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Contact force sensor based on microfiber Bragg grating

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Abstract: We demonstrate a miniature contact force sensor based on a 30-µm diameter microfiber Bragg grating packaged with a conforming elastomer material features extremely high sensitivity up to 0.8-mN to contract force.

OCIS codes: (060.3735) Fiber Bragg gratings; (060. 2370) Fiber optics sensors; (230. 4000) Microstructure fabrication.

1. Introduction

Fiber Bragg gratings (FBGs) are emerging as an important sensing technology in a wide variety of applications due to their many advantages such as simplicity and flexibility over other kinds of optical fibers. FBGs are commonly employed as strain and temperature sensors. They can be used as force sensors by transferring the applied force to strain [1-6]. FBG-based force sensors are generally based on the conversion of applied force to strain by utilizing some mechanical transducers. Some designs also feature temperature insensitivity by referencing only optical power as a means to detect force [3,4] or by using two FBG for self-compensation [5] or by applying Fourier analysis to cladding modes losses of the transmission spectrum of a tilted FBG embedded into an elastomer material to extract the sensing signals [6].

There are many applications that require miniaturized force sensors with high sensitivity to measure contact force, especially in medical applications. One such application is in cardiac catheterization where it is important for physicians to know the contact force between the catheters and blood vessel walls in order to avoid damaging the delicate blood vessel networks of the patient during an interventional procedure.

Panagiotis et al reviewed the fiber-optic force sensors for catheterization procedures [7]. The main reasons that fiber-optics sensors are promising candidates are their compact in size, easily manufacturable, potentially low cost, biocompatible and ability to tolerate sterilization procedures. They also revealed that among all the fiber-optics force sensors, sensors based on FBGs are, up to now, the best technology that features all the criteria of miniaturized size (including packages), good sensitivity to minimal touch, high resolution, linear behavior, low hysteresis and most importantly magnetic resonance imaging (MRI) compatibility.

A force sensor based on FBGs was reported for this purpose in 2008 [8]. The force sensor was designed for measuring contact force and integrated with a 7-Fr (equivalent to 2.2-mm) diameter cardiac catheter which was developed by Endosense SA in collaboration with Stanford University and is called TactiCath™. The operation principle of the sensor relies on the deformation of the optical fiber and induced strains to the three FBGs which were held by a deformable elastic polymer material. Whenever a force is applied to the sensor, the flexible inner body is deformed in a micrometer scale and results in stretching or compressing of the FBGs. By monitoring the wavelength shifts of three FBGs arranged at 120° to each other in a circle, the magnitude and position of the applied force can be determined.

FBG-based force sensors are promising candidates for minimally invasive medical (MIS) devices. Wieduwilt et al proposed to use an FBG written in small diameter optical fiber [9] to enhance its force sensitivity and demonstrated experimentally that the sensitivity scales inversely with the fiber cross-sectional area.

In this paper, we propose and experimentally demonstrate a force sensor based on a 30-µm diameter microfiber Bragg grating (MFBG) embedded in a package suitable for use in MIS devices. The enhanced sensitivity of the 30-µm diameter FBG is sufficient for such application and at the same time not too small to handle. The guiding mechanism of the microfiber to ensure the force sensor has a linear force-to-wavelength conversion characteristics is reported. The proposed miniaturized force sensor is potentially useful to provide real time contact force sensor in catheters.

2. Principle

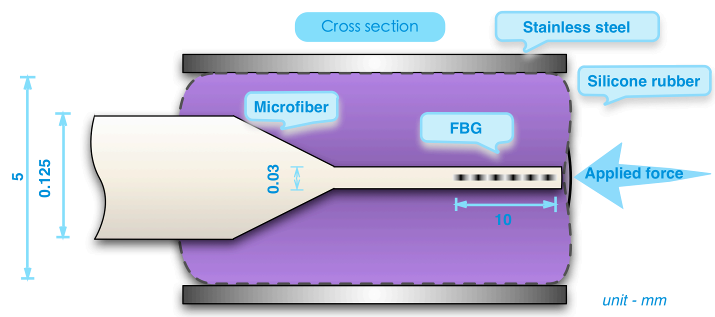

Fig. 1. Schematic diagram of the force sensor based on a microfiber Bragg grating

Figure 1 shows the schematic diagram of the MFBG-based sensor to illustrate how it operates as a force sensor. A 30-µm diameter microfiber was embedded into the center of a silicone rubber, an elastomer material which was then placed inside a non-magnetized stainless steel tube. An FBG located at the end of the microfiber when come in contact with an object such as blood vessels will be compressed, resulting in a shift in the FBG's reflection wavelength. The other end of the microfiber is a standard single-mode fiber with a diameter of 125-µm, is connected to an FBG interrogator (Micron Optic Inc., model SM130). Whenever a small force is applied to the sensor, the silicone rubber together with the grating is slightly compressed in the axial direction because the stainless tube restricts the side-way movement of the silicone rubber. Consequently, the compressive strain induced to the FBG is linearly proportional to the applied force. Once calibrated, the contact force can be determined by monitoring the reflected wavelength of the MFBG. The Bragg wavelength λ_B is given by the expression:

$$\lambda_B = 2n_{eff}\Lambda, \tag{1}$$

where n_{eff} and Λ are the effective refractive index and the pitch of the MFBG. λ_B is proportional to n_{eff} and Λ. When the grating is under compressive strain, these two parameters are changed. The change of Λ is due to physically shortening the length of the grating and the change in microfiber's refractive index is due to photoelastic effect. The relationship of the wavelength shift and axial strain can be expressed as:

$$\frac{\Delta\lambda}{\lambda_B} = (1 - P_e)\varepsilon_{ax}, \tag{2}$$

where P_e is the constant of optic-strain coefficient and ε_{ax} is the axial strain. The proposed sensor has a linear response to compressive strain induced to the grating within the operation range. Ignoring the temperature effect, the shift of reflected wavelength can be simplified to:

$$\Delta\lambda = -\alpha F, \tag{3}$$

where F is the applied force in the linear region and α is the sensitivity to the applied axial force. The sensitivity was found to be ~1.35-nmN^{-1} in this work.

2. Fabrication of the contact force sensor

The microfiber was fabricated by tapering a standard single-mode optical fiber. The fiber was fed into a heating filament and pulled from one end using a glass-processing machine (Vytran's GPX-3400). The fabrication parameters for making the 30-µm fiber taper were as follows: pulling velocity = 1-mm/s, input power to filament = 29-W, feeding speed at pulling the waist = 57.6-µm/s, and taper and waist lengths are all 20-mm. The taper length of the microfiber was long enough to effectively re-couple only the fundamental mode back to the single mode fiber. The 10-mm long apodized FBG was fabricated using standard phase mask technique with a 1061.5-nm pitch phase mask. The apodized FBG was accomplished by scanning with a hamming apodization profile.

Silicone rubber (Rhodorsil RTV-573) was used as the deformable elastomer and put inside a 0.5-mm thick stainless steel tube with a square cross-section of 5 mm x 5 mm was used to restrict the deformation of the microfiber in the axial direction for a small contact force. Consequently, linear contact force-to-wavelength conversion in the MFBG can be obtained. The Rhodorsil RTV-573 is a low viscosity liquid silicone that cured at room temperature by adding a curing agent to a strong flexible silicone rubber. The liquid silicone with 2% weighted catalyst was first filled into a stainless steel mold. After 24-hour, the silicone turned into a solid form. The MFBG was aligned in the center of the tube, with the aid of two fiber holders

3. Experiments and discussion

Figure 2 (a) shows the experiment results of the measurement of contact forces. The reflected wavelength was measured by the FBG interrogator with a resolution of 1-pm. It is clear that the wavelength shift against contact force was linear up to 0.9-N. Exceeding that amount of force, the sensor start to buckle. The sensitivity, maximum and minimum forces of this sensor measured in the linear region were -1.3-nmN^{-1}, 0.9-N and 0.8-mN, respectively. It is experimentally demonstrated that the sensor is fairly linear with R^2 of 0.99646.

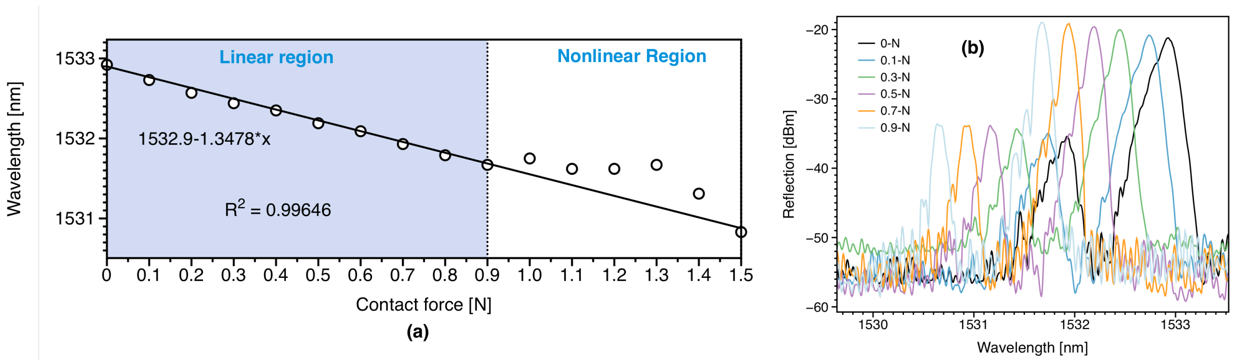

Fig. 2(a). Experimental result of the measurement of contact forces. The solid black line shows the linear fit of the data points up to 0.9-N. (b) Reflection spectra of the force sensor with different axial contact forces.

Figure 2 (b) shows the reflection spectra of the force sensors with different contact forces measured with another interrogator with model SM125. The side peak located at shorter wavelength was a consequence that the LP_{02} excited by the MFBG was re-coupled to the core via the taper. The taper length (20-mm) was designed to couple most of the power of the LP_{02} mode into the cladding and eventually lost. Its reflection power was slightly stronger after packaging because of the higher value of the refractive index of the silicone rubber. However, the reflection of the side peak is less than 10% of the main peak. Therefore, the force sensor effectively returned a single peak information. It was recognizable that the spectrum shape was shaper with larger applied force. As it was due to the differential strain profile along the grating, it implied that the differential strain field along the grating was getting more uniform with higher axial contact force. It was possibly that the air bubbles formed during the de-gassing phase was compressed.

4. Conclusion

A novel miniaturized high-performed force sensor based on a MFBG packaged with silicone rubber and tube is experimentally reported. The operation principle and fabrication of the contact force sensor are demonstrated. The force sensor is characterized by the force testing and the spectra under different contact forces are studied. We believe that the contact force sensor be a promising device to provide real time contact force sensor in catheters.

5. Reference

[1] Y. Yu, H.Y. Tam, W. Chung, and M. S. Demokan, "Fiber Bragg grating sensor for simultaneous measurement of displacement and temperature," Opt. Lett., OL **25**, 1141 (2000).
[2] Z. Weigang, D. Xiaoyi, Z. Qida, K. Guiyun, and Y. Shuzhong, "FBG-type sensor for simultaneous measurement of force (or displacement) and temperature based on bilateral cantilever beam," IEEE Photon. Technol. Lett. 13, 1340–1342 (2001).
[3] T. Guo, Q. Zhao, H. Zhang, L. Xue, G. Li, B. Dong, B. Liu, W. Zhang, G. Kai, and X. Dong, "Temperature-Insensitive Fiber Bragg Grating Force Sensor via a Bandwidth Modulation and Optical-Power Detection Technique," J. Lightwave Technol. **24**, 3797–3802 (2006).
[4] L. Hu, X. Dong, C. Zhao, S. Zhang, and S. Jin, "Temperature-insensitive Load Sensor with a single Fiber Bragg Grating," Proc. of SPIE **7853**, 78532W (2010).
[5] Lifang Xue, Z. Qida, Jianguo Liu, Guiling Huang, G. Tuan, and D. Xiaoyi, "Force sensing with temperature self-compensated based on a loop thin-wall section beam," Photonics Technology Letters, IEEE **18**, 271–273 (2006).
[6] L.-Y. Shao, Q. Jiang, and J. Albert, "Fiber optic pressure sensing with conforming elastomers," Appl. Opt. **49**, 6784–6788 (2010).
[7] P. Polygerinos, D. Zbyszewski, T. Schaeffter, R. Razavi, L. D. Seneviratne, and K. Althoefer, "MRI-Compatible Fiber-Optic Force Sensors for Catheterization Procedures," Ieee Sens J **10**, 1598–1608 (2010).
[8] K. Yokoyama, H. Nakagawa, D. C. Shah, H. Lambert, G. Leo, N. Aeby, A. Ikeda, J. V. Pitha, T. Sharma, R. Lazzara, and W. M. Jackman, "Novel Contact Force Sensor Incorporated in Irrigated Radiofrequency Ablation Catheter Predicts Lesion Size and Incidence of Steam Pop and Thrombus," Circ-Arrhythmia Elec **1**, 354–362 (2008).
[9] T. Wieduwilt, S. Brückner, and H. Bartelt, "High force measurement sensitivity with fiber Bragg gratings fabricated in uniform-waist fiber tapers," Meas Sci Technol **22**, 075201 (2011).