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Review Article

Advancements in Optical Current Sensors for High Power Systems: A Comprehensive Review

Badri Narayan Pandey,[1] Sumit Kumar[2]

Department of Civil Engieneering, K. L University, Vaddeswaram,hra Pradesh

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Corresponding Author:
Badri Narayan Pandey, Advancements in Optical Current Sensors for High Power Systems: A Comprehensive Review
E-mail Id:
narayanbadri452@gmail.com
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A B S T R A C T

A new generation of smart grids may find the inherent benefits of optical sensor technology to be highly useful. These benefits are especially attractive for high voltage applications. A review of optical sensor technologies for electrical current metering in high voltage applications is provided by the authors in this publication. Along with a more in-depth focus on contemporary developments, a brief historical summary is provided. All fibre sensors, bulk magneto-optical sensors, piezoelectric transducers, magnetic force sensors, hybrid sensors are among the technologies covered. The fundamental benefits and drawbacks of physical concepts are explained. Configurations and methods to deal with issues such magnetic field-induced linear birefringence, interference from outside currents, others are described. The most recent technology, including commercially available systems, is given.

Keywords: Optical Current Sensors, Magnetooptic Current Sensors, Fiber Optic Current Sensors, Faraday Effect

Introduction

Over the past ten years, there has been a substantial increase in interest in electrical current metering sensors, particularly for high voltage levels, as a result of the tremendous growth in the usage of electric equipment in industrialised nations and the global expansion of electrical distribution and consumption. When compared to conventional sensors, optical current sensors are much more attractive for high voltage applications (such as in electrical high voltage (EHV) substations) even though they are still too expensive for low voltage applications (such as those in residential areas).

- Immunity against electromagnetic interferences (EMI);
- Electrical isolation (the optical sensors are made of dielectric materials)
- Possibility for measuring AC and DC
- Absence of saturation effects
- Low power consumption
- Small size, lightweight, relatively low cost

Additionally, they frequently connect to optical fibres with huge communication bandwidths, their extremely low absorption loss enables remote detection, high multiplexing efficiency, long-distance data transfer. Additionally, optical current sensors measure the magnetic field produced by the electric current instead of the actual electric current, eliminating the potential electric risks that the high voltage measurements suggest.

The magneto-optic effect (also known as the Faraday effect) and magnetic force (sometimes known as the Lorentz force) are the two main linear effects that allow optical sensors to monitor the magnetic field.

An external magnetic field can cause a rotation in the angle of polarisation of the light travelling through magneto-optic material in sensors that rely on the Faraday effect. The Faraday effect is briefly explained, the various interrogation methods that can be used to question the polarisation rotation angle are also described. Then, the effects of two different types of optical current sensors (all-fiber optic sensors and bulk-optic based sensors) that use this effect are examined. The notion of all-fiber optic sensors is important because it enables straightforward solutions and lowers fibre connection losses because the optical fibre serves as both a sensing element and a communication path.

Tunable sensitivity and immunity to external currents or magnetic fields[1] can be easily attained by winding the optical fibre around the electric conductor. Bulk-optic sensors typically exhibit superior sensitivity and resilience, two characteristics that are crucial in practical applications. In both situations, saturation effects, such those that arise in sensors based on ferromagnetism, are avoided, enabling wider measurement ranges.

When working with high voltage distribution systems, the majority of the optical sensors listed can be fitted without interrupting the current in the conductor. Finally, the potential for hybrid current measurement methods using both established (conventional) and emerging (optical) technologies is also highlighted. These hybrid sensors may be crucial in the initial stages of integrating optical current sensors in the industry, prior to establishing fully optical current measuring devices, in addition to some operational benefits.

Faraday Effect

Michael Faraday observed in 1845 that a left-handed and right-handed circularly polarised light created by an external magnetic field had a different refractive index of glass. Émile Verdet demonstrated in 1854 that the cosine of the angle between the magnetic field and the direction in which the light wave is propagating and the strength of the magnetic field are both related to the angle of rotation of linearly polarised light. This rotation can be formally stated as follows:

$$\theta_f = \int V\vec{B}\cdot d\vec{l} \qquad (1)$$

where, V is the material Verdet constant, which is both dispersive and temperature-dependent,[1-2] B is the magnetic flux density vector and dl is the differential vector along the direction of propagation. This effect is called the Faraday effect or linear magneto-optic effect and can be used to build optical current sensors. Figure 1 illustrates the polarization rotation due to a parallel external magnetic field on a magneto-optical material, such as, glass.

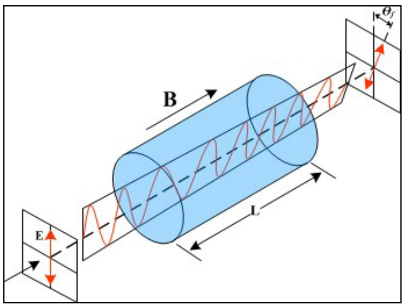

Figure 1.Faraday effect in linearly polarized light.

The Faraday effect differs from the naturally occurring circular birefringence (also known as optical activity) that manifests in some materials in that its sign relies on the magnetic field's orientation relative to the direction that light is propagating.[3] It is hence non-reciprocal. As a result, the rotation of polarisation will be cumulative if the same light travels through the same medium but in the opposite propagation direction.

All materials exhibit the Faraday effect to some degree, its qualities are correlated with the material's other magnetic properties. In paramagnetic and ferromagnetic materials, it fluctuates with temperature significantly more than in diamagnetic ones. In diamagnetic materials, it is linear with the magnetic field; however, in ferromagnetic materials, it saturates, its amplitude often decreases with increasing wavelength.

Interrogation Techniques

There are two basic detection techniques that can be used to determine the Faraday rotation of the azimuth output light: polarimetric and interferometric.

Polarimetric Detection

Basic Polarimetric Scheme

To measure the Faraday rotation of the azimuth of the output light from an optical current sensor, various signal analysis techniques can be applied. A polarimetric detection method, which uses two polarizers, one at the sensor's input and the other at the output, is one approach to detect this rotation. This arrangement is represented schematically in Figure 2. The second polarizer is employed to modify sensor sensitivity and converts the polarisation rotation into a light intensity modulation that can be detected by a photodetector.[1] The first polarizer's goal is to define the initial polarisation state of the light wave.

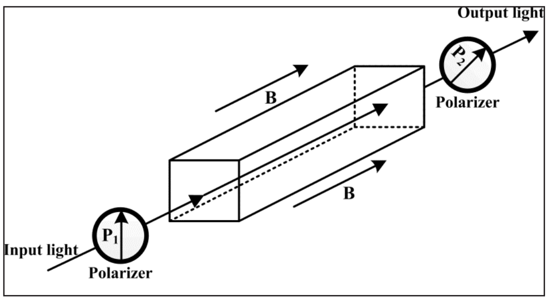

Figure 2.Polarimetric detection scheme

$$I_{out} = I_{P1}\cdot\cos^2(\alpha) \qquad (2)$$

where is the angle between the transmission axes of the polarizers and IP1 is the light intensity after the first polarizer. The maximum sensitivity is attained when this angle is 45 degrees, as shown in Figure 3. This means that any slight change in the plane of polarisation of the light caused by an external magnetic field in the path between the two polarizers, at a relative angle of 45 degrees, will result in a bigger change in intensity at the output.

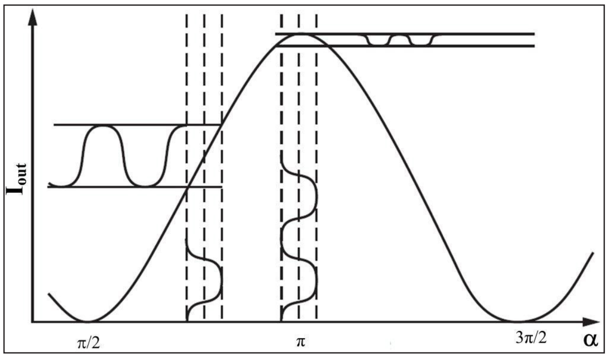

Figure 3.Transfer function of two polarizers showing the transmitted power as a function of their relative angle

Adjusting the polarizers for the maximum sensitivity, the sensor transfer function is:[5]

I = lin [1+sin(2θ)] (3)

In order to eliminate the dependence of the sensor response to the input light intensity fluctuations, the final processed output signal can be obtained by dividing the AC component by the DC component.[1] That is:

S_{AC}=sin(2θf) (4)

Dual Quadrature Scheme

Another improvement of the processing scheme presented above is shown in Figure 4. In this case, the output light is divided into two orthogonal polarizations, through the use of a Wollaston prism, these two signals are detected by two independent photodetectors and processed by an analog circuit that computes the output signal S, given by Equation (4).

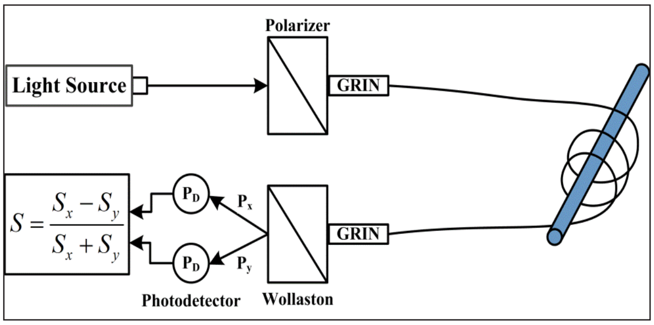

Figure 4. Schematic of the dual-quadrature polarimetric detection incorporating opticalfiber links. Legend: GRIN (GRadientINdex); PD (Photodetector); Pi(I = x,y) optical power in polarizations states

Equation (4) becomes: When the linear birefringence () effect in the sensing element is taken into account and the Faraday rotation is relatively minor.

$$S_{AC}=2\theta_F\frac{\sin\beta}{\beta} \quad \beta\gg 2\theta_F \tag{5}$$

$S_{AC}=2\theta_F$ $\beta\ll 2\theta_F$

The two methods presented above do not take into account the linear birefringence effect, which as can be seen from Equation (5), can greatly reduce the sensitivity of the sensor. Furthermore, because the linear birefringence (β) is usually temperature dependent, severe measurement errors can be introduced. To account for linear birefringence, it is necessary to introduce other detection methods that require more complex signal processing strategies that will be described in the following section.[1]

Interferometric Detection Schemes

The rotation of the plane of polarisation of linearly polarised light was previously studied in the polarimetric detection system. The phase difference between the two circular orthogonal modes (left-handed and right-handed circular polarisation) can be used to analyse this rotation in terms of circular polarisation. An interferometric detection method can be used to do this. In this method, a modulation frequency carrier is created, the optical phase variation that is modulated by the time delay induced between the interferometer's arms will include the information about the electric current. A Sagnac interferometer or unbalanced Michelson or Mach-Zehnder interferometer, among other interferometric configurations, can be used to produce this phase carrier.[1,3]

Figure 5, shows schematically a current sensing Sagnac interferometer, which is commonly used in gyroscopes and it is sensitive to non-reciprocal effects.[4] This interferometer is interrogated by using a heterodyne detection scheme.

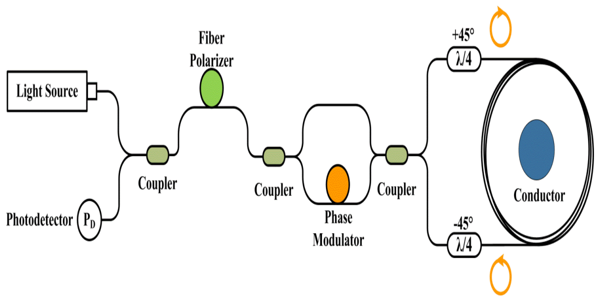

Figure 5.Sagnacloo pinter ferometer current sensor

In this application, light from an optical broadband source is linearly polarised using a fibre polarizer before being injected into the Sagnac loop with crossed 4-wave plates mounted at 45° and 45° angles, for the upper and lower plate, respectively, to the plane of polarisation of the linearly polarised inputs. Each of the counter-propagating waves in this configuration is transformed into an orthogonal circular state. Due to the circular birefringence that the external magnetic field induces, these two counter-propagating waves move through the Sagnac loop at varying speeds.

They are transformed back into linear polarisation modes after passing through the loop and start to interfere after passing through the output linear polarizer. With the addition of the phase modulator to the unbalanced Mach-Zehnder interferometer, which may be utilised to generate the phase carrier, the phase information is obtained. The relative phase accumulated in the Sagnac loop, which is proportional to the magnetic field produced by the electric current on the conductor, can be recovered using either pseudo-heterodyne or heterodyne processing algorithms. The use of this kind of interferometer has some drawbacks, such as vibration and temperature dependent sensitivity.

An improved version of the above system can be done in a reflection configuration, as shown in Figure 6.

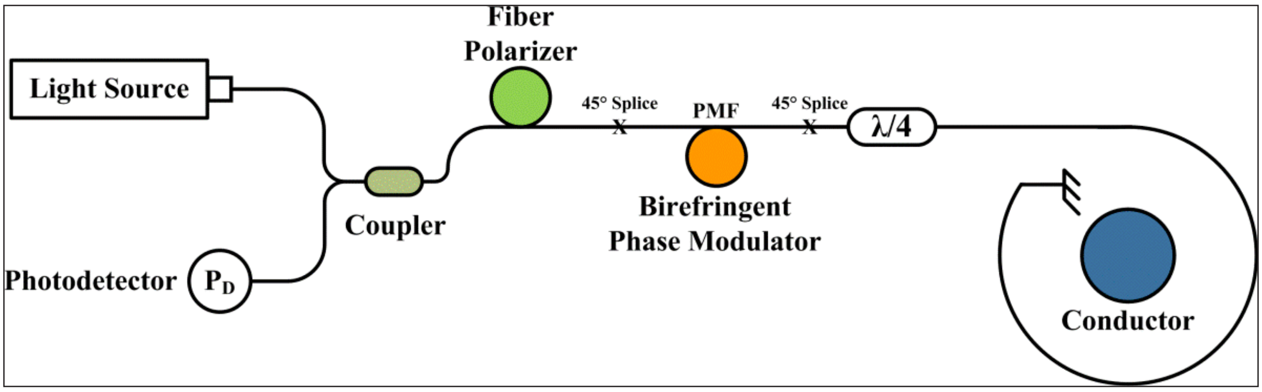

Figure 6.In-line interferometer current sensor

Both polarisations ultimately travel along the same optical route, compensating for any reciprocal effects while yet retaining a phase difference corresponding to the electric current under study. For the same number of fibre spins around the wire, this approach also doubles sensitivity in comparison to the first one due to the operation in reflection.

The polarisation interferometer's capacity to detect minor phase changes caused by small currents is improved by the modulation that was added to it (the length of PMF), close to the 45° splice. Despite the fact that the two mentioned techniques provide for some immunity to reciprocal perturbations, time-varying disturbances that change the PM fiber's birefringence have a different effect on counter-propagating waves and are not compensated [4]. Additionally, since we are using interferometers, a stable optical source must be used, despite the modulation's ability to provide some protection to low frequency noise, the system bandwidth must be limited. The phase difference created by the /4-wave plate, which might have minor variations and therefore modify the system sensitivity, is another significant issue.[3]

State of Art

Optical current sensors come in a wide variety today. Optical current sensors can be divided into four major types[1,5] based on the sensing technique used and the materials selected:

- An all-fiber sensor uses the fibre itself as a transducer. In order to cause a rotation in the angle of polarisation of the light travelling through the fibre, which is proportional to the magnetic field, one uses the magneto-optical effect (also known as the Faraday effect). The fibre is typically wound around the electrical conductor to protect it from outside currents and magnetic fields
- Bulk optic sensor: This type of sensor uses a transducer that is placed close to (or all around) an electrical wire and is made of glass or crystal with a high Verdet constant. The magneto-optical effect is also used to gauge the magnetic field. These sensors are frequently less expensive, more durable, sensitive
- Magnetic force sensors: When a magnetic field is applied to a magnetostrictive element, it causes mechanical changes in the material, following a similar procedure to that of piezoelectric devices. By affixing a fibre Bragg grating (FBG) to the magnetostrictive element, these variations can once more be detected
- Hybrid sensors: These sensors combine existing optical and electromagnetic technologies in a hybrid fashion. The first current transducer in this instance is constructed using traditional electromagnetic technology (such as a Rogowski coil), but its interrogation and information transportation are carried out via an optical fibre system. These sensors are designed to create an interrogation system that benefits from the high level of electrical isolation provided by optical fibres while avoiding problems brought on by birefringence

All-Fiber Sensors

Because the fibre may be easily wound around the electric conductor to be monitored, all-fiber sensors have relatively basic topologies. Additionally, by simply altering the number of turns the optical fibre makes around the conductor, the sensor sensitivity may be altered.[3] The sensors are more susceptible to pressure and temperature gradients, mechanical vibrations, other ambient disturbances than smaller devices (such bulk-optic) because these types of devices typically employ several metres of fibre. transportation are carried out via an optical fibre system.

These sensors are designed to create an interrogation system that benefits from the high level of electrical isolation provided by optical fibres while avoiding problems brought on by birefringence.

Magnetic crosstalk between several conductors can also be an important issue when operating at high currents. Plans have been put out to lessen magnetic crosstalk in three-phase electric systems.[6] However, the sensing method won't be sensitive to outside magnetic fields if it creates a closed circuit around the electrical conductor, as most of them do. Standard silica fibres typically have a lower Verdet constant than bulk optical glasses. Numerous studies have been conducted to raise the fibres' Verdet constant.

In tests, materials like flint glass demonstrated a Verdet constant that was six times greater than that of fused silica and a significantly lower photo-elastic coefficient (780 times).[3,7,8] Additionally, the literature[9] provides a thorough analysis of the most recent transducers that employ flint glass fibres. The paper offers particular details about the sensors (setup arrangements, temperature dependency, accuracy, etc.) and the fibres utilised (Verdet constants, photo-elastic constants, wavelength dependence, etc.), as well as the outcomes of field testing that were carried out. A typical current sensor with flint fibre is shown in Figure 7.

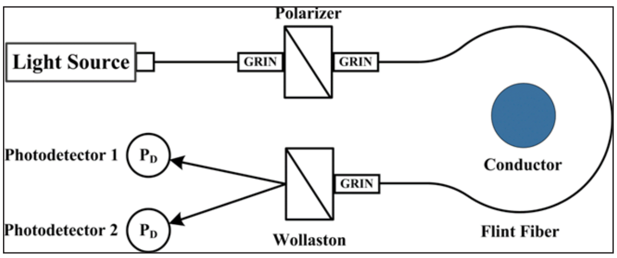

Figure 7.Typical configuration of an optical current sensor with flint fiber

Flint glass fibre performs better than twisted single-mode fibre (which was typically used before flint glass fibre) as a Faraday element, according to a comparison published,[10] which also demonstrated that the system using flint glass fibre is more stable than the system using twisted fibre.

A novel optical glass with a high refractive index for optical fibres was disclosed in 2009, with potential in optical current sensors. The findings indicated that these fibre glasses may have a tiny internal mechanical stress and a Verdet constant that is ten times greater.[11]

The Verdet constant of an optical fibre with a terbium-doped core phosphate was recently demonstrated to be six times greater than that of conventional optical fibres.[10] The same authors also presented a high concentration of terbium-doped fibre with a record Verdet constant of -32 rad/(T m) in 2010.[13] This fibre has a Verdet constant that is 83% larger than commercially available crystals used in bulk optics-based isolators and is 27 times larger than standard optical fibres.

The impact of the linear birefringence caused by mechanical stress (when the fibre is bent, for example), thermal stress, manufacturing flaws, other impacts is another issue with employing the fibre as the transducer. Due to the polarisation state deterioration caused by linear birefringence, the sensor sensitivity is dramatically decreased. As we can see from Equation (5), the linear birefringence can be disregarded if the circular birefringence is sufficiently large. It has been established that a twisted single mode fibre can be used to impose circular birefringence in the fibre.[14] Utilising spun high-birefringence fibres is a comparable strategy.[15] By annealing the fibre, linear birefringence can also be decreased.[16,17] For the Verdet constant dispersion in annealed fibres, theoretical models and actual observations have been provided.[18] There are a few ways to compensate for linear birefringence via the propagation of reflected light, such Faraday rotating mirrors[19] and fibre polarisation rotators,[20] which also double sensitivity for the same fibre length. A Faraday rotator mirror is depicted in Figure 8. This element causes a 90° polarisation shift, coupling light travelling along one axis to that travelling along the opposite axis and vice versa. Given that linear birefringence has a reciprocal effect, the phase difference it causes will be made up for.[19]

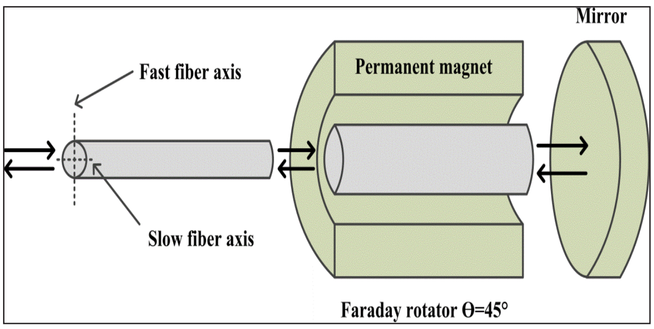

Figure 8.Faraday rotat or mirror

A sensor with the accuracy necessary for the 0.1% class of current metering transformers in the range of 1 kA was developed utilising low-birefringent flint fibre with a very low photo-elastic constant and used reflected light propagation for linear birefringence compensation.[21] There are already some optical electric current sensors on the market. Taking all-fiber current sensors as an example, ABB and NXTphase are two businesses that offer sensors with a functioning concept that is the same as the one in Figure 6 of Figure 6. The first company guarantees accuracy of 0.1% and a range of operation up to 500 kA.[24] The second company, which is likewise in the 0.1% class group, allows DC and AC measurements with a range of operation from 1 to 63 kARMS.[25,26]

Bulk-Optic Current Sensors

As was previously said, all-fiber current sensors are simple to use and increase sensitivity, but they have low Verdet constants and significant linear birefringence. The technology that has been used in industry the most in this context is bulk optic sensors.[1,27]

Bulk optical sensors provide certain clear advantages over all-fiber technologies. These are typically more rigid mechanically and smaller in size. The bulk optic material has very low levels of mechanical and thermal gradients, vibrations, other outside sounds. Additionally, they typically have Verdet constants that are two times larger than those found in optical fibres, because of their low photo-elastic coefficients and low intrinsic linear birefringence, high sensitivity sensors are possible. The fact that the sensor surrounding the conductor need not be made of a single piece of material is another significant benefit. As a result, there is no need to stop the conductor's current during installation.

The primary drawbacks of these sensors stem from the requirement for reflections to take place inside the bulk optic material in order for light to pass around the conductor. The refractive index of the crystal and the surrounding medium (such as air) will determine the reflection angle, which means that a variety of environmental conditions, such as humidity, will have an impact on the sensor. The sensor can be isolated from outside influences to overcome this problem, but doing so will increase the cost of installation and maintenance.[28] Additionally, every time a light reflection occurs internally, the two polarisations will have an optical phase difference. This results in an inevitable error source in a polarimetric or interferometric scheme.[29] Double reflections in each corner of the bulk optical material can be used to solve the issue, with the second reflection compensating for the optical phase difference introduced in the first reflection. This concept is covered by a patent that was filed in 1986,[30] which is depicted in Figure 9.

The elliptical polarisation state in the optical path between the first and second reflections and the signal's nonlinear response to the magnetic field being measured offer another issue with this theory. External magnetic fields will have an impact on the system as a result of this. Since the three conductors in three-phase systems are typically close to one another, this problem has a particular relevance when measuring current in those systems. Additionally, research has been done to reduce crosstalk between various conductors.[6] Another option is to use a triangular-shaped bulk optic material, as depicted in Figure 10, where light is always reflected at the critical angle.[13]

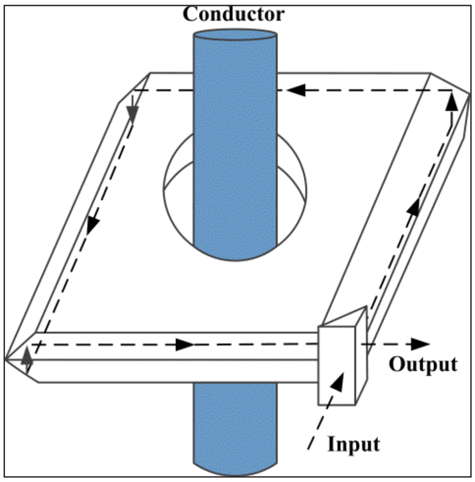

Figure 9.Bulk optic current sensor with double reflection

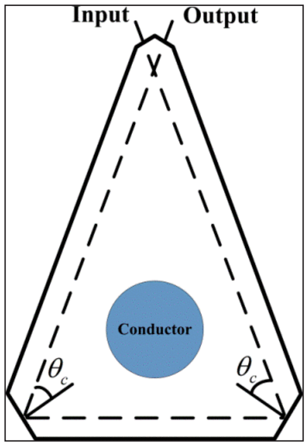

Figure 10.Bulk optic triangular shape current sensor

Compared to the prior configuration, this one is easier. To do this, though, calls for an exact reflection angle cut and a nearly flawless bulk optic material that is well-isolated from outside noise sources. Field concentrators (which consist of an air-gap core surrounding the conductor) and extending the light optical path inside the crystal (by using total internal reflections before the light exits from the sensing element)[32] are two strategies that have been suggested to further increase the sensitivities of these sensors. A circular sensor head was created for this purpose, in which light is pumped into a prism and, at certain angles, travels five times before leaving the prism. This plan improves sensibility and is not affected by outside fields.[33]

Additionally, it is crucial to compensate for linear birefringence in order to maximise the sensor's sensitivity.

It has been demonstrated that a Faraday rotator mirror may reduce the polarisation plane's angle of rotation caused by linear birefringence from 20° to 5°.[36]

Because it alters the sensor's sensitivity, the Verdet constant's dependency on source wavelength is also significant.[37] Additionally, it was demonstrated that errors brought about by a short bandwidth optical source are extremely minimal, making it permissible to utilise models that presuppose a monochromatic light source.[38] Bulk optical sensors exhibit the same temperature dependence of the Verdet constant as all-fiber optic ones. . The temperature was measured as a solution, its impact was mitigated by adding a temperature-dependent correction factor.[39]

The literature contains many intriguing concepts for optical current sensing, but many of them are not intended for high voltage or high current sensing applications. There are, however, specific uses for high voltage[41] and high current.[40] To avoid rotation angle ambiguities when measuring high currents, sensors are often restricted to observations between 0 and 360. This issue was resolved[40] by utilising a method that allowed for measurements up to 720 kA and tallied the instances in which the phase passed 0.

Magnetic Force Sensors

The magnetostrictive effect, which occurs when a ferromagnetic material is exposed to an external magnetic field, causes a mechanical strain in the material, is used by optical fibre magnetic field sensors. For that, an optical fibre is either bonded to the sample or a thin film of a magnetostrictive material is deposited. Metallic glasses as Metglass 2605S2 or Vitrovac 40-60,[44-47] as well as ceramic thin-films (Fe2O4, NiFe2O4, or NixCo1-xFe2O3), were the most often utilised magnetostrictive sensing components.

Since 2000, Terfenol-D, an alloy material with a high magnetostriction coefficient, has been the subject of extensive research. A Terfenol-D rod or ribbon attached to a fibre Bragg grating (FBG) is the most researched optical arrangement.[50] These sensors' tiny size and ability to contain several sensing elements within a single optical fibre, which enables optical multiplexing, are advantages. Microstructured fibres have also been used to test Terfenol-D alloys.[51] A different class of magnetic field detectors that rely on magnetic fluid have recently been proposed.

Magnetostrictive Sensors

There was a lot of work done in the 1980s to detect magnetic fields and/ or electric current using optical fibres and materials that have magnetostriction effects. Yariv et al.[43] investigated the prospect of employing magnetostrictive disruption in optical fibres to detect weak magnetic fields in 1980. Wrapped around a nickel jacket that experiences longitudinal mechanical strain when exposed to a magnetic field is a low loss optical fibre of length L. Dandrige et al.[44] revealed the first experimental proof of the magnetic field sensing properties of optical fibres jacketed with either nickel or metallic glass magnetostrictive materials. Both thin films directly deposited on a single mode fibre (SMF) and bulk magnetic stretchers were examined. The magnetically induced mechanical changes in the optical path length containing the magnetostrictive jacket were detected using an all-fiber Mach-Zehnder interferometer. The magnetometer schematic diagram presented by Dandrige et al. is shown in Figure 11.

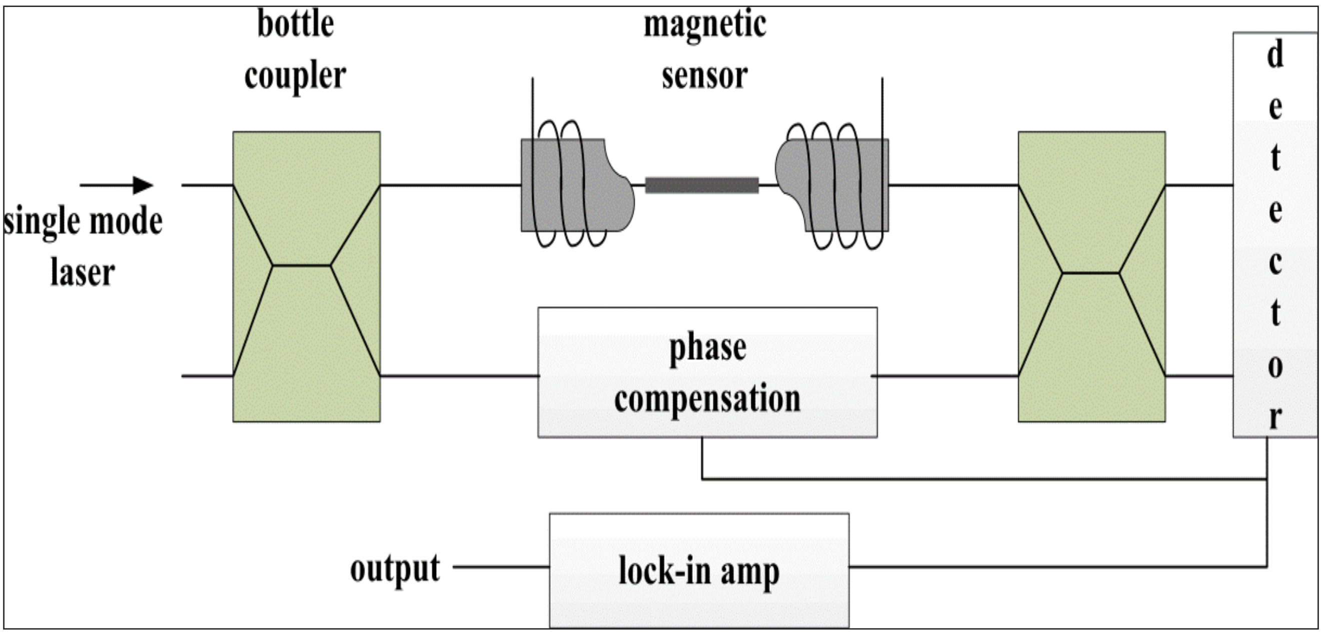

Figure 11.Experimental scheme of fiber optic magnetic sensor

6.37 106 A/m2 was the sensor sensitivity attained using the bulk nickel material. The thin-film thickness determined the response of the first generation thin film coated fibre optic sensors, which was around two orders of magnitude lower. A modest axial magnetic field's effect on mechanical strain in an optical fibre with a magnetostrictive jacket of varying thickness was studied by Jarzynski et al.[48] A number of magnetostrictive materials' sensitivity was determined as a function of jacket thickness.

Unfortunately, these setups may also be susceptible to all other factors that affect the optical path length of the fibre, such as temperature,[52] in addition to magnetic fields. Heaton suggested using a non-magnetostrictive metal-coated element in one arm of the interferometer to measure temperature directly, increasing the sensitivity of fibre optic interferometers to magnetic fields in the process.

Rashleigh[53] presented an SMF coiled in tension around a cylindrical metal component that is magnetically sensitive. The state of polarisation (SOP) of light in the fibre was altered by the magnetic field. A magnetic field as weak as 3.5 104 A/m2 of fibre can be detected using an optical phase sensitivity of 1.76 102 rad/m Oe.

Koo and Sigel[45] described the use of a metallic glass as a sensor element for the detection of extremely low magnetic fields. They employed an all-fiber Mach-Zehnder interferometer in their experiment to test various metallic glasses' sensitivity to magnetic fields. 3.98 107 A/m2 was reported as the lowest magnetic field that could be detected.

Willson and Jones[56] created a configuration for measuring DC magnetic fields using an optical fibre coated with amorphous Fe0.8B0.2 alloy in one arm of a modified magnetometer. The system was analysed in quadrature, permitting the elimination of polarisation variations, in order to achieve a maximum sensitivity. The analysis of a linear region yielded a sensitivity of 102 rad/Tm.

Kersey et al.[57] devised a method for determining weak DC and low frequency AC magnetic fields using an all fibre SMF magnetometer. The experimental setup, which was employed for the first time, was a Michelson interferometer with mirrors made of two cleaved fibre ends covered in silver film. The bulk nickel magnetostrictive element attained detection sensitivities of 1 107 T/m at 20 Hz. The experimental set up is shown in Figure 12.

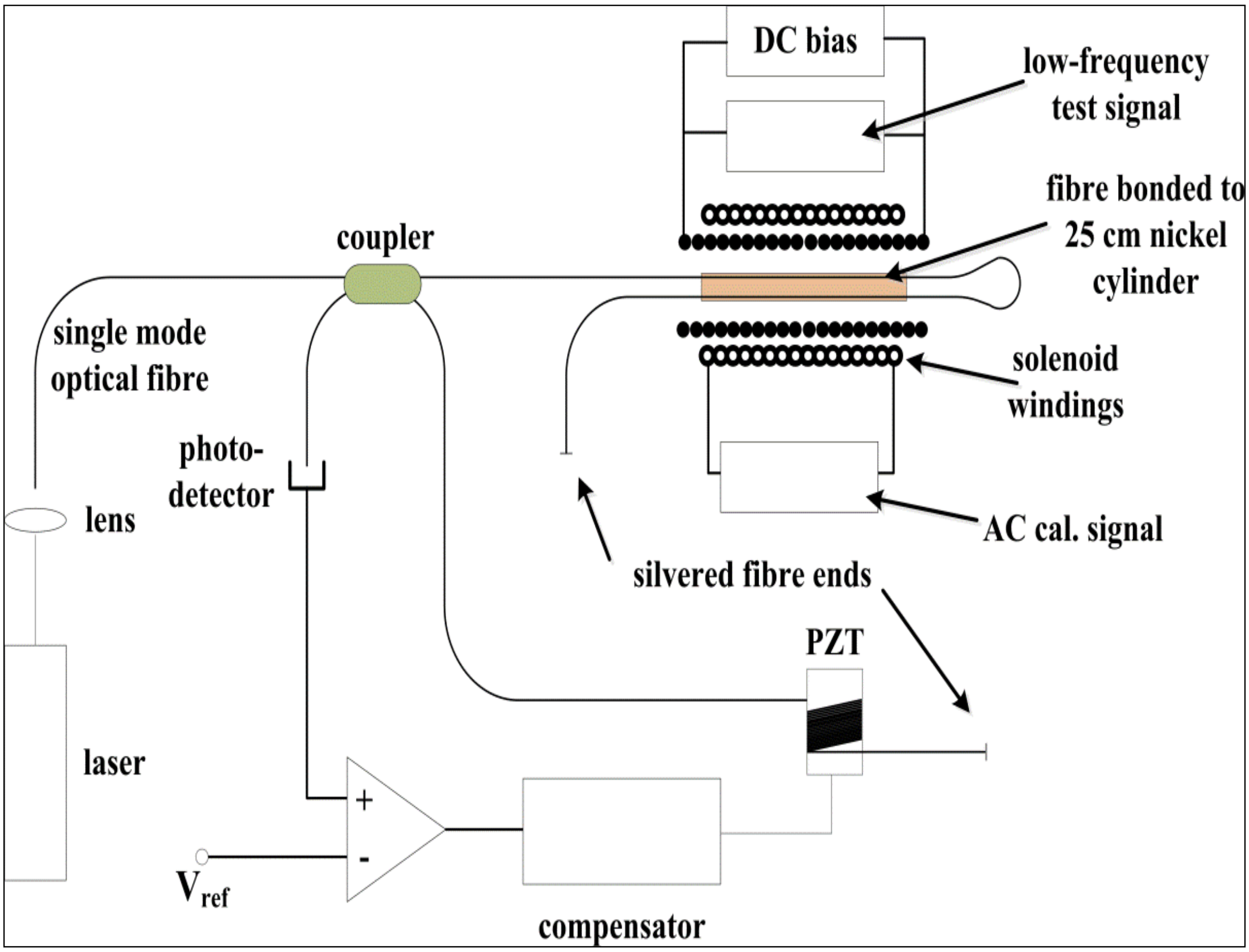

Figure 12.Scheme of the all fiber magnet ometer by Kerseyetal.[57]

Koo et al.[58] employed a fibre Mach-Zehnder interferometer that was passively stabilised using a 3 3 fibre coupler. By exposing the metallic glass to DC and AC magnetic fields, the system response was studied. When using a fibre with a length of 1 m and a bandwidth of 1 Hz, the sensor's sensitivity was in the range of 7.96 105 A/m2.

Kersey et al.[59] announced the first demonstration of a closed-loop fibre optic magnetometer with dynamic magnetostrictive response. The sensor has a sensitivity of 2 nT at frequencies below 2 Hz, making it capable of detecting low frequency and DC changes in magnetic field.

The same group then presented a similar setup a year later, with the primary difference being that they maintained a constant value for the total local field (bias plus ambient) in the magnetometer [46]. They made sure the magnetostrictive sensing element was kept in a zero condition with zero magnetization by stabilising the active-bias field. The magnetic hysteresis of the used metallic glass materials (Metglass and Vitrovac) was reduced by this procedure. Using a short optical fibre (about 0.5 m), a minimum detection of 8 105 A/m was found spanning the frequency range of DC to 20 Hz.

Bucholtz et al.[47] looked into how external disturbances like vibrations and mechanical stress affected the performance of fibre optic magnetometers. By keeping the DC magnetic field at set values, these perturbations may be controlled. The investigation has demonstrated that all interferometric fibre sensors using nonlinear transducing mechanisms could adopt the authors' method. Bucholtz et al.[60] reported the first demonstration of the detection of magnetic fields at frequencies above 50 kHz using a fibre optic magnetometer in 1989. A thick cylindrical metallic glass transducer was placed in one of the fibre arms of a Mach-Zehnder interferometer for this experiment. A heterodyne detection method was made possible by combining high frequency signals in the magnetostrictive sensor, where the transducer served as both the receiving and nonlinear mixing element. A minimum detectable AC magnetic field of 70 fT/Hz at 34.2 kHz was observed by the same group.[61]

Sedlar et al.[49] examined optical fibres coated with magnetostrictive ceramic films using a modified Mach-Zehnder interferometer that was set up in an open-loop mode. The sensors showed exceptional sensitivity and excellent linearity. The materials employed were nickel ferrite, cobalt doped nickel ferrite (NCF2) jackets, cobalt doped iron oxide (Fe2O3), magnetite, nickel ferrite. For optical fibres jacketed with NCF2 material, they were able to attain a minimum detectable magnetic field of 3.2 103 A/m for fibres that were 1 m long and 2 m thick.

Oh et al.[62] suggested a fibre optic sensor for sensing DC magnetic fields based on the extrinsic Fabry-Perot interferometer (EFPI). Extrinsic Fabry-Perot interferometer (EFPI) sensor's input-and-output and reflector arms were made up of an SMF and a Metglass wire magnetostrictive transducer. It demonstrated a low vibration sensitivity and a good heat induced compensation (better than 99%) as a result of the sensor's optical geometry design.

Using high voltage systems, Pérez-Millán et al. [63] showed how to measure electric current in a novel way. A Mach-Zehnder interferometer was used to examine the fibre optic sensor, which made use of the inherent magnetostriction of a conventional current transformer's ferromagnetic core. The sensor did not experience several of the identified flaws in Faraday-based optical current sensors, such as variations in the optical power supply, phase drifts, polarisation dependencies. The experimental setup utilised by Pérez-Millán et al. is shown in Figure 13.

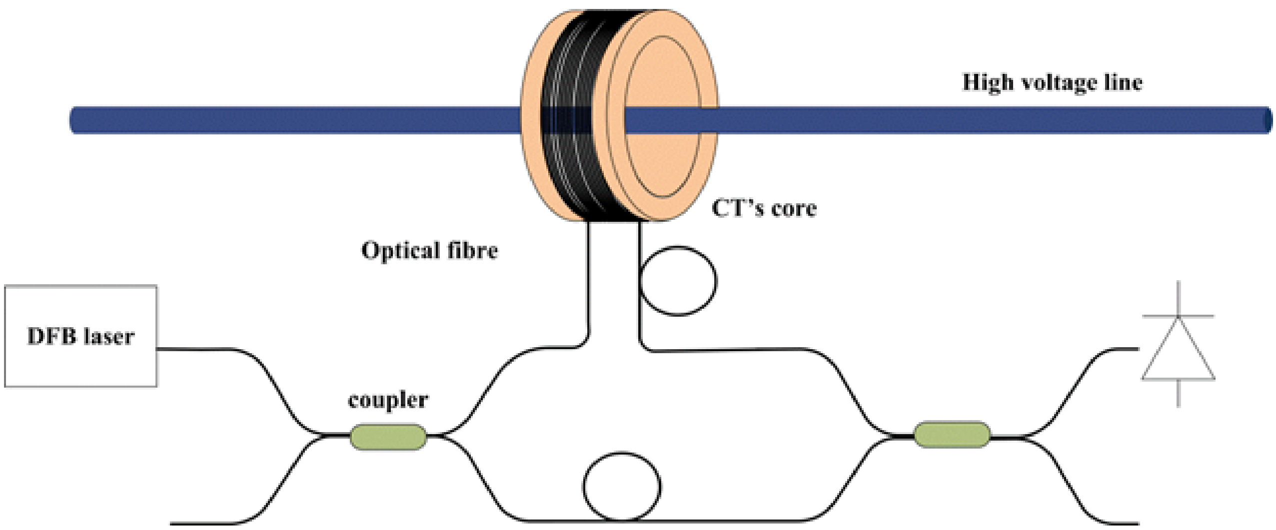

Figure 13.Experimental arrangement used for measuring electric current on high voltage systems

More recently, Djinovic et al.[64] revealed findings from measurements of AC and DC magnetic fields made with a fibre optic interferometric sensor for keeping an eye on structural health. Changes in the optical path length of the cavity between a magnetostrictive wire and a fibre optic tip served as the foundation for the operating concept. A 3 3 single mode fibre coupler was used in the sensing setup, which used a Michelson fibre interferometer. With a 50 nm accuracy and a magnetic field between 50 nT and 800 T, they were able to identify the instant separation between the wire and fibre ends.

Terfenol-D

Mora et al.[50] conducted the first experiment using optical fibre sensors and Terfenol-D alloy to measure static magnetic fields, as shown in Figure 14. The Terfenol-D and Monel 400 alloys, which have similar thermal expansion coefficients, were combined to form the magnetostrictive sensor with temperature adjustment scheme. The two FBGs attached measured the mechanical expansion of both materials caused by changes in temperature and magnetic field. The amplitude of the magnetostriction was proportional to the spectral difference between the two Bragg wavelengths, the temperature fluctuation was proportional to the wavelength shift caused by the grating attached to the non-magnetic alloy (Monel 400).

magnetostrictive effects could be measured using the two methods without regard to temperature. For the first and second approaches, the sensitivity to the magnetic field was 2.44 104 nm/mT and 1.8 104 nm/mT, respectively.

Satpathi et al. [66] designed and tested an electric current optical sensor based on a passive prototype magnetostriction device for high power applications. By fastening a piece of Terfenol-D to an FBG, mechanical strain that was proportionate to the magnetic field amplitude was produced, enabling the optical current sensor concept. The magnetostrictive alloy was exposed to mechanical pre-stress and DC magnetic field bias adjustment in order to get a linear response from it. The sensor had a measured phase shift of 30 for a frequency signal at 60 Hz, its linear electrical current range was from 100 to 1,000 A.

A rod of Terfenol-D that is linked to the optical fibre serves as the basis for the magnetic field sensor Li et al [67] presented, which is based on a dual FBG arrangement. One of the gratings was fixed to the magnetostrictive alloy's ends on both sides, but the other was only attached at one point and had a free end. For easy temperature correction and point measurement reference, a dual FBG design was used. When the applied magnetic flux density was less than 70 mT, the greatest sensitivity was attained at 0.018 nm/mT.

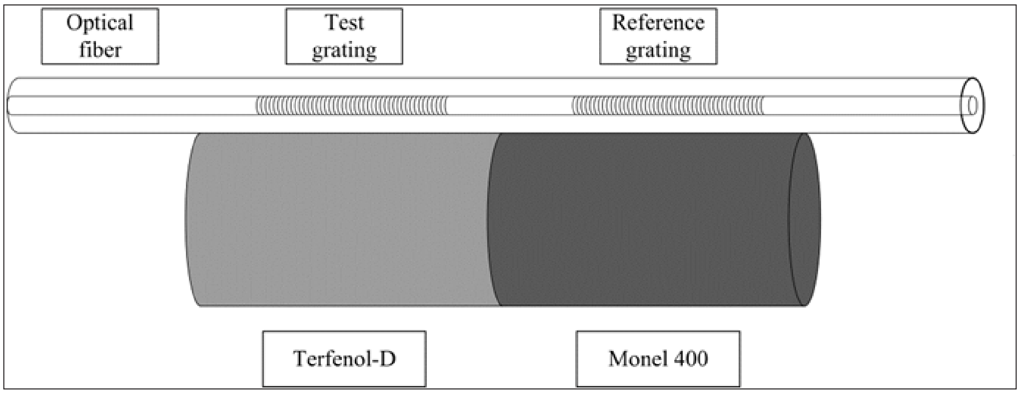

Figure14.Schematic diagram of the fiber sensor proposedby Mora et al.[50]

A linear response of the fibre sensor was confirmed for applied magnetic fields less intense than 4.7 104 A/m (B 60 mT). The spectral sensitivity in this region had a value of (2.31 0.05) 105 nm/(A2m2) and was temperature independent. Yi et al. [65] presented two straightforward strategies for compensating the temperature effects in the FBG based on magnetostrictive materials. The first method involved bounding a single Terfenol-D layer material with two FBGs that were positioned perpendicular to one another. In the second method, two FBGs were physically parallel to one another and layered atop two distinct magnetostrictive bars (nickel and terfenadine). The materials were similar in terms of their thermal expansion coefficients, but their magnetostrictive coefficients were in sharp contrast. The

A fibre optic AC current sensor for high voltage lines based on a uniform FBG mounted on a Terfenol-D piece was introduced by Mora et al. in 2006 [68]. The optical signal from the sensing head was processed in a novel method that enabled the simultaneous measurement of temperature and AC current. The first physical parameter used wavelength shift coding, the second used signal amplitude coding. The sensor's ability to be multiplexed allowed it to function across great distances as well.

Reilly et al. [69] revealed the existence of a sensor that can monitor AC current and temperature simultaneously. A Terfenol-D component that was magnetically biassed and fastened to one FBG made up the device. The sensor could measure AC current at temperatures ranging from 18 to 90 degrees Celsius. Methods for correcting for the nonlinear effects caused by the magnetostrictive alloy were identified and proposed.

Davino et al. [70] presented a method for compensating for hysteresis in a magnetic field sensor that includes a magnetostrictive alloy device. Terfenol-D and an FBG rod were both included inside the sensing head. The magneto elastic material was correctly modelled to account for hysteresis due to the nonlinear effects present in such materials. The algorithm made it possible for the sensor performance to increase.

Figure 15 illustrates a fibre optic magnetic field sensor that was described by Yang et al. [71] in 2009 and used for the first time rather than bulk magnetostrictive materials. Terfenol-D thin films were deposited on etched FBGs using the magnetron sputtering deposition technique. Two techniques to increase sensitivity were shown to work. In one, different diameters of FBGs with cladding etched on them were covered with the magnetostrictive alloy. For a sensor with an 85 m diameter, the greatest response to magnetic field sensitivity was 0.95 pm/mT. The alternative method involved covering FBGs with a multilayer of both FeNi and Terfenol-D magnetostrictive alloys. The multilayer has a sensitivity of 1.08 pm/mT, which is the highest.

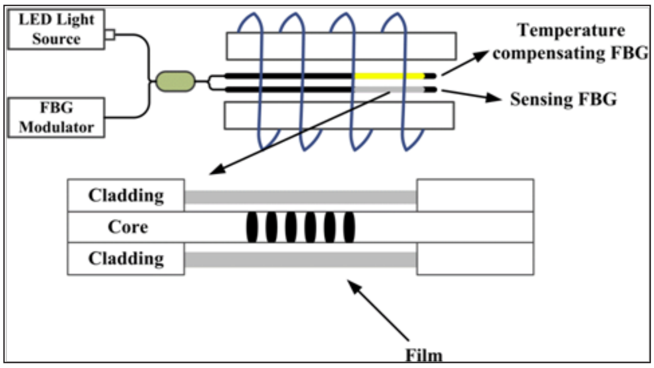

Figure 15.Configuration of optical fiber magnetic sensor used by Yangetal.[71]

Pacheco et al.[72] investigated the relationship between shape anisotropy and the strain response of magnetic field sensors based on magnetostrictive alloys and FBGs. When a biassed uniform field was applied to a 20 mm long Terfenol-D cuboid shape, the greatest sensor sensitivity was 18 /mT. By attaching FBGs along the cuboid containing the magnetic field direction, they were able to detect a significant change in the magnetostrictive response at various places for gradient magnetic fields.

A sensor for measuring the DC and AC magnetic fields was presented by Quintero et al.[73] A layer of a composite that contained Terfenol-D particle-infused composite was applied to the grating. The best magnetostrictive response was achieved utilising a 30% volume fraction of Terfenol-D combined in an epoxy resin matrix as a blinder, after several compositions had been evaluated. Investigated was the impact of a compressive pre-stress in the sensor. Resolution was 0.4 mT without pre-stress and 0.3 mT with pre-stress. Using an FBG interrogation device, the magnetic field's sensitivity was measured to be 2.2 106 mT1.

A new sensor for detecting static magnetic fields was recently described by Smith et al.[74] employing an inscribed FBG and a micromachined slot sputtered with Terfenol-D. Femtosecond laser inscribing was used to generate the grating and the slot. In transmission, the sensitivity to magnetic field was 0.3 pm/mT. Additionally, they performed reflection measurements with various polarisation states, obtaining sensitivities between 0.2 pm/mT and 0.1 pm/mT. The fabrication process is substantially simplified by using a femtosecond laser to inscribe an FBG and produce a micromachined slot.

Quintero et al.[51] reported developing the first fibre optic sensor for magnetic field measurement by fusing a highly birefringent photonic crystal fibre (HiBi PCF) with a Terfenol-D epoxy resin composite material. The HiBi PCF's two eigenmodes were equally excited to create an in fibre modal interferometer. changes in the effective refractive index and cavity length

By subjecting the sensor head to magnetic fields, index were induced. The obtained sensitivity was 0.006 nm/mT over a range of 300 mT. The same composite material was also used to create an FBG. The sensitivity attained for this sensor was 0.003 nm/mT.

Magnetic Fluid

Yang et al.'s[75] 2001 investigation into the physical basis of magnetic fluid film optical transmission in magnetic fields. In the presence of the magnetic field, the initially dispersed magnetic particles gathered to form magnetic columns. The columns were opaque, whereas the liquid phase was translucent. The magnetic fluid film's optical transmission is therefore dominated by the liquid phase. Increased magnetic field strength caused more columns to form, which reduced optical transmission. Later, the same group looked into the magnetic fluid film's refractive index and discovered that it was magnetically regulated in the presence of an external magnetic field.[76,77]

A magneto optic tunable filter based on a long period fibre grating (LPG) coated with magnetic fluid as environment medium was disclosed by Liu et al. in 2007.[78] The LPG attenuation band's centre wavelength shifted by roughly 7.4 nm when a changing magnetic field was applied. The modelling findings and measurements of the refractive index dependence of magnetic fluid on the external magnetic intensity showed good agreement.

Hu et al. [79] created a fibre optic current sensor based on magnetic fluid. The medium of a Fabry-Perot (FP) resonant cavity was the magnetic fluid. The external magnetic field causes fluctuations in the magnetic fluid's refractive index characteristic, the current was determined by the output wavelength of the FP fibre sensor. It was suggested to use an FBG wavelength measurement system for signal demodulation. The thickness and starting concentration of the magnetic fluid had an impact on the sensor's performance, the results showed good linearity.

Dai et al. [80] investigated a new fibre optic sensor based on magnetic fluid and etched gratings. Fe_3O_4 nanoparticle-bearing magnetic fluid was injected into capillaries containing etched FBGs, which functioned as the sensing elements. The most sensitive grating, which displayed an 86 pm wavelength change, was the one with the smaller diameter. According to the experiment results, magnetic fields less than 16 mT cause a reversible response.

According to Thakur et al. [81], a magnetic field sensor made of a photonic crystal fibre and a small quantity of Fe_3O_4 magnetic nano-fluid trapped in the cladding holes of a polarisation preserving photonic crystal fibre. They proved that magnetic fields with sensitivity as high as 242 pm/mT can be simply and very effectively detected.

Later, Zu et al. [82] proposed a magneto optic modulator with a magnetic fluid sheet put on a Sagnac fibre interferometer. The magnetic fluid displayed varied birefringence when the magnetic field was applied, this Faraday Effect resulted in changes in phase and polarisation state.

Zhao et al. [83] reported the use of hollow core photonic crystal fiber (HC PCF) in the fabrication of the cavity of the FP sensor, as shown in Figure 16, which exhibits low transmission losses and insensitivity to temperature variations. The core of the HC PCF was filled with magnetic fluid allowing this way its use as a magnetic sensor. The sensitivity achieved was 0.41 pm/(A/m).

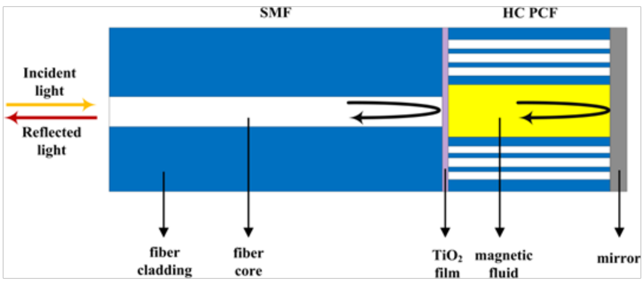

Figure16.Structure diagram of magnetic filled HCP-CFFP sensor proposed by Zhao et al.[83]

A brand-new magnetic field fibre sensor concept based on magnetic fluids was put out by Zu et al.[84] With a magnetic fluid sheet and a piece of polarization-maintaining fibre inserted in a fibre loop, the sensor was set up as a Sagnac interferometer. With a resolution of 47.7 A/m, the wavelength shift sensitivity to magnetic field was 0.21 pm/(A/m). The optical power also changed in response to the strength of the magnetic field, yielding a sensitivity of 5.02 103 dB/(A/m).

Hybrid Sensors

This kind of gadget aims to investigate the pairing of optical fibre sensors and traditional current transducers. The principal benefit is a significant reduction in the cost of the insulation required for a conventional current transducer because the insulation is provided by the fibre optic itself [1]. A typical electrical or electronic current sensor, a current transformer (such a Rogowski coil), or a photo-electronic device are the key components of hybrid sensing systems. These components are interrogated by an optical fibre system. The key component of this setup is an electro-optic converter, which converts optical modulation from electrical current modulation [1].

Numerous optical modulation approaches, including optical phase modulation [85], intensity modulation [86], frequency modulation [87], polarisation modulation [1], chromatic modulation [88], have been disclosed in recent years to modulate the sensor setups. Figure 17 depicts this type of sensor in an experimental arrangement.

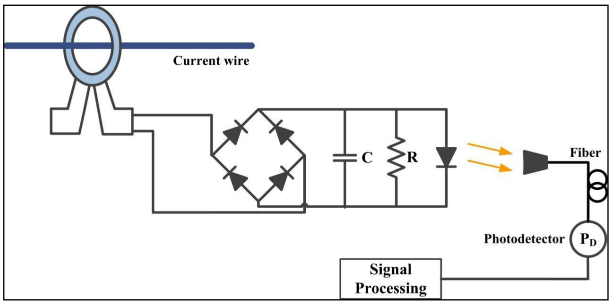

Figure 17.Typical setup of a hybrid sensor configuration

Commercially Available Prototypes

Commercial products for high voltage electrical current measuring based on optical systems are offered by a number of businesses. An optical fiber-based current sensor was created by the company AIRAK for monitoring medium voltage electrical distribution lines (Figure 18(a)). The sensor is incredibly compact (about 11" x 7" x 6.25" (28 cm x 18 cm x 16 cm)) and weighs only 1.25 lbs (0.57 kg). In terms of technical specifications, the sensor satisfies the IEEE 36 kV insulation class, has a resolution better than 0.5% f.s., operates between 5 Hz and 5 kHz, operates between 40 °C and +80 °C, has a full scale measurement range of 1 kA, 3 kA, or 15 kA. The PowerSense DISCOS outdoor current sensor has a dynamic range of 5 A to 20 kA with a measuring accuracy of 2%. It was designed for AC measurement on lines of up to 36 kV.

Companies like NxtPhase (formerly Alstom Grid) and ABB present comparable technologies to measure electrical current on electrical potentials up to 800 kV for higher voltage systems.

For metering applications, the sensor NXCT from NxtPhase (Figure 18(b)) performs better than IEC Class 0.2S and IEEE Class 0.3 accuracy (0.15%) with a dynamic range of 1 A to 4 kA. The sensor can accurately reproduce waveforms up to 6 kHz and monitor short-time current up to 63 kArms (about 1 s). Different sensor weights are provided, ranging from 108 lbs (49 kg) for 72.5 kV to 210 lbs (95 kg) for 800 kV. The sensor can function between 40 and +55 degrees Celsius.

For metering applications, the sensor MOCT from ABB (Figure 18(c)) also has an accuracy performance that exceeds IEC Class 0.2S and ANSI Class 0.15 s. Its dynamic range is 1 A to 4 kA. The technology is capable of reproducing waveforms accurately up to 100 kA. Additionally given are several sensor weights ranging from 110 lbs (50 kg) for 72.5 kV to 410 lbs (186 kg) for 800 kV.

Figure 18(d) also shows an optical current sensor made by SIEMENS, albeit there are no technical specifications available.

Figure 18. Commercially available prototypes for high voltage electrical current measuring based in optical systems: (a) AIRAK's Overhead Mountable Optical Current Sensor

(b) NxtPhase's NXCT Optical current sensor (c) ABB's MOCT (Magneto-Optical Current Transformer) (d) SIEMENS's Optical current sensor.

Conclusions

The state-of-the-art, including commercially available devices, was reviewed together withthe various configurations, physical principles, benefits, drawbacks of optical current sensors for high voltage current sensing applications.

Although linear birefringence can severely impair the sensor's performance, all-fiber sensors can readily achieve immunity from external currents and magnetic fields. It has been demonstrated that commercially available sensors can measure DC current up to 500 kA with 0.1% accuracy and AC current up to 63 kARMS with 0.1% precision.

Bulk magneto-optical sensors are more resistant to mechanical and thermal gradients, vibrations, othedisturbances than all-fiber sensors, while immunity to external currents and magnetic fields is more difficult to achieve. Additionally, they have greater Verdet constants and less linear birefringence, which enable high sensitivity over broad measurement ranges. Commercially available sensors that can detect AC current from 20 A to 20,000 A with a maximum error of 2% have been proven, as have sensors that can measure up to 720 kA.

The utilisation of magnetostrictive substances, such as Terfenol-D, connected to an FBG in an optical fibre can present an intriguing approach for magnetic force optical current sensors. A prototype was able to monitor current in the 100–1000 A range for a frequency signal at 60 Hz using this concept. Additionally, sensors that can gauge DC current have been developed.

In order to try to integrate the greatest qualities of both old-school technology and new-school (optical) technology, hybrid sensors can also be investigated. An optical fiber's insulation could lower the price of the insulation required for a typical current transducer.

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