Optik - International Journal for Light and Electron Optics 177 (2019) 26–35

Contents lists available at ScienceDirect

Optik

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

Original research article

Polyvinyl chloride reinforced soft silicone curvature sensor with optical fiber implantation

Guangkai Sun[a,b], Xu Zhang[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:
Soft sensor
Curvature sensor
Optical fiber
Soft robotics

ABSTRACT

Soft curvature sensors have huge demand in the emerging field of soft robots, rehabilitative robots and morphing flight vehicles. However, the current soft sensors have limitations in sensitivity, repeatability, and fabrication cost, which hinder their practical applications. To address these issues, we propose a soft curvature sensor with soft silicone-polyvinyl chloride mixed substrate and fiber Bragg gratings (FBGs). The major contribution is obtaining a soft curvature sensor with extraordinary high sensitivity and repeatability. Using the pure bending model, the nonlinear relationship between the bending curvature and Bragg wavelength shift is analyzed. The reflection spectrums of the FBGs in the mixed substrate are measured, and the effect of the horizontal position and embedded depth of the FBG is analyzed experimentally. The optimal embedded position of the FBG and the sensitivity and repeatability of the soft curvature sensor is obtained. The results proved that the proposed sensor is soft enough to follow the contour of the object for real time measurement, the maximum sensitivity is up to $328.67 pm/m^{-1}$ in the measurement range of $0m^{-1} \sim 15m^{-1}$, and the fluctuation coefficient of repeated measurement is less than 0.07. The sensor is simple in structure, easy to fabricate and low cost. All these make it to be a promising approach for practical applications in the industrial and medical field.

1. Introduction

The soft curvature sensors have a huge amount of applications in industrial and medical fields, such as large-scale structure monitoring in civil engineering, complicated shaped components testing in aerospace and vehicle engineering, motion measurement of rehabilitative robots for medical purposes, real time pose sensing and closed-loop control of soft robots, as well as shape sensing of flexible skin for future morphing flight vehicles [1–3]. Generally, the soft curvature sensors can be divided into two groups: electrical and optical sensors. In recent years, the fiber optic sensors have received widespread attention and are developing very fast due to their unique advantages over conventional electrical sensors, such as light in weight, small in size, completely immune to electromagnetic interference, inert to chemical and biological environment, and not harmful to human body [4–6]. However, the fiber optical sensors cannot be applied directly to measure the bending curvatures of the objects, an appropriate approach is to embed these sensors into some types of substrates as sensitive elements to form soft curvature sensors [5,6].

To date, several types of optical fiber-based curvature sensors have been proposed, and the sensitive element mainly using fiber

* Corresponding authors at: Beijing Key Laboratory of Optoelectronic Measurement Technology, Beijing Information Science & Technology University, Beijing, 100101, China.
E-mail address: lianqing.zhu@hotmail.com (L. Zhu).

https://doi.org/10.1016/j.ijleo.2018.09.171
Received 3 August 2018; Accepted 29 September 2018

gratings and interferometric structures that are inscribed on the fibers [1–10]. As demonstrated in [1], a directional curvature sensor based on tilted few-mode fiber Bragg gratings (FM-FBGs) has been investigated to simultaneously measure the bending curvature and environment temperature, and the resolution achieves $9.15 \times 10^{-4}\,m^{-1}$ and 0.952°C respectively. This sensor configuration gives prominence to both curvature direction and magnitude measurement, but the tilted FM-FBGs require nontrivial inscription and long running exposure processing which make this configuration can hardly meet the demands for real application under current technical conditions. To improve the sensitivity, the specialty fiber schemes and interferometric structures have attracted extensive research interests [2–8]. As described in [3], a dual side-hole fiber (DSHF) based in-fiber Mach-Zehnder interferometer (MZI) has been adopted as the curvature sensor, which is capable of measuring both of the bending direction and magnitude. In particular, an MZI-FBG mixed curvature sensor is proposed by Yang et al [4]. The sensor comprises a few-mode photonic crystal fiber (PCF) formed MZI structure for curvature measurement, and an FBG inscribed on the PCF for simultaneous temperature measurement. Although the in-fiber interferometric sensors are more sensitive than most other sensor types, they are not favorable for application due to the high structure complexity and fabrication cost [5,6]. To improve practicality, Ge et al proposed a simple but effective sensor configuration, a FBG is embedded into a soft silicone substrate to form a soft curvature sensor that is capable to distinguish the positive and negative bending directions [5]. Although this sensor configuration is practical, and the measurement range is up to $80\,m^{-1}$, the sensitivity is as low as $1.64\,pm/m^{-1}$, and the repeatability and consistency is poor because the deformation of the soft silicone substrate is unlimited, and the silicone material is too soft to transmit the loads consistently in different measurements. Thus, as described above, the current optical fiber-based soft curvature sensors have limitations in sensitivity, repeatability, consistency and fabrication cost. These limitations hinder their practical applications [11–15]. To enable reliable curvature measurement in industrial and medical fields, the practical soft curvature sensors that are sensitive, high repeatability, simple to fabricate and low cost are highly desired.

To address those issues, we propose a novel soft curvature sensor configuration with soft silicone-polyvinyl chloride sheet mixed substrate and FBG sensitive element. Different from traditional optical fiber-based soft curvature sensors that using complex microstructure optical fibers or single silicone substrates, in our approach the standard FBG is embedded into a soft silicone rubber sheet as the sensitive element, and the silicone sheet is bonded with a flexible polyvinyl chloride sheet to form a mixed substrate which is effective in protecting the sensitive element, transmitting the strain loads and adaptable to various objects with different shapes. It should be noted that the mixed substrate is a more effective approach because either the single soft silicone substrate or the polyvinyl chloride sheet substrate has notable shortcomings, such as the sensitivity and repeatability is very low when using a single soft silicone substrate, the single polyvinyl chloride sheet substrate is too resilient and ineffective in protecting the FBG unit. The mixed substrate has taken the advantages of the two materials that are complementary to each other. The detailed sensor design and measurement theory are described in Section 2. The experiment setup and performance analysis are presented in Sections 3 and 4. The proposed sensor is soft enough to follow the contour of the object for real time measurement, and has high sensitivity and consistency in repeated measurements. Besides, the sensor is simple in structure, easy to fabricate and low cost. All these make it a promising approach for practical applications in the industrial and medical field.

2. Sensor design and measurement theory

2.1. Design of the soft curvature sensor

To measure the curvatures of various objects with different shapes, the sensor must be soft and resilient enough to completely stick to the object surface and restore to its original state, and the sensitive element must be fixed and protected by a substrate to make the sensor practical. Here, we propose the use of standard FBG as the sensitive element, and the soft silicone material is used to form a flat substrate to fix the FBG in position. The FBG is embedded into the soft silicone substrate and is well protected. Although the silicone rubber substrate is very soft, it is not resilient enough to restore the original state instantly which seriously affect the repeatability and consistency of the sensor. Besides, the bending induced strain loads in the soft silicone substrate are small, this result in very low sensitivity of the sensor. To address these issues, a resilient polyvinyl chloride sheet is used as the base, and then the soft silicone sheet with embedded FBG is glued on the surface of the polyvinyl chloride sheet to form a novel curvature sensor with mixed substrate which is soft and resilient enough. Fig. 1 shows the schematic of the proposed soft curvature sensor with soft silicone-polyvinyl chloride mixed substrate.

In this approach, the soft silicone substrate is made from Ecoflex™ 00–50 super soft platinum silicone. To embed the FBGs into the silicone substrate, an aluminium mold with a rectangular groove and a top cap is designed and 3D printed. There exist six rectangular narrow deep slots with 0.5 mm width on both sides of the mold, thus the FBGs can be embedded into the substrate by passing the optical fibers through the slots before the liquid silicone rubber is poured. The Ecoflex™ rubber latex is mixed 1A: 1B by volume, poured into the mold and cured at room temperature of 20°C for 24 h with negligible shrinkage. The mechanical properties of the optical fibers and the soft silicone substrate are listed in Tables 1 and 2 respectively. The optical fibers are fixed in position by the precise fiber fixtures, and their depth positions can be adjusted precisely. The cured rubber substrate is very soft, strong and stretchy, it can stretch many times of its original size without tearing, and will rebound to its original form without distortion. The geometric dimension of the soft silicone substrate is 160 mm in length, 100 mm in width, and 3 mm in thickness. Then, a resilient polyvinyl chloride sheet with the same length and width as that of the silicone substrate is prepared and bonded with the silicone substrate to form a mixed substrate. The thickness of the resilient polyvinyl chloride sheet is only 0.5 mm, thus it is flexible and resilient enough to be the base of the soft curvature sensor. The mechanical properties of the polyvinyl chloride sheet are listed in Table 3. Finally, the overall dimension of the soft curvature sensor is 4.5 mm in height, 160 mm in length, and 100 mm in width. The sensitive element used in the curvature sensor is the high strength FBG inscribed by femtosecond laser, the grating pitches are uniform, the overall