High bending curvature withstanding one dimensional angle sensor with fiber Bragg gratings

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ABSTRACT

We report on the development of an angle sensor which can measure at high bending curvature. Unlike the other sensors, the novel angle sensor can be durable and flexible. The sensors consist of one fiber Bragg grating (FBG) fiber which is located in the middle of each sensor, and are fabricated in varying thickness to confirm the relation between the distance of the center of the angle sensor to the core of the FBG node and the radii of curvature at which the sensor can measure. The thinnest sensor has the thickness of 200 µm and can measure at the bending radius of 5 mm. However, its angle measurement error is the largest with 1.25°, because of high sensitivity. Regulating the thickness of sensor, the angles at high curvatures can be measured reliably.

Keywords: Fiber Bragg gratings, Fiber optic sensors, High bending curvature, angle measurement

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1. INTRODUCTION

Recently, there has been an increasing interest in the human body motion tracking research with applications for medical uses, video game control, animation, and others. In order to track human body motion, it is important to obtain precise angular measurements of each joints of the body. To achieve this, many studies have approached this with magnetic, inertial, optical fiber, and various other types of sensors. These sensors have many merits but also have clear disadvantages. For example, the magnetic sensors have high resolution, but its signals and measurements are easily interfered by the ferromagnetic objects present in the environment, resulting in high error [1]. The inertial sensors can be miniaturized and are very portable, but exhibits increasing drift error in the measured values over time [2].

The fiber Bragg grating (FBG) sensor is coming into the light as a technology that overcomes the disadvantages of the previously mentioned sensors. The FBG sensors have the merit of being thin and light, having high resolution, and being largely unaffected by the surrounding environment. The FBG sensor is made by writing Bragg grating within the core of the optical fiber that reflects only a specific wavelength of light. When the sensor experiences strain, the spacing of the Bragg grating changes resulting in the shift in the wavelength of the reflected light. This wavelength shift can be interrogated and the strain experienced by the fiber can be calculated. There is a previously developed sensor that utilizes this longitudinal strain to measure the angle of single axial bend[3]. However, the strain experienced by the optical fiber is too large in comparison to the angle of the bend, which results in low integrity of the sensor due to the optic fiber destruction when measuring bend with high curvature. Another previously researched FBG sensor makes use of a metal beam, to whose surface the FBG sensor gets attached to cause longitudinal strain of the Bragg grating when the metal beam bends[4]. However, due to the high Young's Modulus value of the metal beam, only small deflections with large radius of curvature was measurable with the sensor. Lastly, previous study has developed a sensor that can measure angle of three-dimensional flexure by combining three radially arrayed FBG fibers into one single fiber using epoxy. This method resolves the issue of high Young's Modulus by using an epoxy with similar Young's Modulus as the optic fibers[5]. However, the innate thickness of the cladding and buffer coats that surround the core of the optical fibers results in significant distance between the bending axis of the whole sensor structure and the cores of the three optical fibers, which results in high strain to the FBG and causes large wavelength shifts with high curvature bends preventing accurate measurement of the angles.

In this research, the effect of the distance between the bending center and the FBG core will be investigated by fabricating multiple sensors with varying distance, each using a single FBG fiber and epoxy, and then measuring the

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strain experienced by the FBG in relation to the variation. Additionally, the relationship between the minimum radius of curvature at which the angle can be measured and the d variation will be studied, and the high curvature angle sensor fabrication method will be proposed with the verification of the measurement error range.

2. MATERIALS AND METHODS

2.1 Fiber Bragg grating (FBG) principle

The fiber Bragg grating, which could reflect particular wavelengths of light depending on the distance of segments, lead to change of wavelength of reflected light by variation of stain and temperature. The reflected light from Bragg gratings is called the Bragg wavelength as in (1).

$$\lambda_b = 2n\Lambda \tag{1}$$

where n is the refractive index of an optical fiber core and Λ is the periodic grating pitch[6].

The change of reflected wavelength in response to variations in strain and temperature could be represented by (2).

$$\frac{\Delta\lambda_b}{\lambda_b} = (1-\rho_e)\varepsilon + (\alpha_\Lambda + \alpha_n)\Delta T \tag{2}$$

The first term in (2) is given by the effect of strain on the wavelength shift, where ρ_ε is the strain-optic coefficient and ε is the strain experienced by the grating. The second term notes the thermal effect on the wavelength shift, where α_Λ is the thermal expansion coefficient and α_n is the thermos-optic coefficient for the core of the optical fiber. By this formula, the strain along the neutral axis could be obtained with assumption that the nodes of FBG are at the same temperature.

The axial strain (ε_x) could be approximated by $-\kappa z$, where κ is the curvature and z is the distance from the neutral axis. Therefore, the strain applied on the ith node, ε_i, could be represented as in (3)

$$\varepsilon_i = \kappa_i^{FBGs} d_i \cos(\theta_i^{FBGs} - \theta_i) \tag{3}$$

where κ_i^{FBGs} is the curvature of the sensor, d_i is the distance between the center of ith nodes and neutral axis, θ_i^{FBGs} and θ_i are the angle rotation of sensor and ith node from the bending direction.

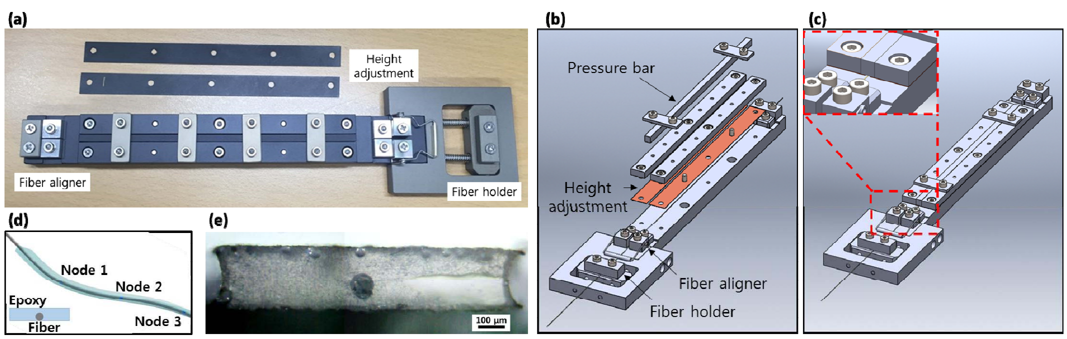


Figure 1. (a) Fabrication jig of FBG angle sensor. (b) and (c) show components of jig and assembling method. (d) Concept design of angle sensor and (e) cross-section of fabricated FBG angle sensor

2.2 Angle sensor fabrication

The FBG fibers were purchased from FBGS (Gill, Belguim). Angle sensor consists of one optical fiber which has 3 FBG nodes in 8mm length at intervals of 20mm. Each FBG node has different reflected wavelength to enable the angle sensor to measure the signals from multiple nodes simultaneously.

A. Sensor Design and Fabrication

The bare FBG fibers could not have effect on strain because the bending center has the same position with the center of fiber's core. Therefore, the node core should have a certain distance from the neutral axis of the sensor. The one FBG fiber was aligned in the middle of the jig's bottom surface to ignore the strain caused by unexpected bending direction such as left and right (**Fig. 1(a)**). Then, the jig was assembled with particular height adjustments which decide the thickness of angle sensor, and the distance between the fiber core and the sensor's neutral axis. Given the various thickness, we could investigate the effect of distance between the core of the FBG node and the neutral axis of the sensor on the wavelength shift of the reflected light. All of the fabricated angle sensors have 150 mm width and 100 mm length, but have varying thickness of 200, 250, and 300µm. The epoxy (EPO-TEK 301, Epoxy Technology Inc.) was poured in the gap between the fiber and the side walls of the jig, topped with pressure using a thin metal piece, and then left in the oven at 65^{o}C for 1 hour to be cured.

2.3 FBG sensor calibration

The FBG angle sensors should be calibrated before using them. The calibration was carried out by bending the sensors with known curvatures, κ_s^{FBG}, to determine the distance d_i and the angle of rotation θ_i. For the calibration of angle sensors, xy-plane, on which deflection is defined as up and down, is required. With the sensors bent in particular curvatures, we could derive the results of strains ε_i from the wavelength shift compared to the reference wavelength at which the sensors were kept straight. d_i and θ_i could be calculated as follow,

$$\varepsilon_i^{up} = \kappa_s^{FBGs} d_i \sin(\theta_0 - \theta_i) \tag{4}$$

$$\varepsilon_i^{down} = -\kappa_s^{FBGs} d_i \sin(\theta_0 - \theta_i) \tag{5}$$

In our experiments, the specific curvatures κ_s^{FBG} were set to be 0.0333 and 0.0385 mm^{-1}.

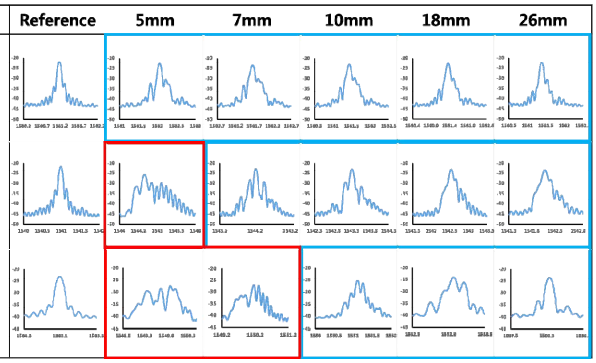
3. RESULTS AND DISCUSSIONS

To confirm that the distance from neutral axis to center of the FBG nodes has effect on limitation of the measurable bending curvature, we compared the wavelength spectrum of reflected light from the angle sensors that have varying thickness, while the sensors were bent with various radii of curvature (**Table 1**). The spectrum from FBG sensors show that the greater distortion occurred at higher bending curvatures. This was because the bending of FBG sensors leads to variation of strain throughout the 8mm long Bragg grating in the nodes, resulting in reflection of multiple wavelengths of light. Since the distortion of spectrum was not significant for the sensor #1 which have the smallest d_i, it could be used to measure the bending angle up to a radius of 5 mm. Under the radius of 5mm, a few sensors broke because the epoxy could not tolerate the strain. For sensor #2 and #3, they could measure the angles at the lowest radius of curvature of 7 mm and 10 mm, respectively. This trend showed that the measurable bending curvature depends on the distance between the centers of FBG fiber and the neutral axis of the sensor. Since the shape sensor which contains three FBG fibers has minimum d_i of 100 µm, the reliable minimum bending radius is only 73 mm[5]. Therefore, these results of spectrum show that the angle sensor could be used to measure angles at higher bending curvatures previously immeasurable.

To evaluate the measurable angles of the sensors, they were bent at specific angles with bending radius of 12 mm where

Table 1. Wavelength spectrum of reflected light from FBG angle sensors for various bending curvatures

	Reference	5mm	7mm	10mm	18mm	26mm
Angle sensor #1 h=200µm d_i=42µm						
Angle sensor #2 h=250µm d_i=67µm						
Angle sensor #3 h=300µm d_i=92µm						



the spectrum could be obtained for all types of angle sensors. The measured angles were approximately same with the actual angles. However, the smaller d_i the sensor has, the larger error was observed. Since the distance of d_i is proportionally related to strain, thin angle sensors had narrow wavelength shift range, which made them highly sensitive and erroneous.

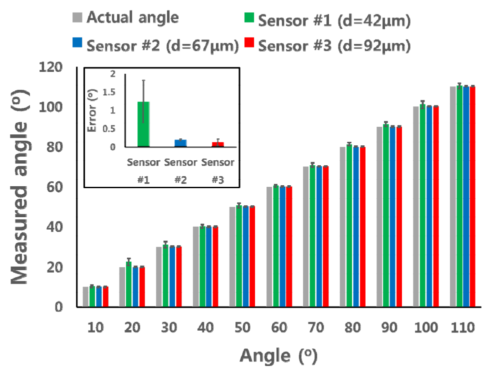


Figure 2. Evaluation of FBG angle sensor. Measured angles at various bending angles at curvature radius of 12 mm

4. CONCLUSION

We have fabricated the angle sensor which can measure angles at extremely high bending curvatures by regulating the distance between the center of the FBG fiber and the sensor, d_i. The thinnest angle sensor allowed for the minimum bending radius of 5 mm. If the epoxy can be substituted with other materials that have low Young's modulus, the angle sensor could measure at higher bending curvature. Although the thinner angle sensors can measure at high curvature, it is highly sensitive and erroneous. Therefore, the distance between the FBG fiber core and the angle sensor center should be chosen in accordance with the target to measure.

5. ACKNOWLEDGEMENTS

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