Chapter 1: Introduction

1.1 Optical Fiber Sensors

The past two decades have seen a rapidly growing interest in the field of fiber-optic sensors. This growth in interest has been brought into effect mainly by the advances made in the related fields like opto-electronics and optical signal processing. Some of the principal reasons for the popularity of optical fiber based sensor systems are [1] small size, light weight, immunity to electromagnetic interference (EMI), passive (all dielectric) composition, high temperature performance, large bandwidth, higher sensitivity as compared to existing techniques, and multiplexing capabilities. Moreover, the widespread use of optical fiber communication devices in the telecommunication industry has resulted in a substantial reduction in optical fiber sensor cost [2]. As a result, optical fiber sensors have been developed for a variety of applications in industry, medicine, defense and research. Some of these applications include gyroscopes for automotive navigation systems [3], strain sensors for smart structures [4,5] and for the measurement of various physical and electrical parameters like temperature, pressure, liquid level, acceleration, voltage and current in process control applications [2].

Information about the measurand is primarily conveyed in all optical fiber sensors by a change in either polarization, phase, frequency, intensity or a combination of the above. Optical fiber sensors can be broadly classified on the basis of their operating principle as intensity based or interferometric type. Intensity based sensors are inherently simple and require simple electronic support. However, sensitivity is often traded off to realize these advantages. Interferometric sensors on the other hand require relatively complicated signal processing techniques but have extremely high sensitivity. Optical fiber sensors are further classified as intrinsic or extrinsic. In intrinsic type of sensors, the fiber functions as both the transmission and sensing element. Thus the parameters to be measured change the light guiding properties of the fiber, which can be detected and demodulated to obtain information about the parameter. Whereas in extrinsic fiber sensors, the fiber merely acts as the transmission medium, bringing light to and from the sensing medium. Mach-Zehnder interferometer, Michelson interferometer and Fabry-Perot interferometer are some of the fiber optic interferometers in use today.

1.2 Magnetic Field Measurement

Magnetic field measurement has become an essential procedure in many industrial, scientific and defense projects today. Weather satellites routinely map the earth's magnetic field for scientific information. Airplanes and ships use the earth's magnetic field to compute direction as well as altitude, in case of airplanes. Measuring magnetic field is one of the primary methods of estimating high voltages and currents in industrial environments. Magnetic field detection is of much interest to defense scientists, particularly in the area of minefield and submarine detection. All the above reasons have made the development of reliable, rugged, extremely sensitive magnetic field sensors, highly essential. Small, fiber optic-based magnetic field sensors could be used for many applications which are inaccessible to electrical based sensors. A variety of optic fiber based magnetic field sensors have already been developed [2]. But these, in general, are relatively large or have low sensitivity when compared to small electrical based semiconductor Hall effect sensors or magnetoresistive sensors commonly in use [6].

Measurement of low level magnetic fields in particular, is the topic of research in many defense and weather related areas these days. Extensive research has been conducted to investigate fiber-based schemes to measure magnetic fields with a higher sensitivity. Some of the fiber and non-fiber based methods presently being studied for low-level magnetic field measurement are presented below.

S. A. Oliver *et al* report the use of a thin magnetic film, which is "read" using the magneto-optic Kerr effect (MOKE) [7]. The researchers report a sensitivity of 2 mOe /Hz $^{1/2}$ at a measurement frequency of 8 mHz. Though the scheme offers good thermal stability and few restrictions on the coherency of the light source, it involves the use of optical components like polarizers, making it difficult for practical applications. Cheol G. Kim *et al* have demonstrated the use of NMR using polarized flowing water for low magnetic field measurement [8]. Their experimental setup has yielded a sensitivity of 0.1 mT within the uncertainty of a few tens per million. Miroslav Sedlar *et al* propose the use of Mach-Zehnder interferometer with the sensing arm jacketed with a 2 μm thick and 1m long magnetostrictive material. The minimum detectable field using this setup was 3.2 mA/m. The sensor length in this case is at least 1m. The Faraday effect in optic fibers provides a simple and convenient method for passive optical measurement of magnetic field as well as electric current. Current sensors based on annealed coils of optic fiber have moderate sensitivity, wide frequency response and excellent temperature stability. Ferrimagnetic iron garnet crystals form the basis of high-sensitivity magneto-optic sensors. Iron garnet crystals are coupled to ferrite flux concentrators to enhance the sensitivity of these Faraday effect-based fiber optic sensors by up to two orders of magnitude [9].

1.3 Application of Fiber Sensors to Magnetic Field Measurement

Optic fiber based sensors can be used in a number of different configurations to measure low-level magnetic fields. Sensors using the Faraday effect in optic fiber have been common for a number of years. These sensors depend on the Faraday rotation induced in fibers carrying linearly polarized light in the presence of external magnetic field. The induced Faraday rotation can be determined polarimetrically by placing the fiber coil between polarizers and measuring the optical transmission through the system [9]. The Faraday rotation can also be measured interferometrically using a Sagnac interferometer [10]. Sensitivity of Faraday-effect sensors can be increased by increasing the length of the fiber exposed to the external magnetic field. The sensors are thus bulky for ultra-low-level magnetic fields.

Another commonly followed approach is to use interferometric fiber sensors to measure the strain produced in a magnetostrictive material in the presence of an external magnetic field. The principal advantage of these sensors is the much improved sensitivity, obtained without increasing the size of the sensor. A Mach-Zehnder type interferometric arrangement can be used with the magnetostrictive material geometrically coupled to the sensing arm as either a ribbon, cylinder sandwich or sputter-coated sheath [11]. An Extrinsic Fabry-Perot Interferometric (EFPI)-based sensor can also be used, with the sensing fiber in the cavity replaced by a highly magnetostrictive material like metglas [12,13]. Sensitivities as low as 100 nT (1 mG) have been obtained in the latter case.

As can be seen from the above discussion, fiber optic magnetic field sensors have shown promising results, particularly in the measurement of low-level fields. The system discussed in the subsequent pages of this thesis is EFPI-based and is passively temperature compensated. The sensors developed are small, light weight and have been demonstrated to measure magnetic fields as low as 50 nT.

1.4 Thesis Objective and Overview

The primary objective of this thesis is to propose, design, implement and test the electronic signal processing in an optical fiber based magnetic field measuring system. The magnetic field measuring system is based on the EFPI fiber sensor and is designed and fabricated at the Fiber and Electro-Optics Research Center (FEORC) as a program sponsored by the U.S. Air Force Phillips Lab, Hanscom AFB. The major objective of this program is to design, fabricate and implement optical fiber-based magnetometers for performing on-board environmental diagnostics. Such an instrument is required by the Air Force and the DoD to be easily incorporated as a standard instrument complement or as a monitoring system on operational and scientific satellites. The approach followed at the FEORC, is the modification of EFPI-based sensors, with the incorporation of magnetostrictive transducer materials on the sensor elements. Although the specific near-term technical objective of the program is the implementation and evaluation of optical fiber-based magnetometers, the design and test results to be obtained are part of a larger vision of alternative methods for the characterization of magnetic fields. The magnetometer developed has a dynamic range of 100 – 40,000 nT (1 mG – 0.4 G) with a resolution of 100 nT. The signal demodulation scheme proposed in this thesis is the Quadrature Phase Shift (QPS) scheme with a microprocessor based implementation.

Chapter 2 explains the basic operating principles of an EFPI sensor, various demodulation schemes commonly used to extract signal from the sensor and brief description of the wide range of applications of EFPI-based sensor systems. Operation of an optical fiber-based magnetic field measuring system and description of the various components of the system follows in Chapter 3. Chapter 4 talks about the necessity, requirements and components of an opto-electronic interface and gives a detailed description of the interface circuitry fabricated and tested during the course of the project, including component specifications and description. Chapter 5 explains the signal demodulation scheme employed in this system and reasons for implementing a microprocessor-based system. Results obtained during the testing and evaluation of the magnetometer are presented in Chapter 6. Conclusions derived from the results presented in the previous chapter and future direction are presented in Chapter 7.