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Comparing FBG and PCF Force Sensors in a Laparoscopic Smart Surgical Scissor Instrument

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Abstract— **This paper presents a sensorized laparoscopic surgical scissor instrument using both a fiber Bragg grating (FBG) and a tapered photonic crystal fiber (PCF) as force sensors. The sensors are located on the blades for the detection of interaction forces generated between the instrument and tissue during cutting. The force sensitivity of each sensorized blade is examined. Results show that the scissor blade-PCF sensor arrangement outperforms the blade with the FBG during static loading calibration experimentation. Moreover, experiments show that the PCF based arrangement is less sensitive to temperature effects than its FBG counterpart. This negates the need for additional temperature compensation sensors and techniques. The PCF sensor was shown to have higher strain measurement sensitivity (2 pm/με) than the FBG sensor (1.2 pm/με).**

Keywords; Photonic Crystal Fiber, Fiber Bragg Grating, Laparoscopic scissors

I. Introduction

Research is ongoing into the use of strain/force sensors in the measurement of interaction forces at the instrument-tissue interface during a range of biological tissue manipulation procedures [1-3]. These sensing schemes only measure interaction and bending forces on the trocar and do not measure grasping and cutting forces. One approach to overcoming this problem is the placement of strain/force sensing transducers either onto the instrument tip or as close as possible to it. Many research groups have indicated that the ideal location for force sensor placement is as close as possible to the site of interaction [1-5], which for MIS is at the instrument tip. However, this is technically the most challenging location for placement of a force transducer owing to space limitations.

Advancement in the area of optical fiber sensing has opened up new possibilities in the development of simple, miniature fiber sensors for medical devices. The advantages of optical sensing technology include; immunity from electromagnetic interference, biocompatibility, sterilizability as well as small strain measurement capacity. Instruments in which the optical the sensor forms an integral part of the end-effector are desirable to enable accurate measurement of complex interaction and cutting forces. Several groups are investigating the use of optical sensing techniques which facilitate the measurement of instrument-tissue force interactions in biomedical applications. Examples include, a six degrees of freedom force-torque-sensor [6], a 2-D fiber optic sensorized hook instrument for retinal surgery [7], and a sensorized surgical needle for use in a MRI environment [8].

More established optical sensing technologies such as FBG's are currently being implemented, and their benefits exploited in sensorising surgical devices. However, there are a number of drawbacks. The principal concern in this is the cross sensitivity nature of the sensor whereby the accuracy of the force measurements is influenced by the effects of localized temperature variations. Therefore, error compensation is required through the use of additional force sensors for the purpose of temperature measurement only [8-10]. However optical sensing employing the use of photonic crystal fiber (PCF) interferometers has been shown to exhibit reduced sensitivity to temperature variation during operation.

This paper presents a direct comparison between PCF and FBG sensorized laparoscopic scissor blades. The performance of both sensing methods under force and temperature loading conditions is assessed. To our knowledge the prototype presented is the first application of a FBG and a PCF sensor in a small scale laparoscopic scissor instrument for the purpose of interaction force measurement.

The remainder of the paper is broken down as follows; a description of both sensing modes and sensor placement is described in Section II. The calibration of the blades is discussed in Section III. The experimental details from static calibration and temperature experiments are presented in Section IV. A discussion and conclusions are presented in Section V.

II. SENSOR TYPE AND PLACEMENT

Localized strain values that are occurring on the surface of the scissor blade close to the point of force generation are obtained from each optical sensing element. The most common practice used in attaching optical sensors to a host structure involves bonding the fiber to the surface using an appropriate adhesive. During loading the fiber elongates or contracts longitudinally with the strained surface resulting in a change in the reflected wavelength spectrum.

A. FBG Sensor

A fiber Bragg grating comprises of a short section of single-mode optical fiber in which the core refractive index is modulated periodically using an intense optical interference pattern [11], typically at UV wavelengths. The wavelength of light reflected by periodic variations of the refractive index of the Bragg grating, λ_G, is given by [12],

$$\lambda_G = 2n_{eff}\Lambda, \quad (1)$$

where n_{eff} is the effective refractive index of the core and Λ is the periodicity of the refractive index modulation. The basic principle of operation of any FBG-based sensor system is to monitor the shift in the reflected wavelength due to changes in measurands such as strain and temperature. The wavelength shift, $\Delta\lambda_S$, for the measurement of an applied uniform longitudinal strain, $\Delta\varepsilon$, is given as [12],

$$\Delta\lambda_S = \lambda_G(1-\rho_\alpha)\Delta\varepsilon, \quad (2)$$

where ρ_α is the photo elastic coefficient of the fiber.

A single FBG sensor is employed in this experimental work. The length of the FBG used is 3 mm, written in the middle of an 11 mm long buffer stripped portion of a standard singlemode fiber. This region was recoated with polyimide to a thickness of 4 - 4.5 µm. The FBG sensors used have a peak wavelength of 1560 nm. The strain and temperature sensitivities of the FBG sensor are 1.2 pm/µε and 10 pm/°C respectively at 1560 nm.

B. PCF Sensor

LMA-10 PCF was used in the fabrication of the tapered interferometer owing to its superior insensitivity to temperature effects. The LMA-10 fiber has a core diameter of 10 µm with 7 rings of holes and a mode field diameter of 7.5 µm. The cladding diameter of the LMA-10 fiber is 125 µm. The fabrication of the tapered interferometer used in these experiments consists of a small section of the PCF spliced on to a standard singlemode fiber pigtail. A carefully controlled fusion splicing process ensured that no interference patterns arose due to hole collapse in the PCF during splicing [13]. The central region of the PCF was then collapsed and thinned down to a micron size to form the tapered region. This is carried out by using a standard splicing machine and while applying the electric arc the fiber is pulled from both sides uniformly. The fabricated PCF taper has a length of approximately 0.3 mm with a waist thickness of approximately 22 µm. The tapered region formed in the PCF is similar to an unclad multimode optical fiber. As a consequence of this, the fundamental mode in the PCF in the region where the holes are open is coupled to the modes of the solid fiber in the tapered region. As a result of this mode coupling, beating between the multiple modes takes place and the transmission spectrum shows an oscillatory behavior [14].

C. Sensor Placement

Surgical scissors are typically only used over the first one third of the blade length (measured from the tip) when making cuts as it allows for better control of the cutting process. Cutting is performed through a series of short dissections using the frontal third of the blades only (Fig. 1). This reduces tissue sliding between the blades [15]. The mechanical design of the scissors places limitations on the placement of the force sensing elements. The strain induced near the tip is substantially lower than that induced at the pivot during normal cutting procedures. Therefore, careful consideration must be given to the placement of the sensor so that the measurement sensitivity of the arrangement is not unduly compromised.

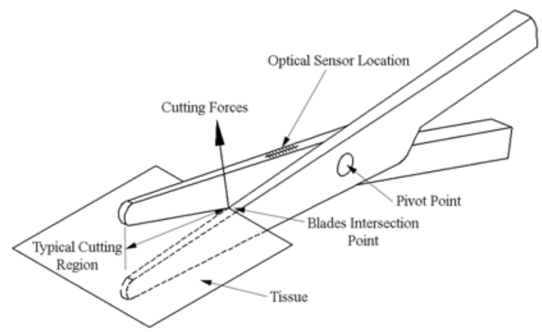

Figure 1. Location of optical strain sensor on the laparoscopic scissor blades.

The strain sensors used in these experiments are placed proximal to the pivot point as far from the blade tip as possible (Fig. 1). This ensures that,

- When the blades are fully opened there is a 6 mm region from the blade intersection point to the pivot which is not used for cutting. Placing the strain sensor within this area means that the full cutting range of the blades is maximized.
- Measurement sensitivity is maximized.
- The sensor is located away from the active cutting region of the blades and in no way interferes with instrument functionality during operation.

The 3 mm FBG sensor was placed 4 mm from the blade pivot. The PCF was also placed 4 mm from the blade pivot. A 2 part fiber optic epoxy (T120-023-C2) with a Young's modulus of 3 GPa was used to bond the fibers to the blades. This high adhesive stiffness ensures good strain transfer from the blade surface to the fiber.

III. Experimental Setup

The sensitivity and resolution of the instrument was evaluated through experimentation using an application-specific calibration rig (Fig. 2). The calibration procedure involves securing the scissor blades in a clamping fixture and applying a series of static loads at a number of locations along the prescribed cutting envelope of the blades. The forces are manually applied to the blades via a low friction slider mechanism and monitored using a button load cell (Transducer Techniques SLB-25) connected to a PC. The force actuation mechanism is attached to a linear translation stage which moves transversely long the blade length. This facilitates loading at discrete locations along the entire working range of the blades from tip to 6 mm from the pivot.

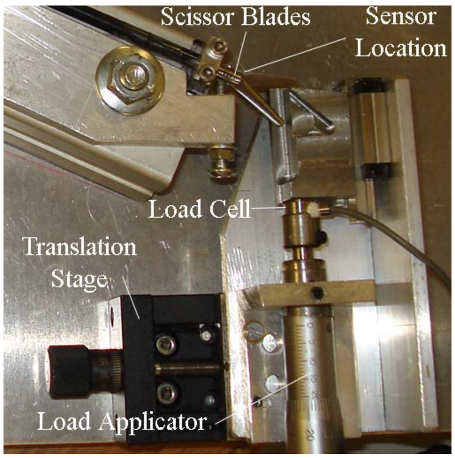

Figure 2. Calibration of the optically sensorized laparoscopic scissor blades.

A. Blade Calibration

The procedure for calibrating the optically sensorized blades was identical for each sensor type. However, different hardware was used for interrogation of the sensor signals in each case. The data from the button load cell is collected using a National Instruments load cell module SG-24, which is connected to a data acquisition board NI6221. A commercial interrogator unit was used to measure the strain from the FBG sensor using an FBG interrogator (Wx-02) from Smart Fibers Ltd. A spectrum analyzer was used to measure the strain from the PCF.

Starting at the blade tip forces were applied normal to the blade cutting edge in increments of 2 N, up to a maximum of 14 N. The strain values obtained from the optical sensor were logged at each load increment. The loads were then reduced from 14 N to 0 N in increments of 2 N. The loading mechanism was then translated along the blade length in 2 mm steps with the incremental loading sequence repeated at each location.

IV. Experimental Details

The experimental calibration results from both the FBG and the PCF sensorized blades are presented. The temperature sensitivity of the PCF sensor is measured and compared to that of the FBG sensor used in these experiments.

A. FBG Blade Calibration

The calibration results for the FBG sensorized blade are shown in Fig. 3. It can be seen that the sensitivity of the sensorized blade is greatest when loaded at the tip and decreases as the position of the applied load moves towards the pivot point. This results in a sensitivity variation from 28.2 με/N to 12.5 με/N over the first one third of the blade length.

Based on observations of the fluctuation in the measured strain caused by noise in the interrogation system, the force resolution was estimated to be 0.32 N from the unfiltered FBG signal; however as the sensitivity increases towards the blade tip the estimated resolution improves to 0.14 N. System noise was estimated to equivalent to be 4 με. Taking the sensitivity at the blade tip as 28.2 με/N the force resolution is estimated to be 0.14 N. At 12 mm from the blade pivot the sensitivity is 12.5 με/N hence the force resolution is 0.32 N.

Obtaining force readings from the FBG sensor, representative of the friction and fracture forces acting on the blade during operation, requires the use of the empirically derived calibration ratio R shown in Fig. 3. The strain measured at any location x along the blade length is multiplied by its corresponding calibration value to obtain the appropriate value, therefore, $F(x) = \varepsilon R(x)$.

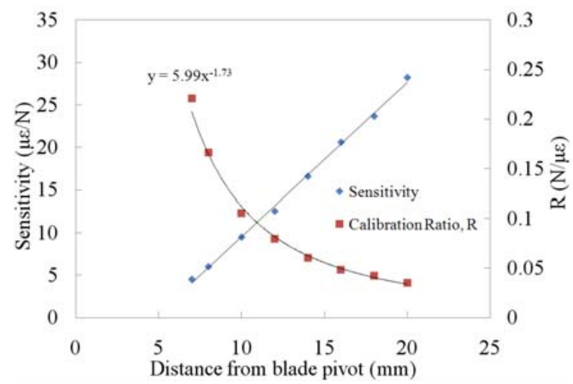

Figure 3. Force sensitivity values and calibration ratio for the FBG sensorized scissor blade.

B. PCF Blade Characterization

Results from the static loading tests on the PCF sensorized blade are presented in Fig. 4. Direct comparison with Fig. 3 shows that the sensitivity of the PCF blade is on average 11% higher under the same loading conditions. This error can be attributed to the fact that the PCF is effectively a point measurement sensor (0.3 mm length) compared to the FBG which takes an average strain value over its 3 mm length. Over the first third of the blade the sensitivity varies from 31.9 με/N at the tip to 12.9 με/N at 12 mm from the blade pivot.

The temperature-induced wavelength shift of the fabricated tapered PCF used in these experiments was measured and is shown in Fig. 5. From the figure it is clear that the wavelength shift induced by the change in temperature is very small (1.1 pm/°C). This small wavelength shift would induce minimal errors in the force induced wavelength shift. FBGs typically have a sensitivity of 10 pm/με. Therefore, PCFs could have added benefits in applications where temperature effects could be detrimental to the accuracy of measurements.

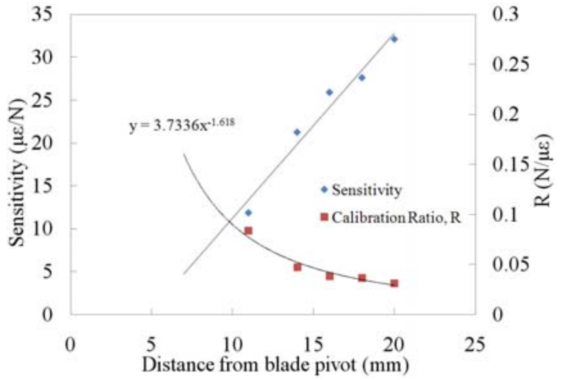

Figure 4. Force sensitivity values and calibration ratio for the PCF sensorized scissor blade.

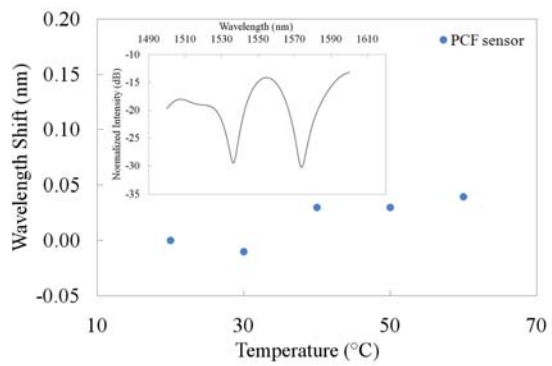

Figure 5. Wavelength shift of the PCF sensor over a 40° temperature range. The measured spectrum of the PCF is shown in the inset.

V. Discussion and Conclusion

A comparative study between two types of optical force sensor employed in a miniature laparoscopic scissor instrument is presented. Of interest are the strain and temperature sensitivities of the two sensors. Experiments show that the PCF sensor has a better strain sensitivity (2 pm/με) that the FBG sensor (1.2 pm/με) and as a result better resolution can be achieved. A slight difference was observed between the sensitivities of both sensor-blade arrangements. The characterization results for both sensor types are presented in Table 1.

TABLE I. Sensing Parameters

	Fiber strain Sensitivity (pm/με)	Blade Force Sensitivity[a] (με/N)	Temperature Sensitivity (pm/°C)
FBG	1.2	28.2 – 12.5	10.0
PCF	2	31.9 – 12.9	1.1

a. Range over the first third of blade length

Temperature experiments on the PCF fiber over a 40°C range confirm that the PCF configuration outperforms its FBG counterpart with minimal variation in the reflected spectrum being observed. This suggests that the use of PCF based optical force sensing is a superior alternative to FBG based sensing. Additionally, the cost of manufacture of the sensor is less than that for a FBG equivalent. The cost of the interrogation unit employed in detecting strain measurements is also lower.

Future work will explore the possibilities of employing PCF optical force sensing in smart surgical devices where interaction force measurements are required without temperature induced errors. The goal is to display the cutting forces to the user in real time via a haptic interface providing the basis for more accurate laparoscopic interventions involving dissecting instruments.

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