Study of Nano-Stereolithography Using Evanescent Light

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Abstract

We proposed a novel stereolithography method using evanescent light instead of propagating light to realize a 100-nanometer resolution. We carried out theoretical and experimental analyses to verify the method. The analyses show that evanescent light energy is sufficient for curing resin and that it is possible to fabricate micro three-dimensional objects with a 100-nanometer resolution.

Keyword: nano-stereolithography, photosensitive resin, propagating light, evanescent light

Introduction

Micro-fabrication 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 Micro Electro Mechanical System (MEMS) and microscopic optical devices as typified by photonic crystal are in huge demand. The micro-stereolithography, one of Micro-fabrication 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][5] have been demonstrated to overcome this problem.

In this study, we propose a novel stereolithography method using evanescent light instead of propagating light. In this method, we consider an application of the near-field optics and apply evanescent light to exposure energy for curing photosensitive resin. Since evanescent light does not propagate but localizes within the near-field region, its resolution is independent of the diffraction limit. It means that it is possible to fabricate micro three-dimensional objects with a resolution of sub-micrometer. By applying this method, we intend to establish the nano-stereolithography with higher accuracy and flexibility. This paper describes theoretical and experimental analyses we performed to confirm the validity of the proposed concept.

Concept of Nano-Stereolithography Using Evanescent Light

Figure 1 shows one of the stereolithography processes on which the proposed method is based. First, incident light exposes and cures liquid resin (Figure 1(a)). Next, the cured resin layer adhering on the base rod is lifted by the raising unit (Figure 1(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)). Doing this loop repeatedly (Figure 1(c)), desired object can be fabricated (Figure 1(d)).

In this process, we propose to use evanescent light as the incident light for exposure energy, while propagating light is generally used. Figure 2 shows the characteristic of our proposed evanescent light exposure (Figure 2(b)) to compare it with the conventional propagating light exposure (Figure 2(a)). In the conventional method, since propagating light transmits through the photosensitive resin, the cure depth depends on the absorption coefficient of the resin. This means the thickness of the cured resin layer is over one micrometer and fabricating an overhang structure is very difficult. Therefore the method of conventional micro-stereolithography currently cannot realize a resolution below one micrometer.

In our method, 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 area of the interface of the glass plate. This light energy is evanescent light, which is independent of the diffraction limit. 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.
For example, when $n_1=1.78$, $n_2=1.49$ and $\lambda_0=488$ nm, the relation of the incident angle $\theta$ and the distance $h$ is represented as figure 4. Assuming that the thickness of the cured resin layer depends on the distance where electric field decays into 1/e of the incidence value, it can be flexibly adjusted from 100 to 700nm by changing the incident angle $\theta$.
Experimental Analysis

To verify the theoretical analyses mentioned above, we developed an experimental apparatus and carried out some experiments. The apparatus appears in Figure 5. It mainly consists of a semiconductor laser as a light source, a titaniferous prism on which a resin tank is set, and a base rod for lifting fabricated micro-objects. The laser beam, the wavelength of which is 488 nm, is split into the beam A and B by the beam splitter. The beam A and B are for the propagating light exposure and for the evanescent light exposure respectively.

The refractive index of the prism is 1.78, which can easily generate evanescent light on the cover glass located on the prism. 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 (KC1042, JSR corp, nd=1.491) is employed as the photosensitive resin. By installing a glass scale on a single axis stage, the base rod can be precisely positioned with a resolution of ten nanometers.

By using the developed apparatus, we carried out basic experiments to analyze the vertical resolution. In this experiment, the laser power, the incident angle and the exposure time are set at 3 mW, 68 degrees and 120 seconds respectively. We firstly checked whether evanescent light energy was sufficient for curing resin. Figure 6 shows the procedure of the evanescent light exposure experiment. Before the evanescent light exposure, the propagating light exposure was performed to fabricate a cured resin substrate. Then we tried to fabricate a single resin layer on the substrate by the evanescent light.

Figure 7 shows an optical microscope image of a fabricated object. A cured resin layer by evanescent light can be seen. It means that evanescent light energy is sufficient for curing resin. Next, by using an atomic force microscopy (AFM), we measured the thickness of the cured resin layer corresponding to the vertical resolution.
Cured resin substrate by propagating light

Cured resin layer by evanescent light

Glass plate 100 µm

Observation area

Figure 7. Optical Microscope Image of the Cured Resin Layer

Figure 8 shows an AFM image and a cross-section profile of the cured resin layer by evanescent light. The thickness of the cured resin layer is evaluated at about 300 nanometers and this fact indicates that micro-objects can be fabricated with sub-micrometer vertical resolution.

Figure 8. AFM image and Cross-Section Profile of Cured Resin

Conclusion
We proposed a novel stereolithography method using evanescent light. We carried out several theoretical and experimental analyses to verify this method. The theoretical analyses suggested that we could fabricate micro-objects with sub-micrometer resolution. Then we developed the nano-stereolithography system, in which photosensitive resin could be exposed by evanescent light as well as propagating light, and carried out basic experiments. The experimental results showed that evanescent light energy was sufficient for curing resin and that a 300-nanometer thickness layer can be fabricated. These results indicate the feasibility of stereolithography with 100-nanometer resolution, which could not be realized by conventional stereolithography methods.

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