# Photonic crystal fibre based modal interferometer with four-beam path interference

S.-S. Li, X.-S. Song, F. Xu and Y.-Q. Lu

In recent years, photonic crystal fibre based modal interferometers have been widely investigated. Owing to the nature of Mach-Zenhder-like interference, the sensing range is limited by the sinusoidal spectrum's period. A splicing approach is proposed and demonstrated to achieve unique four-beam interference so that quadrupled sensing range is obtained without reduction in detection limit, which would be much desired in wide range refractive index, pressure and temperature sensing. As an example, a high-temperature sensor ranging from 28 to 484°C is demonstrated.

*Introduction:* Fibre-optic technologies have experienced tremendous growth in the past three decades. Optic sensors are accordingly investigated for all kinds of sensing applications. Among so many types of fibre, the hollow structure of photonic crystal fibre (PCF) provides a convenient access to the evanescent waves of the guided light without complicated pretreatment [1]. Furthermore, PCF could serve as a modal interference cavity forming a modal interferometer by using splicing or collapsing methods [2, 3]. Thus, the PCF based interferometer has attracted considerable attention owing to its flexibility and the capability for remote measurements. Further researches on its temperature and refractive index sensing applications have been extensively studied [4, 5]. However, the spectrum of a PCF interferometer is basically a Mach-Zehnder-like dual-mode interference pattern showing an ordinary sinusoidal curve with fixed and poor fineness. The maximum sensing range is determined by the spectrum's period, which is the free spectral range (FSR) in other words. Overlapping will occur when the wavelength shift is close to or larger than a FSR. In this case, it becomes somewhat complicated to figure out the actual shift. But wide range sensing is desired in many applications, for example, the temperature sensor working in some industrial environments or in fire alarm systems.

In this Letter, we demonstrate multi-beam interference in a transmissive-type PCF modal interferometer using splicing methods. It is quite easily fabricated and reduplicated. A quadrupled maximum sensing range without resolution reduction is obtained which shows remarkable improvement. To substantiate it, the temperature test was implemented from 28°C, highly to 484°C. The measured temperature sensitivity is normally 6.55 pm/°C and the calculated device accuracy is 2.6°C, which is better than former results.

*Experiments and theoretical analysis:* We previously reported a reflectively-type PCF interferometer [6]. Three-beam path interference was experimentally demonstrated owing to the mode conversion at the PCF's open end. To expand further the sensing range with more beam interference, the idea of cascading transmissive PCF was mentioned [6, 7], while in this work, we would realise the multi-beam interferometer, demonstrate the corresponding fabrication technique and characterise its optical properties.

In our experiment, to form a simple and robust interferometer, two segments of PCF (Crystal Fiber's LMA-25) are spliced together with two singlemode fibres (SMFs), respectively. The PCF consists of a solid core surrounded by three rings of air holes arranged in a hexagonal pattern. According to the Comsol Multiphysics simulation, there are two kinds of major modes in the 1550 nm telecom band. The corresponding inter-modal index difference Δn calibrated by experiments is $7.81 \times 10^{-4}$ [6].

The experimental setup of a transmissive type PCF modal interferometer is illustrated in Fig. 1. An amplified spontaneous emission (ASE) source supplies wide-band input light covering the telecom C + L band. By controlling the splicing parameters, two PCF segments are connected together with a tiny fused transition area. The transmission light through two PCF segments and three fused areas is detected by an optical spectrum analyser (OSA). For a normal transmissive-type PCF modal interferometer, the transmission spectrum presents as a sinusoidal curve. As discussed in former papers [6, 7], we believe that the two major PCF modes can partly convert to each other at the PCFs' centre fused area. Besides, two PCF segments, one of which is different in length from the other one, offer different light paths for the two major modes. Before lights are recombined together into the SMF, there are a total of four kinds of interfered beams with their light paths of $n_1$ $(L + L')$, $n_2(L + L')$, $n_1L+ n_2 L'$ and $n_2L+ n_1 L'$, respectively. If $L' = L/2$, an equally spaced multimode interference is realised in such a dual-mode PCF. The phase retardation of the adjacent modes is $\Delta\phi = \pi(n_1 - n_2)L/\lambda$. As a consequence, the maximum sensing range FSR′(L) is expressed as $2\lambda^2/\Delta nL$. On the contrary, if there was no mode-conversion induced extra beams, a 3L/2-long PCF transmissive interferometer would only have a $\text{FSR} = 2\lambda^2/3\Delta nL$. Therefore, tripled sensing range could be achieved through multi-beam interference. If $L' = L/3$, the FSR″(L)= $3\lambda^2/\Delta nL$ while the FSR of the 4L/3-long PCF transmissive interferometer is FSR″(L)/4. In this way, sensing range could be further expanded by cascading the PCF in a modal interferometer.

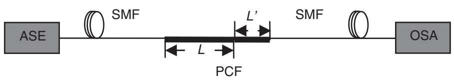



**Fig. 1** *Schematic of transmissive-type cascaded PCF interferometer*

*Results and discussion:* Figs. 2*a* and *b* show typical interference patterns of cascaded PCF modal interferometers in which the ratio of L to L′ are 2:1 and 3:1, respectively. For Fig. 2*a* $L = 22.8$ cm, $L' = 11.4$ cm and for Fig. 2*b* $L = 24$ cm, $L' = 8$ cm. According to the four-beam interference theory, simulation by MATLAB is carried out. The corresponding simulation spectrums are show on the right while the experimental results are on the left. Apart from absolute intensity, the pattern shape and dips' positions coincide with each other for experimental and simulation results. Reading from Figs. 2*a* and *b*, the spectrum periods are 27.12 and 38.91 nm, agreeing well with the theoretically estimated FSR′ = 26.98 nm and FSR″ = 38.45 nm at 1550 nm, respectively. This provides further strong evidence for mode-conversion. Ordinarily there is a trade-off between the sensing range and the detection limit, characterised by period and bandwidth, respectively. But cascaded PCF interferometers provide an access to improve both of them. By introducing multimode interference, large sensing range and narrow bandwidth might be obtained at the same time. Because they are two important parameters of sensors, the cascaded PCF interferometer could be widely used in sensing applications.

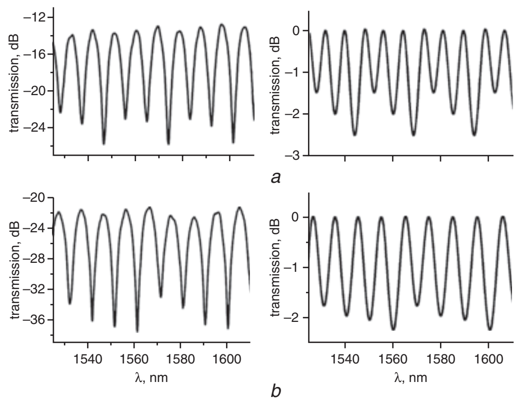
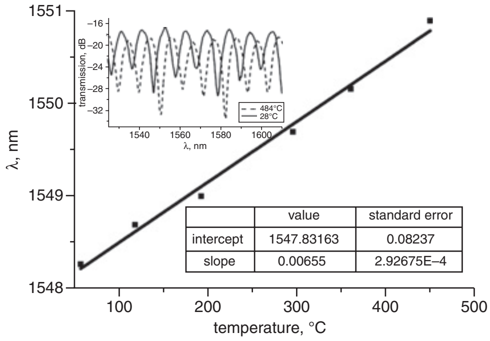



**Fig. 2** *Experimental (left) and simulation (right) interference spectra of 1:2 type and 1:3 type PCF modal interferometer at room temperature*

*a* 1:2 type
*b* 1:3 type

As an example, to implement temperature sensing, a PCF interferometer was placed on a hotplate covered by a vessel in order to heat it symmetrically. Spectral response at different temperatures are recorded for further signal processing. As shown in the inset of Fig. 3, the interference spectrum has a red shift when temperature increases. The solid and dash curves represent the spectra at 28 and 484°C, respectively. Fig. 3 shows the wavelength shift of the interference pattern against temperature. The solid squares are the experimental data and a best-fitted line is also shown. A temperature sensitivity of 6.55 pm/°C, the slope of the line, is obtained. The typical temperature sensitivity is in the 6–8 pm/°C range, according to the former paper [5]. During our experiments, the resolution of the OSA and the thermocouple are 0.02 nm and 1°C, respectively. Besides, the average half-width of valleys is basically 901.5 pm. Thus, device accuracy is estimated to be

2.6°C, which is much better than former results [7]. Thus, the method of cascading PCF to form a modal interferometer did improve the sensing range greatly without reducing its detection limit.




| | value | standard error |
|---|---|---|
| intercept | 1547.83163 | 0.08237 |
| slope | 0.00655 | 2.92675E–4 |

**Fig. 3** *Wavelength shift of 1:2 type PCF interferometer against temperature*
Inset: Interference spectra

Although the samples we fabricated show enough repeatability and the contrast ratio between the maximum and minimum transmission is also stably more than 10 dB, we cannot fully control the detailed variations between dips in each period and make them differ from each other as much as possible. According to the simulations mentioned above, we believe that the mode-conversion process greatly affects the proportion of the converted light and the trend between dips consequently. Thus, factors affecting mode-conversion such as collapsing length and arc intensity might be investigated in detail. Moreover, other methods introducing extra beam interference should be tried, for example, implementing torsion when splicing. Further investigation on the mode-conversion mechanisms is under way.

*Conclusion:* In this reported work, two PCFs with 1:2 or 1:3 lengths are spliced together forming modal interferometers. Choosing suitable splicing parameters, the interference pattern had three or four dips in each period, corresponding to tripled or quadrupled sensing range. Thus, we can get a broader sensing range at similar detection limits by introducing mode-conversion in the cascaded PCF interferometer. This technology could be widely used in various PCF based sensing applications.

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