Dynamic Control of Lateral Evanescent Light Distribution for Microstereolithography

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Satoru Takahashi[1], Takayoshi Oshima[1], Toshimune Nagano[1], Yusuke Kajihara[2], and Kiyoshi Takamasu[1]
[1]Dept. of Precision Engr., The University of Tokyo, Japan; e-mail: takahashi@nanolab.t.u-tokyo.ac.jp
[2]Dept. of Basic Sci., The University of Tokyo, Japan; e-mail: kaji@thz.c.u-tokyo.ac.jp

INTRODUCTION

In recent years, microfabrication 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. Microstereolithography [1-10] is one of the advanced micromanufacturing methods that can fabricate complex 3D microstructures by curing the liquid photosensitive resin [1]. In microstereolithography, a layer-by-layer process [3, 5-8] can fabricate 3D micro structures by laminating a thin film having a desired lateral shape, which is exposed with image formation using a dynamic mask. This process has an advantage in a higher productivity due to the one-shot area exposure compared to a two-photon-absorption process, but has a disadvantage that a spatial resolution mainly depends on a thickness of a film layer having a limit due to a propagating property of freely propagating light.

In order to overcome this critical problem, we're proposing a novel microstereolithography method [8-10] using evanescent light (Fig. 1) instead of freely propagating light. We consider the application of the near-field optics and apply evanescent light to the exposure energy for curing photosensitive resin.

Since evanescent light energy does not propagate but localizes within the near-field region, no surplus growth due to the propagating property of freely propagating light is expected. In order to put the proposed method into practice, one of the most important tasks is to develop a lateral evanescent light distribution control system, which can be applied to microstereolithography. So the purpose of this paper is to develop a dynamic lateral evanescent light distribution control system, with which we can cure a less than 1 μm thin resin layer, having a desired lateral shape.

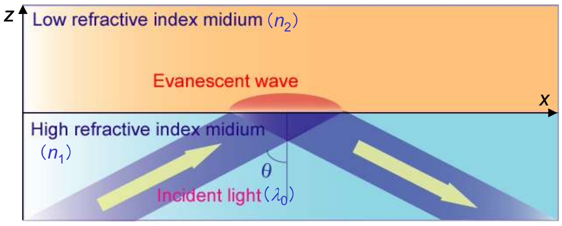

Fig. 1: Evanescent light emerging under TIR condition

MICROSTEREOLITHOGRAPHY USING EVANESCENT LIGHT

Fig. 2 shows the proposed microstereolithography process 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 (Fig. 2(a)). Next the cured resin adhering on the base rod is lifted and liquid resin is refilled at the boundary surface (Fig. 2(b)). Then the evanescent light, which is modulated by a dynamic mask, exposes and cures a next layer (Fig. 2(C)). Repeating this loop, desired object is expected to be fabricated (Fig. 2(d)).

THEORETICAL ANALYSIS OF THICKNESS OF CURED LAYER

In conventional layer-by-layer microstereolithography involving propagating light exposure, cure depth C_d of cured polymer is expressed as follows [1]:

$$C_d = D_p \ln \frac{U}{U_c}, \tag{1}$$

where D_p is the penetration depth (inverse of photopolymer absorption coefficient α), U is the exposure energy, and U_c is the threshold exposure energy.

Consider a light beam traveling from glass (refractive index n_1) into liquid photopolymer (refractive index $n_2 < n_1$). When incident angle θ at the interface is greater than the critical angle, the light beam no longer propagates within the photopolymer and is instead totally reflected. Nevertheless, partially localized energy is present at the boundary. This localized energy is evanescent light [11]. In nanostereolithography, the cure depth depends on attenuation coefficient of evanescent light β as well as absorption coefficient α. The

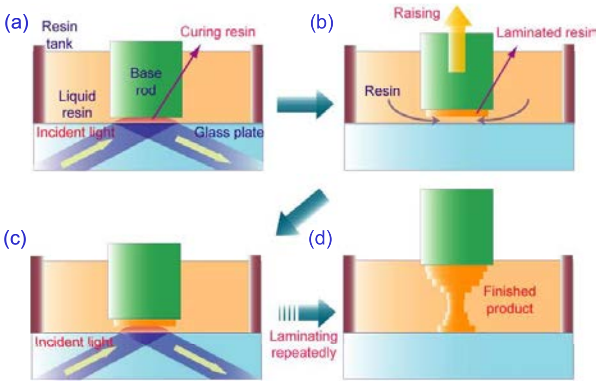

Fig. 2: Microstereolithography process using evanescent light

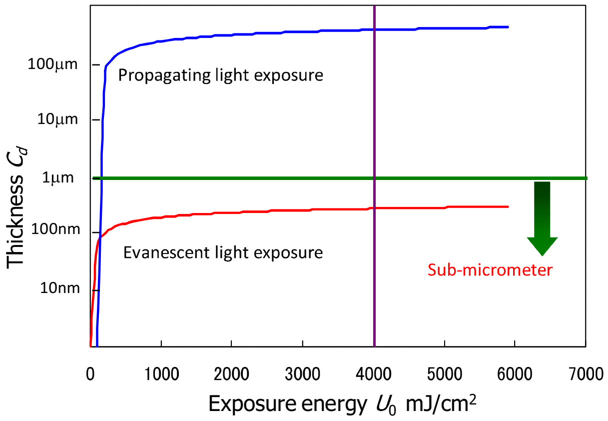

Fig. 3: Theoretical analysis of thickness of cured resin layer

cure depth is inversely proportional to α and 2β. Coefficient α is on the order of 10^2 or 10^3 cm^{-1} and coefficient β is on the order of 10^6 cm^{-1}. Hence, the cure depth largely depends on β. Assuming that photopolymer is an isotropic medium, the cure depth in nanostereolithography is formulated as follows [8, 10]:

$$C_d = \frac{\lambda}{4\pi n_2 \sqrt{(n_1/n_2)^2 \sin^2\theta - 1}} \ln \frac{\tau(\theta)U}{U_c} \quad \left(= \frac{1}{2\beta} \ln \frac{\tau(\theta)U}{U_c} \right), \qquad (2)$$

where λ is the wavelength of the laser beam and $\tau(\theta)$ is the constant depending on the polarization and the incident angle [11].

Fig. 3 shows the relation between cure depth and exposure energy in propagating and evanescent light exposures calculated using equations (1) and (2) under the following condition—$\lambda = 488$ nm, $n_1 = 1.78$, $n_2 = 1.51$, $U_c = 100$ mJ/cm², $\theta = 68$ degree, and P polarization. This graph demonstrates that the cure depth under evanescent light exposure would be calculated to be less than 1 μm, whereas the cure depth under propagating light exposure would be calculated to be more than 100 μm.

DEVELOPMENT OF LATERAL EVANESCENT LIGHT DISTRIBUTION CONTROL SYSTEM

Fig. 4 shows a microstereolithography system, with which we can dynamically control an evanescent light exposure distribution. This system consists mainly of an evanescent light exposure unit using DMD dynamic mask and an automatic focusing unit based on confocal optics.

The evanescent light exposure unit consists mainly of a light emitting diode providing visible at 470 nm as a light source, a high-power objective with a numerical aperture of 1.65, a resin tank located on the objective, and a digital mirror devices (DMD, mirror size:13.7 μm, 769 x 1024 mirrors) for a dynamic mask. A low pass filter at the position of a Fourier transform plane of the DMD mirror plane allows an evanescent light exposure on a photosensitive resin located on a cover glass, which is set with the objective lens under the total internal reflection condition (Fig. 5). This DMD system including the low pass filter has the potential of controlling the lateral evanescent exposure area with a lateral resolution of 250 nm. As shown in Fig. 5, the refractive indices of the

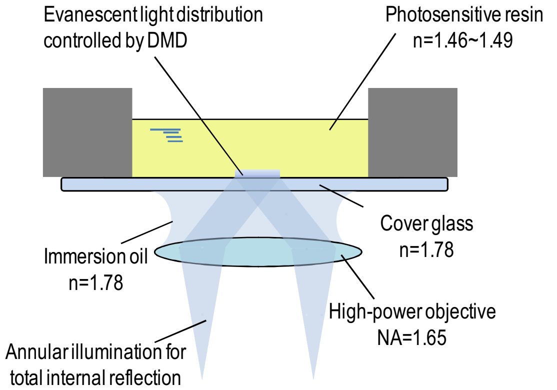

Fig. 5: Evanescent light energy generated with objective

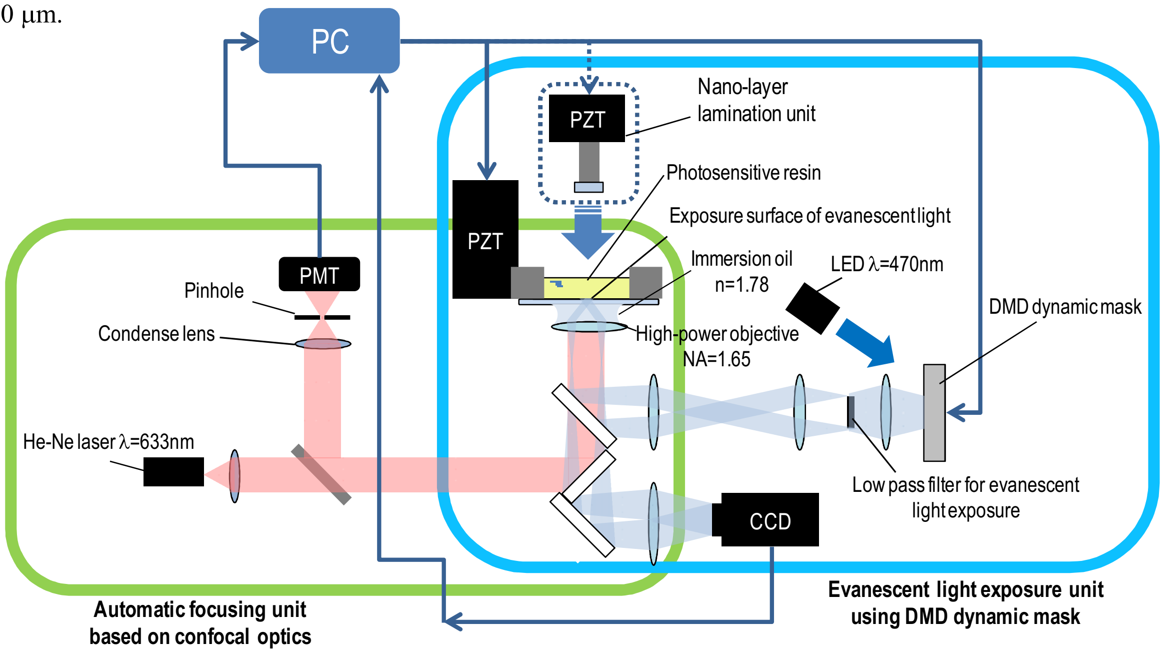

Fig. 4: Dynamic lateral evanescent light distribution control system using DMD

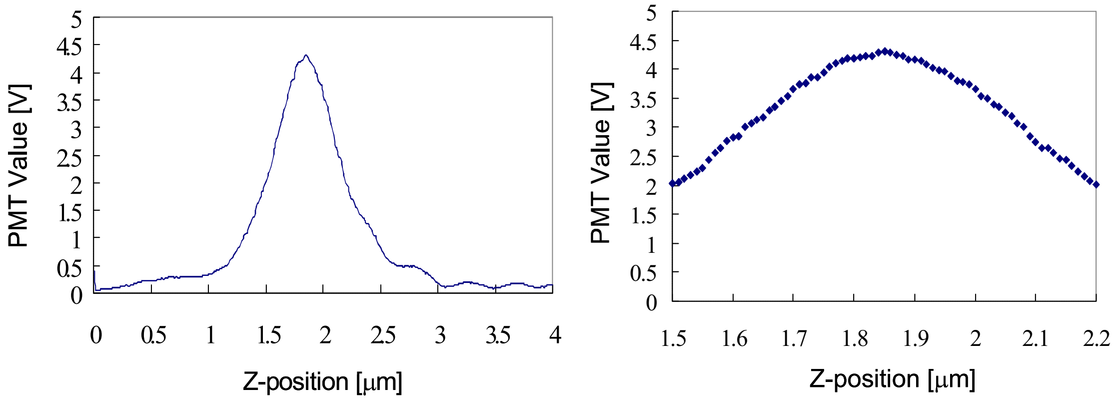

Fig. 6: Variation of PMT values with the position of the exposure surface
(a) From 0 μm to 4 μm (b) From 1.5 μm to 2.2 μm

cover glass and the photosensitive resin (KC1162, JSR Corp.) are 1.78 and 1.51, respectively. The critical angle is 57.4 degrees. The high power objective lens, the tube lens, and the CCD configure the optical microscopic system. This optical system allows direct observation of the curing process of the photosensitive resin.

On the other hand, the automatic focusing unit consists of a He-Ne laser having no effect on the photosensitive resin, the objective lens, the condenser lens, the pinhole, and PZT stages for positioning the exposure surface. In this unit, a beam from the light source at 633 nm is collimated by the lens, enters the objective lens, and is reflected on the exposure surface. The reflected beam enters the condenser lens, the pinhole, and finally reaches the PMT. Outputs of the PMT reach the largest value when the exposure surface is in the focal position. Since the N.A. of the condenser lens is 0.25, the diameter of the Airy Disc is calculated to be 3.09 μm. Hence a pinhole with a diameter of 3 μm is adopted. The DMD mask, the PZT stages are automatically controlled from a personal computer.

EVALUATION OF THE CONFOCAL SYSTEM

First, an examination of the confocal microscopic system was demonstrated to estimate the depth resolution. The exposure surface on the cover glass attached to the slide glass was scanned 4 μm at 10 nm intervals by the PZT stage. The PMT values were recorded 10 times at 0.01 second intervals at every position and an average of 10 values were calculated. Fig. 6 (a) shows a graph of the variation of the PMT values. The horizontal axis means the position of the exposure surface and the longitudinal axis means the average of the PMT values. The PMT value reaches the largest value when the exposure surface is in the focal position. This result indicates that the developed confocal system performs properly. Fig. 6 (b) shows the picked out data. This indicates that the system can provide depth resolution of approximately 100 nm, which is less than the depth of focus of the objective for the exposure.

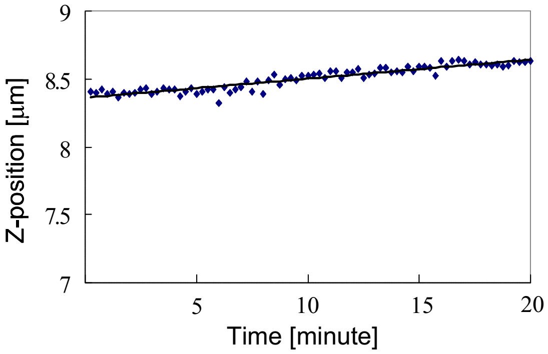

Fig. 7: Positioning repeatability of the focusing system

The positioning process of the exposure surface moves the cover glass to the position of the PMT largest value. For examining the positioning repeatability, the PMT value was measured by scanning the exposure surface by 10 nm (total: 4 μm) again, and the position of the maximum value was outputted. This process was repeated 80 times within 15 seconds. Fig. 7 shows the result. The horizontal axis means the time and the longitudinal axis means the z-position of the maximum value. The standard deviation of natural data was calculated to be 86.4 nm. However, the standard deviation was calculated to be 30.8 nm after removing the drift effects. This result of the positioning repeatability almost meets the required specification, which is less than 100 nm.

EVANESCENT LIGHT ENERGY EXPOSURE EXPERIMENT

With the developed dynamic lateral evanescent light distribution control system using DMD mentioned in the previous section, we performed the evanescent light energy exposure experiment. Fig. 8(a) shows the projection pattern formed with the DMD. Fig 8(b) is the optical microscopic image of a cured resin layer fabricated with the exposure energy of 3.47 W/cm^2 and the exposure time of 3.5 sec. From this, it can be seen that the developed system allows us to control the lateral shape of the cured resin layer under the

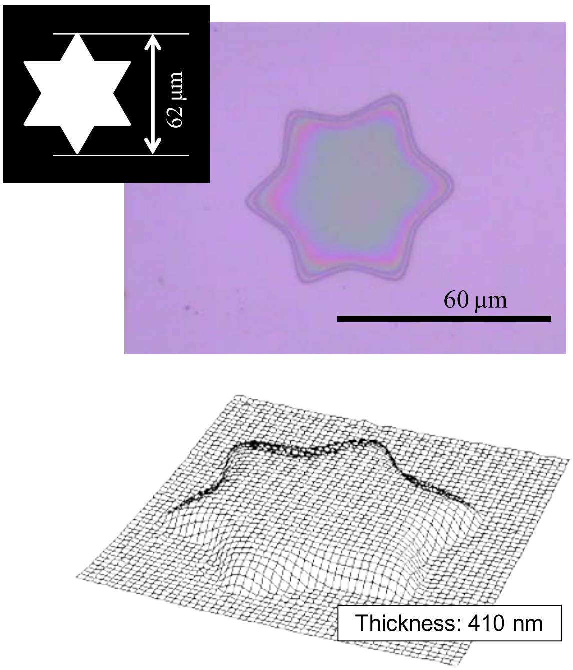

Fig. 8: Cured resin layer under evanescent light exposure
(a) Projection pattern of DMD
(b) Optical microscopic image of the cured resin layer
(c) AFM image of the cured resin layer

evanescent light illumination. In order to estimate the profile of the cured resin layer quantitatively, an atomic force microscope (AFM) was employed. Fig. 8(c) is the AFM image of the cured resin layer. Thickness of this layer is estimated about 400 nm. And Fig. 9 shows a cured resin fabricated under the propagating light exposure, which can be performed by changing the NA of the high-power objective into 0.28. The height of the cured resin under the propagating light exposure is about 140 μm. The comparison of Fig. 8 and Fig. 9 verify the theory that the cure depth under evanescent light exposure can be less than 1 μm, whereas the cure depth under propagating light exposure is more than 100 μm.

CONCLUSIONS

We are proposing a novel microstereolithography method based on a layer-by-layer process using an evanescent light energy. A theoretical analysis indicates that this method has a possibility of curing a resin layer with the thickness less than 1 μm. In this paper, in order to realize the lateral shape control of cured resin under the evanescent exposing condition, we developed the lateral evanescent light exposure system using a DMD dynamic mask with an automatic focusing unit based on confocal optics. With this developed system, we verified that the developed system can provide the function of the lateral shape control of the evanescent exposing resin with a cure depth less than 1 μm. As a future work, we plan to realize the proposed microstereolithography method by laminating multi layers, using the developed single layer curing technique mentioned in this paper.

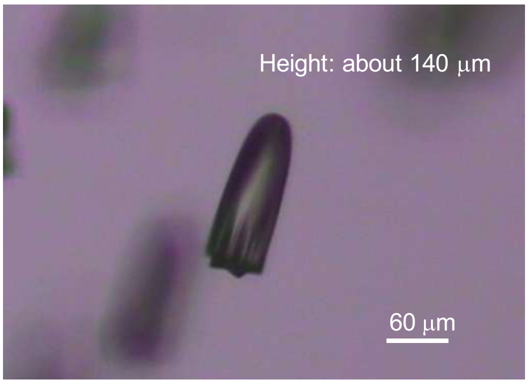

Fig. 9: Cured resin layer under propagating light exposure

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