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Fiber-Bragg-grating-based ultrathin shape sensors displaying single-channel sweeping for minimally invasive surgery

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ABSTRACT

We report on the development of a highly flexible, thin shape sensor that can be integrated into minimally invasive surgery systems. Three optical fibers are arranged in a triangular shape and epoxy molded to produce a sensor diameter of less than 900 μm, ensuring high-bending operation up to 90°. Each fiber contains four fiber Bragg gratings (FBGs) operating at different wavelengths. With simultaneous detection of all the grating signals, the overall curvatures and torsions are interpolated and used for three-dimensional shape reconstruction. Three FBGs located at the same axial location also enables temperature compensation. Real-time shape monitoring with a sampling rate of 3.74 Hz is realized. The average tip position error was 1.50% of the total sensor length.

1. Introduction

Accurate estimation of the position or shape of surgical equipment in the human body is a critical factor for successful minimally invasive surgery. This is usually achieved with external imaging devices, but these can be expensive, bulky, and real-time imaging is often not possible. Furthermore, the large image sensors employed in charge-coupled device cameras for endoscopy place limitations on the invasive surgery [1].

The thin, light, flexible nature of optical fibers offers an alternative imaging system for endoscopic and invasive surgery systems, with the added advantage of being unaffected by the electromagnetic fields of essential external devices used during surgery [2]. The fiber Bragg grating (FBG), in particular, is extremely sensitive to axial strain, which enables accurate bending measurements [3–5]. Single or two-axis FBG operation has been reported to be capable of curvature measurements at a single point [6–10], but there have been few reports of overall shape sensing using distributed FBGs [11]. Metal beams are normally employed for bending sensors; however, a three-dimensional (3D) bending sensor attached to a metal beam has been reported to only be able to measure a tip displacement larger than 10% of the total length [12] because the bending beam theory used for the shape reconstruction is only applicable to small displacements. The Young's modulus of the metal also limits the amount of bending. Quite recently, multicore fiber (MCF)-based sensors for overall shape measurements were proposed by Moore and Rogge [13]. A high bending performance and a minimized sensor cross-section were obtained, although (i) the interference pattern of the ultraviolet light for refractive index perturbation would be out of focus because of the different locations of each core [8], (ii) coupling of the light into each core is difficult, and (iii) MCFs are usually fabricated directly in a draw tower, which makes them expensive and not easily accessible [14]. Moreover, and importantly, the FBGs, which are located at the same longitudinal position, have the same center wavelength, preventing simultaneous signal detection from all the fibers.

In this article, we demonstrate a 3D shape sensor using FBG arrays in three fiber strands embedded in an epoxy to give an overall diameter of less than 900 μm. The radius and flexibility of the host material guarantees high-bending operation up to 90°, and with facilitated and robust light in-and-out coupling, as well as simultaneous detection of all the FBGs, the design overcomes the drawbacks of MCF-based FBG sensors. Our thin sensor can be integrated into tools for minimally invasive surgery such as an active cannula to detect the location of the tip and overall shape of the tool. Real-time shape monitoring with a sampling rate of 3.74 Hz is achieved, and the average tip position error is 1.50% of the total sensor length.

2. Principles

The sensor consists of 12 FBGs in three optical fibers that have different center wavelengths (Fig. 1(a)). The peak wavelength λ_B of

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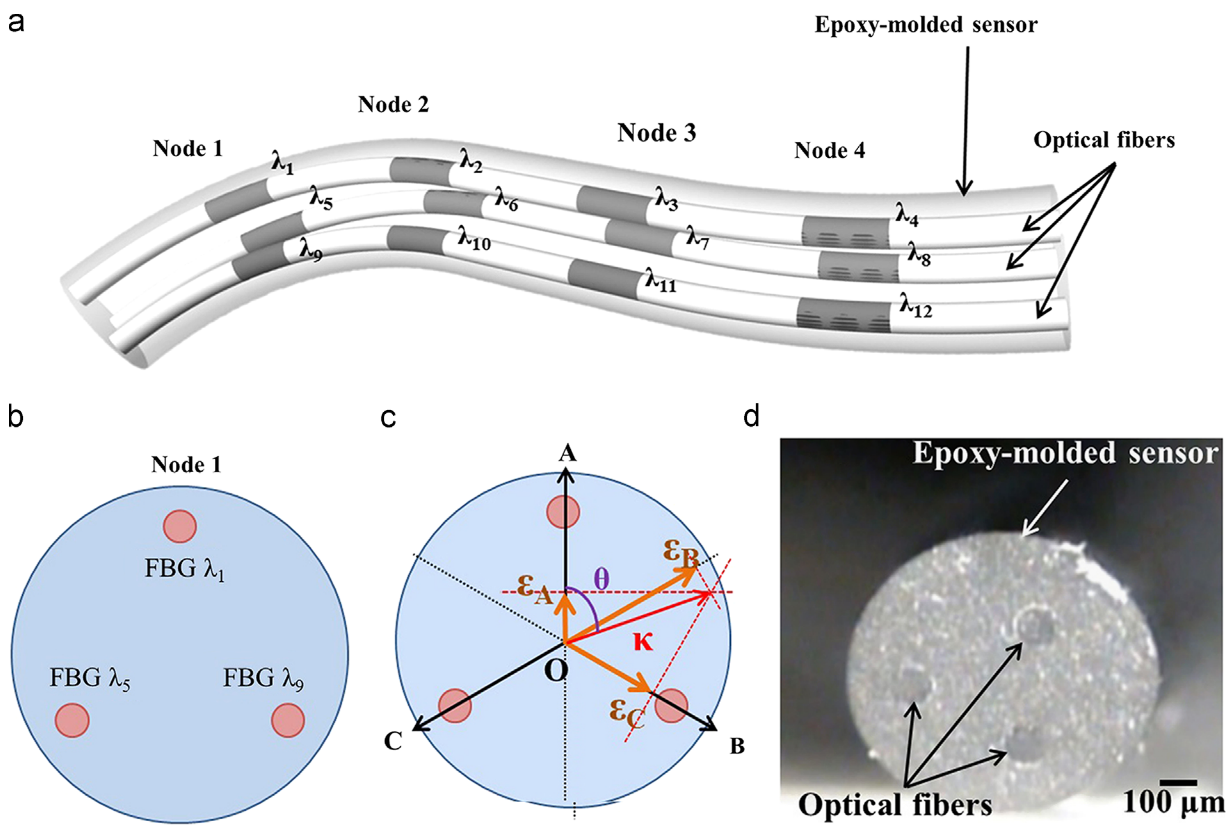

Fig. 1. (a) Three-dimensional view of the FBG shape sensor with multiple nodes and FBGs. (b) Cross-sectional diagram of the fabricated sensor. (c) Curvature and bending direction calculation based on the measured strain data. (d) Cross section of the fabricated shape sensor.

an FBG is determined by the periodic pitch size Λ: $\lambda_B=2n\Lambda$, where n is the refractive index of the optical fiber core. The change of the λ_B due to strain and temperature change can be written as $\Delta\lambda_B=2(\Lambda\ \partial n/\partial l+n\ \partial\Lambda/\partial l)\Delta l+2(\Lambda\ \partial n/\partial T+n\ \partial\Lambda/\partial T)\Delta T$, where the first term is the strain effect and the second term is the temperature effect. The first term can be represented as $\Delta\lambda_B=\lambda_B(1-n^2/2[p_{12}-\nu(p_{11}-p_{12})])\varepsilon$, where ε is an axial strain, p_{11} and p_{12} are components of the strain-optic tensor and ν is the Poisson's ratio [2,15]. The second term can be expressed as $\Delta\lambda_B=\lambda_B(\alpha+\zeta)\Delta T$, where $\alpha=(1/\Lambda)(\partial\Lambda/\partial T)$ is the thermal expansion coefficient and $\zeta=(1/n)(\partial n/\partial T)$ is the thermo-optic coefficient for the core of the optical fiber [2,15]. The refractive index change due to the temperature change does not affect to the strain effect because $\zeta \ll 1$ [15], and thus $\Delta\lambda_B$ is proportional to the strain and temperature change, respectively. If multiple FBGs are located in the same transverse plane (Fig. 1(b)), then the bending direction θ and curvature κ at a certain position can be extracted. We assume here that the nodes in all three FBGs are at the same temperature. When the sensor is bent, the strain along the neutral axis, which passes through the center of the sensor (O), is always zero. Let ε_A, ε_B, and ε_C be the constants of proportionality between $\Delta\lambda_B$ and λ_B in the three FBGs at the same node (Fig. 1(c)). Then, $\varepsilon_A=\kappa d\cos\theta+(\alpha+\zeta)\Delta T$, $\varepsilon_B=\kappa d\cos(\theta-2\pi/3)+(\alpha+\zeta)\Delta T$, and $\varepsilon_C=\kappa d\cos(\theta+2\pi/3)+(\alpha+\zeta)\Delta T$, where d is the distance between the center (O) and each sensor. The bending direction, curvature, and temperature change are

$$\kappa=\sqrt{\left(\frac{2\varepsilon_A-\varepsilon_B-\varepsilon_C}{3d}\right)^2+\left(\frac{\varepsilon_B-\varepsilon_C}{\sqrt{3}d}\right)^2},\ \theta=\tan^{-1}\left(\frac{\sqrt{3}(\varepsilon_B-\varepsilon_C)}{2\varepsilon_A-\varepsilon_B-\varepsilon_C}\right),$$

and $\Delta T=\dfrac{1}{3(\alpha+\zeta)}(\varepsilon_A+\varepsilon_B+\varepsilon_C)$.

To calculate the shape of the sensor, a cubic spline method was adopted to interpolate between the θ and κ values at each of the 500 points along the length of the sensor. The torsion τ, which is the first derivative of θ, is used in the Frenet–Serret formulas [16] as $\mathbf{T}'(s)=\kappa\mathbf{N}(s)$, $\mathbf{N}'(s)=-\kappa\mathbf{T}(s)+\tau\mathbf{B}(s)$, and $\mathbf{B}'(s)=-\tau\mathbf{N}(s)$, where $\mathbf{T}(s)$ is the tangential unit vector, $\mathbf{N}(s)$ is the normal unit vector, and $\mathbf{B}(s)$ is the binormal unit vector to the curve that defines the shape of the sensor parameterized by the arc length s. If we let $\mathbf{r}(t)$ be the position vector of a particle that moves along the curve in 3D space as a function of time t, then we can write $s(t)=\int_0^t ||r'(\sigma)||d\sigma$ and $\mathbf{T}=d\mathbf{r}/ds$. Thus, the 3D position vector $\mathbf{r}$ of the sensor can be calculated by integrating $\mathbf{T}$ when the curvature and torsion at one end of the sensor (defined as the origin) are zero. The curvature and torsion are used to reconstruct the sensor shape using the finite element method (FEM), and the calculated tip position is compared to the position measured by a camera. The number of points for the calculation was selected to be as high as possible without imposing an unreasonable increase in the calculation time.

3. Fabrication

Although the optical fibers are flexible, the fibers themselves cannot be used as strain sensors because the center of the fiber is not affected by bending strain. Thus, the fiber cores are offset from the neutral axis of the bending (Fig. 1(d)) using a cured epoxy. The epoxy molding was performed with a polytetrafluoroethylene (PTFE), which allows both easy separation of the epoxy and the fabrication of submillimeter diameter sensors. To keep the thin PTFE tubes straight during curing, we constructed the tube fixation jig shown in Fig. 2. The upper and lower jigs have semi-circular grooves with a length of 150 mm and a diameter that is exactly the