High temperature high sensitivity optical fibre sensor based on multimode fibre Bragg grating

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Published in Micro & Nano Letters; Received on 28th May 2018; Revised on 29th September 2018; Accepted on 11th October 2018

A multimode fibre Bragg grating (MMFBG) is experimentally demonstrated in this work. The light from the lead-in optical fibre transmits to the MMFBG, the Bragg gratings in multimode fibres show multiple reflection peaks due to the coupling among all bounded modes. Some reflection peaks are reflected back to the lead-out fibre core by the MMFBG. Finally, the spatial frequency spectra of the reflection peaks are detected by the detection device. As the temperature variates, the changes in the transmission spectrum will be observed. Experimental results show that the MMFBG responds to temperature and the temperature sensitivity is 0.0114 nm/°C. The MMFBG has the advantages of compact structure, anti-electromagnetic interference, and stable chemical property, which has great potential in temperature measurement.

1. Introduction: Temperature measurements are important in various industrial fields, such as aircraft, petroleum, and steel industry. Due to the advantages of good insulation, resistance to electromagnetic interference, low cost, light weight, stable chemical performance, compact structure, and ability to work in harsh environment, optical fibre sensor has been widely investigated for temperature measurement. Most of these studies are based on the analysis of the spectral variation. Fibre Bragg grating (FBG) [1–4], long period grating [5], Michelson interferometer [6, 7], Mach–Zehnder interferometer [8–13] and Fabry–Perot interferometer [14–16] have been studied extensively. Several well-known devices, as mentioned above, can be directly used for temperature measurement. However, there are many common disadvantages, such as poor cascade performance, low-temperature stability, and poor reproducibility. Owing to its low cost, small size, and easiness in fabrication [17, 18], the FBG has attracted great attention [19].

As early as 1989, the East Hartford Joint Technology Research Center [20] first engraved the FBG based on ultraviolet (UV) light. The fibre grating filter was successfully produced by the interference of two beams. This method not only effectively improves the engraving efficiency but also controls the wavelength of the FBG by changing the angle of two beams, which greatly promotes the practicality of FBGs. FBG has become a hot spot of research in recent years. Getinet Woyessa *et al.* [21] presented a temperature sensor with a FBG structure, and a temperature sensitivity of 17.3 pm/°C is obtained within the range of 20–110°C. Tianliang Li *et al.* [22] presented a FBG sensor with temperature compensation based on the thermal expansion of the sensor structure, and a temperature sensitivity of 8.66 pm/°C was achieved within a temperature range of 30–90°C.

Due to the small core diameter of single-mode fibre (SMF), the SMF is difficult to couple with other optical devices, and the multimode FBG (MMFBG) has been used to measure the ambient temperature. Furthermore, the MMFBG has an advantage of easiness in coupling with different light sources. MMFBG has also been widely studied [23–25]. Changgui *et al.* [23] proposed an MMFBG in multimode propagation, and the spectra characteristics and potential applications of these gratings were discussed. Chun-Liu Zhao *et al.* [25] presented an MMFBG, and the results show that the temperature sensitivities are almost the same at different transmission peaks. However, the range of detection is small, only from room temperature to 100°C.

In this Letter, an in-fibre MMFBG was used for temperature sensing measurement. To achieve the temperature data in a large dynamic range, we monitored the different reflection peaks and discussed the temperature response. The temperature measurement principle was analysed and different reflection peaks were separated from the reflectance spectrum. As the temperature changes, the different peaks changed correspondingly. The experiment results show that the temperature response at different peaks is similar, and the fibre optic sensor has the potential to enable high-temperature measurement.

2. Principle and design

2.1 Principle: To analyse the sensor, a temperature measurement system is set up, as shown in Fig. 1. The light output from the lead-in optical fibre is transmitted to the MMFBG, some higher-order models are separated from the transmission spectrum and other modes are reflected back to the lead-out fibre core by the

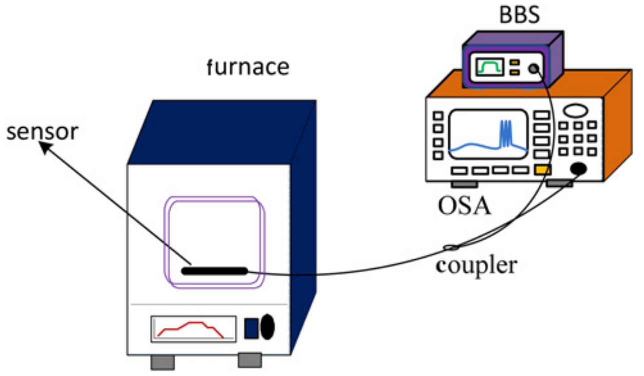

Fig. 1 *Diagram for the temperature measurement. OSA: optical spectrum analyser; BBS: broad-band light source*

MMFBG. Finally, the spatial frequency spectra of the higher-order models are detected by the detection device.

The optical path difference is affected by the thermo-optic effect and the thermal expansion effect based on MMFBG. As a result, the length variation and effective refractive index variation of the MMFBG are related to the ambient temperature. The FBG wavelength is as follows:

$$\lambda_{\infty}^{m} = 2n_{\text{eff}}^{m}\Lambda. \tag{1}$$

The grating spacing is Λ, and the effective refractive index is represented by n_{eff}. When MMFBG is affected by ambient temperature, the reflection spectrum will drift. When the effective refractive index variation and the wavelength variation are related to temperature, it is easy to get the reflection peaks proportional to the temperature variation from the formula. In other words, the reflection peaks will change with the outside temperature changes. The ambient temperature can be monitored from the spectrum (Fig. 2).

The fabrication technology of fibre grating is based on the phase mask. The beam is divided into diffraction beams, and they have equal light power. The beams interfere with each other and form the fringes. The refractive index of the core is modulated under a high light intensity. The method of using a light source and phase mask to make FBG is critical. At the same time, the combination of the intensity of the light source and phase mask can enable the control of the grating, and the special structure of the grating, such as MMFBG, can be produced. This method not only greatly simplifies the fabrication process of FBG, but also improves the efficiency of industrialisation. It is the most commonly used method to write the grating. The FBG and MMFBG used in this experiment are fabricated by UV exposure through a phase mask.

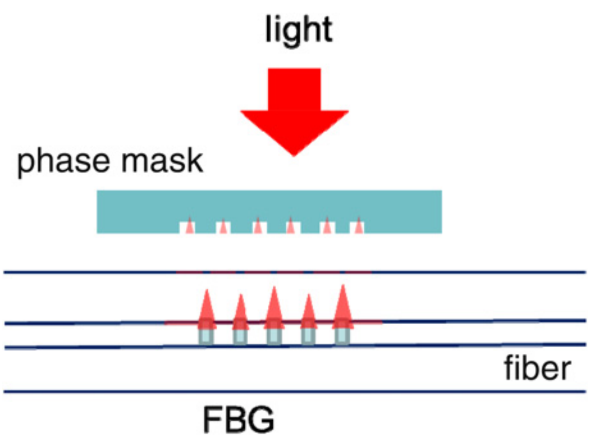

Fig. 2 *Fabrication of FBG by UV exposure through a phase mask*

The phase mask is a phase grating etched on a quartz substrate. It has the function of suppressing zero order and enhancing the first-order diffraction. The engraving period of the grating is half of the mask period. What's more, reproduction mainly relies on the production process, which mainly controls the quality of mask, the optical path layout of a grating engraved process, light source stability, and the control of writing time.

Since the sensors have the nature of wavelength encoded, the grating structure is of great importance. In our experiment, the number of gratings is 1000/cm, where the longitudinal direction refers to the axial direction, and the Bragg grating is engraved in the radial direction. At the same time, since the core diameter of the MMFBG is larger than FBG, the irradiation time of the MMFBG is greater than that of FBG. Fig. 3 shows the structure diagram of FBG. The core/cladding diameters of FBG are 10 μm/125 μm, and the effective refractive index of multimode fibre is 1.4680/1.4627. Fig. 4 shows the schematic configuration of MMFBG. The core/cladding diameters of the multimode fibre are 65 μm/125 μm, and the effective refractive index of the multimode fibre is 1.4930/1.4573.

2.2 Experiment and Discussions: Fibre gratings used in this work are made by UV exposure. Their length is selected as 1 cm to ensure sensing accuracy and resolution. Using the optical microscope, the pictures of the fibre grating are obtained, as shown in Fig. 5. The left side is FBG, and the right side is MMFBG. Due to the large diameter of the MMFBG, its etching time is longer than that of FBG. Therefore, MMFBG can be seen from the picture. Fig. 6 shows the picture of the temperature-sensing system. It consists of a broad-band light source and the optical spectrum analyser whose resolution is 0.02 nm. The FBG and MMFBG are placed in a furnace with a resolution of 1°C. With the change of the external temperature, the pitch of the grating is different. As a result, the spectrum will drift. Through the temperature

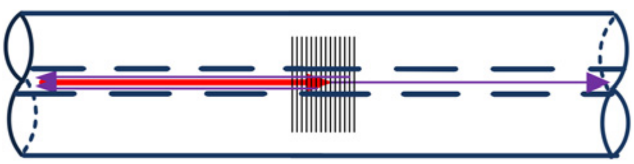

Fig. 3 *Structure diagram for temperature measurement based on FBG*

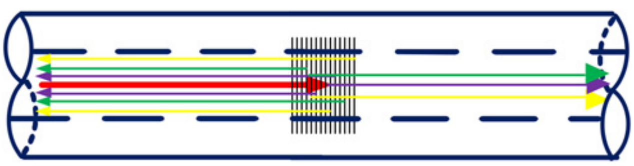

Fig. 4 *Structure diagram for temperature measurement based on MMFBG*

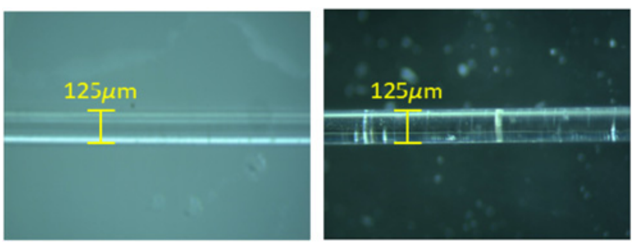

Fig. 5 *Pictures of FBG and MMFBG. Left side: side view of FBG. Right side: side view of MMFBG*

doi: 10.1049/mnl.2018.5233

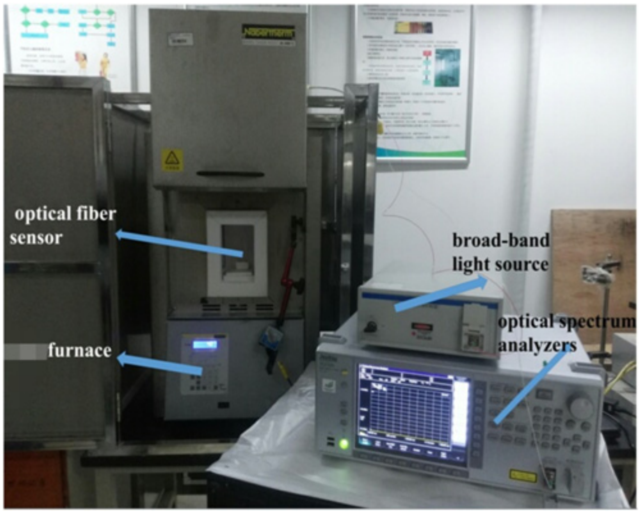

Fig. 6 *Actual picture for temperature measurement based on optical fibre sensors*

sensing system, the spectrum corresponding to the sensors at a different temperature detection point can be demodulated.

The refractive index periodic modulation in the core will gradually disappear when the sensor is used in high temperature. Also, the FBG can only tolerate a high temperature of 300°C, otherwise, the FBG will be completely erased [26]. To summarise, the temperature setting needs to be <300°C. The fibre grating is fixed in the furnace and temperature is set as 30, 60, 90, 120, 150, 180, 210, 240 and 270°C successively. The reflection centres of the FBG are recorded, and the measured transmission spectra are shown in Fig. 7.

The peak located at 1568.785 nm is monitored as shown in Fig. 8, and the temperature ranges from 30 to 270°C. To study the thermal effect, the FBG is placed in a furnace. The dots are the measured data, and the least squares linear fit is used to get the fitting line. The experiment results show that the temperature response sensitivity is 0.0102 nm/°C and the linearity is 0.999. Since a high temperature could cause the refractive index difference to become small until it disappears, the written grating is erased. The optical fibre core of MMFBG (10 µm/125 µm) is thicker than that of FBG (65 µm/125 µm), which increases the irradiation time during fabrication. As a result, the refractive index difference is hard to be erased and the temperature range is increased.

To ensure that the coating layer had been removed, the temperature was heated up to more than 300°C, and then cool down to 50°C throughout the experiment. Then, the MMFBG is measured in the

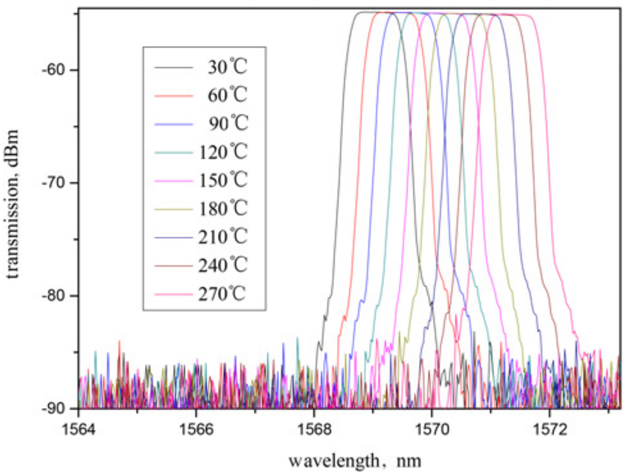

Fig. 7 *Transmission spectrum drift of FBG with different temperatures*

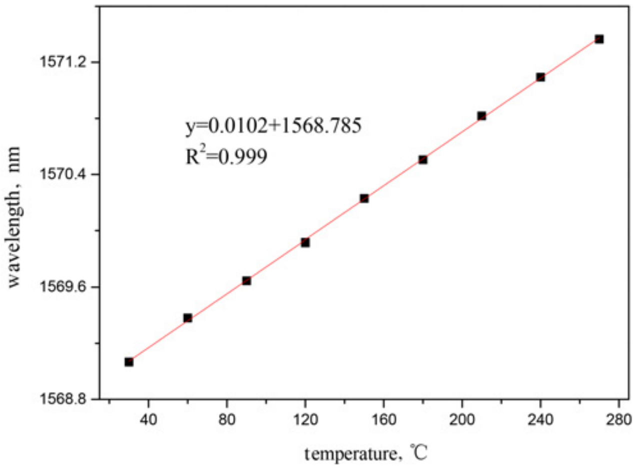

Fig. 8 *Transmission spectrum response of FBG*

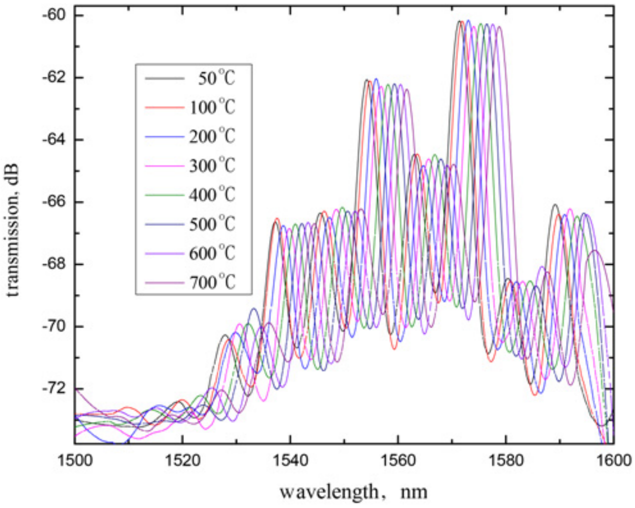

Fig. 9 *Transmission spectrum drift of MMFBG with different temperatures*

furnace with a temperature of 50, 100, 200, 300, 400, 500, 600, 700°C, respectively. The stability of the grating is good within the temperature measurement range and the measured transmission spectra are shown in Fig. 9.

The repeatability of the sensor is good in the temperature measurement range. In the process of repeated use, the sensitivity and peak strength of sensors are kept in a stable range. The peak located at 1553.596 nm is monitored, and the temperature range is from 50 to 700°C. To study the thermal effect, the MMFBG is placed in a furnace. The dots are the measured data, and the least squares linear fit is used to fit a line. As shown in Figs. 10–12, the experimental results show that the measured response sensitivity is 0.0114 nm/°C during the seven temperature experiments. In the same way, the peaks located at 1570.752 nm and 1588.596 nm are monitored, and the experiment results show that the measured response sensitivities at 1570.752 and 1588.596 nm are the same. The temperature response sensitivity is 0.0114 nm/°C with a good linearity within a temperature range of 50–700°C. In other words, the experiment results show that the temperature response at different peaks is similar, and the spectral shape is almost fixed during the drift process. As a result, the ambient temperature can be detected through the overall drift of the spectrum. The increase in the temperature range is caused by the increased irradiation time. Owing to the large proportion of the multimode fibre core, the expansion coefficient of the sensor increased, which led to

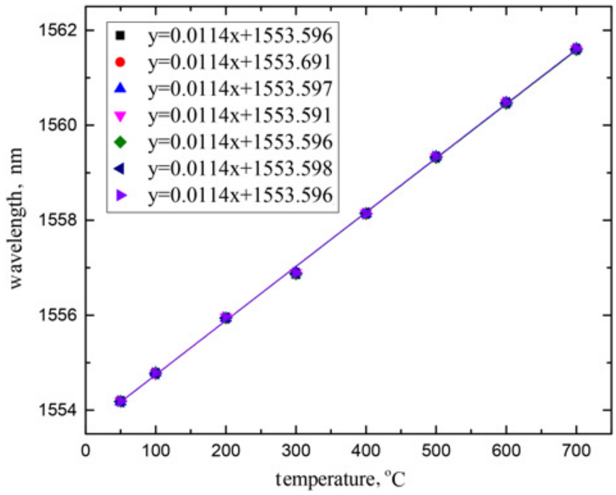

Fig. 10 *Transmission spectrum response of MMFBG based on the central wavelength near 1553.596 nm during seven temperature experiments, respectively*

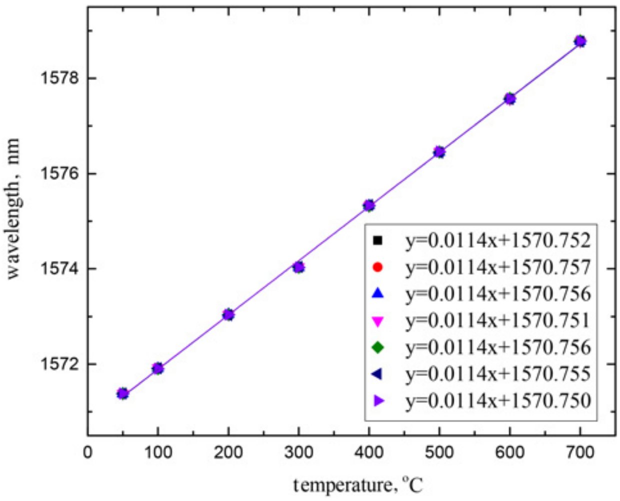

Fig. 11 *Transmission spectrum response of MMFBG based on central wavelength near 1570.752 nm during seven temperature experiments, respectively*

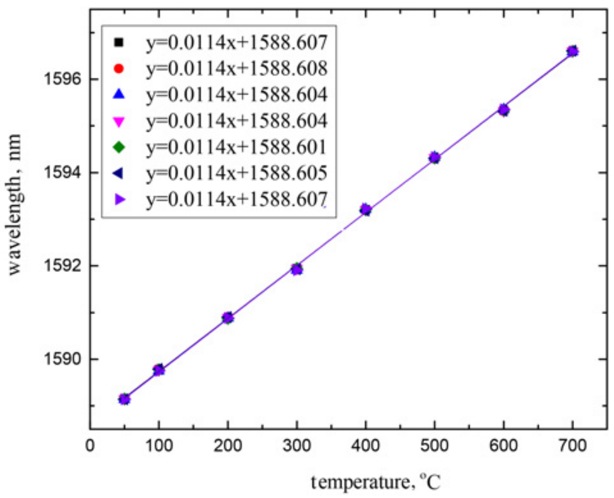

Fig. 12 *Transmission spectrum response of MMFBG based on central wavelength near 1588.596 nm during seven temperature experiments, respectively*

increased temperature sensitivity. Since the MMFBG and FBG have different thermal expansion coefficients, there is a slight increase in temperature sensitivity. Compared with FBG, the temperature sensitivity of MMFBG is improved, and the temperature range is also increased.

3. Conclusion: A sensing configuration is composed based on MMFBG for temperature measurement. It can effectively improve the temperature sensitivity and the temperature measurement range. Experiments are carried out to analyse the sensor's performance, and the temperature sensitivity is 0.0114 nm/°C over a temperature range of 50–700°C. The MMFBG has great potential in temperature measurement, which can provide effective state parameters for monitoring and diagnostic systems in aerospace, petrochemical, and other fields.

4. Acknowledgments: This work was supported by the 973 Program (grant no. 2015CB057402), the National Natural Science Foundation of China (grant nos. 91748207, 51608437, 51720105016, and 51421004), the China Postdoctoral Science Foundation (grant no. 2017M613114), the Shaanxi Postdoctoral Science Foundation (grant no. 2017BSHEDZZ69), the Fundamental Research Funds for the Central Universities (grant no. xjj2016011), the Open Foundation of the State Key Laboratory of Fluid Power and Mechatronic Systems (grant no. GZKF-201617), the Research Project of State Key Laboratory of Mechanical System and Vibration (grant no. MSV201813), and the 111 Program (grant no. B12016). We also appreciate the support from the International Joint Laboratory for Micro/Nano Manufacturing and Measurement Technologies.

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