Photonic crystal fibre based high temperature sensor with three-beam path interference

S.-S. Li, Z.-D. Huang, X.-S. Song, S.-Y. Zhang, Q. Zhong, F. Xu and Y.-Q. Lu

Photonic crystal fibre (PCF) modal interferometers are widely used for sensing applications. Owing to the intrinsic Mach-Zehnder-like dual-mode interference there is a trade-off between sharp spectral response and wide sensing range. A three-beam path interferometer induced by mode-conversion in a single dual mode PCF end face is experimentally demonstrated. Doubled free spectral range is obtained owing to the three-beam path interference, which is suitable in sensing large index change, wide temperature variation and strong applied pressures. As an example, a temperature sensor with the sensitivity of 8.17 pm/°C is demonstrated ranging from room temperature to 520°C. The mechanism and further improvements of the multi-beam path interferometers are also discussed.

Introduction: Over the past 30 years, fibre-optic technologies have experienced tremendous growth. A big interest in this field is to develop high performance interferometric fibre-optic sensors [1]. Different approaches, in which the guiding mechanisms of an optical fibre can be modulated by external factors, have been exploited. The hollow structure of photonic crystal fibres (PCFs) provides a convenient access to the evanescent waves of the guided light without complicated pretreatment. The first attempt to construct an interferometer with a PCF was reported in 2001 by MacPherson *et al.* [2]. Owing to small size, flexibility, immunity to electromagnetic interference and the capability for remote measurements, PCF based modal interferometric sensors have shown advantages in detecting changes of pressure, temperature and environmental refractive index [3–6]. However, owing to the intrinsic Mach-Zehnder like dual-mode interference, the spectrum is just an ordinary sinusoidal curve. The maximum sensing range is determined by the spectrum's period, i.e. the free spectral range (FSR). If the wavelength shift is large closing to a FSR, the spectrum almost overlapps at its original curve. In this case, it is not easy to read the actual spectral shift. However, wide range sensing is desired in many applications, for example, temperature sensors working in some industrial environments or in fire alarm systems.

In this Letter, we propose to tailor the reflective PCF interferometer's spectrum by inducing an extra interfered beam path. A doubled maximum sensing range without resolution reduction is obtained. A temperature sensor working up to 520°C is demonstrated with a sensitivity of 8.17 pm/°C. In comparison with previously reported fibre sensors with ∼200°C measurement range [4, 5], our approach shows a remarkable improvement.

Experiments and theoretical analysis: In our experiment, a segment of PCF (Crystal Fiber's LMA-25) is spliced to a singlemode fibre (SMF) forming a simple and robust interferometer. The PCF consists of a solid core surrounded by three rings of air holes arranged in a hexagonal pattern. The diameters of the core, void and cladding are 25.2, 8.4 and 268 μm, respectively. According to the Comsol Multiphysics simulation, there are two kinds of major modes in the 1550 nm telecom band. One of them is the fundamental LP_{01}-like mode with the effective index of 1.445402 while another one is a four-fold degenerated LP11-like mode with the mode index of 1.444549 [7]. The corresponding inter-modal index difference Δn is 8.53×10^{-4}.

Fig. 1 illustrates our experimental setup representing a reflective type PCF sensor. Light from an amplified spontaneous emission (ASE) source is coupled into an SMF through an optical circulator. An L-long PCF is fused to the SMF forming an interferometer. The reflective light from the cleaved right end face is fed back to an optical spectrum analyser (OSA) through the circulator. If the PCF end face was an ideal mirror, the lights would pass through the PCF twice so the interference pattern should be similar to that of a $2L$-long transmissive PCF, which is still a sinusoidal spectrum. However, after numerous experiments, we believe that the two major PCF modes can partly convert to each other at the PCF end reflecting surface. Before the reflected lights are recombined together into the SMF, there are four beam routes in which two mode-converted beams have the same light path. Therefore there are in total three kinds of interfered beams with their light paths of $2n_1L$, $2n_2L$ and $2n_3L = (n_1 + n_2)L$, respectively. Thus an equal spaced multimode interference is realised in such a dual mode PCF. The phase retardation of the adjacent modes is $\Delta\phi = \Delta\beta \times 2L = 2\pi(n_1 - n_2)L/\lambda$. As a consequence, the maximum sensing range $FSR_r(L)$ is expressed as $\lambda^2/\Delta nL$. However, if there was no mode-conversion induced extra beam, an L-long reflective interferometer would only have an FSR of $\lambda^2/2\Delta nL$. Therefore doubled sensing range could be achieved through the mode conversion.

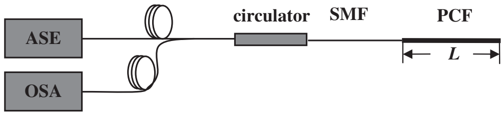

Fig. 1 *Schematic of reflective type PCF interferometer*

Fig. 2 shows a typical reflective interference pattern of a 25.6 cm-long PCF interferometer. It exhibits a more complicated three-beam interference curve rather than a sinusoidal curve. There are two kinds of peaks in the spectrum, one kind is higher and the other kind is lower. The difference between them is generally ∼2 dB, which makes them easily distinguished. The period between adjacent high or low peaks is 10.96 nm reading from Fig. 2, agreeing well with the theoretically estimated $FSR_r = 11$ nm at 1550 nm. The peak-to-valley contrast ratio is around 7–8 dB, which is large enough for sensing applications.

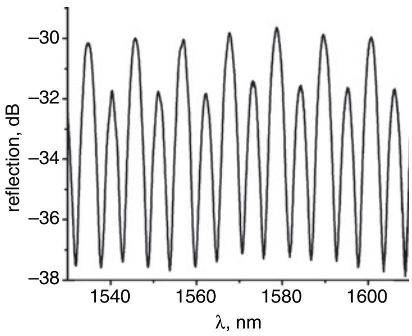

Fig. 2 *Interference spectrum of 25.6 cm-long reflective PCF modal interferometer at room temperature*

To implement the temperature sensing, the PCF interferometer was placed inside a cylindrical hot chamber in order to heat the PCF segment symmetrically. Spectral response at different temperatures is recorded for further signal processing.

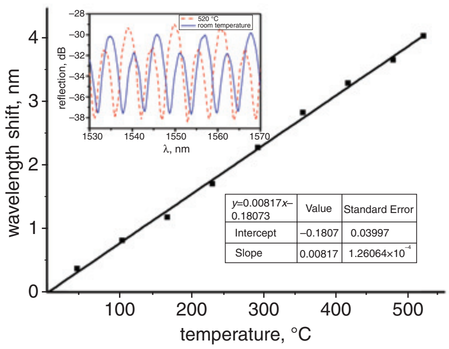

Fig. 3 *Wavelength shift of reflective PCF interferometer against temperature*

As shown in the inset in Fig. 3, the interference spectrum has a red shift when the temperature increases. The solid and dashed curves represent the spectra at room temperature and 520°C, respectively. The thermal expansion coefficient α and the thermal-optic coefficient κ are the same for both the core and the cladding, which are defined as $\alpha = 1/L \times \partial L/\partial T$ and $\kappa = 1/\Delta n \times \partial\Delta n/\partial T$, where Δn is the refractive index difference between the LP_{01} and LP_{11} modes. The temperature sensitivity can be written as $\Delta\lambda/\Delta T = \lambda_m(\alpha + \kappa)$. For fused silica fibres, the thermal expansion coefficient and thermal-optic coefficient are $\alpha = 5 \times 10^{-7}$/°C and $\kappa = 1 \times 10^{-5}$/°C. The typical temperature sensitivity is in the range 6–8 pm/°C [6]. Fig. 3 shows the wavelength shift of the interference pattern as a function of the temperature. The solid squares are the experimental data and a best-fitted line is also shown. A temperature sensitivity of 8.17 pm/°C, i.e. the slope of the line, is obtained. The averaged variation of the best-fitted line and the measured results from the thermal coupler is 3.5%, reflecting the measurement uncertainty based on a linear response assumption. To improve the accuracy, a polynomial fitting curve may be used.

As a sensor, the most important characters include the maximum sensing range and minimum detection limit, but there is a trade-off between them. The maximum sensing range is basically the period of the spectrum while the minimum detection limit is determined by the peak or valley bandwidth. Compared with the normal transmissive $2L$-long PCF interferometer, our reflective PCF interferometer has similar minimum spectral bandwidth but a doubled period. The great advantage brought by the three-beam interference is that a shift around half period is easily detectable because of the 'high' and 'low' peaks. When the high peaks move close to the low peaks, it is easy to distinguish them and read the shifted value. However, in the case of the ordinary transmissive interferometer, the interference pattern would be a sinusoidal curve with the same peak level. If the shift is a little more or less than a period, it only shows a tiny spectrum offset although a large wavelength shift actually happens, bringing difficulty in reading the shifted value. An especially confusing case is that the shift is just a period, but the spectrum looks like no change.

Discussion: In our experiments above, spectra with two kinds of peaks are shown, but the valleys are almost at the same level. As long as the PCF interferometer is fabricated, the spectra are very stable even after many temperature cyclings. The spectra during temperature rising and cooling down have no evident difference, meaning that the hysteresis effect is negligible. However, although the phenomenon of three-beam interference is clear and very repeatable, the spectral shapes are not always consistent, which means the detailed mode converting mechanism at the PCF end face still needs further investigation. We believe that the surface geometry and roughness are both important factors. They may affect the mode exchange at the PCF end face. In addition, the fusion area between the SMF and PCF also may influence the patterns because it determines the power ratio between the two excited modes. As long their relative intensities change, the final reflective spectrum also may change subsequently.

To further expand the PCF sensing range and get sharp spectral resolution, one straightforward idea is to induce more light paths in a PCF interferometer with equal light path spacing. Employing cascaded PCF sections is a viable solution. This might be realised by inducing hole-clasping in certain positions, but the fabricating skills have to be further developed. Nevertheless the model conversion approach really gives us more freedom to design both transmissive and reflective inter-modal interferometers with desired sensing range and spectral resolution.

Conclusion: We have demonstrated a temperature sensor based on a three-beam path PCF interferometer with expanded sensing range. The averaged temperature sensitivity is 8.17 pm/°C ranging from room temperature to 520°C. Approaches to further improve the interferometer's performance are discussed. We believe that the active control of inter-modal conversion will gives rise to many interesting new applications in fibre-optic sensors, measurement equipment and optical communications.

Acknowledgments: This work is supported by the National 973 Program under contract nos 2010CB327803 and 2006CB921805, and the specialised research fund for the Doctoral Program of Higher Education of China. The authors also acknowledge the support from the Changjiang Scholars Program and New Century Excellent Talents Program of China.

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19 June 2010
doi: 10.1049/el.2010.1679
One or more of the Figures in this Letter are available in colour online.

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