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Fibre Optic Magnetic Field Sensors Utilizing Iron Garnet Materials

by

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Abstract

This thesis deals with the subject of fibre optic magnetic field sensors utilizing iron garnet materials. Such materials exhibit a large Faraday rotation which make them advantageous for application in compact magnetic field sensors.

After an introduction, in which fibre optic sensors and optical methods to measure electric current are reviewed, the original research work is summarized.

A system for the measurement of the magneto-optic properties of transparent materials is described. Measurement results, showing the influence of temperature, magnetic field direction and sample treatment on the magneto-optical properties of YIG-crystals, are presented. The properties of thin magneto-optical waveguiding films have also been studied using different light coupling methods. Measurement results obtained for holographic grating, prism and edge (end-fire) light coupling to different substituted YIG films are presented. It is shown that the launching method may affect the properties to be measured.

The design and performance of several versions of extrinsic guided wave fibre optic magnetic field sensors are then reported. The sensors employ substituted YIG (Yttrium Iron Garnet, $Y_3Fe_5O_{12}$) thin film waveguides as sensing elements. Polarization maintaining fibres were used as feed and return to provide two signal channels. The signals were combined in a balanced measurement system, providing insensitivity to both fluctuations in optical power and loss. Sensors have been made both with separate fibres to guide the light to and from the sensing element and with a single fibre for both functions. The two fibre version, although less ”elegant”, is found to have a better performance. This version also makes it possible to determine both the magnitude and sign of the magnetic field. Measurement results indicate a usable measurement range of at least several mT with a noise equivalent magnetic field level of less than 8 $nT/\sqrt{Hz}$.

The design and performance of multimode fibre optic magnetic field sensors utilizing the Faraday effect in an epitaxially grown thick (YbTbBi)IG film is also described. This type of sensor is found to be linear over a range from 27 mT to less than 270 nT. Sensor prototypes suitable for current monitoring in high voltage transmission lines have also been developed.

Descriptors

YIG, iron garnets, rare earth garnets, magneto-optics, optical waveguide, fibre optic sensors, magnetic field measurement, current measurement.

List of publications

This thesis is based on the work contained in the following papers:

A: U. Holm, H. Sohlström and T. Brogårdh, ”Measurement system for magneto-optic sensor materials”, *J. Phys. E: Sci. Instrum.*, vol. 17, p. 885–889, 1984.

B: U. Holm, H. Sohlström and T. Brogårdh, ”YIG-sensor design for fibre optical magnetic field measurement”, *OFS 84*, R. Th. Kersten and R. Kist, p. 333–336, VDE-Verlag, Berlin, 1984.

C: U. Holm and H. Sohlström, *Measurement of YIG crystal characteristics for the design of optical magnetic field sensors*, TR 84.01, Instrumentation Laboratory; Royal Institute of Technology, Stockholm, 1984.

D: H. Sohlström, U. Holm and K. Svantesson, ”A Polarization Based Fibre Optical Sensor System Using a YIG Optical Waveguide for Magnetic Field Sensing”, *Springer proceedings in Physics 44: Optical Fiber Sensors*, H. J. Arditty, J. P. Dakin, and R. Th. Kersten, p. 273–278, Springer-Verlag, Berlin, 1989.

E: H. Sohlström, U. Holm and K. G. Svantesson, ”Characterization of Magnetooptical Thin Films for Sensor Use”, *SPIE Proc Electro-Optic and Magneto-Optic Materials and Applications*, J. P. Castera, vol. 1126, p. 77–84, 1989.

F: K. Svantesson, H. Sohlström and U. Holm, ”Magneto-optical garnet materials in fibre optic sensor systems for magnetic field sensing”, *SPIE Proc Electro-Optic and Magneto-Optic Materials and Applications II*, H. Dammann, vol. 1274, p. 260–269, 1990.

G: H. Sohlström and K. Svantesson, ”A waveguide based fibre optic magnetic field sensor with directional sensitivity”, *SPIE Proc Fiber Optic Sensors: Engineering and Applications*, A. J. Bruinsma and B. Culshaw, vol. 1511, p. 142–148, 1991.

H: H. Sohlström and K. Svantesson, ”The performance of a fibre optic magnetic field sensor utilizing a magneto-optical garnet”, *Fiber and Integrated Optics*, vol. 11, p. 137–141, 1992, also presented at the OFS 8 conference in Monterey, Jan. 92.

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1. The aim and organization of the thesis

The industrial development has created a growing demand for new types of measurement and therefore new types of sensors, to enhance the quality of different processes. The physical environment for the sensors has, at the same time, become tougher and more electromagnetically polluted.

To overcome the electromagnetic pollution and also to achieve other advantages, there has, starting in the mid seventies, been a steadily growing interest in fibre optic sensors. Optical methods have long been used for measurement purposes, but the technological base developed for fibre optic communication applications has widened the scope considerably. Fibre optic remote sensing systems, providing immunity to electromagnetic interference, electrical isolation and a number of other advantages, could now be developed.

The measurement of magnetic field or current in electrical power systems are applications in which these advantages are very significant.

This thesis is to a large extent based on work made as part of the ”Single Mode Sensor Project” that was started in 1981 as a co-operative effort by the *Instrumentation Laboratory of the Royal Institute of Technology*, the *Institute of Microelectronics (IM)* and the *Institute of Optical Research (IOF).* The project was financed by the *National Swedish Board for Technical Development (STU).*

The aim of the project was to study the applicability of single mode optical fibre technology for sensor use. *ASEA AB* (now ABB), one of the proponents of the project, had at that time developed a number of multimode fibre optic sensors. Partly because of their interest the development of a magnetic field or electric current sensor was chosen as the working goal.

Most of the electric current sensors developed at that time utilized the Faraday effect in long lengths of fibre, coiled around the conductor. The difficulties encountered with such sensors led us to study sensors based on localized sensing elements made from materials having a large Faraday rotation, e. g. YIG ($Y_3Fe_5O_{12}$).

During the early stages of the project work, polarization maintaining fibres became available. We then recognized the possibility of a system in which polarisation maintaining fibres were used to carry the light to and from a sensing element in the form of a YIG waveguide.

Studies of multimode sensors using bulk YIG or thick films of substituted YIG , were also carried out. A number of such sensors were developed for different applications.

The aim of this thesis is to study the feasibility of magnetic field sensors based on iron garnet materials. As both single-mode and multimode sensors

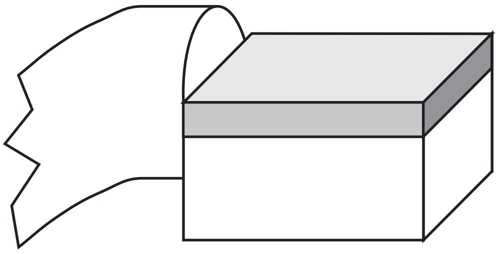

Fig. 1. A magnetic field sensor in the form of a waveguiding "chip" – the idea as envisioned during the initial stages of the project.

are treated, the thesis can also be said to form a comparison of the two types.

Measurement technology is an application oriented research area, and the stress in this thesis is on the sensor development and the material characterization. The papers on which the thesis is based describe different aspects of the sensor development work, from the initial ideas to working sensor prototypes. In this summary I will primarily motivate and discuss the work in order to give a context to the different papers. For this purpose the summary includes an introduction in which the theory is outlined and also some illustrative results, that were omitted in the papers due to the limitations of the conference contribution format. The introduction also contains an overview of fibre optic sensors and current measurement in general. In section 3, I then outline the sensor development and the role of the material characterization. The summary of my work is given in sections 4 and 5. At the end of each of these two sections references are given to the different papers. Finally, in the conclusion, I summarize and speculate somewhat about the implications of the results.

2. Introduction

Fibre optic sensors

Definitions

A *fibre optic sensor* consists of an optical sensing element which under the influence of the quantity to be measured modulates light, and optical fibres to guide the light to and from the sensing element. When also the sensing element consists of optical fibres, the sensor is *intrinsic*, and when the fibres are only utilized to guide the light to and from the sensing element, which is itself external to the fibre, the sensor is *extrinsic*. In literature, the term fibre optic sensor is sometimes reserved for the intrinsic sensors only.

This definition does not include pyrometers that use an optical fibre between the collecting optics and the detector. Formally it also excludes the pyrometric devices that measure the temperature of a metallic film on the fibre end and similar devices where the sensing element ”emits light”, although they are often considered to be fibre optic sensors.

Another class of sensors that should be mentioned in this context are the optically powered electronic sensors or *hybrid* sensors. As all their connections with the outside world are optical, they share many of the advantages of the fibre optic sensors, while at the same time they allow the use of established electronic sensing principles. They may also provide a way for conventional sensors to be integrated into optical sensor networks.

Historical notes

Optical measurement methods have long been used: optical telephone transmission was patented in 1880, and patents from 1927 (Marconi Co.) and 1934 (American Telephone & Telegraph Co.) [1] show the principles of optical fibres, wavelength multiplexing, etc. Without usable optical fibres and laser light sources, however, little progress was made. In the 1960’s the laser was invented and optical fibres became available, figure 2. The rapid development in the optical communications field has since then made optical and electro-optical components available at reasonable prices also for measurement applications.

In the first fibre optic sensors that were developed, bundles of optical fibres were used [2], but similar sensors with single fibres soon appeared [3]. During the early 70’s many of the commonly used sensing principles where developed [4,5,6,7,8]. Since then, the technological advances of the fibre optic communications research and development have immediately been taken advantage of in the sensor community.

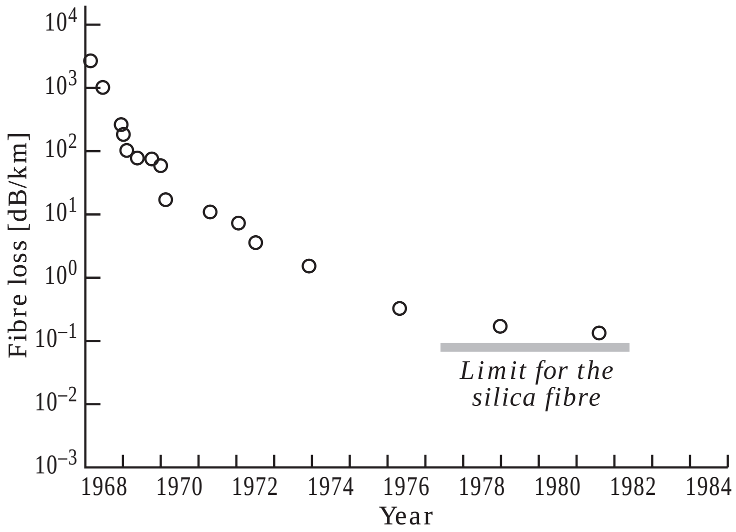

Fig. 2. The minimum losses of fibres developed for optical communications.

The truly unique features of the fibre optic sensors, their immunity to electromagnetic interference and their electrical isolation, were recognized from the very start, and scenarios from the seventies indicated a complete switch to optical measurement technologies. What was not, however, thoroughly recognized was that industry really needed reliable standardized equipment with proven performance, not laboratory prototypes. After a general disappointment at the end of the 80's, there is now in the 90's a renewed optimism, though on a more realistic scale, as the first industrial prototypes of fibre optic sensors are being introduced. One of the leading application areas for this is the electrical power industry, one of the areas where the original interest first stirred, indicating the important role of time and a pioneering application in the acceptance of new technologies.

Principles

Just as with the conventional electric sensors the number of combinations of measurement quantity, sensing principle and output parameter is large. The output parameter, the type of modulation that carries the information from the sensing element is a possible principle of classification.

The optical power or the *intensity* of the returned light is a fundamental parameter. In fact, intensity is the only quantity we can measure. All other quantities must in some way be converted to intensities at one or more detectors and possibly with a variation with time.

The use of the term *intensity* here is somewhat unclear. *Intensity* or *radiant intensity* is, according to international standards, defined as power per solid angle. Although this quantity is modulated when the total power is modulated, it would in principle be more correct to speak of *optical power* and *power modulation*. The use of the term *intensity* as a relative measure of power is, however, established in literature and will also be followed in this text.

In an extrinsic intensity sensor the modulation can take place in an optical system with moving parts [9], a piece of material with an environmentally dependent optical loss [10], etc. In an intrinsic sensor the modulation is caused by a variation in the optical properties of the fibre itself. Several loss mechanisms can be exploited, microbending [11,12], reflections from gratings in the fibre [13], temperature dependent scattering in the fibre [14], losses caused by dopants in the fibre and light decoupling from the fibre [15] are some examples.

Several of these are loss mechanisms that are always present in a fibre optic system. This indicates a major weakness of an intensity based sensor: there is in principle always a loss variation in the optical system and this could not directly be discriminated from variations in the measurand. Often however, some known properties of the measurand signal can be used to separate it from the loss variation.

To completely remove the uncertainty that is created by the loss variation, a system with a reference channel can be used. In such a system two light intensities are measured. If the relation between the influence of the loss and the influence of the measurand is different for the two channels, the influence of the loss can be removed. One realization of this is the *balanced* system in which the sum of the two detected intensities is affected by the system loss and the distribution between them only by the measurand. A similar approach is to use the intensity variations with time to achieve a system that is independent of the absolute intensity. The use of fluorescence decay for temperature sensing has been studied [16].

The *wavelength* of the light can be used to carry information in several ways. The sensing element can cause a wavelength dependent loss and transmit only certain wavelengths of those emitted from a broadband light source [17]. The sensing element can also receive light with one wavelength and emit light with another. The information can then lie in the spectral content of the emitted light [18], in which case it is a true wavelength modulation, or in the intensity of the converted light, in which case it is better described as an intensity based system, perhaps with a reference channel.

The *phase* of the light is used in the very sensitive interferometric sensors [19]. In such a sensor the free-path arms of a conventional interferometer are replaced by optical fibres that make the interferometer much more rugged and at the same time very sensitive to any change in the effective refractive indices or lengths of the fibres. The changes can for example be caused by an absolute rotation, making the device a rotation sensor; the environmental pressure, making it a very sensitive hydrophone or a magnetostrictive perturbation, making it a very sensitive magnetometer.

The *polarization state* of the light can also be utilized in the sensing element. The most usual examples of this are sensors using the Faraday effect, as will be further discussed below, but extrinsic electro-optic electric field sensors [20] and pressure sensors based on photoelastic effects in extrinsic sensors [21] or in fibres [22,23] can also be found in literature. The polarization state can, however, not be used as the information carrying parameter in the fibre.

Most of the sensors that use polarization modulation in the sensing element internally convert it to an intensity modulation. Alternatively, it could be converted to two different intensities creating a balanced system, cf. above. The use of a polarization maintaining optical fibre makes it possible to transmit these two channels in one fibre core.

Single-mode or multimode

Out of the above mentioned parameters, only the wavelength and the intensity can be maintained when the light propagates along a *multimode* fibre. The optical loss variation always present in a practical system, however, limits the applicability of intensity as the information carrier. The many different propagation modes allowed in the multimode fibre, give rise to a dispersion that destroys the phase information and causes a bandwidth limitation for the intensity information.

The core of a *single-mode* fibre is so thin, normally 5–10 µm, that only one mode is allowed. For monochromatic light it has no dispersion. The small dispersion associated with the spectral width of the light can, in many instances, be ignored. The phase information is retained in the single-mode fibre. The phase drift associated with changes of the optical length of the fibre must, however, be taken into account. The polarisation state cannot be maintained for any longer lengths of fibre because the almost perfect circular symmetry of the fibre makes the two orthogonal polarization modes degenerate, allowing the polarization state to change under the influence of the fibre birefringence.

The *polarization maintaining (p. preserving)* fibre is a special type of single-mode fibre with a core that is elliptical or has an anisotropic index of refraction. This removes the degeneracy of the fibre polarization modes, allowing them to exist independently of each other. Polarized light coupled into the fibre will, thus, be distributed into the two polarization modes and will then travel along the fibre without mode coupling. The polarization state is in fact *not* generally maintained as the phase relation between the two orthogonal components present at the input is lost due to the difference in propagation constant for the two modes. The intensity ratio between the light in the two modes is however maintained. Only for the special case where only one polarization mode is excited the fibre is really polarization maintaining.

Planar waveguides

Just as light can be guided in an optical fibre which is a circular waveguide, it can be guided in a planar waveguide. The simplest structure is the *planar slab guide*, figure 3, where a planar film of refractive index n_f is sandwiched between a *substrate* and a *cover* material with lower refractive indices ($n_f > n_s$, n_c). Often the cover material is air ($n_c=1$). In the slab guide there is no confinement of the light in the plane of the film.

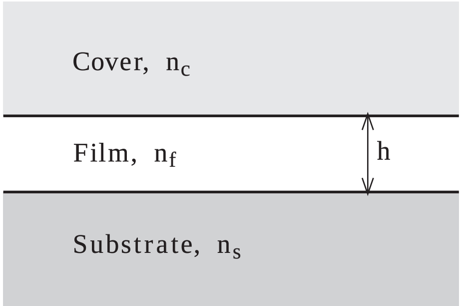

Fig. 3. The planar slab waveguide.

The light is guided in the same way as in an optical fibre, though confined only in one dimension. Just as with the fibre, there are single-mode and multimode guides. Some of the material combinations used for planar guides have much larger index differences than normally used in fibres. Because of this, waveguide thicknesses, h, of 1 μm or less are often necessary to achieve strict single-mode guiding.

In analyzing the guide one has to treat the case of *TE (Electric field transverse to the propagation direction) and TM (Magnetic field transverse to the propagation direction)* state of polarization separately. Due to the different phase shifts on total reflection, the propagation constants will be different for the two cases. For small index differences and with thick guides, the difference in propagation constant between the TE and the TM mode, $\Delta\beta$, is small,

$$\Delta\beta = \beta_{TE} - \beta_{TM}$$

In many practical cases however, the magnitude of $\Delta\beta$ is noticeable.

Below, I will describe how the Faraday effect in a planar waveguide can be treated as a coupling between the TE and TM modes of the same order. This coupling cannot effectively take place if the two modes do not run in synchronism, i. e. if $\Delta\beta$ is far from zero.

As in a slab waveguide there is no confinement of the light in the plane of the waveguide, one must use the planar equivalent of conventional ”bulk optical” methods to control the light in the transverse direction. The alternative is to confine the light in both dimensions with a *channel waveguide.*

Magnetic field measurement

Before dealing with the optical magnetic field measurement methods, a short description of magnetic field measurement in general is relevant.

Magnetic field measurements are not only made to measure the magnetic field itself, but also to provide indirect information about other quantities. Measurement of electric current, rotation speed measurement using a permanent magnet and a pick-up coil, acoustic pressure sensing using

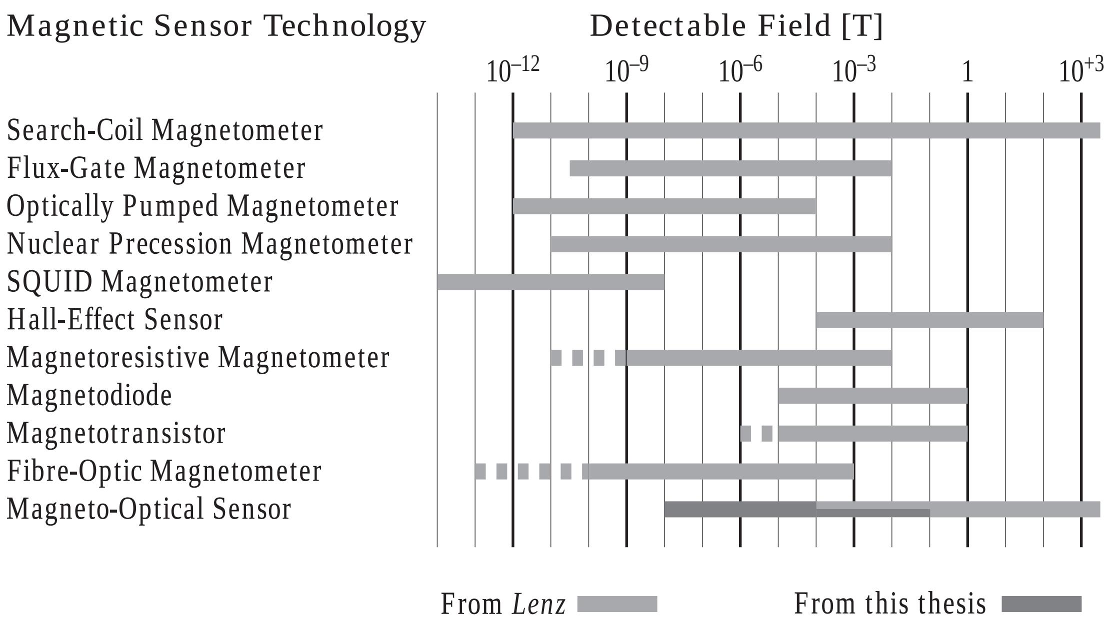

Fig. 4. Magnetic field sensor comparison, adapted from [26]. In addition to the data taken from the reference, the magnetic field range for the sensors demonstrated in this thesis is given.

dynamic microphones, and submarine detection using SQUID:s (Superconducting Quantum Interference Device) to detect perturbations of the earth's magnetic field are some examples. In addition to the large practical differences, the ranges of magnetic field encountered are very different. The measurement of electric current may involve fields exceeding 1 T, while submarine detection demands a noise level around 10^{-11} T [24,25]. The required bandwidths range from about 1 Hz for submarine detection to GHz for EMC measurements.

An overview of some different measurement technologies is given in figure 4. The magnetic field range for the fibre optic sensors demonstrated in this thesis is indicated in addition to the data from the reference. Evidently, sensors utilizing magneto-optical effects cover a large field range. Together with the ”Fibre-Optic Magnetometer”, they cover the entire range given in figure 4 except the very low fields that can only be detected by SQUID Magnetometers.

Measurement of electric current has been the main application considered in this work. It is, therefore, appropriate to widen the view and also have a brief look at current measurement in general.

Measurement of electric current

Current and perhaps voltage are the only quantities that can really be measured with conventional electrical methods. All other quantities are converted to a current or a voltage that can in turn be measured, e. g., by an indicating instrument. It may therefore seem somewhat surprising to find that there is a considerable interest in unconventional methods to measure current in high voltage power systems. A cause for this is that even though the measurement is in principle a simple one, it is in practice complicated for two reasons: the power dissipation in the measurement circuit and the need to keep the display unit at ground potential.

The conventional way to solve this is to use a *current transformer* that transforms the current down to a reasonable level and provides an isolation barrier between the primary winding at line potential and the secondary winding at ground potential. The size and cost of such a current transformer, however, increase with the line voltage. Also, current transformers can only be used for AC measurements. For DC measurements, more complex devices with Hall elements are often used.

The increasingly complex control systems used in the power transmission networks also creates a need for more points of measurement and a wider range of measurement situations. Current metering for billing purposes is usually done with equipment having an accuracy in the order of 0.2% and with a relatively low bandwidth, typically less than 1 kHz. For control and protection purposes, however, errors of 1% or even more are usually accepted. There is even a need for on/off devices that indicate the presence of current over a certain level.

Current transformers with optical downlinks as well as systems using the Faraday effect at microwave frequencies have been investigated [27] . In recent years the interest has, however, been focused on fibre optic systems.

Optical methods for magnetic field and electric current measurement

Two main methods

Most of the work that has been published on optical methods to measure magnetic fields concern either the *Faraday effect* or *magnetostrictive perturbation of optical fibres*. The Faraday effect, which is a change of the polarization state of propagating light under the influence of a magnetic field, is the phenomenon utilized in this work.

Before we further describe the Faraday effect, a short description of the other principle is appropriate. In contrast to the Faraday effect, which can be utilized in both bulk optical elements, planar waveguides and in fibres, the magnetostrictive principle requires the use of fibres. The magnetostrictive principle was first suggested in 1980 [28]. It uses a magnetostrictive material which is mechanically linked to the fibre, for example in the form of a magnetostrictive jacket on the fibre or a bulk magnetostrictive element onto which the fibre is wound. When subjected to a magnetic field the magnetostrictive element will change its form, thereby causing a strain and a change of the length of the fibre. This change of the optical length can be detected if the fibre is placed in one arm of a *Mach-Zehnder* interferometer.

The fibre can be long and as the phase sensitivity of the interferometer is high, this device can potentially be very sensitive [29]. However, it is unfortunately also sensitive to all other parameters that influence the optical length of the fibre, e. g. temperature [30]. Although the measurement of electric current was mentioned as a possible application [31], the driving force of the development was the potential possibility of detecting the small changes in the earth's magnetic field caused by passing submarines. At first nickel was used for the magnetostrictive element, and later *metallic glasses* [32,33]. Different biasing [34] and feedback [35,36] arrangements have been investigated.

Many of the problems with temperature and vibration sensitivity have been overcome with proper jacketing of the fibre and with the use of all fibre optical systems. This type of sensor offers extremely high sensitivity, with noise levels down to 10^{-15} $T/\sqrt{Hz}$ [37], but it is not suited for electric current measurement and other large-signal applications.

Other sensing principles that have been studied are: interferometric detection of the movement of a metal coated fibre in a magnetic field when a current is sent through the coating [38,39,40], surface plasmon resonance [41], liquid crystals [42] and resistor heating [43]. The use of a current transformer that is in turn interrogated by a fibre optic interferometer has also been tried [44].

In this context, the possibilities to use conventional current transformers together with an optical data link for current measurements in high voltage systems should be mentioned. The equipment at high potential could then be powered by pick-off from the power line [45], or be a hybrid sensor, optically powered through the fibre [46].

The Faraday effect

When a material exhibiting the *Faraday effect* is placed in a magnetic field and a beam of linearly polarized light is sent through it in the direction of the field, a rotation of the plane of polarization of the light will occur, figure 5.

The phenomenon was discovered in 1845 by Michael Faraday. Other names for the same effect are the *magneto-optical rotation (MOR), magnetic circular birefringence (MCB)* or the *magneto-optical effect*. The last term is, however, more general and may also include other effects.

The effect is non-reciprocal in nature. This means that when the direction of light propagation is reversed, the direction of rotation as seen from a fixed reference system, is not reversed. A light beam that passes twice through the medium in opposite directions will thus acquire a net rotation which is twice that of a single pass.

The Faraday rotation is proportional to the magnetization of the material,

$$\theta = \int_L k\mathbf{M}\cdot\mathbf{dl}$$

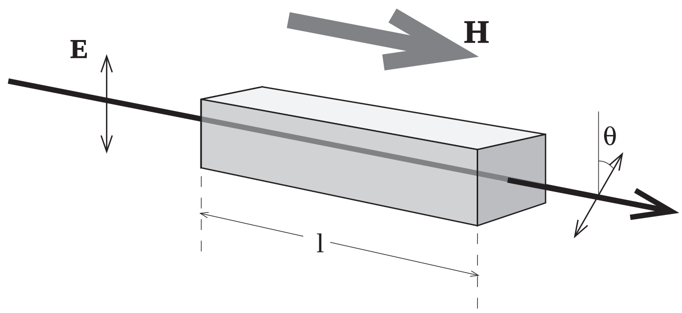

Fig. 5. The Faraday effect

where θ is the polarization rotation, **M** is the magnetization, L is the light path and k is a constant that is dependent on the material in question, the wavelength and the temperature. (Bold letters denote vector quantities.)

In paramagnetic and diamagnetic materials the magnetization and, thus, also the polarization rotation is practically proportional to the magnetic field strength, **H**. One can then describe the rotation in terms of the *Verdet constant, V*,

$$\theta = \int_L V \cdot \mathbf{H} \cdot \mathbf{dl} = \{\text{according to the geometry of figure 5}\} = V \cdot H \cdot l$$

where H is the component of the magnetic field strength parallel to the light propagation direction. (The Verdet constant is sometimes expressed in terms of the magnetic flux density, **B**, which for these materials is linearly related to the magnetic field strength, $\mathbf{B}=\mu\mathbf{H}$.)

In ferri- and ferro-magnetic materials the magnetization is not linearly related to the magnetic field strength, and a Verdet constant cannot be used.

In addition to the magnetic circular birefringence, a linear birefringence can be induced by a magnetization perpendicular to the light propagation direction. This is called *MLB (magnetic linear birefringence)*, *Voigt* or *Cotton-Mouton* effect, though the last name originally denoted a similar effect in fluids due to molecule orientation in the magnetic field. There may also be a magnetic field dependent difference in optical absorption between the linear or the circular polarization states, *MLD (magnetic linear dichroism)* and *MCD (magnetic circular dichroism)* [47,48]. One should, however, keep in mind that there seems to be a considerable confusion concerning the names for these effects in literature.

Besides magnetic field sensing, the main application of the Faraday effect is in isolators and circulators for microwave or optical frequencies though in these applications, the effect is used in a static rather than dynamic manner.

The isolator is a device that allows power to flow in one direction, while the other direction is blocked. The basic design consists of a polarizer followed by a 45° Faraday rotator and a second polarizer with its polarization direction 45° from that of the first one. The 45° angle, however, makes the basic isolator design unsuitable for optical waveguide implementation, and a number of variations of the principle have been tried [49].

A circulator is a similar device but with three ports, in which power incident on one port will emerge at the next port.

The origin of the Faraday effect

The Faraday effect arises from the interaction of the electron orbit and spin with a magnetic field. The electron orbit forms a magnetic dipole that tends to align in an applied constant field. As it, from a classical viewpoint, is a spinning particle, it will react to a perturbing momentum at right angles to the spin axis by *precessing* about the original spin axis, just as a spinning top would do. The electron spin behaves similarly, though this is not obvious from a classical viewpoint. The perturbing momentum can be caused by an electromagnetic wave of "optical" or microwave frequency. The closer this frequency is to the precessional frequency the more marked is the interaction. If they coincide there is a resonance, called paramagnetic resonance or ferromagnetic resonance, depending on the actual material properties.

Macroscopically, the precession has the effect of creating a magnetization at right angles to both the applied constant magnetic field and to the perturbation, cf. figure 6.

The magnetic susceptibility of the material will, under the influence of the steady magnetic field (in the z-direction), become a tensor with off-diagonal components of the form,

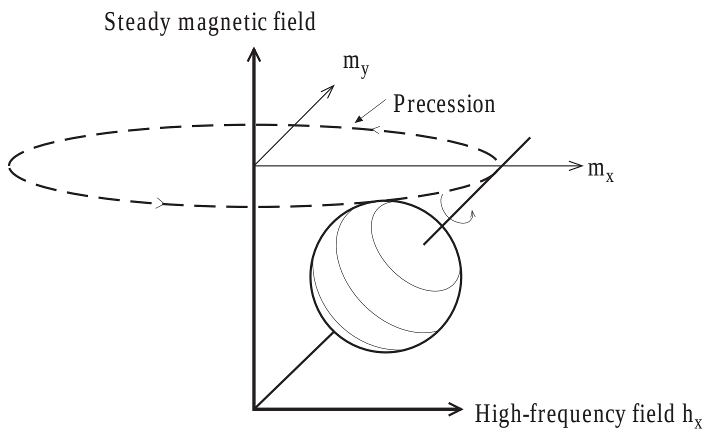

Fig. 6. Electron precession: The high-frequency field h_x creates magnetization both in the x- and the y-direction. After [50].

$$\chi_{yx} = -\,i\,\frac{\omega_M\,\omega}{\omega_0^2-\omega^2}$$

$$\chi_{xy} = +\,i\,\frac{\omega_M\,\omega}{\omega_0^2-\omega^2}$$

where ω is the angular frequency of the applied high-frequency field, ω_0 is the precession angular frequency and ω_M is a factor that depends on the material and the magnetization. The expressions become somewhat simpler if we consider instead the magnetic susceptibility for a left or right circularly polarized perturbing high frequency field,

$$\chi_R = \frac{\omega_M}{\omega_0-\omega}$$

$$\chi_L = \frac{\omega_M}{\omega_0+\omega}$$

$$\mu_R = \mu_0\left(1 + \frac{\omega_M}{\omega_0-\omega}\right)$$

$$\mu_L = \mu_0\left(1 + \frac{\omega_M}{\omega_0+\omega}\right)$$

In these expressions we recognize the resonances discussed above. If loss terms are included, the resonances will be damped and the permeabilities will have imaginary parts, causing loss and dichroism.

The strong interaction between neighbouring atoms in ferri- and ferromagnetic materials causes these materials to have several resonances at different frequencies and with different strengths, creating rather complicated frequency (wavelength) dependencies for both the real and the imaginary terms.

Light propagation in magneto-optical materials

To understand how the Faraday effect influences the light propagation, the wave equation is a suitable starting point. For an infinite medium with no external electrical polarization, the wave equation can be written,

$$\nabla^2\mathbf{E}(\mathbf{r},\,t) = \mu\varepsilon\frac{\partial^2\mathbf{E}(\mathbf{r},\,t)}{\partial t^2}$$

The solution to this is a plane wave with the phase velocity given by,

$$u = \frac{1}{\sqrt{\mu\varepsilon}}$$

Waves with different circular polarization states will have different μ:s, and thus travel with different speeds.

A linearly polarized wave can be seen as the sum of two circularly polarized waves with equal amplitude but opposite directions of rotation. As these two waves propagate with different speeds, they will acquire a phase difference proportional to the travelled distance. In terms of their sum, the phase difference has the effect of rotating the linear state of polarization by an angle which is equal to half the phase change.

If we want to study the influence of the Faraday effect on the light propagation in a waveguide with different propagation constants for the TE and TM modes, this simple reasoning is not applicable. Instead one can use the *coupled-mode formalism* [51]. In this formalism one studies how a small perturbation causes a coupling between the orthogonal eigenmodes of the unperturbed medium. In the literature this perturbation is normally in the electrical permittivity ε, causing an electric polarization **P**. As only the product of μ and ε appear in the wave equation, the Faraday effect can be treated as a perturbation in ε of the following form,

$$\Delta\varepsilon = \begin{bmatrix} 0 & -i\delta & 0 \\ i\delta & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \cdot \varepsilon_0$$

$$\delta = \frac{\omega\omega_M}{\omega_0^2 - \omega^2}$$

With this approach, one finds for the case with only one of the modes exited, that the power in the other mode can be represented by,

$$F = \frac{1}{\left(1 + \left(\frac{\Delta\beta}{2\theta}\right)^2\right)} \sin^2\left[\sqrt{\theta^2 + \left(\frac{\Delta\beta}{2}\right)^2} \cdot z\right]$$

where $\Delta\beta$ is the difference between the propagation constants of the two modes, θ is the polarization rotation per unit length in a homogeneous medium, and z is the distance along the propagation direction. If $\Delta\beta=0$ this simplifies to,

$$F = \sin^2 (\theta \cdot z)$$

From the above, it is evident that $\Delta\beta$ should be smaller than θ if any appreciable amount of power is to be coupled between the modes.

Electric current sensing using the Faraday effect

Glass sensing elements

The first optical current transducers utilizing the Faraday effect used bulk optical glass elements interrogated by an open path light beam, figure 7.

Using two detectors, and a polarization separating prism, a system which is not affected by variations in the optical loss, can be achieved, figure 8 [52].

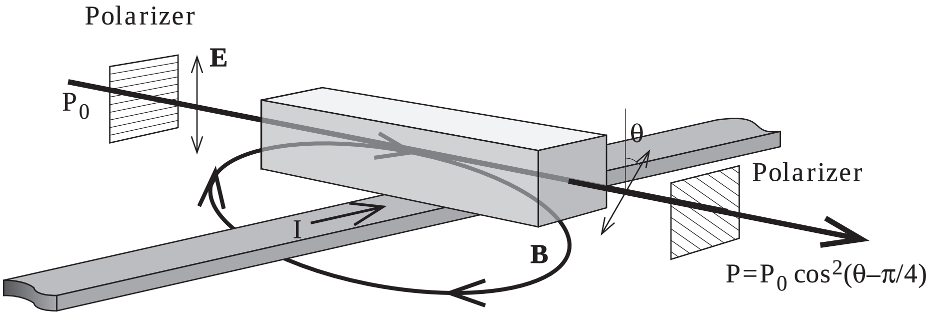

Fig. 7. The simplest form of an optical current sensor utilizing the Faraday effect.

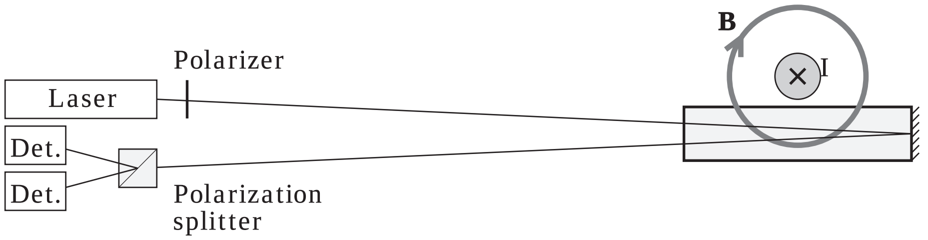

Fig. 8. A bulk optic current measurement system with polarization state detection. As the Faraday effect is non-reciprocal the two-way pass through the sensing element effectively doubles the rotation.

The sensor is sensitive to the total magnetic field, thus, also to the contributions from other conductors nearby. Also, the distance between the conductor and the sensing element will influence the scale factor. With two sensing elements, one on each side of the conductor, a differential system is achieved, reducing the influence from conductors at large distances. [53]

An *iron core* reduces the position dependence and the influence of external fields, but as the iron core must have a relatively large gap to accommodate the glass sensing element, some sensitivity to the conductor position and to external fields will remain.

A more fundamental approach is to use a basic property of the magnetic field encircling the conductor,

$$\oint_L \mathbf{H}\cdot\mathbf{dl} = \iint_S \mathbf{i}\cdot\mathbf{ds} = I$$

where **i** is the current density through the surface S, with the contour L, and I is the total current through S.

This means that if the sensing light path completely encircles the conductor, fig 9, the sensor becomes insensitive to external fields and independent of the conductor position in the sensing element. This can be approximated with a bulk sensing element with a central hole for the conductor or sensing element assembled from several pieces of glass. The reflections at the corners must be suitably arranged not to influence the polarization state of the light. [54]

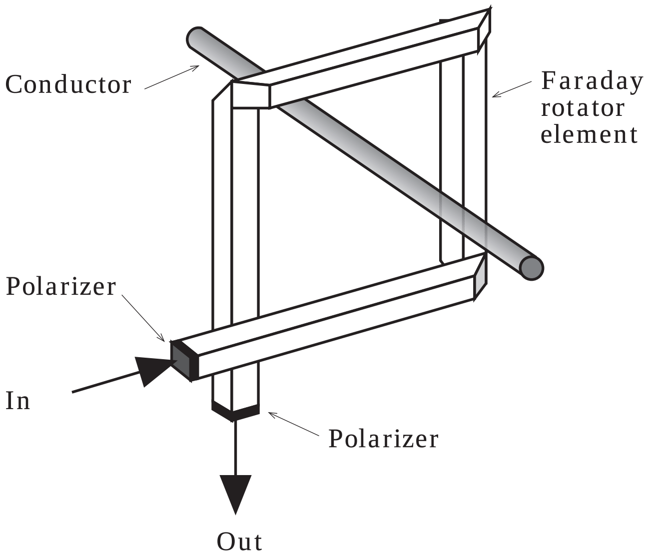

Fig. 9. A glass sensing element that encircles the conductor, after [55]

The early experiments were made with glass sensing elements having relatively small Verdet constants, typically about 10^{-5} rad/A, requiring long sensing elements for good sensitivity. Although YIG ($Y_3Fe_5O_{12}$) and other materials with much larger polarization rotation were studied [56], no transducers using such materials were presented. Multiple reflections were, however, tried to reduce the physical size of the sensing element without sacrificing optical path length [57,58].

Devices to measure both the current and the voltage simultaneously were also presented. [59,60]

With optical fibres many of the problems associated with the open optical path could be eliminated [61]. The possibilities with optical fibres, however, go further than that. The sensing element can be made from an optical fibre. Although the Verdet constant of the fibre material is not high, about $4 \cdot 10^{-6}$ rad/A, a measurable rotation can be achieved with a long fibre, and with the fibre wound round the conductor, a good approximation of the closed line integral of the field is achieved.

There was a considerable interest in this type of device at the end of the 70's and the results were promising [62]. The bending of the fibre in the coil, however, causes a temperature dependent linear birefringence that quenches the circular birefringence caused by the Faraday effect. Several methods have been tried to overcome this problem.

If the fibre is twisted, a circular birefringence ”bias” is introduced, which is magnetic field independent and large enough to quench the linear birefringence. This bias birefringence is, however, temperature dependent [63]. With the sensing fibre divided into sections with opposite twists, the bias rotation and the temperature dependence can be cancelled and with the use of polarization maintaining fibre for the downlead, the vibration sensitivity is reduced [64]. A similar approach is to use a fibre with a strong birefringence which is almost circular [65]. This circular birefringence is strongly temperature dependent. Techniques to compensate for this have, however, been studied [66].

The fibre can be wound into a coil in such a way that the beat length (the fibre length that causes a phase difference of 2π between the two orthogonal linear polarization modes) is equal to the circumference of the fibre coil. When an external field is then applied to the fibre coil, the periodic magnetic field that is in this way applied to the fibre will cause a net polarization rotation. [67,68,69]. A principally similar scheme is to use a polarization maintaining fibre with a very short beat length and arrange a periodic magnetic field with the same period [70].

A more fundamental approach is to anneal the coiled fibre to remove the temperature dependent linear birefringence [71].

Also, the Faraday effect is temperature dependent. The use of a temperature dependent linearly birefringent optical element has been suggested as a way to introduce a temperature dependent partial quenching of the Faraday effect, thereby reducing the effective temperature dependence [72].

In addition to the simple polarization detection system described above, a number of interferometric systems to detect the polarization rotation has been presented [73]. Closed-loop systems [74] and heterodyne detection systems [75] have been studied. A system for simultaneous measurement of two currents has also been presented [76]. To eliminate the influence of reciprocal effects in the fibre, some of these systems utilize *Sagnac* interferometers [77,78]. The non-reciprocity of the Faraday effect also makes it possible to use a *Fabry-Perot* resonator to increase the effective polarization rotation [79].

Experiments with techniques to make the sensor output independent of variations in the Verdet constant [80], or to convert the polarization rotation to a spectral modulation [81], have been made.

The *measurement bandwidth* of Faraday sensors with bulk glass or fibre coil sensing elements is limited by the transit time of the light in the sensing element [82],

$$B_{3\ dB} = \frac{0.44}{\tau} = 0.44 \cdot \frac{c}{n} \cdot \frac{1}{2\pi r} \cdot \frac{1}{N}$$

where c/n is the speed of light in the fibre, N the number of turns in the fibre coil and r is the radius of the fibre coil. With N=100, r=0.1 and n=1.5 a bandwidth of 1.4 MHz is achieved. Obviously, there is a trade-off between sensitivity and bandwidth. With high pulsed currents the sensing element can be made short, giving very large bandwidths. A number of systems with bulk glass [83] or fibre sensing elements [84,85] for measurement of transient currents in the 10^6 A range have been presented. Other specialized applications such as aerospace [86] current measuring and space plasma current measurements [87] have been studied. There is also a potential for distributed magnetic field sensing [88].

Although the use of an optical fibre coil for current measurements may in principle seem straightforward, the practical application of the technology is, however, complicated by the linear birefringence of the fibre and many optical current metering devices that are installed in the high voltage power lines are of the bulk optical type [89,90].

Other materials

Optical fibres with high Verdet constants may increase the applicability of current sensing using fibre sensing elements. Terbium doped silica fibre [91], with a Verdet constant of $1.2 \cdot 10^{-5}$ rad/A, and doped plastic fibre [92], with a Verdet constant of $2 \cdot 10^{-5}$ rad/A, have been developed.

The alternative solution is to use a compact sensing element made from a material with a Faraday rotation larger than that of the glasses. A small sensor head is an advantage in many applications, including current measurement using an iron core.

BGO ($Bi_{12}GeO_{20}$) [93], BSO ($Bi_{12}SiO_{20}$) [94,95] and ZnSe [96] offer Verdet constants of about $7 \cdot 10^{-5}$ rad/A, which is about an order of magnitude higher than that of the silica fibre material. Certain glasses also have Verdet constants that are almost as high. A considerably higher Verdet constant, about $2 \cdot 10^{-3}$ rad/A, is achieved with $Cd_{1-x}Mn_xTe$ [97,98,99,100,101,102].

YIG and substituted YIG offer polarization rotations which, for many applications, is larger than that of $Cd_{1-x}Mn_xTe$ by about an order of magnitude. As YIG is a ferrimagnetic material, it can, however, not be directly compared to the paramagnetic and diamagnetic materials mentioned. Since YIG is the material chosen in this work, it will be further described below.

YIG

YIG, *Yttrium iron garnet* is a *ferrimagnetic* garnet crystal with the composition $Y_3Fe_5O_{12}$. It is transparent for light with a wavelength longer than about 1.1 µm. At 1.3 µm and 1.5 µm, wavelengths at which reliable light sources and detectors are readily available, the optical loss is very low. YIG has a substantial Faraday rotation in large parts of the optical and microwave spectrum. Crystals of optical quality can be grown from flux melts or grown epitaxially on substrates. Epitaxially grown films can be used as high quality optical waveguides exhibiting the Faraday effect [103]. YIG crystal material, often in the form of polished spheres, are used in microwave components.

The crystal lattice of YIG is rhombohedral, almost cubic, with the iron atoms occupying two different kinds of sites in the lattice, figure 10. For this reason the formula is sometimes written $Y_3^{3+}Fe_2^{3+}Fe_3^{3+}O_{12}^{2-}$.

The magnetic properties of the crystal are mainly determined by the iron atoms. The iron atoms in the two kinds of sites interact antiferromagnetically with each other, giving a net magnetic moment equal to that of one atom. The Yttrium is magnetically polarized by the field from the iron atoms, but it has little influence on the strength of the magnetic interaction.

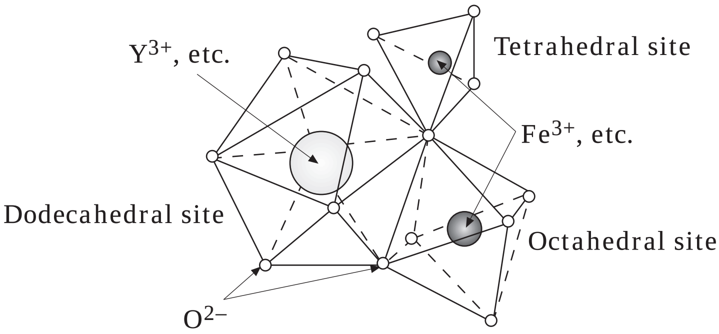

Fig. 10. The different kinds of atomic sites in YIG, after [106].

This is evident from the fact that all *rare-earth iron garnets* (RIG, $R_3Fe_5O_{12}$ where R is a rare earth) have a Curie temperature of about 550 K [104]. The Curie temperature is the temperature at which the thermal agitation breaks down the magnetic ordering of the atoms and the material ceases to be ferromagnetic. The Curie temperature can therefore be used as a measure of the strength of the magnetic interaction. The Curie temperature for pure YIG is 559 K [105]. The net magnetic moment for the rare earth garnets is, however, influenced by the rare earth, in several cases giving *compensation points*, where the temperature dependent magnetic moments of the different kinds of atoms cancel each other at a specific temperature, figure 11. YIG, however, does not have any compensation point.

It is possible to substitute part of the yttrium with other rare earths, giving mixed rare earth garnets. Also, other substitutions can be made, but this normally has little effect on the magnetic interaction. Bismuth substitution is an exception as it increases the strength of the magnetic interaction, thereby increasing the Curie temperature.

If the iron is substituted, the magnetic interaction is weakened, giving a lower Curie temperature.

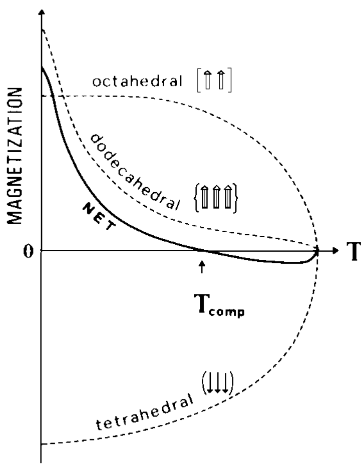

Fig. 11. Qualitative behaviour of the different contributions to the net magnetization of rare earth garnets having a compensation point. From [107].

The *lattice constant* of pure YIG is such that it can be epitaxially grown on substrates of GGG, Gadolinium gallium garnet ($Gd_3Ga_5O_{12}$). Such substrates of high quality are readily available. For substituted films, the substitutions of the film and substrate must be combined to give the proper lattice constants.

The *magnetic anisotropy* in pure YIG is mainly cubic and not so strong. Strain, however, strongly affects the magnetic anisotropy [108]. Epitaxially grown YIG films can, therefore, have easy directions of magnetization in the plane of the film, or perpendicularly to it, depending on the film strain caused by the lattice mismatch. In addition to the strain anisotropy, there can also be a growth-induced anisotropy, arising from a certain ordering of the magnetic ions in the growth process.

Because of the ferrimagnetic properties of the material, volumes of equal direction of magnetization, so called *magnetic domains* will form. The domains are separated by thin *Bloch walls* where the magnetization direction is changed. The domain size is determined by a magnetostatic energy balance that depends on the material properties and the sample geometry.

With thin bulk samples and epitaxially grown films with suitable anisotropy, the domains can form two-dimensional patterns extending through the entire thickness of the film, figure 12. Under certain conditions this pattern degenerates to small circular domains, *bubbles*. These bubbles can be moved around in the film, created and annihilated by small perturbations in the field. This is the phenomenon that was used in the bubble memories, in which more than 1 Mbit of information could be stored in the form of a bubble pattern in 1 cm^2 of iron garnet film [109].

For a large sample with many domains, the actual form of the individual domains and their movement when an external field is applied seems to be stochastic. For the entire sample or a large part of the sample the behaviour of the domains, however, averages out and the net magnetization reflects the variations in the applied magnetic field. There is however a tendency for the domain walls to stick to imperfections in the material, such as lattice dislocations, causing discontinuities in the magnetization change.

The direction of magnetization of the individual domains will also change

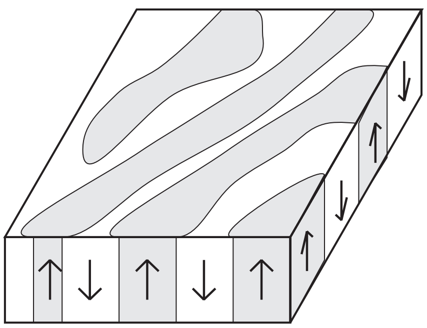

Fig. 12. Two-dimensional domain pattern in thin sample with an out of plane anisotropy.

under the influence of an applied field. The magnetic anisotropy will, however, keep the magnetization approximately along the easy directions. When the net magnetization of the sample cannot be adjusted to the external field through redistribution of the domains between the easy directions only, a rotation of the magnetization direction within the domains will occur. For a very strong applied field, the magnetization will be completely aligned with the field.

The rapidity with which the magnetization of the material can be changed is limited by the dynamic properties of the domain wall movements. This gives an upper frequency limit somewhere in the 10 MHz to GHz range [110]. Very little work has however been done in measuring the frequency response of YIG material based devices [111].

The contribution to the magneto-optical rotation per unit length from the different atoms can be described by a formula from [112],

$$\theta = (A_m+A_e)M_{Fe}^{o}+(B_m+B_e)M_{Fe}^{t}+(C_m+C_e)M_R$$

The indices ”m” and ”e” indicate contributions from different kinds of resonances and the superscripts ”o” and ”t” indicate octahedric and tetrahedric positions for the iron atoms. Apparently, the contributions from the iron atoms in the two kinds of sites are different. In the reference, $A_e/B_e=1.72$ is given.

The magneto-optical rotation increases with decreasing wavelength from 3 µm to 0.5 µm [113]. At 1.15 µm, the saturation rotation is about 200°/cm ($3.5\cdot10^2$ rad/m) for pure YIG. Bismuth substitution can increase this value by a factor of more than 10 depending on the composition; 7400°/cm ($13\cdot10^3$ rad/m) has been reported at 1.15 µm [114]. The magneto-optical rotation is temperature dependent, but it has been shown that substitutions can reduce this dependence substantially [115,116].

It is important to remember that the magneto-optical rotation of ferrimagnetic materials, just as the magnetization, microscopically always has the saturation value. When measurements show other values, it is either because the magnetization is not parallel to the measuring light beam or because the light path goes through several domains with different magnetization directions.

The rare earth garnets also possess a magnetic linear birefringence in the order of 100°/cm ($1.7\cdot10^2$ rad/m) [117,118]. For bismuth substituted YIG, literature data also indicate a magnitude which is about half that of the magneto-optical rotation [119].

The index of refraction for pure YIG is 2.15. As the index for GGG is 1.95, a YIG film on a GGG substrate can form a high quality optical waveguide.

Using ion beam etching, or wet etching and multilayer growth, it is possible to make *strip* or *channel* waveguides in YIG film [120]. The technologies used to define the channel are, however, not so well developed. Furthermore, all changes made in the magneto-optical film will change not only the optical properties, but also the magnetic properties such as the anisotropy, etc.

3. Starting points for the sensor development work

A conclusion from the above description of YIG and other rare earth garnets is that they, compared to other magneto-optical materials, have many favourable features such as a large magneto-optic rotation, well-defined magnetic properties and good optical quality in the near IR. Furthermore, particularly with the epitaxially grown films, many of these properties can be altered at will through a number of substitutions. Unfortunately however, some of the properties are interlinked, mainly through the mechanical strain, in such a way that they cannot easily be independently optimized. We have, therefore, not considered it fruitful to design any devices based on a ”perfect” magneto-optical material that has not yet been developed. Instead, our approach has been to find device structures that are useful for a *demonstration* with existing materials or with relatively simple modifications of known compositions. For similar reasons, no experiments have specifically been made to measure the bandwidths of the experimental sensors. No evidence of bandwidth limitations has, however, been found in measurements of magnetic fields at frequencies up to about 1 MHz.

The most striking feature of this type of material for sensors, is the large Faraday rotation. To achieve a polarization rotation of 90° (or a complete TE to TM conversion in the waveguide case) at 1.3 μm, from less than 1 mm to about 6 mm of optical path length is needed, depending on the material in question. The volume of the sensing element can, thus, be made very small, in the order of 1 mm^3. With a sensing volume of this size, the spatial variations of the magnetic field can be resolved. This is in contrast to the sensors using glass sensing elements. They often require a large sensing element and/or a closed measurement path.

In the design of a measurement system that utilizes a YIG or substituted YIG sensing element either in the form of a bulk crystal or a waveguide, there are a number of system design options. To be able to choose between these, we had to acquire a thorough knowledge of the properties of the material. As the available literature data, relevant for this application, were insufficient, this knowledge had to be gained through measurements.

For the single mode sensors we have, in order to avoid alignment problems, decided to work with waveguiding sensing elements only. The relatively large index difference between GGG and YIG, however, poses some problems. Guides that are single mode in the near infrared region are very thin, less than 1 μm. A slab guide of this kind will have a large linear birefringence that prevents the TM–TE conversion.

A number of techniques have been used to solve this problem. Multilayer structures with a layer between the GGG and the iron garnet film have been investigated [121]. A magnetic field that shifts its direction with a period that is equal to the beat length between the TE and TM modes can also be used. In this way, a net conversion can be obtained even with a relatively large $\Delta\beta$ [122].

At an early stage of our project a periodic cover structure in GGG on top of the YIG waveguide was suggested as a means to achieve a net conversion with a single mode YIG waveguide [123].

We have, however, used another approach. Because of the high optical quality of the YIG waveguides, the coupling between the different modes in a multimode guide is negligible for the propagation distances in question. As it is also possible to achieve a fibre to waveguide coupling that only excites the fundamental mode of the waveguide, a relatively thick guide can effectively be used for single mode use [124]. For the fundamental mode, this kind of guide has a relatively small $\Delta\beta$ that can be cancelled by a moderate strain-induced $\Delta\beta$ introduced during the film growth [125]. The magnetic properties of the film are also influenced by the strain necessary to achieve a small net $\Delta\beta$ but it is possible to achieve a usable device with this approach.

Some of the critical design decisions then were:

- To use or not to use a magnetic bias field.
- One fibre for sending light to the sensing element and for receiving the signal, or separate fibres for the two functions.
- The selection of a suitable optical configuration that allows a measurable polarization modulation and an acceptable optical loss. A channel waveguide structure or a slab guide combined with some other means of controlling the light propagation are two of the options for this purpose.

The available selection of film types for waveguiding sensors was quite small. The YIG films were originally developed for bubble memory use and have later been modified for use in display units, printers [126,127], waveguiding optical isolators [128] and sensors.

For the multimode sensors, which are of a more immediate interest from the application point of view, a design which is suitable for production must be selected.

In the multimode case a larger selection of useful materials was available. The bulk YIG material that we initially used for the multimode sensors was originally produced for microwave applications and had to be cut and polished to optical quality. Later when the thick (≈100 μm) epitaxially grown films with large magneto-optical rotation were developed, mainly for optical isolator use, we could use this type of material for the multimode sensors.

As the material characterization measurements went on, we were gradually able to transform the original sensor ideas envisioned at the start of the project, into practical sensor designs. In reality, of course, the influence also went the other way: The sensor design ideas made further measurements necessary. Below, however, the material characterization measurements and the sensor prototype experiments are presented in separate sections.

4. Material characterization measurements

Bulk materials

Measurement options

The magnetic and magneto-optical measurements that can be made on bulk YIG crystals can be divided into two categories, those made on *homogeneously magnetically saturated* samples and those made on *non-saturated* samples. Microscopically, the saturated state is the only one that exists and macroscopically, it is the only well-defined state. Examples of phenomena that are studied are the influence of material composition, temperature, wavelength, etc. on the saturation rotation. Such measurements are of interest not only from an application point of view, but also for material science, as they provide information about the nature of the magnetic interactions. Results from these types of measurements are, however, relatively well covered in literature, and will not be further described here.

For sensor applications, the properties of YIG also at low applied fields are of interest. These include the domain structure and how it is influenced by the crystal orientation, sample geometry, sample treatment and temperature.

Some measurements such as the measurement of the net magnetization of the sample and its dependence on external factors, can be made using magnetic methods [129]. Most of these results can, however, also be indirectly obtained from magneto-optical measurements and as our main interest is in the magneto-optical properties, this is the approach we have taken. The optical methods also facilitate changes of the measurement volume, which is a key measurement parameter.

If the sample is thin and the domains are large enough, a *focused light beam*, figure 13 a, allows the behaviour of a single domain or domain wall to be studied. Ideally, with a beam passing through only one domain, one should obtain the same results as those obtained for a homogeneously saturated material. One can then study changes in the domain magnetization direction and the effect on the magnetization and magneto-optical rotation caused by, for example, temperature.

With a *large diameter beam*, figure 13 b, the contributions from the different domains will be averaged. The exact nature of the averaging process is rather complicated as the pattern of the domains will act as a phase grating. For a thin sample with a two-dimensional domain pattern as in figure 13, the resulting polarization rotation can often be approximated using the area ratio between the two kinds of domains.

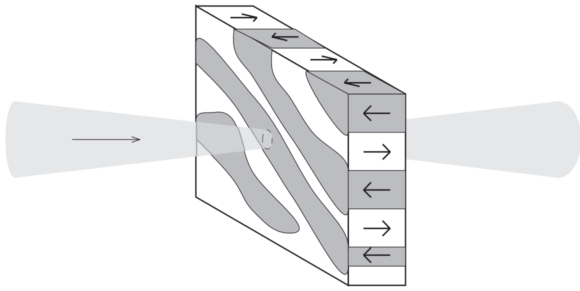

Fig. 13 a. Small measurement volume.

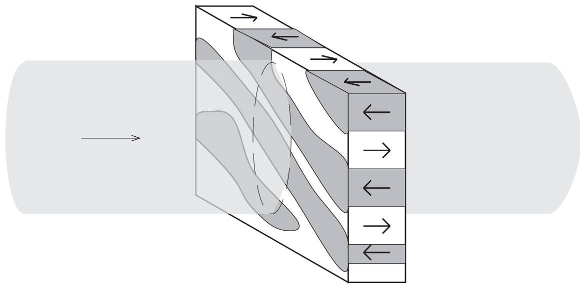

Fig. 13 b. Large measurement volume.

Measurement set-up

To study the magneto-optical properties of bulk materials, a measurement system according to the principle shown in figure 14 has been used. Linearly polarized light is sent through the measurement object. The beam transmitted by the measurement object has its plane of polarisation rotated by an angle θ. In a polarization splitting Wollaston prism, the beam is split into two orthogonal polarization components with the intensities I_1 and I_2. From these two values, and the input intensity I_0, the polarization rotation and the optical loss of the material can be calculated.

Other polarization detection principles such as the use of polarization modulation or rotating analysers are also possible [130]. The simple two-detector system was chosen mainly because it was also adaptable for evaluation of sensor prototypes.

The holder for the measurement object was temperature controlled and surrounded by coils allowing a magnetic field of arbitrary direction to be

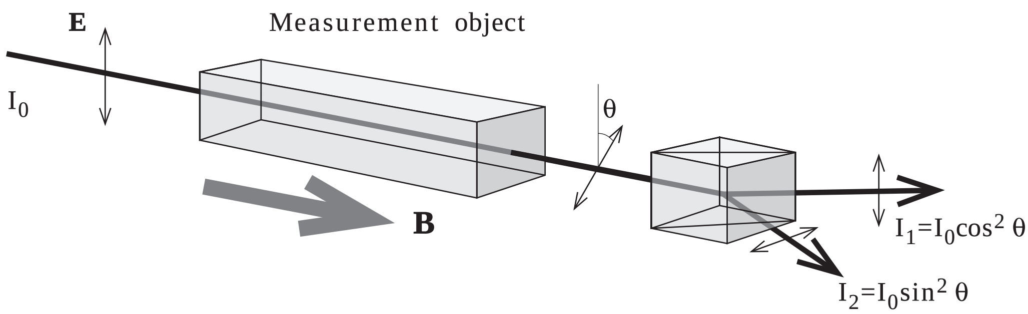

Fig. 14. Measurement system principle.

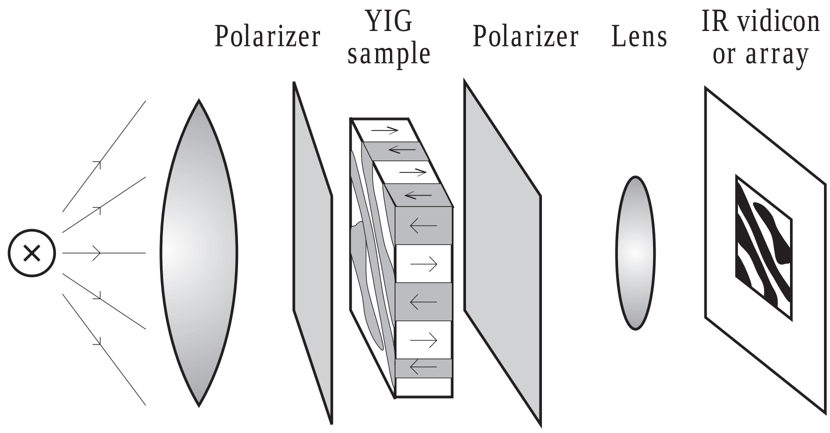

Fig. 15. Domain visualizing set-up.

generated. To allow automatic calibration and measurement routines, the system was designed with computerized control and data acquisition.

For a qualitative display of domain patterns, a set-up according to figure 15 was used.

Measurement results

Large measurement volume

Our first measurements of the magneto-optical rotation versus the applied field were made with a 200 µm diameter light beam through a cube 2×2×2 mm of YIG, figure 16. This rather discouraging result was, however soon supplemented with other results indicating that a larger light beam diameter and sample annealing improved the results, cf. the prototype sensor results below.

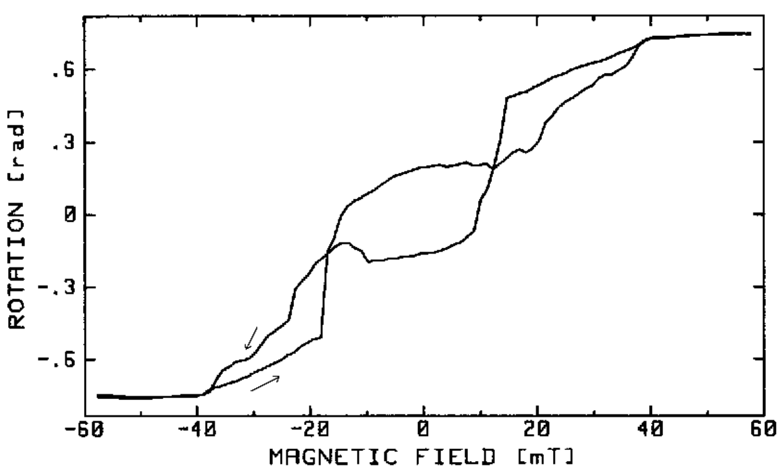

Fig. 16. Magneto-optical rotation versus the applied magnetic field for a 2×2×2 mm YIG cube as measured with a 200 µm diameter light beam with λ=1.15 µm.

We also found that a thinner sample with a two-dimensional domain structure gave a more reproducible result, though at the cost of a lower rotation, about 5° for a single pass through a 0.3 mm YIG slice.

Later, however, epitaxially grown Bi-substituted thick YIG films giving 22.5° rotation in a 0.13 mm film became available. The domains in this type of film are also smaller, giving a more efficient averaging effect. The well-controlled growth conditions for these films should also give a smaller number of defects which should allow the domain walls to move more freely.

Small measurement volume

When a 0.13 mm thick (YbTbBi)IG film on a GGG substrate is observed in the IR through suitably arranged polarizers in a set-up according to figure 15, a two-dimensional domain pattern is observed. The average domain width is in the order of 12 µm. The application of an external magnetic field changes the area ratio between the two kinds of domains, figure 17a,b. At high field levels, close to saturation, the majority of the small domains disappear, leaving a pattern with a lower spatial periodicity, figure 17c. For this specific material, the remaining domains shrink to bubble-like form just before saturation, figure 17d.

When measurements on materials of this kind are to be interpreted, one should remember that the periodic domain structure will work as a phase grating for the light component with a polarization state that is perpendicular to that of the input beam. Fig 17e,f,g show examples of diffraction patterns obtained with the (YbTbBi)IG film for similar conditions as those used for 17a,c,d. The diffraction patterns have been recorded with a set-up similar to the one in figure 15, though with the camera focused on infinity, i.e. the light source. The second polarizer is set to block the central beam when no field is applied. The central beam is, however, not completely extinguished in 17e. With field applied, the central beam will have its polarisation rotated, and it will thus pass the second polarizer and saturate the CCD array. The polarization of the diffracted light is always perpendicular to that of the input beam.

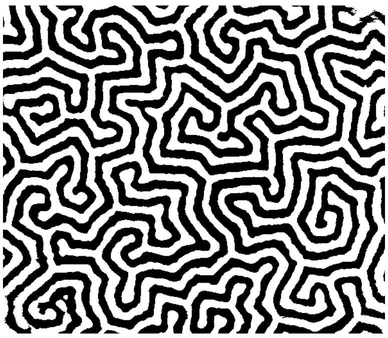

Fig. 17a. Domains in 0.13 mm (YbTbBi)IG film with no external field applied. Picture height corresponds to 0.54 mm.

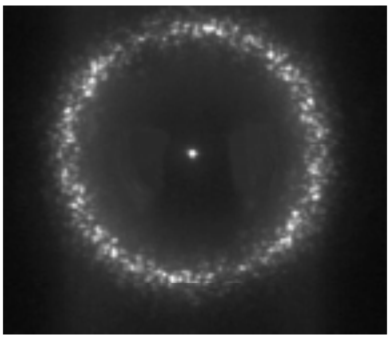

Fig. 17e. Diffraction from a domain pattern like the one in 17a. The diffraction angle is approximately 2.6°, corresponding to a domain width of 12 µm.

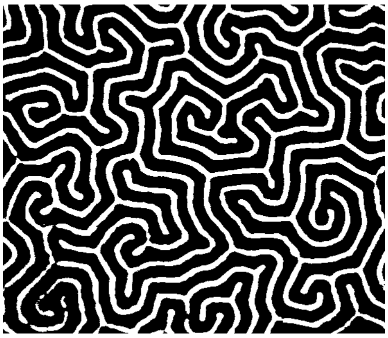

Fig. 17b. Domains in 0.13 mm (YbTbBi)IG film with 50 mT applied perpendicularly to the film. The domain pattern is nearly unchanged. Only the width ratio has changed.

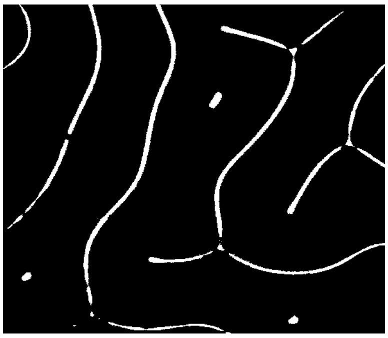

Fig. 17c. Domains in 0.13 mm (YbTbBi)IG film with slightly less than 100 mT applied perpendicularly to the film. Some of the domains from a and b are still visible.

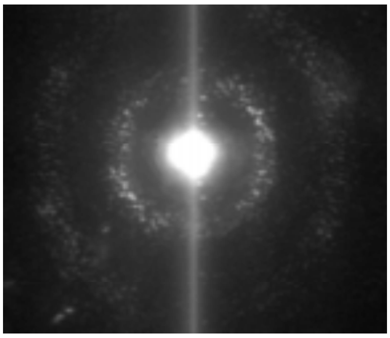

Fig. 17f. Diffraction from domain pattern similar to the one in 17c. First order diffraction at 1.6°, indicating a domain width of 20 µm. Second order diffraction just visible.

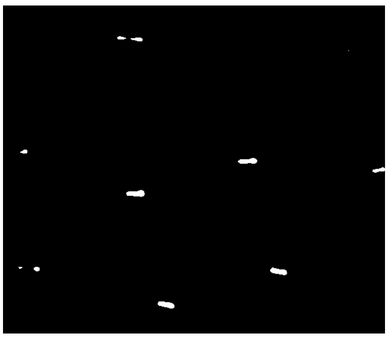

Fig. 17d. Domains in 0.13 mm (YbTbBi)IG film with about 100 mT applied perpendicularly to the film.

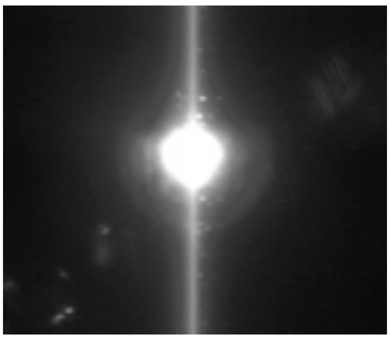

Fig. 17g. No diffraction is observed when all domains have disappeared.

a) b)

Fig. 18. Domain patterns in 0.3 mm slice of pure YIG.
a) with no external field applied.
b) with a magnetic field applied perpendicularly to the plane of the sample.

Similar results obtained with a 0.3 mm YIG slice are shown in figure 18. The average domain width is, in this case, in the order of 0.1 mm.

To get more quantitative results we used the above mentioned measurement system with the beam focused down to a diameter smaller than the domain width. Results as the one in figure 19 were then obtained.

In this figure, the domain structure at two different temperatures is shown. It can be seen that both the rotation within the domains and the domain pattern differ. The polarization rotation in each domain is smaller at the higher temperature. Our measurements of polarization rotation versus magnetic field over a larger volume, however, show an increase in the sensitivity (dϕ/dB) with temperature. This can be explained by a saturation field H_S that decreases with increasing temperature. These results, that are both in agreement with work published by others, indicate a way to reduce the temperature dependence of sensors made from YIG and substituted YIG material [131].

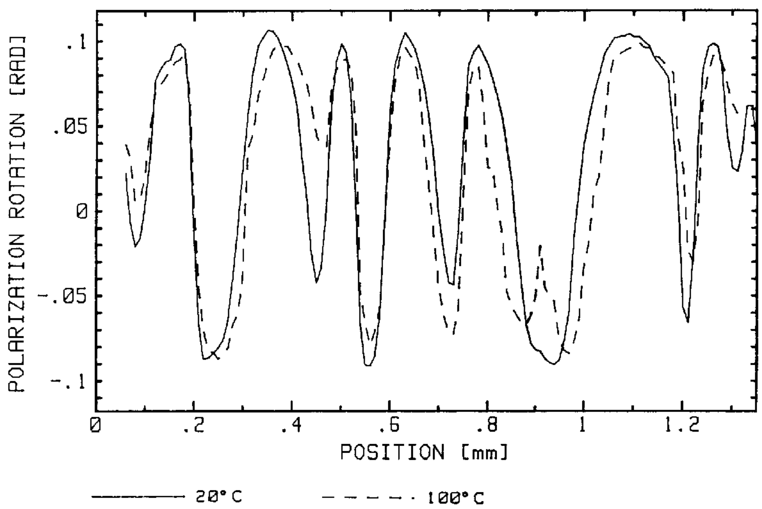

Fig. 19. Polarization rotation as measured with a 30 μm diameter beam scanned across a 0.3 mm thick YIG sample. Applied field perpendicular to slice plane 33 mT. Measured at 20°C and 100°C.

Sensor design considerations

From the measurement results, we were able to draw some conclusions concerning how to design sensors based on bulk YIG crystals:

- A thin crystal with a one-layered domain pattern , simplified the analysis and gave good results, though at the cost of a reduced rotation.
- A probing light beam much wider than the domain size, and preferably covering a large part of the crystal surface, reduced the effect of single domain behaviour.
- Annealing the crystal after sawing and polishing improved the results.

Waveguides

Measurement options

Most of the magneto-optical measurements on waveguiding samples are, principally, similar to those made on bulk samples. The situation is, however, complicated by the role of the linear birefringence. Furthermore, the cases differ in the means by which the light is coupled into and out of the material. For the waveguide characterization measurements, methods based on holographic grating, prism and end-fire light coupling, have been used.

The grating based method was used to determine accurately the linear birefringence and the saturation value of the magneto-optical rotation. In these measurements a grating, which is formed in photoresist on top of the waveguide, works as a distributed light coupler. A sketch of the measurement set-up is shown in figure 20.

The sample is turned to the coupling angle corresponding to the mode to be studied. As the coupling angle is, within the divergence of the laser beam, the same for the TE and TM modes of the same order, a polarizer and a retarder can be used to excite an arbitrary state of polarization at the input point. As the light propagates along the guide, a small fraction will continuously be coupled out, allowing the evolution of the intensity and the polarization state to be studied.

To determine the linear birefringence and the magneto-optical rotation,

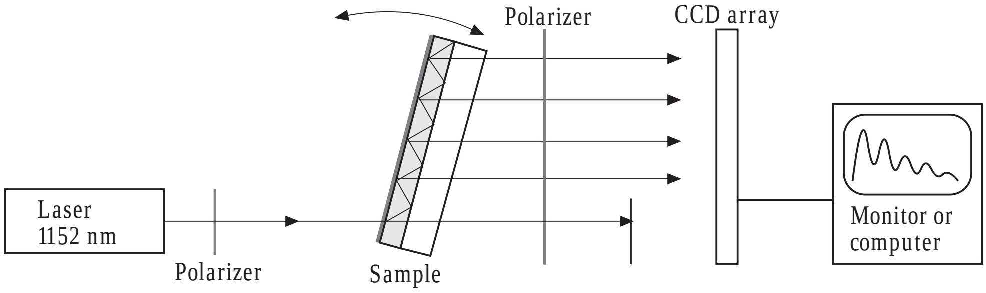

Fig. 20. Experimental set-up for the grating based measurements

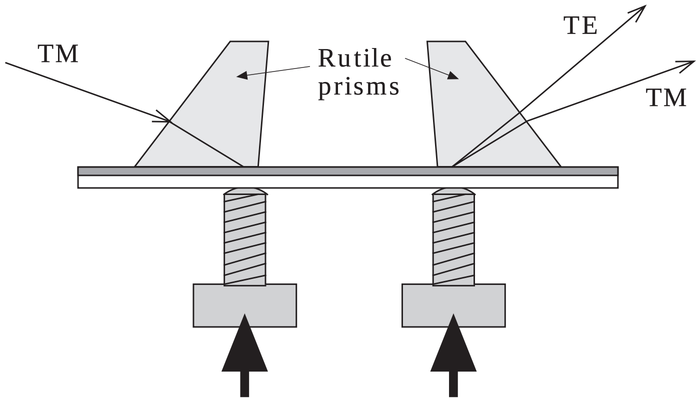

Fig. 21. Prism coupling method.

the spatial distributions of the outcoupled light under different magnetic field and input polarization conditions is recorded [132].

Even though the grating method can be used to measure the polarization rotation under different magnetic field conditions, it is more convenient to use the prism coupling method to study the variations in the rotation once the saturation value is determined.

A prism with an index of refraction equal to or higher than that of the guide is brought into contact with the guide by mechanical pressure, figure 21. Light impinging on the prism–guide interface with a suitable angle can then couple to a waveguide mode. Similarly, light can be coupled out through a second prism. For YIG waveguides, rutile is a suitable prism material. As rutile is birefringent, the TE and TM modes will have different coupling angles. With only one of the polarization modes excited at the input, the fraction of light converted can easily be monitored under different magnetic field conditions. Just as in the bulk measurement case, we have used a computer controlled measurement set-up to provide relevant magnetic field variations.

A number of experiments were also made with the fibre end coupled directly to the waveguide edge (butt-coupled). This method, in contrast to the prism method, does not involve any mechanical perturbation of the sample during the measurement. On the other hand, the samples must be specially prepared with polished edges.

Results of the waveguide measurements

The grating based method was used in an early stage of the project to select samples with sufficiently small linear birefringence to allow a large TE–TM mode conversion in the fundamental mode. Most of the samples we have used allowed a conversion of 90% or more. The results shown in this summary, except where is otherwise indicated, are obtained with 6.4 µm thick samples of Gd,Ga substituted YIG film on GGG substrate with a saturation polarization rotation of 150°/cm ($2.6 \cdot 10^2$ rad/m) at λ=1.15 µm. This material was known to be ”easy in plane”, i. e. the magnetization of the

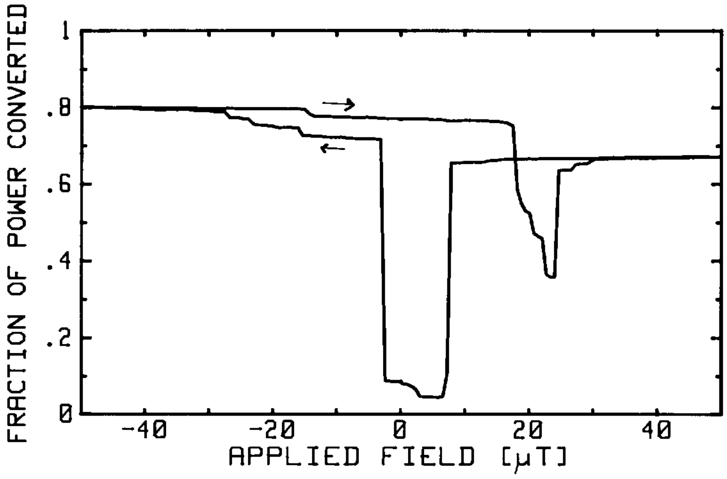

Fig. 22. TM to TE mode conversion versus a magnetic field applied in the plane of the film and parallel to the light propagation direction. The interaction length was 4 mm.

film could move relatively easily in the plane of the film but could not easily be turned from the plane of the film [133,134].

Our first results with prism coupling seemed, just as in the bulk measurement case, somewhat discouraging, figure 22. With a 50 μT field applied parallel or anti-parallel to the light propagation direction, the conversion is rather high and between those two extremes, the conversion goes down. There is, however, a large hysteresis, and the magnetization apparently changes in steps.

We found that the mechanical waveguide strain induced by the pressure applied to the prisms was responsible for part of the hysteresis. This is

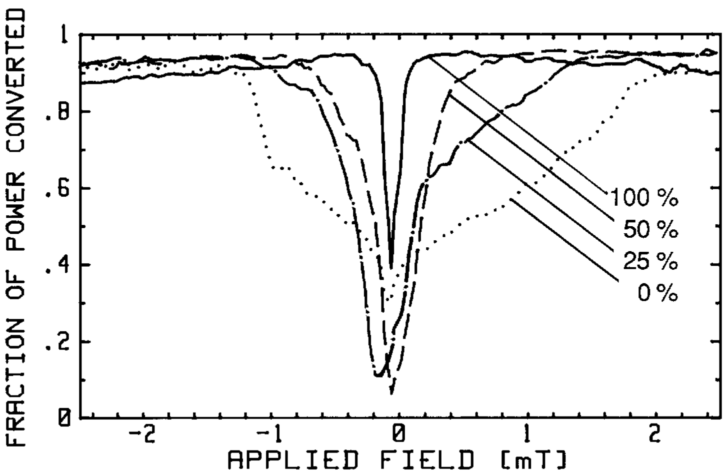

Fig. 23. TM to TE conversion, measured through a butt-couple fibre, versus the magnetic field applied in the plane of the film and parallel to the light propagation direction. The parameter is the pressure applied to the coupling prism.

demonstrated by the results shown in figure 23. Here, the conversion is measured through a fibre, butt-coupled to the edge of the waveguide sample. A coupling prism was also applied to the sample using different amounts of pressure. Evidently the pressure applied to the prism influenced the magnetic behaviour.

With the material used a ”bias” field, in the plane of the film and perpendicular to the field to be measured, was found to be necessary to obtain an unambiguous and smooth result even with the prism removed. To select an appropriate magnitude for this bias field, we applied a field of constant amplitude but with variable angle in the plane of the guide. The conversion was then plotted versus the angle of the applied field. One could then observe the variation in conversion and, thus, also how the magnetization followed the direction of the applied field. Starting with a very weak field, figure 24a, we noticed that even though the magnetization followed the applied field there was a strong anisotropy. With higher field magnitude,

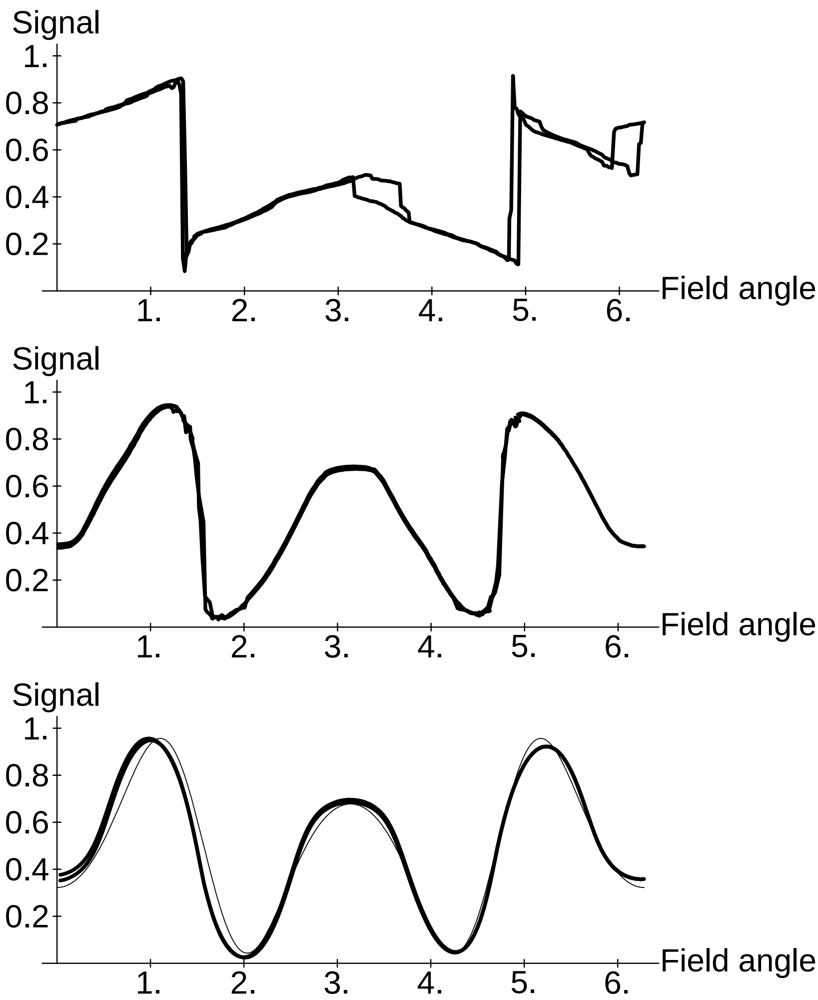

Fig. 24. The conversion versus the direction [rad] of an applied field for a two-way light pass in a 7.6 mm long sample. a) 100 µT field magnitude, b) 1 mT field magnitude c) 5 mT field magnitude (thick line) and theoretical calculation (thin line)

figure 24b, we could observe how the magnetization direction more and more closely followed the direction of the field. In figure 24c, with a 5 mT field, the magnetization almost completely follows the direction of the applied field. Although there are some deviations from the theoretical curve, the measured curve is smooth and free from hysteresis. This indicates that the 5 mT field was strong enough to create a single domain with a magnetization which could then be rotated by the field to be measured.

In order to study the magnetic behaviour of a channel structure in the film, experiments were made with strip waveguides delimited by parallel slits sawn through the waveguiding film. The hysteresis problems were, however, found to increase. A probable explanation is that the ”channel structure”, and the rough sawn edges, affected the domain structure. Some experiments with etching of YIG were also made [135].

Sensor design considerations

From measurements such as those described above, we drew the conclusion that with this type of material, which was known to have a relatively small anisotropy, a bias field of about 5 mT was needed to achieve a reproducible sensor behaviour.

The use of a bias field, however, limits the applicability of the sensor in several ways. The bias field may disturb the measurement situation in an unacceptable way. If the bias field is to be supplied by a permanent magnet, the effects of strong overload fields on this magnet must be considered. It may also prove difficult to find a magnet material that maintains the bias field constant over the temperature range required. On the other hand, there is in principle also a possibility to use a temperature dependent bias field to partly compensate the temperature dependence of the sensor material.

An alternative approach is, as will be shown below, to use a material with a strong anisotropy.

Partly because of the results that were obtained in the channel waveguide experiments, and partly because of the extent of process development work necessary to make channel waveguide structures, we also decided to use slab guides only.

Paper reference

The design and performance of the measurement system for bulk samples are discussed in paper A. In this paper, some examples of results are also given. The results are more fully described in paper C, and the sensor design rules are given in paper B.

The different waveguide characterization methods and the role played by the pressure applied to the prisms are covered in paper E.

The use of a variable in-plane field to select a suitable bias field, is described in paper G.

5. Sensors.

Single-mode systems

The sensing element of a measurement system with polarization maintaining single-mode fibres could, in principle, be either waveguiding or bulk optical. To avoid alignment problems, we have decided to work only with waveguiding sensing elements in our single mode systems. With a thickness of 5–10 µm, the sensing elements have been capable of carrying several modes, but we have shown that it is possible to use them effectively as single mode guides, butt-coupled to fibres.

The other two coupling methods that we have used in the characterization work can also be used in sensor configurations. The prism coupling method, however, lacks the ruggedness and potentially low cost that the butt-coupling and grating methods have. While we have preferred the simple butt-coupling in our sensors, grating coupling is a good alternative, particularly for thinner guides which cannot be effectively butt-coupled to fibres.

The basic principle of a waveguiding sensing element in combination with polarization preserving fibres is demonstrated in figure 25. One of the polarization modes of the fibre is used to carry linearly polarized light (white arrow) to the sensing element, where it is launched into the fundamental TE mode of the planar waveguide. In the waveguide, part of the optical power is converted to the TM mode (graded arrows). The light is then coupled into the return fibre, which is oriented in such a way that each of the modes of the planar guide matches one of the fibre polarization modes. At the output end of the fibre, the light from the two fibre modes is separated and detected. The detector outputs are then combined to give an intensity independent signal that is a measure of the magnetic field.

With this configuration it is not possible to detect the sign of the

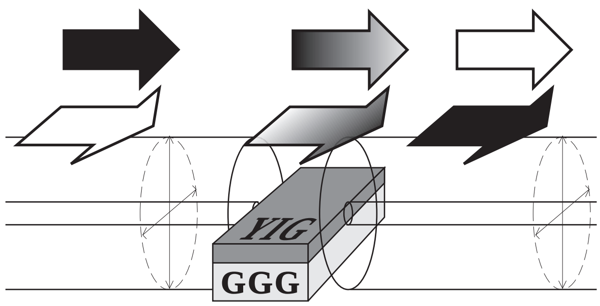

Fig. 25. Basic sensing principle

magnetic field. Fields that are parallel to, or anti-parallel to the light propagation direction, cause TE to TM coupling factors that are equal in magnitude and, consequently, they cause equal amounts of light to be coupled into the TM mode. However, if the return fibre is mounted with its birefringence axes at ±45° to those of the waveguide, the amplitude in each of the fibre modes will be a linear combination of the amplitudes of the TE and TM waveguide mode fields leaving the waveguide, giving a suitable anti-symmetric sensor behaviour. This is in analogy with a conventional bulk optic polarization rotation measurement set-up with the analyzer rotated 45° or –45° from the input polarizer orientation.

The absence of a lateral light confinement leads to a severe light loss when a configuration as the one in figure 25 is used. The loss can be of acceptable size only if the sensor is very short. Consequently, there is then a trade-off between polarization rotation and loss, but with materials having a very large Faraday rotation, it is possible to find a useful compromise. This is demonstrated by the results obtained with a sensor using a short bismuth-substituted YIG waveguide having a saturation magneto-optic rotation of about 1000°/cm ($1.7 \cdot 10^3$ rad/m) at 1.15 µm, figure 26. This waveguide had a strong out-of-plane anisotropy.

The idea was that this anisotropy should replace the bias field necessary with the other waveguiding sensors. The sensor output versus the applied field is shown in figure 27. A hysteresis effect appears for field magnitudes less than 1 mT. For such field levels, the magnetization direction is almost perpendicular to the film plane. For larger field levels, the performance is as expected, i.e. a smooth field versus conversion relationship. It is also evident from the non-symmetry of the curve that the return fibre was not correctly mounted, but was rotated slightly off the intended angular position with its birefringence axes at 45° from those of the input fibre. The imperfections of this experimental prototype should, however, not conceal the fact that the design principle is working. With another material having a stronger anisotropy it may be a viable concept.

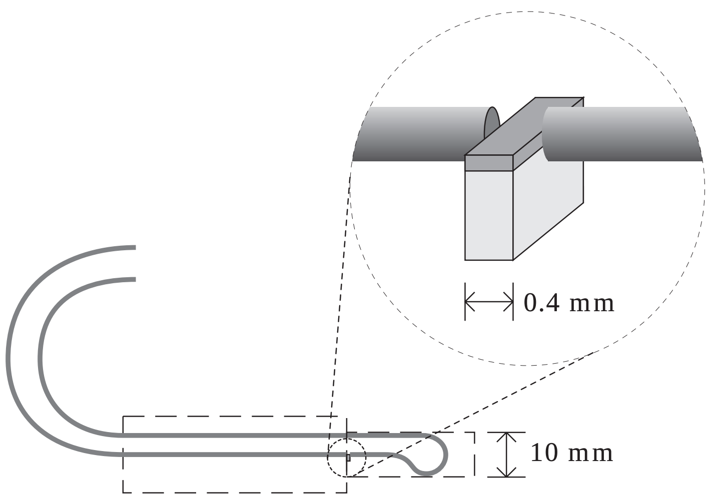

Fig. 26. Two-fibre sensor with 3.7 µm Bi-substituted waveguide.

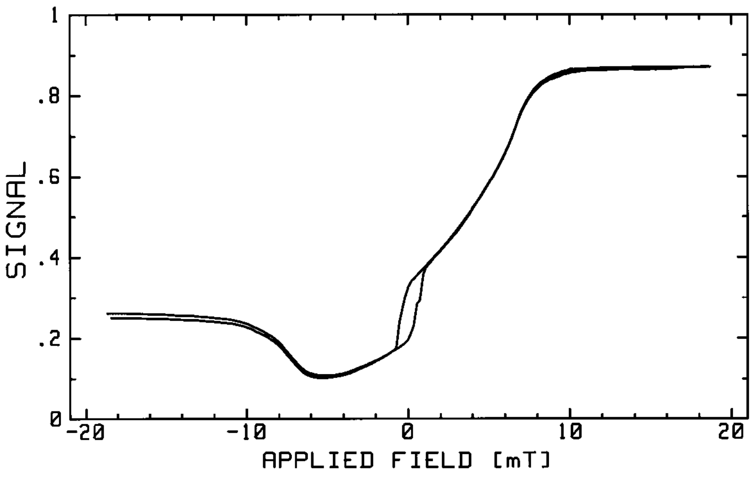

Fig. 27. Sensor output versus the applied field for a sensor according to figure 26.

An approach that in addition to solving the loss problems also allows the input and output fibres to be mounted side by side instead of in line on opposite edges of the waveguide, is to make a focusing reflector on the waveguide, figure 28a. In the experimental sensors, this reflector was made by polishing the rear edge into a semicircular form. A thin gold coating was then applied. Etched waveguide mirrors or grating reflectors are alternatives that could be taken into consideration. An experimental prototype is shown in figure 29.

As the Faraday effect is nonreciprocal in nature, the mode conversion of the forward and backward trip will add, making the effective interaction length twice the sensing element length.

This is the single-mode sensor design for which we have recorded the largest amount of test data. Results obtained with a sensor prototype with a 7.6 mm long Gd,Ga substituted YIG waveguide of the kind previously mentioned, are shown in figure 29. A bias field of 5 mT was used according to the sensor design considerations in the previous section of the summary.

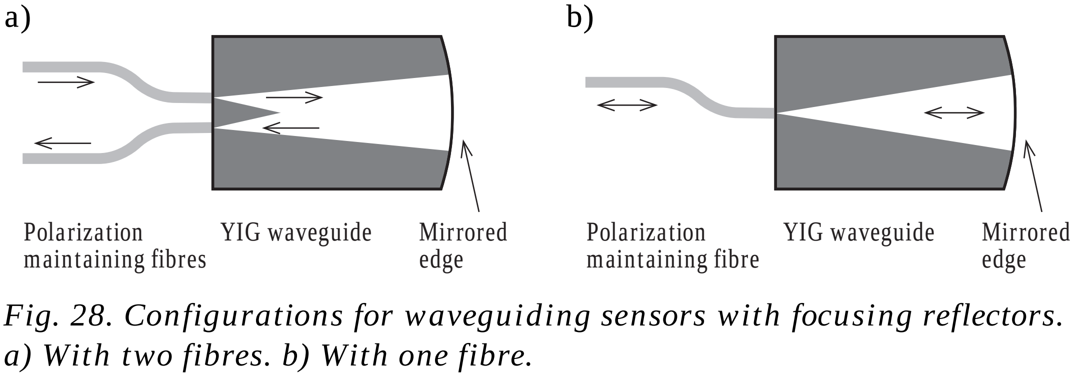

Fig. 28. Configurations for waveguiding sensors with focusing reflectors. a) With two fibres. b) With one fibre.

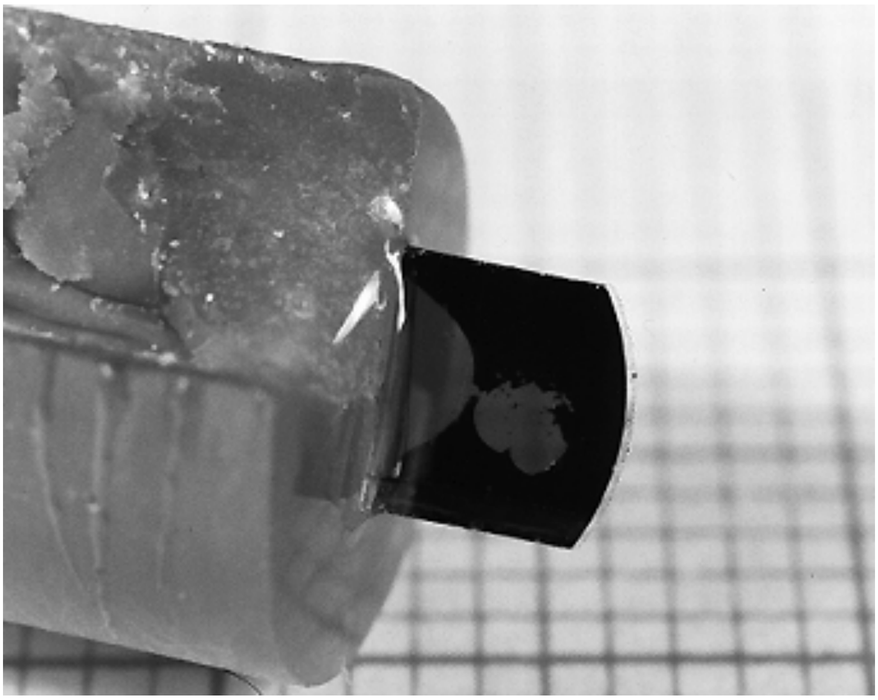

Fig. 29. Experimental sensor according to fig 28a.

The results show the expected sensor function with a central smooth sensing range and a slope reversal at approximately ±2 mT, figure 30. This indicates that the optical power couples back into the mode which it was originally launched into, equivalent to a polarization rotation of more than 45°. A sensor with a shorter interaction length would give a monotonous relationship.

Tests made with a spectrum analyzer, confirm the good signal quality and indicate a detector and amplifier noise level equivalent to about 8 nT in a 1 Hz bandwidth with a 5 mT bias field. The detection limit of the sensing

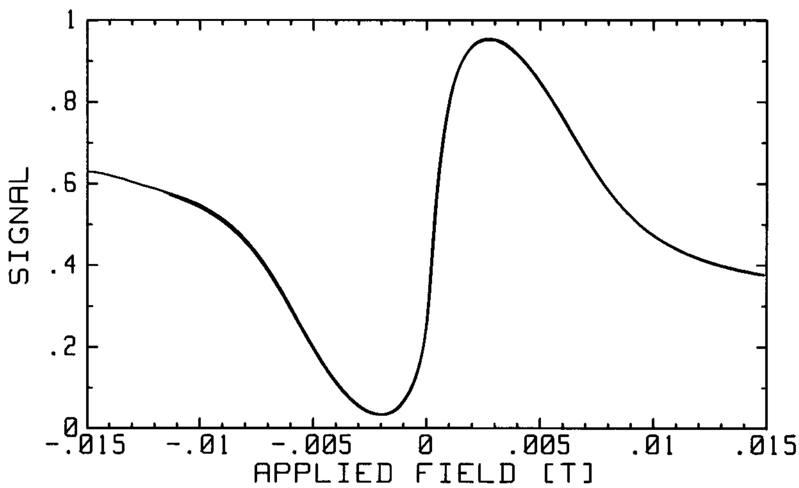

Fig. 30. Sensor output versus the applied field for the folded two-fibre design. Bias field 5 mT perpendicular to the axis of the sensing element.

element is, thus, lower than this value. By increasing the bias field, the measurement range can, of course, also be scaled to higher values.

We have also made a sensor where the same polarization maintaining fibre is used to guide the light both to and from the sensing element, figures 28b and 31. In such a configuration, the 45° displacement of the return fibre needed to achieve directional discrimination, is obviously not possible. For systems covering large distances, it is an advantage with only one fibre. Typically, however, such systems will include discontinuities in the fibre, e.g. removable connectors without index matching. Reflections from such discontinuities will be a problem in a one-fibre system. The reflected power will interfere with the light returning from the sensing element. As the phase angle between the unwanted reflection and the signal is determined by the length of the optical path to the sensing element, which will vary with the environment, rapid amplitude variations will take place. Although only one of the channels is affected, the performance of the balanced sensing system can be severely degraded.

The optoelectronic unit needed in a one-fibre system is also much more complex than the one in a two-fibre system. In addition to the polarization splitter, an extra beamsplitter, to couple the laser light into the fibre, is needed, figure 32. As the light has to pass this extra beamsplitter twice, the loss introduced is large. Furthermore, the risk of stray light from the laser falling on the detectors is substantial.

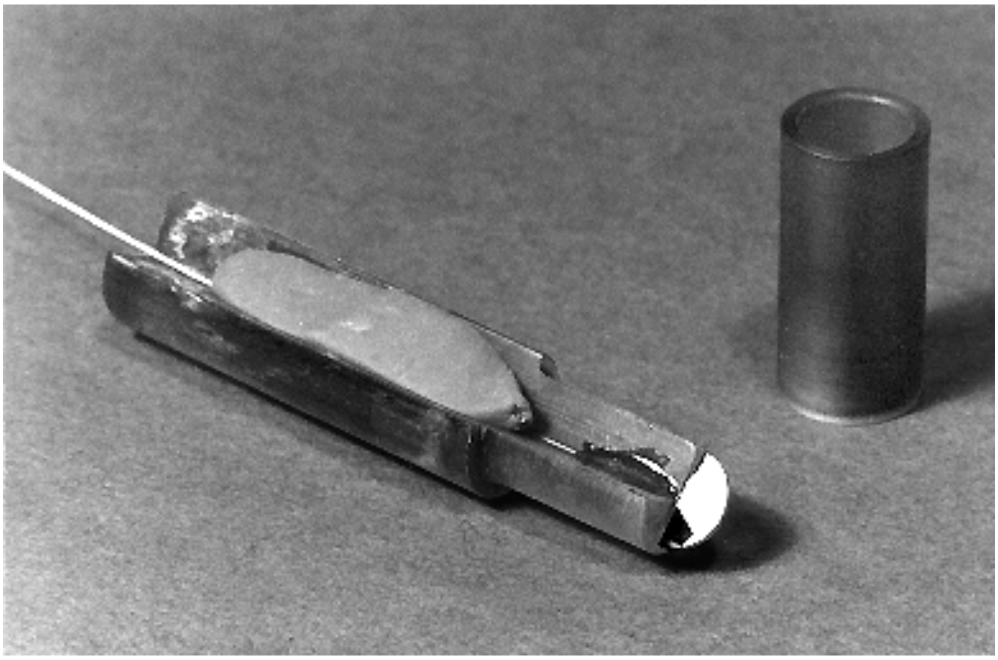

Fig. 31. Experimental one-fibre sensor according to figure 28b.

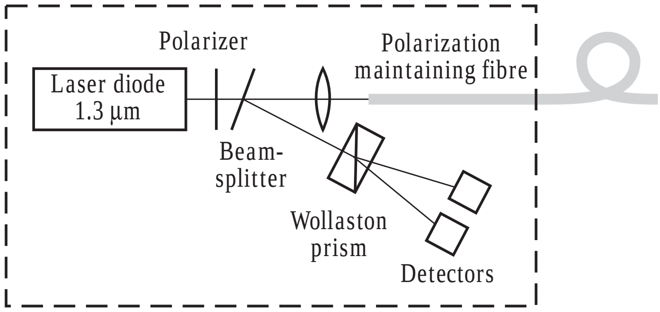

Fig. 32. Optoelectronic unit for one-fibre sensing system.

Using a 1.3 µm laser with short coherence length we have, however, obtained good results with a one fibre system with no removable connectors and with the fibre ends obliquely cut to avoid reflections, figure 33. The sensing element is similar to the one used in the two-fibre sensor. The non-symmetry of the curve is, at least partly, due to the non-symmetry of the sensing element caused by the oblique mounting of the fibre.

The systems described here are balanced, i.e., the sum of the optical power from the two channels is independent of the measurand and only dependent on the system loss, while the distribution of power between the two channels is ideally only dependent on the measurand. This is completely true for the light path to the sensing element but only approximately so for the path from the sensing element to the detectors. Loss mechanisms that unequally affect the two fibre polarization modes in the return fibre, will influence the output signal.

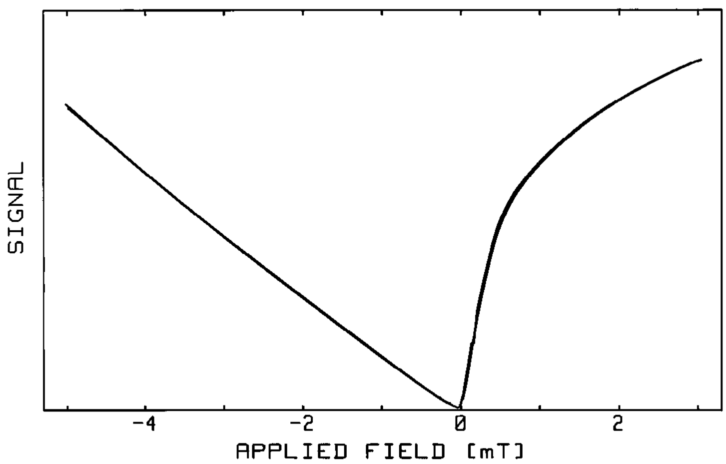

Fig. 33. Output signal from one-fibre sensor according to figure 28 b with an optoelectronic unit according to figure 32. A bias field of 3 mT in the plane of the waveguide is used.

Multimode systems

Iron garnet materials can also be utilized in multimode fibre optic magnetic field sensors. Such sensors provide a technologically simpler approach that may be more appropriate for many applications. Figure 34 shows the basic principle. Light is launched into and returns from the sensing element through multimode optical fibres. Polarizers are placed on both sides of the crystal. The intensity of the light transmitted through the second polarizer depends on the polarization rotation in the crystal.

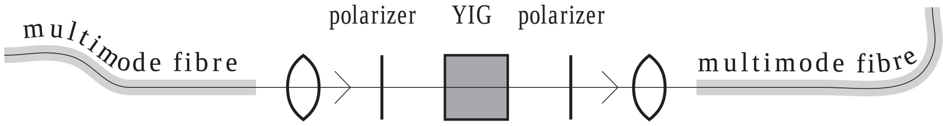

Fig. 34. Basic principle for the intensity based multimode sensors.

Different relative orientations of the transmission axes of the two sensor polarizers will produce very different sensor characteristics. To achieve a sensitivity to the direction of the applied magnetic field, a maximum unambiguous range and a maximum sensitivity to small fields, an angle of 45° between the polarizer axes can be chosen. In this case, the polarization rotation in the sensing element should not exceed 45°. For certain applications, other polarizer orientations are more favourable.

In most applications, it is unpractical to have the fibres on opposite sides of the sensing element. Thanks to the non-reciprocity of the Faraday effect it is, just as in the single-mode case, possible to use a folded design, figure 35. In this illustration, I have also indicated the use of a thick YIG film rather than a bulk crystal.

The DC field characteristics of such a sensor is shown in figure 36. The sensor was realized with an epitaxially grown 0.13 mm thick (YbTbBi)IG layer on a GGG substrate. The thickness of the layer was chosen to give a single pass maximum rotation of 22.5° at 1.3 μm.

The saturation points fall at approximately ±100 mT. Using a spectrum analyzer the output signal was measured for different levels of applied 1 kHz field from 27 mT (1% distortion) down to 270 nT.

The measurement results are summarized in figure 37, where the signal amplitude is plotted versus the applied 1 kHz field amplitude. Apparently the sensor is, within the experimental accuracy, linear over a range of at least 100 dB. The experimental data show a 1 Hz noise equivalent magnetic field of 1 μT. By decreasing the optical loss of the sensor and by improving

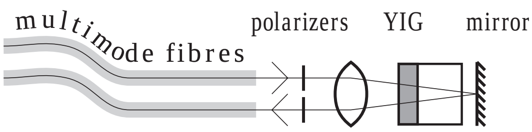

Fig. 35. Folded multimode sensor design

the amplifier, a reduction of this value to 100 nT should be within reach.

The accuracy of this type of sensor is, in most cases, limited by the loss variations in the system and by the temperature dependence of the sensor material. In some applications, e.g. AC measurement, the average value of the mesurand is known. One can then compensate for the slow loss variation. By optimizing the sensor material composition and thickness the temperature dependence of the material can be reduced considerably, less than 1% between –20°C and 80°C has been reported [136].

A recent prototype version of the multimode sensor is shown in fig 38. Other versions are shown in fig 39.

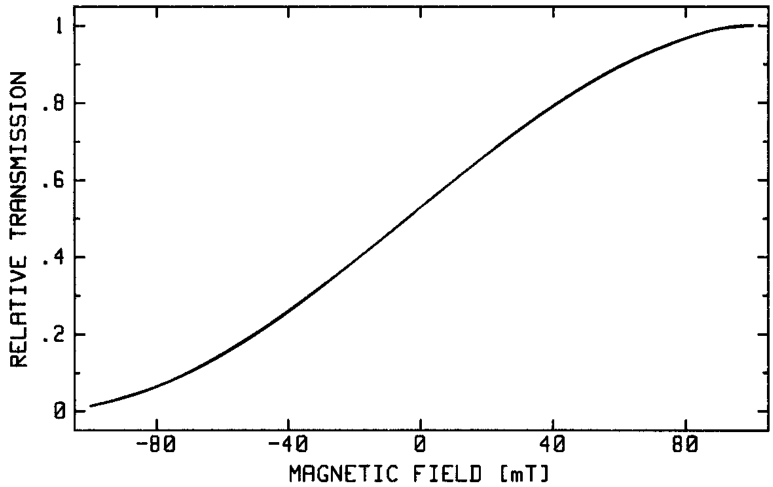

Fig. 36. The magnetic field characteristics of a multimode sensor with an epitaxially grown 0.13 mm thick (YbTbBi)IG layer on a GGG substrate.

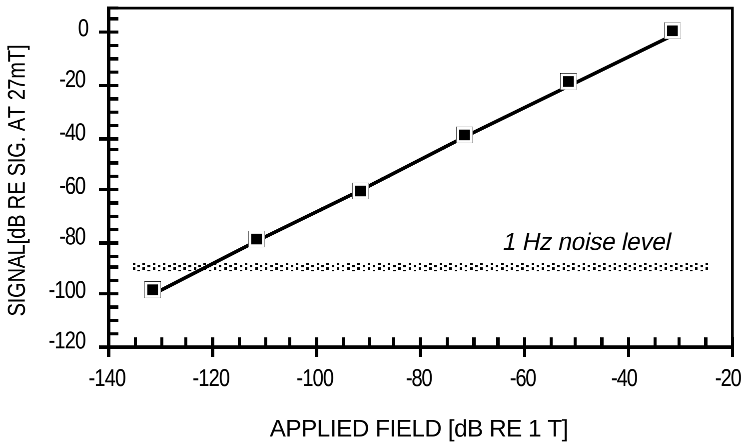

Fig. 37. The signal amplitude versus the applied field.

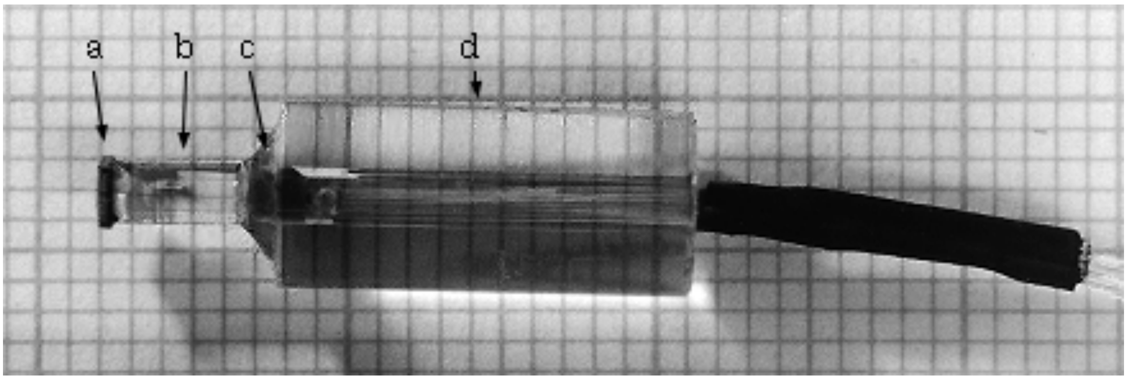

Fig 38. Prototype sensor developed for a field trial in co-operation with ABB Power Systems, with protective cover removed, lying on a piece of paper with mm rulings. a: YIG/GGG sensing element with gold coating, b: gradient index lens, c: polarizers, d: fibre holder made from a piece of glass tube.

Fig 39. Three versions of multimode sensors with folded design

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Paper reference

The waveguiding sensors are first introduced in paper D. Results from an experiment with a two-fibre unfolded system are shown, but the paper is mainly about the one-fibre folded design according to figure 27b in this summary. Different techniques to avoid interference effects are also described.

In paper F, a similar folded sensor is used but with an 1.3 µm semiconductor laser diode light source to reduce the interference problems. A sensor utilizing a very short piece of highly magnetically anisotropic Bi-YIG wave-

guide is also described. In the same paper there is also a description of a number of multimode sensors.

The two-fibre folded design sensor and its performance is treated in paper G.

The performance of the folded multimode sensor is treated in paper H.

6. Conclusions

Fibre optic magnetic field sensors based on iron garnet material have a number of favourable features. They can be made very compact, have large measurement ranges and resolutions in the nT region. The small size is an advantage not only for the point sensing of magnetic fields, but also for current measurement together with an iron core.

Both single-mode and multimode systems are demonstrated in this thesis. The two types of systems differ both in their measurement possibilities and in more practical handling aspects.

Using polarization maintaining single-mode fibre and sensing elements made from few-mode YIG waveguide, several versions of balanced measurement system have been built. The output signal from such a system is approximately independent of the system loss. Sensors have been made both with separate fibres to guide the light to and from the sensing element and with a single fibre for both functions. The two fibre version is, however, less complicated and has a better performance.

While the waveguiding single-mode sensors have some attractive features and perhaps potentially the best performance, the multimode sensors are less complicated to manufacture. As they can be produced at a low cost, they could replace Hall elements, not only in magnetic field sensors, but also for rotation speed sensing, etc. Also for electric current measurement they are a viable alternative. While an accuracy equal to that of precision current transformers has not yet been demonstrated, sensor prototypes suitable for other current monitoring applications in the electric power grid have been developed.

The temperature dependence of the Faraday rotation which at present limits the accuracy of the sensors can be substantially reduced with new sensor material compositions.

The renewed interest in magneto-optical materials may make suitable sensor materials more readily available in the near future.

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Comments on the authorship of the papers

The papers upon which this thesis is based, are written by myself and one or more co-authors from the fibre optic sensor group at the Instrumentation Laboratory. Torgny Brogårdh and Kjell Svantesson have been my supervisors, and their contributions have primarily been to provide good ideas and guidance. Also, their help in the actual writing of the text has been important. It is, however, difficult to quantify these contributions.

Most of the actual research work has been carried out by Ulf Holm and myself. Below I will indicate our different contributions to the papers. In the cases where Kjell Svantesson has made more active contributions to the work, this will also be indicated.

Paper A

Ulf Holm and I have taken equal parts in the development of the measurement system. The mathematical analysis of the performance was however made by Ulf Holm alone.

Papers B and C

Ulf Holm and I have made equal contributions to this work.

Paper D

I have done a major part of this work. The use of a few-mode waveguide with selective excitation was, however, originally suggested by Kjell Svantesson and the basic concepts behind the sensor design were jointly devised by the project group. Ulf Holm's main contribution is in the application of phase modulation to reduce the influence of the reflected light.

Paper E

This paper gives an overview of different methods applied in our characterization measurements. The grating method was devised by Kjell Svantesson and the results shown in the paper were obtained by him and Ulf Holm. The work on prism coupling and edge coupling was mainly done by myself.

Paper F

This paper gives a summary of our sensor work up to that time. Most of the work on multimode sensors was done by Ulf Holm and the work on single-mode systems was done by myself.

Paper G

This is primarily my work. Although he is not mentioned as a co-author, Ulf Holm has assisted in developing the model used in fig 6c, 7 and 8.

Paper H

This is primarily my work.

Paper abstracts

A: Measurement system for magneto-optic sensor materials

U Holm, H Sohlström and T Brogårdh

A system for the measurement of magneto-optic properties of IR-transparent materials is described. The system is designed for the characterization of fibre optic magnetic field sensor materials. Measurement results on YIG-crystals are presented. The accuracy of Faraday rotation and light transmission measurements are ±2 mrad and ±2% respectively. Important features for the sensor characterization are light beam scanning, temperature control and flexible magnetic field generation. A desktop computer is used for system control and data acquisition. The system is expected to be of great importance for future sensor development.

B: YIG-sensor design for fibre optical magnetic field measurement

U. Holm, H. Sohlström and T. Brogårdh,

Aiming at the design of a magnetic field sensor utilizing the Faraday effect, we give in this paper a description of measurements of magneto-optical properties of YIG. We also give sensor design rules based upon these measurements.

C: Measurement of YIG crystal characteristics for the design of optical magnetic field sensors

U. Holm and H. Sohlström

Measurements of the magneto-optic properties of YIG crystals, aiming at the design of fiber optic magnetic field sensors are presented. The Faraday polarization in YIG samples of different shapes, in applied fields –60 mT to +60 mT is given. The effects of temperature, perpendicular fields and sample treatment is studied. With thin, 0.3 mm samples, the linearity of the relationship between applied field and polarization rotation is found to be good with deviations from linearity of less than 1%.

D: A Polarization Based Fibre Optical Sensor System Using a YIG Optical Waveguide for Magnetic Field Sensing

Hans Sohlström, Ulf Holm and Kjell Svantesson

A sensor system utilizing a polarization maintaining fibre for the optical signal transmission and a planar optical waveguide for magnetic field measurements is presented. The system is based on polarization modulation originating from the TE to TM mode conversion in a magneto-optical thin film of Gd,Ga substituted YIG (Yttrium Iron Garnet).

E: Characterization of Magneto-optical Thin Films for Sensor Use

Hans Sohlström, Ulf Holm and Kjell G. Svantesson

As a part of a fibre optical sensor development project we have made an evaluation of different optical waveguiding techniques to study the properties of thin magneto-optical films. Because of the application the methods are focused on the determination of the Faraday rotation, the linear birefringence and the dynamics and anisotropy of the magnetic properties of the samples. Measurements using holographic grating, prism and edge (endfire) light coupling to different substituted YIG films are presented. The advantages of the different methods are discussed and it is shown that the launching technique may affect the properties to be measured. Film stress caused by the prism coupling method is found to influence the magnetic anisotropy.

F: Magneto-Optical Garnet Materials in Fibre Optic Sensor Systems for Magnetic Field Sensing

Kjell Svantesson, Hans Sohlström and Ulf Holm

Magneto-optical garnet materials such as YIG, undoped as well as substituted, exhibit a large Faraday rotation. This fact makes them potentially suitable as sensing elements in fibre optic magnetic field sensor systems.

We describe both an intensity based multimode system using bulk materials and a singlemode polarization based system using waveguiding films. A number of different material compositions, such as undoped YIG, (Gd,Ga)- and different Bi- substituted YIG have been used for the sensor elements. Measurement results are presented and discussed. A detection limit in the μT range and a measurement range exceeding 10^4 have been achieved.

G: A waveguide based fibre optic magnetic field sensor with directional sensitivity.

Hans Sohlström, Kjell Svantesson

In this paper we report on the design and performance of an extrinsic guided wave fibre optic magnetic field sensor. The sensor utilizes a substituted YIG (Yttrium Iron Garnet, $Y_3Fe_5O_{12}$) thin film as the waveguiding sensing element. A polarization maintaining fibre downlead was used to provide insensitivity to both power and loss fluctuations. The design makes it possible to determine both the magnitude and the sign of the magnetic field.

Measurement results indicate a usable measurement range of at least several mT with a noise equivalent magnetic field level of less than 8 nT/$\sqrt{\text{Hz}}$.

H: The performance of a fibre optic magnetic field sensor utilizing a magneto-optical garnet

Hans Sohlström, Kjell Svantesson

The design and performance of a multimode fibre optic magnetic field sensor utilizing the Faraday effect in an epitaxially grown thick (YbTbBi)IG film is reported. The sensor is found to be linear over a range of more than 100 dB.

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