AIP | Applied Physics Letters

Ultra-highly sensitive surface-corrugated microfiber Bragg grating force sensor

Wei Luo, Jun-long Kou, Ye Chen, Fei Xu, and Yan-qing Lu

Citation: Appl. Phys. Lett. **101**, 133502 (2012); doi: 10.1063/1.4754838

View online: http://dx.doi.org/10.1063/1.4754838

View Table of Contents: http://apl.aip.org/resource/1/APPLAB/v101/i13

Published by the American Institute of Physics.

Related Articles

In-line Mach-Zehnder interferometer composed of microtaper and long-period grating in all-solid photonic bandgap fiber
Appl. Phys. Lett. 101, 141106 (2012)

Note: A resonant fiber-optic piezoelectric scanner achieves a raster pattern by combining two distinct resonances
Rev. Sci. Instrum. 83, 086102 (2012)

Lithium niobate nanoparticulate clad on the core of single mode optical fiber for temperature and magnetic field sensing
Appl. Phys. Lett. 101, 043102 (2012)

Simultaneous measurement of refractive index and temperature by integrating an external Fabry-Perot cavity with a fiber Bragg grating
Rev. Sci. Instrum. 83, 053113 (2012)

Multiplex and simultaneous measurement of displacement and temperature using tapered fiber and fiber Bragg grating
Rev. Sci. Instrum. 83, 053109 (2012)

Additional information on Appl. Phys. Lett.

Journal Homepage: http://apl.aip.org/

Journal Information: http://apl.aip.org/about/about_the_journal

Top downloads: http://apl.aip.org/features/most_downloaded

Information for Authors: http://apl.aip.org/authors

ADVERTISEMENT

AMERICAN PHYSICAL SOCIETY'S OPEN ACCESS JOURNAL

PRX

Committed to Excellence

Physical Review X
prx.aps.org

Downloaded 09 Oct 2012 to 180.209.2.100. Redistribution subject to AIP license or copyright; see http://apl.aip.org/about/rights_and_permissions

APPLIED PHYSICS LETTERS **101**, 133502 (2012)

Ultra-highly sensitive surface-corrugated microfiber Bragg grating force sensor

Wei Luo, Jun-long Kou, Ye Chen, Fei Xu,[a] and Yan-qing Lu[b]
National Laboratory of Solid State Microstructures and College of Engineering and Applied Sciences, Nanjing University, Nanjing 210093, People's Republic of China

(Received 3 August 2012; accepted 12 September 2012; published online 25 September 2012)

We experimentally demonstrate a microfiber Bragg grating force sensor with ultra-high sensitivity. The fiber Bragg grating (FBG) is inscribed in a microfiber tapered from standard non-photosensitive single-mode fiber by focused ion beam machining method, and has a compact size (~112 μm in length). Small diameter increases the force sensitivity of such grating when acting as a force-sensing element under tensile loads. We have demonstrated force sensitivity as high as ~3146 nm/N around the resonant wavelength of 1538 nm, which is three orders of magnitude larger than FBGs in untapered fibers. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4754838]

Fiber Bragg gratings (FBGs) are periodic variation in the refractive index (RI) along fiber length. Since their appearance in 1978,[1] FBGs have been widely used as sensing elements in many applications, owing to their unique advantages including simplicity, immunity to electromagnetic interference, light weight, and multiplexing capability. FBGs are usually employed as strain and temperature sensors. But, force sensing is also possible. A number of FBG-based force sensors have been proposed for different purposes such as catheterization procedures and other applications.[2–4] Most of them operate by monitoring the shift of Bragg wavelength caused by the applied force. The sensitivity of typical FBG force sensor found in literature is ~1 nm/N.[5] Using micro-electro-mechanical systems (MEMS) technology and high RI contrast materials; Reck *et al.* demonstrated a FBG force sensor with sensitivity of ~14 nm/N.[6] Nevertheless, the sensitivities of conventional FBG force sensors are still not high enough in some applications. Moreover, miniaturized FBGs with high sensitivities to measure force are required in many applications. One such application is in micro-mechanical systems where knowing the contact force between components is important to avoid the damage of the systems during operations. Standard FBGs are fabricated by exposing conventionally sized photosensitive fibers to an intense ultraviolet interference pattern that produces weak index modulation. Thus, the grating lengths are more than several millimeters, which greatly limits the compactness of the sensors.[7] An alternative solution to realize both smaller size and higher sensitivity is to reduce the fiber diameter.[8] According to the force sensing principle, as the FBG diameter decreases, the force sensitivity increases strongly. With the emergence of low-loss microfibers over the past decade, shorter and stronger FBGs have been possible, and thus can be used as force sensors with enhanced sensitivity.

Several techniques to inscribe microfiber gratings in non-photosensitive fibers have been proposed, such as wrapping microfibers around microstructured rods,[9] processing with CO_2 lasers,[10] femtosecond lasers,[11] and milling with a focused ion beam (FIB).[12–14] The first can be used to make compact FBGs but it needs extra polymer coating. The second and third techniques can only be used to write long period gratings or long high-order FBGs which means that the grating length is still long. Among these techniques, FIB milling is highly suited for nano-fabrication due to its small controllable spot size and strong RI modulation flexibility, which can efficiently shorten the grating length. Adopting this method, Liu *et al.*,[12] Ding,[14] and Kou *et al.*[13] from several different groups have inscribed short and strong FBGs on a microfiber or a tapered fiber probe. The length of the gratings are typically tens of micrometers to hundreds of micrometers with deep surface corrugations.

In this letter, we demonstrate a miniaturized FBG force sensor inscribed by FIB milling in a microfiber, which is tapered from a standard non-photosensitive single-mode fiber. This microfiber Bragg grating (MFBG) force sensor can measure small tensile forces with extraordinary precision, and the force sensitivity is ~3146 nm/N around the resonant wavelength of 1538 nm. The sensor is very compact with a length of several hundreds of microns, and can be further shortened by optimizing machining parameters.

Monitoring the shift in the Bragg wavelength λ_B caused by the measurand is a commonly used principle of FBG sensors. Below, we will concentrate on the mechanical effect alone, disregarding the temperature effect.

The Bragg condition of FBG can be written as

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

where the effective index n_{eff} is a function of radius r, core index n_c, cladding index n_{clad}, temperature T and strain ε, and the period Λ is a function of T and ε. When a longitudinal mechanical force is applied to FBG, both n_{eff} and Λ are changed, and $\Delta\lambda_B$ can be described by[15]

$$\begin{aligned}\Delta\lambda_B &= 2n_{eff}\Delta\Lambda + 2\Lambda\Delta n_{eff}\\ &= 2\Lambda n_{eff}\left\{1 - \frac{n_{eff}^2}{2}\left[p_{12} - \nu(p_{11}+p_{12})\right]\right\}\varepsilon,\end{aligned} \tag{2}$$

---

[a] Electronic mail: feixu@nju.edu.cn.
[b] Electronic mail: yqlu@nju.edu.cn.

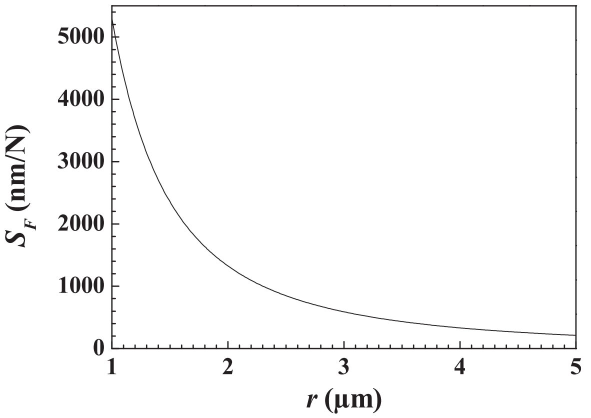

FIG. 1. Calculated force sensitivity S_F as a function of fiber radius r.

where ν is the Poisson ratio, p_{11} and p_{12} are the components of the Pockel's strain-optical tensor of the fiber material. We define the effective photo-elastic coefficient p_{eff} as

$$p_{eff} = \frac{n_{eff}^2}{2}[p_{12} - \nu(p_{11} + p_{12})]. \tag{3}$$

Then, $\Delta\lambda_B$ can be written as

$$\begin{aligned}\Delta\lambda_B &= 2\Lambda n_{eff}(1 - p_{eff})\varepsilon \\ &= (1 - p_{eff})\frac{\lambda_B}{EA}F,\end{aligned} \tag{4}$$

where F is the longitudinal force, E the Young's modulus of the fiber material, and A the cross-sectional area of the fiber.

From Eq. (4), the force sensitivity S_F can be given by

$$S_F = \frac{\Delta\lambda_B}{F} = \frac{(1 - p_{eff})\lambda_B}{\pi r^2 E}. \tag{5}$$

Thus, it can be concluded that S_F is inversely proportional to the square of the fiber radius r^2; in other words, we can have a force sensor with higher sensitivity using a FBG in a smaller-diameter fiber. Figure 1 shows the calculated results of S_F versus r with assumed value $\lambda_B = 1538$ nm. The numerical value of p_{eff} is 0.21, and E for a single-mode fiber is 73 GPa in our calculation. From the figure, we can see a microfiber with 2.5 μm diameter is expected to have $S_F \sim 3392$ nm/N. This is much higher than the S_F recorded with conventional FBG force sensors reported in the literature.[5,6]

The microfiber used in our work is fabricated from 125 μm-diameter non-photosensitive single-mode fiber using the flame-brushing technique.[16] By controlling the flame movement and the fiber stretching rate, we obtain microfibers of several microns in diameter. The manufactured microfiber has long, 125 μm-diameter pigtails at each end, enabling easy connections to other fiberized components.

We use a 2.5 μm-diameter microfiber for Bragg grating inscription. The fiber is firmly fixed onto a silicon wafer while in the FIB machining chamber (FEI Strata FIB 201). The wafer helps to avoid charging by the gallium ion beam.[12] The perpendicular gallium ion beam periodically etches 50 nm-depth grooves on the surface of microfiber. The grating has 200 shallow corrugations with period $\Lambda = 560$ nm and the total length is ~112 μm, which is much shorter than the FBG fabricated in conventional optical fiber. Λ is determined by the Bragg condition of FBG, Eq. (1). Figure 2 shows FIB images of the MFBG. The groove face is very sharp and smooth. Every groove is 50 nm in depth, located at the position with the local radius around $r = 2.5$ μm.

The setup used to test the MFBG force sensor can be seen in Figure 3. The reflection of the MFBG is measured by a broadband source near 1550 nm and an Ando AQ6317B optical spectrum analyzer (OSA) through a circulator. When measuring the reflection of the MFBG, the fiber containing the MFBG is vertically placed. One end of the fiber is fixed, and a longitudinal force is applied at the other end by adding weights. The weight-bearing portion of the fiber is a sharp taper tip, and reflection is minimal over the whole broadband spectrum in the microfiber without the MFBG.[13] Hence, the reflection at the tip end is negligible and the detected signal only results from the light reflected by the grating.

Figure 4(a) shows the reflection spectra of the MFBG force sensor under different axial forces. The spectra indicate an extinction ratio of ~17 dB at the Bragg wavelength, which is achieved with a 112 μm-long Bragg grating and is enough for sensing applications. The reflection peak sidelobes are asymmetric in the reflection spectra possibly because the MFBG does not provide a strictly sinusoidal profile as the machining parameters are not optimized yet. When the grating profile is nonuniform, the group delay and dispersion of the reflected light determined from the phase of

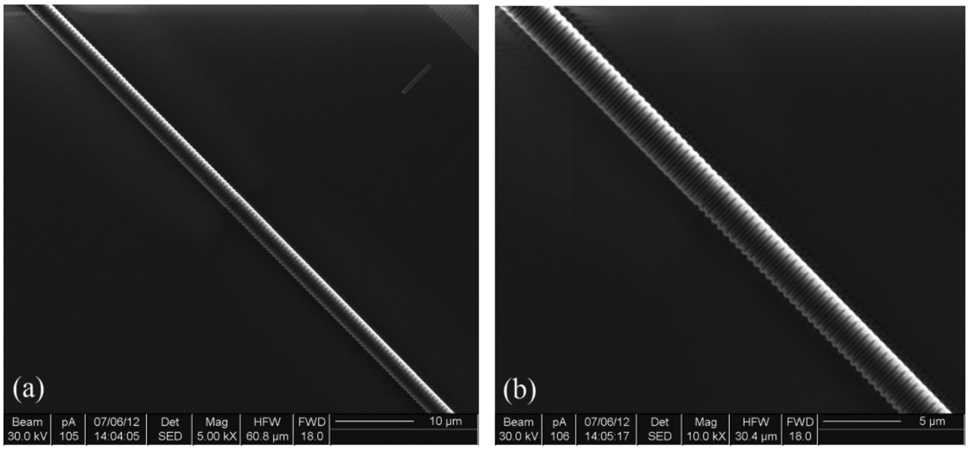

FIG. 2. (a) FIB image of the MFBG with 200 periods (~112 μm in length and $\Lambda = 560$ nm). (b) Magnified image of the grating.

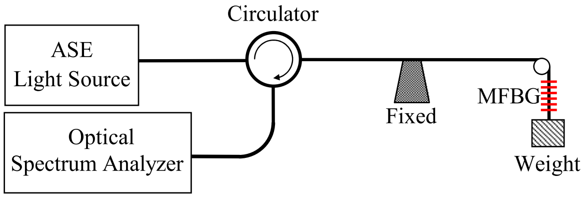

FIG. 3. Measurement setup for the MFBG force sensor.

the amplitude reflection coefficient no longer have symmetry about λ_B, hence producing the side-lobe asymmetry in a manner similar to the principle of the apodized grating discussed in the literature.[17] The figure shows that the MFBG Bragg wavelength red shifts when force is applied to the sensor. The force is very small but the shift in λ_B is relatively large, demonstrating that the force sensor has high sensitivity.

Moreover, the response of the 2.5 μm-diameter MFBG to the applied force as determined by the Bragg wavelength shift is linear up to $\sim$0.00724 N (Fig. 4(b)). From the data, we calculated the S_F for the sensor to be $\sim$3146 nm/N using linear fitting. This is three orders of magnitude larger than that recorded in FBGs inscribed in untapered fibers.[5] According to Eq. (5), the theoretical sensitivity of a 2.5 μm-diameter MFBG around resonant wavelength of 1538 nm is calculated to be $\sim$3392 nm/N. It agrees well with the experimental data. The possible reason for the minor difference between experimental and theoretical values is the slightly non-uniform diameter of the microfiber. When an axial force is applied to the MFBG, the loading condition and deformation of the MFBG are different from that of conventional uniform FBGs. The MFBG not only has an extension in the longitudinal direction but also has a deformation in the fiber cross-section. We did not consider this situation in our analysis.

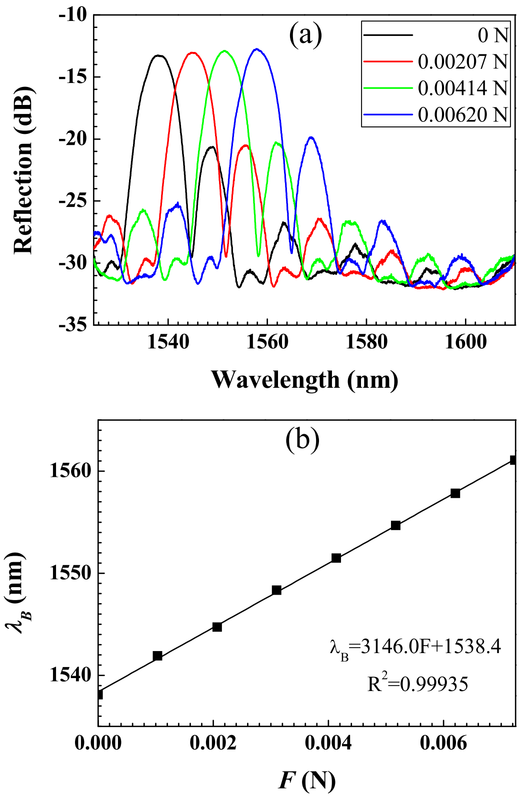

FIG. 4. (a) Reflection spectra of the MFBG force sensor under different forces (0 N, 0.00207 N, 0.00414 N, and 0.00620 N). (b) Bragg wavelength shift of a 2.5 μm-diameter MFBG as a function of the applied force.

The traditional FBG sensors usually have problems with cross sensitivity between force and temperature. The S_F of our MFBG force sensor is much higher than its temperature sensitivity ($\sim$20 pm/°C).[15] Thus, the influence from small temperature variations during force sensing can be ignored.

The Bragg wavelength shift of our MFBG against stretching force is linear up to $\sim$0.00724 N. The sensor will break with forces exceeding this value. Thus, this force sensor is suitable for high-accuracy micro-force sensing but its measurement range is limited.

In summary, we proposed and experimentally demonstrated a MFBG force sensor with high sensitivity produced by FIB milling. Conventional FBGs are inscribed in the core of Ge-doped photosensitive silica fiber by phase masking that has weak RI modulation and strong dependency on fiber material. Compared with these standard FBGs, FIB-milled MFBGs have advantages in strong RI modulation, compact size, and flexibility without limitation of the fiber material. The fabricated grating is relatively short (only 112 μm) with as few as 200-period and 50 nm-deep corrugations on the surface of a 2.5 μm-diameter microfiber. The total length of the grating is an order of magnitude shorter than that of gratings fabricated by other techniques. It provides great benefit for the miniaturization and integration of the force sensors. The S_F is inversely proportional to the FBG cross-sectional area. With smaller diameter, a FBG based on microfiber has an inherent advantage of high S_F. A calibration of a 2.5 μm-diameter MFBG sensor was performed, giving a S_F of $\sim$3146 nm/N around the resonant wavelength of 1538 nm. All these performances are better than FBGs with much bigger size or other similar MFBGs before. The advantages of compact size, high sensitivity, easy interrogation, and simple fabrication offer great prospects for developing miniature micro-force sensors with precision measurement capability.

This work was supported by the National 973 program under Contract Nos. 2011CBA00200, 2012CB921803, and 2010CB327800 and the NSFC program under Contract Nos. 11074117 and 60977039. The authors also acknowledge the support from PAPD and the Fundamental Research Funds for the Central Universities.

[1] K. O. Hill, Y. Fujii, D. C. Johnson, and B. S. Kawasaki, Appl. Phys. Lett. **32**, 647 (1978).
[2] K. Yokoyama, H. Nakagawa, D. C. Shah, H. Lambert, G. Leo, N. Aeby, A. Ikeda, J. V. Pitha, T. Sharma, and R. Lazzara, Circ Arrhythm Electrophysiol **1**, 354 (2008).
[3] P. Polygerinos, D. Zbyszewski, T. Schaeffter, R. Razavi, L. D. Seneviratne, and K. Althoefer, IEEE Sens. J. **10**, 1598 (2010).
[4] K. M. Chung, Z. Liu, C. Lu, and H. Y. Tam, IEEE Photon. Technol. Lett. **24**, 700 (2012).
[5] W. Zhang, X. Dong, Q. Zhao, G. Kai, and S. Yuan, IEEE Photon. Technol. Lett. **13**, 1340 (2001).
[6] K. Reck, E. V. Thomsen, and O. Hansen, Opt. Express **19**, 19190 (2011).
[7] K. O. Hill, B. Malo, F. Bilodeau, D. C. Johnson, and J. Albert, Appl. Phys. Lett. **62**, 1035 (1993).
[8] T. Wieduwilt, S. Brückner, and H. Bartelt, Meas. Sci. Technol. **22**, 75201 (2011).

[9] F. Xu, G. Brambilla, J. Feng, and Y. Q. Lu, IEEE Photon. Technol. Lett. **22**, 218 (2010).
[10] H. Xuan, W. Jin, and M. Zhang, Opt. Express **17**, 21882 (2009).
[11] X. Fang, C. R. Liao, and D. N. Wang, Opt. Lett. **35**, 1007 (2010).
[12] Y. Liu, C. Meng, A. P. Zhang, Y. Xiao, H. Yu, and L. Tong, Opt. Lett. **36**, 3115 (2011).
[13] J. Kou, S. Qiu, F. Xu, and Y. Lu, Opt. Express **19**, 18452 (2011).
[14] M. Ding, M. N. Zervas, and G. Brambilla, Opt. Express **19**, 15621 (2011).
[15] J. L. Kou, M. Ding, J. Feng, Y. Q. Lu, F. Xu, and G. Brambilla, Sensors **12**, 8861 (2012).
[16] G. Brambilla, F. Xu, P. Horak, Y. Jung, F. Koizumi, N. P. Sessions, E. Koukharenko, X. Feng, G. S. Murugan, J. S. Wilkinson, and D. J. Richardson, Adv. Opt. Photon. **1**, 107 (2009).
[17] T. Erdogan, J. Lightwave Technol. **15**, 1277 (1997).