Development of a nano-stereolithography system using evanescent light for submicron fabrication

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INTRODUCTION

In recent years, micro-fabrication technologies have developed dramatically and fabrication methods have become required, by which small devices on the order of micrometer can be fabricated precisely. In particular, methods of fabricating MEMS and microscopic optical devices as typified by a photonic crystal are in huge demand. Micro-stereolithography is a micro-manufacturing method that can fabricate complex 3D microstructures by curing liquid photosensitive resin in a layer-by-layer process [1]. By this method, small 3D objects with micrometer resolution can be fabricated rapidly and this method has attracted more attention.

However, conventional micro-stereolithography method has some technical issues. Since it uses propagating light as the exposure energy, surplus growth is generated, which causes a dimension error and makes it difficult to fabricate a complex structure like overhang. In addition, since the resolution of fabrication sizes is restricted by the diffraction limit, it is almost impossible to fabricate submicron structures. Various approaches have been demonstrated to resolve these issues [2][3][4][5].

In this study, we propose a novel stereolithography method that uses evanescent light instead of propagating light [6]. We consider the application of the near-field optics and use evanescent light as the exposure energy. Since the evanescent light energy does not propagate but localizes within the near-field region, surplus growth is not generated. Furthermore, the resolution is independent of the diffraction, so that it becomes possible to fabricate 3D structures with 100-nanometer scales. By this unique method, we intend to establish the nano-stereolithography that can fabricate complex 3D microstructures with a resolution of sub-micrometer.

In this paper, we develop a nano-stereolithography system that generates evanescent light and has a high-resolution imaging system. Using this developed system, we carried out fundamental experiments. The results suggest that our proposed nano-stereolithography method allows us to fabricate complex 3D structures with a resolution of sub-micrometer such as microchannels and photonic crystals.

CONCEPT OF NANO-STEREOLITHOGRAPHY USING EVANESCENT LIGHT

In this section, we describe the characteristics of evanescent light that is a key factor of our method and explain the nano-stereolithography.

Evanescent light

When light crosses materials with different refractive indices, the light beam will be partially refracted at a boundary surface, and partially reflected. Assuming that an angle of incidence is shallower than the critical angle, the light beam will stop crossing the boundary altogether and instead totally reflect back internally. Under this optical condition, nevertheless, there occurs partially localized energy at the boundary (Figure 1). The energy is evanescent light.

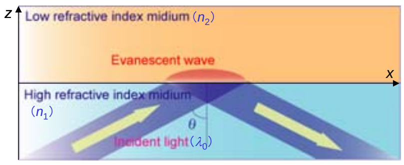

FIGURE 1: When an angle of incidence θ is shallower than the critical angle, there occurs evanescent light at the boundary.

The electric field E_2 of evanescent is expressed as follows by applying Maxwell's equations and Snell's law.

$$\mathbf{E}_2 = \mathbf{A}\exp(i\omega t)\cdot\exp(-\frac{z}{Z_{ev}})\cdot\exp(-ik_2 x\frac{n_1}{n_2}\sin\theta) \qquad (1),$$

$$(Z_{ev} = \lambda_0 / 2\pi n_2\sqrt{(n_1/n_2)^2\sin^2\theta - 1})$$

where the axis perpendicular to the boundary of Figure 1 is z, the axis equivalent to the boundary is x, the amplitude is A, refractive indices of mediums are n_1 and n_2 ($n_1 > n_2$), the wavelength of the incident light is λ_0, the angle of incidence is θ, the angular frequency is ω, and the wavenumber in the low refractive index medium is k_2. This equation indicates that the evanescent light energy decays exponentially with distance and it is localized within the range of the wavelength.

Nano-stereolithography

Figure 2 shows a schematic diagram of the nano-stereolithography method using evanescent light. First, the incident beam at a shallower angle than the critical angle generates evanescent light at the boundary, which cures liquid photosensitive resin (Figure 2(a)). Next the cured resin adhering on the base rod is lifted and liquid resin is refilled at the boundary surface (Figure 2(b)). Then the evanescent light, which is modulated by a variable mask such as an LCD, exposes and cures a next layer (Figure 2(C)). Doing this loop repeatedly, desired object is fabricated (Figure 2(d)).

Since the 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.

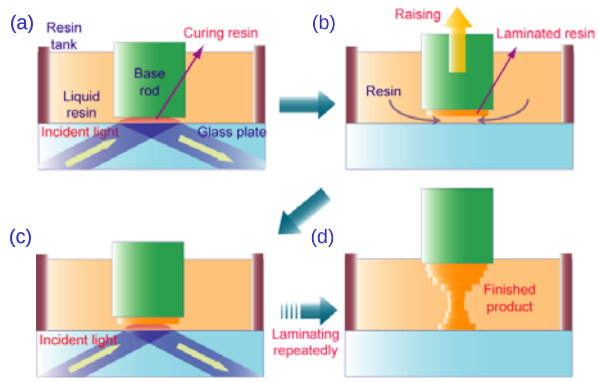

FIGURE 2: Schematic diagram of the nano-stereolithography method using evanescent light.

DEVELOPMENT OF A NANO-STEREOLITHOGRAPHY SYSTEM

Shown in Figure 3 is a developed nano-stereolithography system using evanescent light. It mainly consists of a solid state diode pumped laser providing visible output at 488nm, a high-power objective with a numerical aperture of 1.65 for forming a totally reflected beam, a resin tank located on the high-power objective, and a PZT stage, accuracy positioning of which is 1 nanometer, for lifting cured resin layers.

The light beam oscillated by the laser source propagates through a collimating lens system (Lens1 and Lens2) and is modulated by a variable mask such as an LCD or a DMD. The modulated beam is constrained to pass through

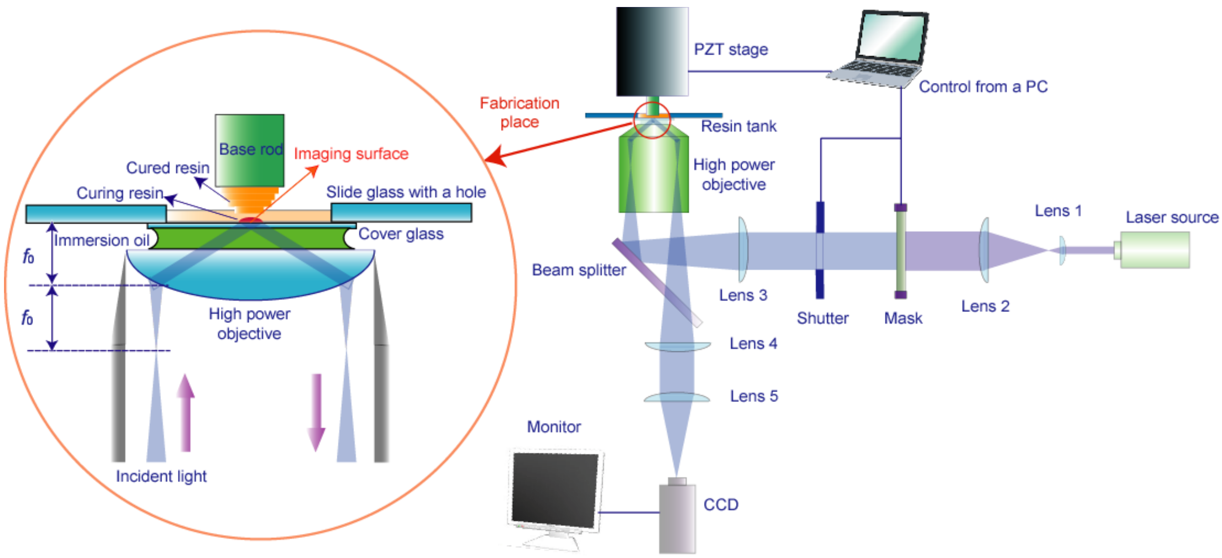

FIGURE 3: A developed nano-stereolithography system using evanescent light (Right) A modulated beam passes through the periphery of the objective's pupils and evanescent light is generated in the liquid resin. (Left) The exposure surface is equivalent of the imaging surface of the variable mask.

the periphery of the objective's pupils. It emerges from the front lens of the objective and passes into a cover glass of high refractive index through the immersion oil. Then on the top surface of the cover glass, evanescent light is generated in the liquid resin. The refractive indices of the immersion oil, the cover glass, and the photosensitive resin (KC1162, JSR corp.) are 1.78, 1.78, and 1.51 respectively. The critical angle is 57.4 degrees.

Notice that this exposure surface is equivalent of the imaging surface. The lens3 and the objective reduce the light intensity distribution 110 times from the distribution at the mask position. By installing a tube lens (Lens4 and Lens5) and a CCD, an optical microscope can be configured for infinity correction with the high power objective for evanescent generation. This microscope system allows us to directly observe a curing process of the photosensitive resin. A slide glass with a hole forms a resin tank and the PZT stage lifts the base rod during the layer-by-layer process. The mask, the PZT stage and an electronic shutter are controlled from a PC.

EXPERIMENT FOR 2D FABRICATION

In this section, we describe an experiment for 2D submicron fabrication carried out to verify the imaging system of the nano-stereolithography system.

Experimental condition

Figure 4 shows a pattern set at the mask position. With this pattern, a discoidal cured resin with a submicron groove should be fabricated by evanescent light exposure. Shown in Table 1 is the exposure condition.

TABLE 1: Exposure condition.

Angle of incidence	Exposure energy	Exposure time
65 degrees	600 mW/cm^2	4 seconds

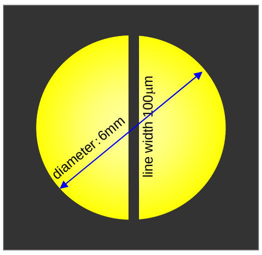

FIGURE 4: A pattern with a rectangular masking, with which a discoidal cured resin with a submicron groove should be fabricated.

Results and discussion

Exposed by the modulated evanescent light, a discoidal cured resin with a groove was fabricated. We analyzed the resin with a white light interferometer (NewView 5000, Zygo corp.) after a gold evaporation process. The result is shown in Figure 5. The thickness of the resin was about 300 nanometers, which has not been realized by the conventional method using propagating light exposure. The width of it was about 900 nanometers. This result suggests the possibility of 2D submicron fabrication and it suggests that complex shapes like a microchannel could be fabricated through the layer-by-layer process.

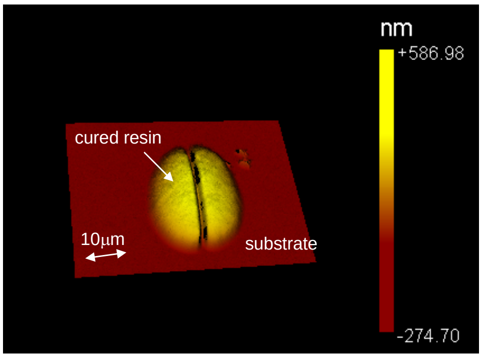

FIGURE 5: The result of the fabricated pattern analyzed by a white light interferometer, which suggests the possibility of 2D submicron fabrication.

EXPERIMENT FOR 3D FABRICATION

We describe an experiment for 3D submicron fabrication in this section. It is most important that we verify the lamination process for the layer-by-layer process of stereolithography. For the first step, we attempted to fabricate steps shown in Figure 6. The thicknesses of these steps are all about 500 nanometers.

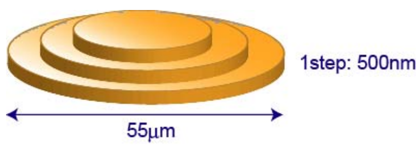

FIGURE 6: These steps are attempted to fabricate to verify the lamination process.

Experimental condition

Diameters of the mask patterns were 6mm, 4mm, and 3mm respectively, so that expected diameters of fabricated steps would be 54μm, 36μm, and 27μm respectively. The exposure condition was the same at the table 1.

Results and discussion

Figure 7 shows the fabricated steps with the developed nano-stereolithography system. The microscope image shows that the diameter of each step was approximately equal to the expected diameter. The AFM analysis shows that the thickness of each step was about 500 nanometers.

This result indicates that laminating cured resin layers of submicron thicknesses, namely nano-steps, is possible with the developed nano-stereolithography system. Applying the photofabrication of periodic submicron structures using standing evanescent light [7] to this lamination process, photonic crystals for visible range are expected to be fabricated.

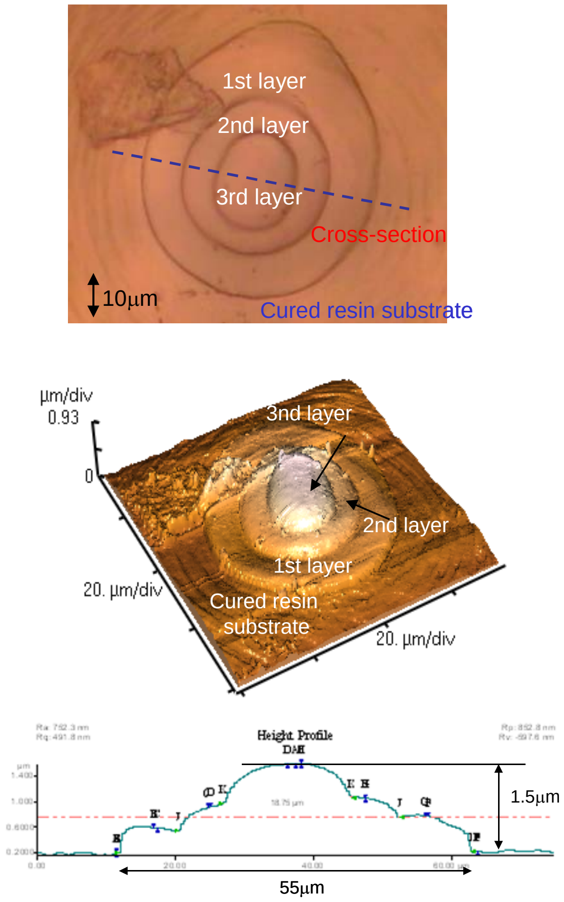

FIGURE 7: Fabricated nano-steps. (TOP) Microscope image. (Middle) AFM image. (Bottom) Cross section of the AFM.

CONCLUSION

We developed the nano-stereolithography system using evanescent light, which mainly consists of a laser at 488nm, a high-power objective with a numerical aperture of 1.65, and a PZT stage, accuracy positioning of which is 1 nanometer.

Two fundamental experiments were carried out with this system for verifying the imaging system and the lamination process. In the first experiment, a discoidal cured resin with a groove, the width of which was about 900 nanometers, was fabricated. In the second experiment, nano-steps were fabricated, the thickness of which were about 500 nanometers.

These facts suggest that complex submicron structures such as microchannels and photonic crystals could be fabricated with our proposed method.

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