Design of Resonant Magnetic Field Sensor Based on Magnetostrictive Optical Fiber Micro-cantilever

Cheng Xu, Yueming Liu, and Yuchan Liu

Abstract In this paper, a magnetostrictive-based optical fiber micro-cantilever resonant magnetic field sensor is proposed. The magnetic field sensor is based on the optical fiber end face design of the optical fiber micro-cantilever beam. The surface of the optical fiber micro-cantilever beam is plated with a magnetostrictive film, and the two form a double layer micro-cantilever beam structure. The magnetostrictive film generates a magnetostrictive effect under a magnetic field, which causes the double-layer cantilever structure to deflect and change its resonant frequency. The magnetic field can be determined by detecting the change in resonant frequency. Then use ANSYS simulation software to simulate the resonance frequency of the double-layer micro-cantilever structure under the magnetic field, and obtain the relationship between the magnetic field and the resonance frequency, in order to optimize the size of the double-layer cantilever structure, and then obtain the best sensitivity of the magnetic field sensor. The simulation results show that: when the double-layer micro-cantilever structure is 90 μm long, the thickness of the fiber-optic micro-cantilever is 2 μm, and the thickness of the magnetostrictive film is 3/5 of the thickness of the fiber-micro-cantilever, the magnetic field sensor can reach the maximum sensitivity of 40,760 Hz/Gs.

Keywords Optical Fiber Micro-cantilever · Mgnetostrictive Film · ANSYS · Resonance

1 Introduction

Magnetic field sensors are devices that convert magnetic fields and their changes into other signals and output them, which is closely related to human life and has a wide range of applications in production, scientific research, and military. A traditional

C. Xu · Y. Liu (✉) · Y. Liu
China Jiliang University, HangZhou, China
e-mail: 07a0402054@cjlu.edu.cn

Y. Peng and X. Dong (eds.), *Proceedings of 2019 International Conference on Optoelectronics and Measurement*, Lecture Notes in Electrical Engineering 726,
https://doi.org/10.1007/978-981-33-4110-4_29

magnetic field sensor is a device that converts a magnetic field and its variation into an electrical signal output. For example, magnetic flux gages, Hall sensors, etc. Magnetic flux gages use the non-linear relationship between magnetic induction and magnetic field strength to measure the magnetic field under the saturation excitation of a high-permeability magnetic core in the measured magnetic field. The magnetic field is measured using a linear relationship between the Hall potential and the magnetic field. And these traditional magnetic field sensors use electric current when transmitting electrical signals. The magnetic effect of the generated current will interfere with the magnetic field to be measured, causing the sensor to generate errors when measuring the magnetic field. The optical fiber magnetic field sensor overcomes this shortcoming. Using the characteristics of all-optical fiber transmission, the magnetic field signal is converted into an optical signal, which eliminates the interference of the magnetic effect of the current on the magnetic field detection. The sensor probe is made on the sensor, so that the sensor is miniaturized, and the magnetic field in small and narrow places can be measured.

In this paper, a magnetostrictive-based optical fiber micro-cantilever resonant magnetic field sensor is proposed. The magnetic field sensor is based on the optical fiber end face design of the optical fiber micro-cantilever beam. The surface of the optical fiber micro-cantilever beam is plated with a magnetostrictive film, and the two form a double layer micro-cantilever beam structure. The magnetic field sensor uses a double-layer micro-cantilever structure as a magnetic field sensing element.The magnetostrictive film generates a magnetostrictive effect under a magnetic field, which causes the double-layer cantilever structure to deflect and change its resonant frequency. The magnetic field can be determined by detecting the change in resonant frequency, of the double-layer micro-cantilever structure in the magnetic field sensor, the resonance of the double-layer micro-cantilever structure under the magnetic field was simulated, and the structure was optimized to obtain higher sensitivity.

2 Resonance Theoretical Model of Double-Layer Micro-cantilever

Cantilever structure is a widely used structure in sensors, which has been used in biological, chemical, acceleration, humidity, force, heat and other sensors. When used as a sensor, it has two working modes: static and resonant. For the resonant mode, the resonant frequency of the cantilever beam is usually changed based on factors such as surface stress and mass. The working principle of the magnetic field sensor proposed in this article is: the double-layered micro-cantilever structure plated with a magnetostrictive film is affected by the magnetic field, and the magnetostrictive effect of the upper layer of the magnetostrictive film causes the magnetostrictive film and the optical fiber micro-cantilever. There is a mismatch between the stresses [1], which causes the double-layered micro-cantilever structure to deflect, which causes the resonance frequency of the double-layered micro-cantilever structure to change,

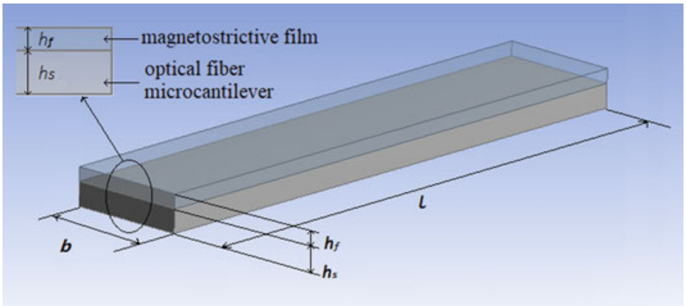

Fig. 1 The structure of double-layer micro-cantilever beam

and the magnetic field can be detected by detecting the change of the resonance frequency.

Based on the important role of the double-layer micro-cantilever structure, we analyze the resonance of the double-layer micro-cantilever structure under the influence of magnetic field. The structure of a double-layer micro-cantilever beam is shown in Fig. 1. The double-layer micro-cantilever structure has a length of l and a width of b; the thickness of the optical fiber micro-cantilever is h_s, the density is ρ_s, the Young's modulus is E_s, and the Poisson ratio is v_s; The thickness of the magnetostrictive film is h_f, the density is ρ_f, the Young's modulus is E_f, and the Poisson's ratio is v_f. Ignoring the effects of gravity and other factors, when the double-layer micro-cantilever structure is not affected by the magnetic field, the magnetostrictive film does not produce a magnetostrictive effect, and the double-layer cantilever beam remains straight.

First, we discuss the resonant frequency of a single-layer micro-cantilever. The resonance frequency of a uniform, flat and thin cantilever beam can be solved by the one-dimensional Euler–Bernoulli differential equation. For a micro-cantilever with a length of l, a width of b, and a thickness of h, the differential equation of motion is:

$$\tilde{E}I\frac{\partial^4 z(x,t)}{\partial x^4} = -\rho A\frac{\partial^2 z(x,t)}{\partial t^2} \tag{1}$$

where $\tilde{E} = E/\left(1 - v^2\right)$,$\tilde{E}$ is Biaxial tensile Young's modulus [2-3]; I is moment of inertia, $I = bh^3/12$;A is the cross-sectional area of a cantilever beam, $A = bh$;t is time; ρ is density. The boundary conditions of the cantilever beam are:

$$z(x = 0) = z'(x = 0) = z''(x = l) = z'''(x = l) = 0 \tag{2}$$

Solving Eq. (1) with Separated Variable Method, Let z (x, t) = Z (x) T (t), and bring it into Eq. (1) to get:

$$\beta^4 = \frac{\rho A \omega^2}{\tilde{E} I} \tag{3}$$

Bringing the boundary conditions into Eq. (3) gives the frequency equation:

$$\cos(\beta_n l)\cosh(\beta_n l) = -1 \tag{4}$$

Bring the solution in the frequency equation into Eq. (4) to get the resonance frequency of the single-layer micro-cantilever beam:

$$f_n = \left(\frac{(\beta_n l)^2}{2\pi}\right)\sqrt{\frac{\tilde{E} I}{\rho A l^4}} \tag{5}$$

The solution to the frequency is $\cos(\beta_n l)\cosh(\beta_n l) = -1$, the equation is $\beta_1 l = 1.875$,$\beta_2 l = 4.694$,$\beta_3 l = 7.855$.......

For a double-layer micro-cantilever structure composed of a fiber micro-cantilever with a thickness h_1 and a magnetostrictive film with a thickness of h_2, $\tilde{E} I$ is replaced by $\overline{\tilde{E} I}$, which is the equivalent bending stiffness, ρA is replaced by $\overline{\rho A}$, which is equivalent linear density,

$$\overline{\tilde{E} I} = \tilde{E}_s I_s + \tilde{E}_f I_f \tag{6}$$

$$\overline{\rho A} = \rho_s A_s + \rho_f A_f \tag{7}$$

Therefore, when the influence of gravity and other factors is ignored, the double-layered micro-cantilever structure is not affected by the magnetic field, and the magnetostrictive film does not produce a magnetostrictive effect. The resonance frequency when the double-layer cantilever is kept flat is:

$$f_n = \left(\frac{(\beta_n l)^2}{2\pi l^2}\right)\sqrt{\frac{\overline{\tilde{E} I}}{\overline{\rho A}}} \tag{8}$$

When the double-layer micro-cantilever structure is affected by the magnetic field, the magnetostrictive film produces a magnetostrictive effect, which causes the stress mismatch between the magnetostrictive film and the optical fiber micro-cantilever beam, which results in a double-layer micro-cantilever structure. Deflection (this article assumes that the double-layered micro-cantilever structure does not come into contact with the end face of the fiber after bending), and the double-layered micro-cantilever structure is shown in Fig. 2 after it is bent.

The axial strain ε_x of the double-layer micro-cantilever beam structure along the beam length direction is divided into two parts: tensile strain ε_s and bending strain ε_b, which is $\varepsilon_x = \varepsilon_s + \varepsilon_b$, The tensile strain ε_s reflects the change in the axial length

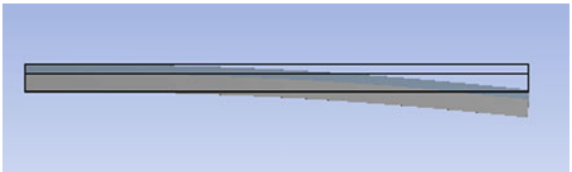

Fig. 2 The deflection of double-layer micro-cantilever beam structure

of the double-layer micro-cantilever structure, and the bending strain ε_b reflects the change in deflection. The resonance frequency of the double-layer micro-cantilever structure is mainly affected by the bending strain ε_b. Under the influence of the magnetic field of the double-layer micro-cantilever structure, when the deflection no longer changes, the stress between the magnetostrictive film and the optical fiber micro-cantilever reaches equilibrium $\sigma_s = \sigma_f$ [4], which is

$$\sigma = \sigma_s = \sigma_f = \frac{E_s}{1 - v_s^2}(\varepsilon_s + v_s \varepsilon_s) = \frac{E_f}{1 - v_f^2}\left[\left(\varepsilon_f - \lambda_s\right) + v_f\left(\varepsilon_f + \frac{\lambda_s}{2}\right)\right] \quad (9)$$

When the double-layer micro-cantilever structure is deflected, the expressions of the radius of curvature and the stress and equivalent bending stiffness between the magnetostrictive film and the optical fiber micro-cantilever are [5]:

$$R = \frac{\overline{\tilde{E}I}}{\int_s \sigma_s (z - z_c) dA_s + \int_f \sigma_f (z - z_c) dA_f} \quad (10)$$

z_c is the height of the neutral plane,

$$z_c = \frac{\left(\tilde{E}_s b\left(z_s^2\right) + \tilde{E}_f b\left(z_f^2 - z_s^2\right)\right)}{2\left(\tilde{E}_s b(z_s) + \tilde{E}_f b\left(z_f - z_s\right)\right)} \quad (11)$$

Assume that the double-layered micro-cantilever beam structure becomes a circular arc with a radius of curvature R as the radius after deflection [6]. A segment of the arch micro-elements is subjected to a force analysis [6],

$$\frac{\partial^6 v(\varphi, t)}{\partial \varphi^6} + 2\frac{\partial^4 v(\varphi, t)}{\partial \varphi^4} + \frac{\partial^2 v(\varphi, t)}{\partial \varphi^2} \frac{\overline{\rho A}}{\overline{\tilde{E}I}} R^4 \frac{\partial^4 v(\varphi, t)}{\partial \varphi^2 \partial t^2} = 0 \quad (12)$$

where φ is the angular coordinate in polar coordinates, t is time, and $v(\varphi, t)$ is the radial displacement component, let $(\varphi, t) = V(\varphi)\sin(\omega t + \theta)$, Substituting into Formula (12), we can get,

$$\frac{d^4 V(\varphi)}{d\varphi^4} + 2\frac{d^2 V(\varphi)}{d\varphi^2} + \left(1 - \chi^2\right)V(\varphi) = 0 \quad (13)$$

where $\chi^2 = \frac{\overline{\rho A}}{\overline{\tilde{E}I}} R^4\omega^2$. In general, $\chi > 1$, with which as the boundary conditions, the general solution of Eq. (11) is obtained as,

$$\cos\left(\frac{\xi l}{R}\right)\cosh\left(\frac{\eta l}{R}\right) + \frac{1}{\xi\eta}\sin\left(\frac{\xi l}{R}\right)\sin\mathrm{h}\left(\frac{\eta l}{R}\right) + 1 = 0 \tag{14}$$

Let $\xi = \sqrt{\chi + 1}, \eta = \sqrt{\chi - 1}$, get

$$\cos\left(\frac{\sqrt{\chi+1}l}{\mathrm{R}}\right)\cosh\left(\frac{\sqrt{\chi-1}l}{\mathrm{R}}\right) + \frac{1}{\sqrt{\chi^2-1}}\sin\left(\frac{\sqrt{\chi+1}l}{\mathrm{R}}\right)\sin\mathrm{h}\left(\frac{\sqrt{\chi-1}l}{\mathrm{R}}\right) + 1 = 0 \tag{15}$$

By solving the above formula numerically, we can get the non-array definition of χ, χ_n (n = 1,2,3, ...) It can be seen from the above formula that the resonance angular frequency ω corresponding to each χ value is the nth-order resonance angular frequency ω_n, Bringing the value of χ_n into the formula $\chi^2 = \frac{\overline{\rho A}}{\overline{\tilde{E}I}} R^4\omega^2$ can obtain the resonance angular frequency ω_n. In this way, we can solve the resonance frequency F_n of each order of the double-layered micro-cantilever beam structure,

$$F_{nb} = \left(\frac{\chi_n}{2\pi R^2}\right)\sqrt{\frac{\overline{\tilde{E}I}}{\overline{\rho A}}} \tag{16}$$

Thus, the sensitivity of the double-layer micro-cantilever structure under the magnetic field can be obtained,

$$\mathrm{S} = \frac{\triangle f}{\triangle H} = \frac{F_{nb} - f_n}{\triangle H} = \frac{\left(\frac{\chi_n}{2\pi R^2} - \frac{(\beta_n l)^2}{2\pi l^2}\right)\sqrt{\frac{\overline{\tilde{E}I}}{\overline{\rho A}}}}{\triangle H} \tag{17}$$

3 Design and Optimization of Magnetic Field Sensor Structure

The magnetic field sensor is designed with an optical fiber micro cantilever on the end face of the optical fiber. The top surface of the optical micro cantilever is plated with a layer of magnetostrictive film, the magnetostrictive film forms a double-layer micro cantilever structure with the optical fiber micro-cantilever. The sensor structure is shown in Fig. 3.

Due to the limitation of the fiber size, in order to achieve the best sensitivity of magnetic field measurement, this paper needs to design the optimal size parameters of the double-layer micro-cantilever structure on the end face of the fiber. The main structures on the fiber end face are fixed ends and double-layer micro-cantilever

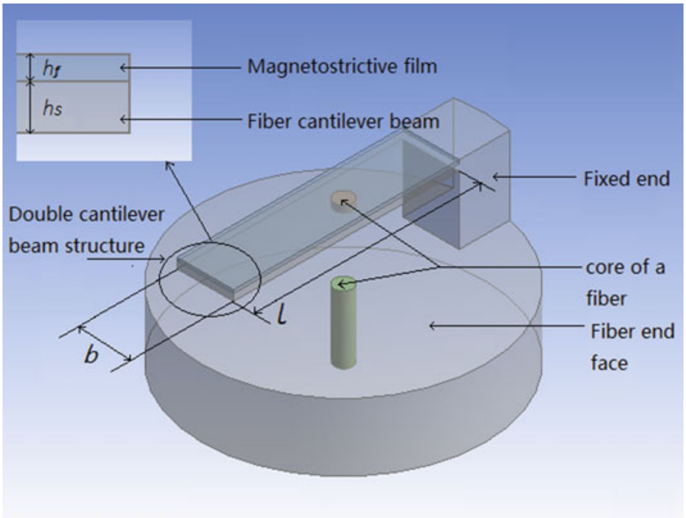

Fig. 3 The structure of the magnetic field sensor

beams. The sensitivity of the magnetic field sensor is mainly affected by the double-layer micro-cantilever structure. The sensitivity Formula of the magnetic field sensor is:

$$\mathrm{S} = \frac{\triangle f}{\triangle H} = \frac{(F_n - f_n)}{\triangle H} \tag{18}$$

Substituting the dimensional parameters of the double-layer micro-cantilever structure into Eq. (9) to simplify the first-order resonance frequency of the double-layer micro-cantilever structure without being affected by the magnetic field,

$$f_n = \frac{(1.875)^2}{2\pi l^2}\sqrt{\frac{\left(\frac{E_s h_s^3}{(1-\upsilon_s^2)} + \frac{E_f h_f^3}{\left(1-\upsilon_f^2\right)}\right)}{12\left(\rho_s h_s + \rho_f h_f\right)}} \tag{19}$$

According to Formula (17), among the structural parameters of the double-layer micro-cantilever beam, the length l of the beam, the thickness h_s of the optical fiber micro-cantilever beam, and the thickness h_f of the magnetostrictive film have an influence on the resonance frequency. Therefore, this paper uses ANSYS software to analyze the influence of the structural size parameters of the double-layer micro-cantilever on the sensitivity of the magnetic field sensor, and to obtain the structural size parameter with the highest sensitivity of the magnetic field sensor through simulation and optimization. This paper uses a single-mode fiber as a reference. The fiber diameter is about 125 μm and the core diameter is about 8 μm. The magnetic field is applied along the length of the cantilever beam and applied in a direction parallel

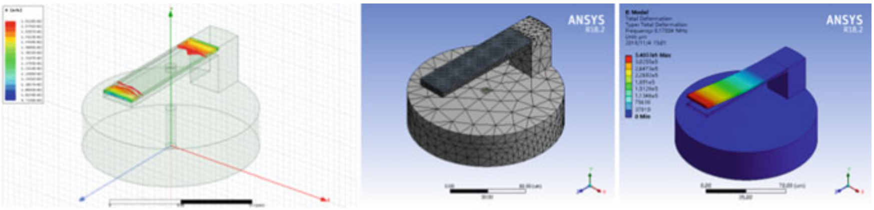

Fig. 4 The simulation flowchart in ANSYS

to the magnetic field. The grid uses a tetrahedral element to double-layer micro-cantilever. The beam structure is divided into 6000 elements, and the simulation flowchart is shown in Fig. 4.

First, the thickness h_s of the optical fiber micro cantilever and the thickness h_f of the magnetostrictive film are simulated and analyzed separately. Under the same magnetic field, the sizes of h_s and h_f are changed to obtain the sensitivity of the double-layer micro cantilever with different thicknesses, as shown in Fig. 5.

In Fig. 5, the abscissa is the ratio of the thickness of the magnetostrictive film to the thickness of the optical fiber micro-cantilever; the ordinate is the sensitivity of the double-layer micro-cantilever structure, and the unit is Hz/Gs. As can be seen from the figure, when the thickness of the optical fiber cantilever is 2 μm and the thickness of the magnetostrictive film is 3/5 of the thickness of the optical fiber cantilever under the same magnetic field, the sensitivity of the double-layer micro cantilever structure is the highest, which can reach 39,900 Hz/Gs.

At this time, the thickness of the fiber micro-cantilever and the magnetostrictive film were determined. Next, we simulated the influence of the structure length of the double-layer micro-cantilever on the sensitivity. Due to the fiber size limitation, the total length of the double-layer micro-cantilever structure and the fixed end must be equal to or less than 125 μm. In order to reduce manufacturing difficulties, the

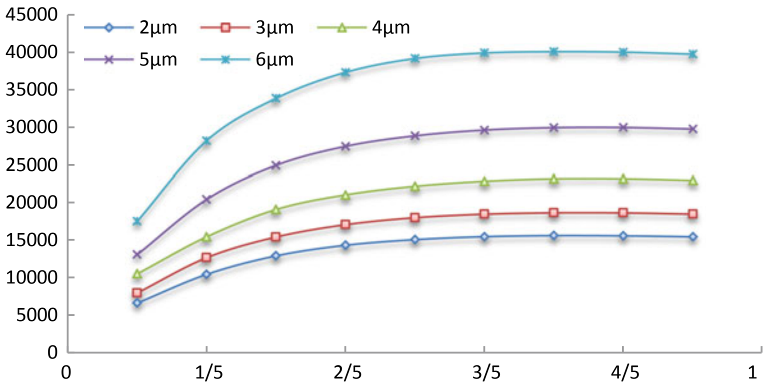

Fig. 5 The sensitivity of double-layer micro-cantilever structures with different thicknesses under magnetic field

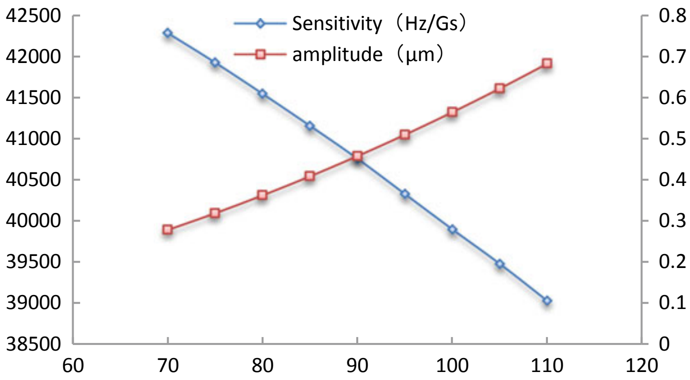

Fig. 6 The sensitivity and amplitude of double-layer micro-cantilever structures with different lengths

total length of the double-layer micro-cantilever structure and the fixed end is fixed at 125 μm. Only the length of the fixed-end is changed to achieve the change of the length of the double-layer micro-cantilever.

According to Formula (17), the larger the double-layer micro-cantilever structure is, the smaller the resonance frequency is. The larger the length of the double-layer micro-cantilever structure, the larger the resonance amplitude. The principle of detecting the vibration of a double-layer micro-cantilever structure is: detecting the change in the light intensity of the optical signal reflected by the structure back to the optical fiber. Therefore, the larger the resonance amplitude, the greater the change in light intensity, the higher the resolution of the frequency measurement, and the stronger the immunity to interference. Therefore, when optimizing the length of the double-layer micro-cantilever structure, we need to ensure that both the sensitivity and the amplitude are large. Under the same magnetic field, changing the size of l to obtain the sensitivity and amplitude of the double-layer micro-cantilever structure with different lengths, as shown in Fig. 6.

In Fig. 6, the abscissa is the length of the beam, the unit is micrometer; the ordinate is the sensitivity of the double-layer micro-cantilever beam, the unit is Hz/Gs. It can be seen from the figure that the sensitivity curve and amplitude curve of the double-layer micro-cantilever structure intersect at a beam length of 90 μm. Therefore, when the double-layer micro-cantilever structure length is 90 μm, compared with other double-layer micro-cantilever structures, the length has both a large sensitivity and a large amplitude. The sensitivity can reach 40,760 Hz/Gs and the amplitude can reach 0.46 μm.

4 Conclusion

This paper proposes a magnetostrictive fiber-optic micro-cantilever resonant magnetic field sensor, which is designed with an optical fiber micro cantilever on the end face of the optical fiber, and a layer of magnetostrictive film is plated on the optical fiber micro cantilever. The two constitute a double-layer micro cantilever structure. It uses frequency as the output signal and uses all-optical transmission without current interference. Therefore, this magnetic field sensor has the advantages of strong anti-interference ability and high sensitivity. Based on the important role of the double-layered micro-cantilever structure in the magnetic field sensor, the magnetic field-frequency characteristics of the double-layered micro-cantilever structure were simulated and optimized to obtain higher sensitivity. The optimal size after simulation optimization by ANSYS software is: when the double-layer micro-cantilever structure is 90 μm in length, the thickness of the optical fiber micro-cantilever is 2 μm, and the thickness of the magnetostrictive film is 3/5 of the thickness of the optical fiber micro-cantilever, the magnetic field sensor it can reach the maximum sensitivity of 40,760 Hz/Gs.

References

1. Shen F, Lu P, O'Shea SJ, Lee KH, Ng TY (2001) Thermal effects on coated resonant micro-cantilevers. Sens Actuators A Phys 95(1):17–23
2. Bigaud D, Szostkiewicz C, Hamelin P (2003) Tearing analysis for textile reinforced soft composites under mono-axial and bi-axial tensile stresses. Compos Struct 62(2):129–137
3. Forster B, Mollaert M (2004) European design guide for tensile surface structures. Brussel: Tensi-Net 293–322
4. Ripka P (2003) Advances in fluxgate sensors. Sens Actuators A 106(1):8–14
5. Du T, de Lacheisserie E (1993) Magnetostriction: theory and applications of magnetoelasticity. CRC Press, Boca Raton, FL
6. SeshiaAA, PalaniapanM,RoessigTA, HoweRT, GoochRW,SchimertTR,MontagueS (2002) A vacuum packaged surface micromachined resonant accelerometer. J Microelectromech Syst11(6):784–793