Putting the World in a Spin - Fibercore's Spun Optical Fibers for the Current Sensor Industry

A. Gillooly

Fibercore Limited, Fibercore House, University Parkway, Southampton Science Park, Southampton,
Hampshire, SO19 9TY, UK, andy.gillooly@fibercore.com

ABSTRACT

Spun HiBi and spun LoBi fibers for operation around 1310nm are presented to address the global demand for fiber optic current sensor and optical current transformers for new infrastructure projects and the Smart Grid. Spun HiBi fibers are shown to be able to be suitable for high accuracy current sensors whilst spun LoBi fibers are shown to be more optimized for lower sensitivity sensors.

Keywords: spun, fiber, current, sensor, transformer

1 INTRODUCTION

With the ever growing demand for electrical power, power systems around the world are under increasing strain to reliably deliver the power across existing infrastructure. To address this need, some power systems have upgraded their voltage levels to 200kV and even 500kV in some cities in China. These upgrades require substations to be upgraded to handle extra high voltages, typically requiring larger pieces of equipment and increasing the footprint of the substation. In city spaces, land is at a premium, requiring any new infrastructure equipment to be compact, reliable and cost effective. Fiber optic current sensors (FOCS), otherwise known as optical current transformers (OCT), offer significant advantages over traditional current sensing technologies: the size and weight of the sensors is reduced in comparison with existing technologies, the sensor element is naturally decoupled from the voltage line, there is minimal electrical interference on the signal line, they offer extremely fast response times with high measurement accuracy and they do not explode during catastrophic failure, unlike oil-filled electrical insulation towers.

Although FOCS have existed for decades, the demand has been limited to niche applications. However, with the growth of the BRIC nations: Brazil, Russia, India and China, new power infrastructures are being built with a view of making them Smart Grids, capable of transferring digital information through fiber optic networks. FOCS can be designed to be compatible with the IEC 61850 protocol to allow incorporation into the Smart Grin to give live voltage and current measurements across the full grid allowing intelligent decisions to be made about power distrubution across the power network.

The basic principle of FOCS and OCTs is to measure polarization rotation due to the Faraday effect. The Faraday effect is the rotation of the polarization state of light, β, when it passes through a magnetic field, B, induced by an electrical current. The larger the electric current, the greater the magnetic field and hence the larger the polarization rotation.

Historically, FOCS system manufactures attempted to manufacture current sensors using standard telecoms fibers. However, the inherent random birefringence within these fibers caused significant limitations on the sensing accuracy. Techniques where developed to twist the fibers which ultimately created mechanical failure when the fibers were exposed to rapid thermal changes due to the torsional forces exerted on the fiber.

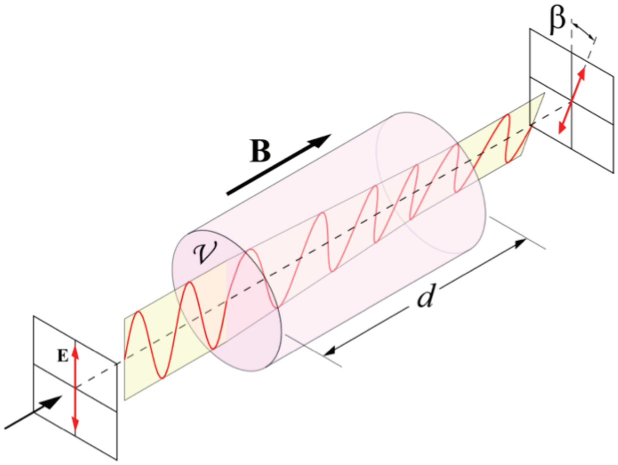

Figure 1: Polarization rotation as linearly polarized light passes through a material with a Verdet constant, V, and a distance, d. The polarization rotation, β, is proportional to the magnetic field, B.[1]

Alternative methods of stripping the coating off the fiber and annealing the bare glass were developed, however due to the difficulty of stripping long lengths of coatings, poor yields and short lengths were fundamental limitations to this technique. Subsequently, spun optical fibers were invented where the fiber is spun during the fiber drawing stage, this creates a rotation along the length of the fiber which is locked into the fiber with no torsional force. The rotation causes the inherent birefringence effects to be axially rotated many times over the length of the sensor, averaging out the negative effects of the birefringence. If birefringence exists and is dominant along one axis of the sensor, the polarization rotation will become locked or slowed down. This breaks the linear response between the electric current and the rotation, giving rise to an inaccurate response between polarization rotation and the current. For certain application, such as metering, it is critical to have the highest level of accuracy, subsequently requiring spun optical fibers.

To address the global demand for high quality, application oriented spun optical fibers, Fibercore have developed two fibers, SHB1250 spun HiBi fiber for high accuracy current sensors and SLB1250 spun LoBi fiber for lower accuracy current sensors.

2 SPUN LOBI FIBER

A spun LoBi fiber is single mode (SM) fiber which is spun during the fiber drawing stage, averaging out the inherent birefringence induced during the fiber manufacturing processes.

When the spun LoBi fiber is coiled, bend-induced birefringence is created within the fiber which reduces the maximum sensitivity of the FOCS. As the coil diameter is reduced or as the number of coils is increased, the stress on the fiber cumulatively increases, creating higher total birefringence and making the measurements less sensitive [2]. Subsequently spun LoBi fibers are typically used in low sensitivity FOCS or OCTs which have a large coil diameter and a relatively low number of coils. These limitations ultimately limit the applications that the spun LoBi fibers can be used in but they offer a cost effective, manufacturable and scalable solution if the highest accuracy levels are not required.

3 SPUN HIBI FIBER

For high sensitivity FOCS and OCTs, it is advisable to use spun HiBi fiber. This fiber differs from the spun LoBi fiber by having a polarization maintaining (PM) axis which is formed by Fibercore's Bow-Tie structure. Through careful balance of the spin pitch of the fiber with an accurately controlled level of birefringence, a fiber is designed that can overcome the effect of bend-induced stress occurring from the coiling process yet still be highly sensitive to the Faraday effect. Subsequently longer lengths of spun HiBi fiber can be used than spun LoBi fiber this allows more coils of fiber with smaller coil diameters to be used, giving a higher sensitivity [2].

The HiBi nature of the fiber creates a level of birefringence which is greater than the induced birefringence encountered during coiling or due to transient pressure-induced local birefringence encountered during temperature variation and mechanical vibrations (as might be encountered in switchgear applications). The designed birefringence therefore swamps out the effects of these external cause of birefringence leaving the inherent fiber birefringence as the dominant factor effecting the fiber's sensitivity and linearity to the Faraday effect. Because the fiber's polarization maintaining axis is axially rotated along the length of the fiber, there is no single axis effecting the polarization rotation, the effect of the fiber's birefringence is averaged over the number of axial rotations along the length of the fiber. This therefore maintains the linear response but at a small sacrifice to overall sensitivity which can be compensated for by using more coils of fiber.

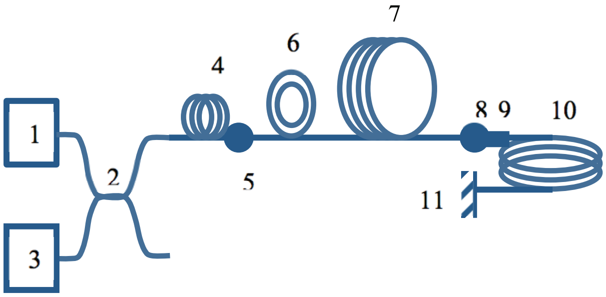

Figure 1: Optical schematic for a high sensitivity fiber optic current sensor, showing (1) broadband erbium doped light source, (2) coupler, (3) photo detector, (4) polarizer, (5) 45^o splice, (6) fiber modulator, (7) 900m long delay coil, (8) 45^o splice, (9) quarter wave plate, (10) 16m of spun HiBi fiber, (11) mirror.[3]

4 WAVELENGTH

The Verdet constant is proportional to $1/\lambda^2$ so to achieve higher current magnitude sensitivities, it is recommended to use shorter wavelengths. Fibercore's SHB1250 and SLB1250 are designed for use at 1310nm to give a higher Verdet constant than at 1550nm. This enables the use of standard low cost telecoms components, such as light sources and fiber couplers and accesses the 1300nm low attenuation window – particularly beneficial for long fiber length sensors.

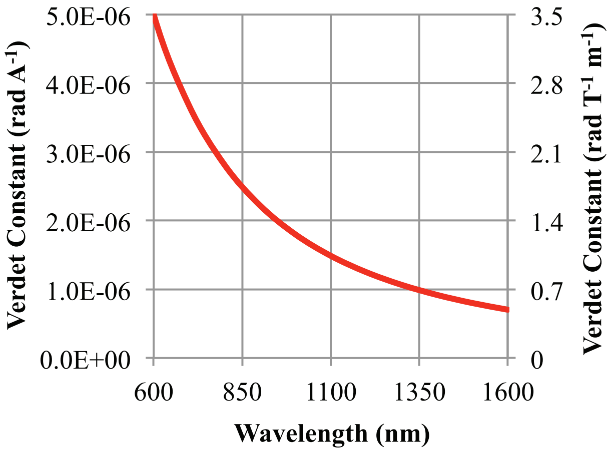

Figure 3: Variation in Verdet constant with wavelength for a silica core fiber [4].

5 SENSOR LENGTH

The sensitivity of a fiber optic current sensor is linearly proportional to the number of coils of fiber wrapped around the current conductor. If a longer length of fiber is used, more coils can be achieved, giving a higher sensitivity. In a coil, the Faraday phase shift, φ, is proportional to:

$$\varphi \,\alpha\, V \cdot N \cdot I \tag{1}$$

Where V is the Verdet Constant, N the number of coils and I the current flowing through the conductor. Published work uses various lengths of spun HiBi fiber, including 16m [3] and 19m [2] of spun HiBi fiber. Spun LoBi fibers are typically used in commercial products in lengths around 5m where the shorter length is required to minimize induced birefringence but subsequently limits the maximum sensitivity of the device. To increase the sensitivity of both HiBi and LoBi systems, a reflector may be used at the end of the sensor fiber to give a double-pass, achieving double the Faraday shift.

6 COILING

The Faraday rotation per unit length, f, is dependent on the coil diameter, D, of the fiber, the current, I, being passed through the conductor and the wavelength of operation, such that:

$$f \propto \frac{I}{\lambda^2 D} \tag{2}$$

Therefore it is advantageous to use a coil of fiber with a small diameter to achieve a high level of Faraday rotation. However, as a fiber is bent, the bend induced birefringence increases, reducing the maximum sensitivity of the fiber. Lamming and Payne [2] define the maximum sensitivity of the fiber when bent, SB, as:

$$S_B = \frac{L_B^2 / L\prime_P^2}{1 + L_B^2 / L\prime_P^2} \tag{3}$$

Where L'p is the elliptical beat length of the fiber and L_B is the unspun linear beat length. Because the fiber also has an inherent sensitivity level, based on the spin pitch and natural birefringence, the total sensitivity of the fiber, S_T, is given by:

$$S_T = S \times S_B \tag{4}$$

Where S is the inherent sensitivity of the fiber. Using the equation for S_T, a graph may be drawn showing the total sensitivity of spun HiBi fiber and spun LoBi fiber as the coil diameter is reduced, as shown in Figure 4. Spun HiBi fibers allow the fiber to be coiled into smaller coil diameters than the spun LoBi fiber. However, because the fiber has an inherent birefringence which reduces the Faraday rotation rate, the maximum sensitivity is around 90% rather than the 100% maximum sensitivity from the spun LoBi fiber.

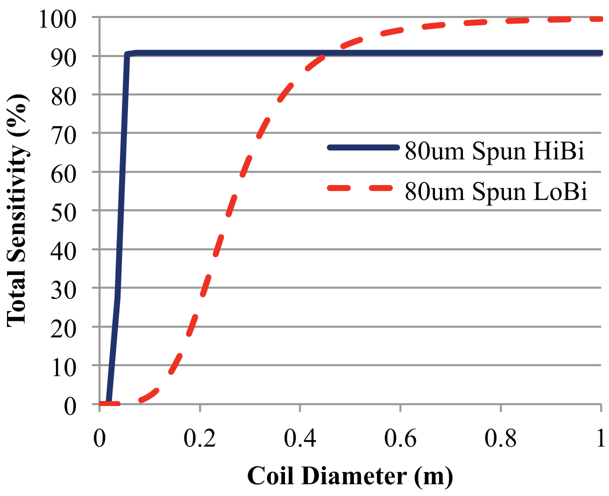

Figure 4: Theoretical comparison of the sensitivities achieved using an 80µm cladding diameter spun HiBi fiber and an 80µm cladding diameter spun LoBi fiber.

7 FIBER DIAMETER

The stress within a coiled fiber is relative to the fiber cladding diameter and the coil diameter. The larger the cladding diameter, the higher the stress across the fiber. Subsequently this effects the sensitivity of the spun LoBi and spun HiBi fibers as shown in Figure 5 and Figure 6.

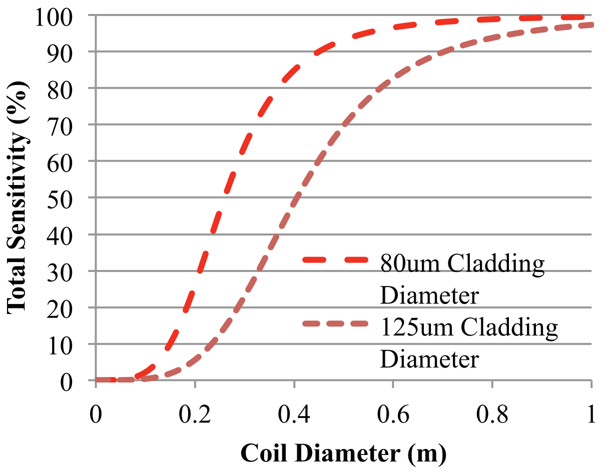

Figure 5: Spun LoBi fiber sensitivity variation with coil diameter and cladding diameter.

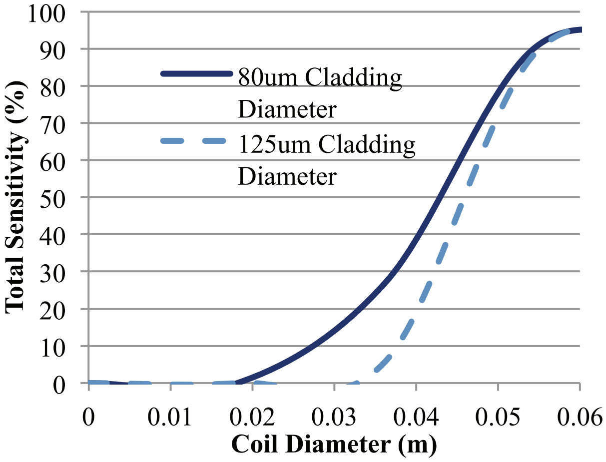

Figure 6: Spun HiBi fiber sensitivity variation with coil diameter and cladding diameter.

In terms of theoretical sensitivity analysis for spun LoBi fibers there is a real benefit in moving towards an 80µm cladding diameter design, this will also give a reliability benefit as the lower stress levels in smaller cladding diameter fibers results in longer mechanical lifetimes when the fiber is coiled [5]. But for spun LoBi fibers there is negligible real benefit.

The benefit of reduced cladding diameter for a spun LoBi fiber can be off-set by a reduction in sensitivity due to micro-bend induced local birefringence related to the packaging quality of the final sensor. Causes of micro-bends can include regions of pressure due to contracting glues, compressions in connectors and points where one fiber crosses over another. The reduced cladding diameter means the fiber is significantly less stiff than a 125µm cladding fiber as stiffness in a cylindrical object is proportional to d^4 where d is the fiber diameter. Therefore to realize the benefit of reduced cladding diameters in a spun LoBi fiber, the quality of the packaging technique needs to be exceptional.

8 SPINNING VS. TWISTING

Spun fibers are spun, not twisted. They have the axial rotation locked into the fiber during the fiber drawing process. This means that there are no torsional stresses within the fiber. A twist is where after manufacturing the fiber, a mechanical twist is applied by applying torsion to the fiber, this induces a high level of internal stress within the fiber.

Historically, researchers have tried twisted standard telecoms fibers to create circular birefringence within the fiber [6] with the aim of overcoming bend-induced birefringence. However, twisting fibers can cause reliability problems [7]. During thermal cycles, particularly in thermal-shock situations, the rapid change in the twist-induced torsional stresses can cause mechanical failure of the fiber.

Whilst spun LoBi fibers can benefit from the twist process to average out the effect of coiling the fiber, it is difficult to create a process which will accurately and repeatedly put in the twist and guarantee high reliability over a wide range of temperatures. It is worth noting that if the twist is put in the opposite direction to the spin direction, then worse performance may be achieved as the applied twist effectively untwists the spin. Subsequently, spun HiBi fiber is designed to not require twisting, saving process time and improving reliability.

REFERENCES

[1] http://upload.wikimedia.org/wikipedia/commons/thumb/c/cb/Faraday-effect.svg/2000px-Faraday-effect.svg.png - Published under GNU Free Documentation License, Version 1.2.
[2] R. Lamming and D. Payne, "Electric Current Sensors Employing Spun Highly Birefringent Optical Fibers", Journal of Lightwave Technology, vol. 7, no. 12, 2084-2094, 1989
[3] V.P Gubin, et Al, "Use of Spun optical fibers in current sensors", Quantum Electronics, vol. 36, no. 3, 287-291, 2006
[4] J. Noda, et Al, "Dispersion of Verdet constant in stress-birefringent silica fiber", Electronics Letters, vol. 20, no. 22, 906-908, 1984
[5] L. Jeunhomme, "Single-Mode fiber Design for Long Haul Transmission", IEEE Journal of Quantum Electronics, Vol. QE-18, No. 4, pp. 727-732, 1982
[6] R. Ulrich and A. Simon, "Polarisation optics of twisted single-mode fibers", Applied Optics, vol 18, 2241-2251, 1979
[7] A.J. Barlow and D.N. Payne, "Polarisation Maintenance In Circularly Birefringent Fibers", Electronics Letters, vol. 17, no. 11, 388-389, 1981