A miniature fiber Bragg grating pressure sensor for in-vivo sensing applications

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ABSTRACT
A miniature FBG pressure sensor is reported. Two optical fibers containing FBG arrays are twisted together and the sensing elements are enclosed in a specially designed structure to detect variations in the ambient pressure. It provides an overall diameter of ~1 mm which is extremely beneficial for the studies of peristalsis in the gastrointestinal tract and flow in the vascular system. The static and dynamic responses of the miniature catheter were calibrated and the results are presented.
Keywords: Fiber optic sensor; Fiber Bragg gratings; Manometry; Medical optics instrumentation; Gastrointestinal disorder.

1. INTRODUCTION
Fiber Bragg gratings (FBG) are simple, intrinsic sensing elements inscribed into the core of an optical fiber, one can measure the Bragg wavelength shift to monitor variations in localized physical quantities such as pressure, strain and temperature¹. FBG based sensors provide key advantages such as small size, flexibility, wavelength-encoding nature and the ability for quasi-distributed measurement through wavelength division multiplexing (WDM) techniques. As a result, FBG sensors have generated many significant research projects and various implementations have been demonstrated in different areas of study, ranging from structural health monitoring and defense technology to medical applications. One of the important emerging applications in the medical field is the in-vivo measurement of physical parameters such as pressure and temperature ²,³.

This project is based on our previous work on measurement of Functional Gastrointestinal Disorders (FGID). FGID’s represent a number of disorders affecting different parts of the gastrointestinal tract, such as dysphagia, abdominal pain, irritable bowel syndrome, diarrhea and constipation⁴. While the majority of these diseases are perceived as benign medical conditions, they pose significant impacts on the patient’s quality of life and on global health care resources. FGID’s are poorly understood and can be the result of multiple interrelated disorders, which increases the difficulties for precise diagnosis and satisfactory treatments. To improve the current state of diagnosis and treatment we need a better understanding of the underpinning pathophysiology of the disorders, this can be achieved through in-vivo studies of the functionality and the sequencing of the muscular peristalsis in the upper, i.e. esophagus, and lower, i.e. colon, gastrointestinal tract.

The preferred method for in-vivo monitoring of the peristaltic patterns is to measure pressure variations at spatial intervals of ≤10 mm along the region under investigation, this is known as high resolution manometry (HRM)⁵. Our group has previously developed a fiber optic manometry catheter consisting of multiple FBG elements written into a continuous length of single mode fiber with each FBG rigidly fixed in a localized pressure sensitive structure. This design provided a small diameter and high flexibility, which are vital parameters for smooth and comfortable intubation into the patient. WDM techniques were used to allow simultaneous interrogation of up to 144 sensors without expanding the overall diameter. We have published the in-vitro and in-vivo trial results of the FBG catheter for measuring peristalsis in the esophagus⁶ and colon⁷. There is however desire for a catheter of smaller diameter to minimize distension in the GI tract during measurement, for example the presence the catheter will tend to initiate a peristaltic response as the gut attempts to pass the catheter in an anal direction. A smaller device would also be preferred for intravascular measurement, urology, and pediatric gastroenterology. In this paper we report a new miniaturized design of the FGB catheter that further reduces the array diameter while also providing temperature compensation capability. Static
pressure sensitivity comparisons between the two designs as well as the dynamic response of the miniature catheter are presented.

2. MINIATURE CATHETER DESIGN

The cross-section schematic of the miniature catheter is shown in Figure 1. The basis of the catheter consists of two optical fibers, both containing series of 3 mm long FBG elements at a 10 mm spatial separation, placed in contact and twisted around each other in a spiral form. The critical component of the design is that the positions of the FBG elements on both fibers are coincident so that the spiral creates FBG pairs at each of the sensing region. Each FBG in the sensing pair describes an arc of approximately equal and opposite radius which provides an inherently opposite response to sideways deformations. For example, when pressure is applied from the top, the top FBG experiences compression which reduces the Bragg wavelength while the bottom FBG is elongated and the Bragg wavelength is increased. The degree of the differential Bragg wavelength shift can then be used to infer the applied pressure. An important advantage of the close contact of each FBG pair is that any temperature fluctuation to the sensor causes a common mode variation which is independent to the pressure-induced differential wavelength shift. This feature is particularly beneficial for studies in the human esophagus where the subject is required to swallow liquid at room temperature that dynamically cools the esophageal body during the swallow.

Figure 1. Cross-section schematic of the miniature catheter.

The fibers are glued to cylindrical metal casings on either side of the FBG regions and the array of sensing elements is then enclosed in a thin silicone diaphragm. The casing has an opening that allows the silicone diaphragm to act directly on the top FBG so that it is deflected sideways with increasing external pressure; the bottom FBG does not touch the inner wall of the casing to allow freedom of movement and certain degrees of isolation to perturbations. Any changes in the ambient pressure causes the diaphragm to contract inward against the top FBG that in turn is pressed toward the bottom FBG, which induces the differential Bragg wavelength shift as described above. The metal casings have a diameter of 0.7 mm and with the silicone diaphragm in place the structure has an overall diameter of ~1 mm which is significantly smaller than our previous design (~3 mm) and is similar to that described by Singlehurst et al. The actual catheter is then formed by sealing the silicone sleeve at the distal end and splicing FC/APC fiber optic connectors at the proximal end. Figure 2 shows a dimension comparison photograph of our two catheter designs.

Figure 2. Photograph showing both the standard 3 mm catheter (top) and the miniature 1 mm catheter (bottom).

The FBG arrays were monitored using an FBG Scan 804 interrogator supplied by FOS&S (FOS&S, Geel, Belgium).
3. VALIDATION TESTS

The pressure sensitivity of the miniature catheter was calibrated against that of the previous standard design by testing the sensor arrays in a pressurized tube. The pressure inside the tube was gradually increased from 0 to 300 mmHg, which more than covers the pressure variation range normally encountered in-vivo, and the corresponding Bragg wavelength shift is recorded. Figure 3 shows the plots of typical wavelength shift as a function of pressure during calibrations for both the miniature and standard catheter. Note that for easy comparison the plot of the standard design response has been inverted to show a positive wavelength change. The standard deviation between the recorded data and a linear regression was less than 3.1 mmHg over the range 0 to 150 mmHg.

Figure 3. Pressure sensitivity calibration results of standard and miniature catheters with linear polynomial fits.

The calibration results from both catheter designs indicate a linear response between applied pressure and the corresponding Bragg wavelength shift, this is important for accurate subsequent analysis in the real measurement. It is also evident that the pressure sensitivity of the miniature catheter is less than that of the standard design, this is somewhat reasonable because the standard model consists of only a single fiber suspended which is much more pliable when pressed while the twisting of two fibers in the miniature design is more rigid. Nevertheless the miniature catheter provides a satisfactory level of sensitivity for analysis and demonstrates the differential wavelength shift that in principle is temperature insensitive. Figure 4 shows the preliminary test result of the temperature dependent wavelength shift of both top and bottom FBG. Equal responses indicate the differential wavelength shift will indeed be temperature independent.

Figure 4. Preliminary measurement result showing that both FBGs in the sensing pair respond identically to temperature variation.
To test the high frequency dynamic response of the miniature catheter, it was immersed in a water tank and functioned as a hydrophone array to measure acoustic waves emitted by commercial underwater transducer positioned 11 cm away. In this measurement a tunable filter demodulation scheme was used where a narrowband laser source was tuned to the side of the FBG spectral-band on one of sensing elements. As the Bragg wavelength shifts, the reflected intensity is modulated accordingly and this dynamic intensity variation is measured by a fast photodetector and analyzed on an oscilloscope. Figure 4 shows the overlapped typical spectral power densities measured during excitation by 20, 100 and 200 kHz acoustic signals.

Figure 5. Spectral response of the miniature catheter for measuring 20, 100 and 200 kHz underwater acoustic waves.

Strong spectral signals indicate that the sensor element is detecting the acoustic wave accurately and sensitively. These test results give us confidence that this miniature catheter is capable of both low and high frequency measurements with good sensitivity.

4. CONCLUSION

In this paper we have reported a miniature FBG based pressure sensor that utilized two optical fibers twisted together, which is an improvement over our previously demonstrated device in terms of smaller overall diameter and temperature insensitivity. Calibration results show that this miniature catheter is able to provide satisfactory low and high frequency responses. Future work will involve design modifications to enhance sensitivity. This device is currently being used in a series of in-vitro validation tests that will be reported in the near future.

REFERENCES