INVESTIGATION OF POTENTIAL INDUSTRIAL AND COMMERCIAL APPLICATIONS OF THE FIBER FABRY-PEROT INTERFEROMETRIC OPTICAL SENSOR

Shayne Xavier Short
University Undergraduate Fellow, 1992-1993
Texas A&M University
Department of Electrical Engineering

APPROVED

Fellows Advisor ____________________

Honors Director ____________________

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Shayne Xavier Short
Advisor: B. Don Russell, Ph.D., P.E.
Department of Electrical Engineering

University Undergraduate Fellows Program
University Honors Programs
Texas Engineering Experiment Station
The Texas A&M University System
College Station, Texas 77843
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Investigation of POTENTIAL INDUSTRIAL and COMMERCIAL APPLICATIONS of the FIBER FABRY-PEROT INTERFEROMETRIC OPTICAL SENSOR

Shayne Xavier Short, Student Member

Sponsor: B. Don Russell, Fellow
Power System Automation Laboratory
Electric Power Institute
Department of Electrical Engineering
Texas A&M University
College Station, Texas 77843-3128

ABSTRACT

There has been a strong interest in optical sensing devices lately. The non-conductive characteristics of optical fiber provide a means to insulate completely from the potential high voltages and large currents indicative to an electric power system. In addition, this optically insulating technology provides a means to monitor and detect parameters free from electro-magnetic interference (EMI) and radio frequency interference (RFI) that are present in electrical switchyards and relay stations [1]. Traditionally, ferromagnetic current and voltage transformers have served the power industry; however, a revolutionary leap towards innovative, optically-based sensing systems is preferred for a number of reasons, including safety consideration and economic viability. Optical sensing devices may be designed to very compact, relatively lightweight packages facilitating cheaper cost of manufacturing, easier non-disruptive installation, as well as alleviating the possibility of catastrophic explosion observed in current transformer breakdown.

Limitations of the traditional means of monitoring and measurement lie with their extremely high cost of manufacturing, emplacement, and maintenance. Additionally, ferromagnetic methods must insulate from large voltages and isolate from large currents in their design consideration. Industrial standard silica (SiO_2) optical fibers use light instead of current to transmit information. This removes the intense electric stress of the sensing environment from the monitoring and control environment. In particular, it is this intrinsic, insulating characteristic that allows an optical fiber sensor to be implaced in a power system with an optical fiber data link to a monitoring and control system. This allows for the major design consideration to be the protection of the integrity of the optical fiber link, not the voltage insulation and current isolation necessary for traditional means. It completely removes the most important safety design constraint of traditional means - - electrical insulation and protection.

This research program dealt directly with the Fiber Fabry-Perot Interferometer (FFPI), an optical sensor that has been under development at Texas A&M University for the past six years. Most notably, Chung Lee, Ph.D., inventor and patent holder of the sensor, and Henry F. Taylor, Ph.D., at Texas A&M have been most instrumental in the sensor's development, testing, and ruggedization. Laboratory testing has supported the Fiber Fabry-Perot Interferometer's (FFPI) function in a variety of practical applications which include but are not limited to: temperature sensing, ultrasonic and acoustic pressure sensing, voltage sensing and most recently current sensing applications. In addition to the development of the device physics of the sensor itself, much research has focused on the fiber optic signal processing required to integrate fully the Fiber Fabry-Perot Interferometer (FFPI) into an existing power system.

This research project possesses the possibility for a very real impact to the electric power industry. This paper will focus most directly on the evaluation of the Fiber Fabry-Perot Interferometer (FFPI) in applications as a temperature sensor and a voltage sensor in conjunction with a Piezo-electric transducer (PZT). The three parameters most fully addressed are voltage, current, and temperature monitoring and measurement with their implications for safe, efficient control of an electric power system. A possible current sensing application using the Fiber Fabry-Perot Interferometer (FFPI) with a magneto-strictive element, analogous to the voltage sensing scheme utilizing the FFPI in conjunction with the PZT, is also introduced.

Keywords: fiber Fabry-Perot interferometer, optical sensing, temperature sensing, electric power systems, fiber optics, high voltage (HV) insulation, voltage and current transducer.

INTRODUCTION

Optical fiber provides a means of monitoring and detecting parameters free from electro-magnetic interference (EMI) and radio frequency interference (RFI). Ferromagnetic current and voltage transformers have reliably served the electric utility industry since their conception; however, ever-increasing number of relays connected to each transformer winding has grown exceedingly large [2]. These traditional, point sensing, ferromagnetic means of monitoring do not possess the multiplexing capability to integrate the increased demand of electric sensing customers – a single transformer can monitor and measure only one point in a power system at a time. Growth of the power system and integration to other existing networks require, in addition to the new infrastructure for the new system itself, more current and voltage transformers to serve reliably and safely the larger power system. Several configurations of optical sensors show increasing promise of multiplexing capabilities.

Optically-based sensing systems are preferred for a number of reasons, including safety consideration, economic viability, multiplexing capability, size and weight, and less maintenance requirements. Optical sensing devices may be designed to very compact, relatively lightweight packages facilitating potential cost of manufacturing, easier non-disruptive installation, as well as alleviating the possibility of catastrophic explosion observed in current transformer breakdown. Limitations of the traditional means of monitoring and measurement lie with their extremely high cost of manufacturing, emplacement, and maintenance. For example, one voltage transformer in an extra high voltage (EHV) transmission network may cost up to one quarter of a million dollars. Optical sensors show promise for reducing manufacturing costs by over one order of magnitude (less than $25,000 per unit). Additionally, ferromagnetic methods require insulation from large voltages and isolation from large currents as a design consideration. Industrial standard silica (SiO_2) optical fibers use light instead of current to transmit information. Optical fiber is immune to the electro-magnetic interference (EMI) existent in most electric power systems. In particular, it is this intrinsic characteristic that allows an optical fiber sensor to be implaced in a power system with an optical fiber data link to a monitoring and control system. In a traditional sensing scheme, voltage insulation and current isolation are the primary design constraints. The intrinsic characteristics of the optical fiber perform this function innately, thus allowing the major design consideration to be the methodology of protecting the optical fiber data link.

This research program dealt directly with the Fiber Fabry-Perot Interferometer (FFPI), an optical sensor that has been under development at Texas A&M University for the past six years. Most notably, Chung Lee, Ph.D., inventor and patent holder of the sensor, and Henry F. Taylor, Ph.D., professor and director of the Institute for Solid State Electronics

(ISSE), Department of Electrical Engineering at Texas A&M have been most instrumental in the sensor's development, testing, and ruggedization. Laboratory testing has supported the Fiber Fabry-Perot Interferometer's (FFPI) function in a variety of practical applications which include but are not limited to: temperature sensing, ultrasonic and acoustic pressure sensing, voltage sensing and most recently current sensing applications. Recently, Been-Huey Wann, a graduate student in Electrical Engineering, completed a Master of Science thesis using the Fiber Fabry-Perot Interferometer (FFPI) with a Piezo-electric transducer (PZT) as a voltage sensor [3]. Currently, Youngil Park, a Ph.D. candidate in Electrical Engineering, has continued this research in an effort to further the responsiveness and ruggedness of this particular sensing application as well as preliminary research using the Fiber Fabry-Perot Interferometer (FFPI) as a current sensor in a similar configuration with a PZT as well as a configuration with gold coating on the FFPI utilizing induced thermal heating of the gold coating [4]. In addition, a possible current sensing application using the Fiber Fabry-Perot Interferometer (FFPI) with a magneto-strictive element, analogous to the voltage sensing scheme utilizing the FFPI in conjunction with the PZT. All experimentation and testing in this study was conducted with the direct assistance and cooperation of Youngil Park. For the FFPI to integrate into a power system, it must, like any sensor, be able to acquire data in a form that is easily evaluated, and it must be able to interface with existing infrastructure. Related research at Texas A&M University has dealt exclusively with developing the signal processing for the FFPI. This is absolutely necessary for the Fiber Fabry-Perot Interferometer (FFPI) to integrate fully into an existing power system [5].

This research project possesses the possibility for a very real impact to the electric power industry. This paper will focus most directly on the evaluation of the Fiber Fabry-

Perot Interferometer (FFPI) in applications as a temperature sensor and a voltage sensor in conjunction with a Piezo-electric transducer (PZT). Of the several parameters that need continuous real-time monitoring, current, voltage, and temperature head the list in degree of importance and necessity. These three parameters are most fully addressed with their implications for safe, efficient control of an electric power system. The Fiber Fabry-Perot Interferometer's (FFPI) optical sensing technology provides a means to insulate completely from the high voltages, large currents, and possible high temperatures indicative to an electric power system. A multitude of different optical sensor design types have been researched and studied, as well as the many that are still under intensive study at the time that this paper was written; however, none offers a combination of wide dynamic range, scalability, reliability, cost-effectiveness, and ruggedness to ensure enough economic incentive to begin industrial production and distribution on a large scale.

The purpose of this study was twofold: first, to evaluate existing optical sensing technologies and discern any apparent advantages and disadvantages that the Fiber Fabry-Perot Interferometer (FFPI) possesses in comparison to other state-of-the-art technologies. And, second, to direct research progress of the Fiber Fabry-Perot Interferometer (FFPI) in an effort to produce a particular configuration incorporating the FFPI with its electrically insulating fiber optic characteristics to a more rugged, ideally 'scalable' device capable of integration to an existing power system. Through this, an evaluation of the Fiber Fabry-Perot Interferometer (FFPI), in particular, its potential industrial and commercial applications, has been realized.

BACKGROUND of OPTICAL SENSORS

Temperature Sensor Developments

There have been many attempts to design a ruggedized temperature sensor capable of integration into a power system, both optical and non-optical. Industry has long relied upon the copper thermocouple; however, insulation from high voltages can still be a problem in particular applications due to the method by which it transmits information - - a voltage signal through a copper wire.

The majority of optical temperature sensing devices include some bulk optic temperature sensitive material that is attached to an optical communication fiber. Other applications including temperature sensitive material other than the optical fiber include coating the fiber with a temperature sensitive polymer [6]. Sensors integrating some other device into their sensor design are referred to as extrinsic sensors. For extrinsic sensors, the fiber serves solely as a communication link between the sensor and the optical electronics used to generate an electrical output signal from the optical signal for recording and display purposes [7].

Still, some optical temperature sensors utilize the fiber itself as the temperature sensitive material. These are referred to as intrinsic sensors. For example, one application using a Mach-Zehnder Interferometer, a two fiber sensor with one serving as a reference arm, employs one fiber as the temperature sensor itself [8]. In a Mach-Zehnder Interferometer, light is launched through both fibers, sensor and reference, and a phase shift is realized in the sensor fiber with respect to the reference fiber. Particularly in temperature sensing applications, it is a thermal effect that creates this phase shift in the reference fiber.

Perhaps the most innovative of optical temperature sensors is the Fiber Fabry-Perot Interferometer (FFPI), the optical sensor on which this research focuses. The FFPI uses the fiber itself as the sensor, and requires no reference arm. The FFPI sensor will be addressed in detail later in this paper.

A Fluoroptic™ Thermometer with a fiber optic probe has been developed and and implanted in a three-phase (3ϕ) auto-transformer [9]. A total of eight probes were installed with no multiplexing as each individual sensor required its own fiber optic extension between the probe end at the penetration device and the Fluoroptic™ instrument module. The sensor performed well, providing a linear relationship between winding temperature rise over oil and series winding current; however, the fiber optic probe lacked a high degree of oil resistivity, and an absence of multiplexing capability created problems with probe reconnecting for various instruments [9].

In addition, the Electric Power Research Institute (EPRI) has shown an interest in measuring hot spot winding temperatures of operating power transformers [10]. An improvement program was initiated to improve the all-quartz fiber Fluoroptic™ Thermometer probes. With ruggedization as the main design element, EPRI continued to develop a prototype monitor for winding temperature measurement in power transformers [11]. The actual sensing device comprises of two jacketed optical fibers butted up against one sensor face. The light signal travels in one fiber, traverses across the temperature-sensitive material sensor, and is recollected at the other optical fiber (Fig.1) [11]. The change in reflected light intensity is used to determine the relative temperature of the material upon which the sensor is mounted [11].

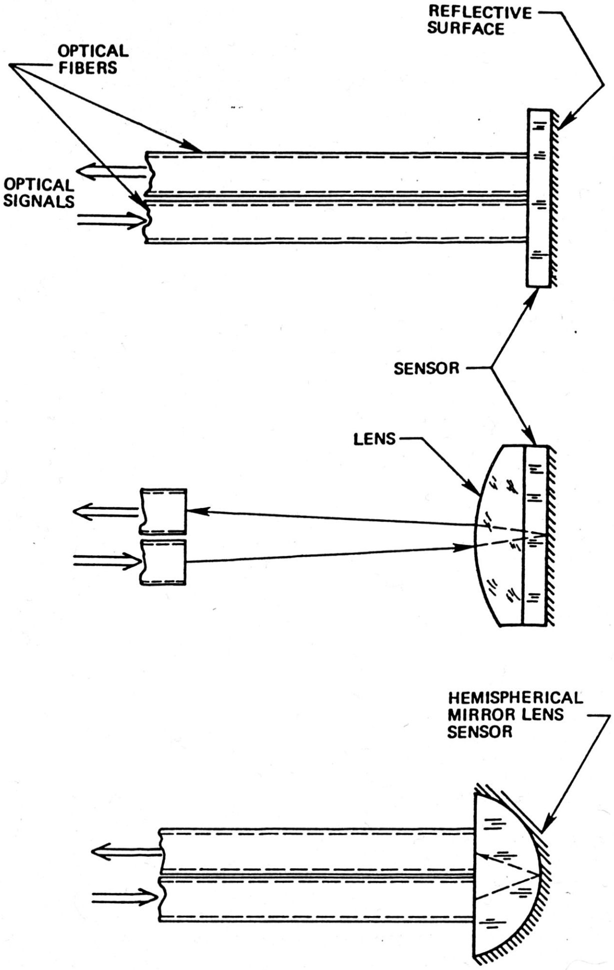


Figure 1: Fluoroptic^{TM} Thermometer Design Scheme [11]

Voltage Sensor Developments

Voltages in power systems must be monitored continuously. Accurate measurement of voltages in power systems is essential to ensure the delivery of high quality, inexpensive electric power. Most importantly, safety concerns demand accurate monitoring and measurement of voltages in power systems.

The most widely accepted method for measuring voltage via optical technology is known as the Pockels Effect. This method is analogous to the Faraday Effect, by which a magnetic field created by a current carrying conductor causes linearly polarized light to experience a rotation, except that in using the Pockels Effect, the polarized light is circular, not linear, and the present electric field forces a phase shift of the light relative to both orthogonal axes, not just one [12]. The phase shift of the light is referred to as retardance (Γ) and is given as [12]:

$$\Gamma = 2\pi \eta_o^3 r_{(u,k)} \frac{LE}{\lambda}$$

where,

- Γ = the Retardance (rad)
- η_o = ordinary index of refraction (-)
- $r_{(u,k)}$ = the Electro-optic constant ($\frac{\mathrm{m}}{\mathrm{V}}$)
- L = length of the optical axes (m)
- E = the present electric field ($\frac{\mathrm{V}}{\mathrm{m}}$)
- λ = wavelength of the light source (m)

Another application utilizes coating an optical fiber with a Piezo-electric plastic film. Piezo-electric materials react to the presence of an electric field by either contracting or expanding, depending on the polarity of the applied electric field with respect to the Piezo-electric's intrinsic polarity. More on piezo-electricity will be provided later. For this particular application, as an electric field induces a strain on the Piezo-electric plastic coating of the fiber, it transmits that strain directly to the fiber [13].

One application particularly relevant to this research program incorporated a Piezoelectric transducer (PZT) in a power line voltage sensing application. This method used the principle of Piezo-electricity inducing a strain on the PZT element, also inducing a strain on the optical fiber bonded to it [14]. The design uses a voltage dividing principle with two elements - - the capacitance of the PZT to which the optical fiber is bonded and the 'stray' capacitance to ground. One major drawback to this application is that in the design, a 'stray' capacitance to ground is assumed. This 'stray' capacitance may be highly variable. It is a function of a multitude of environmental conditions: temperature, humidity, atmospheric pressure, etc. Since no ground potential is established, it is difficult to assume, with a high degree of accuracy, the precision of this design scheme. In this application, the PZT induces a strain on the optical fiber bonded to it. This design incorporates no optical interferometry as in the Fiber Fabry-Perot Interferometer (FFPI) experiments utilizing PZT phenomenon addressed in detail later in this paper.

Current Sensor Developments

Current sensing in a power system is of utmost concern. Electrical utilities are charged to supply very high-quality, consistent power. Industrial and manufacturing plants such as automotive factories, textile factories, and even oil refineries are all large customers of electric power. Current levels must continually be monitored for revenue metering and protection measurements.

Recent emphasis has been placed on the development of a solely-optical current sensor for ruggedized power system applications. Several optical current sensors utilize the phenomenon of the Faraday effect, or the magneto-optic effect. This is similar to the Pockels

Effect, except that by the Faraday effect the laser light experiences rotation due to a magnetic field, not an electric field. By this phenomenon, linearly polarized light will experience a particular angle of rotation if traveling through a Faraday sensor in the presence of a magnetic field. This phenomenon has been under continually study in search of current sensing applications for over 25 years [15].

The Faraday effect utilizes the relationship of Ampère's Law between magnetic field intensity (H) and current (I) around a current carrying conductor given by:

$$I = \oint_{o}^{l} H \cdot dl$$

where,

- I = current through the conductor (Amps)
- H = Magnetic Field Intensity ($\frac{\text{Amp}}{\text{m}}$)
- l = closed loop path around conductor (m)

The Faraday rotation of the linearly polarized light traveling through a Faraday cell can be summarized as follows (Faraday Effect Rotation) [16]:

$$\theta = \mu_o \mu_r V \oint_{o}^{l} H \cdot dl$$

where,

- θ = Faraday rotation of polarization azimuth ($^\circ$)
- μ_o = relative permeability of free space ($4\pi \times 10^{-7}\frac{\mathrm{H}}{\mathrm{m}}$)
- μ_r = relative permeability of the material (-)
- V = Verdet constant, function of the material ($\frac{^\circ C}{T \cdot m}$)

The Faraday effect may be employed in a bulk optic system. A magneto-optic current transducer (MOCT) mounts a Faraday rotator completely around a current carrying conductor [2,17,18]. A light emitting diode (LED) launches a light signal into an optical fiber with a Faraday sensor. The polarization angle of the light is altered inside of the rotator and is then returned through another optical fiber to determine its change in intensity. A schematic drawing of the MOCT design configuration is included (Fig.2).

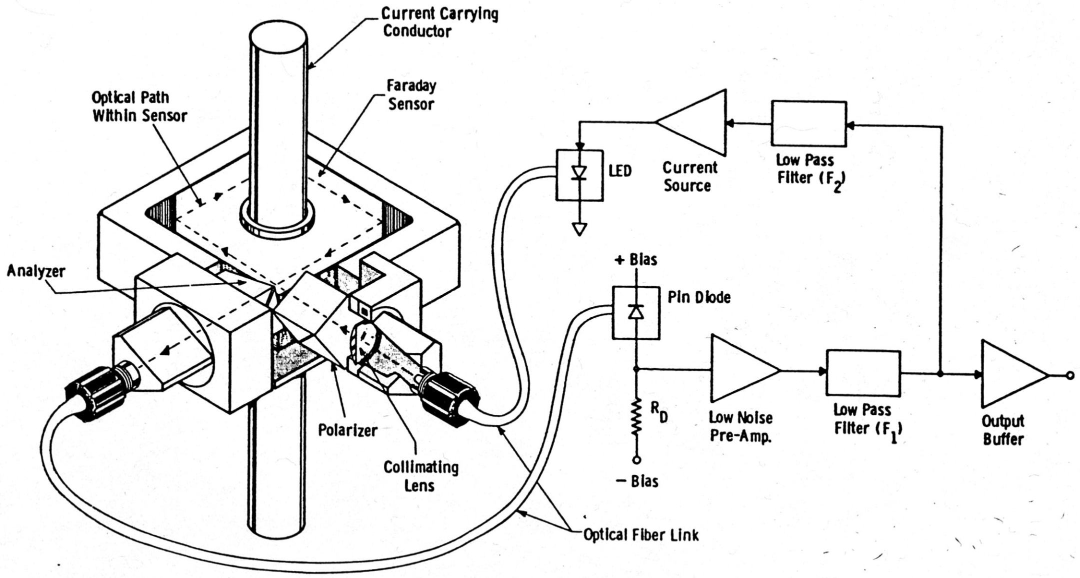


Figure 2: MOCT Bulk Optic Faraday Sensor [18]

Another bulk optic Faraday cell has been placed in the air gap of a small, toroid current transducer (CT) [19]. In the air gap, where the relative permeability is nearly unity ($\mu_r \approx 1$), the linear magnetic field intensity allows for a virtual linear relationship between light rotation and magnetic field intensity. The intensity modulated light entering the Faraday cell experiences polarization rotation upon passing through the cell (Fig.3).

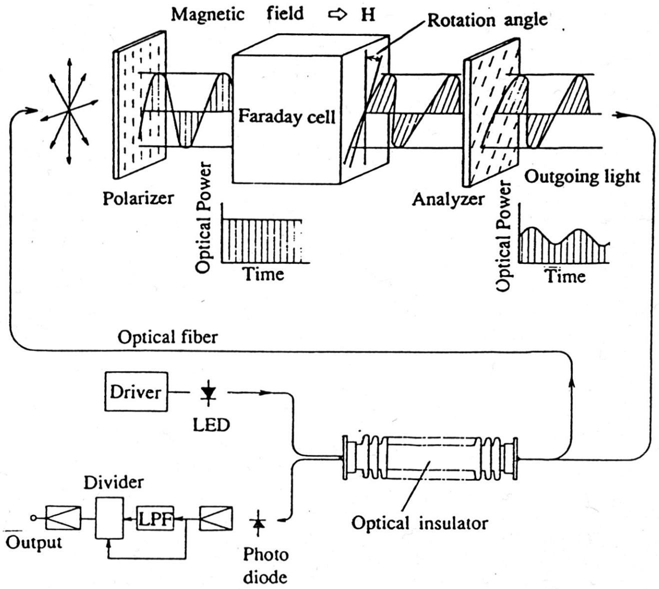


Figure 3: Bulk Optic Faraday Cell in Toroid CT [19]

Coiled optical fiber has also been studied for use as a Faraday rotator [16]. Coiled optical fiber produces additional circular birefringence in which the Faraday effect is distinguishable to any inherent fiber birefringence. Light travels to and from the fiber coil via two sections of polarizing fiber in much the same way of other Faraday sensors. Intrinsic, optical fiber current sensors, upon refinement and ruggedization, propose the most simplistic, practical solution to the optical current sensing challenge. The sheer simplicity of one example of an optical fiber current sensing coil is included (Fig.4).

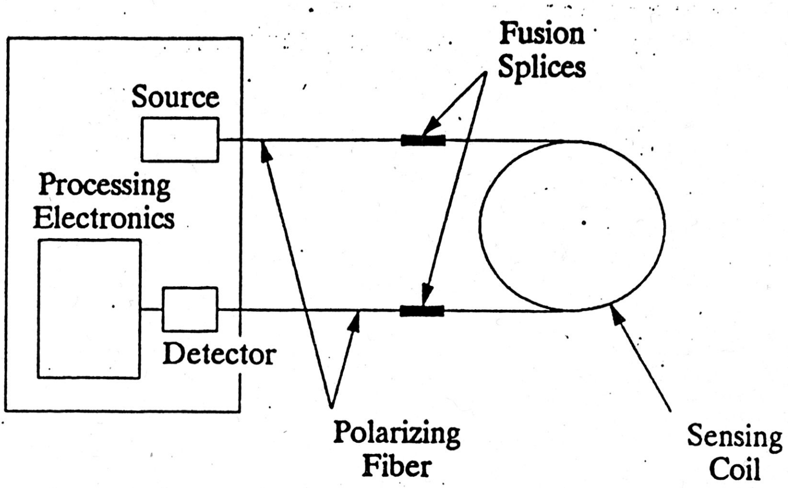


Figure 4: Coiled Fiber Current Sensing System [16]

FIBER FABRY-PEROT INTERFEROMETER DEVELOPMENTS

FFPI Operating Principle

A new approach for optical sensing has been demonstrated using the Fiber Fabry-Perot Interferometer (FFPI) at Texas A&M University. The FFPI utilizes the phase shift of laser light in a dielectric cavity to determine relativistic changes of the environment in which it is placed. The interferometer's dielectric cavity is comprised of two internal mirrors. A titanium-dioxide (TiO_2) film is produced at the end of one fiber; it is then spliced to another uncoated fiber [20]. The process is repeated to create the second successive mirror of the interferometer. As light enters the cavity, an interference pattern establishes between the dielectric mirrors. Interference fringes of the cavity are reproduced by a thermally-induced chirping with a pulse-modulated laser [20]. The round trip phase shift of the laser light, after reflection from the cavity back to a photodetector is represented by [3]:

$$\phi = \frac{4\pi}{\lambda}\eta L$$

- ϕ = phase shift of the laser light (°)
- η = index of refraction of the optical fiber, same as in the FFPI cavity
- L = optical path distance (OPD) of the dielectric interferometer cavity
- λ = free space wavelength of the laser light source

A small perturbation in this phase angle is a function of all three parameters and can be summarized as follows:

$$\Delta\phi = \frac{4\pi}{\lambda}(\eta\Delta L + L\Delta\eta) - \frac{4\pi}{\lambda^2}L\Delta\lambda$$

assuming that $\frac{\Delta\lambda}{\lambda} \ll 1$.

Particularly for low frequency power applications (f $\approx 60Hz$), the length change of the interferometer cavity is dominant in the preceding relationship and can be represented by the linear relationship as follows:

$$\Delta\phi = \frac{4\pi}{\lambda}\eta\Delta L$$

It is this characteristic of the relative phase shifting that is employed, in some capacity, for the following sensing applications.

FFPI Temperature Sensor Developments

Temperature measurement using the Fiber Fabry-Perot Interferometric (FFPI) sensor is based upon the fact that that the optical path distance (OPD) of the interferometer cavity will expand or contract as it comes into contact with a warmer or cooler temperature.

For a thermal perturbation (ΔT), the phase change of the light signal is given as follows [4]:

$$\Delta\phi = \frac{4\pi}{\lambda}(\eta\frac{dL}{dT} + L\frac{d\eta}{dT})\Delta T$$

The Fiber Fabry-Perot Interferometric (FFPI) temperature sensor has shown the greatest temperature sensing range of any optical sensor. The FFPI has been characterized over a 1250°C temperature range from -200°C to 1050°C [21].

ELECTRO-OPTIC LABORATORY TESTING

Two Fiber Fabry-Perot Interferometric (FFPI) temperature sensors were placed in the primary windings of a power transformer. The primary copper windings were exposed easily by bending back the protective cardboard sheathing surrounding the windings that separates the two respective windings, primary and secondary. The sensors were fabricated at Texas A&M University. The sensors were manually placed in the windings using a plastic/metal epoxy. This specific design required a small segment of fiber optic cable to connect the sensor, inside of the transformer, to the exterior of the transformer, from where the optical signal would be relayed to its signal electronics. Once the sensors were installed and tested to verify proper function, the bridge fibers from the sensors were then spliced to an insulated duplex cable housing two fiber-optic cables - - one for the top sensor and one for the bottom. An additional test was conducted to ensure the proper function of the sensors after splicing the duplex cable to the original fiber optic strand attached to the FFPI temperature sensor.

Preliminary testing using a Hewlett Packard DC current/voltage power supply was conducted in an Optics Laboratory of the Wisenbaker Engineering Research Center (WERC) at Texas A&M to verify temperature sensing capabilities under adverse conditions of the FFPI temperature sensor. The purpose of this particular test was twofold. First, assurance of temperature sensing function while submersed in the cooling oil of a transformer was paramount as many electrical generating systems utilize oil as their main temperature cooling element. Undoubtedly, the FFPI, when introduced to industry, will come into contact with some temperature sensing application requiring submersion in oil or some other liquid cooling agent. Second, the actual sensitivity of the temperature sensing characteristics of the FFPI was to be determined prior to the transformer's transport to the Downed Conductor Test Facility (DCTF) of Texas A&M's Riverside campus for high voltage testing. In the laboratory testing, the secondary windings of the transformer were shorted to avoid creating any potentially dangerous voltages. The power supply was connected directly to the primary. The maximum current producing capabilities of the power supply were $2.5A$ over a $75V$ range determined by the intrinsic open-circuit impedance of the primary windings of approximately 30Ω. Review of the DC test using the Hewlett Packard current supply indicated, as hypothesized prior to the actual experiment, that the top FFPI would experience more rapid temperature elevation than the sensor mounted lower in the primary windings due to excitation by a DC source. Results from the WERC Laboratory DC Temperature Test are included (Fig.5).

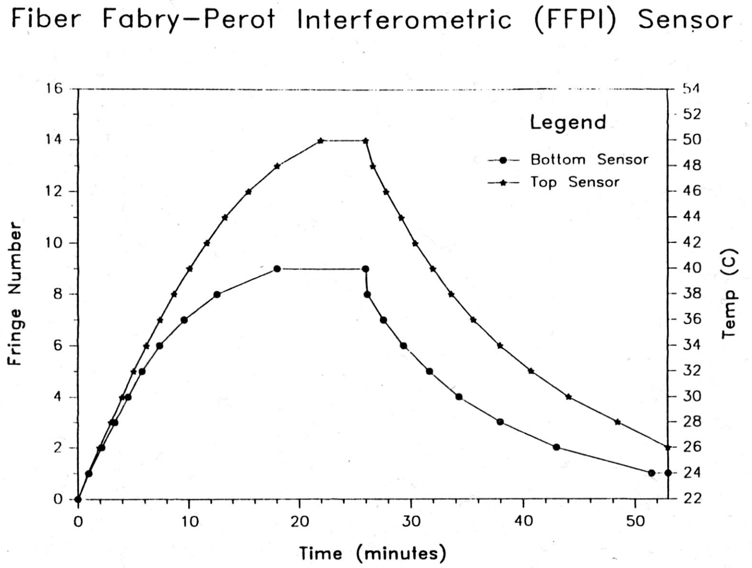


Figure 5: WERC Laboratory DC Temperature Test

Texas A&M DCTF Riverside Campus Test

Testing at the Downed Conductor Test Facility (DCTF) involved connecting full rated input line voltage to the primary, with a load rack connected to the secondary. The FFPI optical electronics were connected prior to the closing of the line. This allowed experimental data to be retrieved from a stable, unexcited point of an ambient temperature of approximately 24°C.

The transformer was transported to the testing site two days prior to the actual test date to ensure that the transformer was at an ambient equilibrium temperature and no temperature rising or falling during the actual test could be attributed to the distinct temperature difference between the laboratory in WERC and the Riverside campus 20 miles away, had the transformer been moved to the DCTF the day of the test. The resistive load rack attached to the transformer was capable of dissipating $6kW$ of power, but the transformer itself was rated for $10kW$. This underrated load resulted in an extremely long time constant required to bring the transformer to a saturated temperature level. Experimental results from the DCTF Field Temperature Test are provided (Fig.6). Data was retrieved while monitoring the rising temperature of the windings with an indication of eventual limiting to an exponential ceiling. The temperature was monitored for 45 minutes of rated voltage excitation. The test was then terminated because of the excessive time require to saturate the transformer with such an underrated load. Therefore, only temperature increase could be observed and monitored for the test at the DCTF. Results from the DCTF, despite incomplete temperature saturation, modeled nearly identical temperature rise in the copper windings, as anticipated, due to excitation by an alternating current (AC) power source.

The sensors embedded in the transformer where submersed in the cooling oil for over three months before the tests at the DCTF were conducted. The sensors themselves, because of their deep submersion, could not be inspected either before or after the testing conducted at the DCTF. However, the fiber optic cable connecting the FFPI sensors to the insulated duplex cable inside of the transformer was visually inspected and manually handled before and after the DC testing in the Optics Laboratory in WERC. No apparent damage if the silica (SiO_2) fiber cable was observed after submersion for a duration of three months in the

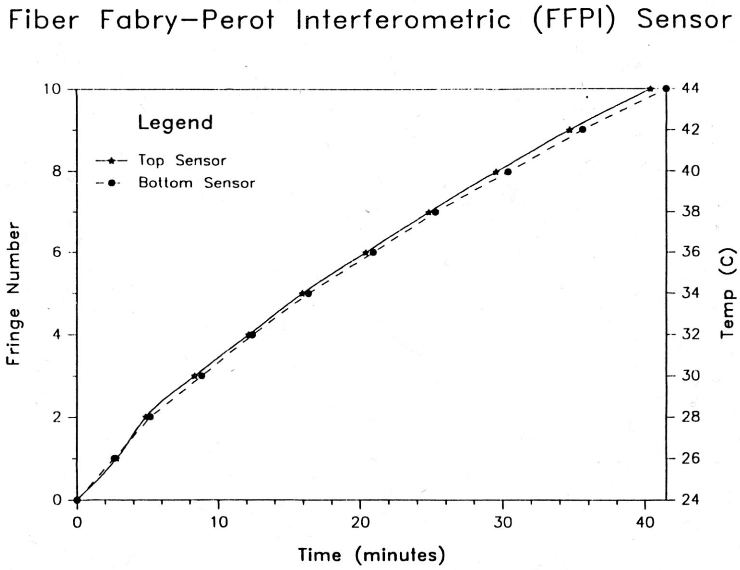
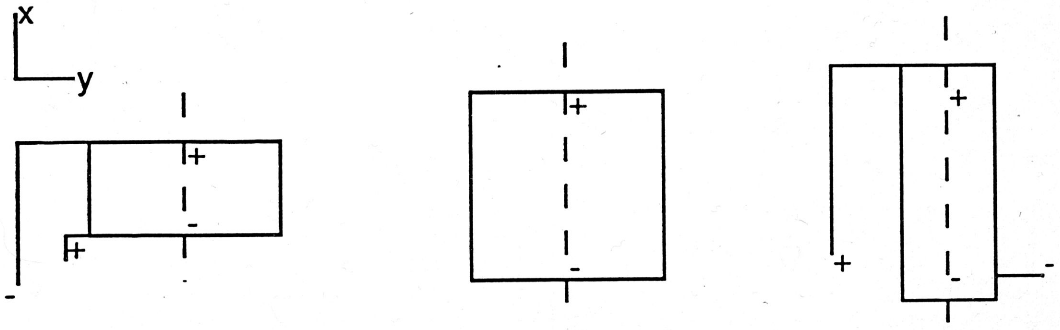


Figure 6: DCTF Field Temperature Test

cooling oil of the transformer. No decrease in the intensity of the transmitted optical signal resulted because of this submersion or exposure to full rated input voltage to the primary. The ruggedness of the FFPI optical sensors was demonstrated upon observation of their proper light signal carrying capabilities after three months of submersion in oil.

FFPI Voltage Sensor Developments

The Fiber Fabry-Perot Interferometer (FFPI) has been used in conjunction with a Piezo-electric transducer (PZT) in application as a voltage sensor. The principle on which this configuration works is the expansion and contraction of the PZT at the frequency of the voltage applied to it. At $60Hz$ frequency applications, particularly electric power applications, PZT's can easily respond and model identically the frequency at which applied voltage is modulating. The response characteristics of the FFPI have been introduced, so now the response characteristics of a plate type PZT, like the type used in the FFPI experiments, will be presented in order to understand precisely how the FFPI responds in this particular design scheme. As a voltage is applied to a rectangular PZT, it responds according to the applied voltage by the following [22]:



Voltage Applied
Opposite Polarity

No Voltage
Applied

Voltage Applied
Along Polarity

Figure 7: PZT Expansion and Contraction [22]

$$\Delta W = \frac{d_{31} V W}{\text{thk}} \qquad \Delta L = \frac{d_{31} V L}{\text{thk}} \qquad \Delta thk = d_{33} V$$

where,

- W, L, thk = width, length, and thickness of the plate PZT
- V = the voltage applied to the PZT
- d_{31} = constant of induced PZT strain, along length and width
- d_{33} = constant of induced PZT strain, along thickness

As the amplitude of the input voltage varies, so does the amplitude of the output optical signal. Using a digitizing oscilloscope, the output optical signal from the FFPI can be observed at $60Hz$. A $1kHz$ carrier frequency is put on top of the output optical signal to alleviate low frequency noise in the optical electronic system. Included is a figure, taken from an experiment utilizing the FFPI with a PZT in a voltage sensing application (Fig.8, p. 33). This, as all other experiments for this program, was executed with coordination between the Institute for Solid State Electronics (ISSE) and the Electric Power Institute's Power System Automation Laboratory (PSAL) at Texas A&M. Youngil Park, a Ph.D. candidate in Electrical Engineering, was most instrumental in working jointly with the PSAL in coordinating and conducting these and all other tests for this program. The output optical signal, as observed on a digitizing oscilloscope in included in the top half of the figure entitled, FFPI Input Voltage and Output Optical Signals (Fig.8). The lower portion of this figure is the input, or applied voltage to the PZT, a $60Hz$ voltage signal with amplitude ($V_{max} \approx 3V$).

For this experiment, the electrodes were connected opposite to the polarity of the poling axis. Therefore, a positive half cycle of the applied voltage waveform will, by matter of sign convention, cause contraction and a negative half cycle of the applied voltage will cause expansion. It can be observed from the waveforms that when the applied voltage reaches the maximum of its negative half cycle ($V= -3V$), that the PZT is expanded to its maximum (ΔL_{max}), and the FFPI expands as well, thus causing the greatest phase shift and the maximum amplitude in the output optical signal. It can also be seen, that as the applied voltage signal reaches the maximum value of its positive half cycle ($V= +3V$), that the PZT returns to its previous value, thus inducing very little to no (ΔL). Therefore, the greater the amplitude of the applied electrical signal, the greater will be the amplitude of the output optical signal. This can provide a RMS measurement of the applied electrical signal by means of analyzing the magnitude of the output optical signal.

As the longitudinal axis of the PZT contracts and expands, so does the optical path distance (OPD) of the interferometer, thus altering the intensity of the reflected laser light. It is this change in intensity, due to its phase change because of the contracting and expanding OPD of the interferometer, that results in a distinguishable output optical signal.

FFPI Current Sensor Developments

The most recent developments using the Fiber Fabry-Perot Interferometric (FFPI) sensor has been in the area of current sensing. In a joint project between the Institute for Solid State Electronics (ISSE) at Texas A&M University and the Sensor Technology Research Center at Kyungpook National University, Teagu, Korea, two different schemes for optical current sensing using the FFPI have been researched and studied here at Texas A&M [4]. Youngil Park, a Ph.D. candidate in Electrical Engineering at Texas A&M has played a key role in these two optical current sensing studies. A brief synopsis of this project's findings is provided.

One method involved coating a FFPI with gold. Gold was chosen as the resistive material because it is inert in air, thus minimizing any potential damaging effects to the FFPI, and it can survive at high temperatures [4]. This coating served as the resistive element through which current was forced, causing resistive heating in the FFPI.

For a thermal perturbation (ΔT), the respective change of the phase angle is given as follows [4]:

$$\Delta\phi = \frac{4\pi}{\lambda}(\eta\frac{dL}{dT} + L\frac{d\eta}{dT})\Delta T$$

This relationship is based upon the precept that the temperature change (ΔT) of the FFPI is proportional to the electrical power dissipated in the gold resistive element by [4]:

$$\Delta T \propto P(= i^2 R)$$

This method is advantageous because the FFPI itself is the current sensor, since the gold is coated directly to it. It requires no additional elements. However, with this application, it is difficult to filter out the optical signal harmonics, particularly if the filter in the system does not have good characteristics [4].

A different application used the FFPI in conjunction with a Piezo-electric Transducer (PZT). The principle by which a current sensor using a PZT with a FFPI is analogous to the application using it as a voltage sensor. As a current travels through the PZT, the intrinsic impedance of the PZT will create an electric field across this 'resistive' element, thus creating a similar effect of expansion and contraction that changes the optical path distance (OPD) of the interferometer [4]. For this sensor, the phase change is mainly dependent on the length change caused by an alternating current and is represented by:

$$\Delta\phi = \frac{4\pi\eta}{\lambda}(\frac{dL}{dT})\Delta I$$

where,

$$\Delta I \propto A \cos \omega t$$

This application does show promise and has produced linear response at low currents, but it is susceptible to thermal effects due to the sensitivity of the FFPI as the PZT heats up because of the current excitation. This particular application is presently employed using a Thermal Electric Cooler (TEC) to avoid any thermal effects due to the heating of the PZT. Possibly, a larger PZT in this application could reduce the thermal effects as it could dissipate more heat by itself.

One possible way to utilize the length changing characteristic of the FFPI sensor in a current sensing capacity would be with a magneto-strictive element. In much the same way that a PZT contracts and expands in the presence of a uniform electric field, magneto-strictive elements contract and expand in the presence of a magnetic field. This design is advantageous to using a PZT with a FFPI for current sensing applications because the parameter that links the length change of the FFPI to the current is a magnetic field, not an electric field, thus making it more amenable to current sensing applications. However, application attempts in using magneto-strictive materials have not shown as promising as utilizing a material as simplistic as a PZT.

CONCLUSIONS

The Fiber Fabry-Perot Interferometer (FFPI) has shown most promising in temperature sensing applications in both laboratory and field testing. The ability of the silica (SiO_2)

glass-type fiber sensor to survive such adverse conditions as submersion in the cooling oil of a transformer and complete insulation from the environment support the possible future introduction of the FFPI temperature sensor to industrial scale electric power systems. In addition, the small-scale characteristics of the sensor allow its implantation in extremely closed, tight spaces. In the transformer experiments, the sensors were installed in the transformer's windings without altering the physical structure of the transformer in any significant manner. Also, the fiber optic information relaying cables were extremely small, permitting snaking and weaving through extremely tight and narrow places inside of the transformer in order to connect the sensor to its optical electronics. Extensive testing and analysis have confirmed the Fiber Fabry-Perot Interferometric (FFPI) optical sensor's capability for potential industrial and commercial application for optical temperature sensing in rugged power systems and other electric environments of intense electrical stress. In related experimentation, the FFPI was embedded in an aluminum mold and still maintained a linear response to temperature change over a 150°C temperature range [23]. Perhaps a FFPI temperature sensor could be included in the manufacturing process of industrial infrastructure.

The Fiber Fabry-Perot Interferometric (FFPI) optical sensor has also shown great promise in applications as a voltage sensor. Testing in conjunction with a Piezo-electric transducer (PZT) have demonstrated the FFPI's ability to respond to a $60Hz$ voltage waveform modulation of the PZT. A very important and relevant application of the FFPI in terms of power system applications is that of a voltage sensor. The most important characteristic that the FFPI sensor can provide for voltage sensing is high voltage insulation. Although this particular insulating function can be achieved by using optical fiber to communicate between an electrical sensor in a power environment and a monitoring and control environment, the FFPI in conjunction with a PZT proposes a solution that will require no additional electronic circuitry in the power system, but only the FFPI itself and a PZT - - thus greatly reducing costs and maintenance problems.

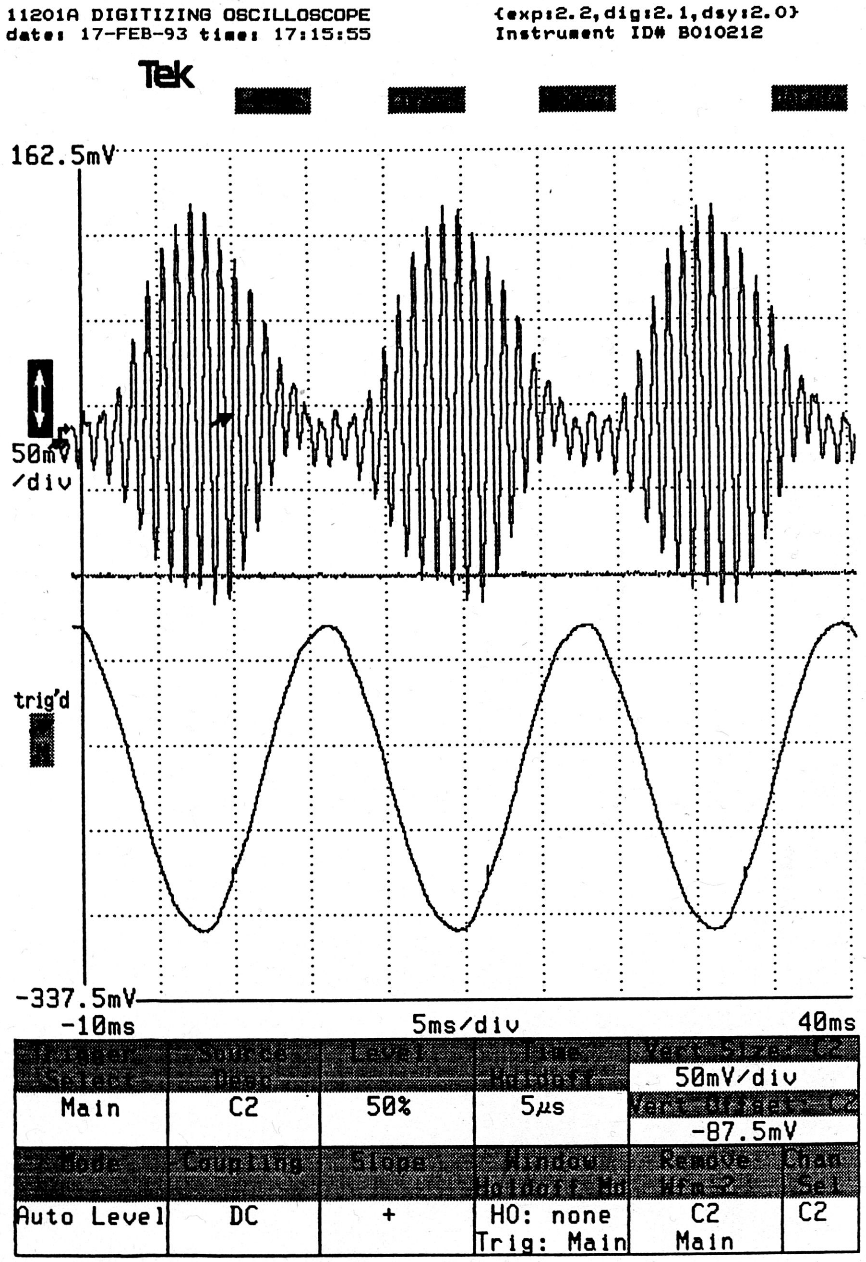
Another application using the Fiber Fabry-Perot Interferometric (FFPI) optical sensor in conjunction with a PZT in application as a current sensor also provides incentive for further research. However, when utilizing a thick PZT (thk $\approx 2.5cm$), a very large current must be applied to the PZT to establish an electric field large enough to induce contraction and expansion, thus creating a large enough (ΔL) in the FFPI to create a phase change in the corresponding optical signal. In the voltage applications with the FFPI and a thick PZT, a voltage of $(\approx 10V)$ was required to induce contraction and expansion. In the current applications with a thick PZT, not enough change (ΔL) was induced to cause any distinguishable change in the output optical signal at low current levels.

A thinner PZT is more responsive at low voltage levels, as induced by an applied current or applied voltage, from the relative thickness of the PZT. The thicker the PZT, the greater the ability to survive and respond to large voltage levels - - those voltage levels which would be seen in an electric power system. There is a definite trade-off between what type and thickness of PZT is chosen for FFPI sensing applications, and how distinguishable of a change is created in the optical output of the sensor. Several parameters must be evaluated in developing the best design to suit a specific application.

This research program has served as another motivation to continue researching and developing methods for optical sensing of parameters in electric power systems. The insulating characteristics of optical sensing technology may revolutionize the electric power sensing industry. The Fiber Fabry-Perot Interferometer (FFPI) has demonstrated its ability to endure the stresses indicative of electric power systems. It is an excellent candidate for potential integration into existing power system measurement for monitoring and control.

RECOMMENDATIONS for FURTHER RESEARCH

The Fiber Fabry-Perot Interferometer (FFPI) optical sensor has demonstrated the ability to monitor parameters in electric power systems. Further development using the FFPI should concentrate on current and voltage sensing. These two parameters are imperative to ensure the safety and reliability of a power system. For proper control of any power system, data must be extracted, analyzed and utilized to control and affect the system. The development of the FFPI optical sensor for power system control is an extended vision of the FFPI's application. Presently, the need to develop the FFPI, in some particular sensing scheme, is paramount to stepping towards the ultimate goal of utilizing optical control in electric power systems. Further research and development, with ruggedness as a primary directive, of the FFPI in voltage and current sensing applications is the most relevant direction of work that may lead to the eventual integration of the FFPI optical sensor in control applications for electric power systems.



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Auto Level	DC	+	HO: none Trig: Main	C2 Main	C2

Figure 8: FFPI Input Voltage and Output Optical Signals

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