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Fabrication of an optical lens array using ultraviolet light and ultrasonication

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ABSTRACT

A technique to form an optical lens array using an ultraviolet (UV)-curable resin and ultrasound was investigated. A UV-curable gel film was formed on a glass plate having four lead zirconate titanate (PZT) transducers. Excitation of the transducers generated a lattice flexural vibration mode on the glass plate. The acoustic radiation force acted to deform the surface of the gel film, so that a lens array could be fabricated on the gel film. The lens array was exposed to UV light under ultrasonication to cure the UV-curable film. The quality factor of the transducer resonance was decreased upon curing of the resin film because the cured resin dampened the vibration of the plate. The acoustic characteristics of the UV-curable gel film were measured by using an ultrasound pulse technique at the MHz range. The sound speed of the gel increased from 987 to 1006 m/s (increase of 1.9%) as the UV exposure time increased. The attenuation coefficient also increased and the larger attenuation of the resin caused the lens array to have a lower quality factor.

1. Introduction

Optical lens arrays are powerful tools that can control the distribution of light intensity and play an important role in the optical industrial field for applications such as liquid crystal displays, optical communication devices, and optical sensors for wavefront aberrations. A lens array can be fabricated using various methods, such as by primitive metallic molding with etching processes [1]. The ion diffusion method can be used to fabricate a microlens array by changing the refractive index of the glass substrate gradually by exposure of the substrate to ions [2–4]. The refractive index of the glass substrate depends on the density of the ion, and the graded distribution of the refractive index in the glass can be obtained by exchanging the ions in the glass substrate with other ions. Several methods for the fabrication of optical microlens arrays have been developed to downsize these optical components. In the reflow method [5], a lens array can be fabricated by melting a resist film on a substrate and utilizing the surface tension of the resist. However, these microlens array fabrication techniques require costly equipment and multiple fabrication steps.

Nakagawa and colleagues have proposed a technique for the fabrication of periodic structures for optical device applications using acoustic waves [6,7]. An optical phase grating can be fabricated in a Ta_2O_5 thin film by generating a standing-wave field of surface acoustic waves (SAW) on a substrate during sputtering of the film. There have been several reports in the literature on techniques for the handling of liquids using the acoustic radiation force of sound waves. Kondoh and colleagues have reported the transport of droplets using SAW on a lithium niobate substrate and the acoustic radiation force [8,9]. Friend et al. have also reported microfluidic flow induced by SAW [10,11]. Ding et al. have reported a noncontact ultrasound transportation technique for liquid that utilizes a high-intensity acoustic field [12]. Wallrabe's group has performed several studies on variable-focus liquid lenses that employ hydrogels [13,14]. The application of such techniques has enabled the shape and focal length of a variable-focus lens to be changed by the radiation force of sound waves [15]. Our group has investigated an optical lens with a variable focal length using ultrasound vibration [16–18], and a lens array with a variable focal length and lens pitch was successfully developed [19]. Here, we propose a simple technique for the formation of a lens array using an ultraviolet (UV)-curable resin and ultrasound.

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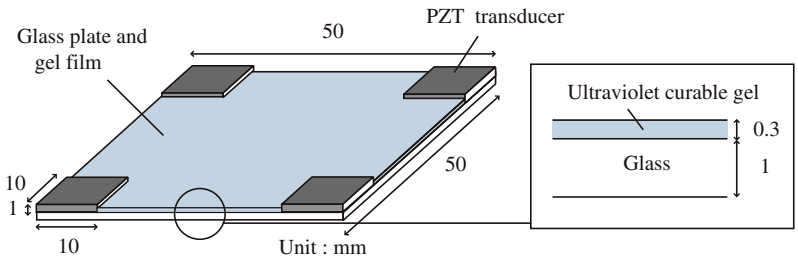

Fig. 1. Configuration of the gel film, glass plate, and four transducers.

The lens profile was controlled by an acoustic radiation force and the curing state of the resin was monitored through the electric characteristics of the ultrasound transducer. The acoustic characteristics of the resin under UV exposure were also investigated.

2. Materials and methods

In the fabrication process of the lens array, a 300 μm thick gel film of UV-curable resin (X-34-4184(A/B), Shin-Etsu Chemical, Tokyo, Japan; refractive index: 1.40; specific gravity: 1.03; viscosity after mixing: 2.7 Pa s; coefficient of linear contraction: 0.1%) was formed on a square glass plate ($50 \times 50 \times 1\ mm^3$) in a darkroom, as shown in Fig. 1. Four rectangular piezoelectric lead zirconate titanate (PZT) transducers ($10 \times 10 \times 1\ mm^3$) were bonded at the four corners of the glass plate using epoxy resin. The resin can be cured by mixing the X-34-4184-A and -B gels (the ratio of A:B was 1:1 in the prototype) and irradiation with UV light with a total energy of 2000 mJ/cm^2 and a wavelength of 365 nm. Under UV light exposure, a platinum catalyst is activated so that the resin can be cured through a hydroxylation reaction. The curing time is dependent on the temperature, where a higher temperature gives a shorter curing time; the curing times at 25, 50, and 100 °C after exposure to UV light at 2000 mJ/cm^2 were approximately 60 min, 5 min, and 30 s, respectively. Electrical excitation of the PZT transducers at the resonance frequency of the glass plate generates a lattice flexural vibration mode on the plate, and different acoustic energy densities are produced in the gel and air at the gel surface. The acoustic energy difference induces a static force, known as the acoustic radiation force [20,21], in the gel that causes its surface to be statically deformed toward the air. The gel can be cured during deformation under ultrasonication by irradiation with UV light.

3. Fabrication of the lens array

Fig. 2 shows the representative vibration mode for the glass plate at 91 kHz, which was predicted by finite element analysis (FEA) using the commercial FEA software ANSYS 11.0 (ANSYS Inc., Canonsburg, PA, USA). The fundamental flexural vibration mode of the transducers generates a lattice vibration mode in the glass plate. Fig. 3 shows the surface profile for the gel film on the glass plate excited with an input voltage of 25 V_{pp} at around 90 kHz that was measured using a confocal laser microscope (LT-9000, Keyence, Osaka, Japan). The measurement area was $40 \times 40\ mm^2$ at the center of the plate. The gel deformation pattern corresponds to the flexural vibration mode for the glass plate because the acoustic radiation force generated at the loop points was larger, and a lattice lens array was fabricated on the gel film. The number of lenses among the four transducers was 21. The lens pitch was approximately 6.8 mm, which corresponds to half the wavelength of the flexural vibration of the plate. The lens array at the gel surface was exposed to UV light with a wavelength of 365 nm and at 0.085 mW/cm^2 during ultrasonication, so that the

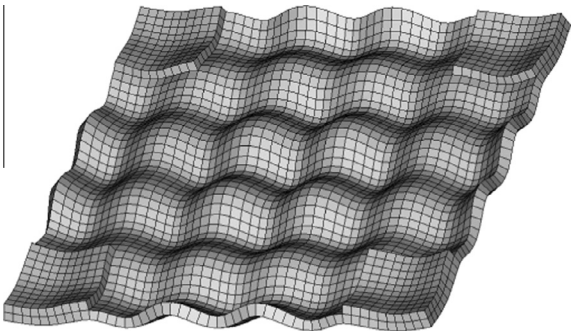

Fig. 2. Vibration mode for the glass plate at 91 kHz as calculated by FEA.

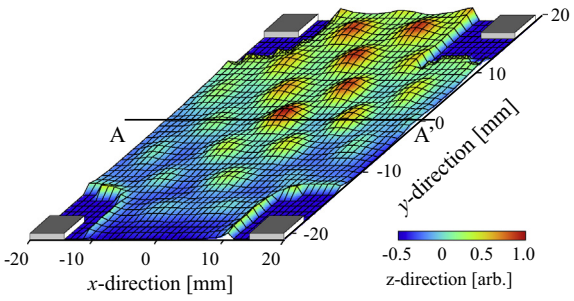

Fig. 3. Surface profile for the UV-curable gel at 90 kHz.

UV-curable film was cured and the deformation was maintained. The surface temperature of the gel was measured with a radiation thermometer and was slightly above room temperature (20 °C) to 30 °C due to attenuation of the high-intensity ultrasound.

Fig. 4 shows cross-sectional profiles for the gel film scanned along the line A–A′ in Fig. 3 at several UV exposure times during ultrasonication. The profiles were scanned 20 s after switching off the ultrasound and UV light, and one scan was completed in 2 s. Thus, the gel was under continuous UV light irradiation and ultrasonication, except during the cross-sectional profile measurements and during measurements of the frequency characteristics of the electrical admittance. When the ultrasonication was switched off, the acoustic radiation force did not act on the surface of the gel, so that the gel returned to the default profile through a transient state. Fig. 5 shows the temporal change in the height of the lens at the center of the glass plate ($(x,y) = (0,0)$). These results indicate that the transient response time of gel motion increased significantly after ca. 10 min upon curing of the gel, and the gel could not return to the default profile within 20 s. There was a large variation in the lens height of the lens array because the lens height correlates with the vibration amplitude of the glass plate. The larger electric input gives a larger lens height due to the resulting larger acoustic radiation force, and the lens height is gradually