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TITLE:

A Random-displacement Measurement by Combining a Magnetic Scale and Two Fiber Bragg Gratings

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KEYWORDS:

Fiber Bragg grating, package, random displacement, magnetic scale, direction discrimination, temperature compensation

SUMMARY:

A protocol to create a full-range linear displacement sensor, combining two packaged fiber Bragg grating detectors with a magnetic scale, is presented.

ABSTRACT:

Long-distance displacement measurements using optical fibers have always been a challenge in both basic research and industrial production. We developed and characterized a temperature-independent fiber Bragg grating (FBG)-based random-displacement sensor that adopts a magnetic scale as a novel transferring mechanism. By detecting shifts of two FBG center wavelengths, a full-range measurement can be obtained with a magnetic scale. For identification of the clockwise and counterclockwise rotation direction of the motor (in fact, the direction of movement of the object to be tested), there is a sinusoidal relationship between the displacement and the center wavelength shift of the FBG; as the anticlockwise rotation alternates,

the center wavelength shift of the second FBG detector shows a leading phase difference of around 90° (+90°). As the clockwise rotation alternates, the center wavelength shift of the second FBG displays a lagging phase difference of around 90° (-90°). At the same time, the two FBG-based sensors are temperature independent. If there is some need for a remote monitor without any electromagnetic interference, this striking approach makes them a useful tool for determining the random displacement. This methodology is appropriate for industrial production. As the structure of the whole system is relatively simple, this displacement sensor can be used in commercial production. In addition to it being a displacement sensor, it can be used to measure other parameters, such as velocity and acceleration.

INTRODUCTION:

Optical fiber-based sensors have great advantages, such as flexibility, wavelength division multiplexing, remote monitoring, corrosion resistance, and other characteristics. Thus, the optical fiber displacement sensor has broad applications.

To realize targeted linear displacement measurements in complex environments, various structures of the optical fiber (e.g., the Michelson interferometer[1], the Fabry–Perot cavity interferometer[2], the fiber Bragg grating[3], the bending loss[4]) have been developed over recent years. The bending loss requires the light source in a stable station and is unsuitable for environmental vibration. Qu et al. have designed an interferometric fiber-optic nanodisplacement sensor based on a plastic dual-core fiber with one end coated with a silver mirror; it has a resolution of 70 nm[5]. A simple displacement sensor based on a bent single-mode–multimode–single-mode (SMS) fiber structure was proposed to overcome the limitations on the measurement of the displacement range; it increased the displacement sensitivity threefold with a range from 0 to 520 µm[6]. Lin et al. presented a displacement sensor system that combines the FBG together with a spring; the output power is approximately linear with the displacement of 110–140 mm[7]. A fiber Fabry–Perot displacement sensor has a measurement range of 0–0.5 mm with a linearity of 1.1% and a resolution of 3 µm[8]. Zhou et al. reported a wide-range displacement sensor based on a fiber-optic Fabry–Perot interferometer for subnanometer measurements, up to 0.084 nm over a dynamic range of 3 mm[9]. A fiber-optic displacement sensor based on reflective intensity modulated technology was demonstrated using a fiber collimator; this had a sensing range over 30 cm[10]. Although optical fibers can be fabricated into many kinds of displacement sensors, these fiber-based sensors generally make use of the tensile limit of the material itself, which limits their application in wide-range measurements. Thus, compromises are usually made between the measurement range and sensitivity. Moreover, it is difficult to determine the displacement as various variables occur simultaneously; especially, cross-sensitivity of the strain and temperature could damage the experimental precision. There are many discrimination techniques reported in the literature, such as using two different sensing structures, using a single FBG half-bonded by different glues, or using special optical fibers. Thus, the further development of optical fiber displacement sensors requires high sensitivity, a small size, great stability, full range, and temperature independence.

Here, the periodic structure of the magnetic scale makes a full-range measurement possible. A random displacement without a limited measurement range with a magnetic scale is achieved.

Combined with two FBGs, both temperature cross-sensitivity and the identification for the direction of movement could be solved. Various steps within this method require precision and attention to detail. The protocol of the sensor fabrication is described in detail as following.

PROTOCOL:

1. Fabrication of the fiber Bragg grating

1.1. To enhance the photosensitivity of fiber core, put a standard single-mode fiber into a hydrogen-loaded airtight canister for 1 week.

1.2. Fabricate the fiber Bragg grating using the scanning phase-mask technique and a frequency-doubled, continuous wave argon-ion laser at a wavelength of 244 nm.

1.2.1. Focus on the optical fiber with a cylindrical lens and an ultraviolet (UV) laser beam. Imprint the grating (periodic modulation of refractive index) in the photosensitive core by using a phase mask (parallel with the fiber axis) placed in front of the fiber. The light output by the laser is shaped and perpendicular to the phase mask. Place the fiber at the position of the ±1 order diffracted light for UV exposure.

1.3. After UV inscription, place the two fiber Bragg gratings in a 100 °C oven for 48 h to remove any residual hydrogen, until the reflectivity of the fiber grating is reduced by 10%, the 3 dB bandwidth is reduced by 0.1 nm, and the center wavelength is shifted by 0.8 nm. This step is called the annealing processing. The parameters of FBG will not change after the annealing processing.

NOTE: The central wavelengths of these two FBGs are 1,555.12 nm (1#FBG) and 1,557.29 nm (2#FBG) with grating lengths of 5 mm.

2. Preparation of the magnetic scale and the matching clamp

2.1. Determine the size of the permanent magnet according to the previously described design[8]. The description of the permanent magnet is shown in **Table 1**.

2.2. Design the slot of the magnetic scale, whose dimension matches the permanent magnet, as shown in **Figure 1**.

2.2.1. Confirm the dimension of the matching clamp and set a distance of 22.5 mm between the two slots in the clamp. In order to remove magnetic field interference, the clamp is made of stainless steel.

2.2.2. Set a distance of 10 mm of the pitch in the magnetic scale (τ) to distinguish the direction of movement, and set a distance of 22.5 mm ($(2+1/4)\cdot\tau$) between the two detectors. Two detectors can obtain the displacement characteristic according to the following formulas, which can achieve sinusoidal function variations by a phase difference of 90°, where x is the displacement, $F_{1\#FBG}$ and $F_{2\#FBG}$ are the magnetic force of the two detectors, and B is a constant. The structure of the magnetic scale and its matching clamp are shown in **Figure 1**.

$$\begin{cases} F_{1\#FBG} = B \cdot sin(2\pi \frac{x}{\tau}) \\ F_{2\#FBG} = B \cdot \cos(2\pi \frac{x}{\tau}) \end{cases}$$

2.3. Put permanent magnets into the slots of the clamp, with the magnetic N/S alternately arranged. Cylindrical permanent magnets are only magnetized in the axial direction, and its magnetic vector is 750 kA/m.

3. Fabrication of the displacement sensor

3.1. Prepare a mixture of heat-curable fiber optic epoxy (glue) by adding 100 mg of hardener (Component A) to 200 mg of resin (Component B), as shown in **Figure 2**.

3.2. Measure the distance of fiber pigtail, approximately 10 mm between the end face of fiber pigtail and the grating region, and then, score it with a fine-point marker.

3.3. Use a fiber optic stripper to peel the fiber coating and strip it from the marker position of the previous step.

3.4. Clean the surface of any remaining polymer with dust-free paper. Position the blade of a high-precision fiber cleaver perpendicular to the fiber optic cable and cut it.

3.5. Put a permanent magnet on the hot plate and place a spring with a length of 15 mm above the permanent magnet.

NOTE: The length of the spring is the main element of the preloaded force in the next step.

3.6. Glue the fiber obtained from step 3.3. Place the pigtail of the fiber inside of the spring, as shown in **Figure 2**, and cure the adhesive (Epoxy #1) for 30 min at 150 °C.

NOTE: These three combined parts are called *1#P*.

3.7. Put *1#P* into the tapered pipe and use adhesive tape to fix the permanent magnet. as shown in **Figure 3**. Place adhesive exactly above the permanent magnet, and cure the adhesive (Epoxy #2 is the same as Epoxy #1) for 30 min at a temperature of 150 °C. Then, apply the preloaded force by hand to the fiber Bragg grating; the pretightening force allows the fiber to be in a nonbending state.

NOTE: These combined parts are called the FBG detector. The FBG detector is responsible for converting the signal of the magnetic force into the signal of the displacement parameters.

3.8. Remove the adhesive tape; the production of this step is called *2#P*.

3.9. Splice an APC-type single-mode connector to the end of the *2#P* fiber using a fusion splicer, following manufacturer's instructions.

3.10. Fix two FBG detectors into the slot of the clamp, and then, fix the clamp to the displacement platform.

4. Building the testing system

4.1. Power the high-speed wavelength interrogator with the built-in optical switch.

4.2. Turn on the amplified spontaneous emission (ASE). Guide the light into the input-output fiber and propagate it to the FBG-based displacement sensor. Then, the reflection spectra modulated by the sensor reflects it to the interrogator via the input-output fiber again.

4.3. Connect the interrogator to the computer with an ethernet cable, based on the UDP protocol.

4.4. Connect the optical circulator to the optical spectrum analyzer (OSA) with a minimum resolution of 0.02 nm, for monitoring the Bragg wavelength shift.

4.5. Power the stepper motor with 24 V.

4.6. Change the speed of the motor by adjusting the DIP switch of the stepper motor controller. With the external control port, the stepper motor controller can be driven in half-step, normal, and other drive modes, as shown in **Table 2**, and on-chip PWM chopper circuits permit switch-mode control of the current in the windings based on an MCU.

4.7. Adjust the distance between the two detectors and the magnetic scale.

4.7.1. Adjust until there is a better sinusoidal curve between the displacement and the magnetic field.

4.7.2. Adjust until there are well-described methods to stimulate the best distance[11] because cylindrical permanent magnets with opposite magnetic fields are arranged adjacent to each other.

NOTE: There is a sinusoidal relationship between the displacement and the magnetic field when there is a suitable distance between the magnetic scale and the detector. The magnetic force has a linear relationship with the magnetic field. According to Hooke's law, force has a linear relationship with strain, and the center wavelength shift of FBG is linear with strain applied on the FBG; thus, a sinusoidal curve can be obtained.

4.7.3. Separate the two detectors from each other for 22.5 mm.

NOTE: (m ± 1/4)τ equals 22.5 mm (m is a positive integer, m = 2), τ is the pitch of the magnetic scale, and (m ± 1/4)τ ≤ the total length of the magnetic scale, where τ equals 10.

5. Evaluation of the designed displacement sensor

5.1. Adjust the distance between the detector and the magnetic scale to be 1.5 mm and, then, fix the clamp.

5.2. Plug the APC-type connector end of the sensor into the interrogator port and start the configuration software. Set the sampling frequency of the interrogator to 5 kHz for a real-time recording of the FBG center wavelength change over time. Push the button to control the motor by an increment of 40 µm each time (type F, as shown in **Table 2**). Different types represent different steps. If the motor works with type F, the motor can have the smallest step interval and the highest displacement accuracy.

5.2.1. Plug the APC-type connector end of the sensor into the OSA port and start the configuration software. An OSA and interrogator monitor the central wavelengths shift of FBGs. Save the data from the static state calibration.

5.3. Alternate the clockwise and anticlockwise rotation of the motor in a dynamic state. Save the data as above.

5.4. Put the sensor on the hot plate and conduct a temperature calibration experiment. Change the temperature of the hot plate from 25 °C to 90 °C.

5.5. Perform data analysis.

5.5.1. Import the data in a .csv format from the static calibration experiment into **MATLAB**. Employ the **findpeaks** function to extract the center wavelength of the fiber Bragg grating. Use the sinusoidal function from the **curve fitting tool** to fit the relationship between the center wavelength and the displacement, as shown in **Figure 5a**. The fitting residual errors between sample points and the fitting curve also are depicted in **Figure 5b**. The two Fourier fitting curves between the center wavelength shifts and the linear displacement despite the original phase are here:

$$\begin{cases} \lambda_{1\#FBG} = 0.5353 \cdot sin(2\pi \frac{x}{10}) + 1555.12, R^2 = 0.998 \\ \lambda_{2\#FBG} = 0.5217 \cdot cos(2\pi \frac{x}{10}) + 1557.29, R^2 = 0.999 \end{cases}$$

5.5.2. Import the data into the processing software. Using the curve fitting tool, process the data obtained from a dynamic clockwise rotation (forward movement) and an anticlockwise rotation (backward movement) of the motor (**Figure 6**).

5.5.3. Process the data obtained from the temperature calibration experiment as above (**Figure 7**).

REPRESENTATIVE RESULTS:

The distance, ranging from 1 mm to 3 mm[11], between the magnetic scale and the detector enabled the detection of the linear displacement with a sinusoidal function. A distance of 22.5 mm between two detectors enabled this approach to realize detection of the direction of an object's movement with a phase difference of 90°. The two detectors were separated from each other for (m ± 1/4)τ (m is a positive integer) and (m ± 1/4)τ ≤ the total length of the magnetic scale, where τ = 10 mm and m = 2 are used in the experiment described here (**Figure 1**). The composition and structure of the displacement detector are shown in **Figure 2**. The key of the packaging process is to apply a preloaded force to the FBG; when there was a movement, the magnetic force between the magnetic scale and the detector would change (**Figure 3**), and the axis stress distribution of the FBG would be uniform as the spring stretched or compressed. The measurement system is based on the ASE, the interrogator, and the OSA, which characterizes the sensor's center wavelength signature (**Figure 4**). The OSA, with a minimum resolution of 0.02 nm, was more accurate than the interrogator when measuring the spectrum statically. OSA has a high resolution; it is more suitable than the interrogator in static calibration experiments.

The results of static calibration (**Figure 5a**) and corresponding residual errors (**Figure 5b**) revealed that the designed detector allows the exploration of the random-displacement position at its best. For the identification of the forward and inverse movement direction of the motor, as the forward movementalternates, the center wavelength shift of the 2#FBG detector has a leading phase difference of around 90° (+90°). As the inverse displacement alternates , the center wavelength shift of the 2#FBG displayed the sinusoidal function variations by a lagging phase difference of around 90° (-90°) (**Figure 6**). The temperature cross-sensitivity on the proposed sensor could be eliminated by a differential sine function. A positive or negative change in the phase angle could be obtained. The direction of the displacement could easily be solved, as mentioned previously[12]. In brief, the data collected from the temperature calibration experiment is shown in **Figure 7**. It can be known that the temperature sensitivity (K_T) of both FBG detectors is the same when the temperature interference is not ignored in this system. The relationship between the displacement and the wavelength shifts can be expressed as follows; thus, temperature compensation is the merit of this system.

$$\begin{cases} \dfrac{\Delta\lambda_{1\#FBG}}{\lambda_{1\#FBG}} = D\cdot\sin(2\pi\dfrac{x}{\tau}) + K_T\cdot\Delta T \\ \dfrac{\Delta\lambda_{2\#FBG}}{\lambda_{2\#FBG}} = D\cdot\cos(2\pi\dfrac{x}{\tau}) + K_T\cdot\Delta T \end{cases}, \quad \frac{\Delta\lambda_{1\#FBG}}{\lambda_{1\#FBG}} - \frac{\Delta\lambda_{2\#FBG}}{\lambda_{2\#FBG}} = \sqrt{2}D\sin(2\pi\frac{x}{\tau} - \frac{\pi}{4})$$

The uncertainty from the data fitting shows that the maximum uncertainty is almost parallel with the maximum amplitude of the sinusoidal fitting curve. There can be some improvement to make uncertainty smaller so that the uncertainty represents the property of the sensor. We took the balanced point (5 mm, a position in which the detector is opposite in polarity to the magnetic scale) and the maximum amplitude (2.5 mm, a position in which the detector has polarity to the magnetic scale) of 1#FBG as an example (depicted in **Figure 5b)**, and the repeatability of the measurement (10 counts) is shown in **Figure 8**. It is clear that the balanced point (5 mm) was more stable than the maximum amplitude (2.5 mm), and the maximum residual error (7.5 pm) occurred on the maximum amplitude (2.5 mm) of 1#FBG. The accuracy of the displacement measurement is 0.69 μm.

$$\lambda_{1\#FBG} = 0.5353 \cdot sin(\, 2\pi \frac{x}{10}) + 1555.12$$

$$|\, \lambda_{1\#FBG} - 1555.12| = 0.0072$$

$$\rightarrow\rightarrow x = 0.69 \ \mu\text{m}$$

Automatic control and production, especially for machine monitoring in serious oil-contaminated circumstances, need optical fiber-based long displacement. Thus, the designed optical fiber sensor can be used in steel and iron process.

FIGURE AND TABLE LEGENDS:

Figure 1: The magnetic scale and matching clamp.

Figure 2: Composition and structure of the displacement detector.

Figure 3: Method of applied preloaded force during packaging.

Figure 4: Experiment setup for displacement measurements. The system is based on the ASE, the interrogator, and the OSA, which characterize the sensor’s center wavelength signature. This figure is reprinted with permission from Zhu et al.[11].

Figure 5: Static calibration and residual errors. (**a**) The relationship between the displacement and the two FBGs wavelength shift. (**b**) The fitting curve residual error between the original data and the sinusoidal curve. This figure is reprinted with permission from Zhu et al.[11].

Figure 6: Identification of the clockwise and counterclockwise rotation direction of the motor. This figure is reprinted with permission from Zhu et al.[11].

Figure 7: The relationship between the center wavelength and temperature. This figure is reprinted with permission from Zhu et al.[11].

Figure 8: The repeatability of the measurement.

Table 1: Description of the permanent magnet. This table is reprinted with permission from Zhu et al.[11].

Table 2: Description of the microstep driver.

DISCUSSION:

We have demonstrated a new method for random linear displacement measurements by combining a magnetic scale and two fiber Bragg gratings. The main advantage of these sensors is random displacement without limitation. The magnetic scale used here generated a periodicity of the magnetic field at 10 mm, far beyond the practical limits of conventional optical fiber displacement sensors, such as the displacement mentioned by Lin et al.[7] and Li et al.[8]. The temperature-dependent displacement sensor is also suitable for experiments involved in remote monitoring.

The preloaded force on the FBG is the critical step in the packaging protocol of the FBG-based magnetic detector. When the spring is stretched or compressed, a uniform axis stress distribution of the FBG is obtained. A distance of ($m \pm 1/4)\tau$ between two detectors is essential to ensure that the entire system recognizes the direction of movement.

This new displacement measurement technology requires a reduced susceptibility to vibration. The sensors may also be improved by reducing their sensitivity to humidity changes, which are affected by the spring in the detector. Future work could focus on the development of software algorithms to eliminate vibration affection. This displacement sensor system can become commercially available if the pitch of the magnetic scale can be decreased as the commercial electronic magnetic scale.

This sensor can be used to measure random displacement without range limitation with respect to existing methods. Although the protocol here has been proven to be effective as a displacement sensor, it can also be used to measure other parameters, such as velocity and acceleration.

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DISCLOSURES:

The authors have nothing to disclose.

REFERENCES:

1. Salcedadelgado, G. et al. Adaptable Optical Fiber Displacement-Curvature Sensor Based on a Modal Michelson Interferometer with a Tapered Single Mode Fiber. *Sensors.* **17** (6), 1259, 10.3390/s17061259 (2017).
2. Milewska, D., Karpienko, K., Jędrzejewska-Szczerska, M. Application of thin diamond films in low-coherence fiber-optic Fabry Pérot displacement sensor. *Diamond and Related Materials.* **64**,

169–176, 10.1016/j.diamond.2016.02.015 (2016).

3. Zou, Y., Dong, X., Lin, G., Adhami, R. Wide Range FBG Displacement Sensor Based on Twin-Core Fiber Filter. *Journal of Lightwave Technology.* **30** (3), 337–343, 10.1109/JLT.2011.2181334 (2012).

4. Zhao, J., Bao, T., Kundu, T. Wide Range Fiber Displacement Sensor Based on Bending Loss. *Journal of Sensors.* **2016** (2016-1-27), 1–5, 10.1155/2016/4201870 (2016).

5. Qu, H., Yan, G., Skorobogatiy, M. Interferometric fiber-optic bending/nano-displacement sensor using plastic dual-core fiber. *Optics Letters.* **39** (16), 4835–4838, 10.1364/OL.39.004835 (2014).

6. Wu, Q., Semenova, Y., Wang, P., Muhamad Hatta, A., Farrell, G. Experimental demonstration of a simple displacement sensor based on a bent single-mode–multimode–single-mode fiber structure. *Measurement Science & Technology*. **22** (2), 025203, 10.1088/0957-0233/22/2/025203 (2011).

7. Lin, G., Adhami, R., Dong, X., Zou, Y. Wide range FBG displacement sensor based on twin-core fiber filter. *Journal of Lightwave Technology.* **30** (3), 337–343, 10.1109/JLT.2011.2181334 (2012).

8. Li, M., Guo, J., Tong, B. A double-fiber F-P displacement sensor based on direct phase demodulation. *The International Conference on Optical Fibre Sensors*. **8421**, 84212R, 10.1117/12.968592(2012).

9. Zhou, X., Yu, Q. Wide-range displacement sensor based on fiber-Optic Fabry–Perot Interferometer for Subnanometer Measurement. *IEEE Sensors Journal*. **11**, 1602–1606, 10.1109/JSEN.2010.2103307 (2011).

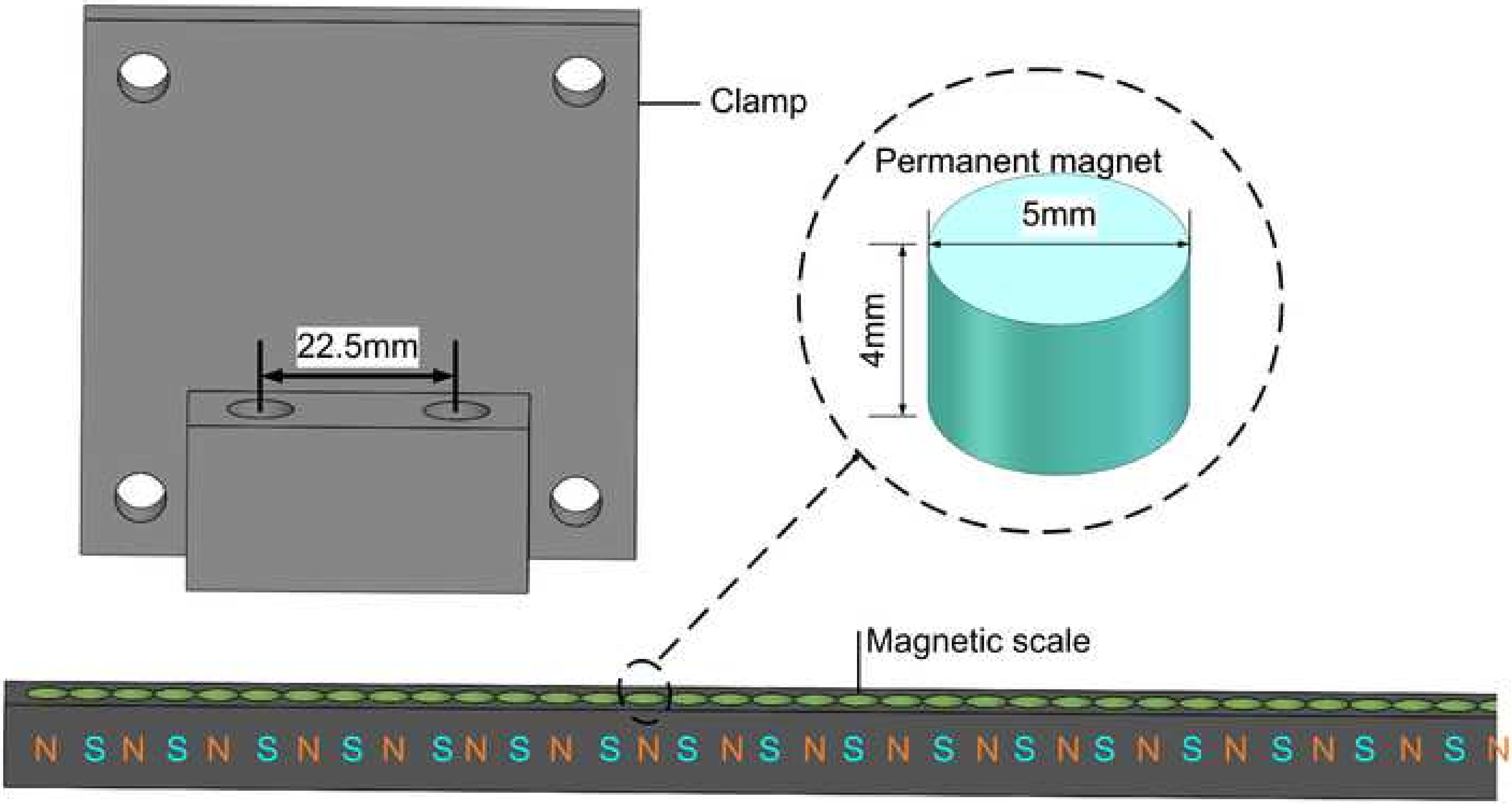
10. Shen, W., Wu, X., Meng, H., Huang, X. Long distance fiber-optic displacement sensor based on fiber collimator. *Review of Scientific Instruments*. **81** (12), 123104-1-23104-4, 10.1063/1.3518971 (2010).

11. Zhu, L., Lu, L., Zhuang, W., Zeng, Z., Dong, M. Non-contact temperature-independent random-displacement sensor using two fiber bragg gratings. *Applied Optics*. **57** (3), 447, 10.1364/AO.57.000447 (2018).

12. Yu, H., Yang, X., Tong, Z., Cao, Y., Zhang, A. Temperature-independent rotational angle sensor based on fiber Bragg grating. *IEEE Sensors Journal.* **11** (5), 1233–1235, 10.1109/JSEN.2010.2091270 (2011).

13. Liu, J. et al. A Wide-Range Displacement Sensor Based on Plastic Fiber Macro-Bend Coupling. *Sensors.* **17** (1), 196, 10.3390/s17010196 (2017).

Fig.1


Clamp
22.5mm
Permanent magnet
5mm
4mm
Magnetic scale
N S N S N S N S N S N S N S N S N S N S N S N S N S N S N S N S N S N S N S N

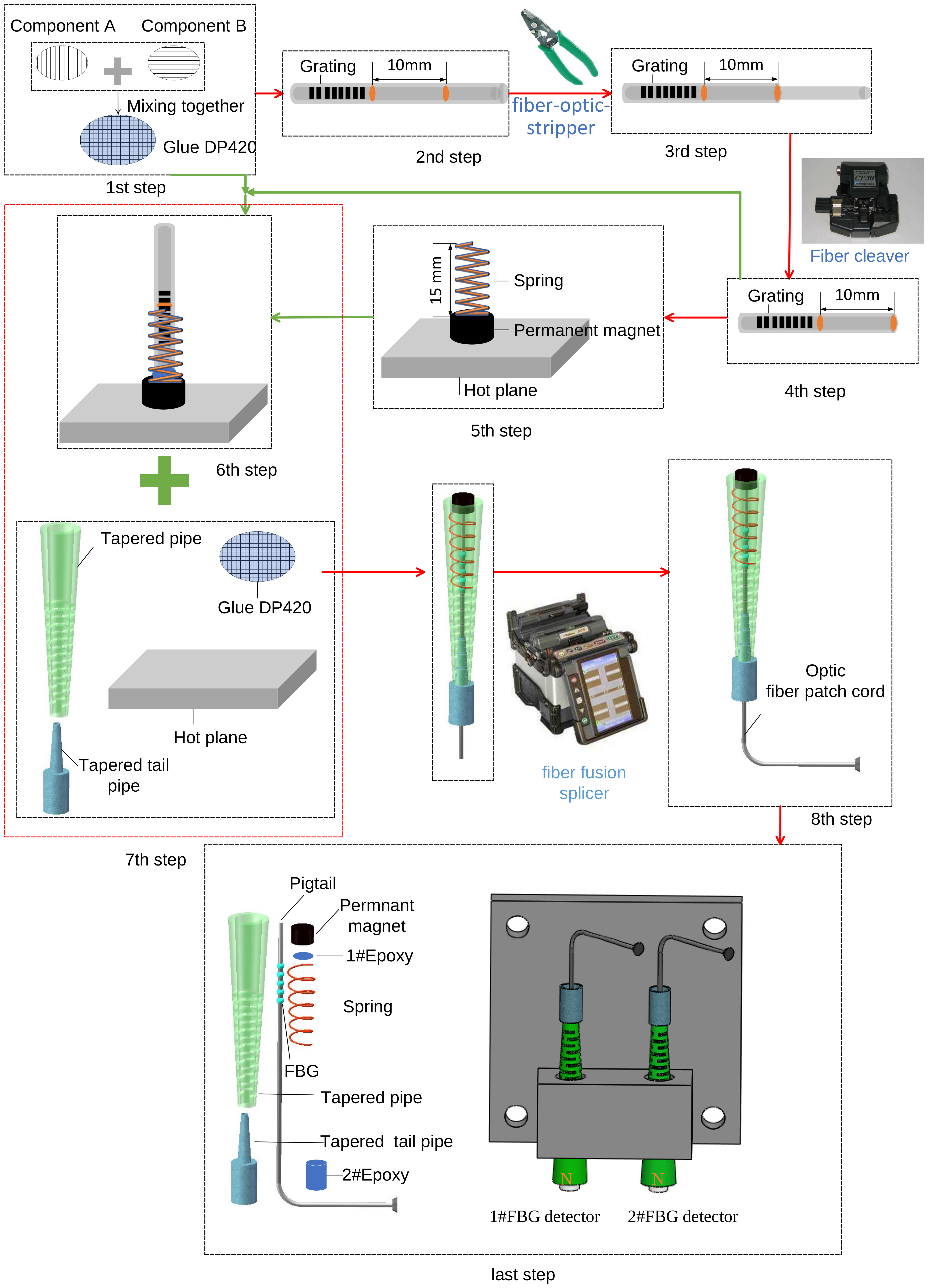

Component A
Component B
Mixing together
Glue DP420
1st step
Grating
10mm
2nd step
fiber-optic-
stripper
3rd step
Fiber cleaver
4th step
15 mm
Spring
Permanent magnet
Hot plate
5th step
6th step
Tapered pipe
Glue DP420
Hot plate
Tapered tail
pipe
7th step
fiber fusion
splicer
Optic
fiber patch cord
8th step
Pigtail
Permnant
magnet
1#Epoxy
Spring
FBG
Tapered pipe
Tapered tail pipe
2#Epoxy
1#FBG detector
2#FBG detector
last step

Fig.3

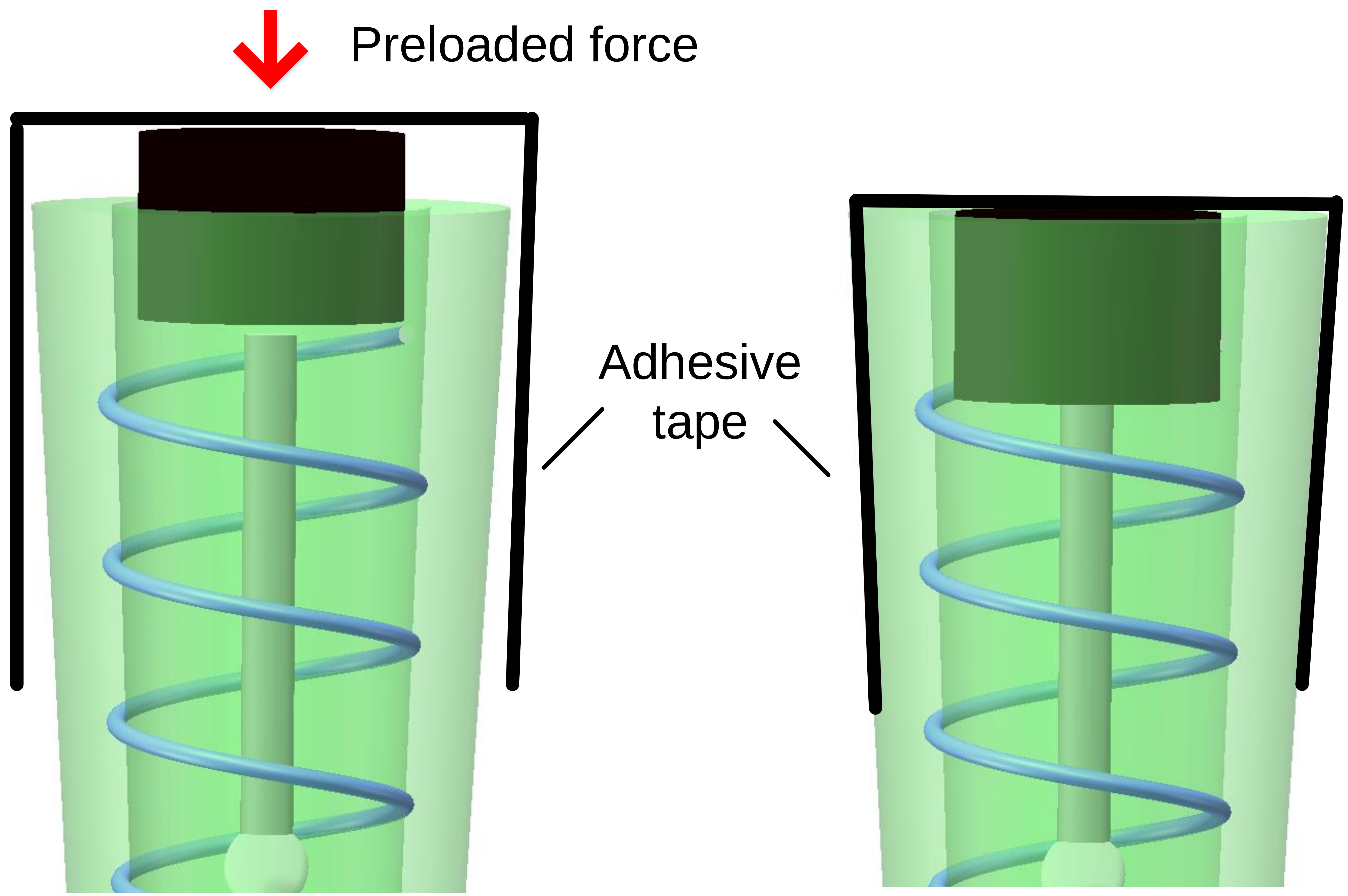
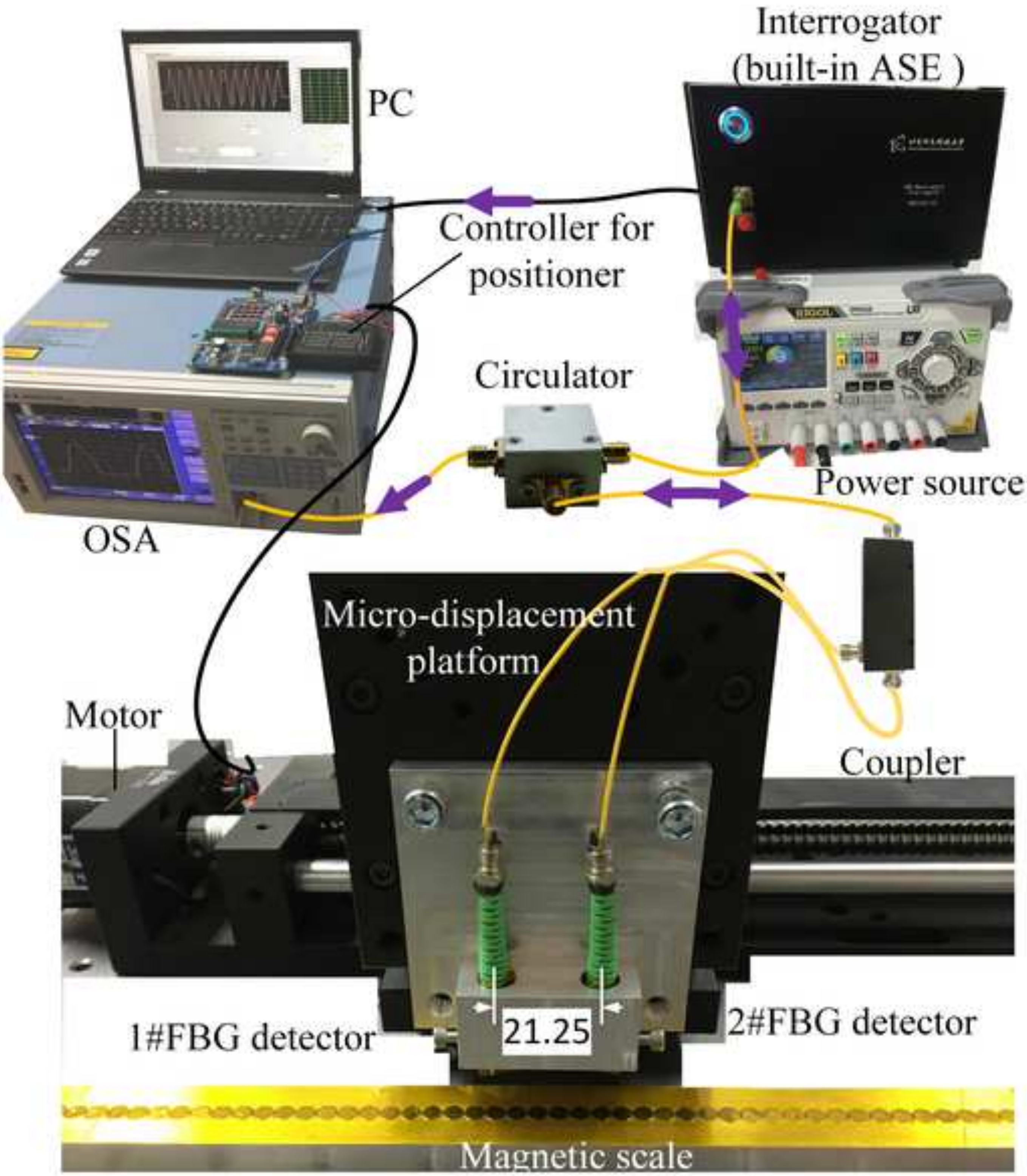


Fig.4



Interrogator
(built-in ASE)
PC
Controller for
positioner
Circulator
Power source
OSA
Micro-displacement
platform
Motor
Coupler
1#FBG detector
21.25
2#FBG detector
Magnetic scale

Fig.5

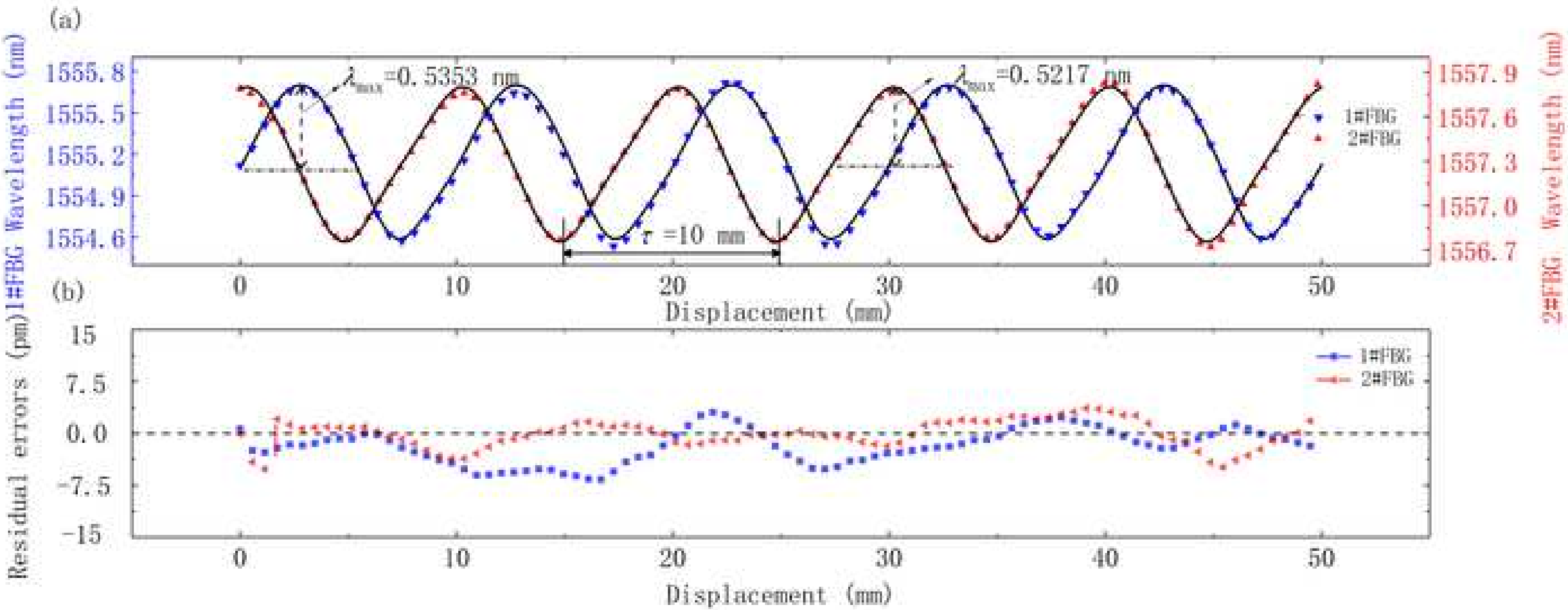
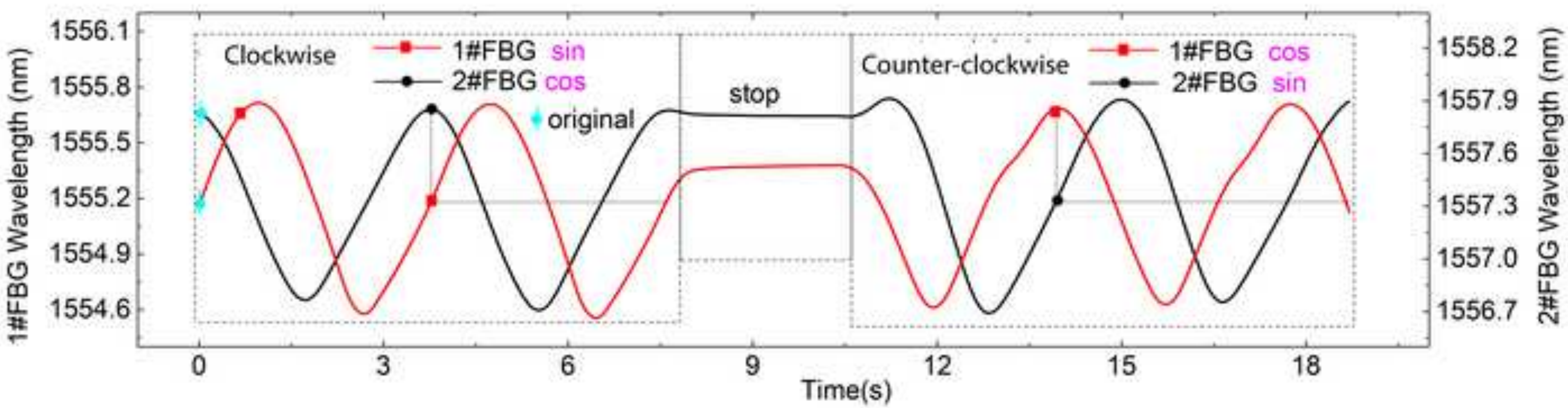

(a)
1#FBG Wavelength (nm)
1555.8
1555.5
1555.2
1554.9
1554.6
λmax=0.5353 nm
λmax=0.5217 nm
τ =10 mm
1#FBG
2#FBG
2#FBG Wavelength (nm)
1557.9
1557.6
1557.3
1557.0
1556.7
0
10
20
30
40
50
Displacement (mm)
(b)
Residual errors (pm)
15
7.5
0.0
-7.5
-15
1#FBG
2#FBG
Displacement (mm)

Figure 6



1#FBG Wavelength (nm)
1556.1
1555.8
1555.5
1555.2
1554.9
1554.6
Clockwise
1#FBG sin
2#FBG cos
original
stop
Counter-clockwise
1#FBG cos
2#FBG sin
2#FBG Wavelength (nm)
1558.2
1557.9
1557.6
1557.3
1557.0
1556.7
0
3
6
9
12
15
18
Time(s)

Fig.7

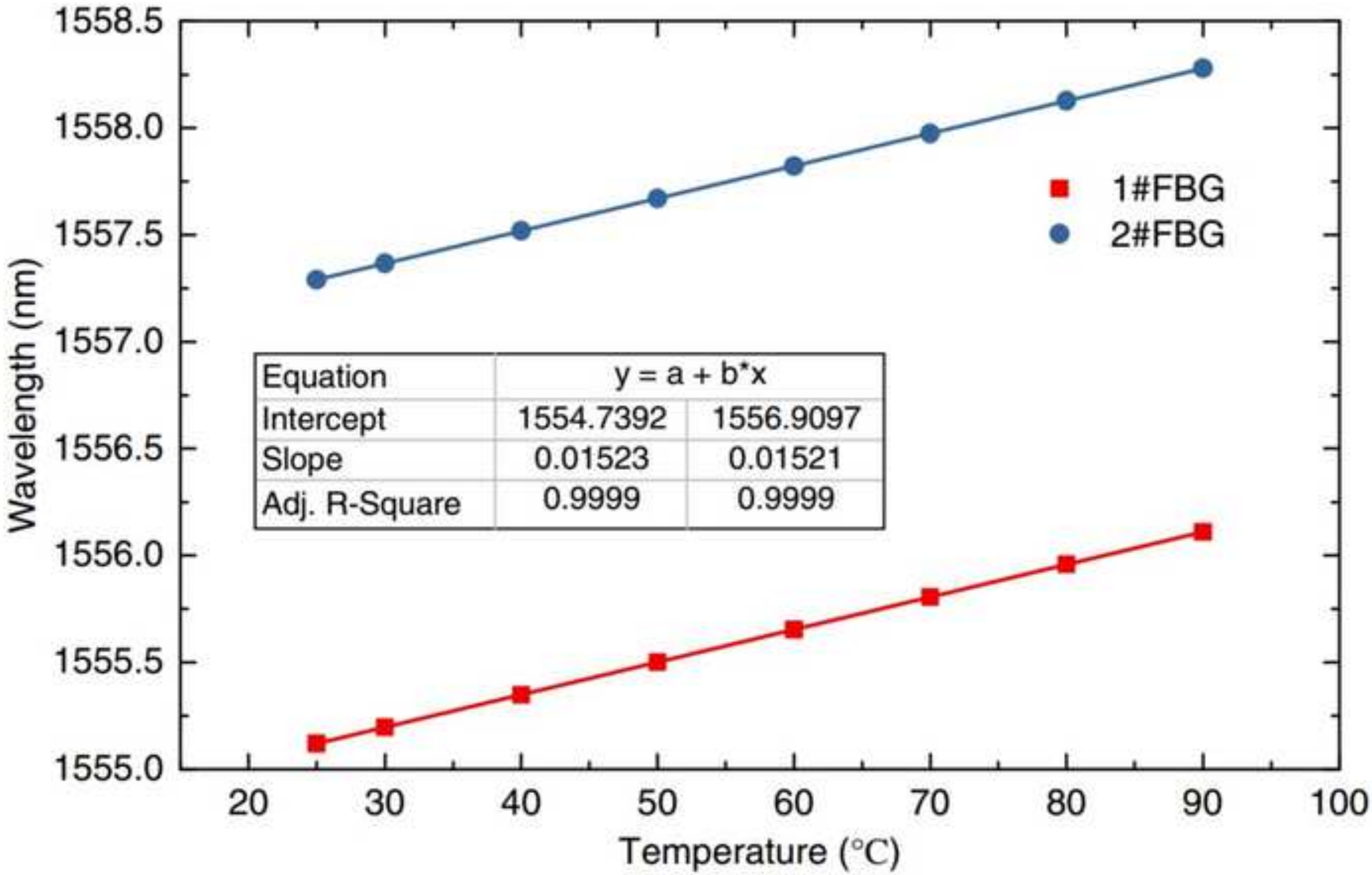
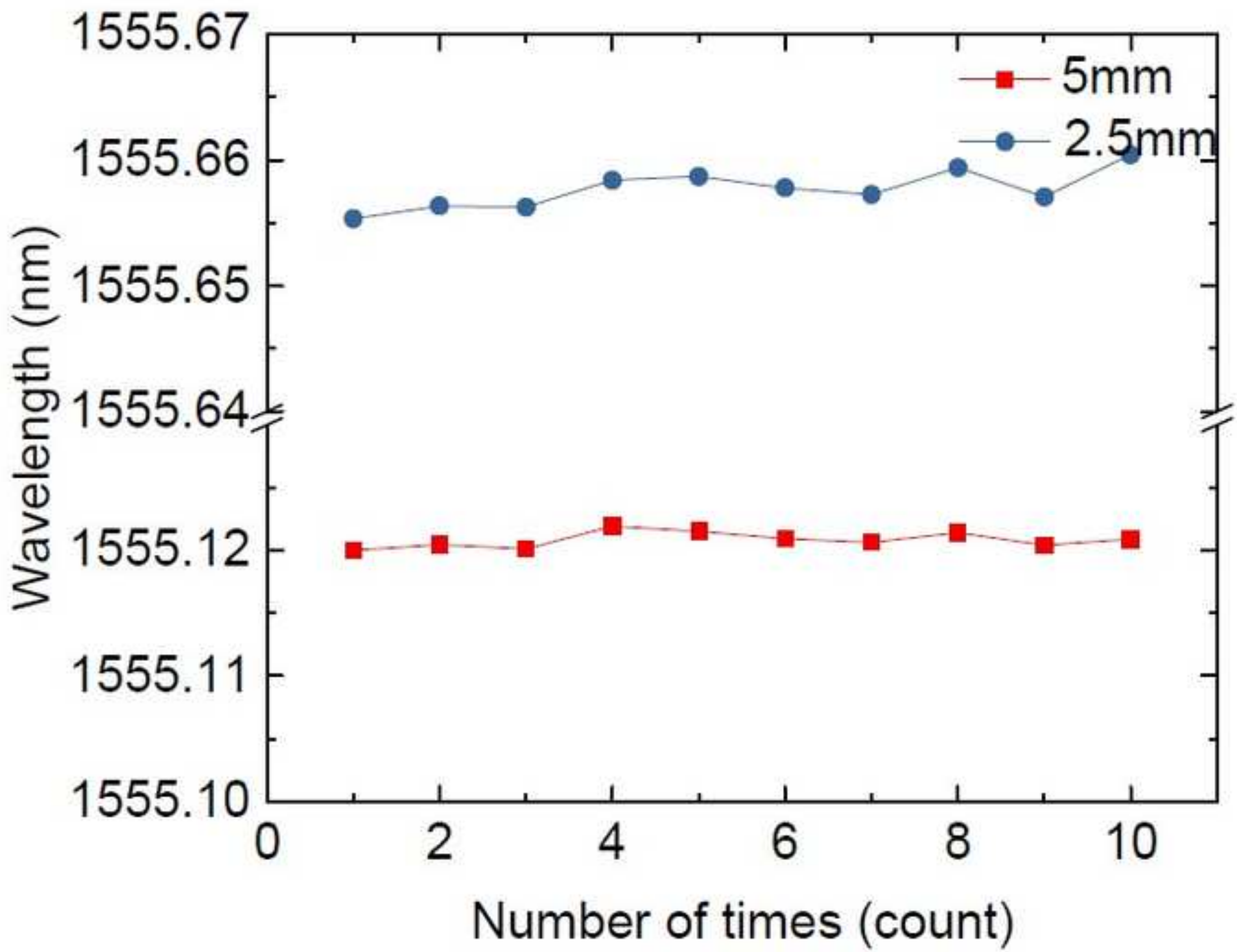

1558.5
1558.0
1557.5
1557.0
1556.5
1556.0
1555.5
1555.0
Wavelength (nm)
20
30
40
50
60
70
80
90
100
Temperature (°C)
1#FBG
2#FBG
Equation | y = a + b*x
Intercept | 1554.7392 | 1556.9097
Slope | 0.01523 | 0.01521
Adj. R-Square | 0.9999 | 0.9999

Fig.8


1555.67
1555.66
1555.65
1555.64
1555.12
1555.11
1555.10
Wavelength (nm)
0
2
4
6
8
10
Number of times (count)
5mm
2.5mm

Name	Parameters
Magnetic Grade	N35
Magnet Material	NdFeB
Surface & Coating	Nickel
Magnetizing direction	N/S pole on both sides of the plane
Size	D5 x 4 mm
M(magnetization)	750 [kA/m]

Type	Steps	Displacement/step (µm)
A	1,600	312
B	2,000	250
C	3,200	156
D	4,000	125
E	6,400	78
F	12,800	40

Name of Material/ Equipment	Company	Comments/Description
ASE	OPtoElectronics Technology Co., Ltd.	1525nm-1610nm
computer	Thinkpad	win10
fiber cleaver/ CT-32	Fujikura	the diameter of 125
fiber optic epoxy /DP420	henkel-loctite	Ratio 2:1
interrogator	BISTU	sample rate:17kHz
motor driver	Zolix	PSMX25
optical circulator	Thorlab	three ports
optical couple	Thorlab	50:50
optical spectrum analyzer/OSA	Fujikura	AQ6370D
permanent magnet	Shanghai Sichi Magnetic Industry Co., Ltd.	D5x4mm
plastic shaped pipe	Topphotonics	
power source	RIGOL	adjustable power
single mode fiber	Corning	9/125um
Spring	tengluowujin	D3x15mm
stepper motor controller		JF24D03M

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Author(s): Lianqing Zhu, Lidan Lu, Wei Zhuang, Zhoumo Zeng, Mingli Dong

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Dear Editor and Reviewers:

Thank you for your letter and for the reviewer' comments concerning our manuscript entitled '*An approach for random displacement measurement by combining magnetic scale and Two Fiber Bragg Gratings*' (ID: JoVE58182). Those comments are all valuable and very helpful for revising and improving our paper, as well as the important guiding significance to our researches. We have studied comments carefully and have made correction which we hope to meet with approval. Revised portion are marked in red in the paper. The main corrections in the paper and the responds to the editor's comments are as flowing:

Responds to the editor's comments:

1. Figure 1 says 21.25 mm??.

Answer: A distance of 22.5 mm ((2+1/4) * τ) is set between the two detectors, where τ equals to 5 mm, thus, picture 1 says 22.5 mm, which has been revised.

2. Figure 5a says .4948 nm? Where does 0.5217 come from? This should be moved to the Representative Results.

Answer: 0.5217 is obtained from data with Fitting tools in Matlab, thus, picture 5a says 0.5217nm, which has been revised.

Pro. Mingli Dong
2018/11/4

Dear Prof. Mingli Dong,

Thank you for contacting The Optical Society.

For the use of material from Lianqing Zhu, Lidan Lu, Wei Zhuang, Zhoumo Zeng, and Mingli Dong, "Non-contact temperature-independent random-displacement sensor using two fiber Bragg gratings," Appl. Opt. 57, 447-453 (2018):

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Let me know if you have any questions.