A high sensitive fiber Bragg grating cryogenic temperature sensor

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At cryogenic temperature, a fiber Bragg grating (FBG) temperature sensor with controllable sensitivity and variable measurement range is demonstrated by using bimetal configuration. In experiments, sensitivities of −51.2, −86.4, and −520 pm/K are achieved by varying the lengths of the metals. Measurement ranges of 293 − 290.5, 283 − 280.5, and 259 − 256.5 K are achieved by shortening the distance of the gap among the metals.

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It is very appealing to use optical sensor to monitor the low temperature in many applications where electric sparks are prohibited or electric current is susceptible to high field and radiation, such as superconducting devices, storage or transport vessels for cryogens or liquid hydrogen fuel tanks, and particle physics experiments[1−6]. Techniques using fiber Bragg gratings (FBGs)[1−4] and erbium-doped fibers (EDFs)[5,6] as sensitive elements have been explored for cryogenic temperature monitoring. EDF sensors are affected by the fluctuation of light source and difficult to stabilize. FBG sensors using wavelength modulation are much more stable and robust. But the intrinsic temperature sensitivity of FBG at cryogenic temperature is too tiny for practical applications. The sensitivity can be improved by either attaching the FBG to materials with large coefficient of thermal expansion (CTE) or covering FBG with large CTE metals[1−4]. However, the improvements of their sensitivities are fixed and limited by the CTEs of the bonding materials[7].

Bimetal is an effective way to tune the strain of FBG in arbitrary proposition to temperature and has been used for enhancing[7,8] and compensating its temperature sensitivity[9−11]. The basic structure of bimetal is shown in Fig. 1. Two metals with different CTEs are fixed at one end and a FBG is fixed in the gap between their other ends. Its general principle is that the strain of FBG will be changed according to temperature.

In this letter, we analyze the reason why current bimetal methods are not able to enhance the temperature sensitivity at cryogenic temperature and propose a method by proper choice of references in bimetal. In experiments, controllable sensitivity and variable measurement range are achieved at cryogenic temperatures, as they have been achieved by bimetal at high temperatures[7,8]. Some problems in practical applications are discussed, including choices of materials below 100 K, solutions to the tradeoff between sensitivity and measurement range, improvements of response speed, and adaptations to explosive environments.

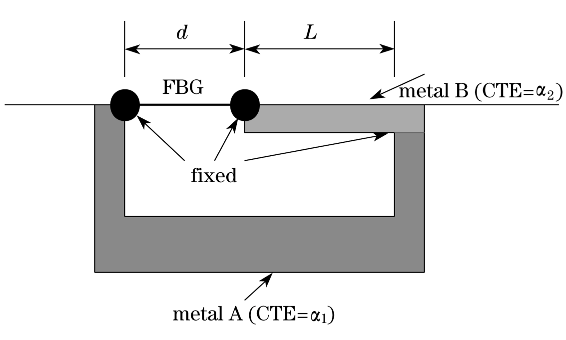

Fig. 1. Basic structure of bimetal FBG sensor.

The reflected wavelength shift of FBG induced by temperature change is[1]

$$\Delta\lambda_{\mathrm{B}}/\Delta T = [(\,1 - P_{\mathrm{e}})\ \varepsilon + \zeta\ ]\ \lambda_{\mathrm{B}}, \tag{1}$$

where $P_{\mathrm{e}}(\approx 0.22)$ is the photo-elastic constant, ζ is the thermo-optic coefficient, and ε is the strain change of the FBG.

In Fig. 1, when the temperature increases 1 K, the distance of the gap between the two metals widens

$$\Delta d = \alpha_1(L+d) - \alpha_2 L,$$

where L is the length of metal B, α_1 and α_2 are the CTEs of metal A and metal B, respectively.

When the FBG is stretched, its strain change in 1-K temperature variation is

$$\Delta\varepsilon = [\alpha_1(L+d) - \alpha_2 L]/d. \tag{2}$$

The temperature sensitivity of bimetal device is thus obtained as

$$\begin{aligned}\Delta\lambda_{\mathrm{B}}/\Delta T &= \{(1-P_{\mathrm{e}})[\alpha_1(L+d)-\alpha_2 L]/d+\zeta\}\lambda_{\mathrm{B}} \\ &= \{(1-P_{\mathrm{e}})[(\alpha_1-\alpha_2)L/d+\alpha_1]+\zeta\}\lambda_{\mathrm{B}}.\end{aligned} \tag{3}$$

By changing the difference between α_1 and α_2, or the ratio of L/d, the temperature sensitivity can be controlled[7].

When $(1-P_{\mathrm{e}})[(\alpha_1-\alpha_2)L/d+\alpha_1]+\zeta = 0$, the device is insensitive to temperature and has potential applications in the field of light filters[9−11]. When $(1-P_{\mathrm{e}})[(\alpha_1-\alpha_2)L/d+\alpha_1]+\zeta \gg 0$, the resonance

Bragg wavelength increases along with the increase of temperature[7,8]; but it does not decrease along with the decrease of temperature after the relaxation of FBG. Due to the limitations of both durable strain of FBG and the control of the room temperature where the device is assembled, it is unpractical for cryogenic temperature measurement.

To enhance the temperature sensitivity at cryogenic temperature, we propose to increase the resonance Bragg wavelength along with the decrease of temperature by taking advantage of $(1-P_e)[(\alpha_1-\alpha_2)L/d+\alpha_1]+\zeta \ll 0$. To satisfy it, we get that $\alpha_1 \ll \alpha_2$ and $L/d \gg 1$.

In most of engineering applications at cryogenic temperature, only a limited range of temperature needs to be precisely measured. For making full use of FBG strain limitation to enhance the temperature sensitivity at a given temperature T_s, the length of FBG in the gap is pre-set as $L_r([\alpha_1(L+d)-\alpha_2 L](T_s-T_r))$ longer than d when mounting the FBG at room temperature T_r, and the longer L_r is, the lower T_s is[8].

The FBGs used in experiments were written with phase masks, their grating lengths were about 14 mm, and their Bragg wavelength and bandwidth (full-width at half-maximum, FWHM) were $\sim$ 1550 nm and $\sim$ 0.15 nm, respectively. A broadband light source with 40-nm spectral width (1525 − 1565 nm) was applied. The accuracy and resolution of the demodulator (Pi05, Beijing Pi-Optics Co., Ltd.) were ± 3 pm and 1 pm, respectively. Invar alloy ($\alpha = 0.8 \times 10^{-6}$ K^{-1}) and aluminum alloy ($\alpha = 22\times 10^{-6}$ K^{-1}, in shape of strip) were used as metal A and metal B, respectively. The FBGs were fixed by epoxy glues. T_r was about 293 K. The signal level of resonance Bragg wavelength was almost the same in all experiments.

Two sensors ($L = 130$ mm, $d = 52$ mm; $L = 116$ mm, $d = 30$ mm) were manufactured. Firstly, metal A and metal B were fixed together by epoxy glues, and then the FBGs were mounted in the gap. After mounted, the FBGs were relaxed at T_r and started to be stretched at about 273 K. They were, respectively, bounded with a platinum-resistance thermometer by aluminum foil, and put down very slowly close to the surface of liquid nitrogen by an electromotor, and so was a bare FBG sensor. The experimental setup is schematically shown in Fig. 2. Their performances recorded in every second are shown in Fig. 3. The experimental temperature sensitivities of the two sensors are −51.2 and −86.4 pm/K, respectively, and agree well with the theoretical ones (−52.7 and −87.8 pm/K). It proves that bimetal is also able to tune the strain of FBG in arbitrary proposition to temperature at cryogenic temperature.

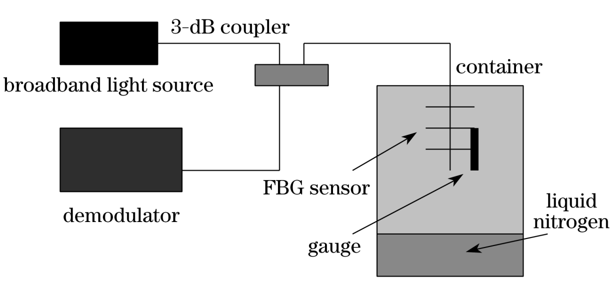

Fig. 2. Experimental system setup.

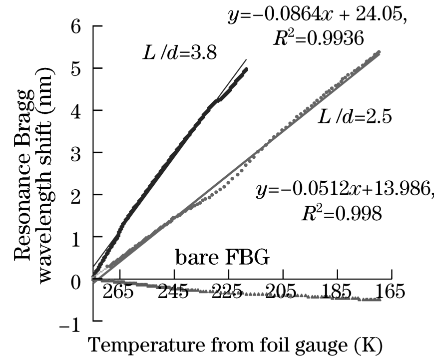

Fig. 3. Performance comparison of FBG sensors.

Another sensor ($L = 360$ mm, $d = 13.5$ mm) was also manufactured. Its L_r was set to different values (0, 0.1, and 0.3 mm) by a special device[8]. After the mounting of FBG, L_r was tuned by moving metal B, handled by hands and measured by a vernier, and then metal B was fixed with metal A by a bolt and a nut. Their temperature responses were measured in a constant temperature slot with accuracy and temperature range of 0.1 K and 243−368 K, respectively. To protect the FBG from being broken due to possible damages at the assembling stage, it was tested in a narrow 2.5-K range and at 0.5-K step. The experimental results are shown in Fig. 4. When L_r is 0, 0.1, and 0.3 mm, T_s is about 293, 283, and 259 K, respectively. And the sensitivities at different L_r values are almost the same (around −520 pm/K). The errors deviating from theory mainly come from the measuring errors of both the distance of the gap and the length of FBG in the gap. The results prove the relationship between L_r and T_s at cryogenic temperature.

The CTE of most metals is not linear in a wide range of temperature, and so is the sensitivity of the sensor. For achieving high sensitivity below 100 K, metal A is better to be made by aluminum, polymethyl methacrylate (PMMA)[4], copper or zinc[2], which have a comparatively larger CTE; Metal B is better to be made by silica[12] or super invar, which have a very low or negative CTE.

In strain enhancing FBG temperature sensors[1−4,7,8], there is always a tradeoff between sensitivity and measurement range due to the strain limitation of FBG. To a normal FBG, the wavelength shift tuned by strain is

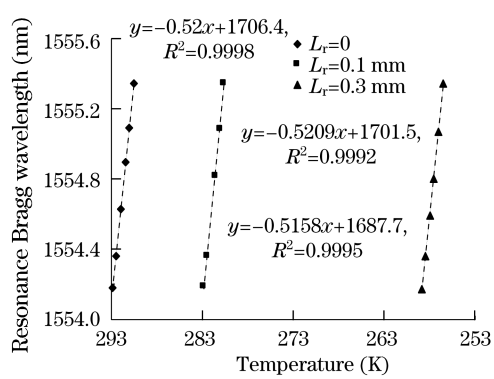

Fig. 4. Measurement range of the sensor at different pre-relaxing lengths of FBG.

about 6 nm. But highly stretchable FBG (52-nm tunable wavelength range) is also available[13]. By using different FBGs, the tradeoff is acceptable to engineering requirements[14,15].

When metal A is a string and with small mass, the sensor is expected to perform high-speed temperature measurements, which is very important in monitoring superconducting transition effects[2]. For applications in explosive environments, the metals could be replaced by PMMA, silica, or glass. At cryogenic temperatures, firmly fixing FBG by epoxy glues becomes harder. FBG metallization and welding may be helpful to eliminate the use of glues.

In conclusion, we solve the problem that current FBG sensors have limited sensitivity at cryogenic temperature by using bimetal configuration. Controllable sensitivity and variable measurement range are achieved at cryogenic temperature in our experiments. This method has the potential for various applications at cryogenic temperatures.

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