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Evanescent Light Exposing System under Nitrogen Purge for Nano-Stereolithography

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Abstract

Micro devices have been attracting attention accompanying industrial development in recent years. Higher-level microprocessing technique to produce them is demanded. The purpose of this study is to establish the novel technique to satisfy 3 functions: sub-μm process resolution, 3-dimensional flexibility and rapidity. This report proposed a nano-stereolithography method using evanescent light instead of propagating light in order to achieve the required functions. However, there are some important problems in exposing and curing process because of oxygen dissolved in photosensitive resin. Nitrogen purge was introduced to exposing unit to remove oxygen from the resin, which allowed us to solve the problem in exposing and curing process.

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Keywords: 3D printers, Nano machining, Micro fabrication, Evanescent light, Evanescent wave, Micro-stereolithography;

1. Introduction

Micro applications like functional devices and metamaterials have been attracting attention accompanying industrial development in recent years, such as microelectromechanical systems (MEMS) and microscopic optical devices. For example, the photonic crystals can be used to control an electro-magnetic wave [1], and the biochips can be used to analyze cells and proteins in biological field [2]. These devices have micrometer-sized or nanometer-sized complex structure. Higher-level microprocessing techniques to produce them are being demanded even today. For example, the processing technique to satisfy 3 functions is required, sub-μm process resolution, 3-dimensional (3D) flexibility and rapidity. So far, it is challenge to establish such techniques.

One of micro fabrication techniques, micro-stereolithography is a rapid prototyping method to build complex 3D microstructures by curing liquid photosensitive resin in a layer-by-layer fashion [3]. With micro-stereolithography method, small 3D structures with micrometer accuracy can be fabricated rapidly. For higher resolution fabrication, it is important for the layers to be thin. However, conventional micro-stereolithography has some difficulties to be applied to the finer fabrication than a micrometer resolution [4]. When a structure with thinner layer than a micrometer is made, penetration of propagating light solidifies not only an intended area but also extra areas, which causes dimension errors. Especially it is difficult to fabricate a complex structure like an overhang shape.

This report proposes a nano-stereolithography method using evanescent light instead of propagating light for exposure energy in order to achieve the required functions. Since evanescent light does not propagate but instead is localized within near-field region, the overcure is not generated. By this approach, this study aims to establish the nano-stereolithography method that can rapidly fabricate complex 3D microstructures with sub-micrometer accuracy [5].

However, there are some difficulties to establish the proposed method. Thickness of a single cured resin layer is not uniform. Thick part is over 1 μm even though it is exposed and cured by evanescent light when its diameter is longer than about 100 μm. This is caused by inhibition to radical polymerization by dissolved oxygen in liquid photosensitive resin. Removing dissolved oxygen from resin can solve the

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problem. To remove oxygen, evanescent light exposing system under nitrogen purge is developed. Some experiments are conducted under developed system in order to verify the effectivity of the system.

2. Concept for nano-stereolithography using evanescent light

2.1. Evanescent light

Fig.1. shows a scheme of evanescent light generation. When light passes through a boundary between 2 different mediums from high refractive index medium to low one, a part of the light beam will be refracted and the other part reflected at a boundary surface. If the incident angle is larger than the critical angle, the refracted light vanishes and all of the light energy reflects back internally. Nevertheless, in this condition, localized energy is present at the boundary surface of the low refractive index side. This energy is the evanescent light [6]. This energy decays exponentially with distance from the boundary at which total reflection occurs.

The electric field E of evanescent light is expressed as follows by Maxwell's equations and Snell's law.

$$E = A\exp\left(-\frac{z}{Z_{\mathrm{ev}}}\right)\exp\left(\mathrm{i}\omega t - \mathrm{i}k_2 x\frac{n_1}{n_2}\sin\theta\right)$$

$$\left(Z_{\mathrm{ev}} = \frac{\lambda_0}{2\pi n_2}\sqrt{\left(\frac{n_1}{n_2}\right)^2\sin^2\theta - 1}\right) \tag{1}$$

where the axis perpendicular to the boundary is z, the axis equivalent to the boundary is x. A, ω and t, respectively, represent the amplitude, the angular frequency and time. The wavenumber in the low refractive index medium is k_2, and refractive indexes are n_1 and n_2 ($n_1 > n_2$). λ_0 is the wavelength of the incident light. θ is the incident angle.

2.2. Nano-stereolithography using evanescent light

Fig. 2. shows a scheme of nano-stereolithography. Photosensitive resin is exposed and cured by evanescent light at the boundary of 2 mediums. Laminating cured resin layers enables us to fabricate 3D structure. When a complex structure like an overhang shape is manufactured, evanescent light can cure thin resin layer without dimension errors caused by transmitted light.

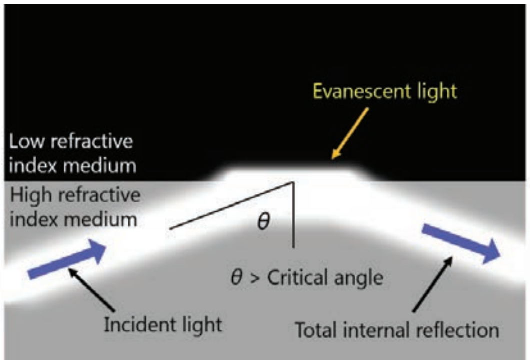

Fig. 1. Scheme of evanescent light generation

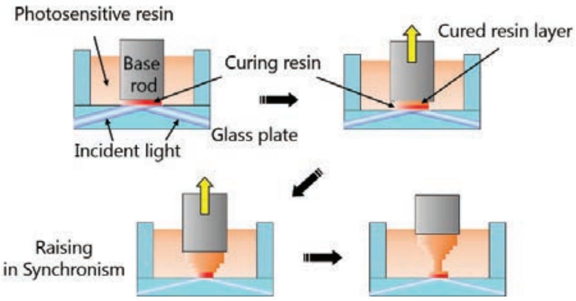

Fig. 2. Process of nano-stereolithography

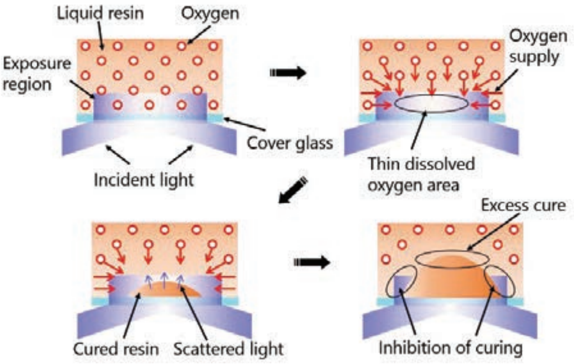

Fig. 3. Resin cure mechanism considering dissolved oxygen and scattered light

This exposure unit needs higher refractive index medium than the refractive index of photosensitive resin. Moreover, the incident angle of the light must be larger than the critical angle.

3. Effect of dissolved oxygen

Photosensitive resin is polymerized by radical reaction. When photosensitive resin including initiator and monomer is exposed to the light, cleavages happen in initiator molecules and free radicals are generated. These free radicals promote free radical polymerization among monomers, which changes liquid resin into solid [7]. However, when dissolved oxygen is present in liquid resin, free radicals react both monomers and oxygen. In this situation, crosslink reaction does not start until oxygen is consumed enough because the speed of the radical reaction between radicals and oxygen is faster than the one between radicals and monomers [8].

Fig. 3. represents resin cure mechanism considering dissolved oxygen and scattered light. After dissolved oxygen are consumed in the exposed area, concentration gradient of oxygen occurs and other oxygen enter the area from surrounding. Consequently, the balance between light energy and oxygen concentration decides whether liquid resin at the point are solidified. Because evanescent light is localized energy in near-field and its exposure area has a high ratio of a surface area to a volume, resin cure is easier to be affected by oxygen supplied from surrounding than other conventional methods using propagating light.