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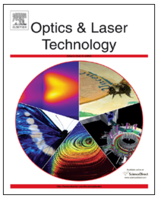

Sensing principle of fiber-optic curvature sensor

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ABSTRACT

A novel fiber-optic sensor, which can measure curvature directly, has been developed in recent years. Its curvature measurement sensitivity is improved by a sensitive zone. To better understand the working principle and improve the performance of the sensor, the ray tracing simulation was carried out by using optical analysis software TracePro, which provides the sensing process for us. The results show that the rays will concentrate to the convex side of bent fiber. That is, the light intensity will increase at convex side and decrease at concave side, which leads to the changes of light leakage at sensitive zone and realizes the modulation to light intensity. The mathematic model of relationship among light loss, parameters of sensitive zone's configuration and bending curvature is presented.

1. Introduction

Although the term deflection curvature of loaded structures is very elementary in the field of strength of materials, this quantity has largely had a theoretical significance only since it is hard to be measured in practice. The material strain and deformation curvature are functionally related quantities and the latter quantity can usually be inferred from the former. The material strain can be measured by numerous devices. However, there are some disadvantages in traditional strain measurement. For example, the strain magnitude decreases with the decreasing of structural thickness for a fixed amount of structural deformation. This implicates that for any strain sensor, however sophisticated, a 'break-even thickness' exists so that the curvature sensor will provide more sensitivity with structures thinner than that [1,2].

In contrast, curvature measurement is position independent across a given structural cross-section. Even along the neutral plane where the strain is zero, the curvature of structural deformation can also be measured [3]. However, the sensors that can measure curvature are rare. An inexpensive conductive ink sensor can detect the curvature, but its measurement range is very narrow, from 0.01 mm^{-1} to 0.1 mm^{-1}[4]. The wavelength-shift technique used by long-period fiber grating and light interferometric technique used by multi-core fiber can also be used to measure the bending deformation [5–7], but these systems are complex and require expensive spectrometers. Based on the principle that the light transmission loss will increase suddenly under big curvature, a fiber-optic sensor is proposed to monitor respiratory chest circumference [8–10]. Because the fiber is untreated, the sensitivity of this sensor is low and it cannot distinguish the bending direction.

With the introduction of the curvature fiber-optic sensor reported recently [11,12], measurement of structural deformation curvature has become easier and more practicable. It is a fiber-optic, intensity-modulated curvature sensor. By different mechanical configuration of curvature fiber-optic sensor, many physical quantities, such as strain, torsion and position, can be calculated from the deflection-curvature measurements [12–14].

2. Structure of fiber-optic curvature sensor

The sensitivity of untreated optical fibers is insufficient to detect the deformation of structures in bending. In order to increase the fiber's sensitivity to curvature, a sensitive zone is introduced on one side of the fiber by precision machining. The cutout produced removes a part of the fiber core and introduces a loss of light propagating along (called "sensitive zone"), as shown in Fig. 1 [15].

The sensor is a light intensity modulation fiber-optic sensor and has following characteristics [16]:

- It can directly measure curvature of structure and is only sensitive to curvature changes instead of stress and temperature.
- It demonstrates polarity. It can distinguish positive bending (sensitive zone is on the convex side) and negative bending (sensitive zone is on the concave side). Positive bending decreases the throughput of light, and is distinguishable from negative bending, which increases the throughput.

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- It is small in size, simple in structure and low in cost. It is very easily made by multi-mode plastic optical fiber, and the detection equipments are very simple.

3. Sensing principle

3.1. Ray-tracing model of bent fiber

In order to understand the sensing principle of fiber-optic curvature sensor, ray-tracing is carried out to simulate the light propagation in fiber. In this work, optical simulation software *TracePro* is used to realize the ray-tracing simulation. Figs. 2–4 show the ray-tracing situations in straight and bent fibers respectively. Y–Z and Y–X are global orthogonal coordinate systems and X–Z is a moving coordinate system that moves with the fiber cross section center. In moving coordinate system X–Z, the orientation of the X axis is coincides with the global X axis and the orientation of the Z axis rotates, pointing from the convex side to the concave side of the fiber.

In Figs. 2–4, the diameter of the fiber is 0.25 mm and the cladding thickness is 0.01 mm. Fig. 2(a) and (b) shows the ray propagation in 6 mm and 100 mm long straight fiber respectively. It is shown from Fig. 2 that the ray propagation path in the straight fiber is well-distributed. In Fig. 3, three total reflections occur in straight segment AB and five total reflections occurred in bent segment BC. From moving coordinate system X–Z in Fig. 3, it is shown that the ray propagation path (ray propagation path no. 1–3) in the straight fiber segment is well-distributed and the disproportionately many reflections (ray propagation path no. 4–9) occur in the bent fiber segment. The ray propagation path concentrates to the convex side of bent fiber. The number of reflections is increased in the convex side and reduced in concave side (there are none in this example). As a consequence, the light intensity will increase at convex side and decrease at concave side. If the "sensitive zone" of the bent fiber is on its convex side (positive bending), a greater number of individual rays will escape relative to the situation when the fiber is straight, and is distinguishable from negative bending (the "sensitive zone" of the bent fiber is on its concave side), which reduce these losses.

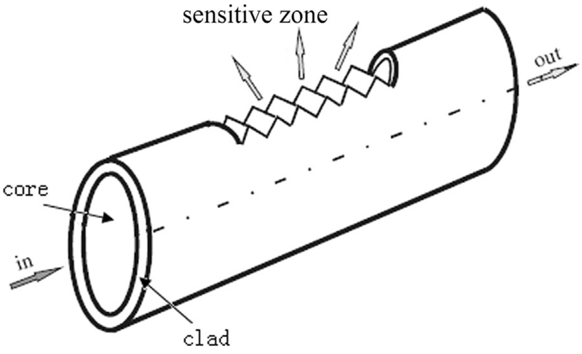

Fig. 1. A fiber with a sensitive zone [1].

Fig. 3 is a situation of large curvature, in which all rays would traverse almost exclusively only the convex side of the fiber. Fig. 4 shows a situation of small curvature. The bent radius is 2000 mm, which is 16,000 times fiber radius itself, so we give a partial enlargement figure of bent fiber. The ray propagation also shows a concentration to the convex side of fiber with big bent radius. However, the convex concentration feature of big radius is weaker than that of small radius. This is why the more rays will escape from "sensitive zone" in smaller bent radius when positive bending, and the less rays will escape from "sensitive zone" when negative bending.

To better understand this convex concentration feature of bent fiber, light intensity distribution across the bent fiber section map (irradiance map) is given in Fig. 5. It shows that the light intensity of convex side is higher than that of concave side, which agrees with the above analysis.

3.2. The mathematical modeling

Fig. 6 shows a bent fiber. The radius of optical fiber is R, and the angle between beam L and the axis of fiber is θ. Beam L enters bent section at point C with an angle φ. The aperture angle θ_b of bent fiber is given by [17]

$$\sin\ \theta_b = [n_{co}^2 - n_{cl}^2 (R+a)^2/(R+h_1)^2]^{1/2}/n_0 \tag{1}$$

where a is the radius of fiber core, n_{co} is the refractive index of fiber core, n_{cl} is the refractive index of fiber cladding, n_0 is the

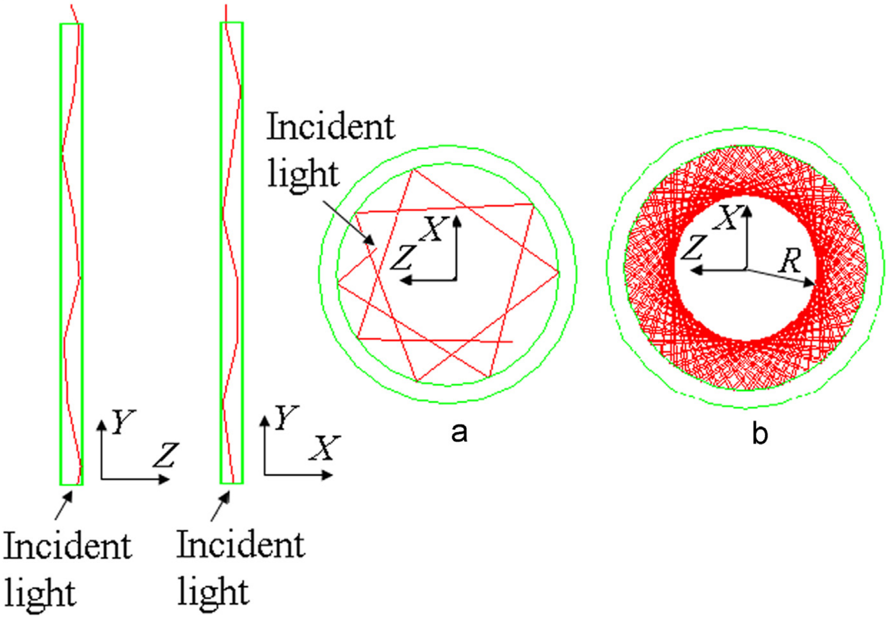

Fig. 2. Light propagation in a straight fiber. (a) Fiber length is 6 mm and (b) fiber length is 100 mm.