Chapter 1 - Introduction

1.1 Importance of Magnetic Field Measurement

The measurement of magnetic fields has been a critical part in various technical areas. High sensitivity magnetic field measurement has been utilized to detect the presence of large ferromagnetic objects such as submarines in the ocean, which change the magnetic field distribution. In industry application, the current flowing in an electric circuitry generates a magnetic field proportional to the current. In principle, current can thus be measured indirectly by measuring magnetic field. The presence and location of some ores under the ground can be detected by measuring the magnetic field distribution, which is largely used by the mine industry. The ballistic control of a long range missile such as ICBM can be realized by the detection of minute earth magnetic field changes during the flight. This type of flight control also can be used to auto-pilot air craft. The measurement of magnetic characteristics of the high temperature superconductors informs the basic physical parameters that represent their superconducting state and provides information about the structure of penetrating magnetic flux and processes connected with their dynamics. The quest to track, detect, and localize vehicles, ships, and aircraft in a constrained area has been increased considerably. The controlling of the intelligent Vehicle Highway System, harbor vessels, and airport runway traffic can be done by deploying an array of magnetic sensors in that restricted area, which provide all-weather detecting capability and good environmental survivability. In most cases, the crafts to be detected have a magnetic signature to be easily distinguishable from the other objects. Since the amplitude of magnetic field is dependent on the distance, the accurate and efficient localization and tracking are possible. The magnetic field detection in mass storage technology is essential for high density information storing systems. The data in the information high way era grow rapidly due to the multimedia, large spreadsheet, and data base in industry. For engineering applications, powerful and sophisticated CAD, 3D rendering, polygon geometry calculations, image processing and almost all engineering software need vast amount of physical resident space for effective calculations. Since the software size has considerably been increased past several years, the faster read and write method, and higher information density are being prime concerns. In order to achieve these technical goals, the precise detection of magnetic field generated by data bit is essential. The precise detection of the magnetic field for the information bit ensures exact data processing. Hence the magnetic field measurements are indispensable for defense systems, geophysics, industry and engineering applications.

1.2 Magnetic Field Sensors

There are several technologies to measure magnetic fields for commercial and military applications. Magnetic field sensors can be classified into non-optical and optical sensors. Among the non-optical magnetic field sensors, the fluxgate sensors are utilized by constructing a simple coil and high permeability core material [1.1]. The measurement of magnetic field is done by comparing the drive-coil current needed to saturate the core in one direction as opposed to the opposite direction. The difference is caused by external magnetic field variation. Faraday's law of induction can be used in search coil magnetometer. A turn of conducting wire onto the high permeability ferromagnetic material core generates electromotive force in the coil as the magnetic field passes through the coiled conductor. The generated current is proportional to the time varying magnetic field. The sensitivity of search-coil magnetometer depends on the area of coil, the number of turns, the permeability of core, and the rate change of magnetic flux through the conducting coil. Since using the law of induction, the sensing is limited to AC variation of magnetic fields. These sensors can be easily designed and fabricated but are susceptible to electromagnetic interference (EMI). The performance is limited by the temperature dependence of the high permeability core material and electronic components used. Superconducting quantum interference devices (SQUIDS) [1.2], non-optical magnetic field sensors, are employed to measure remanent magnetization and susceptibility of geophysical samples, biomagnetic properties of small samples, and electrical current distributions during corrosion process. This sensor system needs cryogenic temperature to achieve superconducting status. Hence the system is built in heavy and large form factor and only operable in laboratory conditions. The Hall-effect sensor is using the potential developing in the semiconductor biased to flow current under influence of external magnetic field. The moving charges in the semiconductor (electrons or holes) experience Lorentz force, that is perpendicular both to their direction of motion and to the direction of the magnetic field. In order to maintain continuity of charge, the charged carriers should be depleted one direction and this generates Hall voltage. By measuring magnitude and polarity of the potential developed, the external magnetic field's amplitude and direction can be determined. Since the potential developed in the semiconductor is very low for few gauss of flux, this sensor is suitable for high magnetic field measurements. The generation of electron-hole pair in the semiconductor is very sensitive to temperature. The temperature induced carriers generate spurious potential which degrades resolution of sensor. All of these sensors are bulky, susceptible to EMI, and show high temperature dependence. On the contrary, optical fiber based magnetic field sensors are immune to EMI and compact in nature. The optical magnetic field sensors are utilizing either change in intensity or phase due to the external magnetic field variation. The technologies to measure relatively high frequency magnetic fields (> 10 Hz) have been developed in the beginning of the sensor system design because of the simplicity of high frequency components measurement in frequency domain. The Faraday effect sensors in both fiber and bulk optic configurations have been demonstrated [1.3]. For the measurement of low frequency magnetic fields (< 10 Hz), the high sensitivity sensor schemes have been developed to measure low flux density, such as magnetostrictive devices [1.4]. The most well developed sensor schemes are the magnetostrictive sensors and Faraday effect sensors because of the effect of magnetic fields change is relatively simply represented in those sensor schemes. The Lorentz force based sensors has been realized by a conductive coating on fiber, which carries current that induce Lorentz force onto fiber to expand physical length of fiber in longitudinal direction [1.5].

The Faraday effect sensors utilize the state of polarization of the optical wave propagates in a medium. The state of polarization at any point in the medium is represented as the electric field vector movement as a function of time at that position.

In general, the polarization is elliptical, the E field vector tip moves as ellipse in space as time varies. This ellipse could become either a circle (circular polarization) or a line (linear polarization) in a specific condition. The state of polarization of propagating optical waves can be expressed as the linear combination of two optical waves that have the orthogonal state of polarizations. If the polarization of the wave changes during the propagation in the medium, the medium has birefringence which is defined as the polarization type of optical wave that is not affected by the medium. Thus the polarization of linearly polarized light remains constant during the propagation in the linear polarizing material. On the contrary, the linearly polarized light shows significant change in the state of the polarization in circular birefringent materials. The amount of change in the state of polarization depends on the optical path length of light in the material, input polarization state, the strength and type of birefringence. The circular birefringence can be induced in some materials by applying magnetic field. Hence by applying linearly polarized light into the materials which show the circular birefringence, the magnetic field strength can be measured.

The magnetostrictive sensors utilize a strain induced by external magnetic field on a ferromagnetic transducer. The transducer converts the strain to optical phase or intensity change in the light propagating the fiber by some way to impose its stain to the fiber in the intrinsic interferometer schemes. The basic structure can be given as a Mach-Zehnder interferometer configuration with a magnetostrictive material boned to a long length of single mode fiber in one of the two arms of the interferometer. Since the strain induced in the magnetostrictive material depends on the total imposed magnetic field on the gage, the longer lengths of gage and fiber attached to the material induce more phase shift in the interferometer. The transducer physically expands the fiber length by induced strain proportional to external magnetic field. The expansion of fiber changes the optical path length of the wave propagating through the fiber. The interferometric sensor configuration in this case is consist of a laser source and two couplers. The optical wave path can be constructed with the optical fiber by two separate arms. The one of the arm has the magnetostrictive sensing element attached by a length of fiber. As the single mode laser source is injected into 2x2 coupler, two splitted half powered original waves propagate in the two arms respectively. Since the one of the arms is stretched by the magnetostrictive transducer, the wave path through the fiber arm has different phase. These waves interfere with each other at the second 2x2 coupler. The intensity from this interference fringe is maximized when the waves phase difference is in-phase at the coupler, or minimized with out-of-phased interference. Thus monitoring the phase change implies to measure the magnetic field imposed to the sensor gage. There are a few basic fiber optic magnetostrictive sensor configurations. The sensor transducer can be made by jacketing the magnetostrictive material over bare fiber or over buffer, demonstrating a long length of sensing fiber [1.6].

The other configuration is utilized by a flat, thin, and rectangle magnetostrictive strip. The fiber attached to the thin magnetostrictive strip is stretched by the external magnetic field. The thin magnetic strip can be formed as a cylindrical shape and the fiber can be wrapped to the magnetostrictive element. The bonded long length of fiber is stretched by expansion of the cylinder. The eventual phase difference in between fiber arms produces the interference fringe proportional to the external magnetic field.

1.3 Optical Fiber Sensor based Measurements

The introduction of optical fiber has changed the way of telecommunications and related fields. The optical fiber provides a large bandwidth, low cost in mass production, and low transmission loss in communication channels. These high performances generate a large capacity and high speed transmission optical lines for high demanding applications such as computer networks for Internet. The improvements in the market enhance the mass productions of opto-electronic components. The improvement of manufacturing techniques and enlarging market raise the technical merit of fiber optic based technology over existing ones. Meanwhile, the availability of opto-electronic parts for sensor applications in lower cost is broadened by the evolution of traditional communication systems to fiber optic based communication systems. Also these new fiber optic sensors can be used to the areas that are too harsh to measure with conventional sensor systems since the optical fiber is usually made by dielectric materials which has the properties of high resistance to vibration, electromagnetic interference, thermal shock, and corrosion. The optical fibers used in sensing applications are mostly made of fused silica with various values of core and cladding refractive indices. The indices can be modulated by injecting the dopants during the manufacturing process to control the index profile and polarization properties. The optical fiber has a shape of a long cylindrical wave guide with different types of core/cladding size and shape. The measurements using optical fiber is describes as the light propagates the in cylindrical optical wave guide with core and cladding modes, the external excitation disturbs the modes to change their propagation properties which can be detected and measured. Fiber optic sensors have been designed and applied to measure the most of physical observables with accuracy, reliability, and compactness as compared to conventional electronics based sensors. There are several advantages of fiber optic based sensors over the conventional sensors. Because the wavelength and phase of optical wave are easily disturbed by exterbances, propagation properties can be modulated with ease. Since the typical wavelengths used in optical fiber sensor based measurement system are in the order of 10^{-6} m, a small change in phase or wavelength due to exterbances can be detected. Also optical fiber has large bandwidth because of the high optical frequency with order of 10^{14} Hz by nature. Hence high resolution and sensitivity are ensured. Since the optical fiber is made of fused silica which is dielectric, the electromagnetic interference (EMI), such as inductive pickup from current carrying conductors and sparks are non-existing. Also there is no ground loop problem. The cross talk in between fibers or other signal carrying conductors is negligible because of evanescent nature of the guided mode in cladding. Hence the measured value by fiber optic sensors are not degraded during the propagation to the analyzing system. Since the dimension of optical fiber is small, the sensor configurations can be compact and light. Because of this advantage, the sensor can be integrated into the integrated opto-electric devices easily. The attenuation of 1550 nm wavelength wave is 0.16 dB/km. This value is hardly satisfied copper based transmission lines. Hence the fiber optic based sensors can be deployed long distances without significant signal degrading and also are ideal for remote sensing. Since the fused silica is made from SiO_2 , the quantity of resource is almost unlimited. The cost of the fiber optic based system can be reduced further. In general, fiber optic sensors can be divided into intrinsic and extrinsic sensors. In intrinsic fiber optic sensors, the sensing takes place inside of the fiber, where as in the extrinsic fiber optic sensors, the sensing is performed outside of the fiber. The hybrid type optical fiber sensors carry information measured by the other types of sensors. The fiber optic sensors can be realized based on the modulation of intensity and phase. The intensity of light is directly modulated by exterbances in the former, where as the phase of propagating waves in the optical fiber is modulated in the latter. Since the output change according to small phase change depends on the gradient of interferometric fringe at given operation point (Q point), the sensitivity of these interferometric sensors is better than those of sensors which measure intensity. The intensity based sensor system can be easily designed and the signal recovery with the system is simple to realize, but limited to relatively low sensitivity applications. The interferometric sensor that can be described as the state of the art technology shows extremely high sensitivity to almost all environmental changes. In the sensing application, only the wanted physical observable should be detected or measured but the ultra high sensitivity sensor scheme like an interferometric sensor usually responds to the other environmental parameters. Hence the measurement isolation in the interferometric sensors is essential to obtain the meaningful data from the experiment. The interferometric sensors can be used to measure temperature, pressure, refractive index of materials, electric field, magnetic field, strain, current, wavelength, rotation, and phase in high resolution and sensitivity with proper design and measurement isolations. Hence the interferometric sensors are well suited for measuring small exterbances with high resolution.

1.4 Technical Objectives

The Faraday effect sensors, the magnetic field measuring sensors, are typically implemented by the induction of a circular birefringence in the fiber by the external magnetic field. Since the Verdet constant of fused silica which is used to fabricate the optical fiber is very small, the large currents is needed to rotate linearly polarized light propagating the fiber [1.7]. Hence the longer interaction length of fiber is needed for the low magnetic field detection. In this case the sensor geometry is not compact and maintaining the linear polarization before the stage of birefringent material is another issue. Even though the high Verdet constant bulk crystal can be used to reduce the required sensing portion length, the system suffers from strict alignment requirement [1.8]. Hence this method is useful only in laboratory environment. The other methods utilizing magnetostriction in ferromagnetic materials show high sensitivity and ease of sensor fabrication. The phase change in a Mach-Zehnder magnetic interferometer using the magnetostrictive material coated optical fiber is a function of wavelength, refractive index of fiber core, interaction jacketed fiber length, strain induced the magnetostrictive jacket material, and the strain-optic correction factor which represents the propagation constant change with axial strain in the fiber core [1.9]. The same strain-optic correction factor can be applied to the sensor gage fabricated by flat and thin magnetostrictive material[1.10]. The strain induced in the magnetostrictive material is not fully transferred to the core of the optical fiber because the losses exist in the interface between the material and the optical fiber. The amount of the transfer depends on the thickness and hardness of adhesive used to attach the fiber to magnetostrictive material, and the fiber physical longitudinal hardness. The efficiency of the magnetostriction transfer is low in these sensor designs. Hence in order to measure the low magnetic field, a long length of fiber or magnetostrictive material is needed in these schemes. Since the thickness of thin magnetostrictive strip is a range of 20~25 μm, the sensor fabricated with this material is susceptible to vibration. The mechanical strength of the sensor gage is weak with this shape of material. Hence the sensor scheme is workable in laboratory conditions. The other scheme using magnetostrictive material employs a cylindrical shape of the material [1.11]. The system requires a long length of fiber (~30 m) wrapped around 5cm long by

4.45cm diameter cylindrical magnetostrictive thin strip. The fiber was bonded to the strip with epoxy [1.12]. The sensor gage configuration of this sensor scheme is not compact and needs long length of fiber to detect low magnetic field. The effect in bent fiber along with small diameter is birefringent. Hence the unnecessary phase change occurs by wrapping the fiber around the magnetostrictive material. The longer length to increase the sensitivity increases the birefringent a lot. Since making sensor compact in this scheme requires a smaller diameter cylinder, the strain in the fiber increases. The strain produces large birefringent in the fiber. The Lorentz force sensors utilizing a conductive coating on the optical fiber. The any charge moving in a presence of magnetic field will experience a force, Lorentz force, which depletes the coated fiber. The magnetic field can be determined by solving equation of motion for vertical displacement of the both ends clamped fiber. The vertical displacement is equated for axial strain of the fiber. But the scheme needs a static deflection condition for determining the magnetic field strength. The conducting coating on the fiber is not suitable for the high voltage environment measurements and susceptible to crosstalk, EMI, and vibration. Hence this scheme is not utilize the basic superiority of optical fiber based sensors over conventional ones.

The signal demodulation method for the sensor systems discussed above generally adapts the lock-in-amplifier for conventional phase sensitive detection scheme and the PZT materials for active temperature stabilization. The lock-in-amplifier is expensive, usable in laboratory conditions only, and the final system including this amplifier is expensive, big, and heavy. The temperature compensation by the PZT material also requires the wrapping the fiber onto the cylinder type compensator or very large PZT driving voltage to induce the enough phase shifts for compensating the temperature induced phase change in the Mach-Zehnder type interferometer and Faraday effects sensors. The overall sensor systems discussed are heavy, complex, big, expensive, and operable only in laboratory conditions.

Here I propose a simple, compact, lightweight, inexpensive, and highly sensitive, optical fiber-based magnetic vector field sensor system. The sensor is based on the extrinsic Fabry-Perot interferometer (EFPI) for the space applications [1.13], [1.14].

In Chapter 2, the principle of the EFPI sensors and basic design considerations are discussed. Chapter 3 explores various performance enhancing techniques for basic sensor design. The system design for 3-dimensional vector magnetic field measurement is presented in Chapter 4. A simple passive/active hybrid temperature compensation and signal demodulation method is proposed in Chapter 5.