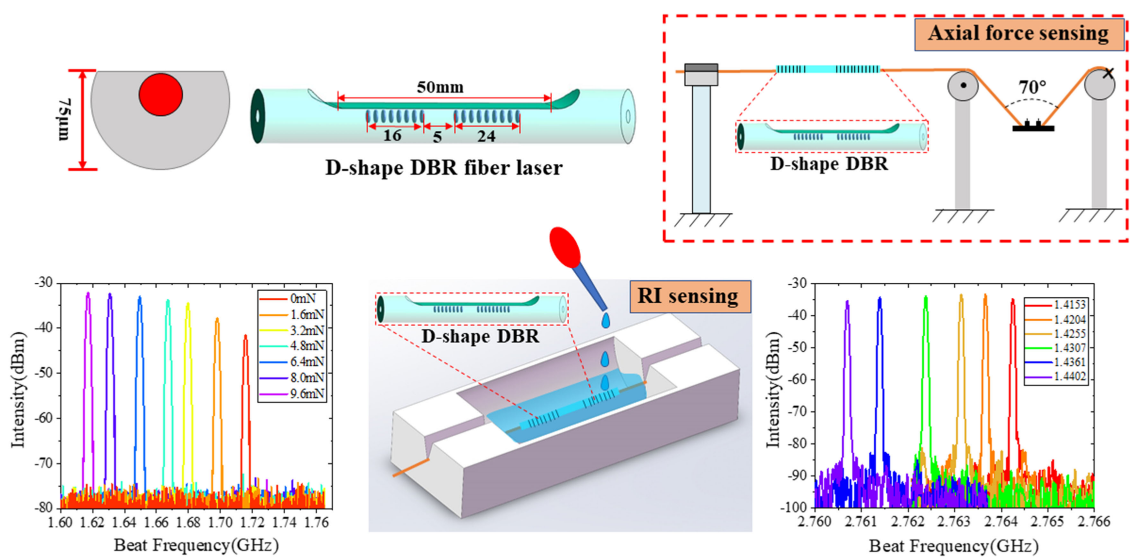
IEEE Photonics Journal
An IEEE Photonics Society Publication

Open Access

Side-Polished DBR Fiber Laser with Enhanced Sensitivity for Axial Force and Refractive Index Measurement

Volume 11, Number 3, June 2019

Xinfeng Yang
Sankhyabrata Bandyopadhyay
Li-Yang Shao
Dongrui Xiao
Guoqiang Gu
Zhangqi Song



DOI: 10.1109/JPHOT.2019.2919392

Side-Polished DBR Fiber Laser with Enhanced Sensitivity for Axial Force and Refractive Index Measurement

Xinfeng Yang, Sankhyabrata Bandyopadhyay, Li-Yang Shao, Dongrui Xiao, Guoqiang Gu, and Zhangqi Song

Department of Electrical and Electronic Engineering, Southern University of Science and Technology, Shenzhen 518055, China

DOI:10.1109/JPHOT.2019.2919392

Manuscript received April 22, 2019; revised May 16, 2019; accepted May 21, 2019. Date of publication May 28, 2019; date of current version June 19, 2019. This work was supported by the startup fund and Post-doctoral research fellowship grants from Southern University of Science and Technology and Shenzhen government. Corresponding author: Li-Yang Shao (e-mail: shaoly@sustech.edu.cn).

Abstract: A highly sensitive optical fiber sensor for the measurement of axial force and refractive index (RI) is presented. The optical sensor consists of a distributed Bragg reflector (DBR) based fiber laser, the laser cavity of the DBR is polished to D-shape by the wheel fiber polishing system. Birefringence has been introduced with side polishing of the fiber, and then, it is utilized for sensing applications. The working principle of the device is based on the principle of the change in beat frequency of the two orthogonal polarization modes of the DBR fiber laser with external perturbations. In this work, it has been shown that the dual polarization beat frequency can be used for RI-based measurement applications along with the measurement of the axial force. The sensitivity of the DBR fiber laser sensor with change in axial force is enhanced significantly with side polishing. Such a device is robust, simple in fabrication and most importantly low-cost interrogation techniques can be used for the detection purpose. A resolution of 5.6014×10^{-8} N has been achieved in case of recognition of axial force and 1.9259×10^{-5} RIU is the observable detection limit for the RI based measurement.

Index Terms: distributed Bragg reflector fiber laser, axial force sensor, refractive index sensor, dual-polarization beat frequency.

1. Introduction

Optical fiber sensors offer several advantages over conventional sensors which include immunity to electromagnetic interference, real-time detection, light weight, compact size and low fabrication cost etc. DBR based fiber sensors have been used for different potential applications over the past few years [1]–[3]. A very competitive strain and temperature sensor with DBR-fiber laser was reported earlier [4]. It has been used extensively in hydrophone-based system [5]. Cladding etched DBR fiber laser sensors was also successfully used as a hydrophone [1]. Highly sensitive innovative force sensor with DBR was demonstrated elsewhere [6]. Very recently fiber laser-based ultrasound sensor for photo-acoustic imaging system has been developed [7]. DBR based fiber laser has been used extensively for simultaneous detection of a bending and torsion [8]. Birefringence property of DBR-fiber laser has been used for the measurement purpose. DBR fiber laser sensor for lateral force measurement was demonstrated successfully with a sensitivity of 10 GHz/N/nm [2]. An array of polarimetric fiber laser sensor based on wavelength and beat frequency hybrid interrogation techniques was used for concurrent measurement of transverse load and temperature [9]. The reported sensitivity towards the transverse load was ~32.85164 MHz/N [9].

In this paper, D-shaped DBR-fiber laser based highly sensitive axial force and RI sensors are proposed. Accurate measurement of axial force is necessary in numerous fields of science and engineering [10]–[12]. Bubble expanded Fabry Perot Interferometer [10], micro silica sphere-based FP sensor [11] and recently FBG based axial force-sensing micro-forceps for retinal microsurgery has been developed [12]. In this work, it has been proved experimentally that the sensitivity of DBR fiber laser sensors with axial force and the surrounding RI (SRI) was enhanced significantly with the penetration depth of the D-shaped fiber. Sensitivity of this sensor with a change in applied axial force is competitively higher with compared to other optical sensors [2], [9]. The reported measured sensitivity of force was ~10 GHz/(N/nm) [2]. Developed D-shaped DBR fiber laser sensors were employed to measure the alteration in SRI and it can be used for selective detection of chemical and biological analytes. Different highly sensitive optical fiber based chemical and biological sensors were reported over the past few years. The basic backbone principle of these sensors is defined by concept of SRI sensing [13]–[15]. Label-free, on-line monitoring platform along with ease of uses are the main advantages of optical fiber-based refractometer. Surface plasmon based resonance sensor, optical fiber grating-based sensors are the most commonly used refractometer among the family of optical sensors [13]–[15]. Very recently different novel type of highly sensitive refractometers has been developed to achieve high sensitivity. These sensors are often pushed in an uncomfortable zone in case of using as data acquisition methods are quite expensive and complex [13]. Often costly interrogation system is required to be associated with developed sensors and makes it inappropriate for numerous fields of applications. In this work, it has been shown microwave based low cost interrogation system can be used as an interrogator for D-shaped DBR fiber laser sensor as beat frequency is being measured with change in axial force and SRI. Temperature sensitivity was also analyzed with DBR fiber laser sensors. Beat frequency tuning of DBR fiber laser with side polishing techniques was demonstrated elaborately and reported earlier [16]. Other complex ways are also used to introduce birefringence in single mode optical fiber [17]. A detail investigation of enhancement of birefringence with side polishing depth is being studied in this paper.

This process of introduction of birefringence is simple and cost effective. Cavity of DBR fiber laser was side polished with different polishing depth and are being used for the measurement of axial force and change in SRI. Temperature-controlled environment was used for SRI based measurements. Microwave interrogation techniques has been employed as beat frequency of the signal was measured. The change in beat frequency of two orthogonal polarization modes of DBR with a variation of axial force and SRI is the basic working principle of D-shaped DBR fiber sensor. The measured sensitivity of this D-shaped DBR sensor with change in axial force was ~48.789 GHz/N having a polish depth of ~50 μm and recorded RI sensitivity with same depth of fiber was found to be ~140 MHz/RIU, which is quite significant for this family of sensors. The proposed sensor apprehends measurement of axial force with advantages of ultra-high sensitivity, compact dimensions for selective applications with modest structure.

2. Design Methodology

The WFPS set up is schematically illustrated in Fig. 1(a). A thin layer of warrior sandpaper (mesh of 1500) was used over the grinding wheel for polishing purpose, movement of the grinding wheel was controlled precisely with three-dimensional motorized translation stage. Fiber was aligned perfectly and stretched with suitable weight. The length of the side-polished section of the fiber was ~5 cm. The fiber was fixed on the polishing machine by five pulleys. In the process, speed of the grinding wheel was 10 revolutions per second and it was kept fixed throughout the polishing process over the fiber surface.

The schematic block diagram of experimental setup has been presented in Fig. 1(b). The optical signal from a 980 nm laser pump (PL-974-500-FC/APC-P-M) with a power of 500 mW was launched

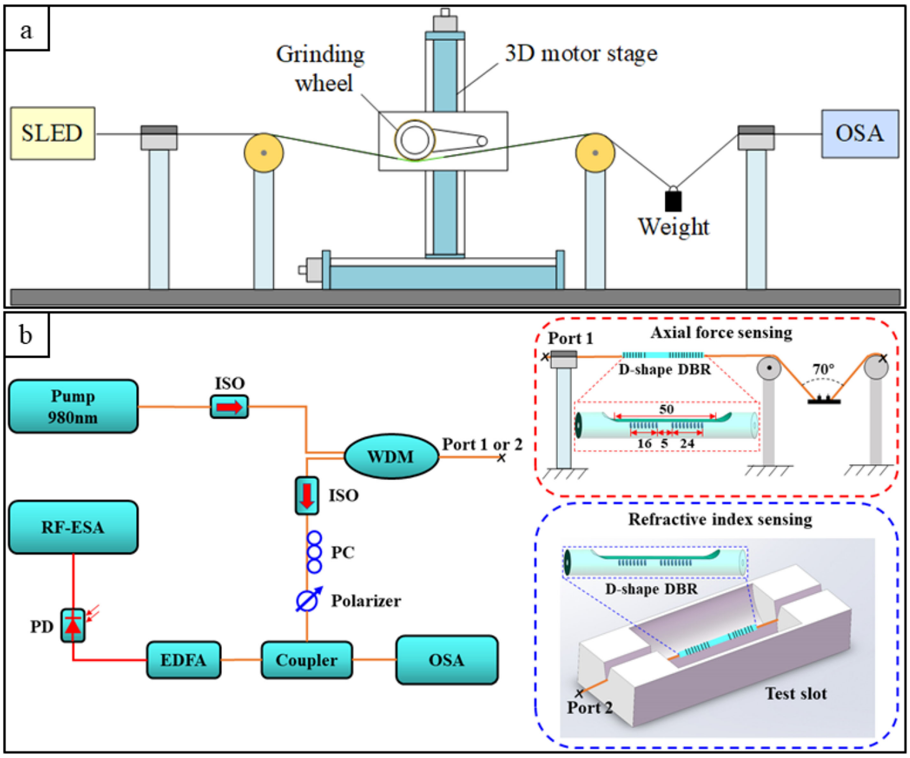


Fig. 1. (a) Schematic diagram of WFPS, (b) Schematic diagram for the DBR based fiber laser sensor system. WDM: wavelength division multiplexer, ISO: optical isolator, PC: polarization controller, PD: photodetector, EDFA- Erbium doped fiber amplifier, RF-ESA; radio-frequency electrical spectrum analyzer, OSA: optical spectrum analyzer. (all the dimensions are in mm).

into the D-shape DBR by means of a 980/1550 nm WDM (WDM 980/1550). The output of the fiber laser can generate two orthogonal polarization modes due to the introduction of birefringence in the fiber. The orthogonal polarization modes are simultaneously projected into the same polarization direction through the polarizer in order to get beat light. PC is used to control the polarization of light in order to maximize the intensity of beat light. Beat frequency was detected in electrical spectrum analyzer (N9030D Keysight) with a bandwidth and resolution limit of 50 GHz and 3 Hz respectively via a PD (KG-PD-12G-A-SM-FA). The backscattered optical signal from the D-shape DBR was blocked by an optical isolator (PIIS1550DP01212). A 3D printing machine was used to fabricate the bucket for the measurement of SRI with DBR fiber laser.

DBR laser cavity was fabricated in an Er–Yb co-doped fiber as prescribed by the other reported work earlier [18], [19]. Fiber (Coractive E-Y305) was exposed to high pressure hydrogen (100 atm) in order to improve its photosensitivity. Cavity was constructed by using two 1549-nm FBGs written in a high photosensitive Er–Yb co-doped fiber by using a 248-nm KrF excimer laser and a phase mask [20], [21], length of one FBG was 16 mm with a reflectivity of ~90%. The other one was of 24 mm in length with 95% reflectivity. A gap of ~5 mm was introduce between the two FBG to form the cavity of the fiber laser.

3. Analytical Model of the D-Shape DBR

A local birefringence is always present in standard single mode fiber (SMF) that came from the slight difference in circular symmetricity. With structural deformation, local birefringence of a normal SMF fiber will change depending on several stress regions inside the optical fiber. A change in internal structure of the fiber can create a huge impact on the birefringence of the SMF fiber. Side polishing is a method to introduce of birefringence in the fiber with creation of asymmetric fiber structure. After a detail analysis of birefringence in SMF, it was shown that the birefringence is a function of polishing depth of the fiber [22].

$$n_y - n_x = \gamma\beta f(d/a) \tag{1}$$

$$\gamma = \frac{1+\nu}{2} \cdot \frac{n^3}{E}(P_{12} - P_{11}) \tag{2}$$

n_x and n_y are the effective indices of the fiber core mode in two different orthogonal direction. β is a number proportional to the frozen in state of the fiber [23], 'a' is the radius and 'd' is the side polished depth of the fiber. P_{11} and P_{12} are the strain optic coefficient, E is the Youngs modulus and ν is the Poisson ratio of the fiber. Circular inclusions in infinite media was applied for the assessment of the birefringence. With increment of side polished depth of the fiber strain-optic coefficient changed and as a result an alteration of birefringence can be observed. A detail derivation of theory was illustrated in earlier work [22].

In the context of DBR fiber laser, which consists of a pair of wavelength-matched fiber Bragg gratings inscribed in core of an active fiber with a suitable separation to form the cavity length of DBR laser. A single longitudinal mode with two orthogonal states of polarization were operated and denoted by x- and y-polarization. The lasing wavelengths of the two polarization states are given by [2]

$$\lambda_x = 2n_x\Lambda \tag{3}$$

$$\lambda_y = 2n_y\Lambda \tag{4}$$

where n_x n_y are the effective refraction index of the two polarization states, Λ is the grating period. Due to the difference in wavelength, fiber laser produces a polarization beat signal. It can be measured with high speed PD and RF-ESA. The values of the beat frequency govern by the equation:

$$\Delta\nu = \nu_x - \nu_y = \frac{c}{n_0\lambda_0}B \tag{5}$$

where n_0 is average index of the fiber, λ_0 is Bragg wavelength of the fiber grating, and B is the fiber birefringence $(n_y - n_x)$.

From equation (5) it can be observed that the beat frequency is directly related with the birefringence of the fiber. Fiber birefringence can be changed in accordance with the strain-optic or elasto-optic coefficient by alteration of magnitude of applied force. As a result, a change in beat frequency will be observed in the RF-ESA. It needs to be mentioned that the change in beat frequency will be distinct with nature of the applied force (Lateral force, tensile force, compressive force etc). The housing of the sensor is also important to find the response of the birefringence with applied force, a detailed theoretical calculation was given elsewhere [24].

4. Experimental Results

A WFPS was used to polish the DBR fiber laser at different polishing depths and then the side polished DBR fiber laser sensors have been used for detection of axial force and measurement of change in SRI. Field emission scanning electron microscopic system has been used for characterization of polishing depth of the fiber. The detail experimental results are being described in this section.

4.1 Measurement of the Axial Force

The optical spectrum of the DBR fiber laser has been shown in Fig. 2 below. Before reduction of the clad diameter by side polish method, only a single peak was observed in OSA (AQ6370D, Yokogawa) and has been shown in the inset of Fig. 2(a). Initial wavelength difference between

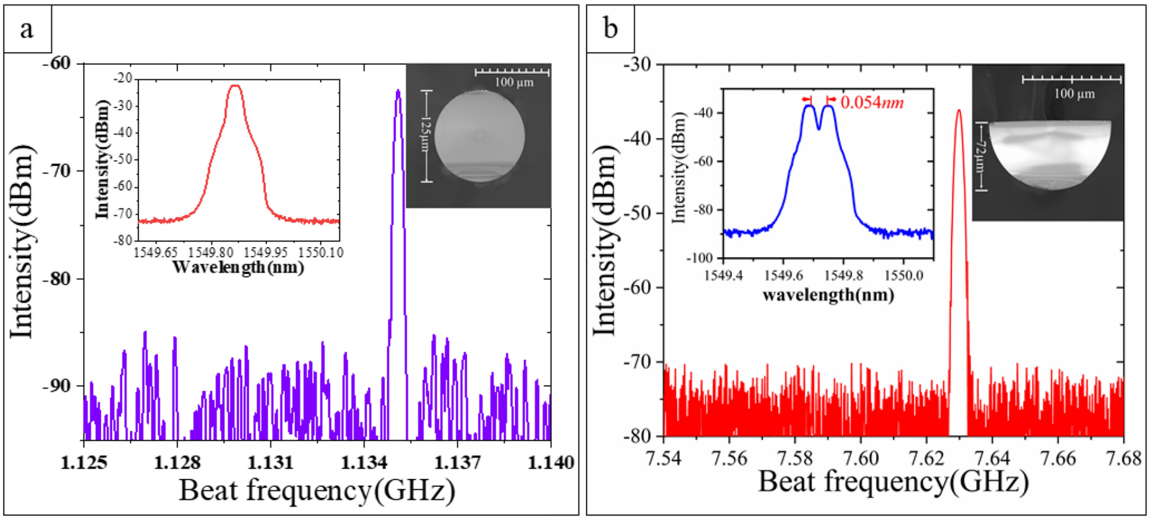


Fig. 2. RF spectrum and optical spectrum (inset) of D-shaped DBR fiber lased sensor with 0 μm [see Fig. 2(a)] and 53 μm [see Fig. 2(b)] side polished depth (Cross section of the fiber has been measured in scanning electron microscopy and shown in inset of each figure).

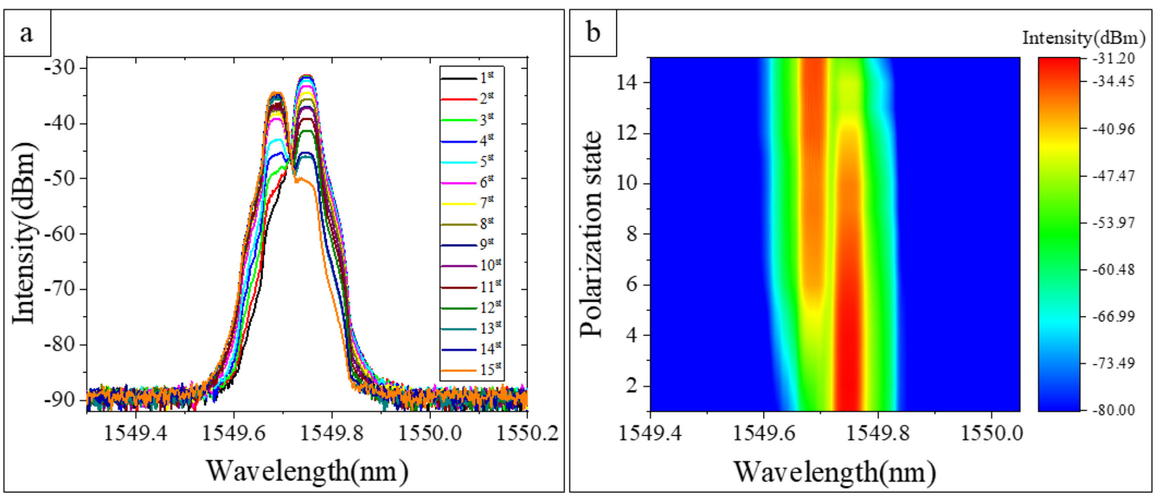


Fig. 3. (a) Optical spectrum of D-shaped DBR with 53-μm polishing depth at different polarization states, (b) Surface contour plot of state of polarization, wavelength and Intensity.

the two polarization modes of DBR is small as birefringence of optical fiber because of their inhomogeneous circular symmetry is trivial. As a consequence, without any polishing the beat frequency of DPBF as low as 1.135GHz and it was found to be ~7.63 GHz with a side polished depth of ~53 μm. Fig. 2(b) show the ESA spectrum of DBR fiber laser with a side polished depth of ~53 μm. Remaining depth of the diameter in vertical direction was ~72 μm and was shown in the inset of the figure and it was measured with scanning electron microscopy. The optical spectrum has been given in the inset of Fig. 2(b). Wavelengths corresponding to the two peaks are ~1549.690 nm and ~1549.746 nm respectively. as shown in inset of Fig. 2(b). The beat frequency was raised up to ~7.63 GHz with side polishing from ~1.135 GHz due to the separation of wavelength of polarization mode by 0.054 nm.

The state of the PC was changed manually in 15 steps, the output spectrum is shown in Fig. 3(a). The polarizer was kept in a stage where equal intensity distribution of two orthogonal polarization

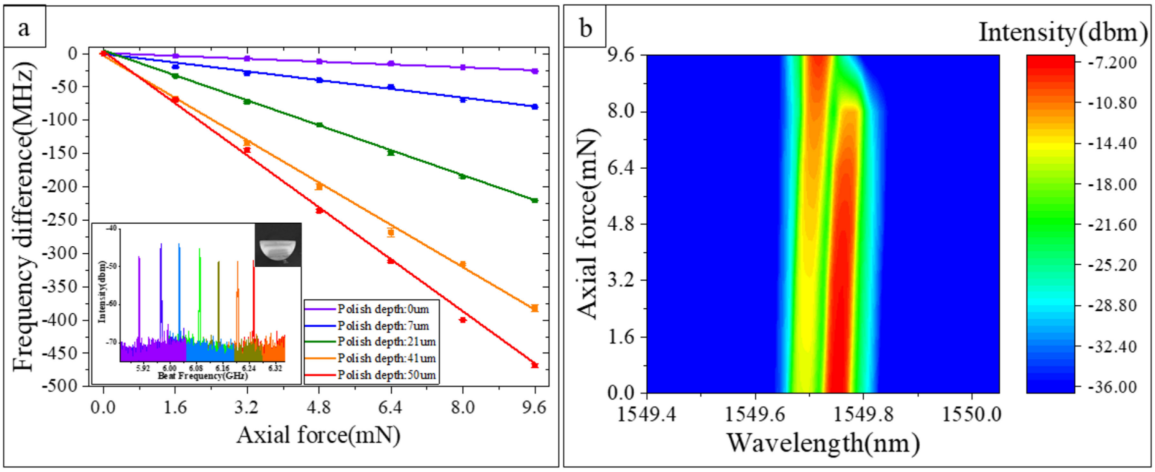


Fig. 4. (a) Shift in beat frequency with change in magnitude of axial force with different depth of polished fiber sensors, (RF spectrum of the sensor with side polished depth of 50 μm has been shown in the inset of the figure). (b) Contour mapping of optical spectral response under different axial force.

modes is observed in OSA. This phenomenon proves that two orthogonal polarization modes are obtained with the D-shaped DBR and the electrical spectrum signal in Fig. 2(b) is beaten by the two orthogonal polarization modes of the D-shaped DBR.

The effect of the axial force on beat frequency was measured with five different polish depths of the fiber ($\sim$0 m, $\sim$7 μm, $\sim$21 μm, $\sim$41 μm and $\sim$50 μm) and the change in beat frequency with a variation of magnitude of applied axial force is being shown in Fig. 4(a). Frequency of the beat signal decreases with enhancement of the magnitude of the axial force as birefringence of the DBR fiber reduces with the application of the applied force. After observing the repeated experimental outcomes, it can be concluded that beat frequency increased with enhancement of the polishing depth of the fiber. It means, effective index (either n_x or n_y) of one of the orthogonal components of core mode was changed significantly with penetration depth of D-shaped fiber and as a result birefringence ($n_x - n_y$) was changed accordingly. Normally in DBR fiber laser sensor beat frequency increases with enhancement of magnitude of the applied force [2]. Effective index (either n_x or n_y) of one of the orthogonal components changes with applied force and as an effect birefringence was changed. A shift in beat frequency was observed in the electrical spectrum [2]. In this work, it is observed that beat frequency decreases with enhancement of the force with D-shaped DBR fiber sensor. It has been concluded that the change in effective index has been occurred in one of the orthogonal polarization modes which was not altered by the penetration depth. The reduction of the beat frequency with change in applied force can be explained as: at first the difference ($n_x - n_y$) was increased due to change in of one of the orthogonal components during side polishing and the other orthogonal component was unchanged by the polishing method. When an external force was applied to the D-shaped fiber effective index of unaltered orthogonal components now begin to change and reduce the difference ($n_x - n_y$) which was initially created by the polished depth. The polishing and axial force alters the effective index of different orthogonal components. In summary, the birefringence ($n_x - n_y$) was initially increased with D-shaped polished fiber reached to a high level with maximum polished depth and then it is reduced with applied axial force as the unchanged orthogonal part now varies to compensate the enhancement in birefringence by the polishing. The change of the birefringence also affects the polarization state of the light and resulting in intensity change of the beat signal. Fig. 4(b) is the contour plot of the spectral map corresponding to the recorded optical spectrum with a change in applied axial force. It can be observed that the sensitivity of the DBR fiber laser sensor with a change in magnitude of axial force enhances abruptly with the side polish depth. The sensitivity reaches maximum when the side polished depth was reached

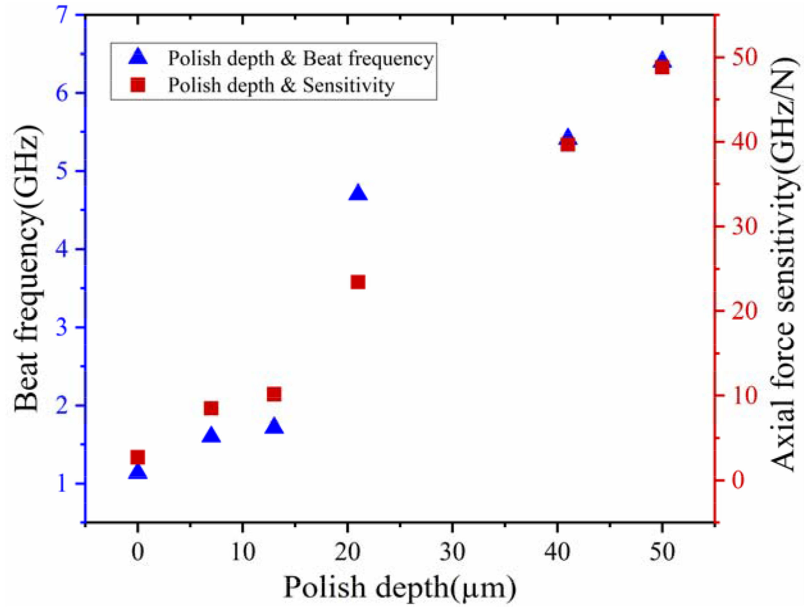


Fig. 5. The variation of beat frequency and axial force sensitivity with different polish depth of the DBR fiber laser sensor.

to ∼50 μm. A reduction of intensity of the electrical signal also observed with the change in side polished depth and intensity decreases abruptly after a depth of 50 μm. Loss of the cavity was higher than the gain after such polished depth and as a result the power level of the output of the laser has been decreased in a massive way. Mechanical stability is reduced with the side polish depth and it was very difficult to handle. As an effect the increment of the depth of the side polishing method was limited by these two factors.

Fig. 5 depicts the variation of beat frequency with side polished depth of the fiber, birefringence was increased due to side polishing and as an effect it alters the beat frequency to a higher value. The axial force sensitivity was enhanced significantly with the polish depth of the fiber. Sensitivity was raised up to ∼48.789 GHz/N with a polish depth of ∼50 μm and without any polish the observed sensitivity was ∼2 GHz/N. The measured detection limit of the sensor was found to be $\sim 5.6014 \times 10^{-8}$ N.

4.2 Sensitivity With Temperature and RI

At first temperature effect of the DBR fiber laser sensors was studied in detail as often RI measurement methods are affected with a change in temperature. Response of the beat-frequency with change in temperature has been shown in Fig. 6. Beat frequency is a linear function of temperature [25] which is controlled by thermo-optic coefficient (material properties of glass fiber). With a change in temperature effective index of orthogonal modes varies according to thermo-optic coefficient of the fiber and as a result a shift in the beat frequency is observed. It has been observed that sensitivity with a change in temperature of DBR fiber laser sensor decreases with side polished depth. Fig. 6 shows the temperature sensitivity of the sensors. With a change in the external temperature the DBR birefringence became smaller and consequently beat frequency decreases in a linear manner. The temperature of the bath was varied from 10 °C to 50 °C to observe the response of the sensor. In order to avoid the influence of change in temperature during the RI measurement, experiment was carried out in a temperature bath with a fixed temperature of 25 °C. Different RI solutions were prepared in deionized water by varying the concentration of sucrose. The RI of the

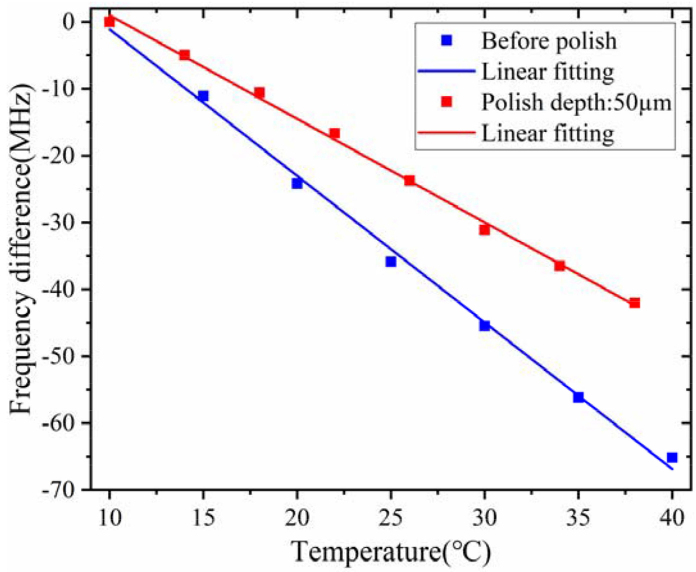


Fig. 6. Temperature response of DBR fiber laser sensor.

solutions was found to be in a zone of ∼1.38–∼1.44. A commercial refractometer was used to measure the RI values of the sucrose solutions.

With a change in SRI, the effective index of one orthogonal core mode of the fiber changed and as an outcome a shift in beat frequency could be recorded in the spectrum. It should be noted that there is no change of effective index of the orthogonal components of core mode without side polishing as the core mode is not interacted with the surrounding medium without any polish. The interaction of the core mode enhanced with side polished depth as observed in case of fiber Bragg grating based refractometer. Response of the beat signal frequency with the change in SRI of the side polished DBR fiber laser has been shown in Fig. 7. Sensitivity enhance with side polished depth, without any polish the DBR laser sensor was not at all sensitive with change in SRI. A small random change in beat frequency without side polished depth was observed mainly because of small change in temperatures of the solutions. Sensitivity of sensor with change in SRI is enhanced abruptly with the side polished depth. Two effect can be considered for the reason of the enhancement of the sensitivity with the polished depth. Firstly, an enhancement of the interaction of the guided mode with surrounding medium by reduction of the clad diameter, this is a very standard way to enhance the guided mode interaction with surrounding medium. In a second way, a change in RI of the surrounding medium might alters the values of elasto optic coefficients of the fiber [22] and a significant change in birefringence might be the reason of the enhancement of the sensitivity. The refractive index sensitivity reaches ∼0.1419 GHz/RIU with a limit of detection of 1.9259×10^{-5} RIU which is quite significant with this family of the sensors.

5. Conclusion

The laser cavity of DBR is polished to D shape by the WFPS and the performance of the sensor in case of change in applied axial force and SRI was studied in an extensive way. The sensitivity of DBR fiber sensors with change in axial force and refractive index measurement was enhanced in a noteworthy manner with depth of polishing. This sensor has shown a sensitivity of ∼48.789 GHz/N with a change in axial force. A ∼20-fold of enhancement of sensitivity with change in axial force was observed in case of polished sensor than unpolished sensor. Ultrahigh-sensitive force sensors can be used in aeronautical engineering, bio-medical based engineering processes, measurement of force of robotic arms, distributive measurements of force in different engineering

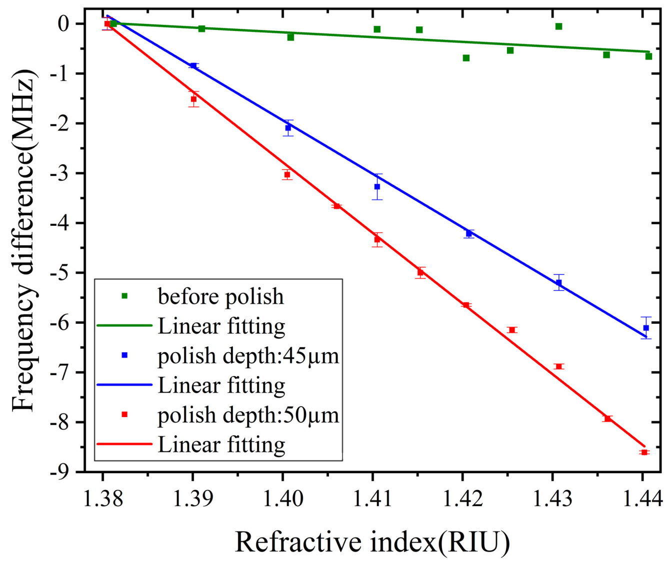


Fig. 7. Shift in Beat frequency with different RI solutions for different side polish depth of DBR fiber laser sensor. Measured sensitivity of the DBR fiber laser sensor with side polished depth ~50 μm was ~140 MHz/RIU.

field of applications. Refractive index sensitivity of DBR reaches ~0.1419 GHz/RIU with a polishing depth of ~50 μm which is quite competitive with these family of sensors, the resolution limit reaches ~5.6014 $\times$ 10^{-8} N and ~1.9259 $\times$ 10^{-5} RIU in case of measurement of axial force and RI of the surrounding medium respectively. Which seems to be excellent in comparison with other optical sensors. Interrogation techniques with this type of set-up will be easier and cost-effective than other highly sensitive plasmonic or grating-based optical sensors. In future the proposed sensors can be used as an alternative system of different biochemical sensing applications with the advantage of low-cost and compact size.

References

[1] L.-Y. Shao *et al.*, "High-frequency ultrasonic hydrophone based on a cladding-etched DBR fiber laser," *IEEE Photon. Technol. Lett.*, vol. 20, no. 8, pp. 548–550, Apr. 2008.
[2] Y. Zhang, B. O. Guan, and H. Y. Tam, "Characteristics of the distributed Bragg reflector flber laser sensor for lateral force measurement," *Opt. Commun.*, vol. 281, no. 18, pp. 4619–4622, 2008.
[3] L. Cheng, J. Han, Z. Guo, L. Jin, and B. O. Guan, "Faraday-rotation-based miniature magnetic field sensor using polarimetric heterodyning fiber grating laser," *Opt Lett.*, vol. 38, no. 5, pp. 688–690, Mar. 2013.
[4] L.-Y. Shao, X. Dong, A. P. Zhang, H.-Y. Tam, and S. He, "High-resolution strain and temperature sensor based on distributed Bragg reflector fiber laser," *IEEE Photon. Technol. Lett.*, vol. 19, no. 20, pp. 1598–1600, Oct. 2007.
[5] B. Guan, H. W. Tam, S. T. Lau, and H. L. W. Chan, "Ultrasonic hydrophone based on distributed Bragg reflector fiber laser," *IEEE Photon. Technol. Lett.*, vol. 17, no. 1, pp. 169–171, Jan. 2005.
[6] C. Lyu *et al.*, "Design evaluation of DBR fiber laser sensor for directional lateral force monitoring," *IEEE Photon. Technol. Lett.*, vol. 27, no. 14, pp. 1515–1518, Jul. 2015.
[7] Y. Liang, L. Jin, L. Wang, X. Bai, L. Cheng, and B. O. Guan, "Fiber-laser-based ultrasound sensor for photoacoustic imaging," *Sci. Rep.*, vol. 7, Jan. 2017, Art. no. 40849.
[8] C. A. R. Dıaz *et al.*, "Combined bending and torsion sensing by induced birefringence in distributed Bragg reflector laser," *IEEE J. Lightw. Technol.*, vol. 37, no. 3, pp. 861–867, Feb. 2019.
[9] B. Liu and H. Zhang, "Polarimetric distributed Bragg reflector fiber laser sensor array for simultaneous measurement of transverse load and temperature," *Opt. Fiber Technol.*, vol. 17, no. 6, pp. 619–625, 2011.
[10] Y. Zhao, F. Xia, M.-Q. Chen, R.-J. Tong, and Y. Peng, "Optical fiber axial contact force sensor based on bubble-expanded Fabry–Perot interferometer, " *Sens. Actuator A, Phys.*, vol. 272, pp. 318–324, 2018.
[11] O. R. Ranjbar-naeini, H. Latifi, M. I. Zibaii, and A. Mousavian, "Measurement of milli-newton axial force and temperature using a hybrid microsilica sphere Fabry–Perot sensor," *Opt. Lett.*, vol. 43, pp. 5210–5213, 2018.
[12] B. Gonenc and I. Iordachita, "FBG-based transverse and axial force-sensing micro-forceps for retinal microsurgery," in *Proc. Int. Conf. IEEE Sens.*, 2016, doi: 10.1109/ICSENS.2016.7808628.

[13] J. Homola, "Surface plasmon resonance sensors for detection of chemical and biological species," *Chem. Rev.*, vol. 108, pp. 462–493, 2008.
[14] J. Albert, L.-Y. Shao, and C. Caucheteur, "Tilted fiber Bragg grating sensors," *Laser Photon. Rev.*, vol. 7, pp. 83–108, 2013.
[15] M. Smietana, M. Koba, P. Mikulic, and W. J. Bock, "Towards refractive index sensitivity of long period gratings at level of tens of μm per refractive index unit: Fiber cladding etching and nano-coating deposition," *Opt. Exp.*, vol. 24, pp. 11897–11904, 2016.
[16] K. Guo *et al.*, "Beat frequency tuning in dual-polarization distributed feedback fiber laser using side polishing technique," *Opt. Exp.*, vol. 26, no. 26, pp. 34699–34710, Dec. 2018.
[17] B. Huang and X. Shu, "Highly sensitive torsion sensor with femtosecond laser-induced low birefringence single-mode fiber based Sagnac interferometer," *Opt. Exp.*, vol. 26, no. 4, pp. 4563–4571, Feb. 2018.
[18] K. Haroud, K. Bohnert, A. Frank, and H. Brandle, "Dispersion effects in a highly birefringent fiber laser sensor with fiber Bragg grating reflectors," *Opt. Lett.*, vol. 27, no. 11, pp. 897–899, 2002.
[19] J. T. Kringlebotn, J. L. Archambault, L. Reekie, and D. N. Payne, "Erˆ3$+$:Ybˆ3$+$-co-doped fiber distributed-feedback laser," *Opt. Lett.*, vol. 19, no. 24, pp. 2101–2103, 1994.
[20] W. Liu, T. Guo, A. C. Wong, H. Y. Tam, and S. He, "Highly sensitive bending sensor based on Er3$+$-doped DBR fiber laser," *Opt. Exp.*, vol. 18, no. 17, pp. 17834–17840, Aug. 2010.
[21] K. O. Hill, B. Malo, F. Bilodeau, D. C. Johnson, and J. Albert, "Bragg gratings fabricated in monomode photosensitive optical fiber by UV exposure through a phase mask," *Appl. Phys. Lett.*, vol. 62, no. 10, pp. 1035–1037, 1993.
[22] R. H. Stolen, "Polishing-induced birefringence in single-mode fibers," *Appl. Opt.*, vol. 25, pp. 344–347, 1986.
[23] W. Eickhoff, "Stress-induced single-polarization single-mode fiber," *Opt. Lett.*, vol. 7, no. 12, pp. 629–631, 1982.
[24] S. Rashleigh, "Origins and control of polarization effects in single-mode fibers," *J. Lightw. Technol.*, vol. JLT-1, no. 2, pp. 312–331, Jun. 1983.
[25] O. Hadeler, M. Ibsen, and M. N. Zervas, "Distributed-feedback fiber laser sensor for simultaneous strain and temperature measurements operating in the radio-frequency domain," *Appl. Opt.*, vol. 40, no. 19, pp. 3169–3175, 2001.