Invited Session Paper

An Optical and Confocal Microscopic System for Nano-stereolithography Using Evanescent Light

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Abstract. A novel stereolithography method using evanescent light has been proposed to realize 100-nanometer resolution. An in-process measurement system with a high accuracy has been introduced to the nano-stereolithography apparatus. To be concrete, an optical microscopic system has been developed to monitor the exposure process and a confocal microscopic system has been established to improve a layer-by-layer process. This optical and confocal microscopic system has provided a horizontal resolution of sub-micrometer and a depth resolution of less than 100 nm.

Introduction

Micro-stereolithography is a common rapid prototyping (RP) [1] technology for fabricating complex three-dimensional (3D) microstructures by curing liquid photosensitive resin in a layer-by-layer process [2][3]. 3D objects with micrometer resolution can be fabricated rapidly, which makes this method more noticeable. However, the conventional micro-stereolithography method remains some critical issues. Since this method uses propagating light as the exposure energy, surplus growth is generated. It causes a dimension error and makes it difficult to fabricate a complex structure like overhang. In addition, it is almost impossible to fabricate microstructures with sub-micrometer resolution since the fabrication resolution is restricted by the diffraction limit. In order to overcome these issues, we have proposed a novel nano-stereolithography method that used evanescent light instead of propagating light as the exposure energy [4]. Since evanescent light energy does not propagate but localizes within the near-field region as figure 1, surplus growth is not generated. Furthermore, the resolution is independent of the diffraction, so that it should be possible to fabricate 3D microstructures with a resolution of sub-micrometer.

Figure 2 shows a schematic diagram of nano-stereolithography 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 through an imaging system generates evanescent light on a glass substrate and the evanescent light energy exposes the photosensitive resin. To confirm the light intensity distribution and to monitor the resin curing, an optical system with a high accuracy like a microscope is required. In the layer-by-layer process, a cured resin layer is lifted by a base rod and a liquid resin gap is created between the cured resin layer and the glass substrate. This process requires a high-accuracy positioning system of the substrate since even a very small gap error makes it impossible to fabricate submicron devices. In this paper, an optical and confocal microscopic system is developed as an in-process measurement system.

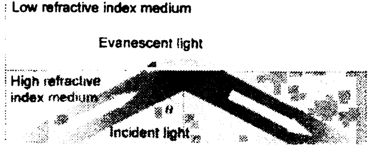


Fig. 1 Evanescent light localizes within the near-field region.

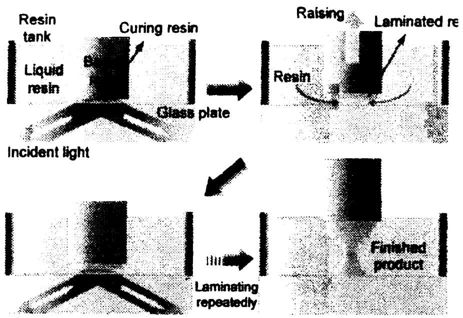


Fig.2 Nano-stereolithography using evanescent light

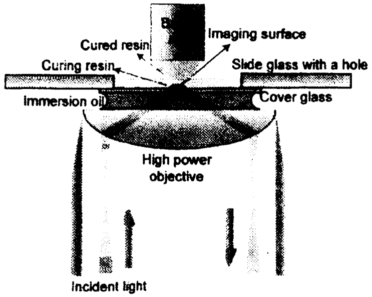


Fig.3 Nano-stereolithography apparatus with a objective, resin tank and a base rod.

Development of an Optical and Confocal Microscopic System

Shown in Figure 3 is a fabrication place of a nano-stereolithography apparatus using evanescent light [5]. It mainly consists of a high-power objective (N.A.=1.65) for forming a totally reflected beam, a resin tank, and a base rod for lifting cured resin layers. A modulated beam passes through a periphery of the objective's pupils and generates evanescent light in the liquid resin. The base rod is lifted in the layer-by-layer process. In the exposure process, a monitoring system is required to observe the light intensity and the resin curing. Therefore, an optical microscopic system has been introduced to the nano-stereolithography apparatus. The horizontal resolution of the optical system should be the order of sub-micrometer for nano-stereolithography.

In both the exposure and the layer-by-layer process, a positioning system of the substrate (cover glass) is absolutely essential. Since the depth of focus of the objective is about 300nm, the depth resolution of the positioning system should be less than 300nm to confirm the light intensity distribution in the exposure process. In the layer-by-layer process, the depth resolution should be less than 100nm as the thickness of each layer is the order of sub-micrometer. A confocal microscopic system has been introduced, which can provide nanometer depth resolution [6][7][8].

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

$$I = |h_1|^2 \left\{ |h_2|^2 \otimes D \right\}, \qquad (1)$$

where h_1 and h_2 are point spread functions (PSFs) of an objective and a condenser lens respectively, and D is a pinhole [9]. Eq. (1) indicates that an objective with a high numerical aperture (N.A.) and a pinhole with a small diameter are required. A diameter of a pinhole should be less than a diameter of an Airy Disc to maximize the effects of the confocal system [10].

Figure 4 shows a developed nano-stereolithography apparatus with an optical monitoring and confocal positioning system. It mainly consists of lasers at 488nm and 633nm, a mask, a electronic shutter, a high-power objective, a resin tank, PZT stages, positioning accuracies of which are 5 nm, a tube lens (Lens4 and Lens5), a charge coupled device (CCD), a condenser lens (N.A.=0.25), a pinhole, and a photomultiplier (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 is 57.4 degrees. The mask, PZT stages and the electronic shutter are controlled from a PC.

The high power objective, the tube lens and the CCD configure an optical microscope. This microscope system allows us to directly observe a curing process of the photosensitive resin.

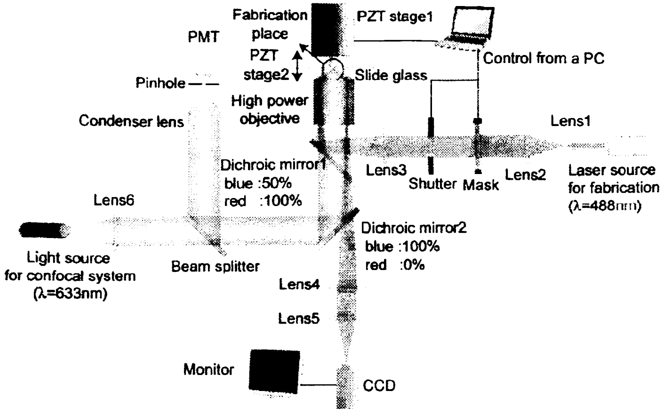


Fig.4 Nano-stereolithography apparatus with an optical monitoring and confocal positioning system

The objective, the condenser lens and the pinhole form a confocal system. In the confocal system, a beam from the light source at 633nm enters the objective and is reflected on the exposure surface. The reflected beam enters the condenser lens and the pinhole, and finally reaches the PMT. Outputs of the PMT reaches the largest value when the exposure surface is in the focal position.

A diameter of an Airy Disc d is expressed as:

$$d = \frac{1.22\lambda}{N.A.}, \tag{2}$$

where λ is a wavelength of the light [10]. As the N.A. of the condenser lens is 0.25, the diameter of the Airy Disc is 3.09μm. Since a diameter of a pinhole should be less than that of an Airy Disc, a pinhole with a diameter of 3μm is adopted.

Evaluation Experiment

A test pattern (Figure 5) was inserted as the mask to verify the optical monitoring system. Line widths were from 500μm to 2.2μm. Line widths on the exposure surface were from 5μm to 22nm since the objective reduced the light intensity distribution 100 times from the distribution at the mask position. Figure 6 shows a CCD image of the light intensity distribution. The line pattern, the width of which was about 200nm, has been determined, which indicated the optical monitoring system had a horizontal resolution of sub-micrometer.

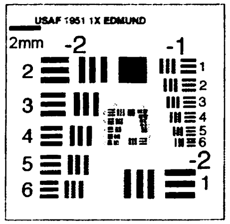


Fig.5 Test pattern

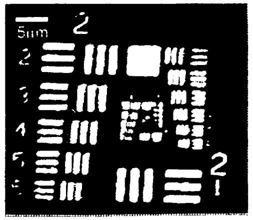
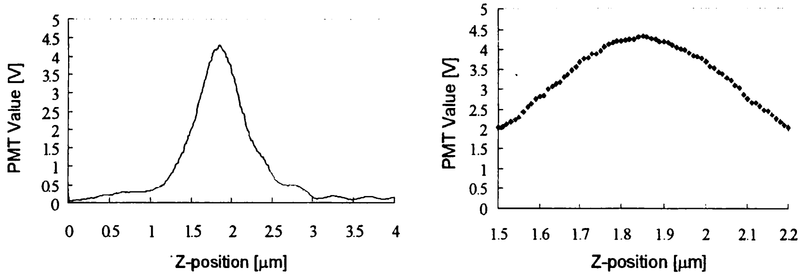


Fig.6 CCD image of the intensity distribution

Another experiment has been demonstrated to estimate the depth resolution of the confocal positioning system. The exposure surface on the cover glass attached to the slide glass was scanned 4μm at 10nm intervals by the PZT stage 2. An average of 10 PMT values at 0.01 seconds intervals were calculated at every position. Shown in Figure 7 is a graph of the variation of PMT values. The horizontal axis is the position of the exposure surface and the longitudinal axis is the average of PMT values. Figure 7(a) shows that the developed confocal system performs properly and Figure 7(b) indicates that the system provides the depth resolution of less than 100 nm.



(a) From 0μm to 4μm (b) From 1.5μm to 2.2μm

Fig.7 Variation of PMT values with the position of the exposure surface

Summary

The nano-stereolithography system with the optical monitoring and confocal positioning system has been developed. The high-power objective (N.A.=1.65), the tube lens and the CCD configure the optical system. The confocal system mainly consists of the laser at 633nm, the high-power objective, the PZT stage, the condenser lens, the pinhole (diameter=3μm), and the PMT. Two verification experiments have been demonstrated, which indicated that the optical system had a sub-micrometer horizontal resolution and that the confocal system provided the depth resolution of less than 100 nm. Nano-stereolithography will be established with this in-process measurement system.

Acknowledgement

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