PHOTOFABRICATION OF PERIODIC SUBMICRON STRUCTURES USING STANDING EVANESCENT LIGHT FOR NANO-STEREOLITHOGRAPHY

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1. Introduction

Microfabrication technologies have recently developed dramatically and have become required by which devices on the order of micrometer can be fabricated precisely. In particular, methods of fabricating MEMS and microscopic optical devices as typified by photonic crystal are in huge demand. The micro-stereolithography, one of microfabrication technologies, have attracted more attention because micro devices can be fabricated rapidly and flexibly[1]. However, the conventional micro-stereolithography method has a critical problem. Since the conventional method uses propagating light for exposure energy, the resolution of fabrication sizes is restricted by the diffraction limit. It means that it is almost impossible to fabricate micro objects with a resolution of sub-micrometer. Then, many kinds of approaches[2][3][4] have been demonstrated to overcome this problem.

In this study, we propose a novel stereolithography method using evanescent light instead of propagating light[5]. Figure 1(A) shows concept of our proposed stereolithography method. As shown in Figure 1(A), an incident angle of the exposure light beam is set over the critical angle. Under this optical condition, there is no longer propagating light transmitting through the photosensitive resin and the light energy is localized only the near-field region of the interface of the glass plate. The laminating process is as follows: First, incident light exposes and cures liquid resin (Figure 1(B)(a)). Next, the cured resin layer adhering on the base rod is lifted by the precise raising unit (Figure 1(B) (b)). Then light beam, which is modulated by a variable mask such as an LCD layer by layer, exposes and cures a next layer (Figure 1(B) (b)). Doing this loop repeatedly (Figure 1(B) (c)), desired object can be fabricated (Figure 1(B) (d)). Since evanescent light energy is localized within the range of the wavelength, the thickness of the cured resin layer is expected to be less than one micrometer. In addition, there occurs no optical transmission, which makes it possible to fabricate overhang structure. Consequently, it is expected that we can realize a flexible fabrication with a resolution of sub-micrometer.

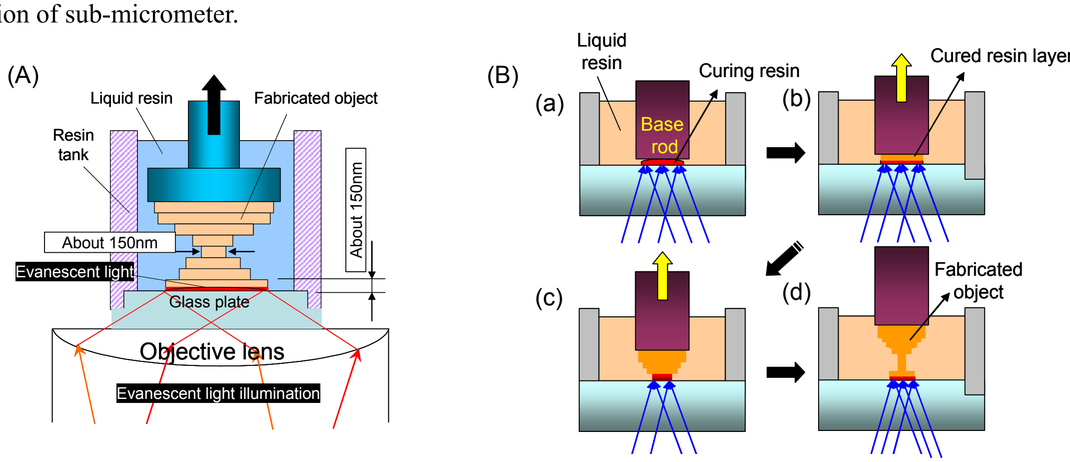

Figure1 Nano-stereolithography using evanescent light
(A) Concept, (B) Process

In this paper, as the first step in order to verify the validity of the proposed concept, we performed the fabrication of in-plane lattice shaped structures, which is strongly required as diffraction grating, diffractive optics, photonic crystals, etc. Theoretical and experimental analyses suggest that the proposed stereolithography method using evanescent light has a potential to fabricate micro three-dimensional objects with a resolution of sub-micrometer.

2. Photofabrication of periodic submicron structures using standing evanescent light

2.1 Theoretical analysis

The standing evanescent light, which is generated by the interference of two totally reflected counterpropagating laser beams, is employed as fine fringe light distribution to exposure the photosensitive resin. In this section, we theoretically analyze the standing evanescent light distribution. Figure 2 shows a schematic diagram of the standing evanescent light produced on a smooth surface of glass plate. The parameter n_1 and n_2 $(n_1 > n_2)$ are the refractive indexes of the glass plate and the resin respectively. The wavelength of the incident light is λ, the incident angle is θ. Then the period of standing evanescent light d can be expressed as follows.

$$d = \lambda / 2n_1 \sin\theta \quad (1)$$

From this equation, it can be seen that the period of the standing evanescent light is independent of the refractive index of the liquid resin n_2 and decreases as the refractive index of the glass plate n_1 increases. For example, when n_1=1.78, n_2=1.51 and λ=488 nm, the relation between the incident angle θ and the period d is represented as figure 3. This diagram shows that the period of the standing evanescent light can be flexibly adjusted at sub micrometer scale by changing the incident angle θ. And figure 4 means electromagnetic field (θ: 60degree) numerically calculated by FDTD simulator, which is based on Maxwell's equations. This electromagnetic field shows a fine period such as 150nm can be also generated in the liquid resin.

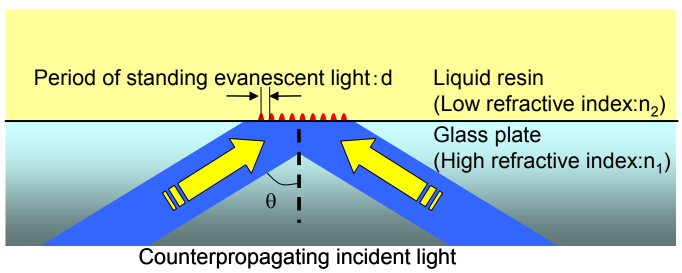

Figure2 Standing evanescent light

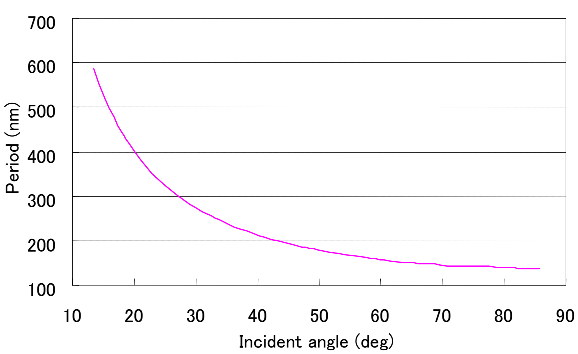

Figure3 Relation between the incident angle θ and the period d

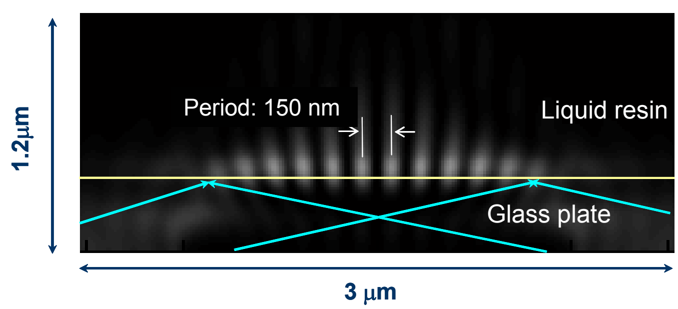

Figure4 Electromagnetic field of standing evanescent light calculated by FDTD simulator

2.2 Experimental analysis

2.2.1 Fundamental experiment using high refractive index prism

To verify the theoretical analyses mentioned above, we carried out a fundamental experiment. Before fabricating periodic submicron structures, we try to fabricate over micron structures using high refractive index prism. The experimental apparatus appears in Figure 5. A titaniferous prism is employed and a semiconductor laser with wavelength of 488nm is used as a light source. The prism and the cover glass are sealed by immersion oil. The refractive indexes of the cover glass and the immersion oil are same as the prism. Urethane acrylate resin (KC1162, JSR corp., n=1.51) is employed as the photosensitive resin. As shown in Figure 5, two laser beams is incident on the prism and totally reflected on the top of cover glass surface. The refractive index of the prism is 1.78, which can easily generate standing evanescent light on the cover glass located on the period of micrometer scale.

Figure 6 shows the typical result of fabricated periodic structures. As shown in this confocal laser scanning microscope image, clear periodic structures with the height less than 1μm and the period of about 5μm can be fabricated by our proposed method.

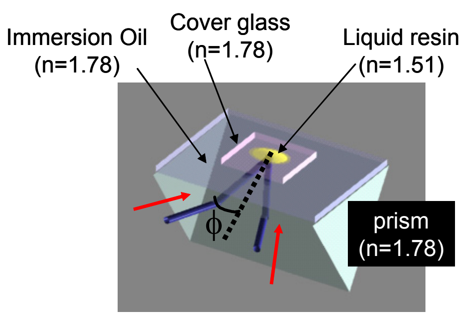

Figure5 Optical configuration using high refractive index prism

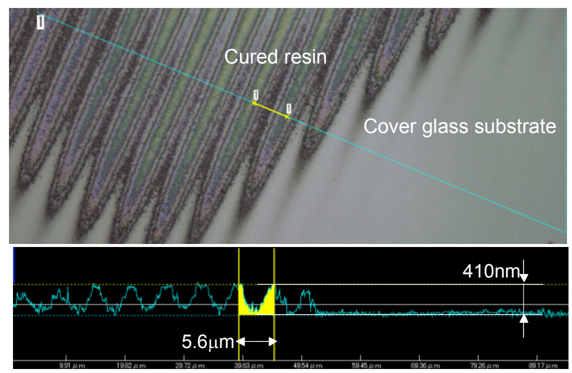

Figure6 Confocal laser scanning microscope image of fabricated periodic structures

2.2.2 Photofabrication of periodic submicron structures

In order to fabricate periodic submicron structures, we developed a standing evanescent light generation system using high power objective. Figure 7 shows the experimental set up of developed system. It mainly consists of a solid state diode pumped laser providing visible output at 488nm as a light source, a high-power objective with numerical aperture of 1.65 for forming the two totally reflected counterpropagating laser beams, a photosensitive resin tank located on the high-power objective. The laser beam is split into two beams by the beam splitter. These beams propagate through the collimating lens system (Lens1, Lens2, Lens3) and are constrained to pass through the periphery of the objective's pupils. They emerge form the front lens of objective and into high refractive index cover glass through the immersion fluid. Then on the top surface of the cover glass, standing evanescent light is expected to be generated in the liquid resin. The refractive indexes of the immersion oil, the cover glass, and the photosensitive resin (KC1162, JSR corp.) are 1.78, 1.78, and 1.51, respectively, which are same settings as the previous fundamental experiment. By installing the tube lens (Lens4), the optical microscope can be configured for infinity correction with the high power objective for evanescent generation. This microscope system allows us to directly observe the curing process of the photosensitive resin.

By using the developed apparatus, we carried out verification experiments curing the photosensitive resin by the standing evanescent light. Figure 8 shows an optical microscope image of a fabricated object in the case of incident angle θ of 15 degree. A cured resin layer by evanescent light can be seen, the diameter of which is about 50μm corresponding to the exposure area of standing evanescent light. And from the atomic force microscopy image (Figure 9), it can be seen that periodic submicron structures with the thickness about 300nm and the period of about 500nm can be fabricated.

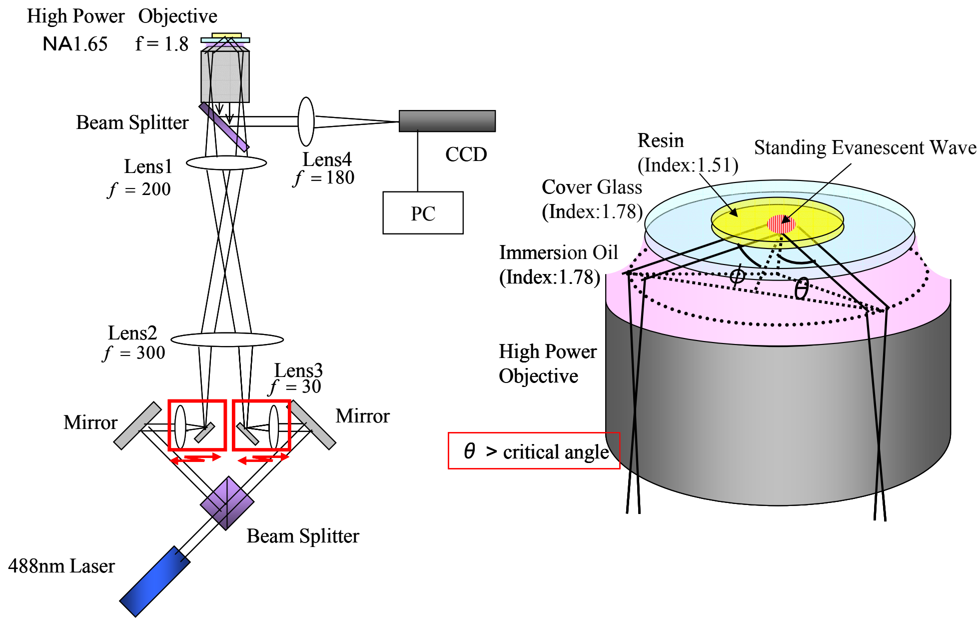

Figure7 Standing evanescent light generation system using high power objective

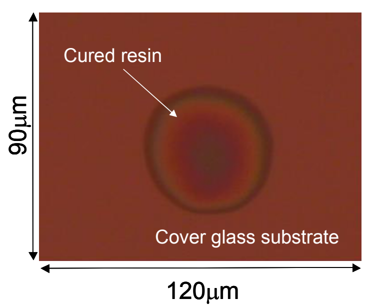

Figure8 Optical microscope image of fabricated object

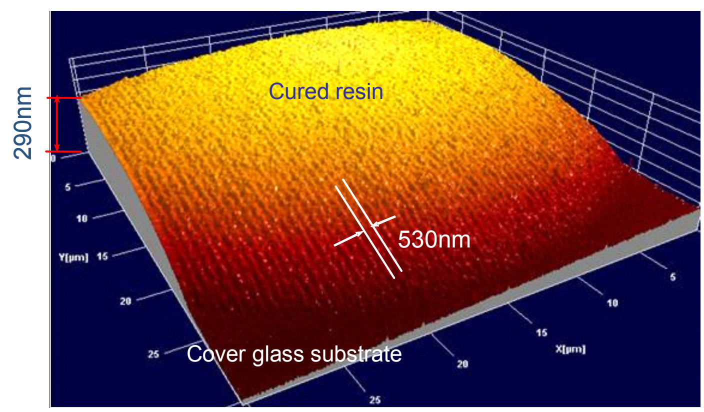

Figure9 Atomic force microscope image of fabricated structure

3. Conclusions

We proposed a novel stereolithography method using evanescent light. By using the proposed method, we tried to fabricate the in-plane lattice shaped structures with the period of sub micrometer scale. Theoretical and experimental analyses show that fabrication of fine periodic structures with a thickness and a period less than 1μm can be realized. And it is suggested that the proposed stereolithography method using evanescent light has a potential to fabricate micro three-dimensional objects with a resolution of sub-micrometer.

Acknowledgement
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