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A NOVEL EXPOSURE METHOD BASED ON DISSOLVED OXYGEN CONTROL FOR NANO-STEREOLITHOGRAPHY USING EVANESCENT LIGHT

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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 one of the advanced micro-manufacturing methods that can fabricate complex 3D microstructures by curing the liquid photosensitive resin [1-4]. In micro-stereolithography, a layer-by-layer process can fabricate 3D micro structures with better productivity due to the one-shot area exposure compared to a two-photon-absorption process, but cannot realize submicrometer spatial resolution due to the diffraction limit of exposure light.

In order to overcome this critical problem, we're proposing a novel micro-stereolithography method [5-6] using evanescent light instead of propagating light. We consider the application of the near-field optics and use evanescent light as the exposure energy for curing photosensitive resin. Since 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 fabrication of 3D microstructures with 100-nanometer scales is expected.

In the research of nano-stereolithography using evanescent light, however, it is true that the cured size control in the vertical direction is not very difficult to be less than 100 nm [6], but the cured size control in the lateral direction is difficult. Actually, there remains a big problem that we cannot experimentally fabricate even about 20 μm sized structures for a long enough exposure time.

In this paper, in order to overcome this critical problem, we analyze the curing characteristics of an evanescent light exposure, focusing on a single layer and discuss about a novel exposure method based on dissolved oxygen.

CONCEPT OF NANO-STEREOLITHOGRAPHY USING EVANESCENT LIGHT

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

Evanescent Light Characteristics

When a light propagates in 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 internally reflect back. Under this total internal reflection condition, there faintly emerges light energy with a localizing size of about 100 nm at the boundary (Figure 1). This energy is evanescent light.

Concept of Nano-stereolithography

Figure 2 shows a schematic diagram of the nano-stereolithography 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 (Figure 2(a)). Next the

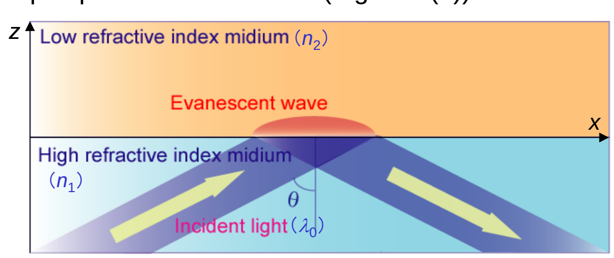

FIGURE 1. Evanescent light emerging under TIR condition.

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 about 100-nanometer scales. 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.

EVAENSCENT LIGHT ENERGY EXPOSURE EXPERIMENT FOR ANALYSIS OF CURING CHARACTERISTICS

Experimental Apparatus with Lateral Evanescent Light Distribution Dynamic Control Unit

In order to analyze the cured characteristics of evanescent light exposure especially in the lateral direction, we developed a nano-stereolithography system (Figure 3), with which we can dynamically control an evanescent light exposure area. This system mainly consists of a solid-state diode pumped laser providing visible output at 488 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 (mirror size:13.7 μm, 769 x 1024 mirrors) allowing us to precisely control the lateral evanescent exposure area with a lateral resolution of 250 nm.

Fundamental Evanescent Light Exposure Experiments

Figure 4 shows a typical comparison of a cured single layer by evanescent light with conventional propagating light, lateral shape of which is geometric shape. The lateral shape of the cured resin of evanescent light is not very sharp by comparing one of propagating light. Especially, almost a hexagonal shape is obtained in a star-shaped exposure. Table 1 shows results of evanescent light exposure experiments in changing the size of a lateral exposure area with constant exposure energy

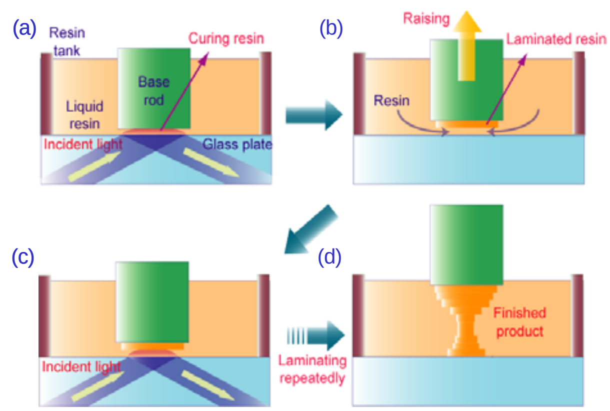

FIGURE 2. Schematic diagram of the nano-stereolithography process using evanescent light.

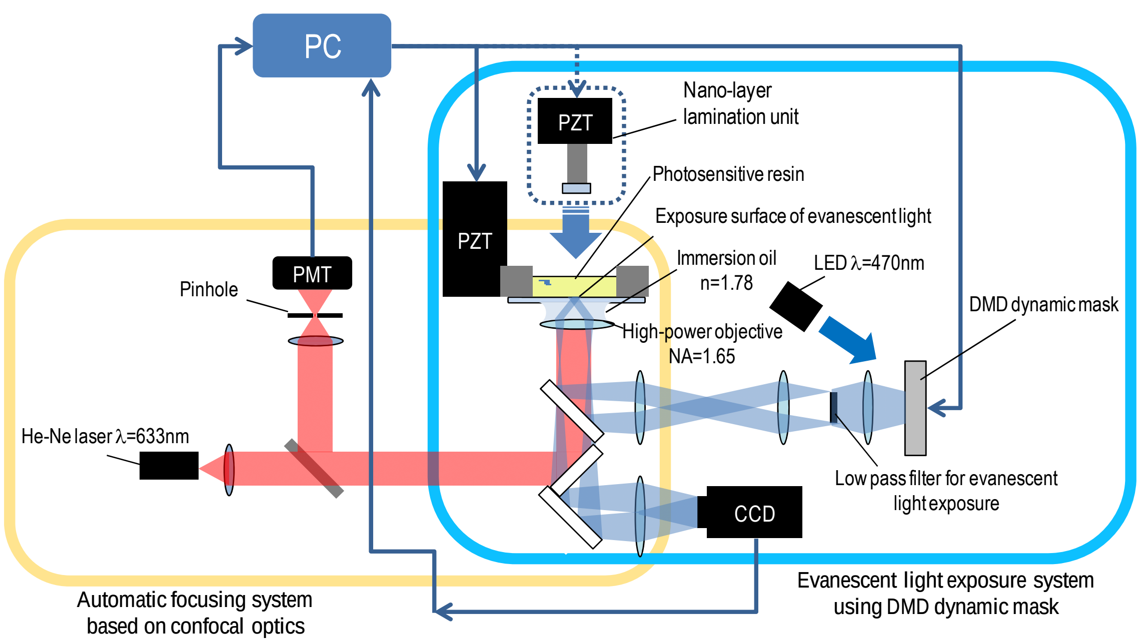

FIGURE 3. A nano-stereolithography system using DVD dynamic mask.

TABLE1. Results of evanescent light exposure experiments in changing a lateral exposure size with a constant exposure energy per unit area per second (30 W/cm^2).

Total exposure energy (J/cm)		40	49	60	80	120	320	> 2250
Exposure size a (μm)	49	not cured	not cured	not cured	cured	cured	cured	cured
	37	not cured	not cured	not cured	not cured	cured	cured	cured
	25	not cured	not cured	not cured	not cured	not cured	cured	cured
	13	not cured	not cured	not cured	not cured	not cured	not cured	not cured
	5	not cured	not cured	not cured	not cured	not cured	not cured	not cured
	2	not cured	not cured	not cured	not cured	not cured	not cured	not cured

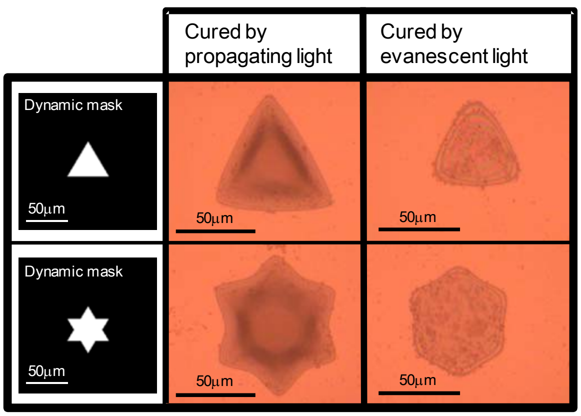

FIGURE 4. Comparison of a cured layer by evanescent light with propagating light.

per unit area per second (30 W/cm^2). This table indicates that the curing characteristics of evanescent light energy depend on the lateral size of exposure, in spite of constant exposure energy per unit area and the size below 13 μm is no longer cured even in extremely large total exposure energy (2250 J/cm^2).

These results may be attributed to dissolved oxygen. Generally speaking, in the exposure process, free radicals induced by light energy do not firstly react with monomers of resin but scavenge dissolved oxygen and photopolymerization process begins only once monomers are able to compete with oxygen [7]. Since the evanescent light energy is substantially localized in the liquid resin, dissolved oxygen would not be scavenged and it would diffuse to the exposure area (Figure 5). A computationally estimated dissolved oxygen

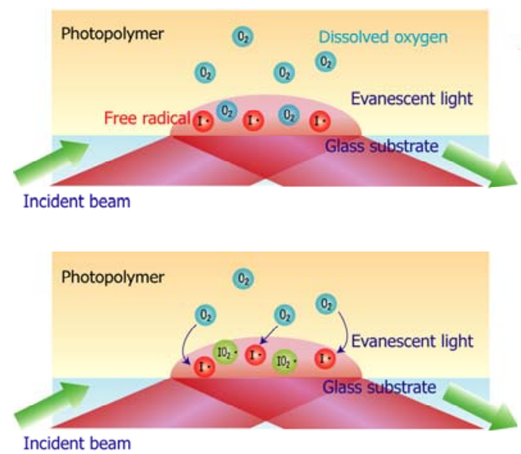

FIGURE 5. Conceptual diagram of influence of dissolved oxygen on evanescent light energy exposure.

distribution gives a good agreement with the experimental result as shown in Figure 6.

VERIFICATION EXPERIMENTS BY 2-STEP EXPOSURE

In order to verify the hypothesis mentioned in the previous section, two-step exposure experiments, in which the first exposure means just controlling dissolved oxygen density and the second does curing the liquid resin, are curried out. Figure 7 and Table 2 show the comparisons between conventional single exposure method and the 2-step exposure method. These results clearly indicate that we can fabricate the finer structure with an adequate exposure time by controlling the influence of dissolve oxygen.

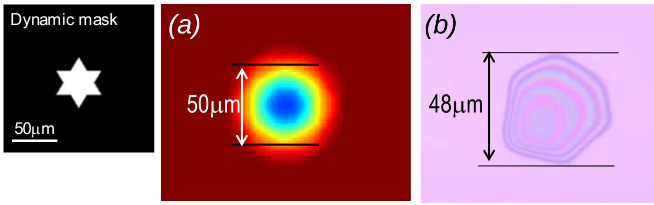

FIGURE 6. Comparison between computationally estimated dissolved oxygen distribution(a) and experimentally cured resin(b).

CONCLUSIONS

In order to analyze the curing characteristics of an evanescent light exposure for realizing a nano-stereolithography using evanescent light, we developed a nano-stereolithography system with DMD dynamic mask, controlling the lateral exposure area of evanescent light. The experimental results indicate that the curing characteristics strongly depend on dissolved oxygen due to the localizing property of evanescent light. And our proposed two-step exposure method has a possibility of being an effective evanescent light exposure by controlling dissolved oxygen density

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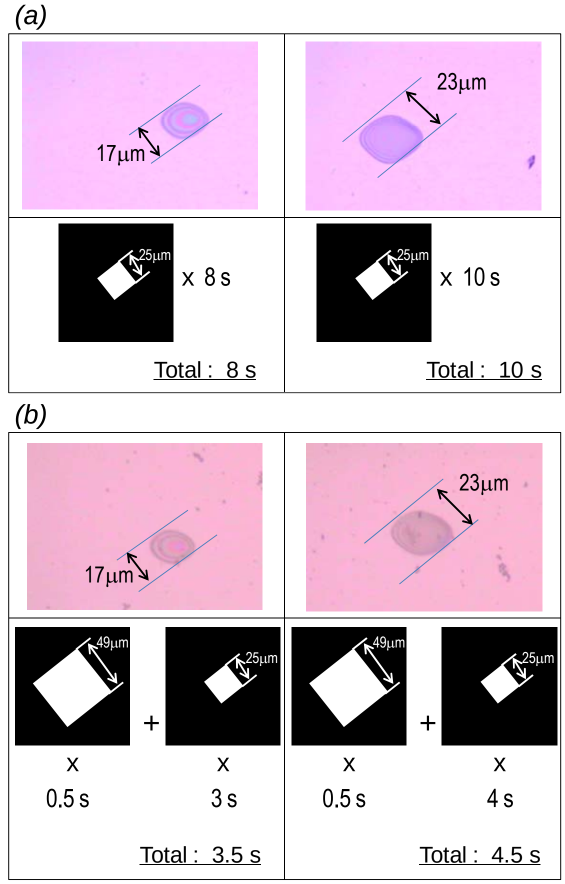

FIGURE 7. Comparison between conventional single exposure method(a) and 2-step exposure method(b).

TABLE2. Effectiveness of 2-step exposure method compared with conventional single exposure method (30 W/cm^2).

Exposure size *a*		13 µm	5 µm	2 µm
Conventional method	Exposure time	> 75 s	> 75 s	> 75 s
	Results	not cured	not cured	not cured
2-step method	Exposure time (1st + 2nd)	3 s	3 s	3 s
	Results	cured	cured	cured

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