ENDOSCOPE CAMERA USING TUNABLE LIQUID-FILLED LENS WITH ANTIREFLECTIVE STRUCTURES

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ABSTRACT

We report tunable liquid-filled lens with antireflective structures (ARS) on a thin flexible membrane of polydimethylsiloxane (PDMS) for endoscope camera. ARS on the membrane significantly enhance light transmission by suppressing Fresnel reflection on air-PDMS interfaces on both planar and curved surfaces. Optimal dimension of ARS was numerically designed by a finite difference time domain (FDTD) method. ARS were fabricated by using template-confined repeated dewetting on a wafer scale. Tunable liquid-filled lens with highly enhanced transmittance was completely packaged with silicon chamber diameter of 4.0 mm for endoscope camera. Optical images with different field-of-view (FOV) were successfully achieved by applying pressures with high light transmission on both planar and curved membrane.

INTRODUCTION

With the increasing demand for tunable focus lens without zooming by mechanical movement, endoscope camera has been miniaturized with tunable lens capable of wide FOV, image magnification, and axial scanning [1, 2]. Tuanble focus lenses have been studied in various methods including liquid-crystal based [3], electrowetting on dielectric (EWOD) based [4], and liquid-filled based tuning methods [5-6]. Among them, tunable liquid-filled lens, which tunes its curvature of the flexible membrane by applying pressures, can be used for a miniaturized endoscope camera to achieve broad tuning range and compactness compared to other tunable lens systems [6]. For the last decases, studies related to miniaturized optical system have been focused on a maximum transmittance by minimizing a reflection on a lens or a substrate [7]. Fresnel reflection, which significantly reduces the transmittance of the lens, can be minimized through antireflection, representatively, antireflective coating (ARC) and antireflective structures (ARS). ARS, biologically inspired from moth-eye structures, prevents Fresnel reflection by destructive interference of incident light through subwavelength nanostructures which have an effective refractive index between two different interfaces. Many research group have been applied ARS to enhance the light extraction and collection efficiency into various substrates, such as silicon, glass, or polymer [7-10]. However, only few studies have been published on the fabrication of ARS on flexible polymer substrates. Fabrications of ARS on membrane have been suffered from drawbacks relevant to the efficiency of transmittance enhancement [11-12]. ARS on flexible membrane can clearly increase the transmittance of tunable liquid-filled lens based on the flexible polymer membrane. S. Bae *et al.* have recently demonstrated tunable liquid-filled lens with ARS on flexible membrane made of poly-dimethylsiloxane (PDMS) in OMN 2017 [13]. This work demonstrated ARS on flexible membrane with the optimal geometrical parameters which satisfying antireflection criteria in visible range by using template-confined repeated solid-state metal dewetting.

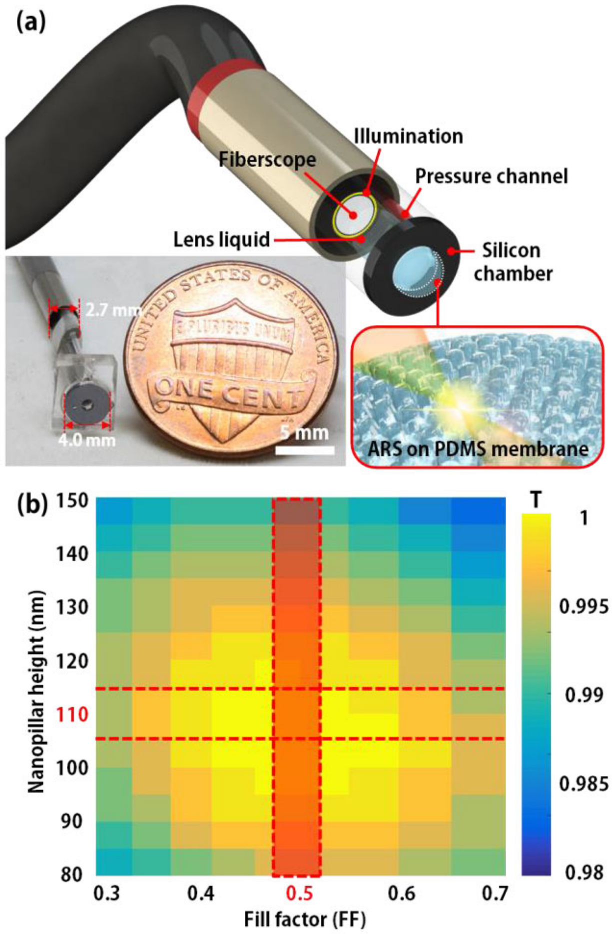

Figure 1: (a) Compact endoscope camera using tunable liquid-filled lens with ARS on flexible membrane. Pressure channel of 0.5 mm diameter is connected to the PDMS slab filled with lens liquid of ethylene glycol due to its high vapor pressure and index matching with PDMS membrane. (b) Optimal geometrical parameters of ARS is numerically calculated by using FDTD method. For nanostructures with a period of 250 nm or less, nanopillar height of 110 nm and fill factor of 0.5 show maximum transmittance in whole visible range. ARS with a fill factor of 0.5 shows self-antireflection applicable to various external media [9].

In this work, we present an endoscope camera using tunable liquid-filled lens with ARS on the flexible membrane fabricated by repeated dewetting. Tunable liquid-filled lens with the ARS membrane is compactly packaged into silicon chamber of 4.0 mm and lens diameter of 1.3 mm with quadrant fluidic channels (Fig. 1(a)). Fiber endoscope with 2.5 mm outer shaft diameter is aligned and integrated with pressure channel at the backward of the tunable lens. Pressure channel supplies positive pressure to the ARS membrane to form convex curvature which acts as a fluidic lens. Whole shaft diameter of integrated endoscope camera is 4.0 mm. Fiber endoscope and pressure channel are covered with SUS 304 stainless tube for protection. ARS on PDMS membrane suppresses reflection from the incident light. Geometrical parameters of ARS was numerically designed by using finite difference time domain (FDTD) methods as shown in Fig. 1(b). Optimal nanopillar height and fill factor, i.e areal fraction of the nanostructures of ARS are 110 nm and 0.5, respectively.

FABRICATION PROCESS

Fabrication process of tunable liquid-filled lens with ARS on flexible membrane is described in Fig. 2. Nanopillar structures on the flexible membrane was replicated by designed glass master template. Glass template for PDMS nanopillar replica was fabricated by template-confined repeated solid-state dewetting on the borosilicate glass. Glass nanohole arrays (GNHs) template satisfying antireflection criteria is generated on wafer scale by using N/MEMS fabrication including metal evaporation, dewetting and reactive ion etching (RIE) processes.

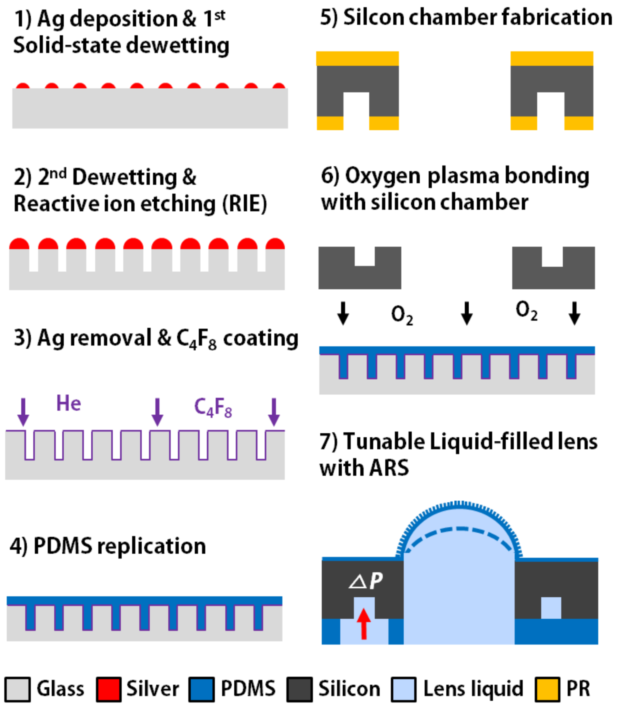

Figure 2: Tuanble liquid-filled lens with ARS was fabricated by using N/MEMS processes including silver film thermal evaporation, thermal dewetting, RIE, wet etching and oxygen plasma bonding processes on wafer scale. Silver nanohole arrays (AgNHs) were generated by repeated solid-state dewetting of 15 nm and 20 nm silver thermal evporation respectively. Both 1st and 2nd deposited silver films were thermally dewetted at 380°C hot plate for 1 hr to generate AgNHs. AgNHs act as metal mask for RIE process. After RIE process, a buffered oxide etchant (BOE, 6:1) was used to widen the hole size to generate desired glass nanohole arrays (GNHs).

Fabricated flexible membrane with ARS was permanently bonded to a silicon chamber with 4 quadrant channels. 4.0 mm diameter of silicon chamber and 1.3 mm diameter of lens was fabricated by deep reactive ion etching (DRIE) on double polished 6 inch wafer (Fig. 3(a)). A single fluidic channel with ethylene glycol was injected inside PDMS slab and variable curvatures were formed by applying pressure inside the chamber. Figure 3(b)-3(c) shows SEM images of GNHs and PDMS nanopillar arrays. GNHs were immersed into 6:1 buffered oxide etchant (BOE) in order to widen the hole size after RIE process of AgNHs to obtain fill factor close to 0.5. PDMS nanopillar arrays were well replicated from GNHs master template. Curing at high temperature can help replicate PDMS nanopillars from GNHs based on heat-induced shear thinning effect [10]. Average nanopillar diameter and fill factor were 0.47 and 190 nm respectively which satisfy antireflection criteria calculated from FDTD method. Average nanopillar height of 110 nm which iss desired height for antireflection criteria from the numerical calculation.

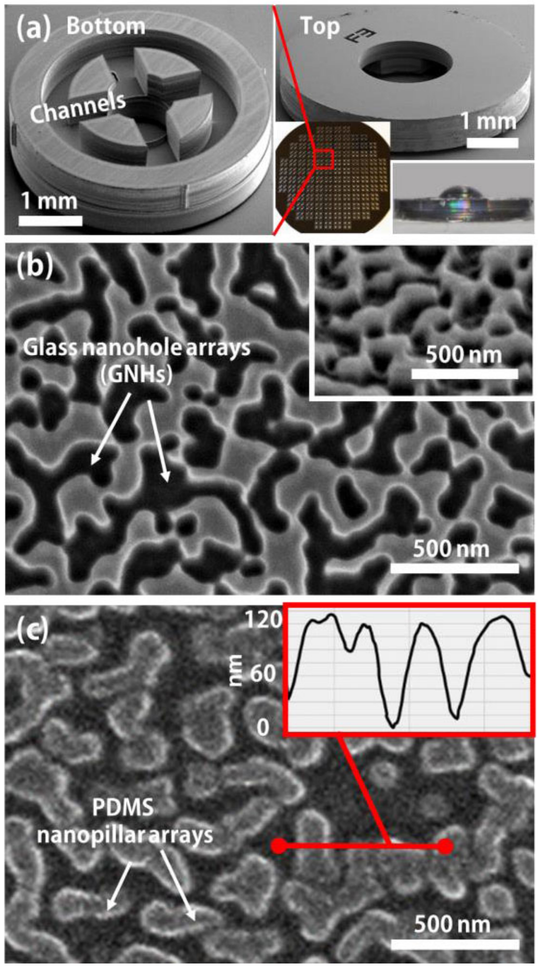

Figure 3: (a) Double side patterned silicon chamber is permanently bonded to the ARS membrane by using oxygen plasma treatment on PDMS nanopillar arrays. Pneumatic pressure is applied to the fluidic channel and variable curvatures is formed with a 1.3 mm lens diameter. (b) SEM images of GNHs. (c) SEM image of PDMS nanopillar arrays for ARS on flexible membrane. Nanopillar arrays are replicated from GNHs master template after hydrophobic coating for anti-stiction. Average fill factor, diameter, and nanopillar height are 0.47, 190 nm, and 110 nm respectively.

FOCAL LENGTH TUNING OF TUNABLE LIQUID-FILLED LENS

Tunable liquid-filled lens was compactly integrated into 4.0 mm silicon chamber aperture and tuned its radius of curvature by applying pneumatic pressure. Focal length of the tunable liquid-filled lens is measured by using a confocal laser scanning microscopy (CLSM) with 533 nm laser. As shown in Fig. 4(a), the focal length of the lens changes from infinity to 1.95 mm according to the driving pressure from 0 to 40 kPa, which is adequate tuning range for miniaturized tunable lens system. Figure 4(b) shows acquired Lenna images depending on variable focal length tunability at applying pressure of 5 kPa and 40 kPa in each. As the applying pressure increases, spherical abberation at the edge of the lens increases so that the the quality of the image deteriorates.

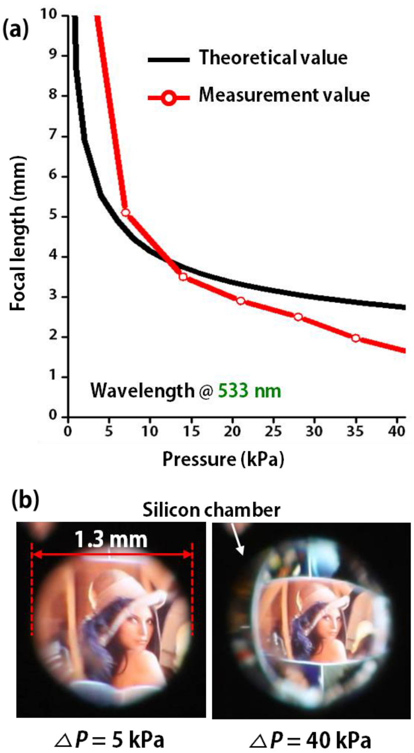

Figure 4: (a) Focal length tuning range of tunable liquid-filled lens from 0 to 40 kPa is measured by CLSM with 533 nm wavelength laser. Measurements from the CLSM is well matched with theoretical values. (b) Optical images are acquired from tunable liquid-filled lens with ARS depending on the appyling pressure at 5 kPa and 40 kPa. As applying pressure increases, radius of curvature becomes larger, focal length becomes shorter, and FOV becomes wider.

TRANSMITTANCE ENHANCEMENT BY ARS ON FLEXIBLE MEMBRANE

Transmittance of planar ARS membrane is measured with a LED source (400–700 nm) and an optical spectrometer. Measured transmittance of bare and PDMS nanopillar membranes with three different heights, 90nm, 110nm, and 130 nm, are presented with a calculated transmittance as shown in Fig. 5(a). Maximum transmittance is achieved in ARS with 110 nm nanopillar height among the different nanopillar heights, providing ~2.8% transmittance enhancement compared with the bare membrane. Optical images reflected from the ARS and the bare membrane are compared at the same light incident angle. Compared with FDTD calculation, transmittance of the optimal ARS shows slight lower than calculation due to the amorphousness of the nanostructures size. In addition, FDTD can not consider a dispersion property of PDMS material during the calculation.

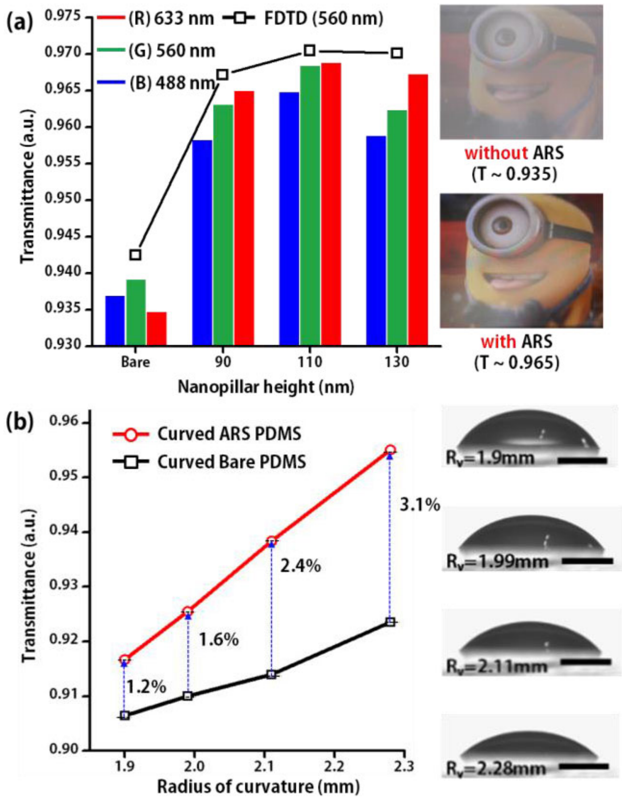

Figure 5: (a) Transmittance on planar ARS membrane is measured by four different nanopillar heights (bare, 90, 110, and 130 nm). ARS with nanopillar height of 110 nm shows the highest transmittance which is designed from FDTD calcuation. Optical images are obtained at certain light incident angle. While the image is blurred by the light reflected from the bare membrane, surface reflection is suppressed on ARS membrane which shows a clear image. (b) ARS on curved membrane shows higher transmittance than curved bare membrane in all radius of curvature regions. Transmittance of both ARS and bare membrane decreases as radius of curvature decreases due to a decrease of normal incidence to the curved surface.

Transmittance of curved membrane was measured by an integrating sphere with the LED source to collect all of the radiated light from the variable curvature. As shown in Fig. 5(b), ARS curved membrane shows higher transmittance than bare membrane in all regions from 1.2% to 3.1%. Even if ARS is expanded or shrinked by the curvature, surface relfection to incident light can be sufficiently suppressed by ARS on flexible membrane. However, transmittance decreases as the radius of curvature decreases, indicating that an increase in surface reflections due to a decrease of normal incidence and a increase of internal reflection [10].

CONCLUSION

We demonstrated the endoscope camera using a tunable liquid-filled lens with ARS on flexible membrane. Tunable liquid-filled lens with a 4.0 mm diameter silicon chamber was compactly packaged with a 2.5 mm fiber endoscope with a fluidic channel. Tunable liquid-filled lens changes its focal length by applying pressure into the channel from 0 to 40 kPa pressure range. Optimal condition of ARS in visible range was calculated by FDTD method. ARS on flexible membrane satisfying antireflection criteria was obtained by N/MEMS fabrication based on template-confined repeated solid-state dewetting on wafer scale. PDMS nanopillar arrays were replicated from glass nanohole arrays master template and permanently bonded to silicon chamber by oxygen plasma treatment. Focal length tuning range were obtained from infinity to 1.95 mm depending on the applying pressure and variable FOV images were achieved by 1.3 mm diameter tunable liquid-filled lens. Transmittance of planar and curved PDMS membrane were measured by using a broadband LED source and a spectrometer in order to compare the transmittance enhancement through ARS. Each cases increase 2.8% and 3.1% of the transmittance compared to bare planar and curved ARS membrane. This advanced endoscope camera with the tunable liquid-filled lens with ARS based on N/MEMS will provide a new vision for minimally invasive surgery applications that requires maximum transmittance and variable focus images in narrow and low illumination environment.

ACKNOWLEDGEMENTS

This work was supported by the National Research Foundation of Korea, funded by the Ministry of Science, ICT & Future Planning (2016013061), and funded by Ministry of Health & Welfare, Republic of Korea (grant number: HI16C1111).

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