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Zhongchao Qiu

Institute of Geophysics, China Earthquake Administration

Jinquan Zhang (✉ zhangjinquan1997@163.com)

Institute of Disaster Prevention

Yuntian Teng

Institute of Geophysics, China Earthquake Administration

Zhitao Gao

Institute of Disaster Prevention

Hong Li

Institute of Disaster Prevention

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Hinge-type FBG Acceleration Sensor Based on Double Elastic Plate

Zhongchao Qiu^{1,2,3}, Jinquan Zhang^{2,3}, Yuntian Teng^{1,3}, Zhitao Gao³, Li Hong³

(1.Institute of Geophysics,China Earthquake Administration, Beijing 100081, China;

2. Hebei Key Laboratory of Earthquake Dynamics, Sanhe 065201, China;

3.Institute of Disaster Prevention, Sanhe 101601, China;)

Correspondence and requests for materials should be addressed to Jinquan Zhang. (1997-, male, from Yantai City, Shandong Province, graduate student, research direction is disaster monitoring technology and engineering safety, E-mail: zhangjinqun1997@163.com) and Yuntian Teng. (1966-, male, from Lanxi City, Zhejiang Province, Ph.D., researcher, research direction is geomagnetic observation technology and instruments, E-mail: hongli_cidp@163.com).

Abstract: It is critical for the health monitoring of large-scale structures such as bridge, railway and tunnel to acquire the medium-frequency and high-frequency vibration signals. To solve the problems of low sensitivity and poor transverse anti-interference of the medium-frequency and high-frequency fiber acceleration sensor, a hinge-type Fiber Bragg Grating(FBG) acceleration sensor based on double elastic plate has been proposed, and the hinge and elastic plate are used as elastomer to realize the miniaturization and transverse interference suppression of the sensor. The MATLAB and the ANSYS are used for theoretical analysis and optimization of sensor sensitivity and resonance frequency, structural static stress analysis and modal simulation analysis, while the test system is built to test the sensor performance. The results show that the resonance frequency of the sensor is 1300 Hz; the sensor has a flat sensitivity response in the middle-high frequency band of 200-800 Hz; the sensitivity is about 20 pm/g, and the fiber central wavelength drift and acceleration have good linearity and stability, while the transverse anti-interference is about 3.16%, which provides a new idea for monitoring of medium-frequency and high-frequency vibration signals in large-scale structures.

Keywords: Fiber Bragg Grating; hinge; acceleration sensor; double elastic plate

1. Introduction

The medium-frequency and high-frequency vibration performance will affect the structural health of large-scale infrastructure such as bridge, track and railway significantly^[1-3]. The acceleration measurement, as an important technical means to monitor the medium-frequency and high-frequency vibration performance of engineering structures, can reflect the vibration situation of several large-scale structures^[4,5]. At this stage, the electric sensor is the main instrument for acceleration measurement, and is characterized with low cost, small volume and relatively mature technology^[6]; however, in the complex situations, it also has disadvantages of poor circuit stability, large signal noise and being is susceptible to electromagnetic interference^[7,8]. Compared with the traditional electrical acceleration sensor, FBG acceleration sensor has the better sensitivity and linearity, better anti-electromagnetic interference and stability, easier distribution and

measurement based on several parameters^[9-11]. Therefore, FBG acceleration sensor is promising in the engineering application of acceleration detection.

Tianliang Li et al.^[12] put forward a diaphragm-type FBG acceleration sensor, which can improve the sensitivity and resonance frequency of the fiber based on the axial characteristics of the suspended fiber of diaphragm structure with a acceleration sensitivity of 20.189 pm/g and a resonance frequency of 600 Hz, as well as a cross-axis sensitivity less than 3.31% for low cross sensitivity. However, it has low linearity of 0.764% and bandwidth of 10~200 Hz, which cannot meet the needs of medium-frequency and high-frequency engineering structure. Khan M M et al.^[13] proposed a FBG acceleration sensor based on cantilever beam structure with L-shaped non-even cross section, which can realize the temperature self-compensation with double FBG. When the resonance frequency is higher than 150 Hz, the sensitivity of the sensor is 0.5%, but when the resonance frequency is lower than 50 Hz, such sensitivity is only 0.5%. Casas-Ramos et al.^[14] put forward a new cantilever-type FBG vibration sensor with a resonance frequency of 227.3 Hz, operation bandwidth of 10-210 Hz, a resolution of 0.006 g, a linearity and relative sensitivity error of 1.9% and $\pm 4.4\%$ respectively. Li Y et al.^[15] proposed a grating fiber acceleration sensor with high sensitivity and large measurement range based on the elliptical flexible hinge structure, a resonance frequency of 356 Hz, a measurement frequency of 0~89 Hz and a sensitivity of 284 pm/g. Bing Yan et al.^[16] put forward a new FBG acceleration sensor based on parallel double flexible hinges, which is formed by two right circular flexible hinges connected in parallel with a measurement range of 30-200 Hz and a sensitivity of 54 pm/g. However, the existing FBG acceleration sensor is widely used in the studies on medium-low frequency, but is insufficient in the field of medium-high frequency, while the medium-frequency and high-frequency acceleration sensor is high in resonance frequency and limited in sensitivity, while there is transverse interference.

This paper presents a hinge-type FBG acceleration sensor based on double elastic plate, which can realize the miniaturization and transverse interference suppression of the sensor with the hinge and the elastic plate as elastomer. The MATLAB and the ANSYS are used for the theoretical analysis and optimization of sensitivity and resonance frequency, the static stress analysis of the structure and modal simulation of sensor structure. The physical sensor has been made based on the simulation results and subject to the experimental measurement in performance.

2. Sensor design

2.1 Sensor structure

The FBG sensor consists of the upper cover, pressure block, rectangular spring, pressure pad, column, elastic body and base as shown in Fig.1, of which the column, upper cover and base are connected through screws, and the screws run through the gasket, rectangular spring and threaded

hole on the column to fix the rectangular spring firmly. With the rectangular springs fixed in the upper and lower ends, the sensor structure can be more stable, and the vibration interference in the non-sensitive direction can be reduced. The elastic body is integral, and there is square hole for space required by fiber vibration reserved at the lower end of base column, and the mass blocks at both ends are connected with each other through the flexible elliptical hinge and middle base. There are through holes arranged in the relevant positions of the housing at both ends of the elastic body. FBG is placed in the groove of the mass block upon a pre-stressing force is imposed to a certain extent, while two ends are fixed through UV glue.

Fig.1 Sensor Structure Model

In the measurement, the sensor is placed horizontally through the circular hole of the base. When the measured object vibrates, the pressing block and the elastic body deform the elastic plate under the action of inertia, and the deformation of the elastic plate is transmitted to the mass block in the elastic body. The FBG is connected with the mass block and the base under two-point packaging technique, and the FBG is suspended between them. In case of vibration of the mass block, two mass blocks will rotate slightly in an opposite direction around the hinge, and the FBG is stretched or compressed, while its central wavelength will drift. The relationship between the central wavelength of the strain is expressed as:

$$\frac{\Delta\lambda}{\lambda} = (1 - P_e)\varepsilon + (\alpha_\lambda + \alpha_n)\Delta T \quad (1)$$

Where, λ is the central wavelength of FBG; P_e is the photoelastic coefficient; α_λ is the coefficient of thermal expansion; α_n is the thermal optical coefficient.

As FBG is sensitive to both strain and temperature, the temperature variation should be controlled within a small range in the experiment.

2.2 Sensor sensitivity analysis

Fig.2 Mechanical Model of Sensor

The mechanical model of the sensor is shown in Fig.2. When the incentive acceleration is along the vertical direction of the sensor, two columns can be considered as a rigid body, since the deformation of hinge in the elastic body is greater than that of the column end, and with the flexible hinge replaced by the ideal hinge, the torque balance can be realized for the whole system under the inertia effect, and the balance equation can be expressed as:

$$2m_1ad_1 + 2m_2ad_2 - 2k_1\Delta l_1 - k_f\Delta l_f \frac{h}{2} - 2k_2\theta = 0 \quad (2)$$

Where, m_1 and m_2 are the mass of the pressure block and mass block; d_1 and d_2 are the distance of the pressure block and the center of mass block from the hinge center; Δl_1 is the displacement of the elastic plate; Δl_f is the stretching distance of the fiber; h is the height of the mass block; k_f , k_1 and k_2 represent the elastic coefficient of the fiber, the elastic coefficient of the elastic plate and the hinge rotation stiffness respectively, and θ is the central hinge rotation angle. The semi-major axis of elliptical hinge is b . Since low hinge rotation angle, the following can be obtained:

$$\theta = \frac{2\Delta l_f}{h} \quad (3)$$

When the length of the pressure block is e_1 ; that of the mass block is e_2 , and that of the elastic base is e_3 , it can be obtained that $d_1 = b + e_1/2$, $d_2 = b + e_2/2$, $l_f = 4b + e_3$ and $\Delta l_1 = (2b + e_2)\theta$.

The elastic coefficient of the fiber k_f is

$$k_f = \frac{A_f E_f}{l_f} \quad (4)$$

Where, A_f is the cross sectional area of the fiber, and E_f is the elastic modulus of the grating. With the rectangular elastic plate used, the transverse vibration interference can be reduced. The elastic coefficient of the elastic plate can be expressed as:

$$k_1 = \frac{E_1 b_1 t_1^3}{6l_1^3} \quad (5)$$

Where, E_1 is the elastic modulus of the elastic plate with equal strength; b_1 is the bottom width of the elastic plate with equal strength; t_1 is the thickness of the elastic plate with equal strength; l_1 is the length of the elastic plate with equal strength.

The rotational stiffness is critical for the sensor, and based on the theoretical formula of hinge stiffness, the rotational stiffness of the hinge can be expressed as:

$$k_2 = \frac{Ewt_2^3}{24bu} \quad (6)$$

Where

$$u = \frac{12s^3 + 14s^2 + 6s + 1}{(2s + 1)^2 (4s + 1)^2} + \frac{6s(2s + 1)}{(4s + 1)^{5/2}} \arctan \frac{1}{\sqrt{4s + 1}} + \frac{6s(8s^3 + 12s^2 + 6s + 1)}{(2s + 1)^2 (4s + 1)^{5/2}} \arctan \frac{2s}{\sqrt{4s + 1}} \quad (7)$$

Where, E is the elastic modulus of the material; w is the thickness of the hinge; c is the semi-minor axis of the elliptical hinge; t_2 is the minimum thickness between hinges; the sensor sensitivity is the ratio of the central wavelength variation of the FBG to the acceleration, and the following can be obtained from the equations (1) and (2)

$$S = \frac{\Delta\lambda}{a} = \frac{(1 - P_e)\lambda_B}{l_f} \frac{4(m_1 d_1 + m_2 d_2)h}{8k_1(2b + e_2) + 4k_2 + k_f h} \quad (8)$$

Where, P_e is the elastic-optic coefficient; λ_B is the central wavelength of the grating; ε_f is the fiber strain; the sensitivity below is the peak-peak sensitivity $2S$.

2.3 Sensor sensitivity analysis

The resonance frequency f is another important parameter of the acceleration sensor, and it is closely related to the available bandwidth of the sensor. In general, the higher resonance frequency leads to wider available bandwidth of the sensor. It is assumed that the rotational inertia of the mass block around the hinge center is J . The potential energy of strain of the fiber can be:

$$J\ddot{\theta} + [2k_1(e_2 + 2b)^2 + k_f(h/2)^2 + 2k_2]\theta = 0 \quad (9)$$

After the equation (8) is substituted into the kinetic equation, the resonance frequency of the whole system is:

$$f = \frac{1}{2\pi} \sqrt{\frac{2k_1(e_2 + 2b)^2 + k_f(h/2)^2 + 2k_2}{J}} \quad (10)$$

Where, the rotational inertia is

$$J = m_1 \frac{e_2^2 + h^2}{12} + m_1 d_1^2 \quad (11)$$

3. Sensor structure simulation analysis

3.1 Influence of structural parameters on the sensor

From equations (9) and (10), it can be known that some key parameters of the sensor, including the minimum thickness between hinges t_2 , the semi-minor axis of the elliptical hinge c , the semi-major axis of the elliptical hinge b , the bottom width of the elastic plate b_1 and the thickness of the elastic plate t_1 , all can influence the sensitivity and resonance frequency significantly, and these parameters can be adjusted greatly in the fabrication of the sensor. Upon analysis on five parameters with MATLAB under the sensor material of 65Mn, the elastic modulus is 210 GPa; the density is 7850 kg/m³; the sensor width is 7mm; the elastic modulus of the fiber is 72 GPa; the effective elastic-optic coefficient is 0.22; the central wavelength of the FBG is 1550 nm, and the length is 5 mm.

The influence of b and c on the sensor sensitivity and resonance frequency when $t = 0.5$ mm, 1.0 mm and 1.5 mm has been discussed in the first group, and after it is assumed that $b_1 = 5$ mm, $t_1 = 0.5$ mm, $1 \text{ mm} \leq b \leq 5 \text{ mm}$ and $1 \text{ mm} \leq c \leq 5 \text{ mm}$, the sensor sensitivity is obtained as shown in Fig.3 (a) and the resonance frequency is shown in Fig.3 (b).

(a) Change of sensitivity with b and c under different t

(b) Change of resonance frequency with b and c under different t

Fig.3 Influence of Parameters b and c on Sensor Performance

From Fig.3, it can be known that the minimum thickness of the hinge t , the semi-major axis of the elliptical hinge b and the semi-minor axis of the elliptical hinge c can influence the sensor sensitivity and resonance frequency significantly. When the sensitivity b is increased, the resonance frequency will be decreased, and when c is increased, the sensitivity and resonance frequency are increased. When t is increased, the resonance frequency is increased greatly. To meet the measurement needs of the sensor, the resonance frequency is within 1600 Hz, and the sensitivity is greater than 12 pm/g, while it is required that $c < 3$ mm and $b > 2$ mm.

The influence of b_1 and t_1 on the sensor sensitivity and resonance frequency when $t = 0.5$ mm, 1.0 mm and 1.5 mm has been discussed in the second group, and after it is assumed that $c = 2.5$ mm, $b = 2.5$ mm, $3 \text{ mm} \leq b_1 \leq 7 \text{ mm}$ and $0.3 \text{ mm} \leq t_1 \leq 0.8 \text{ mm}$, the sensor sensitivity is obtained as shown in Fig.4 (a) and the resonance frequency is shown in Fig.4 (b).

(a) Change of sensitivity with b_1 and t_1 under different t

(b) Change of resonance frequency with b_1 and t_1 under different t

Fig.4 Influence of Parameters b_1 and t_1 on Sensor Performance

From Fig.4, it can be known that the minimum thickness of the hinge t , the bottom width of the elastic plate b_1 and the thickness of the elastic plate t_1 can influence the sensor sensitivity and resonance frequency significantly. When b_1 and t_1 is increased, the sensitivity will be increased, and the resonance frequency will be decreased. When t is increased, the resonance frequency will be increased greatly. To meet the measurement needs of the sensor, the resonance frequency is within 1600 Hz, and the sensitivity is greater than 12 pm/g, while it is required that $t=1.0$ mm, $b_1 > 4$ mm and $t_1 > 0.4$ mm.

3.2 ANSYS simulation analysis

From the analysis on structural parameters, it can be known that the sensor sensitivity and resonance frequency will be influenced significantly when the semi-major axis of the elliptical hinge b , the semi-minor axis of the elliptical hinge c , the bottom width of the elastic plate b_1 and the thickness of the elastic plate t_1 change little. Based on the needs of engineering application, it should be ensured that the resonance frequency is lower than 1600 Hz, and the sensitivity is higher than 12 pm/g. At the same time, since the size and weight of the sensor, it is required that $t = 1.0$ mm, $b = 2.5$ mm, $c = 3$ mm, $b_1 = 5.0$ mm and $t_1 = 0.5$ mm. ANSYS is used for static stress and modal simulation of the sensor parameters. Table 1 presents the sensor parameters.

Table 1 Parameters of FBG Acceleration Sensor

Name	Description	Length (mm)
t	Minimum thickness between hinges	1.0
c	Semi-short axis of the elliptical hinge	3.0
b	Semi-major axis of the elliptical hinge	2.5

b_1	Width of the elastic plate	5.0
t_1	Thickness of the elastic plate	0.5

The sensor is modeled with the structural parameters obtained by the optimization as above, and it should be imported into ANSYS for simulation analysis. Firstly, the model is imported into ANSYS, and the fixed constraint is applied to the sensor model, while 1 g external acceleration load is applied to the whole sensor to obtain the equivalent strain cloud of the model as shown in Fig.5. From Fig.5, it can be known that there is the maximum deformation from the free end of the sensor, and the deformation is decreased to the fixed end. With the maximum deformation of the free end of 0.15, it indicates that the response of external vibration signal can be realized by the sensor structure, and the deformation has no influence on the physical performance of the fiber, and the stability of the sensor can be guaranteed.

Fig.5 Static Stress Analysis of Sensor Structure

The modal analysis is made on the sensor model based on the results of static stress analysis, and the fixed constraint is applied to the base, while the mesh generation is built for the whole model. Upon the modal analysis on the model, the modal frequencies of the first four orders of the sensor can be obtained, and are 1460.3 Hz, 1717.8 Hz, 2251.5 Hz, and 2675.0 Hz, respectively. The first-order and second-order modals as shown in Fig.6. From Fig.6, it can be seen that the resonance frequency of each order of the sensor is different greatly, which shows that the structural sensor has small cross coupling and this can reduce the cross interference.

(a) First-order Modal

(b) Second-order Modal

Fig.6 Modal Analysis on Sensor Structure

4. Sensor test and analysis

The sensor test system mainly includes the function signal generator, signal amplifier, vibrator, FGB interrogator and computer as shown in Fig.7. The function signal generator is of RIGOL series DG1022 model with a sampling frequency of 1 GSa/a, 14 quasi-waveform functions and rich standard configuration interfaces, which can support the users to remotely control the instrument and transmit the data of USB interface through Web. The signal amplifier is of MWY-TZQ50 model from Beijing Weiyun Technology Co., Ltd. with a frequency response range of 1-15000 Hz and a signal-to-noise ratio higher than 75 dB. If it is used with a function signal generator, the function signal can be amplified. The FBG interrogator is of MWY-FBG-CS800 model from Beijing Weiyun Technology Co., Ltd. with a sampling frequency up to 1 kHz, and there is a built-in laser light source, and the light wave emitted is transmitted to the acceleration sensor on the vibrator system through the fiber. Meanwhile, the FBG interrogator can receive the reflection spectrum of FBG, and can finish the spectrum analysis and data acquisition in it, and finally send the data acquired to the computer. With the above equipment, the FBG acceleration sensor test system can be built. The amplitude-frequency characteristics, sensitivity coefficient, stability and transverse anti-interference capability of the sensor can be tested in performance with the system, and the performance parameters of the sensor are obtained.

(a) Flow Chart of Experimental System

(b) Real Picture of Experiment System

Fig.7 Sensor Vibration Test System

4.1 Amplitude-frequency characteristic test

The frequency band range of the sensor depends on the frequency-response curve, so the developed sensor must be calibrated dynamically. The acceleration 10 m/s^2 should be input in the amplitude-frequency test in the sensor as a constant acceleration value. Firstly, the wavelength variation of the sensor under FBG of 100 Hz is measured, and then the wavelength variations should be recorded every progressive increase of 100 Hz as 1 step from 100 Hz. The time-domain response curves of the sensor at 400 Hz and 1100 Hz are shown in Fig.8, while the amplitude-frequency characteristic curve of the sensor is shown in Fig.9.

Fig.8 Frequency Response of the Sensor at 400 Hz and 1100 Hz

Fig.9 Amplitude-frequency Response Characteristics of Sensor

From Fig.8, it can be known that the sensor has the good time-domain response characteristics. From Fig.9, it can be seen that the sensor is up to the maximum wavelength variation at about 1300 Hz, which means that the resonance frequency of the sensor is approximately 1300 Hz. There is a relatively good flatness at 200-800 Hz, and there is a certain error between the actual measured resonance frequency of the sensor and the simulation result upon the theoretical analysis. This is because: (1) the acceleration sensor is small in size and the hinge structure is partially thin, and there is a certain error for insufficient accuracy of processing; (2) no pre-stressing force is considered in the finite element method, and the degree of pre-stressing force applied and the symmetry of UV glue at two sides will affect the hinge rotation and resonance frequency of the sensor at the time of fiber adherence; (3) the vibrator and demodulating system accuracy will lead to a certain error of the test data.

4.2 Sensitivity coefficient test

To obtain the sensitivity characteristics of the sensor, 200 Hz, 400 Hz and 600 Hz are used as test frequencies for sensor sensitivity calibration, and the acceleration step of the vibrator is changed to 2 m/s^2 and is increased from 2 m/s^2 to 20 m/s^2 , while FBG change data at the central wavelength of different accelerations is recorded, and the central wavelength variation curve is drawn as Fig.10.

Fig.10 Sensor Sensitivity Calibration Curve

From Fig.10, it can be known that the sensor sensitivity is 19.25 pm/g under the frequency of 200 Hz, and the coefficient of fitting determination is $R^2=0.9977$. When the frequency is 400 Hz, the sensor sensitivity is 19.55 pm/g, and the coefficient of fitting determination is $R^2=0.9990$. When the frequency is 600 Hz, the sensitivity is 20.3 pm/g, and the coefficient of fitting determination is $R^2=0.9981$. From this, it can be known that the sensor has good linearity.

4.3 Stability test

To test the sensor stability, the output frequency of the vibrator is adjusted to be 400 Hz and 600 Hz respectively, and the accelerations are 6 m/s^2 , 10 m/s^2 and 14 m/s^2 . The output of the sensor is recorded every half an hour. In this test, the relative standard deviation RSD is used to represent the repeatability error of the sensor, and it is expressed as:

$$RSD = \frac{SD}{\bar{x}} \times 100\% = \frac{\sqrt{\frac{\sum_{i=1}^n (x_i - \bar{x})^2}{n-1}}}{\bar{x}} \times 100\% \quad (12)$$

Where, SD is the standard deviation, and $\bar{x}$ is the corresponding mean value.

The test results are shown in Fig.11. When the frequency is 400 Hz, the relative standard deviations of FBG central wavelength drift corresponding to 6 m/s^2 , 10 m/s^2 and 14 m/s^2 are 1.71%, 1.60% and 1.36%, respectively. When the frequency is 600 Hz, the relative standard deviations of the corresponding FBG central wavelength drift are 1.37%, 1.41%, and 1.38%, respectively. Therefore, we can know that there is small repeatability error of the sensor and good stability.

Fig.11 Sensor Stability

4.4 Transverse anti-interference capability

As FBG acceleration sensor has a single degree of freedom, its transverse anti-interference capability is one of important indexes of the sensor. However, the double elastic plate structure designed in this paper is characterized with reduction of transverse rotation and increase of transverse anti-interference of the sensor. The sensor is fixed on the vibrator, and the frequency and the acceleration are adjusted to be 400 Hz and 10 m/s² respectively. In the same vibration environment, the drift of FBG central wavelength under the transverse vibration and longitudinal vibration of the sensor is recorded, while the transverse anti-interference characteristics of the sensor are shown in Fig.12.

Fig.12 Transverse Characteristics of the Sensor

From Fig.12, it can be seen that the drift in a sensitive direction of the sensor is approximately 31.6 pm, and that in a non-sensitive direction will not be more than 1.0 pm, while the wavelength drift in a non-sensitive direction of sensor is only 3.16% of that in a sensitive direction. With the good sensitivity, the relatively strong transverse anti-interference can be realized.

5. Conclusion

To solve the problems of low sensitivity and poor transverse anti-interference of the medium-frequency and high-frequency fiber acceleration sensor, a hinge-type FBG acceleration sensor based on double elastic plate has been proposed. The MATLAB is used for theoretical analysis and optimization of sensor sensitivity and resonance frequency, as well as the analysis and optimization of hinge thickness, hinge radius, mass block size and other structural parameters of the sensor, and the ANSYS is utilized for the structural static stress analysis and modal simulation analysis, while the test system is built to test the sensor performance. The results show that the resonance frequency of the sensor is 1300 Hz; the sensor has a flat sensitivity response in the middle-high frequency band of 200-800 Hz; the sensitivity is appropriately 20 pm/g, and the fiber central wavelength drift and acceleration have good linearity and stability, while the

transverse anti-interference is appropriately 3.16%, which provides a new idea for monitoring of medium-frequency and high-frequency vibration signals in large-scale structures.

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Author Contributions

Z.Q. Supervision on manuscript writing and analyses, J.Z. and Y.T. Design the sensor structure, be responsible for the sensor experiment and wrote the main manuscript text. and Z.G. and L.H. Processing of sensor parts, analysis of experimental results and prepared Figs. 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12. All authors reviewed the manuscript

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