D microstructure.

#### 4. Summary

A new 3D microfabrication method was developed which uses only one femtosecond laser pulse and the computer generated hologram. By this method, complicated 3D microstructure is able to be fabricated inside silica glass simultaneously even though it has elements of different shapes. The key of this method is the

light irradiance distribution control. The light intensity at the whole intended fabrication areas must be between the threshold of refractive index change and of birefringent change if the change of the refractive index microstructure is needed. By using this intensity control technique, various shape of elements are able to be fabricated inside transparent materials, and this holographic 3D microfabrication method may become indispensable for bulk production of various micro devices in near future.

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**References**

- [1] M. Watanabe, M. Miwa, S. Matsuo, H. Misawa, J. Nishii, *Opt. Lett.* **26**, 277 (2001).
- [2] R. R. Gattass, E. Mazur, *Nature Photonics* **2**, 219 (2008).
- [3] K. C. Vishnubhatla, N. Bellini, R. Ramponi, G. Cerullo, *R. Oscillame, Opt. Exp.* **17**, 8685 (2009).
- [4] R. Oscillame, V. Maselli, R. M. Vazquez, R. Ramponi, G. Cerullo, *Appl. Phys. Lett.* **90**, 231118 (2007).
- [5] J. Suzuki, M. Yamaji, S. Tanaka, *Proc. SPIE* **7201**, 72011C (2009).
- [6] Y. Kuroiwa, N. Takeshima, Y. Narita, S. Tanaka, K. Hirao, *Opt. Exp.* **12**, 1908 (2004).
- [7] Y. Hayasaki, T. Sugimoto, A. Takita, N. Nishida, *Appl. Phys. Lett.* **87**, 031101 (2005).
- [8] S. Hasegawa, Y. Hayasaki, N. Nishida, *Opt. Lett.* **31**, 1705 (2006).
- [9] M. Yamaji, H. Kawashima, J. Suzuki, and S. Tanaka, *Appl. Phys. Lett.* **93**, 041116 (2008).

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\*Corresponding author: misty540@1999.jukuin.keio.ac.jp