Fabrication of a spun elliptically birefringent photonic crystal fiber and its characterization as an electrical current sensor

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ABSTRACT

In this paper a spun elliptically birefringent photonic crystal fiber is fabricated and characterized. Its performance as a current sensor, using a polarimetric configuration, was tested and compared against single mode fiber at 633 nm. In particular the sensor sensitivity and linearity was investigated using fiber loops with different radius or number of turns around the conductor. The results obtained show that the spun fiber (40 rotation per meter) is able to suppress quite effectively the effects of the bend induced birefringence as compared to the standard fiber.

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

1. INTRODUCTION

Conventional current transformers for metering and protection applications in high power grids are usually heavy parts of instrumentation with high costs associated to installation and maintenance since they are susceptible to damage by heat, short-circuits or atmospheric electrical discharges. Furthermore, their intrinsic transduction mechanism is prone to saturation effects and often a tight sensitivity/bandwidth compromise is required resulting in the need to use distinct devices according to the particular application. In this context, optical current sensors are becoming a very attractive tool for a new generation of smart grids allowing accurate measurement of power consumption and rapid identification of faults in power systems [1]. They can provide large bandwidth, sensitivity, large dynamic range and immunity to electromagnetic interferences. Comparatively to conventional transformer they can be much lighter and compact and, since they are intrinsically dielectric, they can be more easily insulated. A large majority of optical sensors for electric current are based on the Faraday effect, a circular birefringence induced in the active sensor medium that produces a polarization rotation or a phase delay, depending on the configuration used, that is proportional to the magnetic field.

Since the Faraday sensors respond to the magnetic field, in order to have a univocal measurement of the current it is necessary that the light in the sensor propagates along a closed path around the conductor. This can be easily implemented using an optical fiber as the sensing medium, by winding the fiber around the conductor being monitored. In this case, it is possible to adjust the sensitivity to current by varying the number of turns around the conductor. However, optical fibers have intrinsic linear birefringence, due to inherent irregularities in the manufacture or internal stress that causes susceptibility to temperature and vibration [2]. These can cause quenching of the sensitivity to the magnetic field, reducing the Faraday rotation. This is further aggravated since the winding process introduces bend induced birefringence that can severely limit the sensor operation. To minimize these effects, several techniques were investigated such as submitting the fiber to annealing process to reduce its internal stress, using special glasses (eg. Flint glass), or introducing a bias of linear and/or circular birefringence in the fiber, making it less susceptible to external perturbations. The later solution can be implemented using different techniques like twisting regular fibers or by fabricating fiber with a rotating preform producing a fiber with and intrinsic twist, or spun fiber, having both linear and circular birefringence [3, 4]. While such solutions usually solve the quenching of sensitivity they still display significant temperature dependence due to the different nature of the core and cladding materials. More recently, however, Michie et

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al have proposed the fabrication spun elliptically birefringent photonic crystal fibers made of pure silica to overcome this limitation [5].

In this paper, it is reported the fabrication and use of a spun elliptically birefringent photonic crystal fiber as an electrical current sensor. Sensors fabricated using the spun fiber and regular single mode fiber are characterized and compared in their response to electrical current in different winding conditions.

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 (see section of fabricated fiber is 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. 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 130 µm diameter. The spun fibers were produced by rotating this microstructured preform during the fiber drawing. Typical spin rates were from 3 to 9 rps (rotations per second) and drawing velocity around 7m/min. These parameters generated fibers with a circular period (circular pitch which is related to the number of turns per meter) from 13 to 48 mm and a linear birefringence of 2.5×10^{-5} (633nm) and 3.6×10^{-4} (1550nm). To characterize the main type of birefringence (linear, circular or elliptical) after the fabrication we determined the ellipticity of the fiber, which is an angle from 0º (linear birefringence) to 90º (circular birefringence) that depends on the spin rate. We found such angles to be between 59.0º and 78.0º (633nm) and from 9.3º to 18.2º (1550nm).

A spun fiber fabricated with 40 rotations/m was selected and used to implement a fiber optic current sensor in a simple polarimetric configuration, where the fiber was wound around the conductor, and tested in the setup shown in figure 2. The optical source was a linearly polarized He-Ne laser @ 633nm, followed by a λ/2 plate to control the orientation of polarization at the input fiber. After looping around the conductor at the fiber output, the light was collimated and directed onto a Wollaston prism that allows access to the two orthogonal polarization components. A DAQ NI 6251 adjusted with a resolution of 1.92 mV was used to scan the signals obtained from the photodetectors and perform the operation S= (Sx-Sy)/(Sx+Sy). The result of this operation, performed by a dedicated LabView program, yields an output, $S=2\theta_F$, with a very good common mode rejection to vibration induced noise and optical power drift.

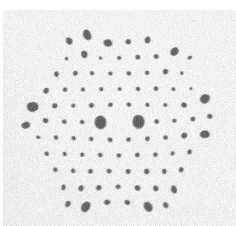


Figure 1. Straight section of the PCF fiber

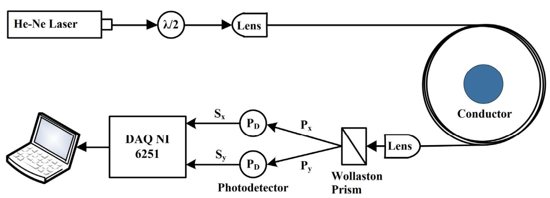


Figure 2. Experimental setup

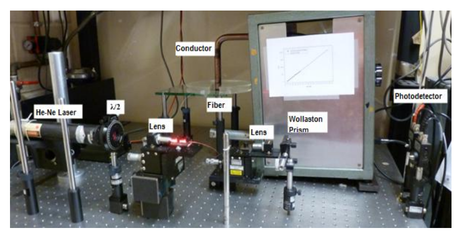


Figure 3. Photo of the experimental setup.

This type of processing, however, cannot compensate for the effects of induced linear birefringence. Therefore the sensor output when using a fiber with both linear and circular birefringence is given instead by:

$$S = 2\theta_F \frac{\mathrm{Sin}\left(\sqrt{(\beta L)^2 + (2\theta_F)^2}\right)}{\sqrt{(\beta L)^2 + (2\theta_F)^2}} \tag{1}$$

with β being the linear birefringence, usually measured in rad/m and L is the length of fiber used, measured in meters. Although silica fibers possess relatively low Verdet constant of 2.1 rad/T.m @ 633 nm, the overall sensitivity can be increased by increasing the number of turns of fiber, N, around the conductor. In such case the accumulated Faraday rotation, θ_F, is given by

$$\theta_F = \mu . V . N . I \tag{2}$$

where μ is the magnetic permeability of the medium, V is the Verdet constant and I the current through the conductor. However, in standard fibers, the increase in number of turns and/or smaller radius of the winding result also in an increase of the bend induced birefringence that compromises the sensor performance.

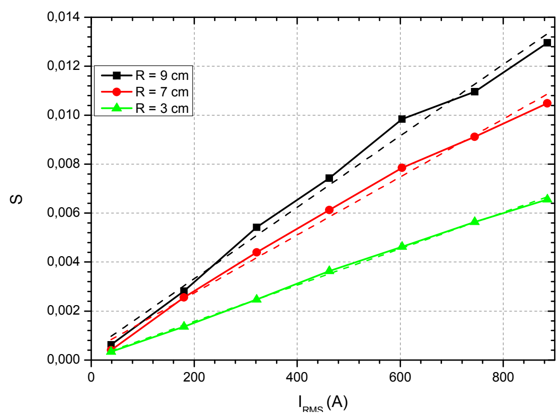
In other to evaluate the performance of the sensors implemented with our spun fiber, a SM630 single mode fiber (core radius = 1.975µm, NA = 0.12, fiber diameter = 125±3µm, coating diameter = 250±15µm) was also tested as a current sensor. Both sensors were characterized in its response to increasing electrical current when using different number of windings or different loop radius.

3. RESULTS AND DISCUSSION

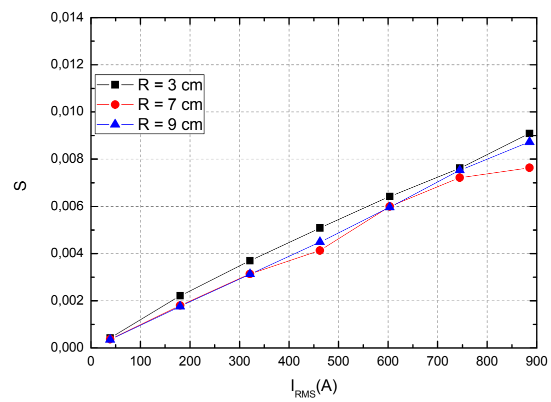
3.1. Test with different loop radius

Two sensors were implemented winding 3 turns of fiber around the conductor, using either SM630 fiber or our 40 rotations per meter PCF. This was done also for distinct loop radius of 9 cm, 7 cm and 3 cm, using distinct acrylic supports, while keeping a fixed number of turns (this was possible by increasing the length of the fiber).

The sensors response to different values of current in the conductor was evaluated in different situations. In all cases similar current increments (~120 Arms) were applied to the sensors in the range 0 to 900 Arms. It was observed that the response of the processed signal, S, had much less noise than individual components, Sx and Sy, regardless of the size of the support. Figure 4 shows the sensor calibration curves obtained in the different situations.



Singlemode SM630 fiber



40 rotation per meter PCF

Figure 4. Sensors calibration curves obtained for a fixed number of 3 turns around the conductor using supports with different radius (R = 9 cm, 7 cm and 3 cm). Left –results of SM630 sensors; Right – results of 40 rotations per meter PCF.

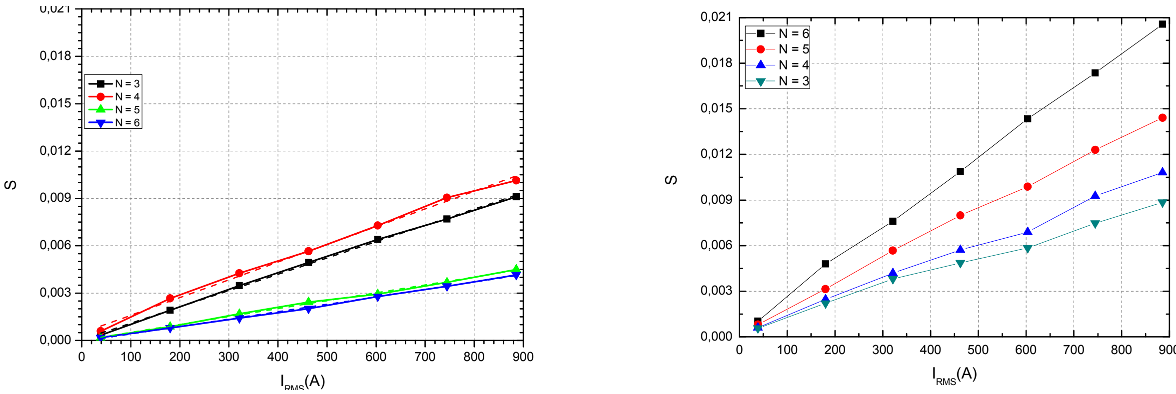
In the absence of linear birefringence it would be expected that all the sensors presented identical response to the current. However, for the single mode fiber, the results show that as the radius of the fiber winding is reduced the level of noise in the sensor signal increased significantly and the sensitivity to current was also decreased. This can be explained by the fact that smaller radius of the loops introduces a more pronounced curvature in the fibers resulting in a greater level of induced birefringence. According to equation 1, this results in a loss of sensitivity.

With the spun PCF fiber, on the other hand, it can be seen in Figure 4 -right, that the sensor response is fairly independent of the radius of curvature, showing insensitivity to the induced linear birefringence. Comparing the results obtained with the SM630 and the PCF 40 rpm, it is clear that with the new fibers there is a substantial immunity to curvature induced noise.

3.2. Test with different number of turns

In a different test, it was changed the number of turns wound around a conductor (3, 4, 5 and 6 turns), while keeping constant the radius of curvature (R= 3 cm). In the absence of linear birefringence, it would be expected that, as the number of turns increases, so does the sensitivity of the sensors, according to equation 2.

The calibration curves obtained with both fibers in the different situations can be seen in Figure 5. The results obtained for the SM630 fiber show that, while for small number of turns (from 3 to 4) it seems to take place a small increase of sensitivity, for larger number of turns (6 and 5) the sensitivity actually decreases. This can be explained by the fact that as the fiber length increases, so does the accumulated linear birefringence, which at a given point due to the increased optical path ends up depolarizing the radiation, quenching the sensors sensitivity to the Faraday rotation. For the spun PCF fiber, on the other hand, the results show a relatively steady increase of sensitivity, demonstrating a relative immunity to the bend induced birefringence.



Singlemode SM630 fiber | 40 rotation per meter PCF

Figure 5. Sensors calibration curves obtained for a fixed radius of curvature (R= 3 cm) and different number of turns around the conductor (N = 3, 4, 5 and 6). Left –results of SM630 sensors; Right – results of 40 rotations per meter PCF.

4. CONCLUSION

A spun elliptically birefringent photonic crystal fiber was fabricated having a spun rate of 40 rotations per meter. Its performance as an electric current sensor was tested and compared against similar sensor built with SM630 single mode fiber. The preliminary results obtained show that the new spun fiber has a relatively high immunity to the effects of bend induced birefringence, enabling the fabrication sensors having small curvature radius and large number of turns around the conductor. Such characteristics will allow the implementation of small and compact high sensitivity fiber optic current sensors suitable for application in smart grids.

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