Spun elliptically birefringent photonic crystal fibre

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Abstract: Elliptically birefringent fibre has been fabricated by spinning the preform of a highly linearly birefringent photonic crystal fibre (PCF) during the drawing process. The resulting Spun Highly Birefringent (SHi-Bi) PCF offers intrinsic sensitivity to magnetic fields through the Faraday effect without the high inherent temperature sensitivities suffered by conventional spun stress birefringence fibres. The ellipticity of the birefringence has been measured and temperature independence has been demonstrated.

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1. Introduction

Form birefringence in photonic crystal fibres offers a novel solution to the problem of high temperature dependence found in conventional stress high birefringence fibres. Panda and Bow-tie are two well known types of commercially available highly birefringent fibres that rely on the differential thermal expansion of two materials. Recently, we reported zero temperature dependence of a linear highly birefringent photonic crystal fibre over the

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temperature range -25°C to 800°C [1]. Further, this result was in agreement with recent theoretical evaluation of such fibres [2]. This is highly attractive for a number of applications, and whilst we focus in this paper on spun HiBi-PCF for current sensing, we note the value of such fibres to other areas including the next generation of gyroscopes.

Electric current sensing using Spun Highly Birefringent (SHiBi) optical fibres is an idea that has been around since the late 1980s [3]. Linear birefringence in the sensing fibre quenches the Faraday-induced rotation effectively reducing the sensitivity to magnetic fields. Spinning a HiBi fibre preform during the fibre draw process adds circular birefringence to a structure that would otherwise have very large linear birefringence [3,4]. The resulting elliptical birefringence partially restores the sensitivity to magnetic fields and retains the desirable polarisation maintaining properties normally associated with HiBi fibres.

A HiBi PCF made using the same methods described in [1] has been spun during the fibre draw process [5,6] (fig 1). In this paper the ellipticity has been determined using a simple approach outlined in the next section. Further, the temperature dependence of the birefringence has been characterised and the results are also presented.

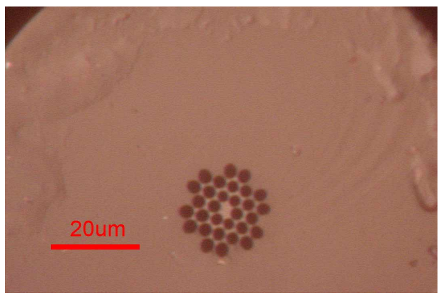

Fig. 1. Spun Highly Birefringent Photonic Crystal Fibre (SHiBi-PCF) cross section.

2. Measuring elliptical birefringence

2.1Background

To understand the effect of spinning the fibre preform on the birefringence of the fibre it is convenient to use the Poincaré sphere. Figure 2 shows elliptical polarisation eigenmodes P+ and P- that are the preserved polarisation states (relative to local axes, which keep up with the spin) of the elliptically birefringent SHiBi PCF. The elliptical birefringence can be represented by the vector $\vec{\rho}$ passing through these preserved states in Poincaré space. The length of the vector $\vec{\rho}$ represents the magnitude of the phase shift per metre induced by the birefringence. Similarly $\vec{\tau}$ represents the spin induced circular birefringence and $\vec{\eta}$ represents the local linear birefringence of the equivalent unspun fibre. For convenience the vector $\vec{\rho}$ has been assigned unit length. The terms $\vec{\eta}$, $\vec{\tau}$ and $\vec{\rho}$ all have the units radians per metre (rad/m). The magnitude of these phase shift terms can be expressed as

$$|\vec{\eta}| = 2\pi / L_B \qquad |\vec{\tau}| = 4\pi / L_T \qquad |\vec{\rho}| = 2\pi / L_{B'} \tag{1}$$

where L_B is the familiar beatlength of the linear birefringence term, L_T is the spin pitch and $L_{B'}$ is the elliptical beatlength in metres [7,8]. In Poincaré space a 2π rotation of any polarisation state is equivalent to a π rotation in the laboratory frame. As a result spinning the fibre preform through 2π radians is equivalent to a 4π rotation in Poincaré space. Hence the factor 4π that appears in Eq (1) for the term $|\vec{\tau}| = 4\pi / L_T$.

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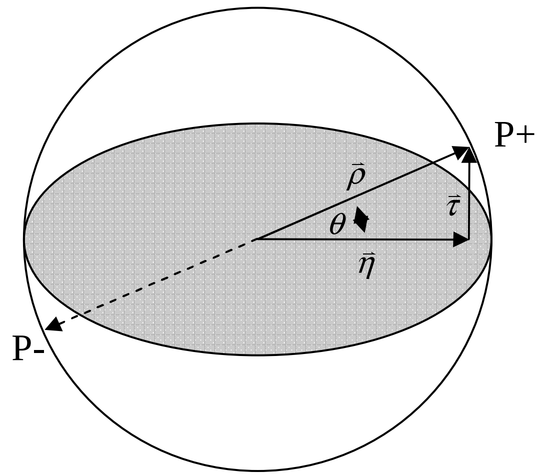

Fig. 2. Representation of polarisation states and birefringence in Poincaré space.

Current sensitivity

The strength of the Faraday effect in a material is represented by *V* the materials Verdet constant where *V* describes the phase shift per unit length between orthogonal circular polarisation states when exposed to a magnetic field parallel to the direction of propagation of light. The sensitivity to current of the SHiBi due to the Faraday effect can be represented by an effective Verdet constant V_s and the phase shift per unit length between the orthogonal elliptical polarisation states P+ and P- is

$$V_s = V \sin\theta \tag{2}$$

where *V* is the Verdet constant of straight non birefringent fibre and θ is the ellipticity shown in Fig 2. From Eq (2) it can be seen that fibre with only circular birefringence, where $\theta = \pi/2$, has the same sensitivity as straight non birefringent fibre [8].

2.2 Measurement approach

A modified version of the crossed polariser method was used to analyse the elliptical birefringent SHiBi PCF [1]. Broadband light from an erbium doped fibre amplified spontaneous emission (EDF-ASE) light source was passed through a fibre pigtailed polarising beam splitter (PBS) spliced to a section of SHiBi PCF. The fibre ends were rotated and aligned to excite roughly equal amounts of power into each elliptical polarisation mode of the SHiBi PCF. The light emerging from the SHiBi PCF end was then analysed with a linear polariser and the wavelength dependent modulation, or interferogram, was observed. In the case of linearly birefringent fibre the output spectrum from a single linear polarisation state can be observed by simply rotating the polariser at the output until the modulation is completely extinguished. The orthogonal state can then be observed simply by rotating the output polariser through +/- 90 degrees.

For the SHiBi PCF the modulation could not be completely extinguished by rotating the output polariser due to elliptical birefringence. The addition of a Babinet-Soleil phase (BSP) compensator between the output end of the SHiBi and the linear polariser allows for some retardance to be added effectively turning the linear output polariser into an elliptical polariser. Alignment and adjustment of the BSP allowed the output modulation to be completely extinguished. The BSP was then calibrated at the operating wavelength to determine the retardance and the ellipticity (θ) of the birefringence was then calculated.

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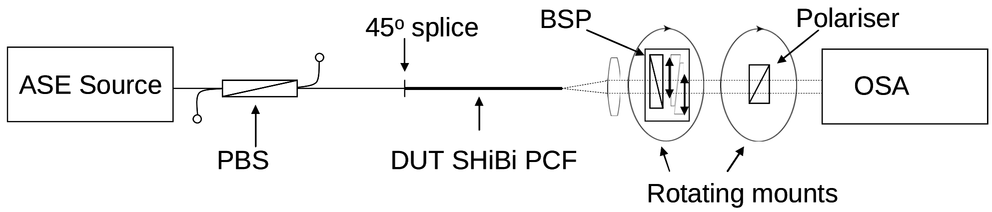

Fig. 3 Experimental set up for measuring the ellipticity of the birefringence.

2.3 Birefringence measurement

The modal (or phase) birefringence B_m is defined as [1]

$$B_m = \left| n_x - n_y \right|, \tag{3}$$

where n_x and n_y are the effective refractive indices for each polarisation mode. The birefringence is often presented in the form of a beat length given by $L_B = \lambda / B_m$ [1], where λ is the free space wavelength. The group birefringence, B_g, can be determined by measuring the period of the modulation seen in the output spectrum and using the following relationship [1]

$$\left| B_g \right| = \left(\frac{\lambda dB_{m(\lambda)}}{d\lambda} - B_{m(\lambda)} \right) = \frac{\lambda^2}{L\Delta\lambda} \tag{4}$$

where L is the length of the SHiBi PCF being tested and $\Delta\lambda$ is period of the spectral modulation seen in the output. However, to determine the modal birefringence from the interferogram the wavelength dependence of the birefringence must be known. For HiBi PCF a power law dependence has been widely used and requires measuring the interferogram over a very broad wavelength range [1].

In the case of SHiBi, figure 2 shows that if the spin-induced circular birefringence and the ellipticity are known then either the elliptical birefringence of the SHiBi or the local linear birefringence of the equivalent unspun HiBi PCF can be calculated using simple trigonometry. As a result this method allows the modal birefringence of the SHiBi PCF to be determined without the need for characterisation over an extended wavelength range.

The spin induced circular birefringence $\vec{\tau}$ can be calculated using Eq (1). The elliptical modal birefringence $\vec{\rho}$ can then be calculated once the ellipticity θ has been determined using the following simple trigonometric relationship

$$\vec{\rho} = \vec{\tau} / \sin\theta = 2\pi / L_T \sin\theta \tag{5}$$

Similarly the value of $\vec{\eta} = 2\pi / L_B$ can be calculated using

$$\vec{\eta} = \vec{\tau} \tan\theta \tag{6}$$

2.4. Temperature dependence measurements.

The group birefringence, B_g, was calculated using Eq (4) from the recorded interferograms obtained using the crossed polariser method configured in reflection. The EDF-ASE source provided enough power that the Fresnel reflection from the cleaved end of the SHiBi-PCF produced a clear interferogram at the output.

The entire SHiBi-PCF was subsequently placed in an environmental chamber and the group birefringence was recorded from -25°C to +100°C. Below 20°C condensation on the cleaved fibre end reduced the Fresnel back reflection and increased the experimental noise.

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5. Results and Discussion

Given that the fibre (fig 1) was drawn from the preform phase at 10m/min with a rotation rate of 1300 rpm, a spin-pitch of 7.7mm is determined. A 630mm length of SHiBi PCF was tested using the experimental set up shown in figure 3 and described above. The periodic modulation seen in the output spectrum (fig 4) was recorded using an optical spectrum analyser and the period and depth of the modulation were determined. The linear polariser at the output was then rotated and the modulation depth minimised but not fully extinguished. The BSP compensator was initially set to zero retardance ($R_i=0^0$) and was arbitrarily orientated relative to the linear polariser. The BSP was then re-orientated so that its fast and slow axes were aligned at 45^0 to the linear polariser. The retardance was then adjusted to fully extinguish the periodic modulation. The BSP was then calibrated by continuing to add retardance until the periodic modulation was again extinguished ($R_i=\Theta$). The

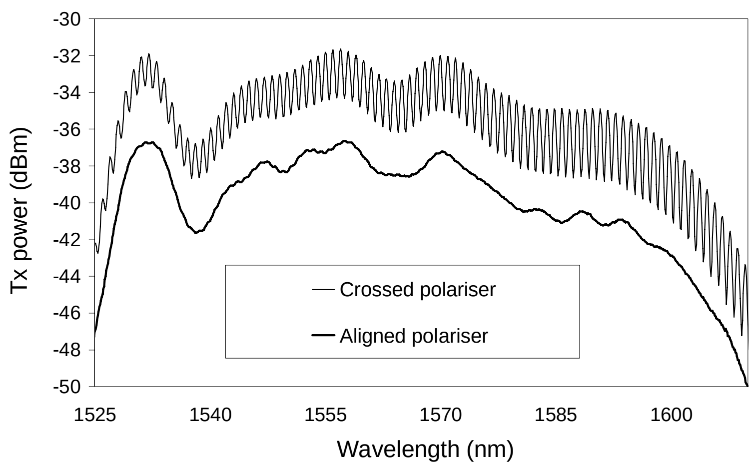

Fig. 4. Interferograms with the periodic modulation both extinguished and maximised.

difference in retardance indicated by the BSP settings R_1 and R_2 for these two positions corresponds to π radians in Poincaré space. From the ratios of the two, the ellipticity of the SHiBi birefringence reduces to $\Theta = [R_1/(R_2-R_1)].\pi$ rad.

For this section of SHiBi an ellipticity of approx $\theta = (0.23 \pm 0.02)$ rad (or approx 13.2^o) was observed. Using Eq (2) above the SHiBi PCF would retain approx (22 ± 4) % of the sensitivity to current of an entirely circularly birefringent fibre.

Using this measured value for $\theta = (0.23 \pm 0.02)$ rad and the spin pitch of $L_p = 7.7$mm we can estimate the phase shift per unit length due to the effective modal birefringence of the SHiBi PCF using Eqs (1) and (5). The twist rate, $\bar{\tau}$ ~1631 rad/m gives a phase shift per unit length between elliptical modes P+ and P- of $\vec{\rho}$ = 7159 rad/m. This corresponds to a beatlength of (0.88 ± 0.06) mm at 1550nm or a $B_m \cong 1.8\times 10^{-3}$. For comparison the elliptical beatlength of $L_{B'}$ = 0.83mm was calculated from the periodic modulation using the methods described by Michie et al [1]. This represents good agreement between the two different methods for determining the modal birefringence of the SHiBi PCF and is supportive of the analysis presented above.

The same section of SHiBi PCF was then configured in reflection and placed inside the environmental chamber. The group birefringence was recorded every 10 degrees between -25 and 100°C. The change in group birefringence relative to the value recorded at room temperature is presented in figure 5 along with results for a HiBi Panda fibre. The increased temperature sensitivity for the Panda fibre is clearly evident in the graph and no change in group birefringence within the experimental error range is observed for the SHiBi PCF. In the case of Spun Panda fibre the ellipticity, and the corresponding sensitivity to current, is then affected by changes in temperature. Although the spin pitch remains relatively constant the Panda fibre's birefringence changes significantly with temperature resulting in large changes in ellipticity and sensitivity to current. The use of SHiBi PCF fibre removes this problem since the ellipticity is now largely temperature independent. Although there remains a small temperature dependence in the basic material Verdet constant, of the order of 70ppm/^{o}C [9], for silica based fibres this effect is still an order of magnitude smaller than the high temperature dependence seen in spun Stress HiBi fibres.

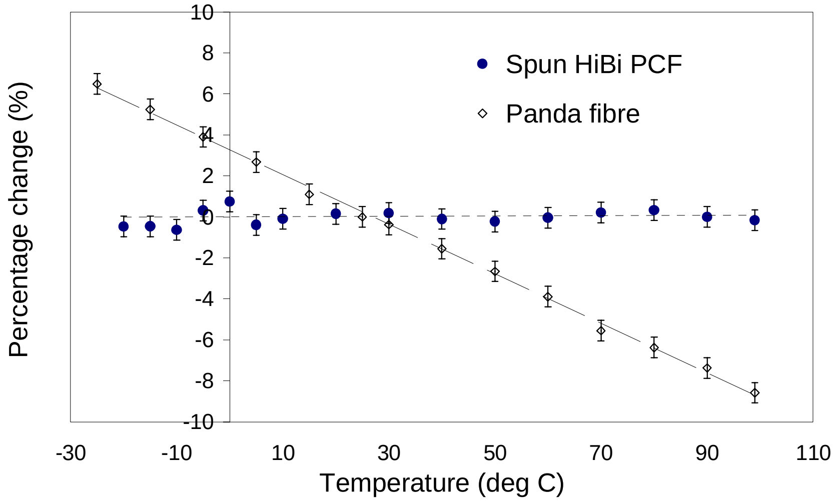

Fig. 5. Group birefringence versus temperature for both a conventional stress birefringence Panda fibre and the SHiBi -PCF

6. Conclusion

The first spun highly birefringent photonic crystal optical fibre has been characterised for ellipticity and temperature dependence. This fibre offers a stable effective Verdet constant with low temperature dependence and low packaging sensitivity.

The use of the Poincaré sphere to represent polarisation and elliptical birefringence allows for an alternative method that is simple to implement for determining the modal birefringence of the SHiBi-PCF structure that does not require measurements over a very large wavelength range.

Further refinements in design will potentially provide broad band polarising properties [10] that will allow SHiBi to be used effectively for current sensing and other variations will undoubtedly find application in established areas such as fibre optic gyroscopes. Additionally, these fibres may permit a level of temperature independent control of polarisation that may be of benefit for new areas such as quantum communications based on polarisation degeneracy between entangled light paths.

Acknowledgments

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