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One-shot stereolithography for biomimetic micro hemisphere covered with relief structure

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ABSTRACT

Biomimetic micro-structured surfaces have been attracting attention in recent years owing to their features, including optical reactivity, wetting property, and sliding property. One of the typical features of these functional structures is that densely arrayed dual-scale structures are present, such as several tens of micrometers of a hemisphere-like form covered with many several micrometer protrusions on the surface. A dual-scale structure similar to this is difficult to quickly and cheaply fabricate using existing methods: semiconductor process, micro stereolithography, and focused ion beam. In this research, a novel technique to fabricate a biomimetic hemisphere-like form covered with a relief structure is proposed. It utilizes the difference between the refractive indexes of two materials and the focusing cone-shaped light with a solid angle, which includes the critical angle formed when light enters from a side where the refractive index is higher than that of the other. In this situation, the refracted light radially expands. Thus, when the low-refractive-index medium is a photocurable resin, it is cured into a hemisphere-like form. In addition, properly modulating the light-intensity distribution of the incident light allows us to create many protrusions, such as a relief structure on the hemisphere surface. In this research, a theoretical model was constructed, and the proposed method was verified by simulation using Snell's law and the Lambert–Beer law. Moreover, apparatus to realize the proposed method was developed, and we practically verified that this method can fabricate a dual-scale structure such as a hemisphere-like form covered with a relief structure.

1. Introduction

Surface microstructures influence several functional features such as optical reactivity, wetting property, and sliding property [1–4]. We have known well that certain natural structures of animals or plants demonstrate superb ability of such surface properties. For example, the eyes of a mosquito have water repelling and anti-reflection functions on their surface [5], and lotus leaves are known for their water-repelling and self-cleansing structures [6,7]. To artificially fabricate such natural structures, micro-fabrication technologies for biomimetic structures have been attracting attention in recent years [8]. Animal or plant surfaces that demonstrate superb functionalities have fine and complex structures [9]. On one of the typical creature surfaces, many protrusions of several tens of micrometers, such as hemispheres, are spread all over, and on each hemisphere-like protrusion (Fig. 1), many protrusions of several micrometers are covered with a relief structure. In other words, functional natural surfaces are composed of dual-scale microstructures such as a hemisphere-like protrusion covered with relief structure, which makes production of artificial biomimetic structured surfaces difficult. The purpose of this research is to propose a novel method to fabricate a biomimetic dual-scale structure, such as a hemisphere-like protrusion covered with relief structures, by one-shot process.

The most famous micro-fabrication techniques are those used in semiconductor processes such as photolithography [10–12], electron-beam lithography [13,14] and so on. These techniques can manufacture nanometer-scale structured surfaces. However, the dual-scale microstructures require a multi-layer process, which is extremely complicated; thus, they are expensive. Micro stereolithography using a layer-by-layer fashion is a superior multi-layer process that is well-known for rapid prototyping [15–17]; nevertheless, it cannot be applied to biomimetic micro structures because the technique has difficulty producing a layer thinner than approximately 5 µm. On the other hand, the focused ion beam process [18] and two-photon-absorption micro stereolithography [19,20] can fabricate micro and complex structures without using a complicated multi-layer process. However, they are scanning processes; thus, they are not suitable from the viewpoint of

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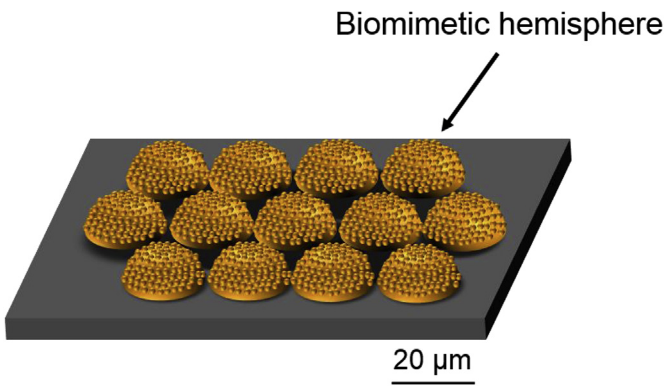

Fig. 1. Schematic figure of a magnified mosquito eye. Many hemispherical forms covered with relief structure exist, which generate functionalities such as hydrophobicity, antifouling, and anti-reflection.

processing time.

In the present paper, a novel fabrication technique for a biomimetic micro and complex hemisphere-like structure using a one-shot process is proposed. The proposed technique controls the behavior of a light beam passing through the boundary from a high to a low refractive index. When the low refractive index medium is a photocurable resin and a focusing light enters the boundary from the high refractive index side, the light energy is radially broadened from the focused point on the boundary and solidifies the resin into a hemispherical form. In addition, the modulating intensity distribution of the focusing light can control the surface shape of the hemispherical form, which allows us to produce a biomimetic micro and complex hemisphere-like structure using only a one-shot exposure. This process means that the proposed technique does not need a complicated and high-cost process and does not require a long time.

In the current research, a novel fabrication technique is proposed, and not only the principle was verified by theoretical analysis but also the feasibility of the proposed method were demonstrated by experiment.

2. One-shot stereolithography of a micro hemisphere covered with relief structure

2.1. Basic concept of hemisphere fabrication

Fig. 2 shows the basic principle of Snell's law. When the refractive index of the medium at the incident side (n_1) is larger than that at the transmission side (n_2), the refractive angle (θ_2) is larger than the incident angle (θ_1). The relationship between the two angles and two refractive indexes follows Snell's law expressed by the following equation:

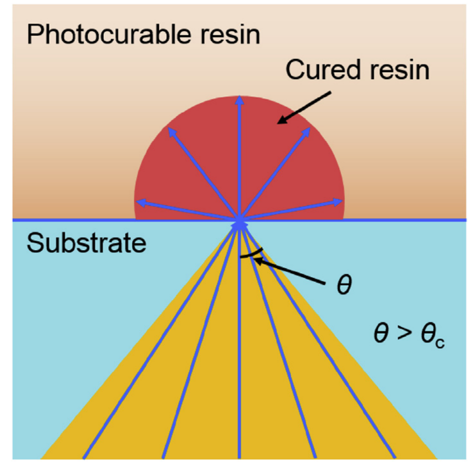

Fig. 3. Hemisphere fabrication concept. θ is the incident angle, and θ_c is the critical angle. Exposure by the focusing light from a high refractive index medium produces a hemisphere because the refracted light radially spreads according to Snell's law.

$$\frac{\sin\theta_2}{\sin\theta_1} = \frac{n_1}{n_2}. \tag{1}$$

The larger the incident angle becomes, the closer the refractive angle approaches 90° [Fig. 2(a)]. When the refractive angle is equal to 90°, the incident angle is called a critical angle [Fig. 2(b)]. Fig. 3 shows that a photocurable resin is assumed to be used as the low refractive index medium, and the light arrives from a high refractive index substrate. If an incident light is a focusing cone-shaped light whose solid angle includes the critical angle, the refracted light is hemispherically propagated along the horizontal direction. By utilizing this phenomenon, the refracted light with a radial direction can be used to cure the filled photocurable resin as a low refractive index medium, which allows us to solidify the resin into a hemisphere-like form.

2.2. Basic concept of the fabrication of a dual-scale structure

To fabricate a dual-scale structure, a relief structure needs to be created on the surface of the hemisphere-like form. The boundary of the cured and liquid resins is determined by the depth of cure derived by the Lambert–Beer law, which is expressed as follows:

$$x_d = -\frac{1}{\alpha}\ln\left(\frac{I_c}{I_i}\right) \tag{2}$$

where x_d is the depth of cure; α is the absorption coefficient, which depends on the material; I_c is the minimum light intensity that can cure the resin; and I_i is the light intensity at the incident point on the boundary between the resin and substrate. The depth of cure is

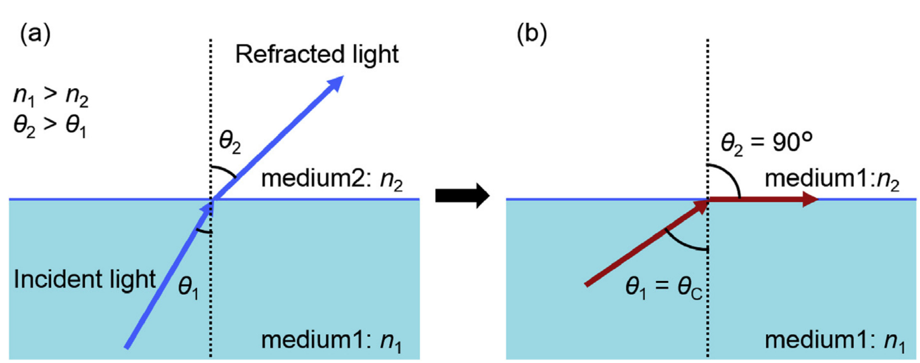

Fig. 2. Refracted light following Snell's law. The light beam is refracted at the boundary, and its refractive angle is larger than its incident angle. The refracted light beam proceeds to the horizontal direction when the incident angle is a critical angle.