Measurement 117 (2018) 252–257

Contents lists available at ScienceDirect

Measurement

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

A sensitivity-enhanced flexible acoustic sensor using side-polished fiber Bragg grating

Cheng Li[a,b,*], Xiaobin Peng[a], Hui Zhang[a], Chao Wang[c,*], Shangchun Fan[a], Shaoqing Cao[d]

[a] School of Instrumentation Science and Opto-electronics Engineering, Beihang University, Beijing 100191, China
[b] Science and Technology on Metrology and Calibration Laboratory, Beijing 100095, China
[c] School of Electrical Engineering, Wuhan University, Wuhan 430072, China
[d] Key Laboratory of Optoelectronic Devices and Systems of Ministry of Education, Shenzhen University, Shenzhen 518060, China

ARTICLE INFO

Keywords:
Side-polished fiber
Fiber Bragg grating
Acoustic pressure sensor
Strain interaction
Sensitivity enhancement

ABSTRACT

A miniature flexible fiber Bragg grating (FBG) acoustic sensor with enhanced pressure sensitivity was fabricated by using a side-polished configuration of ~54 μm depth and ~15 mm length. The photoelectromechanical response of the sensor suspended as a dual-end-fixed beam was characterized based on the acoustic-induced strain interaction with fiber gratings. The opto-mechanical response of the sensor to bending strain was firstly investigated and exhibited about 11 times larger in wavelength shift, in comparison with a conventional bare FBG. Then acoustic testing demonstrated an acoustic pressure-induced wavelength shift of 0.041 nm/Pa and a noise equivalent acoustic signal level of ~1.66 mPa/$Hz^{1/2}$ in the frequency region around 2.5 kHz. Also, a relative flat frequency response with a fluctuation of less than 12.9 dB was achieved in the measurement between 400 Hz and 20 kHz, which is in well agreement with the result obtained by a reference condenser microphone. Along with strain-sensitive nanomaterials, the use of the side-polished FBG could be further extended for highly sensitive acousto-ultrasonic sensors in structural health monitoring and wearable applications.

1. Introduction

Sound pressure is a most common measurement whether in the air or water, typically having amplitudes on the order of mPa (10^{-8} bar) [1]. In recent years, compared with common piezoelectric or capacitive condenser microphones, miniature optical fiber acoustic pressure sensors have attracted much interest due to their advantages over conventional sensors, such as immunity to electromagnetic interference, high resolution, fast response and compact size [2]. The vast majority of sensing methods and techniques currently available in the literature has been demonstrated. Among them, the list of available localized fiber optic acoustic sensors is primarily limited to the intrinsic and the extrinsic Fabry-Perot (F-P) interferometers that utilize different types of elastic materials as a pressure-sensitive diaphragm, such as metal [3], SiO_2/silica [4], polymer [5], silver [6], graphene [7,8] and MoS_2 membrane [9] in order to improve the sensitivity of F-P pressure sensors. In spite of high-sensitivity detection at a single location, the complicated and meticulous process of membrane fabrication and substrate transferring is inevitable. Also, it is very difficult to multiplex these sensors due to high insertion losses introduced by the F-P cavity formed inside the fiber [10].

Fiber Bragg grating (FBG) acoustic sensors can offer a potentially valuable alternative to F-P acoustic sensors, because of easy construction without need of time-consuming fabrication and transferring of sensitive diaphragm, simultaneous measurement of several parameters and being facilely embedded into composite structures, especially for the case of multiplexed operation [10,11]. Furthermore, so far a number of FBG-based pressure or hydrophone sensors have been demonstrated [12–17]. Note that a FBG pressure sensor typically senses the acoustic field change in terms of the intensity modulation of the laser light due to the shift of transmission power spectrum curve of the sensing element for an applied strain along the fiber axes. However, research on pressure sensors conducted earlier showed low pressure sensitivities of 6.28×10^{-5} MPa to 1.8×10^{-2} MPa in fractional change of Bragg wavelength [18]. The low sensitivity to acoustic pressure of the FBG based sensors limits their practical applications, which mainly results from the high Young module of the optical fiber material (72 GPa [19]) that converts the effects of a high pressures applied on the grating in weak deformations [15]. An effective strategy proposed by Hocker [20,21] to overcome this limitation was to deposit low-elastic modulus ring-shaped coatings, such as silicone rubber, to increase hydrostatic pressure responsivities, which revealed that fiber-

* Corresponding authors at: School of Instrumentation Science and Opto-electronics Engineering, Beihang University, Beijing 100191, China (C. Li).
E-mail addresses: licheng@buaa.edu.cn (C. Li), eecwang@whu.edu.cn (C. Wang).

https://doi.org/10.1016/j.measurement.2017.12.027
Received 11 July 2017; Received in revised form 31 August 2017; Accepted 19 December 2017
Available online 19 December 2017

optic acoustic sensors utilizing a composite structure made of a material of lower elastic modulus demonstrated a sensitivity of nearly 2 orders of magnitude greater than that of sensors using bare fiber. Liu et al. further reported a polycarbonate-coated FBG with an increased static pressure sensitivity of $-6.25 \times 10^{-5}\,\mathrm{MPa}^{-1}$, compared to a typical bare FBG [22]. Then M. Moccia et al. fabricated two ring-shaped FBG hydrophones coated with Damival® E 13650 (a polyurethane resin) and Araldite® DBF (an epoxy adhesive resin) materials, respectively [16,23], wherein preliminary experimental studies indicated that a minimum detectable acoustic signal of about $10\,\mathrm{mPa/Hz}^{1/2}$ within the frequency range 4–35 kHz was achieved. However, the gain sensitivity versus acoustic frequency depends on the coating features in terms of size, thickness and materials properties, generally involving specific or complicated sample tests to enable the materials coated on the grating region evenly in thickness. Another viable alternative to enhance the sensitivity is to mechanically weaken the guiding properties of optical fiber. Compared with the methods including tapering, chemical etching and insertion of imperfections, the side-polished fiber (SPF) fabricated by grinding can offer a simpler implementation because the mechanical resistance of the fiber allows an easy removal of a portion of the jacket, cladding and core [24]. More importantly, since the fiber core in a SPF (or D-shaped fiber) is asymmetrically located relatively to the geometrical center of the cross-section of the cladding, FBGs written in SPF fibers present an intrinsic sensitivity to curvature, i.e., a characteristic that does not occur with FBGs written in standard fibers [25]. Therefore, the potential of side-polished FBG sensors for detecting mechanical parameters, such as strain, magnetic field, refractive index (RI), and chemical and biomedical parameters is currently becoming widely acknowledged [25–29]; however the change in RI of the surrounding medium is principally focused on to investigate the evanescent field interaction with fiber gratings that are coated with various sensitive synthetic inorganic materials.

Herein, from the perspective of dynamic acoustic pressure performance, we report a simple, flexible and compact side-polished FBG acoustic sensor without external coatings or membranes, suspended across two fixed supports as a dual-end-fixed beam, with a D-shaped polished zone of $\sim 54\,\mu\mathrm{m}$ depth and $\sim 15\,\mathrm{mm}$ length. Simple bending strain test using plastic circular cylinders with various curvatures is firstly performed to characterize the developed sensor, which exhibits about 11 times larger wavelength shift with greater amplitude due to the more sensitive strain-induced interaction with fiber gratings. Then acoustic pressure test in an anechoic chamber reveals an enhanced pressure sensitivity of 0.041 nm/Pa or $0.26 \times 10^{-4}\,\mathrm{Pa}^{-1}$ in fractional change of Bragg wavelength, by far superior to the FBG-based pressure sensors previously ever reported to our knowledge. Furthermore, the intrinsic advantages of multiplexing and multi-parameter simultaneous measurement could significantly extend the applicability of the presented method, such as acousto-ultrasonic hydrophones and structural health detections.

2. Sensor fabrication and measurement principle

Fig. 1 shows the schematic view of the presented sensor. A commercial FBG (a grating length of 10 mm) with a central wavelength of 1550 nm and a full-width at half maximum bandwidth of 0.32 nm was side-polished by using rough and then fine grinding to the fiber core. The used wheel side-polishing operation is similar to Ref. [30], which enables light leak from the fiber core to the polished surface. Note that the side-polished FBG is fabricated on a side-polishing system (Wan Run Ltd., Wuxi, China). In the first step of the process, the pre-marked FBG region in the fiber will be carefully adjusted to the polishing region of the system. The fiber is then fixed by the holders and tautened by the straight force from the weight. After that, the cylinder grinding wheel is moved from the safety position to the polishing position following a computer-controlled trajectory. The length and the surface roughness of sample is controlled, respectively, by the scanning range of the wheel along the axial direction of the fiber and the granular size of the parabrasive paper which is attached on the surface of cylinder grinding wheel. In this way, the cross section of the polished D-shaped fiber is shown in the inset in Fig. 1(a), where the polished fiber thickness is $\sim 54\,\mu\mathrm{m}$. Moreover, the length of the flat region is $\sim 15\,\mathrm{mm}$ slightly larger than the grating length of $\sim 10\,\mathrm{mm}$. The surface roughness after polishing can be better than $\sim 1\,\mu\mathrm{m}$ after fine polishing process with 12000# sand-paper. The residuals on polished surface can be cleaned by ultrasound equipment. Fig. 1(b) displays the micrograph of the polished surface after ultrasound cleaning. The side view of the polished FBG is given in Fig. 1(c) by a microscope camera (Mshot®, MS60). The sensor is supported at its two ends and fixed by adhesive to increase the response to strain induced by acoustic wave travelling from a loudspeaker positioned perpendicular to the gratings.

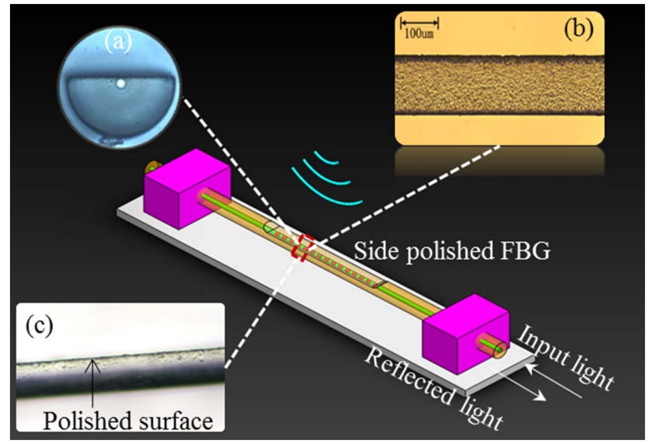

Fig. 1. Schematic illustration of the side-polished FBG acoustic sensor. (a) Cross section of the D-shaped fiber. (b) Micrograph of the polished surface. (c) Side view of the polished FBG.

According to the Bragg's principle, the Bragg wavelength λ_B that is reflected from a conventional FBG sensor is defined by

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

where Λ is the period of the index modulation and n_{eff} is the effective refractive index. Any variation in the two parameters will change the Bragg wavelength λ_B. Hence the side-polished FBG enables evanescent field interaction with its surrounding environment. For an isothermal condition, the Bragg wavelength change $\Delta\lambda_B$ in response to applied tensile strain ε_c can be simplified as [31]

$$\Delta\lambda_B = 2(n_{eff0} + n_\varepsilon)\Lambda_0\varepsilon_c, \tag{2}$$

where n_ε is the strain-dependence factor for the effective index mainly caused by the photoelastic effect; n_{eff0} and Λ_0 are respectively defined as the effective refractive index and index modulation corresponding to the straight fiber, namely, $\varepsilon_c = 0$.

In terms of the interrogation method using a narrow linewidth laser diode, any shift of the spectrum will as a consequence modulate the reflected optical power [32]. For instance, a tunable laser is used to perform the interrogation of several gratings within a single fiber line. On the basis of Bragg wavelength variations in response to the changes in axial strain-dependent curvature denoted by the symbol 'C' in Fig. 2, there exists a linear relation between the wavelength shift of reflected spectrum and the reflectivity of reflected and incident light power in the wavelength range of $\triangle\lambda_B$. Regarding a certain wavelength λ_B, the time-varying reflection of the grating can be defined by $\triangle I = K_\lambda \triangle\lambda_B$ as a function of the time-varying wavelength shift within the linear range, where the coefficient K_λ can be determined by measured spectrum's slope.

In fact, an applied periodic acoustic pressure, $P(t) = A_p\sin(\omega t + \varphi_p)$, will generate the alternating expansions and compressions of the fiber,