Invited Paper

Pressure measurement with fiber-optic sensors: Commercial technologies and applications

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Abstract: Mainly three technologies are presently commercially available for pressure measurement with fiber-optic sensors: intensity-based, fiber Bragg gratings and Fabry-Perot. The first one is probably the simplest and cheapest but it is limited to applications where having 2 fixed or up to 4 flexible fibers is not an issue, whereas the two other technologies require only one fiber. With generally low sensitivity to pressure and prohibitive cost for non-multiplexed measurements, fiber Bragg grating pressure sensors are still limited to marginal applications. Fabry-Perot technology is the best compromise offering at affordable price a great flexibility in terms of pressure ranges, high sensitivity and miniature size suitable for most applications including disposable medical devices.

Keywords: Fiber optics sensors; Sensors; Pressure; Intensity-based; Fiber Bragg grating; Fabry-Perot

1. Introduction
Pressure can be measured over a very broad range from $10^{-12}$ Pa (in extreme vacuum) up to $10^{+12}$ Pa (in explosions) and a very large number of electrical sensor types have been commercialized so far. To convert pressure induced mechanical deformation into an electrical digital signal, such sensor usually rely on different physical principles such as piezoresistive or piezoelectrical principles, inductive or capacitive principles, or even thermo-electrical or acoustic principles. All of these principles have a large number of technological limitations which restrict their full utilization for sensing pressure in environments with important electromagnetic interferences (EMI), elevated temperatures, harsh chemicals or explosion sensitivity. Most of those constraints are actually circumvolved by optical fiber sensors (OFS) which often offer also better long-term reliability and sometimes with the benefit of a smaller size. Being however slightly more expensive than conventional technologies based on electrical and mechanical principles, OFS are usually reserved to niche critical applications, where they remain the best choice. As a consequence, only the leaders of the OFS companies are presently successful to penetrate this exclusive market.

Despite challenges associated with the reality of those markets, an increasing number of OFS starts to become commercial success stories. Although temperature OFS are certainly the most widely spread in the industry with well-known applications ranging from industrial process control, energy, civil engineering to medical [1, 2], pressure measurement is probably the second most important physical parameter that is successfully addressed with OFS. Actually pressure OFS have gained new market shares only in the last past five years as new applications involving mainly medical disposable sensors are now commercialized.

This paper will present the three main pressure OFS technologies that are commercially available as well as some associated applications.

2. Intensity-based pressure sensors
Intensity-based pressure sensors were probably one of the first pressure OFS to be commercialized. The principle behind such sensors is quite simple: the light emitted by a multimode optical fiber tip is collected by another after reflecting on a diaphragm deflecting with pressure. The intensity of the collected light is dependent on the core diameter and position of the optical fibers as well as on their numerical aperture, but it is also directly related to the distance separating the fiber ends and the reflecting diaphragm, allowing direct pressure measurement. The light intensity increases rapidly from zero (when the diaphragm is in contact with the fiber-ends plane) to reach a maximum when the diaphragm plane matches the position where the solid angles of numerical aperture of both fibers overlap the most. As the diaphragm plane moves further away, less light could be collected and the light intensity decreases slowly back to zero. By properly designing the sensor for a selected pressure range providing that only a monotone region of the light intensity curve is used, a unique pressure could be derived from light intensity once the sensor has been calibrated.

The main advantage of this technology resides in the fact that it does not require expensive optical devices to operate. Simple light source such as cheap light emitting diode (LED) and light detector such as photodiode are sufficient to inject and collect light into pig-tailed large core multimode fibers. Even the optical connector usually used in most OFS technologies could be avoided since all the inexpensive optical components could be integrated into the sensor element, allowing a more convenient electrical interface with the data processing unit.
Although it seems that such technology could have the best of both worlds (advantages of optical sensing combined with ease of electrical connection), it is not without a high price to pay due to the intrinsic nature of the measurement itself: light intensity is always dependent on a lot of factors which are often hard to control. For instance, the measured intensity is directly linked to the light source which could fluctuate due to aging or temperature changes and the same apply also for the light detector. Changes in the reflectivity of the diaphragm mirror due to thermal effects or oxidation affects also the sensor long term reliability, especially if the sensor is subjected to high temperatures (>150°C). The thermal expansion of the diaphragm, which could be made of metal or polymers depending on the application, could also induce unexpected apparent pressure shift, furthermore that positioning and orientation of the two fibers relative to the diaphragm could also be affected by temperature changes. The design and the encapsulation of the flexible membrane is therefore often critical and probably the biggest challenges to produce reliable sensors using this technology. This is particularly true if the sensor is used in a harsh environment such as for instance the one encountered in combustion engine chambers, where direct pressure measurement could help to improve the energetic yield by better sparkplug ignition timing capacity. In such harsh chemical environment, the sensor may be subjected to pressures up to 30 MPa with instantaneous gas temperature of about 1 500°C and continuous temperature up to 300°C. Besides long term (>10 years) reliability requirements with hundreds of millions cycles, the highest pressure on such application is probably the price: each cent decrease is significant for the automotive industry. This hurdle truly complicates the market penetration of this OFS technology for which a target price should be below 108...

Another source of intensity unexpected changes is directly linked to fiber losses due for instance to fiber bending, especially when large core fibers are used as often the case in order to maximize light intensity output. Such major drawback could however be avoided by fixing the optical fibers pathway (which is possible for instance in the above cited application) but such option is not always acceptable. For instance in medical instrumented catheters, the fibers have to be flexible and prediction of the intensity losses due to tortuous path is not possible. To solve this problem, one or two additional non-sensing fibers have to be added next to the other fibers to estimate the bending losses [3, 4]. Although theoretically not perfect due to local micro-bending issues, such approach is practically acceptable for adequate compensation, such the case for intensity-based sensors used for intra-cranial pressure (ICP) monitoring. This important application probably still represents the highest market for pressure OFS in terms of number of units sold per year. Since the brain is contained in the skull, a rigid container, any liquid accumulation such as blood or cerebrospinal fluid (CSF) or mass lesions such as tumors, pus or hematoma may increase ICP. High ICP is a common cause of death in neurological patients and sustained high ICP suggests poor prognosis [5]. Forty percent of patients admitted unconscious have high ICP. In this group, high ICP will be the leading cause of death in half of cases [6] and effective treatment of high ICP was proven to reduce mortality [7]. As ICP varies continuously and especially at high ICP, a single measurement may be misleading and therefore, a continuous record of the ICP wave is necessary to avoid missing a sudden rise in ICP [5].

3. Fiber Bragg grating pressure sensors

A lot of research is done on fiber Bragg grating (FBG) sensors, especially concerning pressure measurement, but since FBG intrinsic pressure sensitivity in not very high, those sensors are always designed to amplify the pressure measurement indirectly by sensing the strain instead. Two approaches are commonly used: one consists of attaching the FBG fiber to a flexible diaphragm either orthogonally or in the diaphragm plane in areas where the strain is maximal. In both cases, such designs always imply bulky sensors, often limited to high pressure ranges which are however acceptable for applications in civil engineering or in the oil and gas industry [8] where sensor size is not a real issue. Another interesting approach consists of mounting the FBG sensor in cylindrical assemblies so that increased pressure sensitivity is achieved through mechanical amplification schemes. Many designs are proposed in the literature with variations in coatings and assembly. They are always compromising size and sensitivity to achieve sensor outer diameters (typically in the range of 1 mm or less) usually much smaller than the first approach.

Since the length of the FBG itself is generally in the 5-10 mm range, encapsulated FBG pressure sensors are not really suitable for true point-sensing pressure in very small regions. Also the lack of very high sensitivity to hydrostatic pressure of such sensors limits their use in most applications requiring better performances. However some interesting ones involving FBG sensors could be found in the biomedical field, mostly related to evaluation of pressure in rigid structures involving bones [9, 10] or dental implants [11]. For instance, inter-vertebral disc pressure could be measured with such technology [12, 13].

One important difficulty related to the FBG sensing technology relies in the fact that the sensing grating is about equally sensitive to strain (measuring indirectly the pressure) than to temperature. In applications where temperature is not constant and could vary a lot, this represents a practical problem that has to be addressed either by complex athermal encapsulation or by complicated temperature compensation strategies.

Although performances of FBG pressure sensors could be acceptable for many applications, the fact that most of the time only one pressure measurement is done on single fiber actually limits the potential of such technology. Compared to other pressure OFS technologies, the cost of the FBG interrogator is still too high, even though it reduced significantly over the past decade. Such technology performs well, on a cost-per-measurement basis, only when several measurements are multiplexed on the same fiber. Although some spatially distributed pressure sensing using FBG have been already proposed [14], no high-volume potential application has reached commercial maturity so far.
4. Fabry-Pérot pressure sensors

From the commercial point of view, one of the best OFS technologies for pressure measurement is definitely the one involving Fabry-Pérot (F-P) point sensors. Besides offering also other multiple parameters measurements [15] (such as temperature, strain, displacement, refractive index…) it allows the highest design flexibility as far as the sizes and the pressure ranges are concerned. In all cases of extrinsic F-P pressure sensors, a reflective membrane is assembled above a vacuumed cavity with a semi-reflective layer at its bottom forming a F-P cavity whose length is changing with pressure flexing the membrane. The interference pattern created by the F-P cavity could be used to measure precisely the diaphragm deflection and thus the pressure changes. The light used for F-P cavity interrogation is carried on by an optical fiber (either single or multimode) linking the interrogator and the pressure sensor.

Different F-P interrogation techniques are commercially available and differ mainly on the light source: single wavelength or narrow-band light sources will give a periodic pattern shifting with pressure. Although applicable only for relative pressure measurements (since the sensor has to be referenced each time it is optically connected to the interrogator), this patented interrogation technique [16] commercialized by FISO Technologies, is best fitted for monitoring very fast occurring events such as explosions or blasts [17, 18]. Thanks to the use of efficient light source and detector, the acquisition rate is typically 0.2 MHz but it could be extended to 2 MHz if data post-processing is possible.

If a broadband light source, such as white-light is used, the periodic pattern changes as the interference at different wavelengths become rapidly destructive, except for the zero order where all wavelengths are in phase. By using a Fizeau wedge that creates a linear variation of thicknesses, a cross-correlated interference pattern could be generated in the F-P interrogator to simplify data processing since the maximum intensity peak position then corresponds to the exact position where the optical path difference equals the one created at the F-P cavity. This patented field-proven technology commercialized by FISO Technologies since 1994 has the advantage of providing an absolute measurement of the F-P cavity length with sub-nanometer range precision over several decades of micrometer span, thus giving a very interesting dynamic range. With interrogators that could be as small as the size of a <1 inch thick credit card with OEM competitive price, have an acquisition rate up to 15 kHz or have the capability to offer multiple channels, such technology addresses a broad variety of applications and be more easily and transparently integrated into more complex systems requiring OFS pressure measurement.

The design of the extrinsic F-P sensor strongly influences its applicability in targeted applications. For civil engineering or other industrial applications, the membrane could be machined from metal to create bulky and rough sensors usually for high pressure ranges. Other materials for membrane design such as sapphire are also interesting to improve the reliability of the sensor to very high temperatures such as the ones in many oil and gas well applications. Although the size of the pressure sensor is usually not a real problem for those kinds of applications that could easily accommodate 1-2 inches outer diameter sensor, smaller pressure sensor with equivalent or better performances opens new opportunities. For instance the new miniature F-P piezometer which has been recently proposed [19] could be more easily integrated into instrumented geo-textile or inserted without problem into very small diameter tube temporary wells used traditionally for water level assessment during soil compaction monitoring.

The trend toward further reduction of sensor size is particularly true for medical applications. The added value of integrating miniature pressure OFS into instrumented catheters is now clearly accepted in fields like cardiology where the sensor provides precise in situ blood pressure measurements. Such applications involving disposable medical devices, like for instance in intra-aortic balloon pumping therapy [20] (IABP) or in fractional flow reserve (FFR) evaluation, require low-cost still high-quality sensors manufacturing capabilities. Such challenges have been solved by FISO Technologies which now commercializes high-volume of F-P pressure sensors for several OEM customers. Those sensitive sensors (with flexible diaphragm made from thin silicon) are mass-produced on wafers using well-controlled photolithographic technologies and individually assembled at the tip.

![Figure 1: Examples of F-P miniature pressure sensors commercialized by FISO Technologies. Left: FOP-MIV (Ø 550 µm); Center: FOP-M260 (Ø 260 µm); Right: FOP-F125 (Ø 125 µm)]
of multimode optical fibers using fully automated assembly lines. As presented in Figure 1, several models with decreasing diameters from 550 µm (FOP-MIV) down to 125 µm (FOP-F125) are commercially available. For this FOP-F125 world smallest pressure sensor pushing further the size limits, the membrane is made from glass, which is more flexible than silicon, and assembled over a cavity carved at the tip of the optical fiber using patented technologies [21-24].

5. Conclusion
Several technologies are available commercially for pressure OFS. Each one has its own advantages and drawbacks as presented in this paper, but each one has found also some niche applications where it seems to be the best solution. However real commercial success for such sensor will come from high-volume repeated business and so far only medical applications involving disposable medical devices seems to offer such opportunity. For this specific market, F-P seems to be best positioned since it offers, at a price compatible with the market, great sensitivity sensors with miniaturization appropriate for simplified integration.

6. References