Temperature dependence of birefringence in olarization-maintaining photonic crystal fibres

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In this paper, the temperature dependence of birefringence in polarization maintaining photonic crystal fibres (PM-PCFs) is investigated theoretically and experimentally. Utilizing the structural parameters of the PM-PCF samples in the experiment, two effects leading to the birefringence variation under different temperatures are analysed, which are the thermal expansion of silica material and the refractive index variation due to the temperature variation. The actual birefringence variation of the PM-PCF is the combination of the two effects, which is in the order of 10^{-9} K^{-1} for both fibre samples. Calculation results also show that the influence of refractive index variation is the dominant contribution, which determines the tendency of the fibre birefringence variation with varying temperature. Then, the birefringence beat lengths of the two fibre samples are measured under the temperature, which varies from −40 °C to 80 °C. A traditional PANDA-type polarization maintaining fibre (PMF) is also measured in the same way for comparison. The experimental results indicate that the birefringence variation of the PM-PCF due to temperature variation is far smaller than that of the traditional PMF, which agrees with the theoretical analysis. The ultra-low temperature dependence of the birefringence in the PM-PCF has great potential applications in temperature-insensitive fibre interferometers, fibre sensors, and fibre gyroscopes.

Keywords: birefringence, polarization-maintaining fibre, photonic crystal fibre, temperature dependence

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1. Introduction

Photonic crystal fibres (PCFs) were designed and fabricated in 1996 and have received much attention in the last ten years[1] They have microstructure claddings with periodically arrayed holes, which provide great design flexibility to break the performance limitation of traditional optical fibres. In 2000, the first polarization maintaining PCF (PM-PCF) was reported. This fibre was fabricated with pure silica by the stack drawing method. By enlarging two air holes close to the fibre core, the symmetry of the fibre structure is broken and the fibre shows a high birefringence. One year later, Suzuki *et al.*[2] reported on a PM-PCF with a similar fibre structure, low transmission loss, and ultra-high birefringence, showing its potential in real applications.[2] Up to now, although some new PM-PCF structures have been proposed, such as the PCF with oval holes, the PCF with equivalent ellipse core structure, and so on,[3−8] the PM-PCF with two enlarged holes close to the core is still the easiest one to fabricate and the most popular in research on applications of PM-PCFs. Compared with the traditional polarization maintaining fibre (PMF), the PM-PCF has advantages in the stabilities with respect to environmental variation and exposure to high energy radiation since it is made of pure silica. In particular, its transmission performance is relatively insensitive to the temperature variation, which has great potential for application in temperature-insensitive fibre interferometers, fibre sensors, and fibre gyroscopes.[9−13] However, further understanding of its performance stability with respect to temperature variation is required to guide applications of the PM-PCF.

In this paper, the variation of birefringence, induced by temperature, and its main contribution are demonstrated theoretically and experimentally. Utilizing the structural parameters of two PM-PCF samples, two effects leading to the birefringence variation under different temperatures are analysed, which are the thermal expansion of silica material and the refractive index variation. Then, the birefringence beat lengths of the two fibre samples are measured under temperatures varying from −40 °C to 80 °C and compared with the results of a traditional PMF, measured in the same way.

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2. Theoretical analysis on the temperature dependence of birefringence in PM-PCF

The structure of the PM-PCF is shown in Fig. 1. Figure 1(a) is the sketch of the fibre structure. It can be seen that it has a solid core and a cladding with air holes, which are arranged into a triangular pattern. Two air holes close to the fibre core are enlarged to generate high birefringence. The diameters of the small holes and the two large holes are denoted by d and D, respectively. The pitch of air holes is denoted by P. Figures 1(b) and 1(c) are cross sections of two PM-PCF samples used in the experiment, by which the structural parameters of the two samples are measured and shown in Table 1. The PM-PCFs are fabricated with pure silica. The refractive index of bulk silica is 1.4457 at room temperature (300 K), which is denoted by n_0.

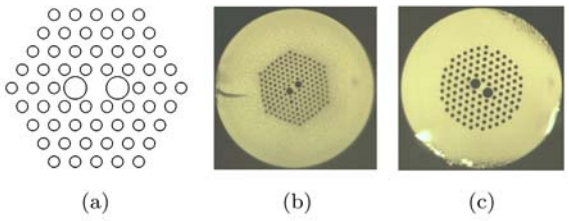


Fig. 1. (colour online) Structure of the PM-PCF, showing (a) the sketch of the PM-PCF and cross sections of sample 1 (b) and (c) sample 2.

Table 1. Structural parameters of the two PM-PCF samples.

Sample	D/μm	d/μm	P_d/μm
No. 1	4.66	2	3.8
No. 2	7.9	3	5.5

When the temperature changes, two effects will influence the transmission characteristics of the PM-PCF. One of the two effects is the thermal expansion of the silica. This will change the structural parameters of the PM-PCF under varying temperatures and is described as

$$A(T) = A_0 \times (1 + \alpha_{\text{therm}} \times (T - T_0)), \qquad (1)$$

where T and T_0 are the actual temperature and room temperature ($T_0 = 300$ K in the calculation), respectively. $A(T)$ and A_0 are structural parameters (including D, d, and P) under actual temperature and room temperature, respectively; α_{therm} is the thermal-expansion coefficient, which is 5.5×10^{-7} K^{-1} for the pure silica. The other effect is the temperature dependence of the refractive index of pure silica, which is described as

$$n(T) = n_0 + n_{\text{therm}} \times (T - T_0), \qquad (2)$$

where $n(T)$ and n_0 are the silica refractive indexes under the actual temperature and room temperature, respectively, n_{therm} is the temperature coefficient of the refractive index, which is 1.2×10^{-5} K^{-1} for pure silica.

In this paper, the beam propagation method (BPM)[13] is used to analyse the temperature dependence of the birefringence in the PM-PCF utilizing the structure parameters of the two fibre samples shown in Table 1. The operating wavelength of the PM-PCFs is set to 1550 nm. Firstly, the transmission characteristics of the two PM-PCF samples under room temperature (300 K) are calculated and shown in Table 2. Figure 2 shows the modal field distributions of two orthonormal polarization modes in the two PM-PCF samples. It can be seen that sample 2 has a larger modal field due to its larger structural parameters. On the other hand, its birefringence is lower than that of sample 1. In the calculation, the birefringence is indicated by B, which is due to the difference in the effective refractive index between the two orthonormal polarization modes in the PM-PCF.

Then, the birefringences of the two PM-PCF samples were calculated under different temperatures. To analyse the dominant effect of the birefringence variation, firstly, only the thermal expansion effect is considered in the calculation, while the refractive index of silica is set to be n_0. The calculation results are shown in Fig. 3. It can be seen that the birefringences of both fibre samples decrease with a temperature increase under the effect of thermal expansion. The temperature coefficients of birefringence are -2.82×10^{-9} and -6.583×10^{-10} for fibre samples 1 and 2, respectively. Both of them are negative.

Table 2. Transmission characteristics of the two PM-PCF samples under room temperature.

Sample	$n_{\text{eff,TM}}$	$n_{\text{eff,TE}}$	B	MFD_{TM}/μm	MFD_{TE}/μm
No. 1	1.4219921652	1.4195224667	2.46969×10^{-3}	4.25	4.36
No. 2	1.4351995864	1.4344971826	7.02404×10^{-4}	6.43	6.51

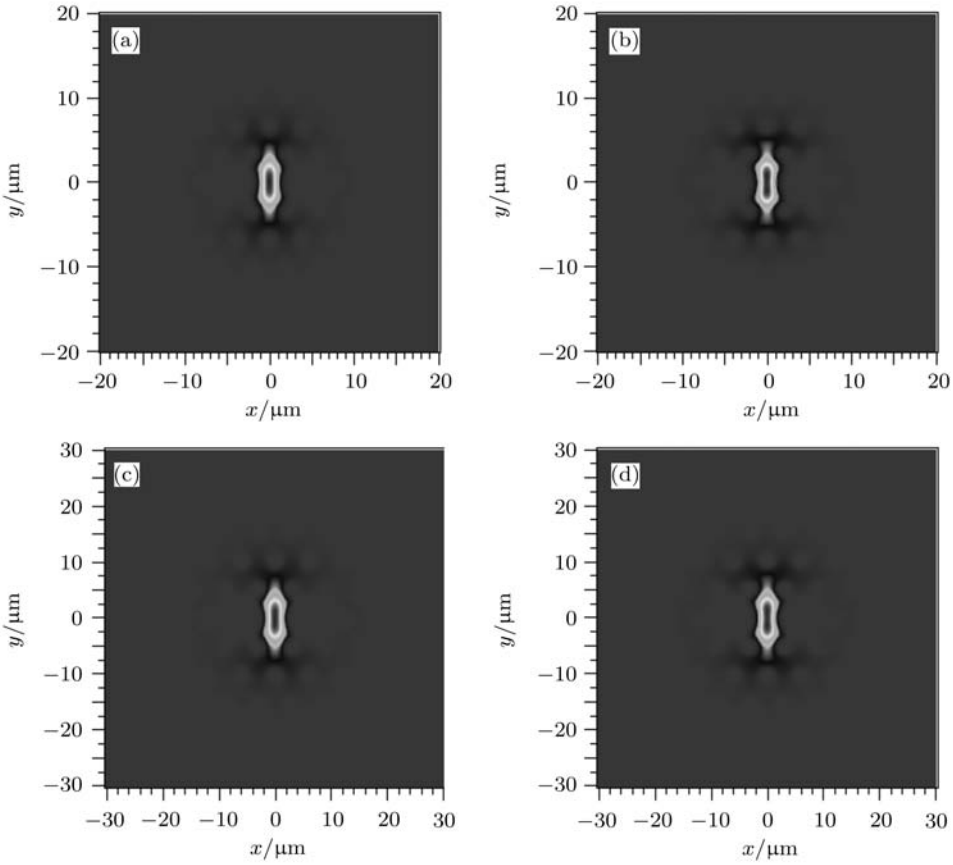


Fig. 2. Calculated modal field distributions of the orthonormal polarization modes in the two PM-PCF samples. Panel (a) is for the TM mode of sample 1, panel (b) for the TE mode of sample 1, panel (c) for the TM mode of sample 2, and panel (d) for the TE mode of sample 2.

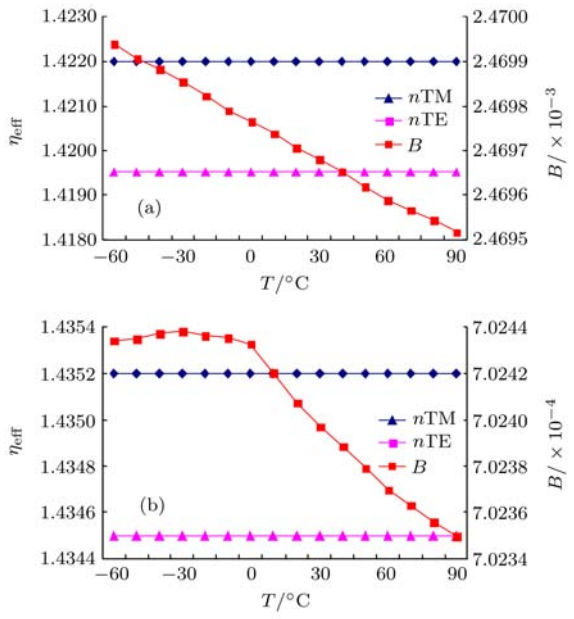


Fig. 3. (colour online) Calculated birefringences of (a) sample 1 and (b) sample 2 with increasing temperature under the thermal expansion effect only.

The effect of variation of the refractive index with temperature increasing on fibre birefringence is also calculated, where the structure parameters are set to be the values under room temperature. The calculation results are shown in Fig. 4. It can be seen that the effects of refractive index in the two PM-PCF samples are different. Temperature coefficients of birefringence are 4.655×10^{-9} and -1.971×10^{-9} for samples 1 and 2, respectively. One is positive, the other is negative.

In real applications, the PM-PCF experiences both thermal expansion and refractive index variation when environment temperature changes. Figure 5 shows the calculated results of the two PM-PCF samples in this case. It can be seen that for both fibre samples, the total birefringence variation is the combined effect of thermal expansion and refractive index variation. The effect of refractive index variation is larger than that of thermal expansion and determines the tendency of the birefringence variation with temperature increase. In the PM-PCF sample 1, the temperature coefficients of birefringence induced by thermal expansion and refractive index variation have different signs. Hence, their contributions on birefringence variation cancel each other out to a certain ex-

tent. On the other hand, in the PM-PCF sample 2, the temperature coefficients of birefringence induced by

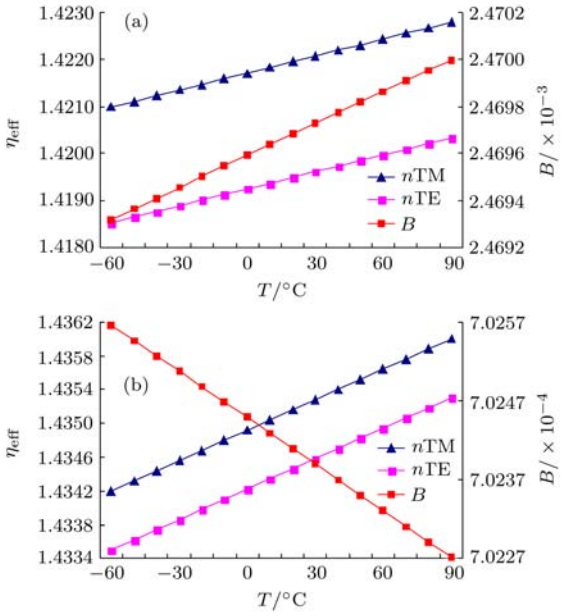


Fig. 4. (colour online) Calculated results of birefringences of (a) sample 1 and (b) sample 2 with temperature increasing under refractive index variation only.

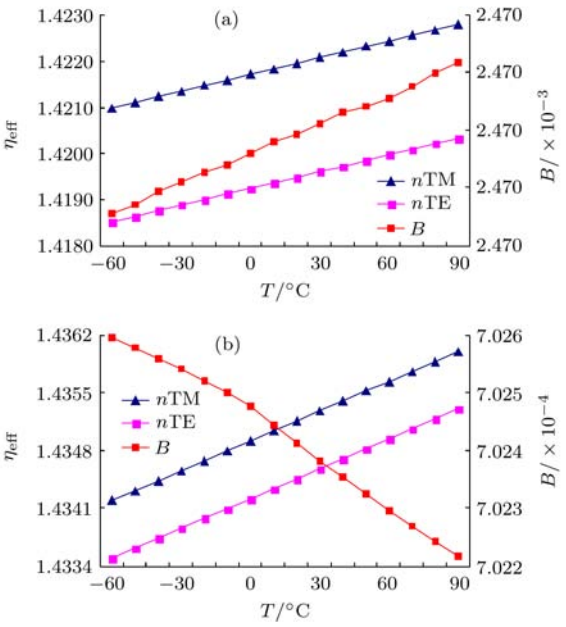


Fig. 5. (colour online) Calculated results of birefringence of (a) sample 1 and (b) sample 2 with increasing temperature under both thermal expansion and refractive index variation.

the two effects have the same signs. The birefringence variation is the superposition of contributions of the two effects. The actual temperature coefficients of birefringence are 1.828×10^{-9} and -2.629×10^{-9} for fibre samples 1 and 2, respectively. Both of them are quite small compared with those of the traditional PMFs. The analysis indicates that the temperature dependence of the birefringence in PM-PCF may be further reduced by properly designing a fibre structure, such that the effects of thermal expansion and refractive index variation are opposite and cancel each other out.

3. Experiment

The birefringent beat lengths of the two PM-PCF samples are measured under different temperatures. The temperature dependence of birefringence in a piece of traditional PANDA-type PMF fibre (fabricated by Yangtze Optical Fiber and Cable Company Ltd.) is also measured for comparison.

The beat lengths are measured by a method based on hybrid Sagnac interferometer,[14] and the setup is shown in Fig. 6. The PM-PCF sample under test is spliced with two ends of a 50:50 fibre coupler to build a hybrid Sagnac interferometer. The fibre samples are inserted into a thermostat to control its temperature. The SM125 is a fibre Bragg grating demultiplexer based on a tunable laser. It has four channels, each of which supports the demultiplexing of a string of fibre Bragg gratings. Their wavelength resolutions are all 1 pm. Their structures are shown in Fig. 6(b). One channel connects to one port of the hybrid Sagnac interferometer, used as a tunable laser source. The other port of the hybrid Sagnac interferometer connects to another SM125 channel with an isolator, by which the transmission spectrum of the hybrid Sagnac interferometer is measured. According to Ref. [14], the beat length measurement error of this method is smaller than 0.001 mm.

Figure 7 shows the transmission spectra of two PM-PCF samples measured by the two hybrid Sagnac interferometers at room temperature. The lengths of the two PM-PCF samples and the measured beat length according to the results shown in Fig. 7 are listed in Table 3. The measurement results of the PANDA-type PMF sample are also listed for comparison. It can be seen that both of PM-PCF samples have shorter beat lengths than the PANDA-type PMF sample, indicating that they have larger birefringences. The birefringence of sample 1 is larger than that of sample 2. These results agree with the theoretical calculations.

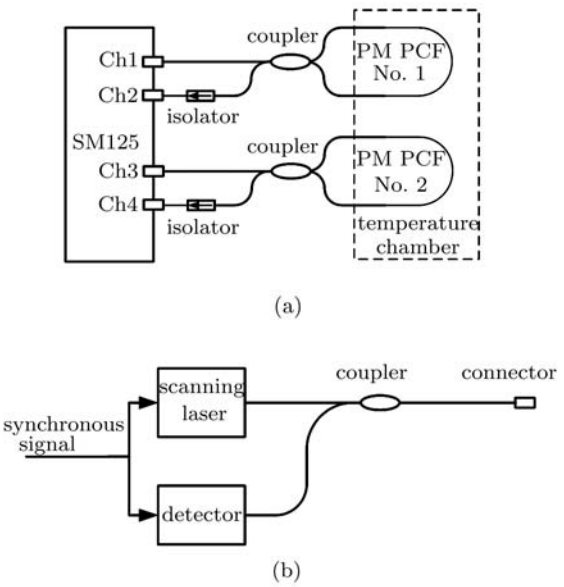


Fig. 6. The experimental setup showing (a) the measurement system and (b) one of channels of the SM125.

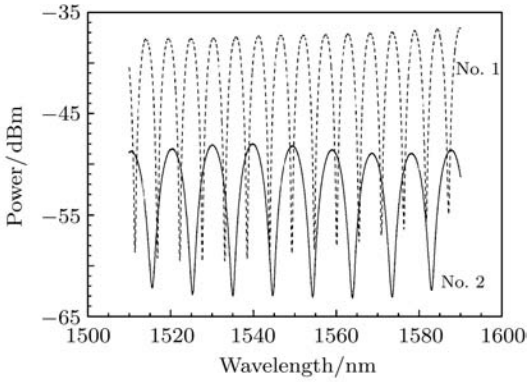


Fig. 7. Transmission spectra of the two PM-PCF samples measured by hybrid Sagnac interferometers at room temperature.

Table 3. Measurement results of the beat lengths of the fibre samples.

Sample	No. 1	No. 2	Panda PMF
Length (L)/cm	30	22	30
Beat length (L_B)/mm	1.045	1.355	2.217

The temperature dependences of birefringences in the three fibre samples are measured in a temperature range from −40 °C to 80 °C. The temperature increase speed is 1 °C/min. Measurements are taken at a certain temperature after a temperature stabilization of 30 min. The measurement results are shown in Table 4.

It can be seen that the beat length of the PANDA-type fibre sample increases with temperature, increasing at a temperature coefficient of 0.0428 mm · K^{-1}. On the other hand, the measured beat lengths of the two PM-PCF samples are almost unchanged as the temperature changes. Considering the fact that the error of this measurement system is smaller than 0.001 mm and the temperature span of the measurement is about 100 °C, the experimental results indicate that the absolute values of the beat length temperature coefficient are smaller than 10^{-5} mm · K^{-1} for both the PM-PCF samples. If B is used to describe the fibre birefringence, it means that the temperature coefficient of B is smaller than a magnitude of 10^{-8}. These results agree with the theoretical analysis, demonstrating the advantage of PM-PCF in low temperature dependence of birefringence. However, when the temperature is low, the measured birefringence obviously increases with the temperature decrease, which can be interpreted by neither the thermal expansion nor the refractive index variation. A possible reason for the birefringence variation is the stress induced by the polymer material of the fibre coating layer under the low temperature. It may be that this is the dominant contribution to the temperature dependence of birefringence in the PM-PCF when the fibre is used in the low temperature environment.

Table 4. Measurement results of the temperature-dependent beat lengths of the fibre samples.

Temperature	PANDA-type PMF/mm	No. 1/mm	No. 2/mm
−40 °C	2.1	1.047	1.366
−20 °C	2.138	1.047	1.359
0 °C	2.177	1.045	1.356
20 °C	2.217	1.045	1.354
40 °C	2.258	1.045	1.355
60 °C	2.312	1.045	1.355
80 °C	2.357	1.045	1.355

4. Conclusions

In this paper, temperature dependence of birefringence in the PM-PCF is investigated. Utilizing the structural parameters of the PM-PCF samples used in the experiment, two effects leading to the birefringence variation under different temperatures are analysed, which are the thermal expansion of silica material and the refractive index variation. The actual birefringence variation of the PM-PCF is the combination of the two effects, which is in the order of 10^{-9} K^{-1} for both fibre samples. Calculation results also show that the effect of refractive index variation is

the dominant contribution, determining the tendency of the fibre birefringence variation under temperature changes. The temperature dependences of birefringence in PM-PCFs may be further reduced by properly designing a fibre structure, such that the effects of thermal expansion and refractive index variation are opposite and cancel each other out. Then, the birefringence beat lengths of the two fibre samples are measured under temperatures varying from −40 °C to 80 °C. The experimental results indicate that birefringence variation due to temperature variation is far smaller than those of the traditional PMF, which accords well with the theoretical analysis. Experimental results show that the birefringence obviously increases with temperature decrease under a low temperature. This may be due to the stress induced by the polymer material of the fibre coating layer under a low temperature.

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