Remote sensing of pressure inside deformable microchannels using light scattering in Scotch tape

KYUNGDUK KIM,1 HYEONSEUNG YU,1 JOONYOUNG KOH,2 JUNG H. SHIN,2 WONHEE LEE,2 AND YONGKEUN PARK1,*

1Department of Physics, KAIST, 291 Daehakro, Daejeon 305-701, South Korea
2Graduate School of Nanoscience and Technology, KAIST, 291 Daehakro, Daejeon 305-701, South Korea
*Corresponding author: yk.park@kaist.ac.kr

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We present a simple but effective method to measure the pressure inside a deformable microchannel using laser scattering in a translucent Scotch tape. Our idea exploits the fact that the speckle pattern generated by a turbid layer is sensitive to the changes in the optical wavefront of an impinging beam. A change in the internal pressure of a channel deforms the elastic channel, which can be detected by measuring the speckle patterns of a coherent laser beam that has passed through the channel and the Scotch tape. We demonstrate that with a proper calibration, internal pressure can be remotely sensed with the resolution of 0.1 kPa within a pressure range of 0–3 kPa after calibration.

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Gas flows in microchannels are one of the important components for the efficient transport of matter or energy in micro-electro-mechanical systems (MEMS) [1]. Over the past decades, a variety of gaseous systems has been miniaturized into microchannel systems, such as a cooling system [2] and a gas analyzer [3]. Gas dynamics in microchannels is also a fundamentally interesting physical phenomenon [4]. Various experimental and theoretical studies have been performed [5–6] to effectively utilize the gas inside such micro-fabricated channels.

In the study of gas [7] flows in microchannels, pressure plays an important role in characterizing or controlling the gaseous environment inside. To engineer the gas flow inside the channel, monitoring pressure is essential [8]. One of the approaches for direct pressure sensing is to create a hole in the channel and insert a needle-like tip of pressure gauge, but doing so can dramatically affect the pressure. To avoid direct sensing, the external transducers [9] and microfabricated built-in sensors [10] were proposed. However, these methods are not cost-effective, especially given their low resolutions [11].

Alternatively, various optical methods to measure pressure have been developed. One type of method is based on optical fiber sensors, such as Mach–Zehnder interferometry [12], Fabry–Perot etalon [13], and fiber Bragg grating [14,15]. They can provide high sensitivity of detecting the pressure-induced deformation in order of a wavelength. However, the use of fiber sensors with microchannels is usually restricted due to the difficulty of integrating them with the channel of a small size. In order to gauge pressure inside deformable channels non-invasively, a diffraction grating embedded in channels [16] and the interferometric measurements of channel membrane [17] were also proposed. Unfortunately, it is necessary to apply complicated external measurement schemes for these methods.

Herein, we propose a simple optical method to measure the gas pressure inside a deformable microchannel. This method exploits speckle patterns formed when a coherent laser beam that has passed through the transparent channel, whose internal pressure is to be measured, is scattered by a scattering layer. A minute distortion in the optical wavefront of a laser beam, associated with the deformation of a channel due to the internal pressure, can result in a large change in the speckle patterns. High sensitivity is gained due to the randomness of the geometric structure of the scattering layer, enabling the change in internal pressure to be easily detected by an ordinary image sensor.

Our idea exploits the scattering of light from a disordered medium. Random scattering occurs when light encounters a medium with inhomogeneous distribution of refractive indexes, or a turbid medium. Due to the complexity of scattering, tiny differences in the incident light are conveyed and amplified in the transmitted field [18].

Historically, speckle patterns have been utilized for precise optical sensing of physical properties of scattering media such as displacement [19], roughness [20], velocity [21], temperature [22], solution concentration [23], and bacteria suspension [24]. Conversely, speckle patterns can also be used to analyze the properties of incident light such as incident angle changes [25], wavelength spectrum [26–28], and images [29–38] instead. To the best of our knowledge, however, there has been no investigation for sensing pressure inside a microchannel using laser speckle [7].
The principle of the present method is illustrated in Fig. 1. To measure the pressure inside a deformable channel, a collimated laser beam makes a pass through a transparent microchannel, below which a layer of Scotch tape is inserted as the scattering medium. The optical phase delay of the beam after being transmitted through the channel is determined by the geometric shape and refractive index of the channel [Fig. 1(a)]. The interior wall of a deformable channel expands when the internal pressure inside the channel increases. Thus, the phase of the transmitted beam now contains the information relevant to the internal pressure inside the channel [Fig. 1(b)]. In general, however, the change in the phase delay is small so that it is barely observable by a conventional imaging system. However, the scattering layer, by further scrambling and diffusing the light to form random speckle patterns via interference, greatly amplifies this difference such that the change in the speckle field can easily be detected by a simple image sensor.

In order to demonstrate proof of these concepts, we implemented a setup as illustrated in Fig. 1(c). It consisted of the parts for controlling and measuring the pressure inside a channel, and the optical part to generate and detect speckle patterns from a scattering layer. We controlled the pressure using a syringe (Kovax-Syringe 30 ml, Korea Vaccine Co., Republic of Korea), whose volume was regulated with a syringe pump (PHD ULTRA CP 4400, Harvard Apparatus, USA) by the infusion and withdrawal of the syringe. To monitor the internal pressure directly as a reference, we directly connected a pressure sensor (PG-30, Copal Electronics, USA) to the syringe body. The resolution of the reference pressure sensor was 0.01 kPa, and the maximum limit of measurable pressure difference was 3.5 kPa. We used microchannels made with polydimethylsiloxane (PDMS), which is a transparent and deformable polymer. The channel dimensions were 30 mm (length) × 4 mm (width) × 100 μm (height), as shown in the inset of Fig. 1(c). The two ends of the microchannel were connected with tubes with an inner diameter of 1/16 in. The two ends of the tubes were then connected by a T-shaped connector, to avoid the pressure gradient inside the channel. At the other end of the connector, the syringe was connected so that the pressure inside the microchannel could be controlled with the syringe pump.

For a coherent illumination source, we used a diode-pumped solid state laser (λ = 532 nm, 50 mW, Shanghai Dream Laser Co., Shanghai, China). The laser beam was incident on the surface of a PDMS microchannel. A scattering layer, made by attaching a single layer of a Scotch tape (Scotch Magic Tape, 3M, USA) on a slide glass, was located under the channel with a separation of 2 cm. Then the light that transmits through the channel will diffuse out by the scattering layer. The scattering layer can also be attached to the channel. The resulting speckle patterns were recorded by a CCD image sensor (INFINITYlite, Lumenera, USA). The distance between the scattering layer and the CCD was adjusted so that one speckle spot contains approximately 10 × 10 pixels in order to maximize the SNR through trial and error approach. The SNR can be potentially improved by using a low noise CCD and optimizing the speckle grain size [39].

To demonstrate the capability of the present method, we systemically measured speckle patterns at various internal pressures that were controlled by the syringe pump and monitored by a reference pressure sensor [Fig. 2]. The pressure was initially set to atmospheric pressure, and monotonically increased and then decreased at a constant rate of 0.09 kPa/s until it returned to the initial pressure. At the same time, the speckle intensity patterns of the transmitted beams were recorded by the CCD sensor. Figures 2(a)–2(h) present the representative beam patterns at various internal pressures in the absence and the presence of the Scotch tape.

In the absence of the Scotch tape, the images show beam profiles with weak diffraction patterns caused by the channel
structure. These images do not vary significantly as pressure is varied [Figs. 2(a)–2(d)]. When a layer of Scotch tape is placed beneath the microchannel, speckle patterns appeared. More importantly, they change significantly to even a small change in pressure [Figs. 2(e)–2(h)]. To quantitatively analyze the change in speckle patterns, we calculated the correlation coefficient \( C \) between two pixelated two-dimensional images of equal size, \( I_1 \) and \( I_2 \), defined as follows:

\[
C = \frac{\sum_{m,n}(I_1(m,n) - \bar{I}_1)(I_2(m,n) - \bar{I}_2)}{\sqrt{\sum_{m,n}(I_1(m,n) - \bar{I}_1)^2} \sqrt{\sum_{m,n}(I_2(m,n) - \bar{I}_2)^2}}
\]

where \( I(m,n) \) is the intensity at the \( m \)th row and \( n \)th column of \( I \), \( \bar{I} \) is its mean value, and the range of summations is the entire image. Figure 2(i) shows the correlation coefficients as a function of time. The correlation coefficient at a given pressure was calculated with the initial image at 0 kPa. The reference pressure (the black line) exhibits a small hysteresis near the peak due to the backlash of a syringe pump.

Correlation coefficients with and without the Scotch tape both follow the trends of a pressure change: they decrease when the pressure increases, and rise again as the pressure decreases. Notably, with the Scotch tape, the correlation coefficient changes more sensitively with the pressure change than it does without the Scotch tape. At 3.5 kPa, the maximum pressure in this measurement, the correlation coefficient with the Scotch tape drops to 0.34, while it was 0.97 without the Scotch tape. This result clearly shows that a layer of Scotch tape causes light diffusion that results in an effective conversion of wavefront change to the intensity change via light interference. Furthermore, the symmetry of the pressure-correlation curves in Fig. 2(i) implies that a similar speckle pattern would be observed at an arbitrary pressure irrespective of the history.

In order to demonstrate the capability of the present method as a practical sensor, we addressed the repeatability and hysteresis of the pressure sensing scheme. In Fig. 3(a), five repeated measurements were performed in which internal pressure was increased from 0 to 3 kPa. Measurements of \( C \) are highly repeatable, with a repeatability defined to be the ratio of the largest error of \( C \) to the averaged \( C \) at the given pressure, of 1.5% for pressures up to 1 kPa. Above 1 kPa, \( C \) increases due to the decrease in the value of \( C \).

To study the hysteresis of the present method, we compared the \( P-C \) curves between increasing and decreasing pressure. Figure 3(b) shows that the present method exhibits slight hysteresis; \( P-C \) curves for increasing \( P \) (the red lines) show \( C \) values higher than those for decreasing \( P \) (the black lines). We attribute this hysteresis in \( C \) measurements to the hysteresis of the channel deformation.

To further investigate the performance of the present method, we quantified the resolution and hysteresis at various measurements of time intervals between consecutive acquisitions of speckle images. To quantitatively compare the hysteresis, we first determined the pressure at which \( C \) becomes 0.5 as the pressured is increased/decreased [Fig. 4(a)]. We defined the hysteresis to be the difference in pressure for the increasing and decreasing states [inset, Fig. 4(a)]. In addition, we defined the resolution as the maximum error range in pressure at an arbitrary pressure, reflecting both hysteresis and repeatability. Figure 4(b) shows the hysteresis calculated at various time intervals. As the measurement of time interval increases, the hysteresis tends to become smaller. This is due to the viscoelastic property of PDMS, which requires some amount of time to restore its original shape after deformation. It also implies that a microfluidic channel with different viscoelasticity requires recalibration.

As shown in Fig. 4(c), the averaged resolution ranged between 0.05 kPa and 0.12 kPa. Resolution increases as the measurement of time interval increases, mainly due to the decrease of hysteresis. Compared to the reported resolution of existing optical fiber sensors for pressure such as 0.11 kPa for Fiber Bragg Grating type [40] and 0.69 kPa for Fabry–Perot type [41], the present method achieved a better resolution with a significantly simpler and more cost-effective setup.

To further investigate the effect of different types of scattering layers on the performance of the present method, we tested multilayered Scotch tape and 15° diffuser [Fig. 4(d)]. As expected, the \( P-C \) curve with a single layer of Scotch tape shows significant enhancement in performance over that without the Scotch tape. Interestingly, increasing the number of tape layers does not significantly increase the sensitivity in pressure measurement (\( p \)-value > 0.4). There was even no difference when
the type of scattering layer is replaced from Scotch tape to 15°
diffuser (p-value > 0.5). This indicates that the method
pre- sented in this Letter does not require a particular scattering
medium to be valid.

In this Letter, we presented a novel optical technique to mea-
sure the pressure inside a deformable microchannel. Exploiting
light scattering resulting from translucent Scotch tape, a small
change in optical wavefront due to internal pressure can result
in a significant change in speckle patterns, allowing the detection
of the internal pressure using a cost-effective but precise method.
This is analogous to the concept of phase contrast microscopy,
which converts a small change in the wavefront due to a phase
object into a significant change in the intensity pattern via inter-
fERENCE USING A PHASE MASK [42]. In previous experiments dealing
with light transport through complex media, small phase changes
were either avoided or minimized [43,44]; however, this work
rather utilizes this phenomenon for effective pressure sensing.

The present method can be readily implemented to existing
microchannel settings because the addition of a Scotch tape
layer and pressure calibration are all that are required. As only
the speckle patterns need to be measured, the overall detection
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