

# Fiber-Optical High-Resolution Esophagus Manometry Based on Drawing-Tower Fiber Bragg Gratings

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*Abstract:* - One application of Fiber Bragg grating-based fiber sensors is their implementation as a distributed pressure sensing catheter for time-space display of swallow waves in the human esophagus. Our plan is to essentially improve the measurement procedure with a feasibility model comprising 30 fiber-optic pressure sensors in a single fiber, spaced less than 10 mm from each other. A well-designed soft plastic coating mantle, which is affected by local pressure, will be used to convert pressure variations into strain variations of the optical fiber core.

*Key-Words:* -fiber Bragg gratings, pressure, medical optics instrumentation, gastrointestinal, biomedical

## 1 Introduction

The esophagus is a hollow tube, which transports food from the mouth to the stomach. Anatomically it is a muscle tube with sphincters at both ends. The sphincters' function is to keep the tube empty from external (food) and internal (acid) intrusions. Swallowing and transport of food from the mouth to the stomach is a highly coordinated neuromuscular event[1]. Dysfunction of the peristaltic transport mechanism causes a variety of diseases such as the gastro-esophageal reflux disease (GERD), esophageal adenocarcinoma, heartburn or pyrosis, achalasia and nutcracker esophagus. Heartburn, for example, occurs when the lower esophageal sphincter does not work correctly and allows an acid reflux back into the esophagus. In case of clinical acatalepsia, the functionality of the esophagus has to be examined with sensors. A clearly defined goal is to make these examinations faster and more comfortable to the patient. The presented catheter with a high number of pres-

sure sensors in close proximity enables the physician to get semi-continuous images of the pressure distribution. Such concepts termed high-resolution manometry (HRM) [2, 3, 4], can be found in the literature.

## 2 Theory

The sensor concept comprises an elastic tube with an embedded fiber Bragg grating. When local pressure is applied to the tube it leads to deformation. Volume conservation of the tube results in elongation of the fiber [5, 6]. This deformation of the fiber leads then to a change in refractive index due to the photoelastic effect and a change of the effective optical grating period. Considering the Bragg reflection wavelength for fiber Bragg gratings,  $\lambda_{\text{Bragg}} = 2n_{\text{eff}}\Lambda$  with  $\lambda_{\text{Bragg}}$  denoting the Bragg reflection wavelength,  $n_{\text{eff}}$  the effective phase refractive index of the guided mode in the fiber, and  $\Lambda$  the grating period inside the

fiber, this change of the grating period can be detected as a variation of the reflected wavelength of the fiber Bragg grating. Since each sensor has its own specific wavelength, multiple sensors can be integrated in line and hence be multiplexed in one sensing fiber (Fig. 1).

The measurement accuracy of the catheter can be estimated through the model of a fluid-filled cell [7]

$$\epsilon = \frac{pA_{\text{catheter}}}{A_{\text{fiber}}E_{\text{fiber}}} \quad (1)$$

where  $p$  is the outer pressure,  $A_{\text{catheter}}$  the catheter diameter,  $A_{\text{fiber}}$  the fiber diameter and  $E_{\text{fiber}}$  the Young's modulus of the fiber. Typical parameters are a catheter diameter of 5 mm, a fiber diameter of 125  $\mu\text{m}$ , and a Young's modulus of 70 GPa.

The expansion of the fiber can then be measured as a wavelength shift of the fiber Bragg grating from the center wavelength according to [8]

$$\Delta\lambda_{\text{Bragg}} \approx 0.78\lambda_{\text{Bragg}}\epsilon \quad , \quad (2)$$

### 3 Drawing-tower fiber Bragg gratings

Fiber Bragg gratings (FBGs) are periodic index modulations inside optical fibers, working as wavelength-selective mirrors. FBGs are affected by temperature and strain and are therefore often applied as temperature and strain sensors. Their small dimensions, their multiplexing capability and their insensitivity to electromagnetic interference makes FBGs ideally suited for the structural monitoring of large engineering systems such as bridges, dams, power stations [9] or airplanes [10]. Especially the small size of the FBGs is highly promising for medical measurement applications [11].

Fiber Bragg gratings can be inscribed during the drawing process of the fiber [12]. An excimer laser (Compex 150T) emits pulses with approx. 150 mJ/pulse at 248 nm. The beam passes a 50/50 power splitter creating two separated beams. These are redirected onto the fiber by means of two mirrors mounted on rotation stages. The superimposing beams form a standing wave on the

fiber, resulting in a permanent periodic index modulation inside the fiber core. The pulse duration is 10 ns, which is fast enough not to average out the interference pattern at the fiber drawing speed applied (10 m/min). Every sensor element is inscribed with a single laser pulse [13]. This process requires fiber glass types with optimized doping compositions and levels. Adequate material compositions contain cerium and/or germanium dopants [14]. FBGs made on the fly during the drawing process (DTG) have several advantages: The cladding process occurs after FBG inscription, which results in uniform cladding with high mechanical stability compared to standard fiber Bragg gratings with local recoating [15]. The minimum spacing between two fiber Bragg gratings is 10 mm, and the reflection is around 10% per grating in the first telecom window and 40% per grating in the third telecom window.

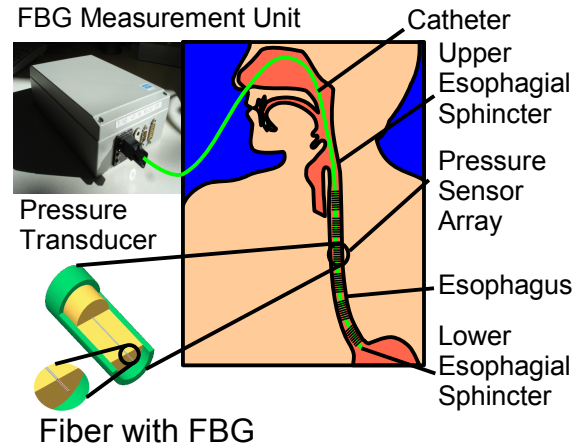


Figure 1: Outline of the esophagus measurement system

### 4 Fiber Bragg grating measurement system

The interrogation system for the fiber Bragg grating reflection as developed at IPHT Jena [9] uses a superluminescent light-emitting diode (SLD) covering a wavelength operating in the first Telecom band (800 nm to 860 nm), a grating and a CCD array. The interrogation system has a scan repetition rate of 1 kHz, which is more than sufficient to measure swallow events. One peristaltic wave takes around 20 seconds [2] which has to be resolved with a sampling frequency of 10 Hz.

The wavelength spacing of the sensors is limited to 1.3 nm to prevent overlapping of the sensing channels. Currently, 32 channels can be measured simultaneously without further multiplexing techniques such as time-resolved detection or switching between several sensing fibers.

## 5 Catheter design and manufacturing process

A measurement system for medical applications has to satisfy various constraints. It has to show maximum sensitivity, compatible with disinfection and sterilization and finally be compatible with the manufacturing process. Finite element calculations with ANSYS have shown that best performance can be achieved with catheter materials with high Poisson number  $\nu$ , a fiber with an outer diameter as small as possible and a catheter diameter as large as possible. The catheter diameter is limited by application conditions and should not exceed 5 mm. To manufacture the catheters, the fibers with the sensor arrays are integrated by an extrusion process with a new generation of thermo-elastic polymers (Thermoplast K, Kraiburg). These materials combine the properties of olefine based elastomers and thermoplastics and offer the potential for medical applications where biocompatibility and resistance to sterilization and disinfection are required.

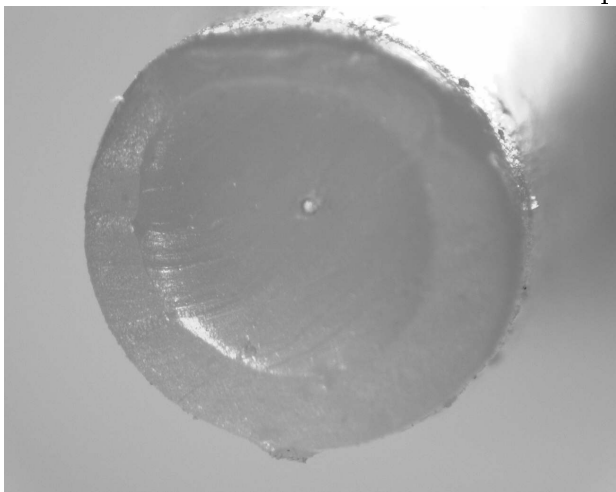


Figure 2: Cross section of the manufactured catheter (3 mm) sample with double layer.

## 6 Sensor characterization

Fiber Bragg grating response to different aerostatic pressures was recorded. Results with a soft coated catheter are shown Fig. 3. The sensor shows linear response to pressure. As the sensing principle bases on volume conservation, neighbouring sensors are slightly affected and show a slight negative response. The sensitivity of three catheters to pressure changes is shown in the following table. The diameter of all catheter samples is 3 mm.

catheter type	sensitivity [ $\mu\epsilon$ /mbar]
hard single layer (80 shore A)	0.22
soft single layer (30 shore A)	0.59
double layer (Fig. 2)	0.23

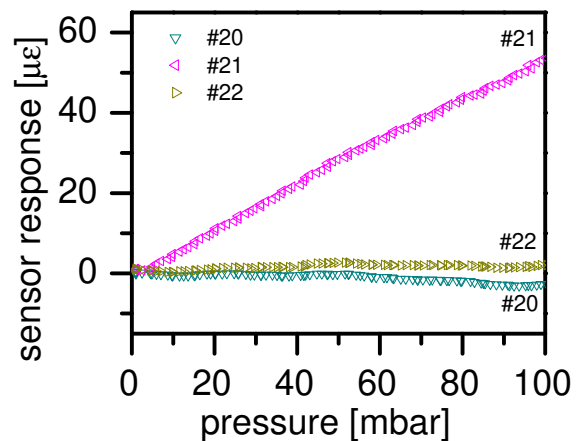


Figure 3: Sensor response of the soft layer catheter (catheter diameter 3 mm and 80  $\mu\text{m}$  fiber diameter).

## 7 Conclusion

The feasibility of a pressure measure concept comprising fiber Bragg gratings and a coating as a pressure transducer is demonstrated. Experiments have shown that the sensor reaches the required sensitivity. Even when the catheter shows effects like cross sensitivity of neighbouring sensors the concept demonstrates a convincing simplicity and therefore its specific potential for medical measurements in various hollow organs, like the anal region, the intestinal tract and the pancreas.

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