Development and preliminary data of integrated temperature-Insensitive lateral force sensor based on linear chirp Fiber Bragg Grating

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Abstract. Lateral force measurement using a cantilever ruler-beam (CRB) sensor based on linear chirp fiber Bragg grating (LCFBG) is proposed and experimentally demonstrated. The lateral force is determined by altering the reflection optical power of LCFBG of which an axial-strain gradient along its sensing is induced. The reflection spectrum intensity responds linearly and monotonically with lateral force increasing from 0 to $\approx 0.6$ N. Experimental results demonstrate that the CRB force sensor can successfully achieve lateral forces prediction with less than 0.0015 N resolution using simply Thorlabs PM100USB optical power meter. And can accomplish an adequate accuracy with RMS error < 0.04N of full scale (0-0.749N). The CRB is chosen in one way or another to resemble steerable catheter flexibility as our intention is to developing catheter force sensor based on temperature-insensitive contact force measurement.

1. Introduction
Fiber Bragg gratings (FBG) has emerged widely in many fields especially in an application wherein the general strain gauges and encoders are not applicable due to the environment, cable networks complexity, and electromagnetic interference [1]. Features like flexibility, nontoxic, chemical inert, and instant response furthered the FBG-based sensor as the best candidate for several medicine disciplines [2].

Extensive studies have proposed FBG-based transducer in miniaturized medicine instruments to measure three-dimensional (3-D) forces in a variety of fields such as soft shapes/assisted-robotics sensors [3], [4], minimally invasive surgery as well as microsurgery [3]–[5]. High sensitivity wavelength shift method (WSM) which is commonly used to monitor the changes of the physical measurand, however, besides the influence of both strain and temperature on it, it is also an error maker when 3-axis force components measurement are desired. Axial strain along device-incorporated fiber houses the FBGs can be induced by both axial and lateral forces, leads to cross-talk error of the wavelength shift response in $z$-direction under exerted force in $x$ or $y$-direction.

Xingchi He et.al. [3], [6] developed 3-D vitreoretinal microsurgery force sensor using 4-FBGs. Authors relied on mechanical means and nonlinear mathematical model to mitigate the WSM-induced cross-talk error between axial/lateral. An analogous presentation can be found in [7] for the development of 3-D catheter distal contact forces for cardiac ablation. Although the inner FBG was mounted in the neutral axis of the developed flexure of the catheter-tip, due to bending deformation under lateral forces yet can introduce significant cross-talk error to interfere with the axial sensing. Recently bandwidth of
the reflection spectrum of the FBG is utilized to monitor force-induced strain instead. Bandwidth can only be tuned if nonuniform strain induced along with the fiber housing the FBG. Thus, temperature and forces in z-direction unlikely to be sensed by the bandwidth. Our previous work presented a novel method utilizing the bandwidth method and tapered FBG to eliminate WSM-induced axial/lateral cross-talk noise [8]. Temperature-insensitive force sensor for catheters using FBG is proposed in [9]. They have presented that the contact force applied on the catheter-tip can be determined directly by measuring optical power meter. This approach proves temperature-insensitive force measurement in which optical power meter is sensitive only to contact forces. However, the results show a nonlinear relationship between the reflection power and forces applied, authors, didn't provide a clear reason.

However, in this paper, we demonstrate a flexible-ruler beam incorporated linear chirp FBG (LCFBG) for lateral force measurement. The main contribution of this paper; (i) we show the linear relationship between forces applied and power measured, (ii) to the best of our knowledge, this the first time using LCFBG and bandwidth tuning, a real-time force measurement compared with actual forces is presented experimentally.

The paper is organized as follow; section 2 briefly introduces the bandwidth and corresponding total reflection power sensing principle, experimental setup clearly described in section 3, section 4 discuss the results obtained, and finally, work concluded in section 5.

2. Sensing Principle
When no force is applied, the original bandwidth of the LCFBG can be expressed as;

\[ BW_{\text{chirp}} = \lambda_{b}(L) - \lambda_{b}(0) = 2n_{\text{eff}}[\Lambda(L) - \Lambda(0)] \] (1)

Here \( \lambda_{b}(L) \) and \( \lambda_{b}(0) \) denotes the longer and shorter wavelengths of LCFBG sensor (see Figure 1(right)), the \( \Lambda \) is the grating period and \( n_{\text{eff}} \) is the effective refraction index.

2.1. Bandwidth Response
The LCFBG is a 10 mm long and is bonded as shown in Figure 1(right) such that the position of the longer grating period (longer wavelengths \( \lambda_{l} \)) is located proximal to the fixed end of the CRB, in contrary the shorter wavelengths \( \lambda_{0} \) are located further up towards the free end. This arrangement theoretically leads to broadening in the bandwidth of the sensor. As the calibration weight is applied transversely, the CRB bends causing the top surface to stretch and as a result, a nonuniform strain induced along the CRB. The nonuniform strain changes with respect of the length of CRB starting from zero-strain at the free-end \( a \) and reaching its maximum value at the fixed-end \( b \).

Consequently, when the CRB bends under the lateral forces a local grating period elongation occurred which could tune the bandwidth of the sensor, both resonance wavelengths denoted in Equation (1) shift accordingly and the difference between these shifts determine the fraction bandwidth variation; it can be expressed as follows;

\[ \Delta(BW_{\text{chirp}}) = 2n_{\text{eff}}(1 + \varphi_{e}).[\Delta \Lambda(L) - \Delta \Lambda(0)] \] (2)

The expression above ignores the small differences between the elasto-optic effects \( \varphi_{e} \) at both ends of the sensor when compared to the pitch elongation. Here the elongation of each period can be found as follow;

\[ \Delta \Lambda(0) = \Lambda(0), \varepsilon(0) \text{ and } \Delta \Lambda(L) = \Lambda(L).\varepsilon(L) \] (3)

Where \( \varepsilon(0) \) and \( \varepsilon(L) \) are the local strain at the starting and ending point of the LCFBG sensor. In our case the \( \varepsilon(L) > \varepsilon(0) \) from which a positive or broaden bandwidth will be observed. From a cantilever beam theory, strain induced by lateral forces can be found as;

\[ \varepsilon(0) = \frac{Fz_{0}R}{E\varepsilon I}, \varepsilon(L) = \frac{F(z_{0} + L)R}{E\varepsilon I} \] (4)

Here the \( z_{0} \) and \( (z_{0} + L) \) are the distance from the free end to the beginning and ending points of the LCFBG sensor, \( E \) and \( I \) are Young’s module and area moment of inertia, respectively. While \( R \) denotes the thickness distance of the CRB from the neutral axis to the surface at which the LCFBG
placed. Thus, the reading signal of the effective bandwidth change is calculated as the summation of the original bandwidth and the fraction variation which is tuned by forces applied as follow;

$$\Delta BW_{eff}(\varepsilon_{ave}) = BW_{chirp} + \Delta(BW_{chirp})$$

$$= BW_{chirp} + \frac{2n_{eff}(1 + \varepsilon_{ave}^2) \cdot R \cdot F}{E \cdot I} \cdot [\Lambda(L) \cdot (Z_0 + L) - \Lambda(0) \cdot Z_0]$$

(5)

Here the coefficient $k_e$ defines the scale factor or responsivity ratio constant of the relationship between bandwidth response and forces applied.

2.2. Integral Power/Energy Response

The energy conservation implies that whenever the effective bandwidth is altered, the total area under the curve proportionally varies. If the bandwidth has broadened, it means more frequencies carry the energy will be in the signal. The total reflection power, therefore, would increase as a result, the expression below describes the variation in total reflected optical power calculation as a function of average strain;

$$\Delta P = \Delta BW_{eff}(\varepsilon_{ave}) \cdot \rho_{LS}$$

(6)

Where the $\rho_{LS}$ is the spectral density of the laser source in mW/nm.

3. Experimental Setup

The CRB force sensor is calibrated with an automated system using LabVIEW software. Figure 1 illustrates the actual calibration setup. A calibration weight (100 g) is attached to the tip of the CRB through a stiff wire. A very precise scale (1 mg resolution) is used to measure the lateral load magnitude applied which is converted later to a force magnitude (gravity magnitude is assumed 9.81 N/Kg) using the program. A 3-axis precision motorized stage is utilized to control the position of the calibration weight above the precision scale. Starting with the calibration weight is fully resting on the scale ($F = 0 \text{ N}$), later by rising up the CRB with respect to the scale, the portion of the weight applied on the RB’s tip is determined. The LCFBG sensor response is sampled at 3 kHz rate using I-MON-256USB (Ibsen) interrogator.

Figure 1. Automated calibration setup system (left), Close-up view of the LCFBG position within the RB (right)

Figure 2 shows the schematic of the experiment setup including the 50/50 an optical splitter and a power meter (PM100USB-THORLAB).
The schematic of the complete experiment setup to measure optical power as loads applied.

Figure 2

The optical power meter is used to measure the real-time total reflection power of LCFBG as loads applied. By leveraging bandwidth interrogation method, the temperature variation will not change the bandwidth (while only shift the reflection spectrum), hence the total reflection power is only sensitive to the forces applied. A temperature controller, heat sink, and a relay are used to control the environmental temperature in the vicinity of the LCFBG sensor as shown in Figure 3. The LCFBG sensor is tested under different temperature values (25°C-35°C). National instrument DAQ is used to acquire the temperature values through a thermocouple attached directly on the RB.

The CRB sensor is calibrated twice, when force is increased by lifting up CRB or the calibration weight (Inc. force) and when force decreased by lowering down the calibration weight (Dec. force), both with 1 mm incremental. In the following sections, the calibration data is used to determine the relationship between total reflection power of the LCFBG and force magnitude applied. Further up, the calibration result is then used accordingly to map the sensor reading to the real-time lateral forces measurement.

Figure 3.

4. Results and Discussion

Referring to Equation (1) and Equation (2), the non-uniform stretching of each grating pitch induced due to the lateral forces will govern the Bragg wavelength resonances \( \lambda(z) = 2n_{eff}\Lambda(z) \). Bending downward the CRB with LCFBG bonded above the neutral axis of CRB leads to stretching every grating pitch according to the strain distribution. To this end, the wavelength shift to the longer wavelength can
be observed. Figure 4 illustrates the spectrum change due to an incremental increase in the applied forces which has been observed during the calibration procedure by I-MON256USB interrogator. The x-axis of the graph indicates the pixel number of the Photodiode array detectors of the interrogator. It is worth mentioning that as the consequence of placement of sensor array design, the incident light of shorter wavelength impinges the higher pixel number.

![Figure 4. Measured change in the spectral profile of the LCFBG under applied forces](image)

It is seen that a total center wavelength shift of 0.897 nm has been observed from 1556.271 nm to 1557.168 nm with an increase of applied forces range (0 N-0.749 N). As mentioned earlier, since the LCFBG is attached above the neutral axis, bending downward the CRB results in local grating-pitch elongation ($\Delta\Lambda(L) > \Delta\Lambda(0)$) which in turn results in broader bandwidth towards longer wavelength direction. This according to the Equation (6) enables the actual force applied to be encoded in the total reflection power.

As an unequal change in temperature within a short segment of the LCFBG is unlikely to occur, thus the main feature of the proposed CRB sensor is a temperature-independent strain measurement guaranteed. The temperature impact is investigated using a heat sink to which temperature controllable heat element is attached to change the environment vicinity of the sensor. Figure 5 depicts the response of the total reflection power of the sensor as the temperature varies from approximately 25 °C to 35 °C. As shown the total change in reflected optical power is smaller than 0.08dB. Even though this value is small enough to consider, however, we attribute this result to the uniformity of the applied adhesive and the accuracy of the power meter. Thus, the results confirm that the output of the system is the only function of the applied forces, independent of temperature.

Two calibration process is performed to guarantee the repeatability of our LCFBG sensor. Increased force denoting raising up the CRB incrementally while recording every step interval (vertically moving up 1 mm) of both forces applied and the total reflection power. The same thing is performed when lowering down the CRB which means decreasing the force. Figure 6 illustrates the linear relationship in both directions of the calibration process, the response of the reflected power of the LCFBG for both directions clearly agree with the mathematical model expressed in previous sections.
Figure 5. System output in response to the temperature at strain-free

It is obvious from the Figure 6, although the force change only ranges from (0N-to-0.749N), yet the change in reflection power is significant enough to be measured with a responsivity of 0.0785 dBm/N for increased force and -0.0825 dBm/N for decreased force. The slight inconsistency in the scale factor of both directions could be attributed to the optical power fluctuation, for which another power meter as a reference power measure capable of removing this noise. Another reason could also contribute to this issue is that the wire-ring loose at the beam tip-hole as the position of the ring was not firmly fixed and changes in its position were observed during the calibration process. The CRB sensor shows excellent temperature-insensitive as expected, in which the total reflection power varies purely only when forces applied.

Figure 6. The total reflection power of the LCFBG sensor measured under the different magnitude of forces applied

The mapping due to the calibration results using linear fitting is illustrated in Figure 7. It shows the calculated lateral force against the actual lateral force in only one direction (one-degree-of-freedom 1-DOF).
Figure 7. The calculated lateral force versus the actual force values using linear fitting

The perfect result of fitting would be a straight line through the origin with a slope of one, the calculated force values, however, are fairly consistent with their corresponding actual values. The slope is close to 1, a trivial error and deviation can be observed with (RMS) error of < 0.04N over the full scale of (0-0.749N) and the highest standard deviation of the results observed is 0.025 N.

5. Conclusion
Real-time force sensing is crucial in nowadays minimally invasive surgeries. To this end, a flexible ruler-beam with an embedded linear chirp FBG sensor to measure lateral forces is presented experimentally. Real time force monitoring is achieved directly using an optical power meter, rather than the slow, bulky optical spectrum analysis which is used in the past. The total reflection power from the LCFBG sensor has shown a linear relationship as desired against the applied lateral forces. The results show that the CRB sensor can provide lateral force measurement with RMS error less than 0.04N. The advantage of the proposed sensor is the temperature-independency, avoiding, as a result, the cross-talk noise of the conventional wavelength shift method. Furthermore, the proposed force sensor experimentally also shows accurate force measurement in real time with a slope of almost 1 when compared with the actual forces. Since the bandwidth of the LCFBG sensor exhibits accurately and linearly response with applied forces, a catheter incorporated LCFBG for 2-DOF contact force sensor mimicking ablation catheterization procedure will be considered as future work.

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