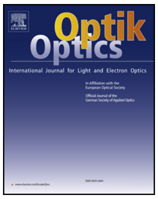
Optik - International Journal for Light and Electron Optics 176 (2019) 559–566

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.com/locate/ijleo


Optik Optics
International Journal for Light and Electron Optics

Original research article

Flexible membrane curvature sensor based on multilayer polyimide substrate and optical fiber implantation

Guangkai Sun[a,b], Yang Hu[a,b], Mingli Dong[a,b,*], Yanlin He[a,b], Mingxin Yu[a,b], Lianqing Zhu[a,b,*]

[a] *Beijing Key Laboratory of Optoelectronic Measurement Technology, Beijing Information Science & Technology University, Beijing, 100101, China*
[b] *Bionic and Intelligent Equipment Lab, Beijing Information Science and Technology University, Beijing 100016, China*

ARTICLE INFO

Keywords:
Flexible sensor
Curvature sensor
Optical fiber
Soft robotics

ABSTRACT

We report a flexible membrane curvature sensor with multilayer polyimide thin film substrate and embedded fiber Bragg gratings (FBGs). The major contribution is obtaining a membrane curvature sensor with extraordinary flexibility and repeatability for the measurement of soft mechanisms and complex structures. The approximate linear relation between the reflected wavelength shift and the bending curvature is analyzed using the pure bending model. The reflection spectra variation of the sensor with the curvature of the measuring object, and the effect of the embedded depth of the FBG sensitive element is analyzed experimentally. The optimal depth position for the implantation of the optical fiber, and the sensitivity and repeatability of the membrane sensor is obtained. The results proved that the proposed membrane curvature sensor is flexible enough to fit tightly on the molded surface of the object for real time measurement. In the curvature range of 0m^{-1}–30m^{-1}, the maximum sensitivity is up to 51.62pm/m^{-1}, and the fluctuation coefficient in repeated measurements is negligible. The membrane sensor is simple in configuration, easy to fabricate and low cost. It has broad application prospects in the field of industrial measurement, medical detecting and monitoring.

1. Introduction

The flexible curvature sensors have recently gained wide attention in many areas of science and engineering including aerospace, robotics, and infrastructure monitoring. These sensors can be applied to measure the curvature of various complex structures, to measure the posture of soft robots in real time, and to monitor the motion of rehabilitation robots for medical purpose. Besides, they can be integrated with the morphing wing structures to realize the shape sensing of morphing aircrafts. To cope with the growing demands for flexible curvature sensors, various solutions have been proposed. Generally, these flexible sensing solutions can be divided into electrical and optical sensing, and the optical fiber sensing solutions have received considerable attention due to their unique advantages, such as light weight, small size, immune to electromagnetic interference, and inert to chemical and biotic environment. However, the single optical fiber sensors can hardly be applied directly to measure the curvatures of various objects because they are fragile and get broken easily. A favorable approach is inserting the optical fiber sensors into certain types of substrates to form flexible sensors.

At present, some kinds of flexible curvature sensors using optical fiber sensing elements have been proposed. As described in [1], a directional flexible curvature sensor using tilted few-mode fiber Bragg grating (FBG) is realized. The structural curvature and

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* Corresponding authors.
E-mail addresses: mingli.dong@outlook.com (M. Dong), lianqing.zhu@hotmail.com (L. Zhu).

https://doi.org/10.1016/j.ijleo.2018.09.122
Received 20 July 2018; Accepted 23 September 2018
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temperature can be measured simultaneously with a resolution of 9.15×10^{-4} m^{-1} and 0.952°C respectively. Although this sensor is capable of measuring both the bending direction and curvature value, the fabrication process of the tilted few-mode fiber Bragg grating is complicated which make the sensor can hardly meet the demands for engineering applications under current technology condition. To increase the sensitivity, the interferometric fiber optic sensors and specialty fiber schemes attract great interest [2–8]. An in-fiber Mach-Zehnder interferometer (MZI) based on dual side-hole fiber is adopted as the curvature sensor, and both the bending direction and magnitude can be measured simultaneously [3]. An MZI-FBG mixed curvature sensor is proposed which comprises a MZI made by the few-mode photonic crystal fiber and an FBG inscribed on the fiber [4]. The curvature and temperature can be measured by the MZI and FBG respectively [9,10]. Although the interferometric fiber optic sensors have high sensitivity, they are not gaining popularity in engineering applications because the fabrication process is complicated and the cost is high [5,6]. A sensor configuration with a FBG embedded into a soft silicone substrate is proposed to improve practicality [5]. The declared measurement range is up to 80 m^{-1}, but the sensitivity is as low as 1.64 pm/m^{-1}, and the repeatability is poor due to the silicone substrate is too soft to fix the fiber in position. Therefore, the current optical fiber-based curvature sensors have serious limitations in sensitivity, fabrication complexity and cost, which hinder their practical applications [11–15]. To improve practicality and realize the accurate measurement of structural curvatures, the flexible curvature sensors that are more sensitive, highly repeatable, simple to fabricate and low cost are highly desired.

To address those issues, we propose a novel flexible membrane curvature sensor based on multilayer polyimide substrate and optical fiber implantation. Different from previous optical fiber-based curvature sensors that either using complicated microstructure optical fibers or soft silicone substrates, a simple but effective approach is proposed. A standard FBG is used as the sensitive element and embedded into a multilayered polyimide thin film to form a flexible curvature sensor. It is notable that the polyimide membrane substrate is a more effective approach because the polyimide film is flexible and has good compatibility with the optical fiber. The FBG can be fixed in position and bending synchronously with the polyimide membrane, which induces high loading efficiency. The proposed sensor is flexible enough, durable for practical applications, easy to fabricate and low cost. The sensor design, measuring principle and experiment setup are described in Section 2 and 3. Section 4 presents the experiment results and data analysis. Conclusions and future works are discussed in Section 5.

2. Sensor design and measurement theory

2.1. Design of the flexible membrane curvature sensor

To measure the curvature values of various structures, the sensor should be flexible enough to fit tightly on the structure surfaces, and the sensitive element must be fixed in position and well protected to make it practical. Here, we propose the use of a FBG as the sensitive element and a rectangular multilayer polyimide membrane as the substrate.

Fig. 1 shows the schematic of the proposed sensor configuration. The optical fiber is embedded into the bonding interface at certain layers of the multilayer polyimide substrate to form a flexible membrane curvature sensor. The FBG is fixed at the transverse central position of the polyimide membrane substrate. The embedded depth of the FBG is defined as the distance between the substrate surface and the optical fiber, and indexed with h_1.

Fig. 2 shows the physical photo of the prepared flexible membrane curvature sensors with fiber embedded depth of 0.1 mm, 0.2 mm, 0.3 mm, 0.4 mm and 0.5 mm respectively. The membrane substrates of the sensors are made from DUPONT™ polyimide thin films, and the material properties are listed in Table 1. Each substrate consists of ten layers of the polyimide films with a thickness of 0.1 mm for each layer. The thickness of the polyimide membrane substrate is 1.0 mm. The properties of the FBG in each sensor are listed in Table 2.

2.2. Measurement principle

As the sensor is placed on the curved structure, the polyimide membrane substrate can bend flexibly and fit tightly on the structure surface. As bending occurs, the embedded FBG is stretched or compressed, the grating period of the FBG is changed, and the reflection peak of the FBG shifts to the longer or shorter wavelength direction.

As shown in Fig. 1(a), the original length of the optical fiber is the same as that of the neutral line of the membrane substrate. Based on the pure bending model [5], as the sensor bends to the state as shown in Fig. 1(b), the length of the neutral line of the membrane substrate, and the length of the embedded optical fiber can be expressed as:

$$L_{PMSN} = \rho \bullet \theta \tag{1}$$

$$L_{Fiber} = (\rho + l) \bullet \theta \tag{2}$$

where L_{PMSN} is the length of the neutral line, ρ is the bending radius of the neutral line, θ is the bending angle, L_{Fiber} is the length of the optical fiber, l is the distance between the optical fiber and the neutral line of the substrate which is defined as the offset distance of the fiber.

Using Eqs. (1) and (2), the variation of the fiber length induced by the bending effect can be derived and expressed as:

$$\Delta L_{Fiber} = L_{Fiber} - L_{PMSN} = l \bullet \theta \tag{3}$$

According to the fiber sensing theory as described in Ref [1,5,12], the FBG reflected wavelength can be expressed as:

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