Localized active-cladding optical fiber bend sensor

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1 Introduction

The goal of this research was to develop an optical sensor capable of measuring multiparameter bending (i.e., bending direction and degree of curvature) at multiple points along a flexible body. Existing fiber optic bend sensors for single- and dual-direction measurements utilize either intensity-based measurements from plastic fibers, long-period gratings (LPGs), or interferometric measurements using a multicore fiber. A distributed optical bend sensor that utilizes a multicore fiber modified with fiber Bragg gratings (FBGs), which allow for point-based multiaxis bend measurements along the length of the fiber, also exists. However, these sensors are incapable of measuring bending direction at multiple localized points along a single-core fiber.

For example, a plastic optical fiber bend sensor, proposed by Kuang, Cantwells and Scully was created by removing a 70-mm section of cladding from one side of an optical fiber using a razor blade. Light traveling within the fiber can thus escape through the modified region, with a higher percentage of light escaping during bending. A linear relationship between the central displacement of the beam and the decrease in transmitted light intensity was demonstrated during testing and could be easily measured. While this design is cost effective, only one single-axis sensor can be created per fiber.

Another technology that can be utilized to create optical bend sensors is the long-period gratings (LPGs), as described by James and Tatam. An example of LPG fiber bend sensors are the sensors proposed by Zhao et al. They proposed three bend sensors, all utilizing LPG but each with a different cross sectional shape: a flat-clad fiber, a four-core fiber, and a D-shaped fiber. All three fibers demonstrated a spectral change through the LPG with respect to curvature. Unlike standard LPG fibers, the flat-clad fiber demonstrated a spectral change in orthogonal planes, while both the four-core and D-shaped fibers demonstrated a percentage of the maximum spectral change when rotated about their central axis. While these three sensors could track bending (degree of curvature and rotation), they are limited to a single location along the length of the fiber.

A multicore optical fiber bend sensor, proposed by Blanchard et al., can potentially measure fiber bending direction. To accomplish this, a photonic crystal fiber with three cores in an equilateral triangle arrangement can be created. Using interferometric measurements, the phase change between the light signals leaving each of the cores can be calculated. The magnitude of the phase changes between the three cores allows for calculation of the degree of curvature and direction of the fiber’s bend. The disadvantage of this sensor is that the measurements are integrated over the length of the fiber, such that the optical fiber is essentially one big bend sensor that is presumed to have a uniform curvature along the entire fiber length.

Another optical bend sensor, proposed by Duncan and Raum, is capable of distributed bend direction measurements along the length of a fiber. In this design, a fiber composed of three cores arranged in an equilateral triangle is utilized. Fiber Bragg gratings (FBGs) are created on each of the three cores at multiple locations along the fiber’s...
length to yield multiple bend sensing locations. Each bend sensing location consists of three FBGs (one on each core), with each FBG measuring the strain at the local position of that core. Together, the three FBGs allow the curvature and direction of bending at that location to be determined. Through optical frequency domain reflectometry utilizing a swept wavelength source, all the identical multiplexed sensors on the fiber can be interrogated. This information can then be processed to infer the shape of the fiber. Precise measurement instruments are needed to make precise interrogations of all the individual bend locations.

1.1 Objectives

We propose a new sensor design that utilizes localized active-cladding fluorescence to create a bend sensor capable of measuring bending at multiple points on a single optical fiber. The new design is an improvement on existing optical bending sensors, because several bending measurements can be made on a single fiber, allowing the spatial requirements of the sensor to be kept very small. The new sensor is also an improvement, because the measurement device needed to monitor the signals from the sensor is readily available. The sensor design relies on axial excitation of three negatively guided point defects that make up a sensorized region in the fiber. That is, each sensorized region of the fiber contains three active cladding zones, spaced 120-deg apart around the circumference of the core (Fig. 1). The modified cladding zones are filled with a quantum dot (QD) fluorophore mixture, each with a different peak emission wavelength to allow for signal differentiation using a simple spectrometer. We describe here the fabrication and initial evaluation of the prototype sensor with a single sensorized region.

2 Design and Fabrication of Sensor Prototype

The physical principles of the new sensor design are based on active-cladding mechanisms. Active-cladding sensors are generally excited through either side excitation or axial excitation. Side excitation refers to excitation of the active cladding by a light source that is normal to the fiber length. This method was not chosen as the excitation mechanism for our sensor because of its large spatial requirement. Instead, axial excitation was chosen so that light propagating within the core excites the active cladding through one of two different interactions. In a positively guiding defect, where the refractive index of the cladding is less than that of the core, the active cladding is excited by the evanescence field of the light propagating within the core. In a negatively guided or leaky defect, where the refractive index of the cladding is greater than that of the core, the active cladding is directly excited by light escaping the core. In axial excitation, the physical constraints are thus minimized.

In our design, the plastic cladding of the optical fiber was modified by creating three 150-μm-diam active-cladding zones that were spaced 120-deg apart around the circumference of the core. This was accomplished by machining holes in the cladding and filling the holes with a QD-epoxy mixture. During excitation, a portion of the fluorescence generated at the active cladding would couple and propagate along the fiber. Mercuse found that minimizing the difference between the refractive index of the core and that of the modified cladding increased the launching efficiency of the fluorescence into guided modes of the fiber.

Our sensor was designed to utilize the property that modes propagating within an optical fiber shift to the outer radius during bending. Sensorized zones located further on the outer radius of the fiber bend would have a higher fluorescence excitation than those located on the neutral axis or inner radius due to the greater interaction with the excitation source. Fluorescence intensity would also increase with bending curvature due to the greater shift of modes to the outer radius of the bend.

2.1 Sensor Fabrication

The new sensor was fabricated using a 300-μm-diam silica-core, plastic-cladding fiber [Polymeric (Phoenix, Arizona) JTFLH300330650], visible spectrum CdSe/ZnS quantum dots (QDs) suspended in toluene [Evident Technologies (Troy, New York) evdot], and medical grade ultraviolet (UV) epoxy [Dymax (Torrington, Connecticut) 141-M]. The QDs were mixed in the UV epoxy that had a refractive index (n_{epoxy}=1.507) slightly higher than the core (n_{core}=1.470), creating three leaky-fiber sensorized zones. The injection mechanism of the QDs in a leaky fiber can be modeled using ray optics, as shown by Marcuse.

2.2 Modified Zone Machining

Unlike other active-cladding fluorosensors where the cladding is removed 360-deg around the fiber core, the new sensor design required three separate modified zones in the cladding, spaced equally around the fiber. An economical, commercially available desktop CO2 laser cutting system [Versalaser (Scottsdale, Arizona) VL-300] was used to create the three defects in the cladding. The CO2 laser cutting system had a maximum power of 30-W, a spot size of 127-μm, and was computer controlled. However, the system was not ideal for cutting with micron accuracy.

The first modification of the CO2 laser system was to align the coordinate axis of the laser and the computer system with micron accuracy. To accomplish this, a special fixture was developed to bridge the gap between the computer and laser systems’ coordinate systems and allow for micron accuracy when modifying the 330-μm-diam fiber.
The fixture used an aluminum base plate with a pocket centered on the top face that was aligned to the axes of the laser system. An acrylic plate held within the pocket of the base plate was modified to create a fiber retaining groove using the laser system. This process allowed the base plate to be aligned with the laser system coordinate axes, while the fiber retaining groove was precisely aligned with the coordinate system of the computer.

Another problem was that the laser head always had to be moving while cutting, and with a 127-μm-diam spot size, a ~150-μm-diam modification could not be created. To create the point modification, the laser was passed over a 150-μm-diam pinhole mounted over the fiber, restricting all but the 150-μm-diam portion of the beam, and creating a ~150-μm modification in the polymer cladding (Fig. 2). The process of “flashing” the laser beam through the pinhole aperture to create specific modification geometry was very sensitive to the distance between the aperture and the fiber surface. To limit the interference effects caused by the laser beam passing through the pinhole, the aperture was positioned as close to the fiber surface as possible.

The last challenge using the CO₂ laser system was to create three identical modified zones in the cladding, spaced 120-deg apart circumferentially. This was addressed by using two mechanical rotators incorporated into the fiber-holding fixture that would rotate the fiber 120-deg after the creation of each hole so that the next could be made (Fig. 3). This method for creating the modified zones was ideal, because it allowed for identical zones to be spaced evenly around the fiber’s circumference.

2.3 Active-Cladding Deposition

After the holes were cut into the cladding of the optical fiber, a mixture of four parts QD solution and one part UV glue was used to create the active-cladding zones. 526-, 564-, and 617-nm QDs were chosen as the fluorophore for their many advantages over organic dyes. Unlike organic dyes, QDs exhibit a symmetric and narrow emission spectrum, allowing easy de-coupling of multiple fluorescence signals measured by the spectrometer (Fig. 4).15,16 QDs are also less susceptible to photobleaching than organic dyes, improving the long-term stability of the sensor.15,17 Lastly, the main advantage of using QDs is that a single excitation source can excite all the QDs with different emission spectra, as long as the excitation source can excite the one with the shortest wavelength emission peak.16

Custom-pulled borosilicate micropipettes [(Warner Instruments Incorporated, Hamden, Connecticut) G100T-3] with 50-μm-diam tips were used to deposit the fluorophore mixture into the modified zone (Fig. 5). The fluorophore...
mixture was drawn into the micropipettes through capillary action, then deposited into the holes in the fiber cladding by manually touching the tip of the pipette to the edge of the hole. This method filled the holes with ~265-pL of solution.

After the desired amount of fluorophore solution was added to the defect in the cladding, the toluene evaporated and the remaining QD/UV glue was cured with a UV light source and the remaining QD/UV glue was cured with a UV light source (Fig. 6). The remainder of the open hole was then filled and sealed using another layer of UV glue to improve mechanical integrity.

2.4 Protective Buffer Creation and Fiber Termination

To protect the fiber during testing and eventual use, a protective buffer was added using an airbrush (Badger, Franklin, Park, Illinois) and a synthetic rubber coating (Performix Plasti Dip, Blaine Minnesota) diluted 1:1 by volume with the appropriate thinner. After the creation of the rubberized buffer, one end of the fiber was terminated to a standard SMA fiber connector using a reusable bare fiber terminal; the other end of the fiber was terminated with a small piece of black vinyl rubber to absorb the laser beam at the end of the fiber. The SMA connection was then polished though 5-, 3-, and 1-μm lapping paper to ensure a nice finish.

2.5 Single-Axis Sensor Prototype

To measure the curvature/fluorescence intensity relationship when the modified zone was on the outermost radius of the bending fiber, a sensor was created with a single modified zone using QDs with a 617-nm emission peak. The change in fluorescence intensity from the straight fiber was measured as the bending curvature of the fiber at the sensorized zone increased from 0.01- to 0.05-mm\(^{-1}\) in 0.01-mm\(^{-1}\) increments.

2.6 Two-Axis Sensor Prototype

Another sensor was created with three modified zones spaced 120 deg apart around the circumference. The three zones were each modified with different QDs. QDs with 526-, 564-, and 617-nm emission wavelengths were used so that each zone’s emission could be easily distinguished from others. The sensor prototype was tested with curvatures of 0.01- to 0.03-mm\(^{-1}\), in 0.01-mm\(^{-1}\) increments, and bending directions from 0 to 360-deg in 30-deg increments.

2.7 Prototype Evaluation

The single-axis prototype with one single sensorized region and one zone was evaluated in a single phase to demonstrate that a fluorophore-doped zone located on the outermost bending radius of a fiber would experience an increase in fluorescence intensity with an increase in bending curvature. The two-axis sensor prototype with one single sensorized region consisting of three zones was evaluated in two phases. The first phase was to demonstrate that a fluorophore-doped zone located on the outside bending radius of a fiber would experience an increase in fluorescence intensity with an increase in curvature. The second phase was to demonstrate the emission patterns of the three modified zones spaced 120-deg apart for different bending directions.

A testing apparatus was designed to measure the fluorescence signal intensity from the sensor when bending in different directions and with different degrees of curvature (Fig. 7). The main components of the apparatus were the following: a 50-mW 405-nm diode laser operating at 10-mW [Coherent (Santa Clara, California) CUBE Laser] to excite the fluorophores, a spectrometer [Ocean Optics (Dunedin, Florida) USB2000] to measure the fluorescence signal, a 50:50 beamsplitter (Thorlabs, Trenton, New Jersey) to allow both the laser and spectrometer to operate on the same end of the fiber, a collimator (Ocean Optics), a rotating fiber clamp (Thorlabs), and a set of cylinders with known curvatures (custom-built) with retention mechanisms. The 405-nm diode laser was passed through a 405-nm bandpass filter (Thorlabs) to remove any excess noise other than the central beam. The laser beam then passed through a polarization-independent 50:50 beamsplitter; half was injected into the fiber through a collimator, while the other half was lost. A portion of the fluorescence generated at each modified zone through axial excitation was recouped to guided modes within the fiber, propagated back, and was collimated into the spectrometer.

Directly after where the fiber was connected to the collimator using a SMA connection, a stationary fiber clamp was used to ensure the fiber would not shift within the bare fiber terminal. This ensured that the coupling efficiency was constant throughout testing. After the stationary clamp, the fiber was clamped to a mechanical rotator that would rotate the fiber about its axis to simulate bending in all bending directions. Slack was left in the fiber between the two clamps to allow for 360-deg rotation without breaking the fiber. The fiber was then bent around one of five known
Realized when the modified zone with the 617-nm QD was arbitrary sensorized zone. A 0-deg bending direction was the testing range.

The curvature resolution increased with increasing curvature and is best represented as a percentage of the measured curvature. The curvature variability was determined for each of the five curvature measurements. The average variability of the fluorescence measurements was within 14% of the mean over the entire testing range. Using the earlier data, the curvature variability was determined for each of the five curvature measurements \[ \frac{\text{STD}(k_{\text{predicted}})}{k_{\text{measured}}} \]. The curvature resolution increased with increasing curvature and is best represented as a percentage of the measured curvature \[ \frac{\text{STD}(k_{\text{predicted}})/k_{\text{measured}}}{k_{\text{measured}}} \]. The curvature resolution was \( \pm 8.5\% \) of the actual measured curvature over the testing range.

### 3 Results and Discussion

#### 3.1 Single-Axis Sensor

As expected, the results showed that as curvature of the bent fiber at the modified zone increased, so did the intensity of the fluorescence emission from the fiber sensor. 50 measurements on the 400- to 1000-nm spectra were taken for each curvature. The average value from the bound region \( \pm 5\text{-nm} \) around the 617-nm peak emission wavelength of the QD was calculated and plotted as a function of curvature (Fig. 8). The measured result was expected due to the shifting of modes to the outer radius of the optical fiber during bending. When curvature increased, so did the amount of light available to interact with the QDs, and thus more fluorescence was generated.

This particular fiber was tested with a bending range from a minimum curvature of 0.01-mm\(^{-1}\) to a maximum curvature of 0.05-mm\(^{-1}\). The corresponding change in detectable fluorescence (the fluorescence measured in the straight sensor subtracted from the fluorescence measured in the bent sensor) ranged from 103 counts at the minimum curvature to 2195 counts at the maximum curvature. The variability of the fluorescence measurements was within \( \pm 14\% \) of the mean over the entire testing range. Using the earlier data, the curvature variability was determined for each of the five curvature measurements \[ \frac{\text{STD}(k_{\text{predicted}})}{k_{\text{measured}}} \]. The curvature resolution increased with increasing curvature and is best represented as a percentage of the measured curvature \[ \frac{\text{STD}(k_{\text{predicted}})/k_{\text{measured}}}{k_{\text{measured}}} \]. The curvature resolution was \( \pm 8.5\% \) of the actual measured curvature over the testing range.

#### 3.2 Two-Axis Sensor

For clarity of description, a reference coordinate system was used to indicate the direction of bend with respect to an arbitrary sensorized zone. A 0-deg bending direction was realized when the modified zone with the 617-nm QD was located on the outermost radius of the bend. For this prototype, ten measurements were taken at each bending direction/curvature combination. The emission spectrum of the straight fiber was subtracted from that of the bent fiber and averaged to obtain a measure of intensity change as a function of curvature. The average spectra are plotted in Fig. 9. For each bending direction, as indicated by the number of degrees above the corresponding panel in Fig. 9, three emission spectra are shown, representing the three different bending curvatures.

Results show a pattern consistent with what was expected. For example, when the 617-nm QD was placed on the outer most surface of the bending fiber (0-deg bend direction), the intensity difference spectra peaked at 617-nm, showing a positive change in intensity emission due to excitation of the 617-nm QD. In the same condition, the spectra show that the 617-nm QD and 564-nm QD zones had a negative change in intensity emission, because both zones were inside the neutral axis of the bending fiber. This same relationship can be seen with the 120-deg bending direction where the 526-nm QD zone was located on the outermost radius, and at the 240-deg bending direction where the 564-nm QD zone was located on the outermost bending radius.

Results in the other bending directions, not along the three main axes of 0-, 120-, and 240-deg, also exhibit expected trends. In these intermediate bending directions, the overall sensor emission spectra were made up of a combination of emissions from two of the three QD-doped zones. For example, in the 60-deg bending direction, the emission spectra show two less intense peaks at 526- and 617-nm wavelengths. This is an accurate representation of what would be expected, since two modified zones were on the outer radius of bending but were equally spaced on either side of the outermost radius of bending. The relationship between the bending direction and the change in fluorescence intensity for each of the three zones at a bending curvature of 0.02-mm\(^{-1}\) is shown in Fig. 10. Fluorescence values in Fig. 10 are the average from a window \( \pm 5\text{-nm} \) around the peak emission wavelength of each modified zone. The difference in the peak intensity values for the three zones is due to different interaction efficiencies of the leaking laser light and the recaptured fluorescence. The slight differences between each zone maximum fluorescence is most likely caused by the small differences in the way the quantum dots self arrange during deposition and are thus prone to slightly different injection efficiencies.

In the main bending axes, where one of the modified zones was on the outer most bending radius, 15 extra measurements were taken for a total of 25 measurements. The extra measurements were taken so that the emission spectra can be compared to the results from the single-axis sensor. The relationship between changes in emission intensity and curvature for each sensorized zone in the multiaxis sensor are superimposed on that of the single-axis sensor (Fig. 11). Results show a consistent trend in increasing fluorescent intensity as a function of sensor bending. The small variability between the two sets of data also suggests that there is little or no cross talk between the sensorized zones in the multi-axis sensor.
4 Limitations

The main limitation of the current prototypes is the large size of the fiber, resulting in a stiff sensor. This leads to breakage whenever the fiber is bent to a larger curvature. The CO₂ laser modification process is currently limited to creating large 150-μm holes in the optical fiber. The 150-μm defect size requires that a fiber with at least 300-μm-diam core be used to fit three modified zones around the circumference. While the 300-μm core fiber is able to carry a greater number of modes of light than a smaller diameter fiber, it also increases the stiffness of the fiber. Using a smaller fiber would increase flexibility, resulting in an increase in durability of the sensors. Ideally, smaller 50- or 100-μm modifications could be made so that three modified zones could fit around the circumference of a 200-μm core fiber.

We postulate that decreasing the size of the modified zones would also increase the bending direction sensitivity. Smaller modified zones would represent a smaller percentage of the overall circumference of the optical fiber, allow-

Fig. 9 Change in intensity spectra from the three modified zone fibers. Each panel represents a different bending orientation (labeled above the panel), each line represents a different bending curvature (labeled below the figure), and each of the three peaks corresponds to the expected peak emission from each QD (vertical lines).

Fig. 10 Bending direction to change in fluorescence intensity relationship for each of the three zones while bending around a constant 0.02-mm⁻¹ curvature.
ing for the same change in bending direction to have a larger change in fluorescence intensity from the straight fiber. However, the potential benefit of the increased sensitivity would have to be balanced by the fact that a smaller modified zone would also produce less fluorescence.

Another limitation with the current prototype sensors is their ability to measure curvatures smaller than 0.01 mm⁻¹. The change in fluorescence from the straight fiber at such small curvatures is very small. A larger excitation power could be used to increase the bending fluorescence signal; however, this would also result in raising the fluorescence signal in the straight bending case. Therefore, this prototype is not sensitive enough to distinguish between small curvatures.

Even though the prototype presented in this work is a multiaxis sensor limited to a localized point along a bend, it demonstrates the concept of the design and feasibility in fabrication. To further develop the sensor, more sensorized regions could be embedded on the same fiber. Each additional sensorized region would require another set of three distinct QDs. Given the available quantum dots, our sensors are currently limited to two localized points if restricted to the visible spectrum, but more if the infrared spectrum is also used. The number of localized bend sensing regions that could be made on a single optical fiber is limited only by the number of distinct fluorophores available, both of which are expected to increase as quantum dot technology progresses.

A potential future application of the multiaxis multipoint bend sensor technology could be the creation of a flexible fiber optic shape tracker. Using an optical fiber with many localized bend sensors spaced at known locations along its length, the overall 3-D shape of the fiber could be determined based solely on the fluorescence from each of the localized regions. This shape tracker would be ideal for teleoperation applications such as colonoscopy or boroscopy. During colonoscopy, displaying the shape of the endoscope to the clinician during the procedure would be beneficial. Yet no sensor technology is currently small enough to fit into the endoscope for tracking its shape. A shape tracker realized in a single optical fiber could easily fit within the working channel of an endoscope to provide an easy, inexpensive solution.

5 Conclusions

The design principle of a bend sensor using an optical fiber with a single sensorized cladding region is described. We demonstrate the concept and feasibility of the sensor by showing that the fluorescence generated and recoupled into the fiber increases when the curvature of the fiber is increased. Expanding on the single-zone results, a modified region comprised of three equally spaced modified zones around the circumference of the fiber is created. Bending direction can be determined by the fluorescence intensity relationships between the three modified zones. The prototype sensors presented in this work demonstrate the feasibility to represent local curvature and bending direction of a point on an optical fiber solely based on the fluorescence signals generated by three active-cladding point modifications. These results set the groundwork for a future distributed bend sensor based on a single optical fiber, where curvature and bending direction could be measured at multiple points along the fiber.

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References


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