Fabrication and characterization of spun HiBi PCF fibers for current sensing applications

I.M.Nascimento[a,b*], G. Chesini[c], A.C.S.Brígida[a,d], J. G. Hayashi[c], J.M.Baptista[a,e], J.C.W.A.Costa[d] M.A.G.Martinez[f], P.A.S. Jorge[a], Cristiano M.B. Cordeiro[c]
[a]INESC Porto, Porto, Portugal.
[b]Faculdade de Ciências, Universidade do Porto, Portugal.
[c]Instituto de Física "Gleb Wataghin", Universidade Estadual de Campinas, UNICAMP, Campinas, SP, Brazil
[d]Universidade Federal do Pará, Belém, Brazil.
[e]Centro de Competências de Ciências Exactas e de Engenharia, Univ. da Madeira, Funchal, Portugal.
[f]Centro Federal de Educação Tecnológica Celso Suckow da Fonseca, Rio de Janeiro, Brazil.

ABSTRACT

In this paper three highly birefringent (HiBi) spun photonic crystal fibers (PCF) are fabricated and their performance are characterized for electrical current measurement. These fibers are tested by coiling them around an electric conductor using three distinct winding diameters with different turns. The results present a very good linear relation with the current and its sensitivity depends on the winding diameter and on the number of turns. For the larger winding diameter, the fiber with lower circular pitch had higher sensitivity and for the smaller winding diameter the best sensitivity result was for the fiber with higher circular pitch.

Keywords: fiber optic current sensor, spun fiber, HiBi fiber, spin pitch, Faraday effect, birefringence, PCF.

1. INTRODUCTION

The measurement of electrical energy is fundamental to determine the quantity of energy needed and the development of sustainable management systems. In this context, electric current sensors are becoming more vital nowadays as they allow accurate measurements of consumption and fast identification of failures on power systems[1].

Typically, electric current transformers technology is used. Although this technology has been relatively reliable and accurate, it has many performance limitations. In a high voltage environment these systems can be easily damaged by heat, short-circuits or atmospheric electrical discharges and it is essential to employ protection circuits and insulation, which requires constant maintenance. Also, due to its high dimension and weight, these devices cannot be suspended on the electric line and their installation is expensive[2,3].

Fiber optic current sensors (FOCS) are an attractive solution for high voltage current measurement since they are light, have intrinsic electric isolation and enable measuring DC and AC currents. A great number of FOCS are based on the Faraday effect, which corresponds to an induced circular birefringence. Depending on the configuration this results on a modulation of the linear polarization modes or a relative phase delay of circular polarization modes, that is proportional to the magnetic field[2].

The sensor can be setup by a single optical fiber coiled around the conductor making it immune to external magnetic fields. Also, the sensitivity of the sensor can usually be increased with the number of turns. However, high number of fiber turns become more vulnerable to environmental perturbations such as pressure, temperature and vibration[4], which can degrade the measurement in both a polarimetric or interferometric configuration. Moreover, due to fiber manufacturing imperfections in geometry and residual stress, bending and pressure contribute to an increase of the linear birefringence, therefore degrading the sensor response. In order to ease these effects several fibers were proposed, including annealing after winding, low birefringence (LoBi) fibers, twisted and spun fibers. These spun fibers can be LoBi or HiBi and are fabricated during fiber drawing, by spinning the preform at a constant rate. From this group the HiBi spun has showed to be better because its nearly independent of additional birefringence produced by bending or vibration[4,5].

*ivo.m.nascimento@inescporto.pt; phone +351 22 040 2301

23rd International Conference on Optical Fibre Sensors, edited by José Miguel López-Higuera, Julian Jones, Manuel López-Amo, José Luis Santos, Proc. of SPIE Vol. 9157, 915723

Typically in these fibers the birefringence is strongly temperature dependent because they use at least two different glass materials with different thermal expansion coefficient, so in order to overcome this problem HiBi PCF fibers are required[6,7]. Also PCF fibers have the advantages of being more bent robust and provide possibility of single mode operation at multiple wavelengths[8].

In this paper the fabrication of three distinct spun HiBi PCF and its characterization as a current sensor in a polarimetric configuration using different winding diameters is reported.

2. PRINCIPLE AND EXPERIMENT

A photonic crystal fiber preform was fabricated by the stack-and-draw process. It consists of five rings of periodic air holes around a central solid core of 2.6 µm diameter. The air holes have the same diameter except for two larger holes in the vicinity of the core that have 3.9 µm (Figure 1). The lattice parameter (diameter of the holes divided by their center-to-center distance, d/pitch) is approximately 0.6 and it was chosen to guarantee that the fiber was singlemode at 633 nm. The internal pressure used to control the diameter of the air holes and the ratio d/pitch was around 100 mbar. The fiber has approximately 127 µm diameter. The spun fibers were produced by rotating this microstructured preform during the fiber drawing. Produced spin rates were 6, 9 and 11 rps (rotations per second) and drawing velocity around 7.3 m/min gives a circular pitch (L_S) of 20.28, 13.52 and 11.06 mm, respectively. These parameters generated fibers with a circular birefringence of 309.9, 464.8 and 568.1 rad/m, respectively. The linear birefringence was determined by the scanning wavelength method using the unspun (0 rps) PCF fiber. The linear beat length (L_B) was measured to be 25.32 mm (248.15 rad/m) at 633 nm and 5 mm at 1550 nm (1256.64 rad/m). We assume this value remains the same for the spun fibers. For this silica fiber, the Verdet constant at 633 is 3.57 rad/(T.m)[9]. In Figure 1 it is shown the straight section of each fabricated fiber and the corresponding mode profile at 633 nm.

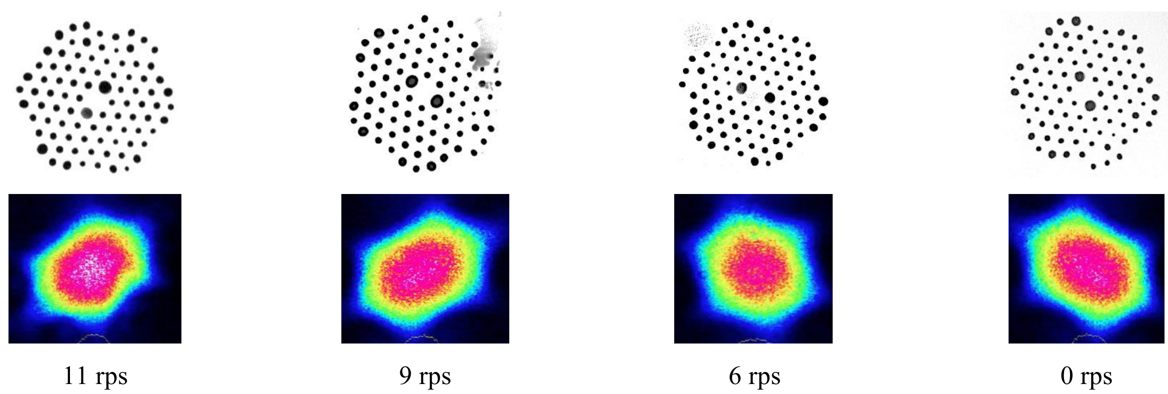


Figure 1 - Straight section of each PCF fiber and corresponding mode profile at 633 nm

In Figure 2 it is presented the setup to characterize the developed fibers for current measurement. Light from a 650 nm SLD source passes a polarizer followed by a half waveplate (λ/2) used to polarization control. Afterwards it is injected into the PCF fiber athwart an objective. When light passes around the conductor experiences Faraday effect and thereby its polarization is rotated. At the end light is collimated and the two orthogonal polarizations are retrieved through a Polarization Beam Splitter and detected by the photodiodes. A program in LabVIEW was developed to acquire and process the two polarizations with a NI DAQ 6343 (1.92 mV resolution) and record the reference signal of the current passing in the conductor.

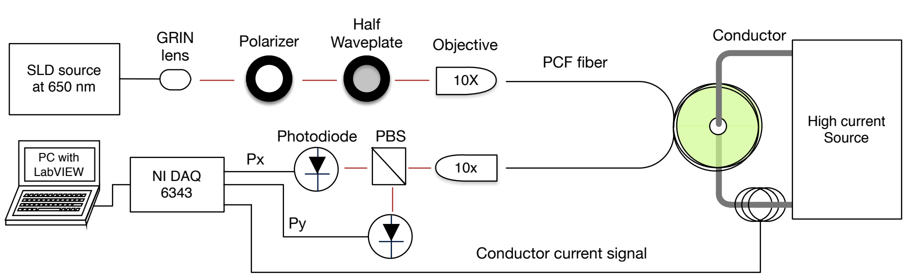


Figure 2 - Characterization setup of the developed fibers for current measurement

Maximum sensitivity for each orthogonal polarization is achieved when the output polarizers are at ± 45 degrees in relation to the input. Performing the operation

$$P = \frac{P_X - P_Y}{P_X + P_Y} = 2\theta_F \tag{2.1}$$

makes the system independent of optical power variations improving noise rejection. For a complete number of N turns the Faraday rotation is

$$\theta_F = \mu.V.N.I \tag{2.2}$$

where μ is the relative permeability of the medium inside the coil, V is the Verdet constant in rad/(T.m) and I is the current passing in the conductor. Taking into account the linear birefringence produced by winding the response degrades $S=P.S_C$, with[4]

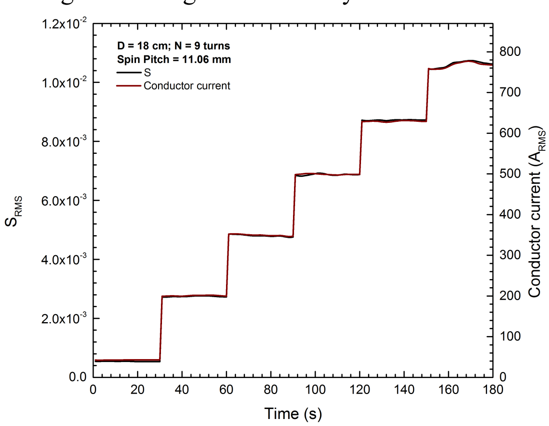
$$S_C = \frac{L_{ind}^2/L_E^2}{1 + L_{ind}^2/L_E^2} \tag{2.3}$$

where S_C is a factor between zero and one, L_{ind} is the linear beat length due to winding and L_E is the elliptical polarization beat length given by

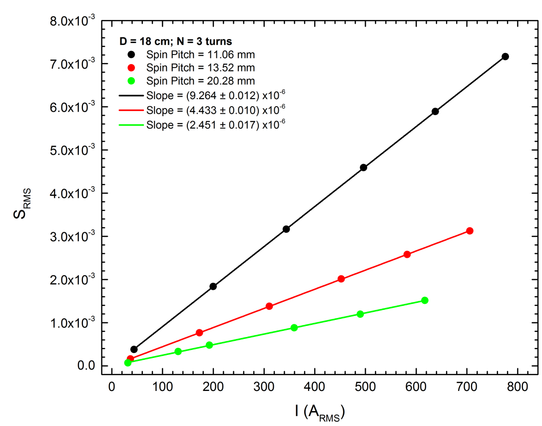
$$L_E = \frac{L_B.L_S}{\sqrt{(4L_B^2 + L_S^2)} - 2L_B} \tag{2.4}$$

3. RESULTS AND DISCUSSION

Using all the four fibers described, tests with different coiling diameters were carried out. In Figure 3 (a) it is presented a single test where the current passing in the conductor was incremented in a step fashion at every 30 s interval. For each step the average and standard deviation are calculated to obtain a calibration curve. In Figure 3 (b) it is seen a good linearity of the sensor response in relation to the electric current, for the three Spun fibers. As expected the unspun one was also tested but no results were achieved due to its extremely high linear birefringence in relation to the small circular birefringence owing to the Faraday effect.



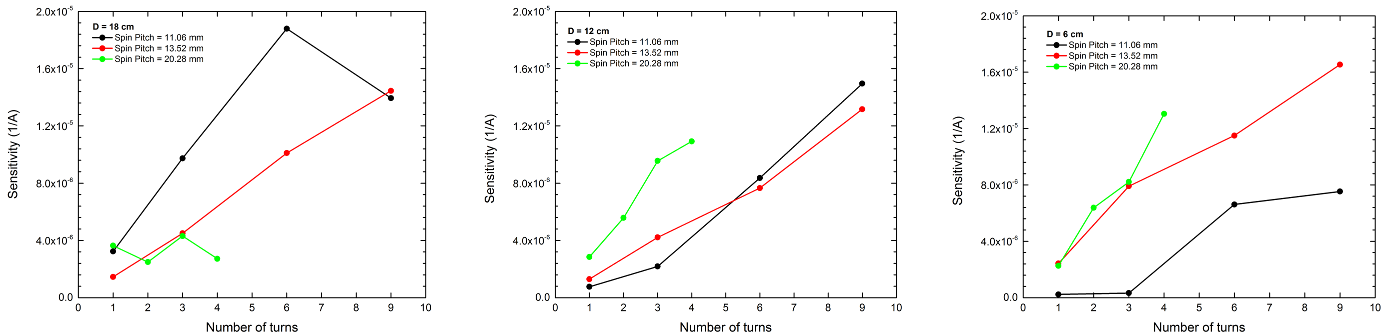
(a)



(b)

Figure 3 - (a) Sensor response to step changes in the applied current and (b) calibrations for the PCF fibers with different spun rates.

In Figure 4 it is shown a compilation of graphs obtained for different coiling diameter, fibers and numbers of turns around the conductor. It is seen in Figure 4 (a), coiling diameter of 18 cm, that the fiber with lower spin pitch gives better results up to 6 turns followed by the ones with 13.52 and 20.28 mm spin pitch, respectively. For this last one, the maximum number of turns was four due to the lack of fiber length availability. With a coiling diameter of 12 cm, Figure 4 (b), the fiber with 11.06 and 13.52 mm spin pitch gave similar results. In the last case, Figure 4 (c), with a coiling diameter of 6 cm the fiber with higher spin pitch presented better results.



(a) (b) (c)

Figure 4 – Sensor sensitivity in function of the number of turns around the conductor with a diameter of (a) 18 cm, (b) 12 cm and (c) 6 cm

From these results it can be seen that for large coil diameter the fiber with lower spin pitch is preferable and for small diameters a HiBi PCF higher spin pitch (lower circular birefringence) is preferable, contributing to better sensitivities.

4. CONCLUSION

In this work we fabricated spun HiBi fibers with different spin pitch: 11.06, 13.52 and 20.28 mm. The developed process of rotating the fiber preform had no observable effects on the microstructure air holes pattern. This is desirable since one wants to maintain the same linear birefringence for different spin rates. The three fabricated spun HiBi fibers showed different behavior according to the coiling diameter. For the 18 and 12 cm coiling diameter the results showed better sensitivities for the fiber with lower spin pitch and for the 6 cm the one with better result was achieved by the fiber with higher spin pitch.

5. ACKNOWLEGMENTS

This work was supported by ANEEL through the research and development program of the companies of the group TBE – Transmissoras Brasileiras de Energia (EATE –Empresa Amazonense de Transmissão de Energia, ECTE - Empresa Catarinense de Transmissão de Energia, ENTE - Empresa Norte de Transmissão de Energia, ERTE - Empresa Regional de Transmissão de Energia, ETEP - Empresa Paraense de Transmissão de Energia, LUMITRANS- Companhia Transmissora de Energia Electrica and STC – Sistemas de Transmissão Catarinense). The authors thank CAPES - Coordination for the Improvement of Higher Education and CNPq - National Council for Scientific and Technological Development for financial support. Ivo Nascimento would like to acknowledge the financial support of FCT (SFRH/BD/80056/2011)

6. REFERENCES

[1] R. J. El-khozondar and A. W. Koch, "Magnetic field inhomogeneity induced on the Magneto-optical current sensors," *Information Photonics* (2011).

[2] F. Rahmatian, "High-Voltage Current and Voltage Sensors for a Smarter Transmission Grid and their Use in Live-Line Testing and Calibration," in *Power and Energy Society General Meeting*, pp. 10–12 (2010).

[3] E. F. Donaldson, G. R. Gibson, N. A. Pilling, and B. T. Taylor, "Hybrid optical current transformer with optical and power-line energisation," *Generation, Transmission and Distribution* **147**(5), 304–309 (2000).

[4] R. I. Laming and D. N. Payne, "Electric current Sensors employing Spun Highly Birefringent Optical Fibers," *Journal of Lightwave Technology* **7**(12), 2084–2094 (1989).

[5] V. P. Gubin, V. A. Isaev, S. K. Morshnev, A. I. Sazonov, N. I. Starostin, Y. K. Chamorovsky, and A. I. Oussov, "Use of Spun optical fibres in current sensors," *Quantum Electronics* **36**(3), 287–291 (2006).

[6] A. Michie, J. Canning, K. Lyytikäinen, M. Aslund, and J. Digweed, "Temperature independent highly birefringent photonic crystal fibre," *Optics express* **12**(21), 5160–5165 (2004).

[7] A. Michie, J. Canning, I. Bassett, J. Haywood, K. Digweed, B. Ashton, M. Stevenson, J. Digweed, A. Lau, et al., "Spun elliptically birefringent photonic crystal fibre for current sensing," *Measurement Science and Technology* **18**(10), 3070–3074 (2007).

[8] P. Russell, "Photonic crystal fibers," *Science (New York, N.Y.)* **299**(5605), 358–362 (2003).

[9] R. H. West, "Dispersion of verdet constant in stress-birefringent silica fibre," *Electronics letters* **20**(22), 20–22 (1984).