Ultra-miniature all-glass Fabry-Pérot pressure sensor manufactured at the tip of a multimode optical fiber

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ABSTRACT

The design and fabrication of an ultra-miniature all-glass pressure sensor with a diameter of 125 µm are presented. The sensor consists of a thin flexible silica membrane fused on a capillary tube section, which is assembled at the tip of a standard multimode fiber, thus forming a Fabry-Pérot air cavity whose length depends on applied pressure. Controlled polishing steps including on-line tuning of the diaphragm thickness during the manufacturing process achieve good repeatability and high sensitivity of the pressure sensor. The prototypes obtained with the described manufacturing method could easily have a sensitivity of \(\sim 2\) nm/kPa (\(\sim 0.3\) nm/mmHg) with a record, so far, of \(\sim 5\) nm/kPa (\(\sim 0.7\) nm/mmHg). The relatively simple fabrication technique using common and inexpensive equipments and materials combined with the fact that such sensitive sensors with multimode fiber could be interrogated with low-cost commercial interrogators (such as those using white-light interferometry) make this option very attractive for many applications involving pressure measurement. The sensor significant size reduction is valuable especially for the medical field, for applications such as minimally invasive patient health monitoring and diagnostics or small animals testing. Disposable sensors with ultra-miniature size will certainly open the way for new medical diagnostics and therapies.

Keywords: Single-point sensor, fiber-optic sensor, white-light interferometry, \textit{in situ} pressure monitoring, low-cost.

1. INTRODUCTION

Pressure fiber-optic sensors have stimulated a great enthusiasm in a large number of applications ranging from automotive to medical, aerospace, civil engineering or oil and gas industries. Important advantages of such sensors are naturally their intrinsic insensitivity to electromagnetic interferences and electric passivity, corrosion resistance and long-term reliability, which give them unique benefits over capacitive or piezo-resistive sensors and make them the ideal solution for harsh environments.

However in the past years, the miniature pressure sensors have become one of the most successful commercial applications in the area of optical fiber sensors (OFS), especially in the medical field where they have already a great potential\textsuperscript{1,2}. The driving force of this emerging commercial success, besides biocompatibility and above-mentioned advantages, is definitely associated with the size of such optical sensors. For medical applications, apart from the fact that the pressure sensitive membrane is perpendicular to the fiber axis is interesting, making this front-mounted sensor not sensitive to lateral pressure artifacts always present in vessels presenting peristalsis. Such small pressure OFS are for instance now integrated into sophisticated and more and more miniaturized medical devices such as instrumented catheters used for minimally invasive diagnostics or therapies\textsuperscript{3}.

Most of commercially available sensitive fiber-optic pressure sensors are presently based on micro-machined opto-mechanical systems (MOMS), where a silicon flexible diaphragm is generally assembled over a glass cavity. Thanks to photolithographic technologies derived from the semiconductor industry, they could be mass-produced on a wafer structure and diced into small chips, generally with diameters of about 0.5 mm, which are then mounted with an adhesive at the tip of an optical fiber. Such sensors structures already obtained some commercial success since they can be
produced in an economic way using well-established technologies derived from the semiconductor industry (several
thousands of sensors could actually be manufactured in batch on a single wafer). Thanks to automated assembly lines
providing outstanding manufacturing repeatability and quality control necessary for medical approval of the final
product, FISO Technologies even commercializes now reliable disposable M0M5 medical pressure sensors used, for
instance, in life-supporting devices. The miniature size of the M0M5 sensors eases its integration in smaller
instrumented catheters used in various minimally invasive surgeries. Besides the new pressure monitoring opportunities
offered by existing miniature OF5, there is still a need for smaller and cheaper pressure sensors for applications where
size becomes even more critical such as for small animals blood pressure monitoring or for less invasive intracranial
pressure monitoring or other similar applications.

Although smaller sensors could be theoretically manufactured with wafer photolithographic technology, there are some
technical practical limitations that complicate the assembly (especially when the dimension reaches the 125 µm range)
and significantly increase the manufacturing difficulties and consequently the final sensor cost, which are obviously
unrelated with single-use sensors for medical applications.

Several research groups have recently proposed new interesting approaches to further reduce the diameter of optical
pressure sensors to be comparable with standard optical fibers diameter by manufacturing the diaphragm directly at the
tip of the lead optical fiber. One of the earliest works proposed an interesting method to assemble by anodic bonding a
silicon diaphragm at the end-face of a ∅400 µm optical fiber micromachined using tip-focused photolithographic
technology. Although such technology could be used successfully in research laboratories with low-volume prototypes
production capabilities, it is practically quite complicated for industrial high-volume applications, especially if the
pressure sensor dimension is further reduced, since the alignment precision requirements increase with sensor diameter
reduction.

A significant size reduction progress was first proposed in the past by our group to achieve the manufacturing of a
sensitive pressure sensor of the same size (∅125 µm) than the one of a standard optical fiber. Using an original
chemical etching approach to create a cavity at the end face of an optical fiber and a controlled “dip and evaporate”
technique to create a very flexible polymer diaphragm over this cavity, a new generation of ultra-miniature fiber-optic
pressure sensors is actually accessible with quite simple methods that were more suitable for industrial manufacturing
processes.

Very recently the development of such methodology was used by our group and others to replace the polymer
material by pure silica to increase the sensor robustness. The all-glass ultra-miniature sensors that were proposed so far
exhibited indeed very promising performances in various conditions. Differences exist however in the sensors
construction and several attempts have been made to increase the sensor sensitivity and to simplify its manufacturability.

Besides all the difficulties associated with the fact that such ultra-miniature sensor manufacturing methods should
remain cost-effective for potential industrial transfer, it is also important that such highly sensitive sensors are
compatible with low-cost commercially available signal conditioners. In the present paper, we report a low-cost
manufacturing method suitable for the production of sensitive ∅125 µm all-glass pressure sensors compatible with
commercial Fabry-Pérot (F-P) white-light interferometry technology.

2. SENSOR DESIGN AND FABRICATION METHOD

The ultra-miniature pressure sensor consists of a multimode optical fiber, an air cavity surrounded by a glass capillary
tube and a thin silica membrane bounded to this tube. The diaphragm and the fiber–cavity interface form a low-finesse
F-P interferometer. The applied pressure causes diaphragm deflection and therefore cavity length variation, which can be
detected by an appropriate interrogation technique such as white-light F-P interferometry. The selection of the
multimode fiber and the cavity length of the sensors prototypes are adjusted to be compatible with low-cost signal
conditioners such as FTI-10, FPI-HR, PM-250, UMI or DMI series commercialized by FISO Technologies.
According to the theory of symmetrical bending of circular diaphragm with clamped edges and loaded by pressure, the maximum deflection is at the center of the diaphragm. The sensor sensitivity (s) characteristic equation\(^{14}\) is:

\[
    s = \frac{y}{P} = \frac{a^4}{E \cdot h^3 \cdot A_p}
\]

where \(P\) is the applied pressure, \(y\) is the center deflection, \(a\) is the diaphragm radius, \(E\) is the diaphragm modulus of elasticity, \(h\) is the thickness of diaphragm and \(A_p\) is a dimensionless stiffness coefficient. From that equation, it is quite obvious that reducing the size of the pressure sensor, and therefore reducing the radius of the diaphragm, has a drastic effect on the sensor sensitivity, since it is proportional to the fourth power of the diaphragm radius. This statement has an important impact on the design of ultra-miniature sensors as reducing the sensor size \(a\) priori has the effect of reducing drastically its sensitivity. So, to keep the sensor sensitivity as high as possible and to compensate for the diaphragm radius reduction, the only solution is either to have a less stiff material or to reduce the thickness of the diaphragm. We used both strategies to produce pressure sensor prototypes with 125 µm diameters. First, a more flexible silica diaphragm replaced the silicon diaphragm of commercial sensors. Then membrane thickness reduction, which actually remains a practical challenge, was obtained by original controlled manufacturing methods.

Fig. 1 shows a front view of the tip of the all-glass ultra-miniature pressure sensor as seen under an optical microscope. It shows an external ring corresponding to the capillary walls surrounding the thin diaphragm which presents concentric Newton rings under white-light illumination. Besides the fact that the transversal dimension of the sensor does not exceed the diameter of a standard optical fiber (125 µm), this type of sensor has also the great advantage of being free of adhesive, which is an interesting feature, for instance, in very high temperature environments as previously mentioned for similar all-glass sensors\(^{10}\). Although such performances are interesting, its use for long-term pressure monitoring at elevated (>400-500°C) temperatures may not be practically possible due to possible surface devitrification and crystals growth problems that may reduce the sensor life expectancy.

![Fig. 1. Front view of the Ø 125 µm pressure sensor tip visualized under white-light illumination of an optical microscope. The capillary walls (periphery) and Newton concentric rings in the diaphragm region (center) are clearly visible.](image-url)
Fig. 2. Schematic sensor manufacturing process performed in 4 steps: 1) A hollow capillary is spliced to a coreless silica fiber; 2) The capillary section is reduced to the appropriate length; 3) A multimode fiber is spliced in order to form a Fabry-Pérot cavity that could be interrogated by white-light interferometry; 4) The coreless silica fiber is cleaved to create a flexible diaphragm that is thinned down using mechanical polishing followed by chemical etching to obtain higher sensitivity.

The sensor fabrication process is schematically detailed in Fig. 2. It consists first of the splicing of a hollow capillary fiber with a coreless silica fiber. The hollow fiber is then cleaved and polished mechanically until a targeted length is achieved. The open cavity is then carefully cleaned in an ultrasonic bath to remove any polishing debris and to expose the flat clean surface of the silica fiber. This structure is then spliced to a cleaved multimode fiber to form a closed air cavity with the two air/glass interfaces forming a low-finesse F-P interferometer that was designed to be interrogated by FISO Technologies commercial white-light interferometers.

The coreless silica fiber is then cleaved 15-25 µm away from the splicing in order to form a thick silica diaphragm that is polished in two steps (illustrated in Fig. 3 and Fig. 4) to significantly reduce its thickness and thus to increase the F-P sensor sensitivity. First, a mechanical polishing step (Fig. 3) is performed using fine paper grid and controlled polishing techniques to reduce any surface defects that could destroy the thin membrane. The fiber tip with the diaphragm is inserted into a ferule that is properly positioned over a rotating polishing surface. During this step, several visual inspections are performed in order to control the polishing rate and to insure that the membrane is not destroyed.

Finally, chemical etching in a closed vessel with cycling pressure is performed (Fig. 4), as previously described, to achieve a higher sensitivity with a finer control. During this final polishing step, a sensor interrogator continuously interrogates the sensor submitted to variable pressures to follow precisely the chemical etching and to stop this process when targeted sensitivity is achieved. As the membrane is chemically thinned down using a hydrofluoric-based solution, the sensor sensitivity increases inversely to the power of three of the membrane thickness according to the aforementioned equation. Practically, this means that its sensitivity increases more and more rapidly as less material remains for the diaphragm and therefore, a tight control of this step is critical to achieve higher sensitivities while not destroying the thin membrane. Such yield improvement allows an overall sensor manufacturing costs reduction.
Fig. 4. Chemical etching of the membrane of the all-glass ultra-miniature pressure sensor with on-line cavity F-P monitoring.

It should be also noted that all previous reported all-glass pressure sensors are using single-mode fibers. In the present work, the lead fiber is multimode, which indeed means that the sensor could be interrogated by field-proven robust technologies such as the white-light Fabry-Pérot interferometry commercialized by FISO Technologies. Such technology is well suited for applications requiring a compact and cost-effective sensor interrogator. The principle of this technology is schematized in the top of Fig. 5. A light source, namely a bright incoherent white-light lamp, is first coupled into a multimode optical fiber of a 2x2 coupler which acts as a 50/50 power splitter. One output fiber is linked to the OFS through an optical connector at the signal conditioner front panel. The second output fiber of the coupler is not used or could be connected to a light detector for light source power monitoring purposes in some configurations. Then, the light-waves travel through the lead optical fiber until they reach its tip where the F-P interferometer pressure sensor is located. Beams undergoing multi-reflections in the F-P cavity of the sensor (whose length is pressure dependent) are re-coupled into the optical fiber from which they originally came from and they travel back, entering the signal conditioner at the optical connector level. Then, the light-waves are again separated by the 2×2 coupler into two fibers. The waves directed back to the light source are lost whereas the other fiber directs them toward an optical box where the light-beam is spread over a Fizeau wedge that reconstructs the interference pattern which is physically recorded using a charge coupled device (CCD). Due to the fact that white-light is used, all wavelengths are present and thus destructive interferences occur except for the zero order where all wavelengths are actually constructive. Thanks to the wedge that creates a linear variation of thicknesses, the cross-correlated interference pattern has a maximum intensity at the exact position the optical path difference equals the one created at the F-P pressure sensor, and few lower intensity peaks symmetrically disposed around the central peak (as given by the interferometer cross-correlation function). Thus finding the sensor optical path difference related to applied pressure simply consists of finding the position of the maximum peak in the CCD interference pattern which is achieved with fast and reliable signal processing.

This robust interferometric method allows accurate and precise F-P cavity length measurement with sub-nanometer range precision over several decades of micrometer span, thus giving a very interesting dynamical range. With accurate F-P cavity length measurement and appropriate calibration, the sensor interrogator can determine precisely the pressure seen by the ultra-miniature sensor. Besides the fact that only low-cost optical components are used for white-light F-P interferometry, the signal conditioner could be very compact. Bottom left of Fig. 5 shows the two parallel channels FPI-HR sensor interrogator recently introduced on the market by FISO Technologies which has a very small footprint (\(\sim 10\times10\times4.5\) cm) and which integrates “intelligent optical connectors” that simplify characteristic data transfer from the sensor to the module. Such DIN-rail snap-on module, which was developed for low-cost and high-volume OEM applications, could be also integrated in the new \textit{evolution} platform (see bottom right of Fig. 5) to create a convenient customizable and upgradeable professional tabletop system. Several versions and expansion units are also available\textsuperscript{15}.

Another advantage of having a multimode fiber for this type of ultra-miniature sensor is related to the optical connector, which is probably one of the weak point of OFS used in practical applications since it assures the critical optical link between the sensor and the interrogator. Even though tremendous progresses have been made in modern optical
connectors with optical losses ranging typically from 0.1 to 0.3 dB for the most popular ones, special care should still be observed when connecting an OFS to its reading unit to avoid that dust particles, finger grease or other contaminants could be present between connecting ferrules. Reduction of problems could be done by properly training the end-user that is still often not aware of the importance of cleaning procedures. Multimode fibers with typically 50-100 µm core diameter have also obviously fewer chances to be catastrophically affected by dusty connectors than single-mode fibers with 5-10 µm core diameter simply due to the fact that there is more core surface between the connecting ferrules. The problems generated by dust are clearly understood in the telecom environment where optical connections are often almost permanent, but this is not usually the case in other industrial or clinical environments where optical connections could be done on a daily basis. Part of this problem could be solved by providing clean disposable connectors and appropriate system maintenance, but still optical connections represent a real practical challenge in an environment where users are often under high stress and should react fast to emergency situations often occurring in clinical environments, for instance.

![Diagram of optical setup](image)

**Fig. 5.** **Top:** Principle of operation of white-light Fabry-Pérot interferometry technology developed by FISO Technologies. **Bottom left:** Compact parallel dual channel FPI-HR sensor interrogator with integrated “intelligent connectors” capable of reading the sensor characteristics while the sensor is connected to this DIN-rail snap-on module. **Bottom right:** two examples of the new evolution platforms where several DIN-rail snap-on modules could be combined to create expandable and customizable table top systems.
Fig. 6 shows a typical calibration curve of the prototypes obtained with the described manufacturing method. It becomes obvious that the sensor cavity length decreases (increase of deflection) linearly as the pressure is increased since the linear correlation coefficient ($R^2$) is very close to unity. The experimental sensitivity obtained from the slope of the calibration curve shows that this type of ultra-miniature pressure sensor could easily have a sensitivity of ~2 nm/kPa (~0.3 nm/mmHg) with a record, so far, of ~5 nm/kPa (~0.7 nm/mmHg), which is higher, to our knowledge, than all previously reported sensitivities for similar all-glass sensors, even about 50% higher that our own published results.\(^1\)\(^9\). It should also be noted that due to the fact that the lead fiber is multimode, the diaphragm displacement is actually averaged over the light spot size (slightly bigger than ∅ 50 µm), indirectly reducing the apparent displacement of the diaphragm center in comparison with the one which would have been measured with single-mode fiber. The high sensitivity achieved in the present work, which could be explained by better manufacturing process control, opens the way for the development of low-cost ultra-miniature F-P pressure sensors suitable for medical applications, which require a minimum resolution of ~1 mmHg over all the physiological pressure range (~250 mmHg).

With such high sensitive ultra-miniature sensors, compatible with commercially available interrogators, it is now possible to consider the development of applications that would not have been possible in the past. Although the presented work demonstrates the manufacturing feasibility of all-glass ultra-miniature pressure sensors with relatively simple methods, further research efforts are presently oriented toward simplified and more efficient manufacturing processes to be able to mass-produce such sensors that ideally should become low-cost products to be suitable for medical applications requiring disposable sensors.
3. CONCLUSION

Miniaturization of a fiber-optic pressure sensor to the size of a standard optical fiber (∅ 125 µm) is very challenging. First, common manufacturing techniques based on photolithographic technologies are harder to implement at this scale with a reasonable low-cost and second, the biggest intrinsic difficulty is that the membrane thickness has to be dramatically reduced to compensate for the diameter reduction while maintaining a high sensitivity. Thus, sensitive ultra-miniature pressure sensors, suitable for instance for medical applications, are difficult to produce cost-effectively.

To solve this problem we proposed an interesting all-glass multimode optical fiber sensor design with original manufacturing methods that allowed reaching sensor sensitivity high enough to address the physiological pressure range with a reliable well-established and low-cost technology using white-light interferometry. The experimental results obtained so far are very promising for the development of new generations of unique commercial products.

Thanks to new technological approaches, recent progresses made in the size reduction of optical fiber pressure sensors open new frontiers for the pressure measurement in restricted areas. With further developments associated with custom packaging, it will be soon possible to monitor pressure in smaller vessels such as the ones of small animals used in many drugs researches, or to develop less invasive medical devices such as smaller instrumented catheters. With efforts presently made to reduce the manufacturing costs, disposable sensors of ultra-miniature size will certainly open the way for new medical diagnostics and therapies or other similar applications.

REFERENCES