Photonic crystal thin-film micro-pressure sensors

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Abstract. We have engineered both the optical and mechanical behaviour of a suspended line defect photonic crystal waveguide to demonstrate an improved sensor response. Utilizing thinner than the conventional photonic crystal membrane increases the mechanical sensitivity and the dynamic range of the sensor. The mechanical sensitivity is also increased by optimizing the membrane pad connected to the core photonic crystal waveguide. The pad optimization also ensures maximum pad flatness under uniform pressure. The overall sensitivity obtained is as high as 6 % optical transmission change per Pa of pressure.

1. Introduction
Photonic crystal structures are increasingly being used for a variety of micro-sensor applications. An important application is the development of highly sensitive microscale pressure sensors for use in medical catheters and in lab-on-chip applications [1-2]. While capacitive-based devices have been widely used for pressure sensors, the frequency range of such devices makes them highly susceptible to electromagnetic interference in the MHz to DC spectral range. In contrast, optical microscale sensors overcome this limitation by being sensitive only to dielectric effects in the optical domain, providing significant performance advantages.

2D planar photonic crystals have been reported to produce micro-pressure sensors with high sensitivity and very small footprint area compared to optical fibre based sensors [3-7]. Point defects in 2D photonic crystal slabs can be used for resonators and sensors by utilizing the very sensitive shift of resonance wavelength by refractive index variation of GaAs [3] or the deformation of the silicon photonic crystal [4] under applied pressure. Realization of such a sensor needs delicate fabrication equipment and high resolution spectrum analyser. Line defects slab photonic crystal can be used similarly and its parameters can easily be adjusted for wider transmission bandwidth and dynamic range and we have previously reported high sensitivity waveguide based PC membrane pressure sensors [5-7].

In this paper, we present significant improvements to the optical and mechanical modelling of the sensor design to create a more robust and stable sensor while simultaneously increasing the overall sensitivity. A thinner than conventional silicon slab photonic crystal has been chosen to increase the dynamic range of the sensor. The engineering of the membrane and its optimization toward maximizing the sensitivity are explained.

This paper is organized as follows. In the next section, we present the basic principle of the sensor. In section three, we present the optical design of the sensor beginning with of SOI wafer dimensions and photonic crystal geometrical parameters needed to achieve good transmission in the telecom range.
of spectrum 1.3–1.6 µm while improving sensitivity. 3D Finite Difference Time Domain (FDTD) analysis is used and we show how the optical response can be improved by switching to a thinner than conventional slab photonic crystal. In section four we describe the mechanical modelling using finite element method and the optimisation of the geometry to achieve higher sensitivity followed by conclusion in section five.

2. Basic Principal of operation
The micro-pressure sensor is essentially an air-bridge silicon line-defect photonic crystal slab waveguide. In Figure 1(a) the schematic of the sensor is shown after fabrication. As can be seen, the photonic crystal is etched into the top silicon layer of a silicon on insulator (SOI) wafer and then the air-bridge is formed by removal of the buried oxide layer under the PC waveguide.

**Figure 1** The SOI photonic crystal sensor under (a) no pressure and b) under uniform pressure over the top surface.

Under a uniform applied pressure, the air-bridge membrane will deform towards the substrate as shown in Figure 1(b). The principle of operation of the device is based on the sensitivity of the PC waveguide transmission to the surrounding material in its proximity. When the bridge is brought closer to the substrate, the evanescent field of the line defect waveguide interacts with the substrate and leaks optical power to the substrate. The overall transmission sensitivity of this PC waveguide based micro-pressure sensor can be expressed as a multiplication of the independent optical and mechanical sensitivities respectively given by

\[
S_{\text{Total Sensitivity}} = \frac{\partial T}{\partial P} = \frac{\partial T}{\partial h} \times \frac{\partial h}{\partial P}
\]

where \( T \) is the optical transmittance, \( P \) is the applied pressure and \( h \) is the photonic crystal height over the substrate.

3. Optical design
In order to improve the optical sensitivity of the sensor we recognized that we had to deviate our design from conventional PC device structure with 220nm device layer to an SOI wafer with top silicon device layer with a thickness of 145nm thickness. The benefit of moving toward to a thinner membrane is two fold. As device layer gets thinner, the line defect photonic crystal made out of it confines increasingly less light in the vertical direction which makes it more susceptible to the surrounding environment. In other words, as the membrane approaches the substrate (on applying pressure), we expect the line defect photonic crystal waveguide mode to see the substrate sooner. As we will show later, it causes the optical sensitivity curve to broaden, and its peak shifts toward higher membrane/substrate gap height. Furthermore, a thinner membrane is also much more mechanically sensitive. The closed form sensitivity equation for thin circular membrane indicates that the sensitivity increases by cubic power of membrane thickness [8]. Typically, the host photonic crystal for a line defect waveguide is a hexagonal lattice with TM light polarization (electric field in the plane of the slab). The lattice geometry has to be chosen so the band gap covers the wavelength of interest. The band diagram is obtained using a 3D plane wave expansion method. For this a lattice constant \( a = 550\text{nm} \), the hole diameter \( D = 320\text{nm} \) are chosen so the band gap extends from 1415–1720 nm.

A line defect PC waveguide is made by removing a row of holes in \( \Gamma K \) direction of the host photonic crystal [9]. In this design, the line defect length was selected as 25 periods. The width of the
input/output channel waveguides to the PC line defect waveguide \( w = \sqrt{3a} \approx 950 \text{ nm} \) was chosen to ensure good coupling of the light into and out of the structure. 3D FDTD simulations were used to obtain the transmission spectrum of the line defect PC waveguide as designed for different heights of the bridge above the substrate as shown in Figure 2a. The transmission decreases as the bridge height decreases and the optical power couples into the substrate as predicted. In Figure 2b the transmission at a target wavelength of \( \lambda_c = 1550 \text{ nm} \) and the transmission sensitivity versus bridge height are plotted. The best optical sensitivity is found to be 0.4%/nm, and it is centered on the bridge height of 280nm. Our investigation shows that the sensitivity curve width (the sensor’s dynamic range) is wider for thinner bridge; however sensitivity is a bit lower. More importantly, the sensitivity peak shifts toward higher bridge gap heights as the bridge thickness reduces. Table 1 compares these designs.

![Figure 2(a) Transmission spectrum of the PC line defect waveguide at different bridge heights. (b) Transmission at wavelength of 1500nm and sensitivity versus bridge substrate gap height](image)

| Slab height(nm) | Period(nm) | Hole size(nm) | Max. sensitivity (%/nm) | Max. sensitivity depth (nm) | Sensitivity FWHM (nm) |
|-----------------|------------|--------------|-------------------------|-----------------------------|-----------------------|
| 380             | 450        | 300          | 0.5                     | 160                         | 150                   |
| 145             | 550        | 320          | 0.4                     | 280                         | 200                   |

4. Mechanical design
The second parameter to consider is the mechanical design of the suspended bridge which will be important for the sensitivity as described previously and also the dynamic response of the sensor to applied pressure. The overall sensor sensitivity can be tailored by keeping the optical design (i.e. the PC waveguide configuration) of the bridge intact while altering the mechanical shape of the bridge. As a benchmark, we started with a simple rectangular platform of dimension 14.30µm × 14.29 µm supported by input/output waveguides of length 22.85 µm on both sides (so the total bridge length is 60 µm). To evaluate the behavior of the membrane under uniform pressure, we simulated the structure using a finite element model with appropriate boundary conditions. When the structure is under 1 Pa uniform pressure, the displacement at the center of the rectangular membrane was found to be 3.37 nm. Using Eq.(1), the best total sensitivity obtained is calculated to be \( S_t = 3.37 \times 0.4 = 1.35 \text{ (%/Pa)} \).

Although the maximum displacement occurs at the edges of the rectangular membrane, however the membrane flatness under uniform pressure as defined by the following equation:

\[
\text{Flatness(\%)} = 100 \times \frac{\text{displacement at centre}}{\text{maximum displacement}}
\]

(2)
is as large as 99.22%.

To improve the mechanical sensitivity, one could increase the length of the supporting input/output waveguide, which would effectively reduce the stiffness of the central platform. However a better approach is to increase the applied force by increasing the area exposed to pressure while keeping the sensor footage constant. Based on this idea, a novel mechanical structure was designed around the photonic crystal waveguide. The new membrane has a 2D PC in the center with the same optical PC line defect waveguide as described previously, but with a larger suspended area. The proposed
mechanical design is shown in Figure 3a where the total size of the membrane is kept at 60 µm. The support thickness was optimized by varying the angle $\phi$ as defined in Figure 3a to maximize the pad flatness. Figure 3b shows the sensitivity and flatness curves versus $\phi$. As can be seen, sensitivity increases as $\phi$ increases, but flatness is maximized at $\phi = 70.5^\circ$ where the sensitivity is 16.54 nm/Pa and flatness is 95.7%.

Figure 3 (a) The new membrane design (b) Sensitivity curve and flatness versus support angle $\phi$ as defined in (a)

The central platform displacement was found to be 16.54 nm/Pa and the overall bridge surface displacement is very flat. Compared to the simple rectangular platform used as a benchmark, the sensitivity is improved by about 5.5 times. Using Eq. (1), one can deduce that the overall sensitivity will increase by 4.9 times ($S_t = 16.54 \times 0.4 = 6.62 \%$/Pa), however the new membrane is slightly less flat compared to the conventional one. Table 2 summarizes the performance of the conventional and the new optimized pads for a couple of sensor sizes. As can be seen the sensitivity of the pad sensor increases by about 5 times as the size increases from 45µm to 60µm.

Table 2, Sensor performance comparison (new/conventional membrane design)

| Sensor area(µm) | Mechanical Sensitivity(nm/Pa) (new/conventional) | Flatness, %/nm (new/conventional) |
|-----------------|-------------------------------------------------|----------------------------------|
| 45              | (3.21/1.11)                                     | (96.6/98.1)                      |
| 60              | (16.54/3.37)                                    | (95.7/99.2)                      |

5. Conclusion
We have shown that how thin line defect photonic crystal waveguide augmented by engineered petal membrane shaped flaps can exhibit very high sensitivity to applied pressure. The dynamic range of the sensor shows improvement and best operation point shifts toward higher slab/substrate gap width. The mechanical shape of the membrane was optimized to obtain maximum flatness under uniform applied pressure.

References
[1] La Z, et al, 2008 "Extracellular superoxide dismutase deficiency exacerbates pressure overload induced left ventricular hypertrophy and dysfunction," Hypertension, vol. 51, no. 1, pp. 19-25.
[2] Miller Inc. 2010 "Cardiovascular Ultra-Miniature Single Sensor Mikro-Tip Pressure Transducer Catheters." http://www.millarinstruments.com/pdf/005-0950B.pdf.
[3] Biallo D, et al, 2007 "High sensitivity photonic crystal pressure sensor," Journal of the European Optical Society-Rapid Publications, vol. 2.
[4] Tung B T, et al, 2011 "Investigation of strain sensing effect in modified single-defect photonic crystal nanocavity," Optics Express, vol. 19, no. 9, pp. 8821-8829.
[5] Bakhtazad A, Sabarinathan J, Hutter J, 2010 “Mechanical Sensitivity Enhancement of Silicon Based Photonic Crystal Micro-Pressure Sensor,” International Symposium on Optomechatronic Technologies (ISOT), Toronto.
[6] Sabarinathan J, Bakhtazad A, Huo X, Hutter J, 2010 “Photonic crystal Pressure Sensors”, US Patent, filed May, 2010.
[7] Wang Y, Bakhtazad A, Sabarinathan J, 2011 “Reflection mode 2-dimensional photonic crystal slab waveguide based micro-pressure sensor,” Proceedings of the SPIE, vol. 8007, 800711.
[8] Di Giovanni M, 1982 Flat and Corrugated Diaphragm Design Handbook Marcel Dekker, Inc.
[9] Chutinan A, Noda S, 2000, "Waveguides and waveguide bends in two-dimensional photonic crystal slabs," Physical Review B, vol. 62, no. 7, pp. 4488-4492.