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A miniature photonic integrated pressure sensor based on a suspended waveguide Bragg grating
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ABSTRACT

This paper presents the development of a miniature photonic integrated pressure sensor based on a suspended waveguide Bragg grating. The sensor leverages microfabrication techniques to create an ultra-compact sensor die, that interfaces seamlessly with a single optical fiber. The design features a silicon waveguide Bragg grating integrated onto a circular membrane, which is pressure-sensitive. The photonic circuit involving the Bragg grating sensor, interconnecting silicon waveguide and grating coupler was fabricated using the ISIPP50G technology and underwent post-processing to create the suspended Bragg grating sensors. The post-processing involved bonding the photonic integrated circuit (PIC) to a fused silica lid with cylindrical cavities, followed by the removal of the silicon substrate to form an approximately 10 μm thick oxide membrane. The cylindrical cavities were created using femtosecond laser-induced chemical etching, and the PIC was bonded to the fused silica carrier using an adhesive layer. The sensor's performance was characterized using a custom-designed clamping setup, demonstrating a clear shift in the reflection spectrum of the Bragg grating as a function of applied pressure making it a promising candidate for applications in environments where traditional electrical sensors are unsuitable.

Keywords: Bragg Grating, Membrane, Microfabrication, Photonic Integrated Circuit (PIC), Pressure Sensor.

1. INTRODUCTION

Monitoring and optimizing production processes have become increasingly critical to reduce energy consumption, minimize raw material usage, and improve product quality. In composite part manufacturing, for example, monitoring parameters such as temperature, pressure, and refractive index—indicative of the degree of curing—is essential. Chip based photonic sensors are particularly well-suited for these measurements due to their high precision, immunity to electromagnetic interference, and compatibility with compact system designs. While on-chip photonic sensors for temperature [1-6] and refractive index [7-9] have seen significant advancements, the development of pressure sensors remains a challenge. This difficulty arises from the need for deformable elements, which are not inherently compatible with standard photonic integrated circuit (PIC) technologies.

Recent progress in micro- and nanoscale pressure sensors has led to substantial improvements in performance and miniaturization. These devices, built using micro/nanofabrication and micro/nanoelectromechanical system (M/NEMS) technologies, have demonstrated remarkable potential due to their compact size and exceptional sensitivity [10]. Various transduction mechanisms, including piezoresistive, capacitive [11], piezoelectric, and resonant approaches, have enabled the creation of high-performance, low-cost, and small-form-factor pressure sensors.

Electrical and optical pressure sensors each come with distinct benefits and limitations. Electrical sensors, such as piezoresistive and capacitive types, are widely adopted due to their high sensitivity, robustness, ease of integration with electronic systems, and scalability through MEMS-based mass production. However, these sensors require electrical currents to operate, are prone to electromagnetic interference and face challenges in achieving extreme miniaturization or integration as multisensors for simultaneous measurement of additional parameters like temperature and refractive index.

Optical pressure sensors, on the other hand, leverage light to detect pressure variations and are valued for their immunity to electromagnetic interference, along with their potential for superior sensitivity and accuracy. These sensors commonly use optical fibers [12-14] or other optical components to measure pressure-induced changes via shifts in wavelength or

light intensity. They excel in environments unsuitable for electrical sensors due to interference or harsh conditions. Nevertheless, traditional optical sensors are often more complex to fabricate and integrate into existing systems compared to their electrical counterparts.

To overcome these challenges, we present a MOEMS-based photonic pressure sensor that combines the advantages of both approaches. Using microfabrication techniques, we have developed an ultra-compact sensor die, that interfaces seamlessly with a single optical fiber. This fully passive sensor is immune to electromagnetic interference and features a silicon waveguide Bragg grating (WBG) integrated onto a circular membrane, which is pressure-sensitive. Additionally, a second WBG located adjacent to the membrane may serve as a reference temperature sensor, enabling multiplexing within the same optical waveguide and fiber interface. This approach allows interfacing the sensors using standard fiber Bragg grating interrogators, commonly used in industry.

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2. SENSOR CONCEPT AND DESIGN

As illustrated in Figure 1, the sensor utilizes a silicon photonic integrated circuit (PIC) featuring a Bragg grating embedded in a silicon waveguide. This waveguide is suspended on a pressure-sensitive membrane composed of oxide layers. When external pressure is applied to the membrane, it deforms, inducing strain along the waveguide. This strain causes a shift in the reflection spectrum of the Bragg grating which can be tracked with a commercial interrogator. A grating coupler is employed to excite the Bragg grating and facilitate readout in reflection, using a single interfacing fiber for both functions. The PIC is specifically designed for transverse electric (TE) mode operation in the C-band, with an operating wavelength centered around 1550 nm.

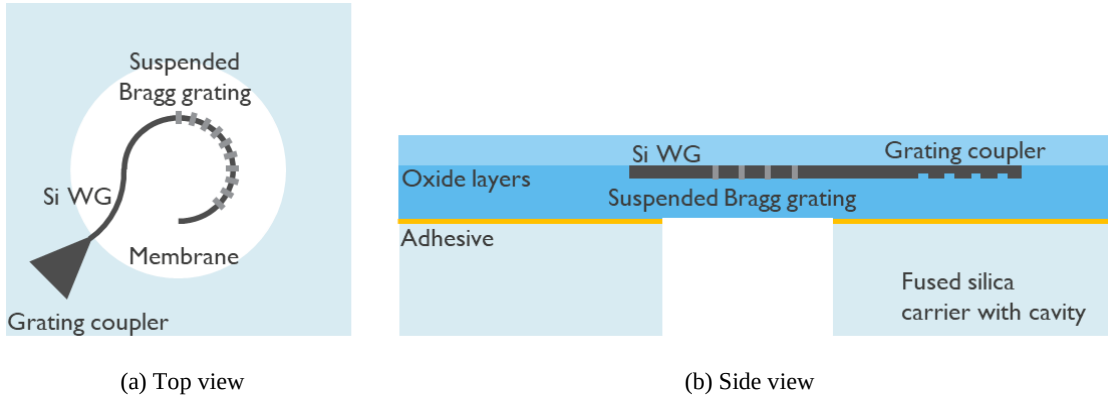


Figure 1. Schematic illustrating the concept of the sensor which relies on a Si waveguide with Bragg grating suspended on a pressure-sensitive membrane.

The sensor design is divided into two main aspects: the mechanical design of the membrane and the photonic design. The mechanical design focuses on optimizing the membrane properties to enhance the conversion of pressure into strain. On the other hand, the photonic design aims to optimize the Bragg grating to produce well-defined peaks or dips in the reflection spectrum, thereby maximizing the accuracy of strain measurements. Additionally, the photonic design encompasses the layout of the waveguide, the sensor structure, and the interfacing grating coupler.

Since the functional photonic layers are fabricated in the imec Passives+ technology (ISIPP50G, crystalline silicon on insulator starting thickness 220 nm [15]) using the Europractice multi-project wafer (MPW) service, the mechanical design is constrained by the materials and thicknesses of the layers used in this technology. Consequently, the membrane thickness was selected to match the total oxide thickness available on the substrate in this technology. The oxide layers include the 2 μm -thick buried oxide (BOX) layer, onto which the silicon waveguide is positioned, and approximately 7-8 μm of deposited oxide layers on top. As a result, the primary parameters for optimization are the membrane diameter and the positioning of the sensor relative to the membrane. A circular membrane was selected for this design, modeled with axial symmetry which allows analysis either analytically or through numerical simulation software similarly to related work we have reported [16]. Assuming uniform pressure is applied to the membrane, the radial and tangential strain (cylindrical coordinates) can be determined as function of the lateral position on the membrane and across its thickness based on a previously established simulation model [16] in which the dimensions of the membrane were

adapted to this application, i.e. the thickness of the membrane was set to 10 μm , and the radius to 50-150 μm . The material was kept as fused silica, since the membrane mostly consists of oxide (ignoring any tiling on other layers). The simulation results depicted in Figure 2 show the relative strain distributions for a certain applied pressure. When investigating the strain across the thickness of the membrane, there is no difference found between the radial and tangential strain. As expected from a mechanical point of view, the strain is zero in the middle of the membrane (neutral axis) and linearly increases in absolute value when moving towards the bottom and top surface and as a result the strain is the highest close to the top or bottom surface of the membrane. As such, it is of interest to position the Bragg grating as close to the surface as possible to achieve most optimal pressure to strain conversion. Here, the Bragg grating is positioned 2 μm from the surface as dictated by the BOX thickness and therefore the induced strain will be approximately 50 % lower compared to the optimal position.

The radial strain varies rapidly across the membrane's radius, making it less ideal for positioning a Bragg grating due to the spectrum degradation that will follow from the non-uniform strain distribution across its length. At the outer edge of the membrane, near the clamping position, an abrupt decrease of the strain is observed. This is likely a consequence of the stringent boundary conditions related to the clamping. The tangential strain increases as the distance from the center decreases. Additionally, the tangential strain remains constant at a fixed distance from the center. This is exploited by positioning the Bragg grating sensor along a circular path with a radius r (smaller than the membrane radius R). This configuration ensures that pressure induces a uniform strain along the length of the Bragg grating, minimizing spectral deformation caused by non-uniform strain distribution along the grating. The distance of the Bragg grating sensor from the center of the membrane will determine how efficient the conversion from pressure to strain will be, as is the case for the depth within the membrane. In this case, however, a trade-off has to be made between a more efficient conversion (closer to the center) and the bend radius of the waveguide (see below), r , with its associated losses. The radius R of the membrane will determine the sensitivity to pressure but also the maximum pressure that can be applied. For the initial experimental design, we selected membrane diameters ranging from 120 to 300 μm .

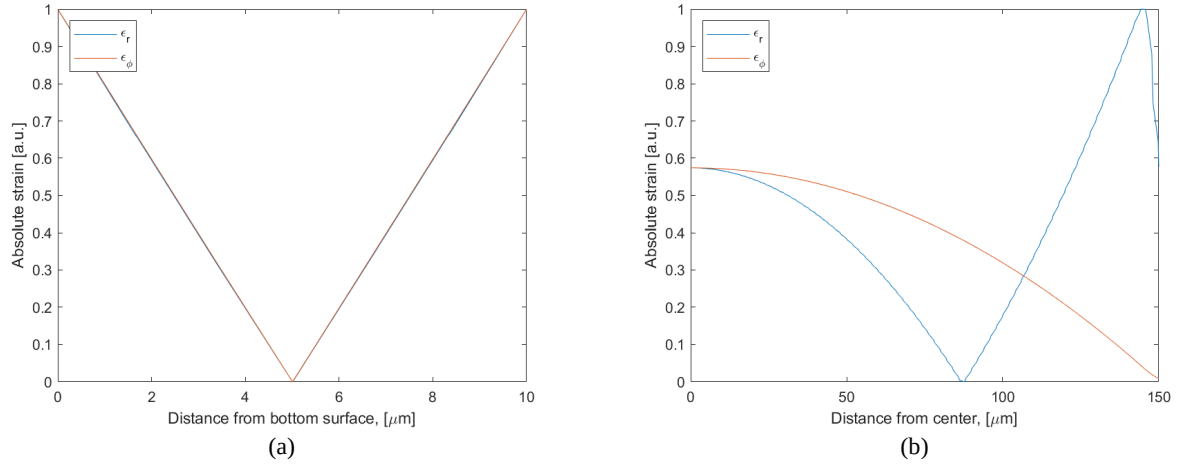


Figure 2. Simulation results of radial and tangential strain (a) across the thickness and (b) along the radius of the membrane.

The impact of waveguide curvature on the resonance wavelength of the Bragg grating can be systematically evaluated by assessing its effect on the effective refractive index of the propagating mode. This analysis was conducted using finite-difference eigenmode (FDE) simulations implemented in Lumerical. In these simulations, key geometrical parameters, including the bend radius and bend angle, were explicitly defined and incorporated into the computational model to capture the influence of curvature on modal propagation. The effective refractive indices for both the etched and unetched regions of the Bragg grating were calculated and compared to those of a straight waveguide under TE polarization. The results revealed that for bend radii greater than 50 μm , the difference in effective refractive index values between the straight and bent configurations was negligible and also bend losses are low.

In detail, the Bragg gratings implemented are surface-relief structures, with varying width along the propagation direction, fabricated on a 220 nm Silicon-on-Insulator platform. This periodicity causes a lobe in the reflection spectrum, shifting with the change in pressure, which can be tracked. Their design is conducted in two steps, with the first

concerning the calculation of all guided modes, along with their associated effective index n_{eff} . The grating pitch (Λ) required, to achieve a Bragg resonance (λ_B) at 1550 nm, can be calculated through the expression:

$$\lambda_B = 2n_{eff}\Lambda,$$

The “starting” waveguide width is 450 nm, with the aim to achieve single mode operation, with minimum losses at 1550 nm. Both TE and TM gratings were simulated, exhibiting different intensity profiles for the electrical field, as shown in Figure 3 (b) and (c) accordingly, with the TE structures achieving higher field confinement. Figure 3 (a) presents the refractive index of the cross-section for the integrated sensor.

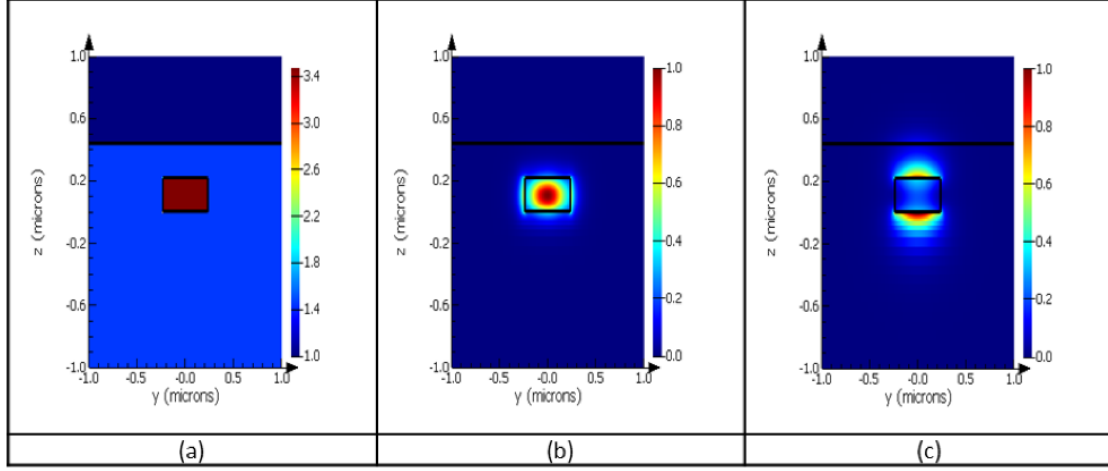


Figure 3 (a) Refractive index profile of the sensor's cross-section. Electric field intensity profile for (b) TE and (c) TM polarization configuration.

The second step consists of calculating and tailoring the grating's spectral response, for the rest of the variables, namely corrugation width and total number of periods. The objective of this step is to maximize the peak reflectivity of this reflection lobe and minimize the bandwidth, as achieving the most accurate tracking of the center of the lobe is critical. For this, commercial simulation packages based on the EigenMode Expansion algorithm are utilized, as frequency domain algorithms are advantageous in terms of the computational complexity. Figure 4 displays the spectrum of the reflection lobe, for a Bragg structure with 10 nm, 20 nm, 30 nm corrugation width, and 100, 200, and 300 periods accordingly. It can be noted that the maximum reflectivity of the gratings increases with an increase in the corrugation width, as well as by increasing the total number of periods. Furthermore, a larger corrugation width yields a larger bandwidth. Since the bandwidth is rather high, also for the smallest corrugation width shown, we have also implemented phase shifted Bragg grating designs, which exhibit a narrow dip in the reflection peak, as detailed in previous work [1, 2].

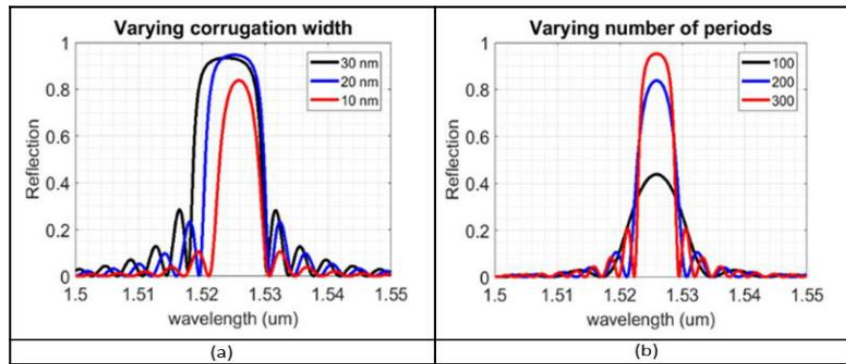


Figure 4 The reflection spectrum of a Si Bragg grating for varying corrugation width (a) and total number of periods (b).

3. FABRICATION PROCESS

Once the photonic circuits were fabricated using the ISIPP50G technology (according to the design described above), and the diced passive silicon-on-insulator (SOI) PICs (5 mm x 5 mm) were received through the MPW service, they underwent post-processing to create the suspended Bragg grating sensors, as shown in Figure 5. The post-processing involved bonding the PIC to a 500 μm thick fused silica lid with cylindrical cavities, the diameter of which defines the membrane size. The Si substrate was then removed to form an approximately 10 μm thick oxide membrane.

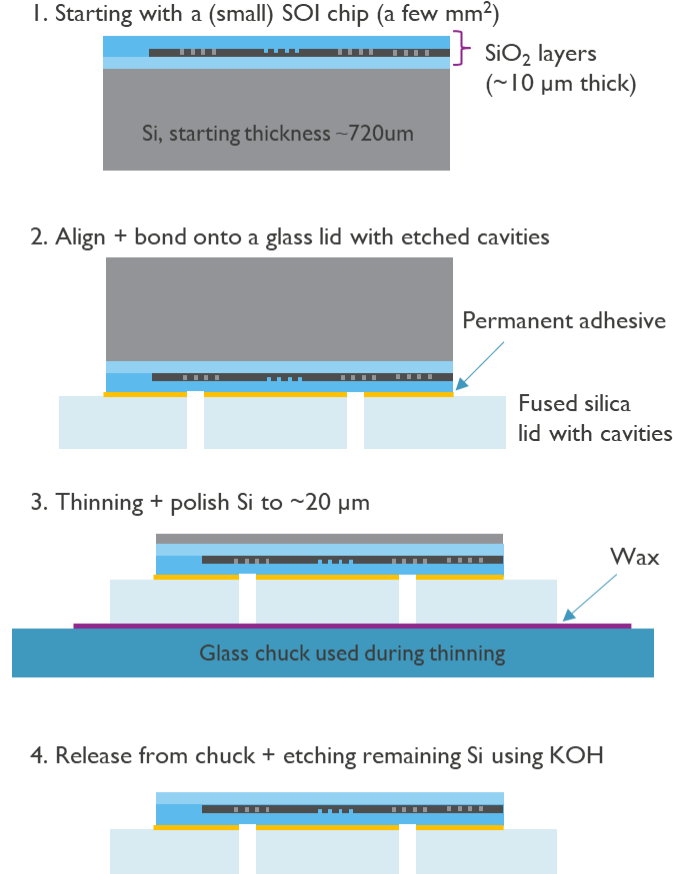


Figure 5. Process flow for realizing the suspended-membrane pressure sensor starting from a small PIC.

Cylindrical cavities with diameters ranging from 120 to 300 μm were created using the femtosecond laser-induced chemical etching (FLICE) technique. In this process, the contours of the 3D structure were first irradiated with tightly focused femtosecond laser pulses, followed by etching with KOH [17, 18] as we have described in previous work [2, 19, 20]. In the same step, alignment crosses were also inscribed in the fused silica substrate. Next, a thin adhesive layer (approximately 1 μm) of Dupont Cyclotene 3022-35 was spin-coated onto the PIC, which was then aligned and bonded to the pre-made fused silica carrier using a Finetech Lambda bonder. After fully curing the adhesive, the bonded assembly was mounted onto a temporary carrier with wax, and the Si substrate was nearly completely removed by grinding. The remaining Si was then entirely removed using KOH etching, leaving only the oxide layers. This two-step substrate removal process was employed because KOH etching is aggressive, and fully removing the substrate with KOH alone would be challenging, as it would also attack the adhesive.

Figure 6 illustrates the fabrication process along with several challenges. Figure 6(a) shows the fused silica substrate after the femtosecond laser inscription of various cylindrical cavities along with four alignment crosses which are faintly visible. Figure 6(b) illustrates a PIC after bonding with the fused silica substrate (seen through the fused silica) showing some misalignment and signs of adhesive that penetrated the cavities visible as darker rings around the contours. Figure 6(c) focuses on a successfully bonded sensor with limited adhesive penetration. Finally, Figure 6(d) presents an example of a sensor after the final KOH etching step (viewed from the PIC side), where small residual traces of Si that have not been fully etched are still noticeable. With the current fabrication parameters, it was difficult to achieve the smallest diameter membrane pressure sensors since there was too much adhesive penetrating into the cavities. However, a sufficient amount of adhesive was necessary to ensure proper bonding. As a result, this manuscript focuses on the 300 μm diameter sensor for subsequent testing.

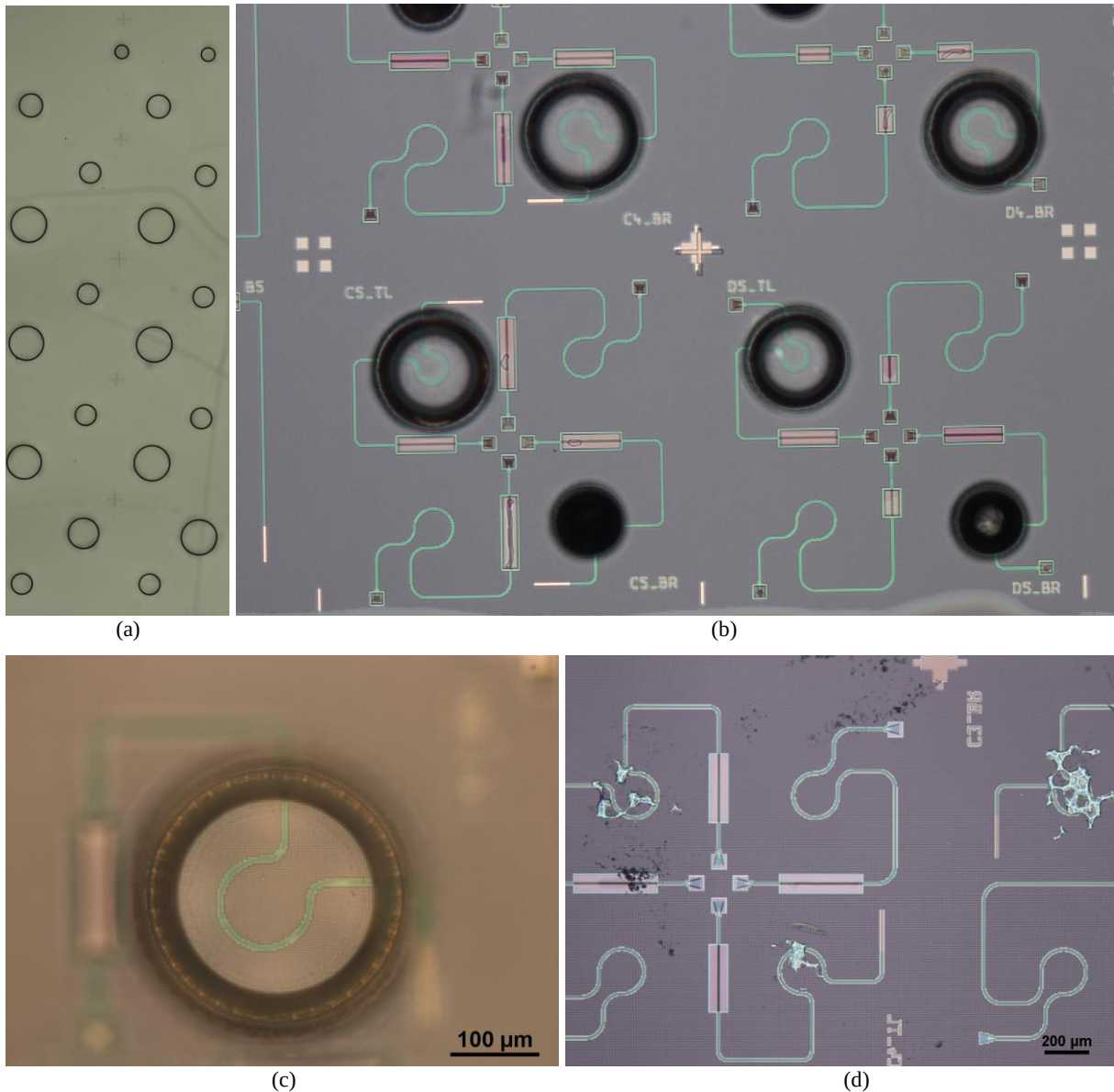


Figure 6. Photos illustrating the fabrication process and associated challenges.

4. SENSOR RESPONSE TO PRESSURE

The pressure characterization was conducted using a custom-designed clamping setup, as illustrated in Figure 7 and detailed in [16]. This device securely holds the sensor substrate while applying pressure to the underside of the membrane through a circular aperture. To prevent damage to the fused silica sensor substrate during tightening, rubber rings were employed to cushion and distribute the clamping force. Dedicated regulators and electronics allowed precisely setting the pressure in a range of 0.005 bar - 1 bar.

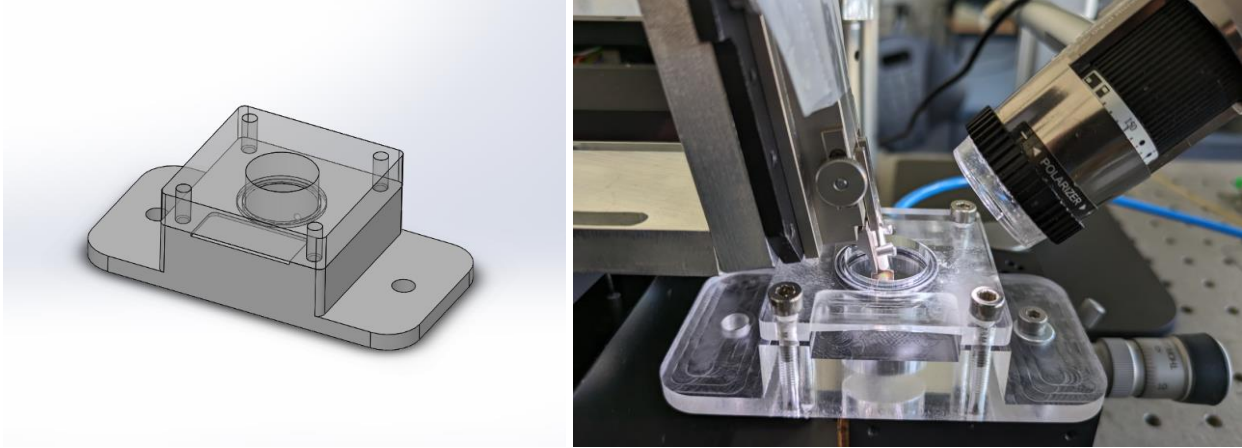


Figure 7. Test setup consisting of a pressure chamber (a) that was connected to a regulated pressurized air supply from the bottom. (b) Photo of the pressure chamber with a clamped PIC of which the grating coupler is interfaced from above using a ball lens interface mounted in a holder positioned at approximately 10° off-normal.

The sensor was clamped into the test device with the fused silica side facing downward, allowing the grating couplers to be accessed from above. A ball lens interface [2, 3] was used to interface with the grating couplers at the proper coupling angle, facilitating readout by providing clearance to the PIC and also avoiding direct reflections from a cleaved fiber tip. It should be noted that the grating couplers were accessed from the back side due to the PIC being flipped during bonding. However, previous studies demonstrated proper Bragg grating readout is feasible in this configuration when combined with a ball lens [2, 3]. The Bragg grating sensors were read out in reflection using an SLED with broadband emission in the C-band, along with a fiber polarization controller, an optical circulator, and an optical spectrum analyzer.

Figure 8 shows the shift in the reflection spectrum of the phase shifted Bragg grating as a function of applied pressure from 0 to 1 bar while keeping the ambient temperature fixed to 22°C . To obtain this graph, the (x, y, z) position of the ball lens interface with respect to the grating coupler was re-optimized for each pressure setting to consistently achieve maximal coupling efficiency. This adjustment was necessary because the fused silica substrate exhibited slight movement at different pressures due to the non-ideal rigidity of the setup. Since the temperature was kept constant, the observed Bragg wavelength shift is clearly a result of the applied pressure which causes strain in the silicon Bragg grating waveguide. However, more detailed testing is required to fully characterize the sensor and to investigate the influence of fused silica bending.

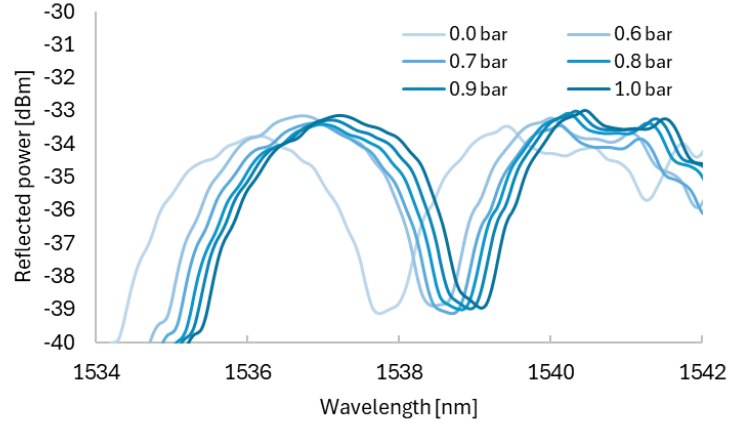


Figure 8. Shift in the reflection spectrum of the phase shifted Bragg grating as a function of applied pressure from 0 to 1 bar. The ambient temperature was fixed to 22 °C.

5. CONCLUSIONS

In this study, we developed a miniature photonic integrated pressure sensor utilizing a suspended waveguide Bragg grating and discussed its design, fabrication and initial characterization. The fabrication process, involving microfabrication techniques, femtosecond laser-induced chemical etching and bonding resulted in an ultra-compact sensor die that interfaces seamlessly with a single optical fiber. Although further testing is needed, initial experimental results confirmed Bragg wavelength shifts as pressure changes, making it a promising candidate for various industrial applications.

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