Non-Destructive Testing on Optofluidic Lens Using Speckle Referencing-DSPI

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Abstract. Tunable optofluidic lenses, ranging from in-plane micro-lenses to bulky out-of-plane lenses, were the subjects of research and analysis with much interest over the past decade. However, a reliable and practically feasible metrological approach and methodology is yet to be developed to study the properties and performance of the optofluidic lenses. In this report, we propose and demonstrate to utilize digital speckle pattern interferometry (DSPI) with the aid of speckle referencing to non-destructively evaluate the performance of a pneumatically driven out-of-plane optofluidic lens through measuring the 3-dimensional interface deformation.

Introduction

Recently, the study of optofluidic systems has intensively attracted the interests of the research community due to the realization of novel properties and functionalities [1, 2]. The optofluidic components possess unique properties, such as the inherent optically-smooth interface, the replaceable functioning liquid and optical tuneability. The tuneability, in most of the cases, is enabled by applying shear stress to the liquid or fluidic interface and subsequently deforming the liquid/fluidic interface. Optofluidic lenses, which can be generally categorized into in-plane [3-5] and out-of-plane lenses [6-11], take advantages of the deformable interface to realize novel functions, such as tunable focal length [12, 13], beam divergence/convergence switching [14] and beam swinging [15]. Owing to these unique properties and novel functions, many applications of optofluidic lenses have been demonstrated ranging from micro-chip flow-cytometry [16, 17], fluorescence detection [18] to bulky optical imaging [19] and photo-acoustic imaging [20] etc. Although a lot of theoretical works have been developed to evaluate the deformation dynamics, little practical methodology has been demonstrated for the 3-dimensional (3-D) measurement of the lens interface. Especially when considering the non-solid-state of the interface, traditional stylus-based profilometer can be hardly applicable to the evaluation of the optofluidic lens interface.

In this paper, we propose to use the non-contact based digital speckle pattern interferometry (DSPI) concept to study the 3-D deformation of an out-of-plane pneumatically-driven optofluidic lens. The speckle pattern interferometry is based on the correlation of two speckle patterns captured before and after the surface deformation to calculate the deformation profile [21-27]. This technique has been widely applied to measure the relevant properties of optically diffusive surfaces in terms of speckle patterns. However, the challenging limitation of this technique to measure the optically smooth interface is its inability to generate a speckle pattern due to the specular reflection from the optically-smooth interface or surface. Here in this report, we adopt a methodology involving speckle patterns.
referencing beam to effectively generate a speckle pattern, and thus demonstrate to non-destructively evaluate the 3-D deformation of the optofluidic lens interface.

Figure 1. Schematic of experimental setup: a digital speckle pattern interferometry with the aid of speckle referencing is used to measure the 3-D deformation of an optofluidic lens interface.

**Experimental Setup and Preparation**

The experimental setup for the 3-dimensional inspection of out-of-plane optofluidic lens is illustrated in figure 1. A fiber pigtailed laser of wavelength $\lambda = 635$ nm and power 1mW (OZ-2000, OZ Optics LTD) was used for the illumination of the optofluidic lens interface and the referencing. The laser beam was split into two beams with the object beam perpendicularly going to the lens interface and the reference beam guided to illuminate a rough reference plate through a piezoelectric transducer (PZT) actuated mirror. The two reflections respectively from the lens interface and the reference plate interfere with each other and effectively form a speckle pattern at the image plane, which can be captured by a CCD camera (resolution 686×818, Allied Vision Technologies GmbH).

The out-of-plane optofluidic lens basically consists of a hollow circular chamber (diameter = 15mm) and a sealing PDMS (polydimethylsioxane) membrane which is optically transparent and mechanically elastic [28]. The fabrication details of the optofluidic lens can be referred to the reference 20. A syringe (5cc, BD plastic) along with a syringe pump (KD Scientific) can be used to inject the functioning fluid (in this case, water with refractive index of 1.33 was used) into the hollow chamber. The continuous injection of fluid can subsequently deform the PDMS membrane and increase the curvature of the lens interface.

**Theoretical Analysis**

The working principle of the digital speckle pattern interferometry to measure surface deformation lies in the correlation of two speckle patterns and extraction of phase difference. Before the optofluidic lens getting deformed, an initial exposure can be recorded which is a result of the interference between the two reflections from the lens interface and the referencing plate respectively, denoted as equation 1. Owing to the injection of fluid into the chamber, the increasing pressure can stretch the elastic PDMS membrane and deform it. After the deformation, a second exposure can be recorded, as denoted by equation 2.
\[ I_1 = I_o + I_R + 2\sqrt{I_o I_R} \cos \varphi \]

\[ I_2 = I_o + I_R + 2\sqrt{I_o I_R} \cos(\varphi + \Delta) \]

where \( I_o \) and \( I_R \) represent the intensity distributions of lens interface and the referencing plate respectively. The subtraction between the two exposures can result in:

\[ \Delta I = 4\sqrt{I_o I_R} \sin(\varphi + \Delta/2) \sin \Delta/2 \]

The phase \( \Delta \) results from the deformation-induced optical path difference, which can be characterized as:

\[ \Delta = \frac{4\pi w}{\lambda} \]

where \( w \) is the vertical deflection of the lens interface driven by the pressure. Because of the randomly diffusive reflection from the referencing plate, the phase \( \varphi \) can be assumed to be a random variable which is uniformly distributed on \((-\pi, \pi)\), and the \( I_R \) obeys the negative-exponential distribution. Therefore,

\[ \langle \Delta I \rangle = 4\left\langle \sqrt{I_o I_R} \right\rangle \left\langle \sin(\varphi + \Delta/2) \right\rangle \sin \Delta/2 = \frac{4}{\pi} \sqrt{I_o \left\langle I_R \right\rangle} \sin \Delta/2 \]

Experimental Results and Discussions

In the experiment, the lens chamber was initially filled with the functioning fluid without trapping any air bubbles in the lens chamber. The object beam was collimated and perpendicularly incident on the interface of the optofluidic lens. Because the PDMS has a very high transmittance [29], a neutral density filter (ND 30A, Thorlab Inc.) was used to attenuate the object beam intensity in order to achieve a good fringe contrast. Before pumping the fluid and increasing the pressure in the chamber, an initial exposure was made to record the interference between the reflections from the lens interface and referencing plate as the baseline. With the syringe pump, the pumping flow rate and pumping volume can be well controlled and defined. Since the interferometry is very sensitive to the deformation, we set a very low flow rate at 1mL/h. As continuously pumping the fluid into the chamber, the pressure inside started to build up, and the membrane began to undergo deformation. During this process, a series of exposures can be made along with recording the corresponding driven pressure. The subtractions of these exposures with the initial exposure can generate a series of concentric fringe patterns which are illustrated in figure 2. The order of interference fringe is highest at the center as the PDMS membrane has the largest deflection there. As continuously deforming the membrane, more fringe rings with higher orders were observed to emerge at the center of the lens interface (from figure 2 (a) to (c)). Qualitatively, the deformation amount of the lens interface can be estimated by counting the order of the interference fringe, and a higher order shows a larger deformation.
To quantitatively study the interface deformation, phase shifting technique can be applied to calculate the phase value of the fringe. The mirror actuated by a PZT device can be used to modify the optical path of the referencing beam. A four step phase shifting is applied by using the calibrated PZT phase shifter shown in fig 1. The CCD camera records the four speckle patterns corresponding to the four applied phase shifts. The phase value at each pixel can be evaluated using the following formula:

\[ \phi(x, y) = \arctan \left( \frac{I_4(x, y) - I_2(x, y)}{I_1(x, y) - I_3(x, y)} \right) \]  

(6)

Figure 3 (a) shows the wrapped phase map of a fringe pattern. Each phase jump from dark to bright represents \(2\pi\) phase variation. To un-wrap the phase map, a software package (isi-Studio, isi-sys GmbH) was used to do the filtering and demodulation. The un-wrapped phase is shown in figure 3 (b) with a continuous phase variation. With a perpendicular incidence of the illumination, the out-of-plane deformation is approximately proportional to the phase variation. According equation 4 and the un-wrapped phase, the 3-D deformation profile can be re-constructed and illustrated in figure 3 (c). Through monitoring the dynamic deformation over the entire lens interface as well as its corresponding driven pressure, the performance of the dynamic light manipulation can thus be estimated and evaluated.
Summary

In conclusion, the measurement of the dynamic interface deformation of a pneumatically driven out-of-plane optofluidic lens is demonstrated using the speckle pattern interferometry with the aid of speckle referencing. It is shown that by applying the phase shifting technique, the phase of the fringe pattern can be quantitatively extracted, and subsequently the deformation profile can be precisely re-constructed. This technique can be used to monitor the uniformity of the deformation over the entire lens interface and thus non-destructively evaluate the optical performance. Further work will be carried out to measure the driven pressure for each interface deformation using a pressure sensor. Thus we will be able to study the relationship between driven pressure and deformation, and therefore evaluate the mechanical properties of the optofluidic lens. It is envisaged that this proposed methodology also has the potential to evaluate the optofluidic lens driven by other mechanisms, such as surface tension [9], magnetism [30], acoustic vibration [31].

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