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Strain tunable optics of elastomeric microlens array

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ABSTRACT

Microlens arrays (MLAs) have attracted great attention with their important applications in many fields, such as optical communications, organic light emitting diodes (OLEDs), thin film photovoltaic cells, and novel bio-inspired devices. The dynamically tunable MLAs whose optical properties can be changed in a controllable manner are especially desirable in some recent developments. In this study, a very simple tuning method via mechanical stretching is proposed to tune the optics of elastomeric MLAs. Theoretical mechanics and optics studies are combined to demonstrate the tunability of elastomeric MLAs under both uniaxial and equibiaxial stretching. The results show that extremely large tuning range of the focal length can be achieved using this method. This theoretical study can provide important implications to not only the design of tunable MLAs, but also developments that require controllable optical elements.

1. Introduction

Optical microlens arrays (MLAs) have been playing important roles in many fields, such as photolithography [1], optical communication [2], organic light emitting diodes (OLEDs) [3], thin film organic photovoltaic cells [4,5], and biomimetic artificial compound eye cameras [6,7]. Some recent advancement in photonics and optoelectronics [8–14] requires tunability of the optics of MLAs, and therefore, a lot of research has been invested to realize tunable MLAs. Different tuning mechanisms, such as strain [15], stimuli-responsive hydrogels [16,17], electrowetting [18], hydraulics [14,19], dielectric [20] and electromagnetic actuation [21], have been utilized to change either microlens shape or refractive index [22] to realize tunable optics. However, among these developments, either costly fabrication and assembly processes are required, or only small tuning range can be provided.

In this paper, we demonstrate a very simple but effective tuning mechanism via mechanical stretching the elastomeric MLAs to tune the optical properties. Very large tuning range can be realized through this method. Fig. 1(a) shows the schematic illustration of the tuning mechanism of elastomeric MLAs via mechanical stretching. The original MLA is composed of a square array of hemispherical elastomeric polydimethylsiloxane (PDMS, Sylgard 184) microlenses. Each microlens has the radius of curvature 0.4 mm, and the distance between neighbor microlenses is 0.92 mm. Under equibiaxial stretching, the shape of each microlens becomes more oblate but keeps axisymmetric and hemispherical. Under uniaxial stretching, each microlens is stretched along the tensile direction, but compressed in the lateral direction. The shape of each microlens surface changes from hemispherical to ellipsoidal. Therefore, each microlens possesses different focusing power along different directions [7,23]. Fig. 1(b) shows the schematic illustration of the ray tracing model for optical simulations. To simplify the optical model, the thickness of the substrate is assumed to be large enough so that light rays converge inside the elastomeric medium. Although this simplification might not comply with some applications, it is sufficient to demonstrate the effectiveness of the tuning mechanism. Modifications to the optical model can be easily done for cases when the focal point

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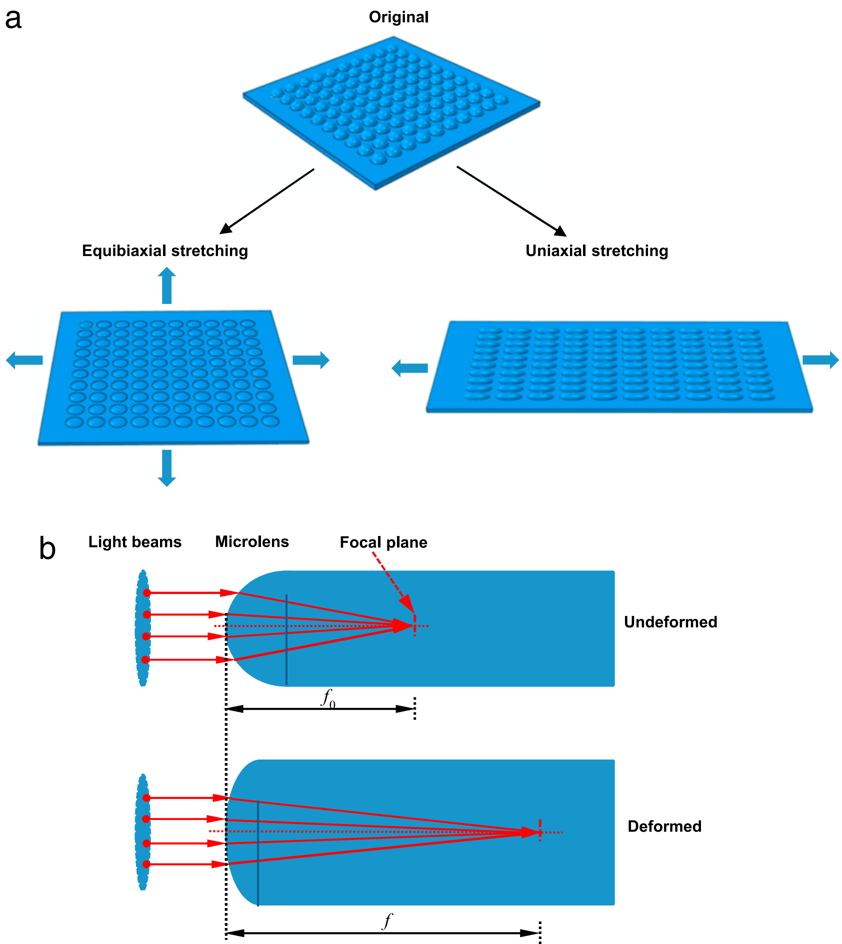

Fig. 1. Schematic illustration of the tuning mechanism of elastomeric microlens arrays (MLAs) via mechanical stretching (a) and the ray tracing simulation model (b).

falls outside of the elastomeric medium. When subject to stretching, the shapes of microlenses change, and their focal lengths change accordingly.

In this work, the deformation of the microlens under both equibiaxial and uniaxial stretching is analyzed by using finite element analysis (FEA). The surface profile of the deformed microlens is then extracted from the FEA model and implemented in the optical ray tracing simulation to study the change in optical properties. Then the height of the original hemispherical microlens is reduced to demonstrate even greater tunability in optics. This study can have important implications for not only the design of tunable MLAs, but also other developments that require controllable optical elements.

2. Results and discussions

2.1. Mechanics of the tunable microlens

Deformation of the microlens is studied when the MLA is subject to both equibiaxial and uniaxial stretching. Finite element analysis (FEA) is adopted to simulate microlens mechanics, by using software ABAQUS. Due to the periodic nature of the MLA, one unit cell that contains a hemispherical microlens and base membrane is used for FEA simulation. Periodic boundary conditions are applied to the side walls of the base membrane. The FEA model is discretized by eight-node, hexahedral solid elements. The whole unit cell is made of PDMS, which can be characterized by Yeoh hyperelastic model [24]. The strain energy density is given by

$$W = \sum_{k=1}^{3} C_k \left(I_1 - 3\right)^k, \tag{1}$$

where $I_1 = \lambda_1^2 + \lambda_2^2 + \lambda_3^2$, λ_1, λ_2 and λ_3 are the principal stretches, and $\lambda_1\lambda_2\lambda_3 = 1$ due to incompressible material behavior. The material constants are $C_1 = 0.285$ MPa, $C_2 = 0.015$ MPa and $C_3 = 0.019$ MPa [7,14].

Fig. 2 shows the deformation and strain contours of the microlens unit cell under both equibiaxial and uniaxial tension. The maximum principal strain contours of the unit cell (upper frame) and the microlens (lower frame) when the MLA is subject to 100% equibiaxial tensile strain are shown in Fig. 2(a). The maximum principal strain in the microlens reaches 120% at the edge, but decays very quickly towards the center. In addition, the shape of the deformed