Faraday Effect Current Sensors 2012
A 19th Century Solution to a 21st Century Problem

Abstract

Back in 1845, when Michael Faraday first demonstrated the interaction between light and a magnetic field in a medium, he cannot possibly have known just how important his discovery was destined to prove in the energy and environmentally-conscious 21st Century.

A ‘false start’ in the 1980s despite advantages over conventional technologies

The use of light to measure the electrical current flowing within a conductor has manifold advantages over the conventional, current transformers currently used for the task. When monitoring electrical power distribution, current transformers carry a high explosion risk, brought about by the possibility of electrical discharge between the conductor and the transformer casing, particularly when combined with the quantities of both cooling-oil and oil-soaked paper contained within the transformer itself. At the other end of the scale, for example when used to measure the transients that develop within electronic circuits subjected to EMP, optical methods deliver the benefits of small-size and high-precision that current transformers simply cannot match. Add in the relative freedom from electro-magnetic interference that comes from the ability to engineer a wholly-passive sensor-head, mounted remotely from any electronic signal-processing by means of optical fibers and the fundamental reliability and reduced maintenance costs of a solid-state product and the attraction of the technology becomes very clear indeed. These four principal benefits of safety, precision, size and reliability incentivised a wide range of research laboratories and commercial companies, including the UK Central Electricity Generating Board (CEGB), Los Alamos, Schlumberger (PSC Enertech) and ABB to develop Faraday-effect current-sensors throughout the 1980s and into the early 1990s. In fact, so significant was the forecast demand for these new sensors that, contrary to popular belief, Fibercore’s very first specialty fiber product was not a ‘Bow-Tie’ Polarization Maintaining (PM) fiber for fiber optic gyroscopes but a spun, low-birefringence (LoBi) fiber, developed in conjunction with the University of Southampton, under contract to the UK CEGB, in 1982.

The advent of the ‘Smart Grid’ breathes new life into ‘old’ technology

History has taught us that it takes more than a good idea to make an innovation successful and this was certainly true for the Faraday-effect current sensor. So-called ‘Killer Technologies’ are very good at galvanising the R&D Communities into developing what look like market-ready products, but without a coincident ‘Killer Application’, commercial failure is virtually guaranteed. We saw the corollary of this with the invention of the Erbium Doped Fiber Amplifier (EDFA) in the mid-1980s, a Killer Technology, if ever there was one, but it was its relevance to the exponential growth of the Internet, not its technical elegance or performance that guaranteed its commercial success. Unfortunately for the Faraday-effect current sensor, no-such Killer Application arose and it was buried in the early 1990s beneath the existing, low-tech but functional competition. Fast-forward to 2011 and we have not one, but a double, Killer Application for the Faraday-effect current sensor - massive investment in new, electrical distribution infrastructure within the BRIC Nations and the ‘Smart Grid’.

The rapid economic development of the BRIC Nations has led to the extension of National or Regional Grids, even into areas that were not previously connected. As is often the case in the large-scale implementation of new technology, the comparative absence of any legacy equipment, and consequent expectations of financial payback has been instrumental in persuading decision makers to invest in the state-of-the-art. And in the low-carbon environment of the 21st Century, state-of-the-art includes the ability to optimize generation based on demand, co-ordinate input to the Grid from nuclear, solar, wind and even micro-generation sites, together with the provision of the information that consumers need to facilitate
more efficient energy consumption. In other words, state-of-the-art means the Smart Grid – and safe, reliable, compact and accurate Faraday-effect current sensors are an essential component in the implementation of the Smart Grid. As a result, Fibercore has seen a resurgence in the demand for fibers designed for current-sensors, particularly for China, Russia and India, or companies supplying hardware into these regions.

Reliability

The Faraday Effect occurs when light comes under the influence of the magnetic field generated by electrical current flowing within a conductor. The influence of the field causes left and right circularly-polarized waves to propagate at different velocities, that is, it induces a property known as circular birefringence. Since linearly-polarised light may be decomposed into two circularly-polarized components of equal amplitude, but of opposite-handedness and different phase, the effect of the relative phase-shift, induced by the Faraday Effect is to induce a rotation of the linear polarization state (Figure 1).

In most applications, the Faraday Effect is maximised by selecting materials with very high Verdet Constants. For example, the optical isolators used to prevent back-reflections in telecommunications lasers typically use Terbium Gallium Garnet (TGG) and optical voltage sensors have been developed using glass that has been heavily-doped with lead. These high Verdet materials enable the manufacture of very compact components but achieving the finesse and discrimination necessary for an effective sensor is more difficult. The germania-doped silica used in optical fiber cores has a low Verdet Constant, but in common with most intrinsic optical fiber sensors, it is the light-guiding properties and ultra-low loss of the fiber that enable the very long path-lengths necessary to magnify what is a relatively small, intrinsic effect. A basic Faraday Effect current sensor is shown in schematic in Figure 2.

Spun Optical Fiber, the secret of successful sensor design

The problem with using a conventional optical fiber in a current sensor is that the fiber itself will induce a rotation of polarization state due to the presence of random birefringence within its core. This random birefringence is caused by microscopic variations in core geometry, stress distribution and even composition introduced during the fiber manufacturing process. Discrimination of rotation caused by the presence of the magnetic field from that induced by this birefringence is practically impossible, particularly when the temperature dependence of the sources of the birefringence is also taken into account. As a result, whilst demonstrating the Faraday Effect in optical fiber is relatively simple, producing a practical current sensor is not.

Fibers may be made to be transparent to polarization by drawing them from a spinning preform (Figure 3). By effectively ‘freezing’ a helix into the fiber, the imperfections responsible for the creation of random birefringence are distributed evenly and their influence on the light travelling within the core is nulled. This technique was pioneered by the University of Southampton Optical Fiber Group in the early 1980s in the research of LoBi fibers for current-sensor development at the UK CEGB and much later, adopted in a somewhat modified form by the Telecommunications Industry to reduce Polarization Mode Dispersion (PMD) in high-bandwidth transmission fibers.

Unfortunately, having removed the intrinsic birefringence of an optical fiber, it is still far from ideal for use in a current sensor. Whilst it could be possible to detect some Faraday rotation in a short length of spun fiber, laid in a straight line along a current-carrying conductor, the low Verdet Constant of the core would severely restrict the ultimate sensitivity of the sensor. In order to take advantage of the fundamental benefit of using an optical fiber over (say) a sensor based on a block of high-Verdet glass, it is necessary to increase the interaction length between the optical and magnetic fields by coiling the fiber around the conductor. In this way, path-lengths of many tens of metres can be created, but with coiling comes induced stress and with stress comes stress-birefringence which, once again, makes it difficult to determine whether the Faraday effect or the birefringence induced the rotation.
In practice, there are a number of ways of getting around the problem of coil-induced birefringence in current sensor design. If the sensor coil is very small and is only to be used in a very controlled environment, it may be possible to strip the fiber coating, and anneal the coil at high temperature (>600°C). This annealing technique was demonstrated successfully at both NIST and Los Alamos in the late 1980s but the extreme fragility of the un-coated coils made the sensors impractical for anything other than specialized, laboratory use. Another method, used in the majority of the commercial systems that were introduced to the electricity generation and distribution industry in the late 80s and early 90s was to twist the fiber by perhaps 30 turns per meter, prior to coiling. At this point it is probably worth clarifying that spun fibers and twisted fibers are very different things. In a spun fiber, the helix is created in molten glass, in the draw, before the polymer jacket has been applied and predominantly without stress, whereas a twisted fiber is just that, a fully-formed and coated fiber that has been put under significant torsional stress by twisting.

The act of twisting induces circular birefringence, which swamps-out the linear birefringence created by the coiling process. This intrinsic circular birefringence is then modified by the Faraday effect. Whilst twisting low-birefringence fibers enabled the manufacture of commercially practical sensors, the torsional stress induced made the coils more susceptible to fracture under thermal shock and the sheer difficulty of handling and packaging a typical 30m length of fiber, containing perhaps 1,000 full twists, impacted manufacturing yields, significantly. Certainly the most elegant and practical solution is to use an intrinsically, circularly-birefringent fiber, fabricated by spinning a PM preform in the draw.

One sensor – four different PM fibers

The schematic shown in Figure 2 illustrates that the Faraday effect current sensor demands more, individual variants of PM fiber than any other fiber sensor type. The sensor head itself will inevitably be located close to areas of very high electromagnetic interference, so separating the head from the signal processing electronics using optical fiber makes a great deal of sense. As a polarimetric sensor, the polarization state delivered to the head must be known, stable and of high extinction, often necessitating lead-ins formed in PM fiber, with the polarization state hardened-up by means of a short length of single-polarization (or ‘polarizing’) fiber. In some designs, interferometric techniques may be used to determine the rotation induced by the magnetic field, requiring delay-lines which also need to be formed in PM fiber. Depending on the precise sensor design, all four PM fiber variants, lead-in, single polarisation, spun and delay-line may need slightly different properties, but all must be splice-compatible and tuned to work together in the overall system. A requirement that benefits enormously from Fibercore’s 30 year history in PM fiber development and un-matched experience in the high-volume manufacture of PM fiber for the Fiber Optic Gyroscope (FOG).

The history of the Faraday effect current sensor proves once again that ‘timing is everything’. It has taken more than 160 years from Michael Faraday’s original discovery for the Killer Technology and the Killer Application to coincide. Today in the 21st Century. Thanks to dwindling global energy resources, concerns over Climate Change, increased Corporate and Governmental Responsibility and the meteoric rise of new global economies the time is right and the future bright for this very special piece of ‘old’ high technology.