2018

A High Sensitivity Temperature Sensor Based on Balloon-Shaped Bent SMF Structure with its Original Polymer Coating

Ke Tian
Harbin Engineering University, China

Gerald Farrell
Dublin Institute of Technology, gerald.farrell@dit.ie

Elfed Lewis
University of Limerick, Ireland

Xianfan Wang
Harbin Engineering University, China

Haidong Liang
Harbin Engineering University, China

See next page for additional authors

Follow this and additional works at: https://arrow.dit.ie/engscheceart

Part of the Engineering Commons

Recommended Citation
A high sensitivity temperature sensor based on balloon-shaped bent SMF structure with its original polymer coating

To cite this article: Ke Tian et al 2018 Meas. Sci. Technol. 29 085104

View the article online for updates and enhancements.
A high sensitivity temperature sensor based on balloon-shaped bent SMF structure with its original polymer coating

Ke Tian1, Gerald Farrell2, Elfed Lewis3, Xianfan Wang1, Haidong Liang1,4 and Pengfei Wang1,5

1 Key Laboratory of In-fiber Integrated Optics of Ministry of Education, College of Science, Harbin Engineering University, Harbin 150001, People’s Republic of China
2 Photonics Research Centre, Dublin Institute of Technology, Kevin Street, Dublin 8, Ireland
3 Department of Electronic and Computer Engineering, Optical Fibre Sensors Research Centre, University of Limerick, Limerick, Ireland
4 Hands and Feet Microsurgery, the Second Hospital of Dalian Medical University, Dalian 116023, People’s Republic of China
5 Key Laboratory of Optoelectronic Devices and Systems of Ministry of Education and Guangdong Province, College of Optoelectronic Engineering, Shenzhen University, Shenzhen 518060, People’s Republic of China

E-mail: pengfei.wang@dit.ie

Received 7 March 2018, revised 26 May 2018
Accepted for publication 1 June 2018
Published 28 June 2018

Abstract
A high sensitivity optical fibre temperature sensor is demonstrated based on a balloon-shaped bent single-mode (BSBS) fibre structure where the fibre retains its original protective polymer coating. The BSBS fibre structure can be simply realized by bending a coated straight single-mode fibre into the balloon shape using a section of silica capillary tube. By adjusting the bending radius of the balloon-shaped fibre section, a modal interferometer between the core mode and the coating mode can be effectively implemented at a suitable bending radius. Considering the intrinsically high thermo-optical coefficient and thermal expansion coefficient of the polymer coating, the BSBS fibre structure offers excellent temperature sensing performance. Experimental results show that the temperature sensitivity is as high as $-2465 \text{ pm/}^\circ\text{C}$ with a resolution of 0.008 °C over the temperature range of 20.7 °C–31.7 °C. Based on its simple fabrication process, very low cost, and experimentally determined high sensitivity coupled with good repeatability, the temperature sensor described in this article could be a competitive candidate in many temperature sensing applications.

Keywords: modal interferometer, fibre bend, polymer coating, temperature measurement

(Some figures may appear in colour only in the online journal)
Polymer coatings are sometimes used to improve the temper- in figure 1. The BSBS fibre structure is composed of a length the investigation described in this article, it was determined that the original manufacturers’ protective polymer coating for an SMF is a good choice and more importantly, by using the original coated polymer instead of other post-coating polymer materials, the fabrication process of the sensor is greatly simplified. In addition, this approach also offers a very uniform coating thickness which cannot easily be achieved by other post-coating methods.

In this article, a high sensitivity fibre optic temperature sensor based on a balloon-shaped bent single-mode (BSBS) fibre structure with its original polymer coating is described. The schematic configuration of the sensor structure is shown in figure 1. The BSBS fibre structure is composed of a length of unstripped SMF, and a capillary tube is used to bend the length of SMF into a balloon shape. With a suitable bending radius, a modal interferometer can be effectively established along the bent fibre section, periodic reflection between the core and the coating occurs. Hence, a modal interferometer is formed because of the different in the effective refractive indexes (RIs) and the optical paths lengths experienced by the light signals propagating in the core mode and the coating modes. In the case of a typical two-mode formed modal interferometer, the output intensity can be expressed by [19]:

\[
I_{\text{out}} = I_{\text{core}} + I_{\text{coating}} + 2\sqrt{I_{\text{core}}I_{\text{coating}}}\cos(\varphi + \varphi_0)
\]  

(1)

where \(I_{\text{core}}\) and \(I_{\text{coating}}\) is the intensity of the core mode and the coating mode, respectively, and \(\varphi_0\) is the initial phase. \(\varphi\) is the phase difference between the core mode and the coating mode which can be expressed as [20]:

\[
\varphi = \frac{2\pi L_{\text{eff}}}{\lambda} \Delta n_{\text{eff}}.
\]  

(2)

Where \(L_{\text{eff}}\) is the effective bent length, \(\Delta n_{\text{eff}} = n_{\text{core eff}} - n_{\text{coating eff}}\) is the effective refractive index (RI) difference between the core and coating mode, and \(\lambda\) is the free space wavelength. When the phase difference meets the condition of \(\varphi = (2m + 1)\pi, m = 0, 1, 2, \ldots\), an interference dip appears at certain wavelengths [21], defined by:

\[
\lambda_m = \frac{2L_{\text{eff}}\Delta n_{\text{eff}}}{2m + 1}.
\]  

(3)

When the surrounding temperature varies, the value of \(\Delta n_{\text{eff}}\) and \(L_{\text{eff}}\) also change because of the well-known thermo-optic
and the thermal expansion effect of materials, and the resulting relative wavelength shift can be expressed as [22]:

\[ \frac{\Delta \lambda}{\lambda} = (\zeta + \alpha) \Delta T \]

where \( \zeta \) and \( \alpha \) are the TOC and the TEC of the materials, respectively. As the polymer coating has higher TOC and TEC values than the silica fibre, the temperature sensitivity is therefore improved.

To investigate the spatial optical intensity distribution within the bent fibre (at the most curved section) and the effect of bending radius on it, numerical simulations based on the beam propagation method (BPM) have been performed. The specific simulation parameters used were: the diameter and RI for the SMF core and cladding are 8.3/125 \( \mu \text{m} \) and 1.4504/1.4447, respectively, and the RI of the polymer coating is assumed to be 1.51. The simulation length of SMF is 12 mm and the free space wavelength was set at 1550 nm. When the bending radii were set as 5 mm, 4 mm, 3 mm and 2.7 mm, the calculated results are presented in figures 2(a)–(d), respectively. From figure 2, it is clear that the optical intensity within the bent fibre is mainly concentrated on the outer side of the bend. Furthermore, considering the optical intensity distribution, it is also clear that light reflection exists between the fibre core and polymer coating, which in turn results in a transmission spectrum which possesses distinct dips at certain wavelengths as a result of interference. From figures 2(a)–(d), it can be seen that as the bending radius decreases, the numbers of reflections within the bent region increases which in turn contributes to increased interference and potentially increased sensitivity. However, when the bending radius is too small, the light energy leaks out of the coating, which can be clearly observed from figures 2(c) and (d). Therefore, an appropriate bending radius needs to be confirmed experimentally to achieve an effective interference pattern.

Prior to a more formal experimental investigation described in the next section and based on the above theoretical analysis and numerical simulations, the transmission spectrum (1520 nm–1600 nm) of a bent fibre structure for different bending radii was investigated experimentally. In this investigation, when the bending radius of the SMF was more than 5 mm, no interference pattern appears within the wavelength range since little or no light energy in the fibre core is coupled into the cladding and coating. The bending radius was decreased from 5 mm to 3.5 mm with a step of 0.5 mm, and the measured results are shown in figure 3. From figure 3, it can be observed that with a decreasing bending radius, the intensity loss of the transmission spectrum increases because more light is coupled into the coating. When the bending radius reaches 5 mm and 4.5 mm, interference fringes appeared, but
possessing a relatively low extinction ratio. With a further decrease of the bending radius to 4 mm, an interference dip appeared which has a relatively large extinction ratio (more than 15 dB). As the bending radius was further decreased to 3.5 mm, more interference dips were detected which means that the free spectral range (FSR) of the transmission spectrum decreases. Moreover, the extinction ratio of these interference dips becomes smaller. If the bending radius continues to decrease, excess light is coupled into the coating and even leaks out from the coating resulting in a large loss. Ultimately, these initial experiments determined that an appropriate bending radius to form a modal interferometer should lie around the region of 4 mm. In the next section, a more detailed experiment is described where a robust bent fiber structure is fabricated based on the use of a capillary tube and UV glue.

3. Experiments and discussion

To fabricate a robust and mechanically stable sensor structure, both ends of the SMF-28 were inserted into a silica capillary tube of length 1.5 cm and inner diameter 600 µm. By moving the silica capillary tube along the fibre, the bending radius of the balloon-shaped section was flexibly adjusted. When a preferred bending radius was reached, ultraviolet (UV) glue was used to immobilize the sensor structure. The entire fabrication process is extremely simple and can even be completed without the use of a fusion splicer. The image of the fabricated sensor sample is shown in the insert in figure 4. Two bend parameter values were measured, the bending radius \( r \) value of 3.86 mm (the bending radius was adjusted to 3.86 mm to obtain the optimum interference dip condition) and the length of the balloon-shaped section \( L \) which is 13.42 mm. The transmission spectrum of the obtained sample was also measured and is depicted in figure 3.

The experimental setup for temperature measurement using the sensor of this investigation is schematically depicted in figure 5. The fabricated sample was placed in contact with the surface of a thermoelectric Peltier cooler using a 3D displacement platform. A stable triple power supply (TTI EL302RT) was used to control the input electric current of the Peltier cooler, and the real-time temperature value of its surface was monitored using a thermocouple (RS 1313). The input SMF of the sample was connected to a broadband light source (BBS, Thorlabs SSFC1005S). The light was transmitted through the sample and finally recorded using an optical spectrum analyzer (OSA, Agilent 86142B).

The transmission spectrum evolution of the sensor when subjected to a temperature range from 20.7 °C to 30.7 °C with a step of 1 °C is depicted in figure 6(a). In order to test the repeatability of this temperature sensor, a reversed measurement cycle was applied with the temperature being decreased from 30.7 °C back to 20.7 °C, and the result is depicted in figure 6(b). As shown in figure 6(a), the selected dip has a clear wavelength shift (27 nm) as the temperature was increased from 20.7 °C to 30.7 °C. When the temperature was decreased, the evolution of the dip feature was reversed compared with the temperature increase process, as presented in figure 6(b).

The resulting wavelength shift of the dip for the temperature increase and decrease processes were plotted and fitted against the temperature in figure 7. From figure 7, both characteristics exhibit a high linear regression coefficient value \( (R^2) \) of 0.9980 and 0.9991, and the temperature sensitivities at the temperature increase and decrease processes were determined as \(-2465 \text{ pm °C}^{-1}\) and \(-2445 \text{ pm °C}^{-1}\), respectively. Based on the transmission spectrum feature evolution with temperature and the determined sensitivities, it is also demonstrated that the temperature sensor of this investigation offers good repeatability on account of the very small differences between the results for the temperature increasing and decreasing cases. Furthermore, given that the 20 pm resolution of OSA used in the experiment, the temperature measurement resolution of this sensor system is estimated to be 0.008 °C.
To confirm the improved temperature sensing performance induced by the polymer coating of optical fibres, a comparison experiment using a stripped SMF based BSBS fibre structure was performed. When the bending radius \( r \) of the BSBS fibre structure was adjusted to 4.31 mm, an available interference dip\(_1\) with a central wavelength of 1573.2 nm was used to perform temperature sensing measurements. The corresponding dip wavelength redshifts as a function of temperature changes are shown in figure 8. From the linear fitting results, one can see that the temperature sensitivity of the bare BSBS fibre structure was determined as 49.5 pm \(^\circ\)C\(^{-1}\). Compared with the BSBS fibre structure with coating layers presented...
above, it is clearly to understand that the temperature sensitivity of the BSBS fibre structure was greatly improved to over 2000 pm °C⁻¹ with the presence of the polymer coating layers of the BSBS fibre structure.

Table 1 shows a comparison of the sensing performance between the temperature sensor described in this investigation and other temperature sensors also cited in this article. From Table 1, it is clear that the temperature sensitivity of the sensor described in this investigation is competitive when compared with other temperature sensors. Comparing temperature measurement resolutions, the value of 0.008 °C achieved in this sensor system is the best among all the temperature sensors included in Table 1. In addition to the direct advantage of high sensitivity and good resolution, this proposed sensor can be fabricated using a very simple process, in return it results in lower cost compared with the other temperature sensors. It is noteworthy that the detectable temperature range in this investigation is limited by the effective working temperature of the polymer coating and the UV glue. The application areas for the sensor lie in areas which demand temperature measurement with very high resolution, to detect minute changes in temperature, for example in medical and biological diagnostics.

It should also be noted that the values of RI, TOC and TEC of the polymer coating of SMFs are likely to vary from the acrylate polymer material formulations provided by the optical fibre manufacturers. As a result, the temperature sensing performance of the BSBS fibre structures constructed using SMFs from different optical fibre manufacturers can be different. To investigate this, a comparison experiment by using a standard SMF provided by the other optical fibre manufacturer (Yofc, China) was carried out. To maintain the consistency of sensor fabrication, the bending radius was carefully adjusted to the same value of 3.86 mm. To maintain the consistency of sensor fabrication, the bending radius was carefully adjusted to the same value of 3.86 mm. The resulting interference dip and its temperature dependent results are shown in Figure 9. From Figure 9, one can see that when the surrounding temperature was increased from 18 °C to 26 °C, the interference dip2 had a significant blue-shift from 1523.8 nm to 1507.14 nm, and a temperature sensitivity of −2120 pm °C⁻¹ was achieved. The discrepancies of the interference dips wavelength location and the temperature sensitivities presented between Figures 4 and 9 were mostly induced by the different formulations of the polymer coating materials used by the two optical fibre manufacturers. Therefore, in order to guarantee the consistency of reproducibility, it is important to use the same SMF to ensure sensing repeatability performance of the BSBS fibre structure based fibre optic sensors.

4. Conclusion

A high sensitivity optical fibre temperature sensor based on a BSBS fibre structure with its original polymer coating has been described. Through bending an unstripped SMF into a balloon shape with the help of a section of silica capillary tube,
a modal interferometer formed by the core mode and coating modes was established at a certain bending radius. Owing to the presence of the original polymer coating, the sensor of this investigation experimentally achieved a high temperature sensitivity of $-2465 \text{ pm} / \text{°C}^{-1}$ coupled with a resolution of 0.008 °C over the temperature range of 20.7 °C–31.7 °C. Given its simple fabrication process, ultra-low cost and experimentally determined high sensitivity and good repeatability, this temperature sensor offers good potential as a competitive candidate for accurate temperature measurement.

Acknowledgments

This work was supported by the National Key R&D Program of China under Grant NO. 2016YFE0126500, the National Natural Science Foundation of China (NSFC) under Grant No. 61575050, the Key Program for Natural Science Foundation of Heilongjiang Province of China under Grant No. ZD2016012, the 111 project under Grant No. B13015, the Government of Ireland International Scholarship programme, and the PhD Student Research and Innovation Fund of the Fundamental Research Funds for the Central Universities (HEUGIP201820).

ORCID iDs

Ke Tian https://orcid.org/0000-0003-0954-9350

References

[12] Li E, Wang X and Zhang C 2006 Fiber-optic temperature sensor based on interference of selective higher-order modes Appl. Phys. Lett. 89 091119