Development of an In-process Confocal Positioning System for Nano-stereolithography Using Evanescent Light

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A novel stereolithography method using evanescent light has been proposed as a means to realize 100-nanometer resolution. An in-process measurement system with high accuracy has been introduced to the nanostereolithography apparatus. Specifically, an optical microscopic system was developed to monitor the exposure process and a confocal positioning system was established to improve the longitudinal positioning accuracy in the layer-by-layer process. A high-power objective lens, a tube lens, and a charge coupled device (CCD) were included in the optical microscopic system, whereas a laser, a high-power objective lens, a piezoelectric (PZT) stage, a condenser lens, a pinhole, and a photomultiplier (PMT) made up the confocal microscopic system. Two verification experiments were conducted, and the results indicated that the optical microscopic system had a horizontal resolution of 200 nm and that the confocal positioning system provided a depth resolution of 30.8 nm. These results indicate that nanostereolithography can be successfully performed with this system.

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NOMENCLATURE

A = amplitude of evanescent light
ω = angular frequency
λ = wavelength
t = time
k_2 = wavenumber in the low refractive index medium
n_1 = refractive index of high refractive index medium (glass)
n_2 = refractive index of low refractive index medium (resin)
θ = incident angle
h_1 = point spread function (PSF) of the objective lens
h_2 = point spread function (PSF) of the condenser lens
D = pinhole size
$N.A.$ = numerical aperture

1. Introduction

Microstereolithography is a common rapid prototyping technology[1,2] that allows the fabrication of complex three-dimensional (3D) microstructures through the curing of liquid photosensitive resin in a layer-by-layer process.[3-5] Small 3D objects with micrometer resolution can be fabricated rapidly, which makes this method very attractive for use in many applications. However, the conventional microstereolithography method has some critical drawbacks. Since this method uses propagating light as the exposure energy, incident light is transmitted through the resin and surplus growth is generated. This causes a dimension error and makes it difficult to fabricate a complex structure such as an overhang. In addition, it is almost impossible to fabricate microstructures with sub-micrometer resolution since the spatial resolution is restricted by the diffraction limit. In order to resolve these issues, we have proposed a novel nanostereolithography method that uses evanescent light instead of propagating light as the exposure energy.[6]

When light crosses materials with different refractive indices, the light beam will be partially refracted at a boundary surface, and partially reflected. Assuming that the incident angle is greater than the critical angle, as shown in Fig. 1, the light beam no longer propagates within the low refractive index medium and is instead totally reflected. Nevertheless, partially localized energy is present at the boundary. This localized energy is evanescent light.[7] The electric field **E** of evanescent light is expressed as follows by applying Maxwell's equations and Snell's law:

$$\mathbf{E} = \mathbf{A}\exp(i\omega t)\cdot\exp(-\frac{z}{Z_{ev}})\cdot\exp(-ik_2 x\frac{n_1}{n_2}\sin\theta) \quad , \quad (Z_{ev} = \lambda / 2\pi n_2\sqrt{(n_1/n_2)^2\sin^2\theta - 1}) \qquad (1)$$

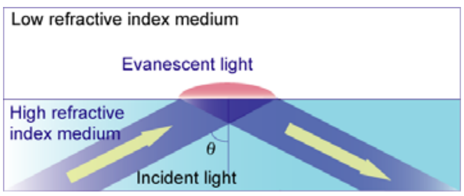


Fig. 1 When the incident angle is greater than the critical angle, localized evanescent light occurs at the boundary

where the perpendicular axis in Fig. 1 is z and the equivalent axis to the boundary is x. Equation (1) indicates that the evanescent light energy decays exponentially with distance and is localized within the range of the wavelength. Since evanescent light energy localizes within the near-field region, surplus growth is not generated. Furthermore, the resolution is independent of the diffraction, so that it should be possible to fabricate 3D structures with sub-μm resolution.

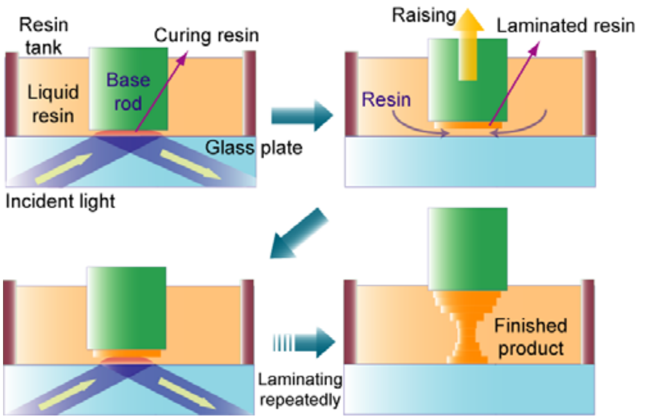


Fig. 2 Schematic diagram of nanostereolithography using evanescent light

Figure 2 shows a schematic diagram of nanostereolithography using evanescent light. This method has two main processes. One is an exposure process and the other is a layer-by-layer process. In the exposure process, incident light passes through an imaging system and generates evanescent light on a glass plate. Then the evanescent light energy exposes the photosensitive resin. To confirm the light intensity distribution and to monitor the resin curing, an in-process system, like an optical microscope, is required. In the layer-by-layer process, a cured resin layer adhering to a base rod is lifted by a PZT stage and a liquid resin gap is created between the cured resin layer and the glass plate. This process requires a longitudinal high-accuracy positioning system of the glass plate since even a very small gap error makes it impossible to fabricate submicron devices.

In this paper, an in-process confocal positioning system with high-resolution is developed for nanostereolithography using evanescent light. Evaluation experiments are then performed.

2. Development of an In-process Confocal Positioning System

2.1 Design of the in-process confocal positioning system

Figure 3 shows a fabrication of a nanostereolithography apparatus using evanescent light.[8] It consists mainly of a high-power objective lens (N.A.=1.65) for forming a totally reflected beam, a resin tank which includes a slide glass with a hole, and a base rod for lifting cured resin layers. The refractive indices of the objective lens, the immersion oil, and the cover glass are all 1.78, and together form a solid immersion lens.

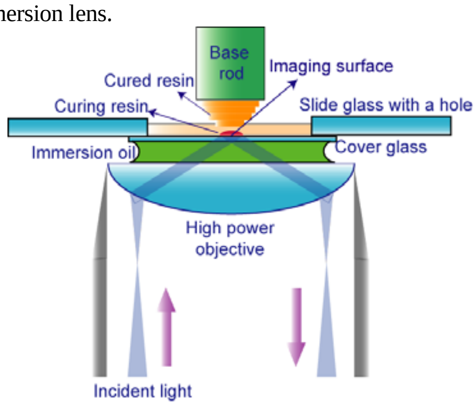


Fig. 3 Fabrication of nanostereolithography apparatus with an objective lens, a resin tank and a base rod

A modulated beam passes through the periphery of the objective's pupils and generates evanescent light in the liquid resin. When the incident angle is greater than the critical angle, evanescent light is generated on the top surface of the cover glass. The base rod is lifted by a PZT stage with a resolution of less than 10 nm in the layer-by-layer process. During the exposure process, a monitoring system is required to observe the light intensity distribution and the resin curing. Therefore, we have introduced an optical microscopic system to the nanostereolithography apparatus. The horizontal resolution of the system should be on the order of sub-micrometers because nanostereolithography using evanescent light fabricates very small devices with sub-micrometer structures.

In addition, during both the exposure and the layer-by-layer process, a longitudinal positioning system of the substrate (cover glass) is absolutely essential. Since the focal depth of the objective lens is about 300 nm, the depth resolution of the positioning system should be less than 300 nm to confirm the light intensity distribution in the exposure process. In the layer-by-layer process, the depth resolution should be less than 100 nm because the thickness of each layer is on the order of sub-micrometers. In this study, we introduced a confocal positioning system which can provide nanometer depth resolution.[9,10,11,12,13]

Providing that a dot object is positioned, an imaging intensity distribution I of the dot object in a confocal system is expressed as[9]:

$$I = |h_1|^2 \left\{ |h_2|^2 \otimes D \right\}. \tag{2}$$

Equation (2) indicates that an objective lens with a high numerical aperture and a pinhole with a small diameter are required. The diameter of the pinhole should be less than the diameter of the Airy Disc size to maximize the effects of the confocal system.[14] The diameter of Airy Disc d is expressed as[15]:

$$d = \frac{1.22\lambda}{N.A.}. \tag{3}$$

2.2 Development of the in-process confocal positioning system

Figure 4 shows the developed nanostereolithography apparatus with an in-process confocal positioning system. It consists mainly of lasers at 488 nm and 633 nm, a variable mask, an electronic shutter, a high-power objective lens, a resin tank, PZT stages for positioning the exposure surface, a tube lens (Lens 4 and Lens 5), a CCD, a condenser lens (N.A.=0.25), a pinhole, and a PMT. The refractive indices of the cover glass and the photosensitive resin (KC1162, JSR Corp.) are 1.78 and 1.51, respectively. The critical angle at the exposure surface is calculated to be 57.4 degrees. The mask, the PZT stages and the electronic shutter can be controlled from a personal computer.

The high power objective lens, the tube lens, and the CCD make up the optical microscopic system, which allows direct observation of the curing process of the photosensitive resin. Since the imaging resolution at the exposure surface is calculated to be 180 nm (wavelength: 488 nm; N.A.: 1.78), the in-process microscopic system is required to resolve 180 nm structures. The size of a single pixel of the CCD is 8.3 μm and the magnifying power of the tube lens is 100 times, and thus this in-process microscopic system has the potential to resolve 83 nm structures, which meets the required specification.

The objective lens, the condenser lens and the pinhole form a confocal microscopic system. In this confocal system, a beam from the light source at 633 nm is collimated by the lens 6, then 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. Output values 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

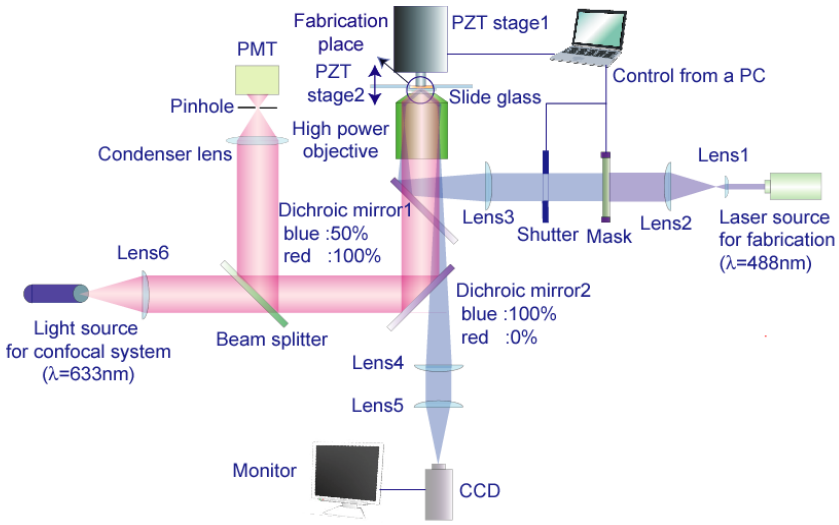


Fig. 4 Nanostereolithography apparatus with an in-process confocal positioning system

be 3.09 μm by Equation (3). Hence a pinhole with a diameter of 3 μm is adopted. For precisely positioning the exposure surface, the exposure surface is scanned with plotting of the PMT values, and then the surface is moved to the position where the PMT value was largest.

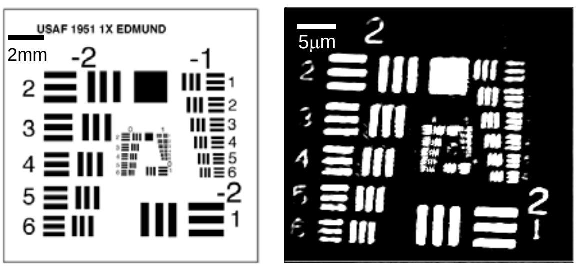
3. Evaluation Experiment

We next performed an experiment to evaluate the in-process confocal positioning system.

3.1 Evaluation of the optical system

First, the horizontal resolution of the in-process microscopic system was examined. This system is required to achieve sub-micrometer resolution, since nanostereolithography fabricates sub-micrometer structures. A test pattern (Fig. 5 (a), Edmund optics) was inserted as the mask and formed images were observed on the CCD to verify the in-process monitoring system. The line widths of the pattern were from 500 μm to 2.2 μm. The line widths on the exposure surface would be from 5 μm to 22 nm, since the objective lens reduced the light intensity distribution 100 times from the distribution at the mask position.

Figure 5 (b) shows a CCD image of the light intensity distribution of the inserted test pattern. As shown in the figure, faithfully formed patterns were obtained. A line pattern, the width of which was about 200 nm, was determined. This result indicates that the developed in-process microscope has a horizontal resolution of sub-micrometers, which is enough for nanostereolithography.



(a) (b)

Fig. 5 (a) Inserted test pattern (b) CCD image of the light intensity distribution

3.2 Evaluation of the confocal positioning system

Next, an examination of the confocal positioning system was performed to estimate the depth resolution. The exposure surface on the cover glass attached to the slide glass was scanned for 4 μm at 10 nm intervals by the PZT stage 2. The PMT values were recorded 10 times at 0.01 second intervals at every position, and the average of 10 values was calculated. Figure 6 (a) shows a graph of the variation of the PMT values. The horizontal axis represents the position of the exposure surface and the longitudinal axis represents the average of the PMT values. The PMT reached its highest value when the exposure surface was in the focal position. This graph indicates that the developed confocal system performs properly.

Figure 6 (b) shows representative data points at z-positions from 1.5 μm to 2.2 μm. This indicates that the system can provide depth resolution of less than 100 nm.

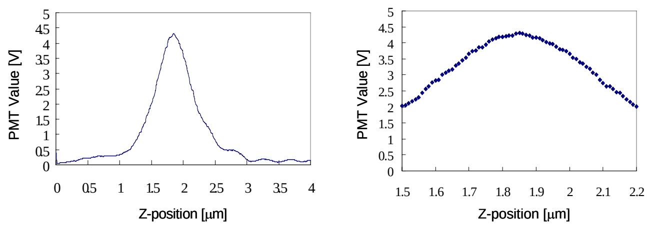


Fig. 6 Variation of PMT values with a change in the position of the exposure surface (a) from 0 μm to 4 μm or (b) from 1.5 μm to 2.2 μm

Then the positioning repeatability was examined. The positioning process of the exposure surface is as follows. First the cover glass (exposure surface) is scanned for 4 μm, with plotting of the PMT values, and then a PZT stage moves the cover glass to the position of the largest PMT value.

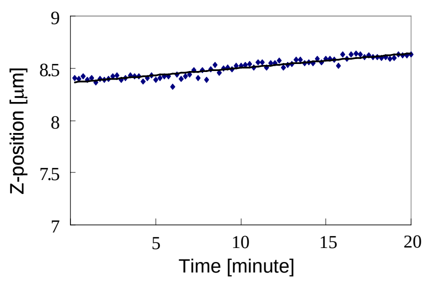


Fig. 7 Outputted PMT values of the positioning repeatability examination. The standard deviation of positioning repeatability was calculated to be 30.8 nm without the drift effects

For the examination experiment, the PMT values were measured by scanning the cover glass for 10 nm (total: 4 μm) again, and the position of the maximum PMT value was outputted. This process was repeated 80 times within 15 seconds (total: 20 minutes). Figure 7 shows the results of the experiment. The horizontal axis indicates the time and the longitudinal axis indicates the z-position of the maximum PMT 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. The drift effects may have been attributed to the PZT stage for positioning the cover glass. This result of the positioning repeatability almost meets the required specification, which is less than 100 nm.

These experiments evaluating the in-process microscope and the confocal positioning system indicate that these newly developed systems can provide sufficient resolution for nanostereolithography using evanescent light.

Summary

A nanostereolithography system with an in-process confocal positioning system was developed. In the in-process microscopic system, a high-power objective lens (N.A.: 1.65), a tube lens, and a CCD made up the optical microscopic system, and this system could resolve 83 nm structures on the CCD via the tube lens. The confocal positioning system consisted mainly of a laser at 633 nm, a high-power objective lens, a PZT stage, a condenser lens, a pinhole (diameter: 3 μm), and a PMT.

Two evaluation experiments were performed, and indicated that the in-process microscopic system had a horizontal resolution of 200 nm and that the confocal positioning system provided a depth resolution of 30.8 nm. We conclude that nanostereolithography can be effectively performed using this in-process measurement system.

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