Temperature independence of birefringence and group velocity dispersion in photonic crystal fibres

A. Ortigosa-Blanch, A. Díez, M. Delgado-Pinar, J.L. Cruz and M.V. Andrés

Experimental results are presented for the dependence of the dispersion and the birefringence of a highly birefringent photonic crystal fibre with temperature. It is shown that, unlike conventional optical fibres, where temperature induces stress regions between the different materials present in their structure, photonic crystal fibres exhibit no dependence with temperature of these optical properties owing to the single material nature of their structures.

Introduction: The effect of environmental factors in optical fibres is a key issue when developing new fibre systems and components. Factors such as temperature and pressure affect many optical properties of optical fibres and it becomes necessary to correct them in order to manufacture reliable fibre systems.

Because of the symmetry present in conventional circularly symmetric optical fibres, they do not maintain the polarisation state of the guided mode along their length. Although they are nominally isotropic, small twists, bends and other stresses impose unknown and uncontrolled birefringence on the fibre, so that the polarisation of the fibre output is unpredictable. Highly birefringent fibres, in which strong birefringence is deliberately introduced during the fibre fabrication, are much more resilient to such environmental factors [1]. The required birefringence can be achieved by making the material forming the fibre birefringent, typically by introducing stresses, as in Bow-Tie or Panda fibres. Thus, the birefringence of both Panda and Bow-Tie fibres relies on the stress imposed on the structure.

These kinds of fibres are usually fabricated using two rods of borosilicate glass inserted on opposite sides of the fibre core at the preform stage. The modal birefringence will then depend on the location and thickness of the stress-applying elements. The effect of temperature on these optical fibres has been well understood for a long time [1, 2]. When temperature changes, the properties of the materials change, leading to geometry and stress changes in the fibre. Changes due to geometry come mainly from the change in size governed by the thermal coefficient of pure silica ($\alpha = 5 \times 10^{-7}/^{\circ}$C). Usually, these changes can be considered negligible. The main effect of temperature on polarisation-maintaining optical fibres is the stress induced in the fibre due to the difference between the materials: a change in temperature will modify the stress distribution and may generate new stress regions that were not present when working at room temperature.

Over the past few years an alternative form of optical fibre waveguides has been demonstrated: photonic crystal fibres (PCFs) [3]. PCFs are silica fibres with an array of microscopic air holes running along their length. These new structures, made only with undoped silica glass and air, have shown remarkable new properties and can outperform conventional fibre optics in several respects. In the fibres considered here, a single missing air hole (i.e. a region of pure silica) embedded within the array forms a region of raised refractive index that will act as the core of the fibre. One of the structures that has proved more interesting is the one known as highly birefringent PCF, i.e. polarisation preserving PCF [4, 5]. Their birefringence relies either on the elliptical shape of their core or the asymmetry of their microstructure and shows a value an order of magnitude higher than that of conventional optical fibres.

Recently, Wegmuller *et al.* [6] have shown experimental results on the temperature dependence of phase and group birefringence over a small range of temperatures for a conventional PCF, i.e. a non-polarisation-preserving PCF. In this Letter, we present a study of the dependence on temperature of the dispersion and birefringence of a highly birefringent PCF. We found that these two parameters show no measurable dependence on temperature in the range from −25 to 55°C.

Experimental results: Fig. 1 shows a scanning electron micrograph of the fibre used in the experiments. The birefringent PCF was fabricated following a modified stack and draw method [5]. The dimensions of the core region are 2.2 and 2.9 μm, respectively, for the minor and major axes, and the average air hole size is 3.5 μm. All the experiments were performed on a 6 m long piece of fibre. The fibre was slightly multimode around 1550 nm. A modal filter consisting of a tapered section was implemented at the end of the microstructured fibre. The taper region, fabricated with the appropriate parameters, scales down and preserves the arrangement of the air hole microstructure [7]. This technique allowed performing all the measurements for the fundamental odd and even HE_{11} modes.

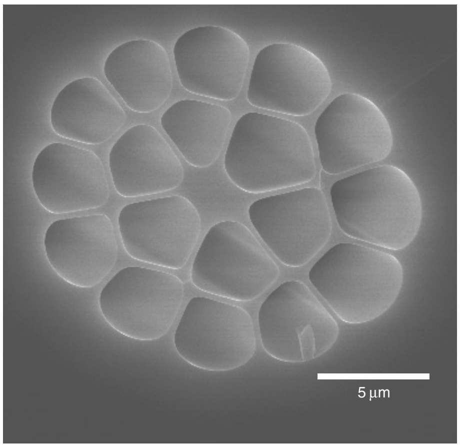

Fig. 1 *Scanning electron micrograph of fibre used in experiments*

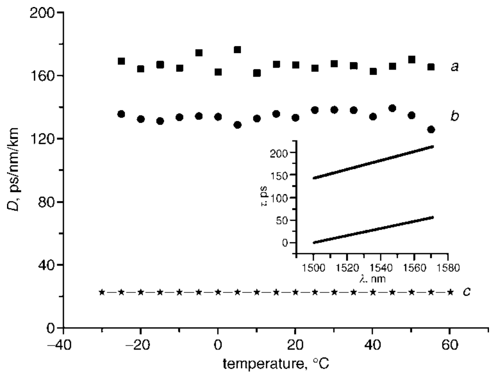

Fig. 2 *Dispersion of polarisation modes (triangles and circles) of PCF fibre under test against temperature and (dashed line) dispersion of silica against temperature*

Inset: Experimental measurement of group delay against wavelength at 20°C. Slopes of these curves give values of dispersion

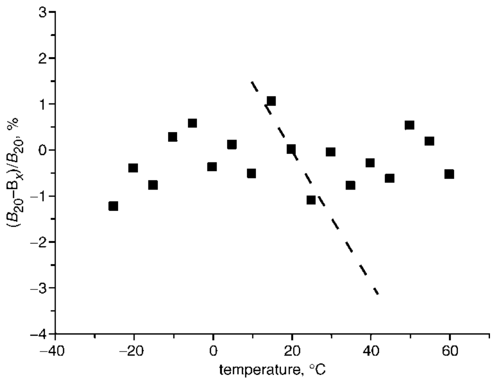

Fig. 3 *Relative variation of birefringence, compared to its value at 20°C, of PCF under test (squares) and conventional Panda fibre (dashed line) with temperature*

The method used to characterise the fibre was the frequency-domain modulated-carrier method [1]. A tunable laser is amplitude modulated at a frequency Ω, 1 GHz in our case, and the phase shift over the length of the fibre is measured by comparing the output phase with the input phase using a vector voltmeter. The phase shift corresponding to each of the eigenmodes is measured and therefore the differential group delay is obtained. This measurement allows the calculation of the group birefringence and the group velocity dispersion of the PCF. The temperature characterisation was performed placing the test fibre inside a temperature chamber. Measurements were taken from −25 to 55°C in 5°C steps with a precision of 0.1°C.

Fig. 2 shows results for the temperature dependence of the dispersion of the fibre. The experimental points correspond to the two different polarisation modes of the fibre. The dispersion of the two polarisation modes show at 1550 nm a mean value of 166 and 133 ps/nm/km, with a standard deviation of 4 ps/nm/km. It is clearly seen that the dispersion for both HE_{11} modes shows no dependence on temperature in the range from −25 to 55°C.

Fig. 3 shows the dependence of the birefringence on temperature. The vertical axis corresponds to the relative deviation from the value of birefringence at 20°C (the fibre under test showed a group birefringence of 7.5 ± 0.3 at 1550 nm). When the fibre was tested under different temperature conditions its birefringence remained constant (standard deviation of 0.5). The Figure also shows, for comparison, the dependence of the birefringence of a Panda fibre with temperature (differential group delay of −1.78 fs/K/m [6]). Therefore we can see that, whereas the polarisation-preserving PCF holds a constant value of birefringence over a wide range of temperatures, Panda fibres, i.e. polarisation-preserving conventional fibres, exhibit an important change of their birefringence with temperature.

The difference in behaviour between conventional fibres and PCFs arises from the fact of having single or multiple material optical fibres. In the case of the PCF, only silica is present in the structure and therefore there are no new stress components due to the change in temperature. Although not observed within the resolution of our system, the contribution of the residual stress appearing in the PCF during fabrication as well as the dependence of the refractive index of silica with temperature could lead to a small dependence with temperature of the dispersion and the birefringence of these structures. However, when working with conventional polarisation preserving optical fibres, the change in temperature induces new stress components between core and the stress regions present in the cladding due to their different thermal coefficients.

Conclusions: We have presented experimental results for the dependence with temperature of the dispersion and the birefringence of a highly birefringent PCF. We have characterised the dependence with temperature of these two optical properties from −25 to 55°C in 5°C steps. We have shown that unlike conventional optical fibres, where temperature induces stress changes between the different materials present in their structure modifying their optical properties, PCFs exhibit no dependence with temperature of these properties due to the single material nature of their structures.

Acknowledgments: The authors acknowledge the financial support from the Ministerio de Ciencia y Tecnología (TIC-2002-04527-C02-01) and the Generalitat Valenciana (GRUPOS03-227).

26 July 2004
Electronics Letters online no: 20046362
doi: 10.1049/el:20046362

A. Ortigosa-Blanch, A. Díez, M. Delgado-Pinar, J.L. Cruz and M.V. Andrés (*Departamento de Física Aplicada-ICMUV, Universidad de Valencia, Dr. Moliner 50, 46100 Burjasot, Spain*)

References

1 Dyott, R.B.: 'Elliptical fiber waveguides' (Artech House, 1995)
2 Noda, J., Okamoto, K., and Sasaki, Y.: 'Polarization-maintaining fibers and their applications', *J. Lightwave Technol.*, 1986, **LT-4**, pp. 1071–1089
3 Knight, J.C., Birks, T.A., Russell, P.St.J., and Atkin, D.M.: 'All-silica single-mode optical fiber with photonic crystal cladding', *Opt. Lett.*, 1996, **21**, pp. 1547–1549; errata, 1997, **22**, pp. 482
4 Ortigosa-Blanch, A., Knight, J.C., Wadsworth, W.J., Arriaga, J., Mangan, T.A., Birks, T.A., and Russell, P.St.J.: 'Highly birefringent photonic crystal fibers', *Opt. Lett.*, 2000, **25**, pp. 1325–1327
5 Ortigosa-Blanch, A., Díez, A., Delgado-Pinar, M., Cruz, J.L., and Andrés, M.V.: 'Ultra-high birefringent nonlinear microstructured fiber', *IEEE Photonics Technol. Lett.*, 2004, **16**, pp. 1667–1669
6 Wegmuller, M., Legré, M., Gisin, N., Ritari, T., Ludvigsen, H., Folkenberg, J.R., and Hansen, K.P.: 'Experimental investigation of wavelength and temperature dependence of phase and group birefringence in photonic crystal fibers'. Proc. Int. Conf. on Transparent Optical Networks, Wroclaw, Poland, July 2004, Vol. 2, pp. 111–114
7 Chandalia, J.K., Eggleton, B.J., Windeler, R.S., Kosinski, S.G., Liu, X., and Xu, C.: 'Adiabatic coupling in tapered air-silica microstructured optical fiber', *IEEE Photonics Technol. Lett.*, 2001, **13**, pp. 52–54