PENINSULA TECHNIKON

Department of Electrical Engineering
Faculty of Engineering

Investigation into the monitoring of microwaves in microwave cavities using optical techniques

by

Matasane Clement Matasane

Submitted in part-fulfillment of the requirement for
Masters degree of technology (Mtech): Electrical engineering
Under the supervision of

Mohammed Tariq Ekeramodien Kahn

DECEMBER 2002

DECLARATION

I, Matasane C. Matasane, hereby declare that the dissertation presented here is my own work and the opinions contained herein are my own and do not necessarily reflect those of the Technikon. All references used have been accurately reported.

Name: Matasane Clement Matasane

Signature:

Date: February 2003

INVESTIGATION FOR MONITORING OF MICROWAVES IN MICROWAVE CAVITIES USING OPTICAL TECHNIQUES

by

Matasane Clement Matasane

ABSTRACT

The purpose of this research or study was to perform an investigation in the use of optical fibers as sensor elements in order to develop a millimetre wave instrument capable of measuring microwave power within microwave cavities. Included in the scope of the project was an investigation of microwaves and microwave power measurements techniques.

The emphasis of the research work was to develop expertise in photonics, by modeling and developing a measuring technique using optical techniques. This was deemed to be highly beneficial in laboratory experimentation and for possible use by microwave technicians. The implementation was amongst others, done by means of computer simulation and associated hardware, together with fiber-optic accessories.

In order to conduct this research a literature and technology survey of current non-optical microwave power measurement technique was done. With this a review different power measurements systems and their relationship towards microwave power measurements was conducted. Within the scope of the project, a study of fiber optics sensors and its components was also conducted, which enabled models for a Mach-Zehnder microwave sensor to be developed. This resulted in the development of inexpensive electronic signal

conditioning and detection techniques to enable measurements that employed a Mach-Zehnder Interferometer for this sensor technique.

Finally, as microwaves are difficult to measure with pure electronic equipment, different approaches were made to investigate the temperature changes and other parameters on optical fiber to avoid damage to it. The specifications of hardware and circuitry suitable to measure these effects were determined.

ACKNOWLEDGEMENTS

I would like to thank my supervisor, Mohammed Tariq Ekeramodien Kahn, for giving me the opportunity to join his research group and for providing such valuable support and technical guidance along the way. His example has taught me a great deal. Deep appreciation also goes to the Interlibrary Department at Peninsula Technikon for their superb skills in allocating the references.

Special thanks to Professor R. Tzoneva and Professor O. Kachienga from University of Pretoria for their support during the research process. Thanks to my supervisor who encouraged me to write publications and delivering papers at international conferences, dealing with part of my work. My thanks also belong to the many outstanding faculty members at the Peninsula Technikon who allowed me to tap their vast expertise and nurtured my desire to learn. In addition, great honor goes to the companies, which gave their support for equipment and courses to attend in order to expand my knowledge within field of my research. Particular thanks to Professor A. P. Staak and H Bowles, who enabled me to get funding to deliver a paper at 5th UICEE, Madras, India. It is a great honor to have worked with the National Laser Centre and the SA-Netconnect during assembling of the project.

I am deeply indebted to my parents, and my family for their continuing love and for providing the supportive environment. Finally, special thanks were long overdue to my wife, who gave birth to my son, Cheli, for her abundant patience in letting me finish what I had started and for offering so much love and encouragement throughout.

This work has been supported by the Peninsula Technikon Department of Electrical Engineering, the Faculty of Research Administration, MTN, and the National Research Foundation.

TABLE OF CONTENTS

GLOSSARY

Absorption - Loss of power in a fiber optic cable resulting from conversion of optical power into heat.

Analogue - A format that uses continuous physical parameters to transmit information. Examples of parameters are voltage amplitude and carrier frequency.

APD - Avalanche photodiode.

Attenuation - In fiber optic cable, attenuation results from absorption, scattering and other radiation losses.

Avalanche Photodiode (APD) - A photodiode that exhibits internal amplification of photocurrent.

Average power - The average level of power in a signal that varies with time.

Bandwidth - The information capacity of a fiber optic cable. Precisely it is usually measured in GHz (1 Billion Hz).

Beam splitter - An optical device, such as a partially reflecting mirror, for dividing an optical beam in 2 or more separate beams.

Cladding - A low refractive index glass or plastic that surrounds the core of the fiber optic cable. Optical cladding promotes total internal reflection for the propagation of light in fiber. The cladding steers light to the core.

Cleaving - The controlled breaking of a fiber so that its end surface is smooth.

Coating - A material put on a fiber optic cable during the drawing process to protect if from the environment.

Coherent light or light waves - This is light of which all parameters are predictable and correlated at any point into time or space, particularly over an area perpendicular to the direction of propagation or over time at a particular point in space.

Connector - A mechanical device mounted on the end of a fiber optic cable, light source, receiver or housing that mates to a similar device. It allows light to be coupled, optically, into and out of a fiber optic cable. A connector allows a fiber optic cable to be connected or disconnected repeatedly from a device. Commonly used connectors include FC/PC, Biconic (BNC), SC, and ST.

Core - The central, light carrying, part of a fiber optic cable. It has an index of refraction higher than that of the surrounding cladding.

Coupler - It is used in 2 contexts. First, it is a passive device that distributes optical power among 2 or more ports and this can be in different ratios. Secondly, it is a multi-pod device used to distribute optical power.

Coupling ratio - The percentage of light transferred to a receiving output port with respect to the total power of all output ports.

dB - Decibel, a measure of loss or equivalently attenuation. It is computed as a standard logarithmic unit for the ratio of 2 powers, voltages or currents.

Detector - A device that generates an electrical signal when illuminated by light. The electrical current is dependent upon the amount of light received.

Dispersion - A general term for those phenomena that cause a broadening or spreading of light as it propagates down a fiber optic cable.

EMI - Electromagnetic interference. It is any electrical or electromagnetic interference that causes an undesirable response, degradation or failure in electronic equipment. Fiber optic cables neither emits or receives EMI.

Extrinsic losses - Signal loss in transmission down fiber optic cable caused by imperfect alignment of fiber optic cables joined by a connector or splice. Contributors to this loss include angular misalignment, axial misalignment, end separation and end finish any imperfect joining caused by connector or splice.

Fiber - Thin filament of glass. An optical waveguide consisting of a core and a cladding which is capable of carrying information in the form of light.

Fiber loss - The attenuation (deterioration) of the light signal in transmission through a fiber optic cable.

Fiber optic waveguide - A relatively long strand of transparent substance, usually glass, capable of conducting an electromagnetic wave of optical wavelength (visible or near visible region of the frequency spectrum) with some ability to confine longitudinally directed, or near longitudinally directed, lightwaves to its interior by means of internal reflection.

Fused coupler - A method of making a multi-mode or single-mode coupler by wrapping fiber optic cables together, heating them and pulling them to form a central unified mass.

Fusion splicing - A permanent joint accomplished by the application of localized heat sufficient to fuse or melt the ends of the fiber optic cable. This process forms a single continuous fiber optic cable.

Graded index fiber - A fiber optic cable where the core has a non-uniform index of refraction. The core is composed of concentric rings of glass where the refractive indices decrease from the center axis.

GRIN - Graded indexes.

Index matching material - A material used at an optical interconnection. It has a refractive index close to that of the fiber optic cable core and is used to reduce Fresnel reflections.

Intrinsic losses - Loss caused by fiber optic cable parameter mismatches when 2 non-identical cables are joined. Examples of such parameters are core dimensions and index profiles.

Laser - An acronym for Light (by) Amplification (by) Stimulated Emission (of) Radiation. This is a device, which artificially generates coherent light within a narrow range of wavelengths.

Light Emitting Diode - LED. A semiconductor diode that spontaneously emits light from the pn junction when forward current is applied.

Lightwaves - Electromagnetic waves in the region of optical frequencies.

Mechanical splice - A splice in which fiber optic cables are joined mechanically for example by being glued or crimped in place. However, they are not fused together.

Microbending - Curvatures of the fiber optic cable which involves axial displacements of a few micrometers and spatial wavelengths of a few millimeters. Micro bends cause loss of light and consequently increase attenuation of the fiber optic cable.

Micrometer - 1 millionth of a meter, abbreviated mm. Also referred to a micron.

MMF - Multi-mode fiber optic cable.

Modes - In guided wave propagation, such as that through fiber optic cable, it is the distribution of electromagnetic energy that satisfy Maxwell's equations and boundary conditions.

NA - Numerical Aperture - The light gathering ability of a fiber optic cable. This defines the maximum angle to the fiber optic cable axis at which light will be accepted and propagated down the fiber optic cable.

Optical fiber coupler - This is used in 2 contexts. In the first it refers to a device whose purpose is to distribute optical power among 2 or more ports. In the second it refers to a device whose purpose is to couple power between a fiber optic cable and a source or detector.

Photodetector - An optoelectronic transducer, such as a pin photodiode or avalanche photodiode.

Photodiode (PD) - A semiconductor diode that produces current in response to incident optical power and used as a detector in a fiber optic cable data link.

Pigtail - A short length of fiber optic cable, permanently fixed to a component. It is used to couple power between the component and the fiber optic cable used for transmission.

Primary coating - The plastic coating applied directly to the cladding surface of the fiber optic cable during manufacture to preserve the integrity of the surface.

Refractive Index - The ratio of the velocity of light in a vacuum to its velocity in the medium. It is a synonym of index of refraction.

Single-mode - A small core, fiber optic cable that supports only 1 mode of light propagation above the cutoff wavelength.

Splice - An interconnection method for joining the ends of 2 fiber optic cables in a permanent or semi-permanent fashion. Thermal fusing may carry out splicing or it may be mechanical.

Splicing - The permanent joining of fiber optic cable ends to identical or similar fiber optic cables without using a connector.

ST - A keyed bayonet connector type similar to a BNC connector. It is used for both multi-mode and single-mode fiber optic cables.

Step index fiber - A fiber optic cable, either multi-mode or single-mode, in which the core refractive index is uniform throughout so that a sharp step in refractive index occurs at the core-to-cladding interface.

Wavelength - Distance an electromagnetic wave travels in the time it takes to oscillate through a complete cycle.

Wavelength Division Multiplexer - A passive fiber optical device used to separate optical signals of different wavelengths carried on 1 fiber optic cable.

CHAPTER 1

INTRODUCTION

Photonic circuits are becoming increasingly prevalent in areas such as communications, signal processing, and optical computing and designs [Liu and Li, 1992]. As the potential applications continue to be proposed, the complexity of optoelectronic components and sensors has expanded to meet these new challenges.

These have encouraged improvements in light sources; optical fibers, cables, and connectors; and photodetectors. Capitalizing on the availability of optical components, there has been significant progress during the past few years toward the development of a new class of sensors employing fiberoptic. These sensors are capable of detecting acoustic fields, linear and rotational acceleration, electric and magnetic fields, and many other physical parameters. In effect, the sensor modulates some feature of the lightwave in an optical fiber such as the intensity or the phase.

Usually phase modulation must be converted to an intensity modulation prior to detection. This may be accomplished by means of an optical interferometer. The resulting signals (intensity or phase) can be telemetered to places other than the location of the sensor (transducer, modulator) by means of a fiberoptic signal transmission (telemetry) system. The optical signal may be in analog or discrete form and the system may operate with or without optical-to-electrical or electrical-to-optical signal conversion.

The fiber optic sensors described in this manual may use fiberoptic transmission systems as well as electrical or electromagnetic transmission systems. Even for the simplest case, one in which a visual field or image is to be transmitted in a coherent-fiber cable, the fiber bundle itself must serve as the sensor and all the aspects of achieving lightwave acceptance by optical fibers must be considered.

PURPOSE

This document on fiberoptic sensors is designed to be a stand-alone document intended to serve many purposes. It provides a basic background for understanding the concepts that make up the field of fiberoptic, particularly as they apply to fiberoptic sensors. It describes the properties of optical fibers, then fabrication, and the properties of light sources and detectors associated with fiberoptic sensors. Specific emphasis is placed on design considerations that make use of these components and for associated connector, splices, couplers, and cables.

Different schemes have been described which may be used for controlling lightwaves in order to sense a physical parameter. These control schemes are discussed in this document, including interferometry for phase detection arrangement and intensity modulation as is the application to be focussed on for use in design of an instrument capable of measuring microwave power in microwave cavities, that is in commercial and laboratory use. This is based on phase modulation detection. Included are the sensor topology used, optical mathematics methods and functions used for signal detection and their transfer functions for phase detection using a fiber optic Mach-Zehnder Interferometer. The aim of this document describes the possibilities and investigations for the phenomenon of microwave energy effect applied to the fiber optics within the microwave cavity (that is, the investigation of the microwave energy effects on fiber optics with the aid of fiber optic Mach-Zehnder interferometer).

CONTENTS BY CHAPTER

Following this brief Introduction (Chapter 1), Chapter 2 gives the literature review and survey of common microwave measurement sensors to new technology being investigated. It describes the principles and definitions of microwave power towards microwave energy effect in microwave cavities. The fundamentals of power measurements to improve or design a new sensor capable of using fiber optic as a sensor are described. This will overcome the surface mount sensor commonly found in basic microwave cavities. Chapter 3 is devoted to the properties of the basic component of the fiberoptic sensor. Electromagnetic wave (lightwave) propagation in optical fibers in terms of the wave equation; the coupling of lightwaves in and out of fibers. Fundamentals of fiber optics and their theory applications are important. They play major role due to their advantages and properties in transmission and sensing department. Chapter 3 describes its fundamentals associated with light propagation and in different types of fiber, which had been used and introduction of its basic components that are considered during transmission, processing and electronic circuits used for measurements.

Finally, the chapter closes with a discussion of the characteristics and limitations of photodetectors with special emphasis on their importance and use in connection with the output signal from a fiberoptic sensor.

Chapter 4 follows with a discussion of the various means for connecting fiberoptic sensor inputs to electrical or optical sources and outputs to photodetectors or display devices. In this chapter, the overview of fiber optic sensors is discussed, and its common use and where they can be found for special different applications. Included are the basic concepts of fiber optic use and their potential within the environment. It also gives brief on various common type of sensors and multiplexing and modulation of the signal measurand.

The operation of fiberoptic sensors cannot be well understood without an understanding of the various actions and interactions that can take place by and among lightwaves. Many of these interactions are the basis for sensing physical parameters. This chapter turns primary attention from general principles and techniques used in the operation of fiberoptic sensors to a description of the sensors themselves and their components. Intensity modulation sensors and phase modulation devices are discussed; giving different type of modulation techniques that can be used within fiber optic sensors.

Chapter 5 includes interferometrics and phase modulation. This outlines an understanding of its operation, as to how it can be phased with phase modulation with respect to its mathematical functions and responses to physical measurements. It describes the method on developing a model for the Mach-Zehnder interferometer fiber optic sensor. Chapter 6 describes the investigations the temperature changes to avoid damage to the fiber, particularly looking at the size of the fiber used. The intention is to design the hardware and circuitry suitable to measure its effects within the cavity. This indicates clearly of the process carried out on designing the electronic circuit modules and interconnections of the whole setup. It describes the work carried with the aid of Mach-Zehnder Fiber Optic Interferometer sensor, the scheme of experimental setup, photodetector, laser module, couplers and patch cords, and the sensitive elements, which make up the interferometer.

Chapter 7 is devoted to the computer-based model of the microwave power within the fiber as being modelled by using FemLab, toolbox of Matlab. A computer-based model of the thermal response incorporating conduction within the fiber, by treating it in a series of concentric at different temperature during thermal transient is a further development that must be investigated. This will be looking at the thermal response incorporating conduction and radiation caused by microwave energy.

As measurements will be taken using fiber optic Mach-Zehnder Interferometer, this is to identify the physical mechanisms related to an understanding of the thermal transient induced in an optical fiber microwave sensor when exposed to microwave power. That is, the response of the single mode fiber without secondary coating to microwave power must be investigated. The study should also include the response of the optical fiber to a transient in temperature. Conclusions and comments about the experiment and design are mentioned in Chapter 8.

References and bibliographies pertinent to the subject are included in this document. The appendices include some of the techniques involved in handling and installing fiber optic sensor components, together with the publications made during the research. The glossary of terms and definitions in the field of fiberoptic with emphasis on the terms used to describe the design, and operations of fiber optic sensors are included at the beginning of the document.

Many topics and concepts related to fiber optic sensors, their operating principles, and supporting theory are included in the glossary so as not to overburden the reader with too many details while the main topics are being discussed. For example, concepts concerning various types of fiberoptic sensors and interferometers are described in the glossary.

While an attempt has been made to make the chapters as independent and readable as possible, a complete understanding of some of the sensing techniques employed may require careful study of all of the chapters and many of the references, especially on mathematical analysis of them. A large number of drawings have been included in the report to help in understanding the implications of fiber optic sensor and different sensing mechanisms. This report contributes to these fiber optics measurements, fiber optic sensor technology and some of the applications that make this field interesting, which is still in its early infancy, and one of the most promising new developments.

CHAPTER 2

LITERATURE REVIEW AND SURVEY

The use of microwave technology in power measurement in laboratory and commercial work has shown an increase in recent decades [Udd, 1989]. Since power measurement has important commercial sub-divisions, this requires reliable equipment and appropriate high accuracy measurement techniques. As the objective is to use fiber optics to measure microwave power within a microwave cavity, it is important to investigate such power and the components or devices used in order to measure the desired signal power, presently. As a result, tracing different definitions and their relationship towards microwave power measurement, together with techniques used in different instruments is important as these will help in the present sensor development, which is the topic of this thesis.

2.1 THE IMPORTANCE OF POWER MEASUREMENTS

A system's output power level is frequently the critical factor in the design, and ultimately the purchase and performance of almost all RF (radio frequency) and microwave equipment. The first key factor in this development is the equity in trade, and the second being the measurement uncertainties, which cause ambiguities in the realizatio of performance of the equipment.

Being a challenge to detect microwave signals, it is necessary to convert the signal power directly or indirectly into some form of mechanical or visible energy [HP Application Notes 64-1A]. Furthermore, as it is critical when specifying the components that make up the system, the equipment and techniques to be used must be accurate and traceable to monitor the absolute magnitude of the output power flowing during operation.

Power measurement is based on the detection of microwave energy generated by a magnetron into the microwave cavity with respect to its heating and absorption effects. Microwave cavities use various combinations of electrical circuits and mechanical devices to produce and control an output of microwave energy for heating.

2.2 MICROWAVE CAVITY DESIGN AND OPERATION

2.2.1 WHAT ARE MICROWAVES?

Microwaves are very short waves of electromagnetic energy that travel at the speed of light (3×10^8 m/s). Microwaves used in microwave cavity are in the same family of frequencies as the signals used in radio and TV broadcasting. Generally speaking, the system of a common microwave cavity is divided into two fundamental sections, the control and high-voltage section. However, the heart of every microwave cavity is the high voltage (3800 volts) system, which is the magnetron tube. Its purpose is to generate microwave energy at a frequency of 2450MHz.

2.2.2 DETECTION OF MICROWAVES

Generating significant power at microwave frequency is inherently expensive [HP Application Notes 64-1A]. As one will be looking at the power range from 1watt to 800 watts at a frequency of 2450MHz, this could be costly. Methods, which are useful to indicate the presence of microwave signals and the measurement of their relative magnitudes, are essential in some cases to determine the absolute magnitude of the power in the system. These could be measured or represented by other parameters during the test.

The currently employed devices for sensing and measuring average power at Radio Frequencies (RF) and microwave frequencies (2500 MHz), each use a different kind of device to convert the RF and microwaves power to a measurable DC (Direct Current) or low frequency signal. These are surface mount devices (thermistor, thermocouple, and the diode detector) as described. Each device has some advantages and disadvantages over the others and also some measurement uncertainty for power transfer and calibration. Hence these devices need provision for isolation from thermal and physical shock, and must keep leakage small so that microwave power does not escape from the mount in a shunt path around it. They should be kept at close thermal contact. Also point contact devices are required on detection regions and this limits the RF and microwave frequencies for absolute power measurement.

In regard, many systems are continuously monitored for output power during ordinary operation. As a result, large number of power measurements and their importance dictates that measurement equipment must be accurate, repeatable, traceable and convenient, together with the techniques used.

Different techniques are used to detect microwave power in different applications. There are currently considerable interests in techniques utilizing optical fibers for the different measurements. There is also a potential advantage in systems using optical fibers as the fiber could both be the transmission medium and the transducer, which is electrically safe, immune to EMI (electromagnetic interference), and chemically inert. Therefore, it can be used in adverse environments, especially for particular purpose in use for microwave power measurement as its parameters (refractive index, and length) could be of interest during the experiment. Hence the review and literature survey on microwave energy and technology on current non-optical microwave power measurement devices is important to be defined. These will clarify the purpose and objectives of the anticipated design. Review of the microwave cavity design and operation, together with its basic structures, microwave generation and their effects towards power usage is also useful to give an idea on how it works and what factors does one has to expect.

2.3 NON-OPTICAL POWER MEASUREMENTS

These give basic power measurements, principles and techniques towards artifact of using fiber optic as a sensor within the environment to measure microwave power. It deals with different definitions within microwave measurements relating to different instruments used. It discusses different techniques used to measure microwave power in different instruments on applications to various frequencies. It also focuses on principles of the devices used in the instruments and their detection of the signal power present in the environment.

2.4 BASICS OF MICROWAVE SYSTEMS

The term microwave is used to denote that part of the electromagnetic spectrum for which the free space wavelength is less than about 0.5metres extending into the region of millimetric wavelengths. In terms of frequency the coverage is about 0.5GHz to 100GHz, and more. On characteristic, that becomes possible to consider radiation at such wavelength in terms of quasi-optical behaviour [Sander, 1987].

2.4.1 MICROWAVE MEASUREMENTS

2.4.1.1 PRINCIPLE OF MICROWAVE MEASUREMENTS

Several techniques for the measurement of power in waveguides were developed, but are in adequate in common applications; therefore direct measurements of power are not always possible at the desired level. Also, attention should be made that measuring any unknown quantity is done by comparing it with a known quantity, which is taken at that time as a standard [HP Application Notes 64-1A]. With respect to these, the designed performance of a system can only be achieved if the component parts are behaving according to the assumed specification.

Further, the selection of proper equipment and measuring techniques depends primarily on the accuracy, speed and costs required by the application. Some applications require knowledge of both amplitude and phase characteristics of microwave.

2.5 POWER MEASUREMENT

By and large, the measurement of power replaces the measurements of voltage and current in numerous relative measurements, as these quantities tend to lose their meaning in the distributed circuits encountered in typical microwave applications [Laverghetta, 1988]. Most instruments for power measurement commonly used are thermal type. However, measurement of power in a microwave circuit is fundamental, unlike voltage or current and it is independent of the position in a waveguide.

Direct measurements of power are not always possible at the desired level. The interest is in measuring power to determine the cost of work performed in terms of energy expended. In most applied sciences, a power measurement application establishes a means for evaluating the work capability and efficiency of the devices. The continuous effort is to design a more efficient systems that will increase the work capability of microwave devices that leads to higher accuracy requirements in measurement art. In this, several questions are laid as where to start analyzing the signal available at the port.

(a) What is the quality of the signal, which is given?
(b) Is it modulated or not?
(c) It's stability?
(d) What kind of response does it have?

Furthermore, for better power measurements, there are four key steps in selecting a power meter and the sensor that influence their accuracy, economy, and technical match to the application:

(a) Understanding the signal under test
(b) Understanding measurement uncertainty and tractability
(c) Understanding sensor and power meter technologies and features
(d) Making performance comparisons and considering your installed equipment.

Hence it is important to characterize a source that delivers power through a waveguide to a load, as that power delivered to the load is the available power from the source. An obvious way of measuring power is to measure the heat produced on absorption. This technique is useful above a few watts and it depends on the conversion of microwave power to heat energy [Bailey, 1985].

In addition, the selection of proper equipment and measuring technique depend primarily on the accuracy, speed and cost required by the application. Some applications require knowledge of both amplitude and characteristic of the microwave components and are usually made in design laboratories. Therefore, the signal analysis can form this category as to one, which deal with the basic measurements such as power measurement of the device concerned, hereto giving the basic power measurement techniques.

However, a system's output power level is frequently the critical factor in the design, and ultimately the purchase and performance of almost all RF (radio frequency) and microwave equipment. The first key factor is the equity in trade, and secondly, the measurement uncertainties cause ambiguities in realizable performance of the equipment [Laverghetta, 1988].

This leads to define power measurement with respect to its different solutions in systems measurements, as it does have units and definitions. Commonly, there is relative power, usually expressed in decibels (dB).

$$\mathrm{dB} = 10 \log \frac{P}{P_{ref}} \qquad 2.1$$

Apart from this, there is an average power to be discussed. It is very popular and is also used in specifying almost RF and microwave systems. However the fundamental definitions of power is energy per unit time. But the important question to resolve is over what time is the energy transfer rate to be averaged when measuring or computing power? In a more mathematical approach to power for a continuous wave is to find power at given frequency.

$$P = \frac{1}{nT_0}\int_0^{nT_0}\{e_p \sin(\frac{2\pi}{T_0}t)\times i_p \sin(\frac{2\pi}{T_0}+\phi)\}dt \qquad 2.2$$

Where n is the number of AC periods, T_o is the AC period, e_p and i_p represents the peak values e and i, ϕ is the phase angle between e and i. This yields for n =1, 2, 3, ...

$$P = \frac{e_p i_p}{2}\cos\phi \qquad 2.3$$

Above all this, brings a question of why it is important to measure microwave power in microwave cavities. By response, since power measurement is the major factor on industry, laboratories and commercial places, it is important that it can be duplicated at different times and at different places. Hence, as mentioned, it requires well-behaved equipment, good measurement technique, and common agreement as to what is the standard watt range to indicate when used.

Furthermore, there are other types of power measurements in microwave work. In most applications, they require knowledge of average power in a device; the other requires peak power over periodic pulse.

For the average power, the sum of all instantaneous values of power are divided by the period over a given time period. This means that the energy transfer rate is to be averaged over many periods of the lowest frequency involved, which is simply defined as follows.

$$P = \frac{1}{T}\int_0^T\{e\times i\}dt \qquad 2.4$$

Where P is an average power, T is the period of the lowest frequency component of e(t) and e(t), e(t) and I(t) is an instantaneous values of voltage and current. For ac circuit, average power is expressed mathematically by

$$P = E_{rms} \times I_{rms} \times \cos\phi \tag{2.5}$$

Where E_{rms} and I_{rms} is equated as $E_{rms} = \frac{e_p}{\sqrt{2}}$ and $I_{rms} = \frac{i_p}{\sqrt{2}}$.

However, for the peak pulse power, the measured is averaged with the time during the pulse in on. That is, energy transfer rate is averaged over the pulse width, τ. With this, the rectangular microwave pulse is obtained.

$$P_{pk} = \frac{P_{ave}}{Dutycycle} \tag{2.6}$$

Duty cycle is $\frac{\tau}{T}$. The pulse width τ is considered to be time between 50% rise or fall-time of amplitude points. The fundamental standards of microwave power lie in dc or low frequency, ac power, which may be used for comparison or substitution when accurately, measured.

In addition, since microwave sources are sometimes pulse-modulated, it is necessary to differentiate between measured powers (that is, mean (or average) power, pulse power and peak power). Mean and pulse are time-averaged values. They differ in time interval involved in the averaging. The RF power at the peak of the pulse modulation is termed peak power ($P_{(peak)} = \frac{V_p^2}{R}$). Measurement of peak power (P_p) is however difficult, method to determine is to calculate it from mean power (P_m). It is equated by $P_p = \frac{kP_m}{Tf}$, where k is a constant; T is the time and f being the frequency [Cheung and Levien, 1985].

2.6 COMMON MICROWAVE POWER SENSORS

Power measurements made at microwave frequencies are by means of thermal sensitive devices. They measure the heat generated by the microwave energy present in that device and convert it into another form of signal, which is detectable by the devices used within the cavity. Such devices fall under one of the three common categories. That is, thermocouple, bolometer (microwave power up to 10mW average is measured using this technique, that is when power is dissipated in a resistive element, a corresponding change occurs in the element's resistance), and calorimeter (convert input power into heat and observed by change of resistance produced in them) [HP Application Notes 64-1A].

From an economic point of view; we are interested in measuring power to determine the cost of work performed in terms of energy expended. In order to detect microwave signals, it is necessary to convert the signal power, directly or indirectly into some form of mechanical or visible energy as to detect the presence of the signal. Few basic microwave devices are given below. These give their difference of operation and detecting techniques towards microwave, though they are based on waveguides of lower frequencies.

2.6.1 THERMOCOUPLE POWER MEASUREMENTS

The thermocouple is formed when two wires of different metals have one of their junctions at a higher temperature than the other. The difference in temperature produces a proportional voltage. The device is used to measure the temperature rise, which dissipates microwave power; by appropriate calibration, the temperature change is converted to an indication power. They have excellent sensitivity and are especially useful as power monitors; their primary applications are in low and medium power areas.

2.6.2 BOLOMETRIC POWER MEASUREMENTS

Bolometer is a device for detecting electromagnetic radiation by converting it to heat and measuring the subsequent change of electrical resistance. It is made up of a wire, which is subjected to microwave radiation; it changes its resistance because of the resultant heating. It is useful in measurements in which accuracy is of importance, but they are comparatively of low sensitivity. It measures up to about 10mW average power. The basic is that, when power is dissipated in a resistive element, a corresponding change occurs in the element resistance.

2.6.3 VERY-LOW LEVEL MICROWAVE POWER MEASUREMENTS

A very low-barrier schottky diode power sensor makes it possible to measure power as low as 100 picowatts over a frequency range of 10MHz to 18GHz. Its power range is –20 to –70dB, a range where most other sensors become noisy or subject to thermal drift. This is diode detector [Pratt, 1975].

2.6.4 THERMOELECTRIC POWER SENSOR FOR MICROWAVE APPLICATIONS BY COMMERCIAL CMOS FABRICATION

Thermocouple-based power sensors have been one of the most widely used tools for microwave power measurement. These sensors employ a simple principle of RF power to thermal power conversion, which is then indirectly measured. In this application, a matched terminating resistor dissipates the RF energy as heat that is converted into dc voltage by one or more thermocouples, thus providing an accurate measurement of true root mean square (rms) power absorbed by the resistor. This operates efficiently up to 20GHz and more [Milanovic et. al, 1997].

2.6.5 PRECIZION MEASUREMENT OF MICROWAVE POWER USING RESISTIVE SENSORS

Point contact or schottky diodes are basically used to detect the envelope of a microwave pulse. Unfortunately they can handle only a small amount of power of the order of 1watt. It is placed in the waveguide and fed by a current source. This is a resistor sensor of a bar shaped n-type silicon (Si) with ohmic contacts on both ends. When subjected to the strong electric field of the microwave pulse, electrons gain some additional energy and a steady state occurs, which means the electron energy is grater than equilibrium one [Dagys et. al., 1996].

Measurement capability is a vital for fiber optics as it is in other technology, but optical measurements differ in important ways from others. Proper measurements require careful definition and control so that everyone knows exactly what is being measured and what it means.

2.7 BASIC OPTICAL MEASUREMENTS TECHNIQUES

Fiber-optic measurements involve light and other quantities, such as the variation of light with time, in the same way important electronic measurements involve electric fields and currents. This brings the observation on how light intensity varies a function of time, which requires measuring time as well as light. Working with light means measuring an optical power, and usually must be measured as function of time position and wavelength.

2.7.1 OPTICAL POWER

Specialized terminology makes fine distinctions about quantities related to optical power as they involve complex quantities. Basic measurable quantities related to optical power are illustrated in the table.

Table 2.1: Quantities Related To Optical Power

Energy (Q)	Amount of light energy
Optical power (P or ϕ)	Flow of light energy past a point at a particular (dQ/dt)
Intensity (I)	Power per unit solid angle
Irradiance (E)	Power incident per unit area
Radiance (L)	Power per unit solid angle per unit projected area

Power measures the rate at which electromagnetic waves transfer light energy, mathematically it is expressed as

$$P=\frac{d\phi}{dt}=\frac{d(energy)}{d(time)} \qquad 2.7$$

Compared to electrical power, for light and other forms of electromagnetic radiation, optical power is proportional to the square of the light wave amplitude (measuring. the electric field in the wave).

With types of optical power measurements indicated, optical power can be measured not just by itself, but also in terms of its distribution angle or space. Hence, the main concern of fiber-optic measurements is with total power (in the fiber or emerging from it), but other light-measurement units must be considered [Hecht, 1998]. These introduced the light detectors, irradiance and intensity, peak and average power, energy, wavelength, spectral response measurements, phase and interference of the light waves.

Measurements of optical power require knowing the wavelength and duty cycle. The power may be output from a light source, power emerging from a length of optical fiber, or power in some part of the system. The simplest optical measurement instrument includes the fiber connector, calibrated detectors and light source, electronics for signal processing and a display.

2.8 MEASUREMENTS USING FIBER OPTICS

The technology and applications of optical fibers have progressed very rapidly in recent years [Udd, 1989]. Optical fiber, being a physical medium, is subjected to perturbation of one kind or the other at all times. It therefore experiences geometrical (size, shape) and optical (refractive index, mode conversion) changes to a larger or lesser extent depending upon the nature and the magnitude of the perturbation. In communication applications one tries to minimize such effects so that signal transmission and reception is reliable.

On the other hand, in fiber optic sensing, the response to external influence is deliberately enhanced so that the resulting change in optical radiation can be used as a measure of the external perturbation. In communication, the signal passing through a fiber is already modulated, while in sensing, the fiber acts as a modulator. It also serves as a transducer and converts measurands like temperature, stress, strain, rotation or electric and magnetic currents into a corresponding change in the optical radiation.

Since amplitude (intensity), phase, frequency and polarization characterize light, any one or more of these parameters may undergo a change. The usefulness of the fiber optic sensor therefore depends upon the magnitude of these changes, and its ability to measure and quantify the same measurand reliably and accurately.

CHAPTER 3

FIBER OPTICS TECHNOLOGY

3.1 INTRODUCTION

The principles behind fiber optics have been known since antiquity and have been used for centuries in such devices as prisms and illuminated fountains. Although early scientists worked out the theory, little progress was made until the 1950's. Since then, there has been explosive development with most of the current effort being aimed at making fiber-optics less expensive and a better carrier of light in instrumentation and environment monitoring.

Optical fiber was only a scientist's dream two decades ago, but today this extraordinary technology is a reality and is transforming the way the world sends and receives information as light being the carrier of the data transmitted. It is still in its infancy and more researches will bring many breakthroughs in this millennium. For an example, developing a microwave detector using fiber optic. With the design to be carried, one has to look at its fundamentals towards sensing purposes to detect microwave energy. This research is intended for the fiber optics technology for sensing purposes in commercial microwave cavities.

3.2 FUNDAMENTALS OF OPTICAL FIBERS

The basis of fiber optics is in the refractive index (or index of refraction) of the cable. In free space, light travels at 3×10^8 m/s, (c). This is the theoretical maximum speed of communication, but this speed can never be obtained unless the transmitting medium is air. One of light's basic properties is that its velocity is related to the frequency, (f) and the wavelength, (λ) as shown by Equation 3.1.

$$c = \frac{\lambda}{f} \qquad 3.1$$

When light enters a transparent material it no longer travels at the speed of light. It now travels at a speed related to the material's refractive index (n) as shown by Equation 3.2.

$$n = \frac{c}{V} \qquad 3.2$$

where V is the velocity when light enters the material. When light traveling in a dielectric material passes through a boundary to a second material, such that 'n' (from Equation 3.2) of the new material is less than the original, part of the light will be reflected back and part will be bent (or refracted) as it enters the new material. This is caused by the change in the speed of the light since the two materials have different refractive indices. This relationship at the interface of the two materials is shown in Equation (3.3), and is called Snell's Law [Hetch, 1993].

$$n_1 \times \sin(\phi_1) = n_2 \times \sin(\phi_2) \qquad 3.3$$

Where n_1 and n_2 represents medium 1 and 2 as showed in Figure 3.2. When using an optically denser material (a higher refractive index) and as the incident angle becomes smaller, the refracted angle will approach zero. Thus, for smaller angles, total internal reflection will be obtained. This is the main objective of fiber optics. All light traveling down the fiber should ideally be totally reflected back into the medium at the fiber interface, so that the light will continue to propagate down the material. If this doesn't take place, losses will occur and transmission will not be possible within the fiber.

According to the law of reflection, the reflected ray will be at the same angle as the incident ray. For large angles as the glass or air interface, light will be reflected. Yet, as this angle decreases, a point is reached where the light ray in air entering the glass will become parallel to the glass surface. This is known as the critical angle of incidence. When the incident angle is less than the critical angel, the condition of total internal reflection is satisfied. This concept is really an idealized situation. In practice there is always some optical energy tunneling through the interface, which comes about from the electromagnetic wave theory of light. Optical fibers have three basic layers as shown in Figure 3.1[IEEE Communications, 1996].

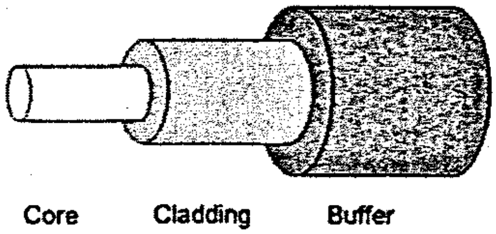


Figure 3.1: Fiber Structure

The first layer is the single solid dielectric cylinder core, which is mainly glass (silica). It has a refractive index n_1. This is the medium that the light is propagated down through. Surrounding the core is the cladding, which has a refractive index of n_2 that is less than n_1. This means that total internal reflection will occur. Although the cladding is there, it is not really necessary for the light to propagate down the fiber. The cladding really serves several other basic purposes. Its main function is to reduce scattering loss resulting from discontinuities at the core surface. It also adds mechanical strength to the fiber and protects it from coming in contact with surface contaminants [Keiser, 1993 and Jeunhomme, 1983]

The last layer is a buffer coating around the cladding. This plastic material is abrasion-resistant and it adds further strength to the fiber. It also buffers the fibers from small geometrical irregularities, distortions, or roughness on adjacent surfaces that come in contact with the fiber. Optical fibers come in two main types. These are brought about by different material compositions in the fiber core. The first type is when the core material is uniform throughout. This is appropriately called a step- index fiber (SI) as shown in Figure 3.2 [Dakin and Culshaw, 1988].

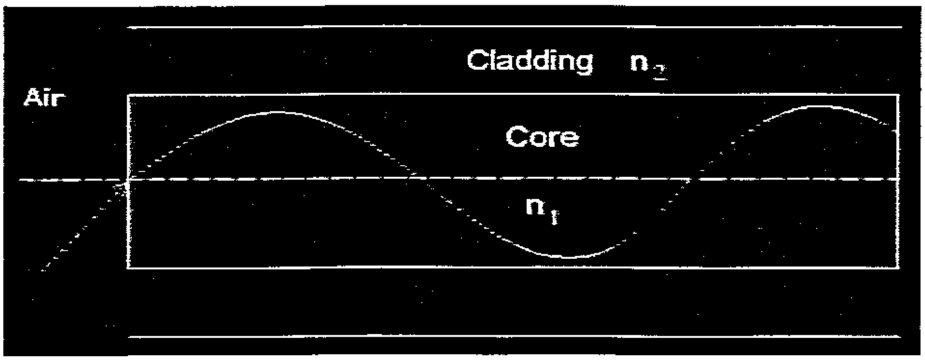


Figure 3.2: Step Index Fiber

This is due to the abrupt change at the core-cladding interface where all reflection takes place. The second type of fiber has a varying core composition. The refractive index of the core at the center is n_1. Then the index is allowed to vary as a function of distance from the center to the radius of the core, which will be n_2. This is called a graded-index fiber (GI). Light in this fiber does not reflect at the core or cladding interface. Instead, it takes a sort of sinusoidal path down the fiber. Due to its path and the relationship between the values of n, a much high velocity of light can be obtained than with a SI fiber. Both of these types of fibers can then be divided into single mode and multimode fibers [Keiser, 1993 and Drietrich, 1981].

Modes are the different principle patterns of electric and magnetic field lines traveling down the fiber core. A single mode fiber is one in which only one pattern of the electric field is able to propagate down the fiber due to its size. Multimode fiber allows many patterns to travel down the fiber simultaneously. Comparing size, single mode fibers are very small in diameter and multi mode is comparatively larger.

Multimode fiber has many advantages over single mode fiber. Multimode fiber is much larger and therefore precision does not need to be as exact. This alone seems to make it the better choice. Not only that, but the larger core makes it easier to send optical power down the fiber. This also facilitates the connection of two fibers together. Another advantage is that light can be sent into a multimode fiber by a light emitting diode (LED), while single mode fibers must generally use laser diodes.

Although LED's have less optical output than laser diodes, they are easier to make, cheaper, require less complex circuitry, and have a longer lifetime than laser diodes. This makes them more desirable in many applications. The main problem with multimode fiber is that it suffers from intermodal dispersion. When light is sent into a fiber, each of the modes carries part of the optical power of the transmission. Each of these modes travels at a slightly different velocity down the length of the fiber causing a delay in time as the pulse travels. This delay causes the pulse power to be spread out in time and could affect neighboring bits. This is what is known as intermodal dispersion. It can be greatly reduced by using a graded-index fiber instead of a step-index fiber, allowing the signal to have a larger bandwidth. Single mode fibers allow much higher bandwidths, as intermodal dispersion is not present [Christian, 1989].

In order to make fiber as a realistic sensor transmission medium, fibers with low signal losses are necessary. This is determined by the quality of the fiber manufacturing process. To mention this, different types are stated.

3.2.1 MULTI-MODE STEP INDEX FIBER

Multi-mode step index fiber is the simplest of all the fibers used. The diameters are very large in comparison to single-mode step index fiber. It should be noted that the expression step index means that there is an abrupt change in the refractive index at the core or cladding boundary [Barker, 1985].

Multi-mode step index fiber can collect light very easily because of the large core diameter and large NA. The typical Numerical Aperture (NA) of multi-mode step index fiber is between 0.2 and 0.4.

Multi-mode step index fiber is primarily affected by material dispersion, which is caused by the wavelength dependence of the refractive index of the fiber. In other words, different wavelengths of light travel at different speeds through the fiber. Waveguide dispersion is not a negative factor in multi-mode step index fiber because the presence of many modes in the fiber effectively eliminates any problems. Profile dispersion does not add to the overall dispersion of multi-mode step index fiber and can be ignored [Culshaw, 1984].

3.2.2 MULTI-MODE GRADED INDEX FIBER

The term graded index means that the core refractive index is high at the center and gradually decreases to the cladding refractive index at the core or cladding boundary. Multi-mode graded index fiber is typically made with core or cladding diameters of 50mm or 125mm and 62.5mm or 125 mm. The typical NA of multi-mode graded index fiber is the same as multi-mode step index fiber, between 0.2 and 0.4.

3.2.3 SINGLE-MODE STEP INDEX FIBER

Single-mode step index fiber is designed to eliminate high order modes. As the name implies, only one low order mode will propagate through the core [Barker, 1985].

It is more difficult for single-mode step index fiber to collect light because of the small core diameter and small NA. The typical NA of single-mode step index fiber is between 0.1 and 0.15. Since single-mode step index fiber only has one mode that propagates the core, multi-mode (intermodal) dispersion does not affect the bandwidth of the fiber [Christian, 1989 and Culshaw, 1984].

Discussing dispersion in a single-mode step index fiber, the spot size of the fiber should first be defined. That is, the spot size is the diameter of the fundamental mode in a single mode fiber.

3.3 USE OF OPTICAL FIBER AS SENSOR

Some of the ways to make the running of fiber more cost effective is to use lower grade fiber optics, or to use fiber-optic cable made of plastic instead of glass. The speed and bandwidth capabilities of fiber optics allow it to be used in sensing technology that was previously unavailable. An exciting current use for fiber optic technology is in industrial field applications. Many times it is not the high data rate characteristic that makes it attractive, but its high resistance to electromagnetic interference [Kahn, 2000].

The main and important rapidly developing field is the use of optical fibers in sensing external conditions such as strain, pressure, displacement, temperature, acoustic waves, current, magnetic and electric fields. It provides several advantages over their electrical counterparts. These include high bandwidth, small size, lightweight, corrosion resistance, geometrical flexibility and an inherent immunity to electromagnetic interference (EMI) [Udd, 1991].

The general principle behind a fiber optic sensor is surprisingly simple. In most fiber optic communication applications, for an example, it is undesirable for the lightwaves travelling through the fiber optic cable to be affected by the environment because this will cause the message being sent to be possibly disrupted/distorted. A fiber optic sensor measures the changes in the light exiting the optical fiber sensor and can calculate the property of the environment that caused the change. Some common applications of fiber optical sensors are: strain gauges, fluid level sensors, temperature sensing, and industrial process monitoring, just to name a few of its use.

The evolution of fiber optic sensor application in the marketplace greatly depends on the availability of less expensive components that are used in development of fiber optic sensors. The maturation of fiber optic communication technology will slowly expand the applications for fiber optic sensors as the costs of laser sources and single-mode couplers decline and their performance in fiber optic sensing systems improves. Areas such as aerospace, automotive, electric utility, chemical or gas, food processing, and medical or health care will significantly benefit from the development and expansion of fiber optic sensors.

Another examples are in construction. The security of structures designed by civil engineers demand periodical monitoring. The current methods are often tedious and require the intervention of specialized operators. The resulting cost and complexity limit the frequency of these measurements where they are taken. There is obviously a real need for a tool that would allow automatic and permanent monitoring from within the structure itself with a high degree of precision and good spatial resolution. This is an area where fiber optics has a huge future.

3.4 APPLICATIONS OF FIBER OPTICS

With the advent of lasers and semiconductor optoelectronics, a great revolution in modern optics took place. Rapid developments in fiber optics gave an additional impetus to this. Holography and Fourier Optics are well known photonic techniques. The above developments have led to the birth of a new discipline, popularly called Photonics.

In photonics, photons play a role akin to electrons in electronic materials, devices and circuits. As a result, a large number of activities, which were traditionally in, the electronic domains are now shifting to the realm of photonics. To mention a few, progress in the use of photonics in sensing, signal processing, communication and computing has been rapid. The main advantages are in terms of speed and security.

It is also well known that in addition to the high technology and scientific activity, a whole range of mass items like compact discs, photocopiers and laser printers have been the result of photonic technologies. Wide ranges of fiber optic sensors are fast reaching the market place. Freedom from electromagnetic interference and unprecedented speed and bandwidth are prime reasons for all the success in photonics. One of the exciting fields wherein photonics is expected to play a significant role is smart structures and intelligent systems of interest in engineering. This is where the real challenge lies even in the case of fiber optic sensors and photonic communication and control systems. In smart structure applications, composite materials, fiber optic sensing and telemetry systems, piezoelectric actuators and microprocessor based control schemes seem to offer the best advantages as of now [Dakin and Culshaw, 1988].

3.5 FIBER OPTIC SENSORS TECHNOLOGY

The technology and applications of optical fibers have progressed very rapidly in recent years. Optical fiber, being a physical medium, is subjected to perturbation of one kind or the other at all times. It therefore experiences geometrical (size, shape) and optical (refractive index, mode conversion) changes to a larger or lesser extent depending upon the nature and the magnitude of the perturbation. In communication applications one tries to minimize such effects so that signal transmission and reception is reliable.

On the other hand, in fiber optic sensing, the response to external influence is deliberately enhanced so that the resulting change in optical radiation can be used as a measure of the external perturbation. In communication, the signal passing through a fiber is already modulated, while in sensing, the fiber acts as a modulator. It also serves as a transducer and converts measurands like temperature, stress, strain, rotation or electric and magnetic currents or waves into a corresponding change in the optical radiation. Since amplitude (intensity), phase, frequency and polarization characterize light, any one or more of these parameters may undergo a change [Giallorenzi et. al, 1982]. The usefulness of the fiber optic sensor therefore depends upon the magnitude of this change and therefore gives the ability to measure and quantify the same reliable and accurate measurand.

The advantages of fiber optic sensors are freedom from electromagnetic interference (EMI), wide bandwidth, compactness, geometric versatility and economy. In general, FOS is characterized by high sensitivity when compared to other types of sensors. It is also passive in nature due to the dielectric construction. Specially prepared fibers can withstand high temperature and other harsh environments. In telemetry and remote sensing applications it is possible to use a segment of the fiber as a sensor gauge while a long length of the same or another fiber can convey the sensed information to a remote station [Kersey and Dandridge, 1990, Farhad, 1993]. Many signal processing devices (splitter, combiner, multiplexer, filter, delay line etc.) can also be made of fiber elements thus enabling the realization of an all-fiber measuring system. Recently, in photonic circuits, integrated optics has been proposed as a single chip optical device or signal-processing element, which enables miniaturization, batch production, economy and enhanced capabilities.

There are a variety of fiber optic sensors. These can be classified as follows; namely, based on the modulation and demodulation process a sensor can be called as intensity (amplitude), a phase, a frequency, or a polarization sensor. Since detection of phase or frequency in optics calls for interferometric techniques, the latter are also termed as interferometric sensors. From a detection point of view the interferometeric technique implies heterodyne detection or coherent detection. On the other hand intensity sensors are basically incoherent in nature. Intensity or incoherent sensors are simple in construction, while coherent detection (interferometric) sensors are more complex in design but offer better sensitivity and resolution.

Fiber optic sensors can also be classified on the basis of their application. Physical sensors (e.g. measurement of temperature, and stress); chemical sensors (e.g. measurement of pH content, gas analysis, spectroscopic studies, etc.); bio-medical sensors (inserted through catheters or endoscopes which measure blood flow, and glucose content). Both the intensity types and the interferometric types of sensors can be considered in any of the above applications [Kahn and Thompson, 2000].

Extrinsic or intrinsic sensors are another classification scheme. In the former, sensing takes place in a region outside of the fiber and the fiber essentially serves as a conduit for the to-and-fro transmission of light to the sensing region efficiently and in a desired form. On the other hand, in an intrinsic sensor one or more of the physical properties of the fiber undergo a change as mentioned above.

3.5.1 BASIC COMPONENTS

A fiber optic sensor in general will consist of a source of light, a length of sensing (and transmission) fiber, a photodetector, demodulator, processing and display optics and the required electronics as illustrated by Figure 3.3 below.

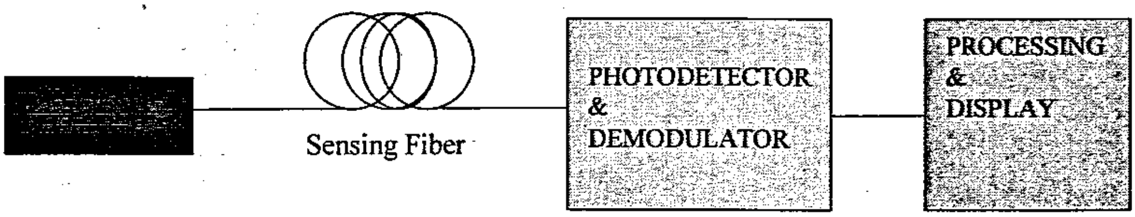


Figure 3.3: Basic of fiber optic sensor

3.5.2 TYPES OF OPTICAL FIBERS

Optical fibers are thin, long cylindrical structures, which support light propagation through total internal reflection. An optical fiber consists of an inner core and an outer cladding typically made of silica glass, although, other materials like plastics are some times used. Three types of fibers are in common use in Fiber Optic Sensors (FOS). The multimode (MM) fiber consists of a core region whose diameter (~50 mm) is a large multiple of the optical wavelength. The index profile of the core is either uniform (step-index) or graded. Plastic fibers have a step index profile and a core size of about 1-mm. The microbend type or the evanescent type intensity sensors use MM fibers. Multi-mode fiber has the advantage that it can couple large amount of light and is easy to handle, both the advantages arising from its large core size [Culshaw, 1984, Udd, 1991, and Farhad, 1993].

Single mode (SM) fiber is designed such that all the higher order waveguide modes are cut-off by a proper choice of the waveguide parameters as given by Equation (3.4) below.

$$V = \frac{2\pi a}{\lambda}\sqrt{(n_1^2 - n_2^2)} \qquad 3.4$$

Where, λ is the wavelength, a is the core radius, and n_1 and n_2 are the core and cladding refractive indices, respectively. Single mode (SM) fiber is an essential requirement for interferometric sensors.

The SM fiber mentioned above is not truly single mode in that two modes with degenerate polarization states can propagate in the fiber. This can lead to signal interference and noise in the measurement. The degeneracy can be removed and a single mode polarization-preserving fiber can be obtained by the use of an elliptical core fiber of very small size or with built in stress. In either case light launched along the major axis of the fiber is preserved in its state of polarization. It is also possible to make a polarizing fiber in which only one state of polarization is propagated. For an example, polarimetric sensors make use of polarization preserving fibers. Thus, multimode fiber, single mode fiber and polarization preserving fiber are the three classes of fibers which are used in the intensity type, the interferometric type and the polarimetric type of sensors, respectively [Personick, 1985, Giallorenzi et. al, 1982, and Udd, 1991].

3.5.3 SOURCES

Semiconductor based light sources offer the best advantages in terms of size, cost, power consumption and reliability. Light emitting diodes (LEDs) and laser diodes (LDs) are the right type of sources although in laboratory experiments the He-Ne laser is frequently used. Features of LED include very low coherence length, broad spectral width, and low sensitivity to back reflected light and high reliability. They are useful in intensity type of sensors only. Laser diodes on the other hand exhibit high coherence, narrow line width and high optical output power, all of which are essential in interferometric sensors. Single mode diode lasers are made using distributed feedback or external cavity schemes.

High performance Mach-Zehnder and Fabry-Perot type sensors need single mode lasers. LDs in general are susceptible to reflected (feedback) light and temperature changes.

They are also less reliable and more expensive. Coupling of light from source to fiber is an important aspect and may call for special optical devices. Use of pigtailed source can alleviate this problem but such devices cost more. Fiber lasers and amplifiers are fast becoming commercial products and may play an important role in future fiber optic sensors.

3.5.4 DETECTORS

Semiconductor photodiodes (PDs) and avalanche photodiodes (APDs) are the most suitable detectors in fiber optic sensor (FOS). Avalanche photodiode (APD) can sense low light levels due to the inherent gain because of avalanche multiplication, but need large supply voltage. Various noise mechanisms associated with the detector and electronic circuitry limit the ultimate detection capability. Thermal and shot noises are two main noise sources and need to be minimized for good sensor performance. Silicon PD is good for visible and near infrared (IR) wavelengths. Generally there is no bandwidth limitation due to the detector as such, although the associated electronic circuits can pose some limitation [Kersey and Dandridge, 1990].

3.6 CONCLUSION

Fiber optics has become a very important part of modern day technology. Although it is still in its infant stages, fiber optics has an enormous amount of potential and seemingly endless application possibilities. Since the days of John Tyndall's demonstration of light guided in water and Alexander Gram Bell's presentation of the photophone, fiber optic technology has advanced tremendously. As being the logical solution for the present day, fiber optics is replacing most existing communication and sensing medium standards to achieve better monitoring and signaling in different environments.

The main advantages of fiber optics have been stipulated and it should be noted that each of the main types of fiber media discussed have characteristics which make them difficult to choose. As a result, by using one these fibers within microwave power measurements to develop a fiber optic sensor capable of detecting microwave energy, fiber optic sensor topology has to be discussed in order to find or compare their responses and behaviour. This would enable us choose which type of sensor technique to use for the power measurement and find their importance and compare their advantages and disadvantages.

CHAPTER 4

AN INVESTIGATION INTO SENSOR TOPOLOGY AND OVERVIEW OF FIBER OPTIC SENSORS

This chapter provides an overview of the fiber optic sensors technology, the technology associated with it and the inherent advantages. It classifies groups of the fiber sensors, and the environment that can be used in, especially the design concepts and layout of the sensor. The sensitivity and limiting parameters involved within fiber optic sensors are also described to provide information as to what type of modulators or gratings can be used. This gives a series of limitations imposed by variable losses in the system related to the environment or the effect to be measured.

As these trends continue, the opportunities for the fiber optic sensor designers to produce competitive products is increasing and the technology is expected to assume an ever more prominent position in the sensor marketplace. In these discussions, the basic types of fiber optic sensors that are being developed are briefly reviewed followed by a discussion of how these sensors are and will be applied.

4.1 INTRODUCTION

The fiber optic communication industry has literally revolutionized the telecommunication industry by providing higher performance, more reliable telecommunication links with ever-decreasing bandwidth cost. This revolution is bringing about the benefits of high volume production to component users and a true information superhighway built of glass.

In parallel with these developments fiber optic sensor [Udd, 1991] technology has been a major user of technology associated with the optoelectronic and fiber optic communication industry. Many of the components associated with these industries were often developed for fiber optic sensor applications. Fiber optic sensor technology has in turn been benefited by the development and subsequent mass production of components to support these industries. As component prices have fallen and quality improvements have been made, the ability of fiber optic sensors to displace traditional sensors for rotation, acceleration, electric and magnetic field measurement, temperature, pressure, acoustics, vibration, linear and angular position, strain, humidity, viscosity, chemical measurements and a host of other sensor applications, has been enhanced. In the early years of fiber optic sensor technology most commercially successful fiber optic sensors were squarely targeted at markets where existing sensor technology was marginal or in many cases nonexistent.

The inherent advantages of fiber optic sensors which include their ability to be lightweight, of very small size, passive, low power, resistant to electromagnetic interference, high sensitivity, wide bandwidth and environmental ruggedness were heavily used to offset their major disadvantages of high cost and unfamiliarity to the end user.

4.2 BASIC CONSIDERATIONS FOR INTENSITY BASED FIBER OPTIC SENSORS

Fiber optic sensors are often loosely grouped into two basic classes referred to as extrinsic or hybrid fiber optic sensors, and intrinsic or all fiber sensors. Figure 4.1 illustrates the case of an extrinsic or hybrid fiber optic sensor [Udd, 1991]. It consist of optical fibers that lead up to and out of a box that modulates the light beam passing through it in response to an environmental effect.

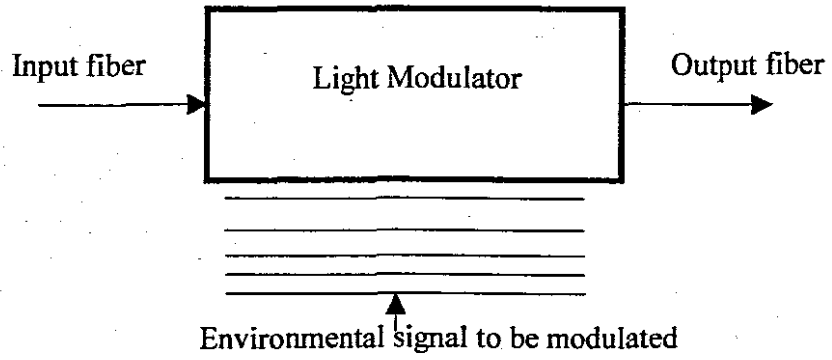


Figure 4.1: Extrinsic fiber optic sensors

In this case an optical fiber leads up to a box, which impresses information onto the light beam in response to an environmental effect. The information could be impressed in terms of intensity, phase, frequency, polarization, and spectral content or other methods. An optical fiber then carries the light with the environmentally impressed information back to an optical and or electronic processor. In some cases the input optical fiber also acts as the output fiber. The intrinsic or all fiber sensors shown in Figure 4.2 uses an optical fiber to carry the light beam and the environmental effect impresses information onto the light beam while it is in the fiber. Each of these classes of fibers in turn has many subclasses with, in some cases; other subclasses consist of large numbers of fiber sensors. It relies on the light beam propagating through the optical fiber being modulated by the environmental effect, either directly, or through environmentally induced optical path length, which changes the fiber itself.

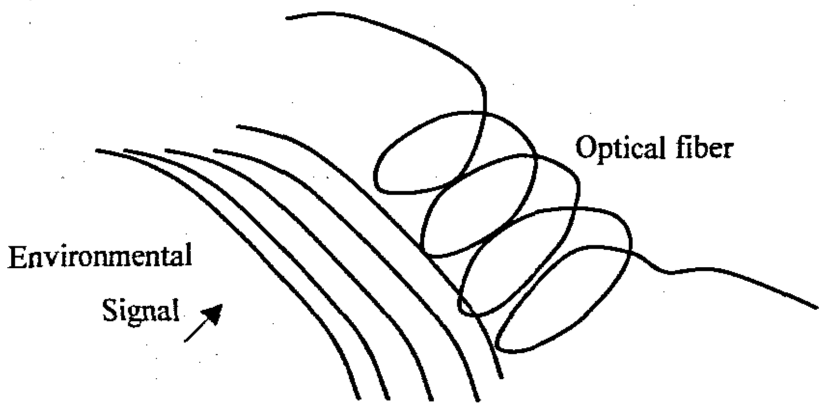


Figure 4.2: Intrinsic fiber optic sensors

In some respects the simplest type of fiber optic sensor is the hybrid type that is based on intensity modulation [Yao and Asawa, 1983, and Lagokos et. al, 1981]. Figure 4.3 shows a simple closure or vibration sensor that consist of two optical fibers that are held in close proximity to each other. Light is injected into one of the optical fibers and when it exits the light expands into a cone of light whose angle depends on the difference between the index of refraction of the core and cladding of the optical fiber. The amount of light captured by the second optical fiber depends on its acceptance angle and the distance, d ,between the optical fibers. When the distance, d, is modulated, it in turn results in an intensity modulation of the light captured.

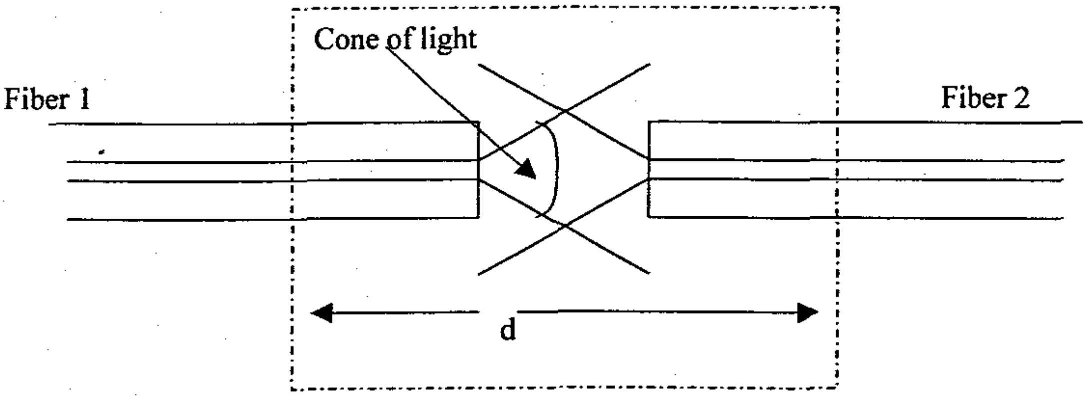


Figure 4.3: Closure and vibration fiber optic sensors based on numerical aperture. It can be used to support door closure indicators and measure levels of vibration in machinery

A variation on this type of sensor is shown in Figure 4.4. Here a mirror is used that is flexibly mounted to respond to an external effect such as pressure. As the mirror position shifts the effective separation between the optical fibers shift with a resultant intensity modulation. These types of sensors are useful for such applications as door closures where a reflective strip, in combination with an optical fiber acting to input and catch the output reflected light, can be used.

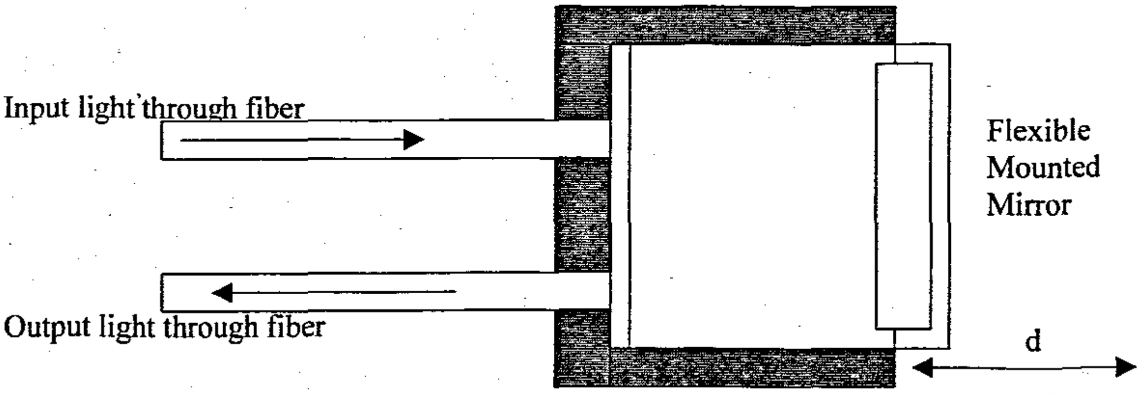


Figure 4.4: Numerical aperture fiber sensor based on a flexible mirror can be used to measure small vibrations and displacements

By arranging two optical fibers in line, a simple translation sensor can be configured as in Figure 4.5. The output from the two detectors can be proportioned to determine the translational position of the input fiber.

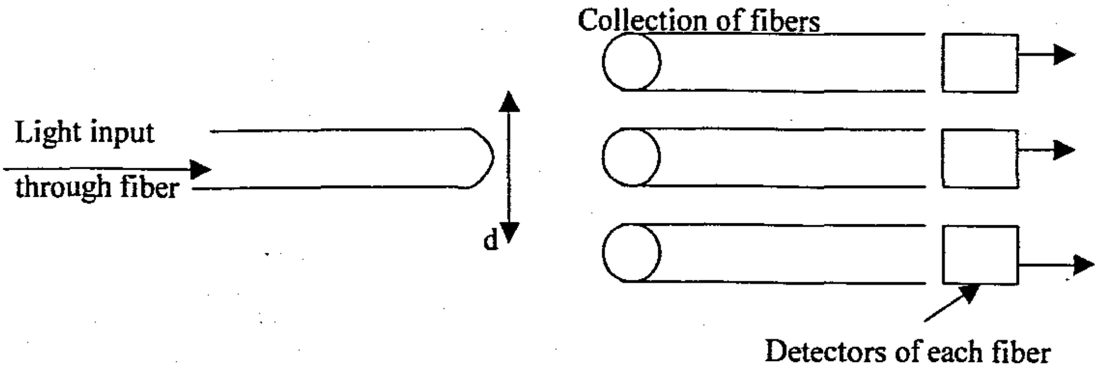


Figure 4.5: Fiber optic translation sensor based on numerical aperture.

Several companies have developed rotary and linear fiber optic position sensors to support applications such as fly-by-light [Udd, 1994]. These sensors attempt to eliminate electromagnetic interference susceptibility to improve safety, and to reduce shielding needs to reduce weight. Figure 4.6 shows a rotary position sensor [Fritsch, 1989] that consists of a code plate with variable reflectance patches placed so that each position has a unique code. A series of optical fibers are used to determine the presence or absence of a patch.

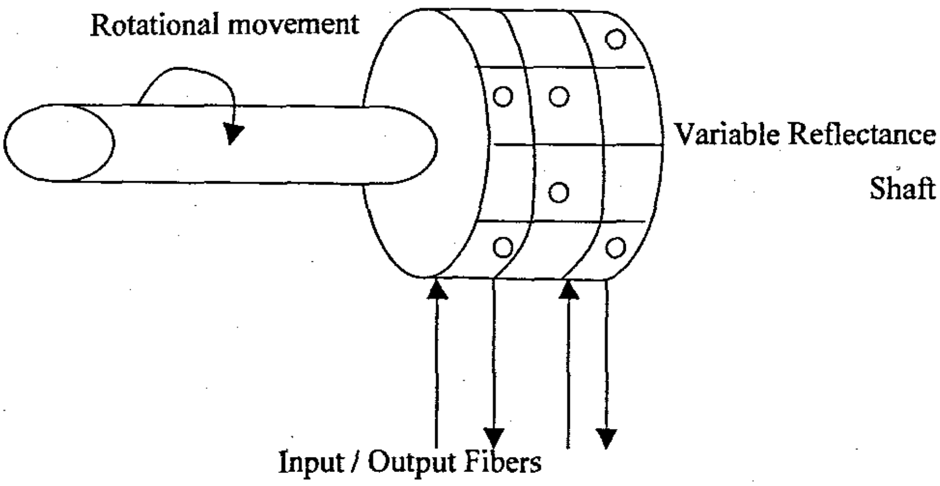


Figure 4.6: Fiber optic rotary position sensor based on reflectance.

An example of a linear position sensor using wavelength division multiplexing [Fritsch, 1986] is illustrated by Figure 4.7. Here a broadband light source, which might be a light emitting diode, is used to couple light into the system. A single optical fiber is used to carry the light beam up to a wavelength division multiplexing (WDM) element that splits the light into separate fibers that are used to interrogate the encoder card and determine linear position. The boxes on the card of Figure 4.7 represent highly reflective patches while the rest of the card has low reflectance. The reflected signals are then recombined and separated out by a second wavelength division-multiplexing element so that a separate detector reads out each interrogating fiber signal.

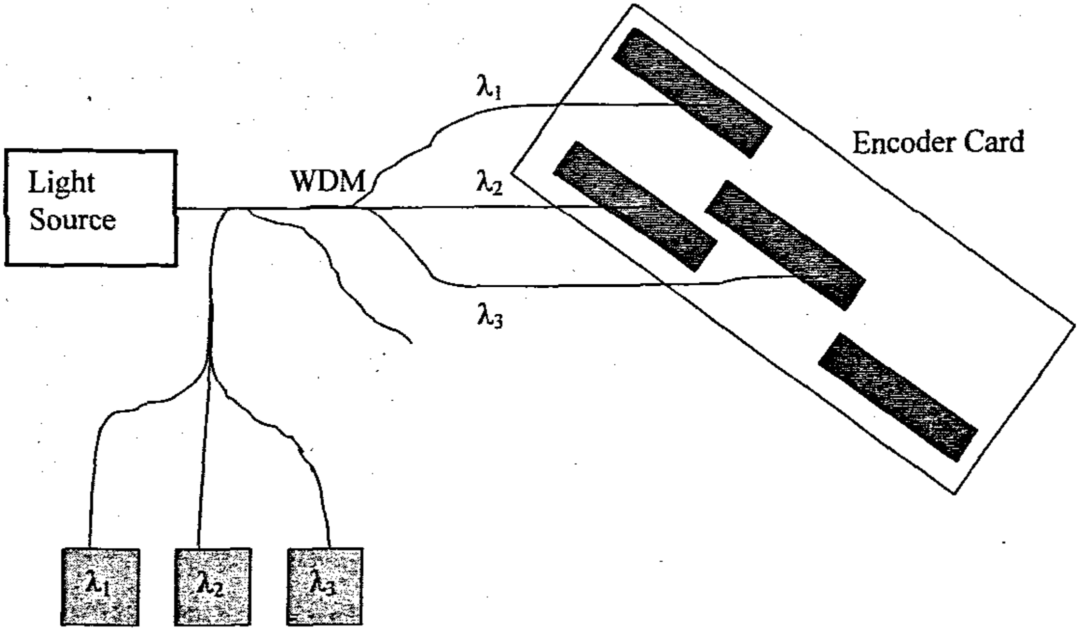


Figure 4.7: Linear position sensor using wavelength division multiplexing. It decodes position by measuring the presence or absence of reflective patch at each fiber position as the card slides by via independent wavelength separated detectors

A second common method of interrogating a position sensor using a single optical fiber is to use time division multiplexing methods [Varshneya, 1987]. In Figure 3.8 a light source is pulsed. The light pulse then propagates down the optical fiber and is split into multiple interrogating fibers. Each of these fibers is arranged so that they have delay lines that separate the return signal from the encoder plate by a time that is longer than the pulse duration. When the returned signals are recombined onto the detector the net result is an encoded signal burst corresponding to the position of the encoded card.

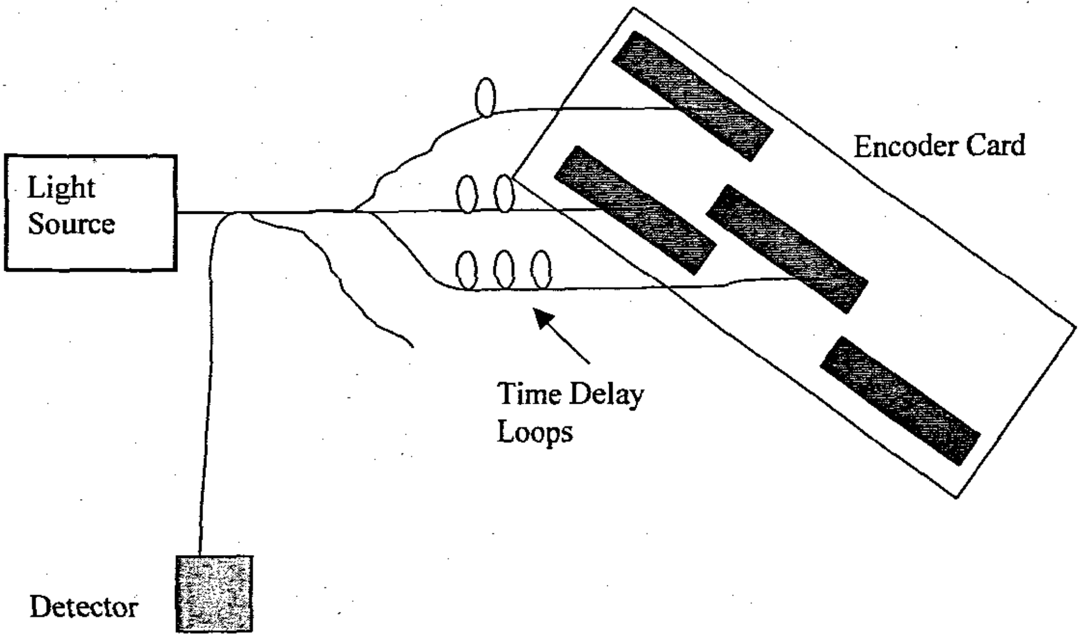


Figure 4.8: Linear position sensor using time division multiplexing measure. It decodes card position through a digital stream of on/off dictated by the presence or absence of a reflective patch

These sensors have been used to support tests on military and commercial aircraft that have demonstrated performance comparable to conventional electrical position sensors used for rudder, flap and throttle position [Udd, 1994]. The principal advantages of the fiber position sensors are immunity to electromagnetic interference and overall weight savings. Another class of intensity based fiber optic sensors is based on the principle of total internal reflection. In the case of the sensor in Figure 4.9, light propagates down the fiber core and hits the angled end of the fiber. If the medium into which the angled end of the fiber is placed has a low enough index of refraction, then virtually all the light is reflected when it hits the mirrored surface and returns via the fiber. If however the index of refraction of the medium starts to approach that of the glass, some of the light propagates out of the optical fiber and is lost resulting in an intensity modulation.

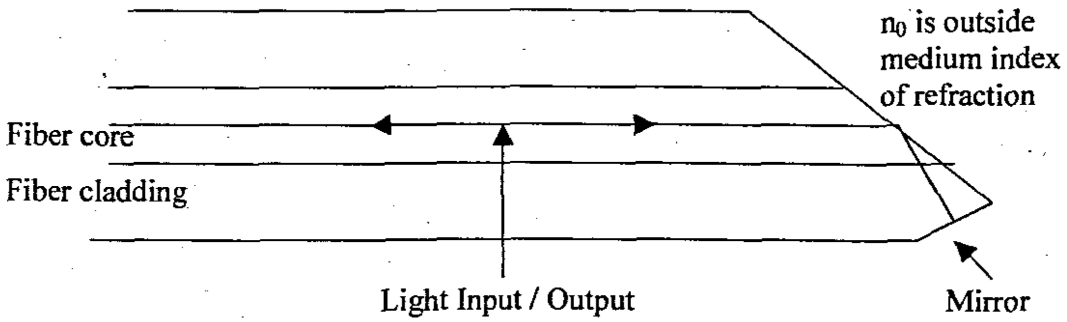


Figure 4.9: Fiber sensor using critical angle properties of a fiber for pressure, or index of refraction measurement, through measurements of the light reflected back into the fiber

This type of sensor can be used for low-resolution measurement of pressure or index of refraction changes in a liquid, or gel with one-to-ten percent accuracy. Variations on this method have also been used to measure liquid level [Snow, 1983] as shown by the probe configuration of Figure 4.10. When the liquid level hits the reflecting prism the light leaks into the liquid greatly attenuating the signal.

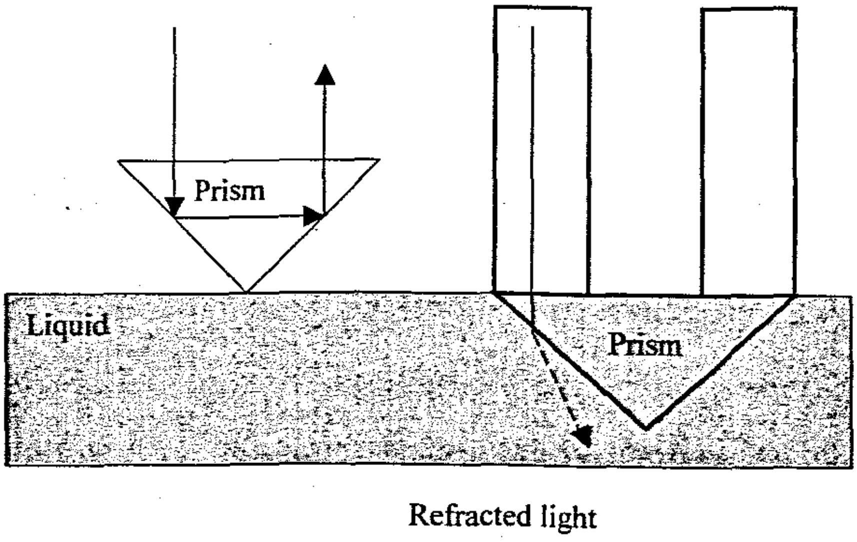


Figure 4.10: Liquid level sensor based on total internal reflection detects the presence or absence of liquid by the presence or absence of a return light signal.

Confinement of a propagating light beam to the region of the fiber cores, and power transfer from two closely placed fiber cores can be used to produce a series of fiber sensors based on evanescence [Clark and Burrell, 1988, Murakami and Sudo, 1981]. Figure 4.11 illustrates two fiber cores that have been placed in close proximity to one another. For single mode optical fiber [Nolan, 1991] this distance is on the order of 10 to 20 microns.

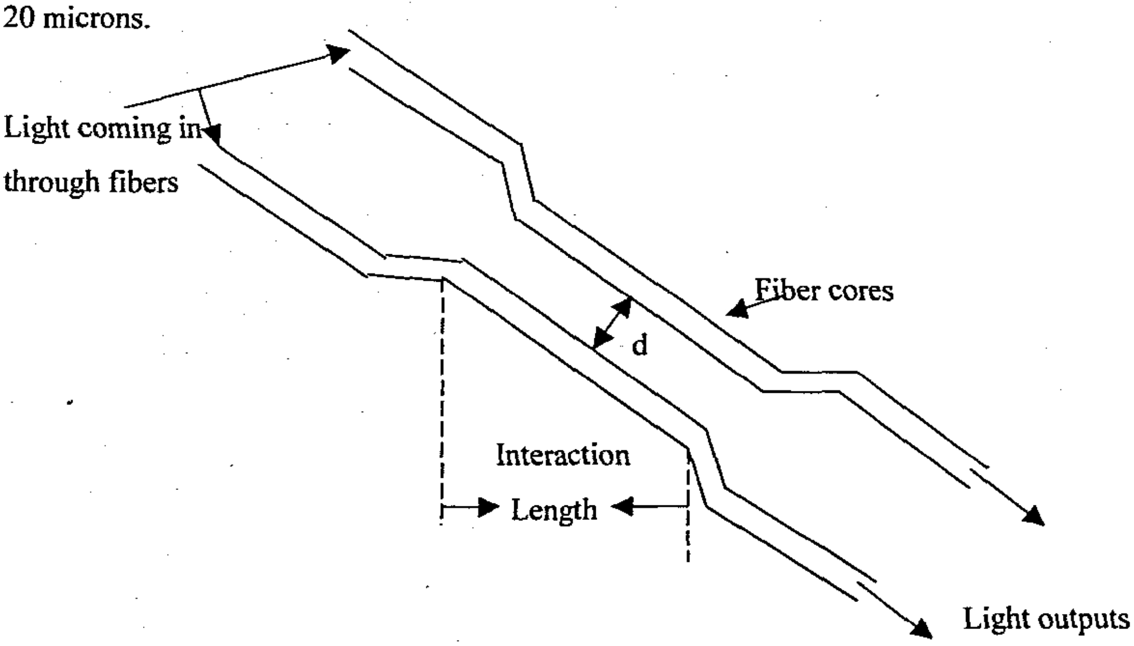


Figure 4.11: Evanescence based fiber optic sensors rely on the cross coupling of light between two closely spaced fiber optic cores. Variations in this distance due to temperature, pressure or strain offer environmental sensing capabilities

When single mode fiber is used, there is considerable leakage of the propagating light beam mode beyond the core region into the cladding or medium around it. If a second fiber core is placed nearby this evanescent tail will tend to cross couple to the adjacent fiber core. The amount of cross coupling depends on a number of parameters including the wavelength of light, the relative index of refraction of the medium in which the fiber cores are placed, the distance between the cores and the interaction length. This type of fiber sensor can be used for the measurement of wavelength, spectral filtering, index of refraction and environmental effects acting on the medium surrounding the cores (temperature, pressure and strain). The difficulty with this sensor, which is common to many fiber sensors, is optimizing the design so that only the desired parameters are sensed.

Another way that light may be lost from an optical fiber is when the bend radius of the fiber exceeds the critical angle necessary to confine the light to the core area and there is leakage into the cladding. Microbending of the fiber locally can cause this to result with resultant intensity modulation of light propagating through an optical fiber. A series of microbend based fiber sensors have been built to sense vibration, pressure and other environmental effects [Berthold, 1987, and Spillman, 1980]. Figure 4.12 shows a typical layout of this type of device consisting of a light source, a section of optical fiber positioned in a microbend transducer designed to intensify the modulated light in response to an environmental effect and a detector. In some cases using special fiber cabling or optical fiber that is simply optimized to be sensitive to microbending loss can implement the microbend transducer.

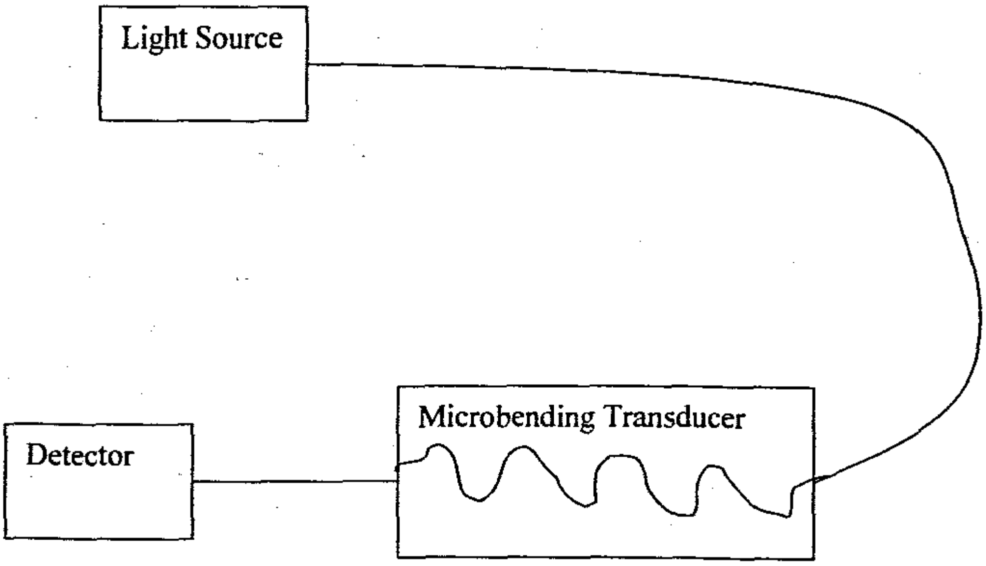


Figure 4.12: Microbend fiber sensors are configured so that an environmental effect results in an increase or decrease in loss through the transducer due to light loss resulting from small bends in the fiber

One last example of an intensity-based sensor is the grating based device [Udd, 1985] shown in Figure 4.13. Here an input optical light beam is collimated by a lens and passes through a dual grating system. One of the gratings is fixed while the other moves. With acceleration the relative position of the gratings changes resulting in intensity modulated signal on the output optical fiber.

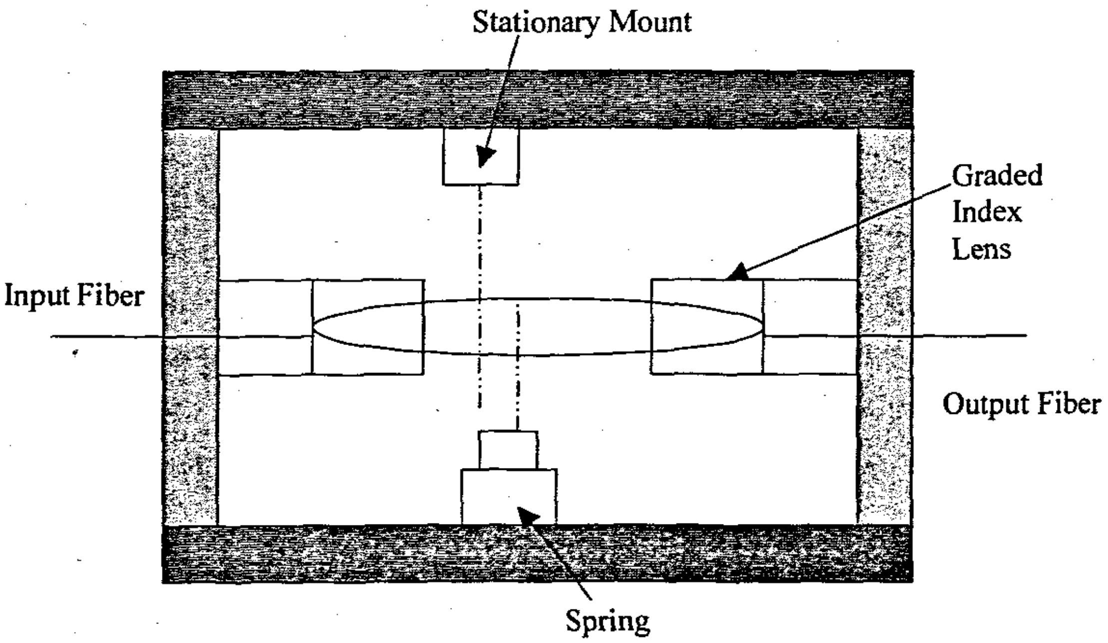


Figure 4.13: Grating based fiber intensity sensors measure vibration or acceleration via a highly sensitive shutter effect

One of the limitations of this type of device is that as the gratings move from a totally transparent to a totally opaque position the relative sensitivity of the sensor changes as can be seen from Figure 4.14. For optimum sensitivity the gratings should be in the half open half-closed position. Increasing sensitivity means finer and finer grating spacing, which in turn limit dynamic range.

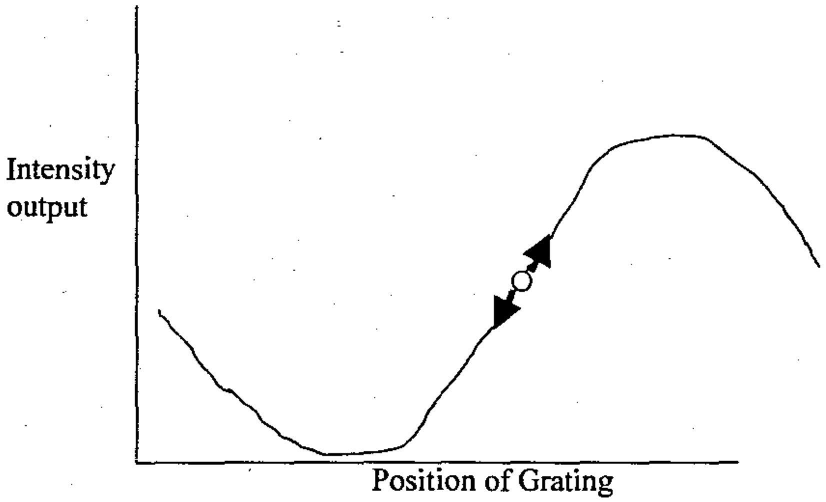


Figure 4.14: Dynamic range limitations of the grating based sensor of Figure 4.13 are due to smaller grating spacing increasing sensitivity at the expense of range

To increase sensitivity without limiting dynamic range, use multiple part gratings that are offset by 90 degrees as shown in Figure 4.15. If two outputs are spaced in this manner the resulting outputs are in quadrature as shown in Figure 4.16.

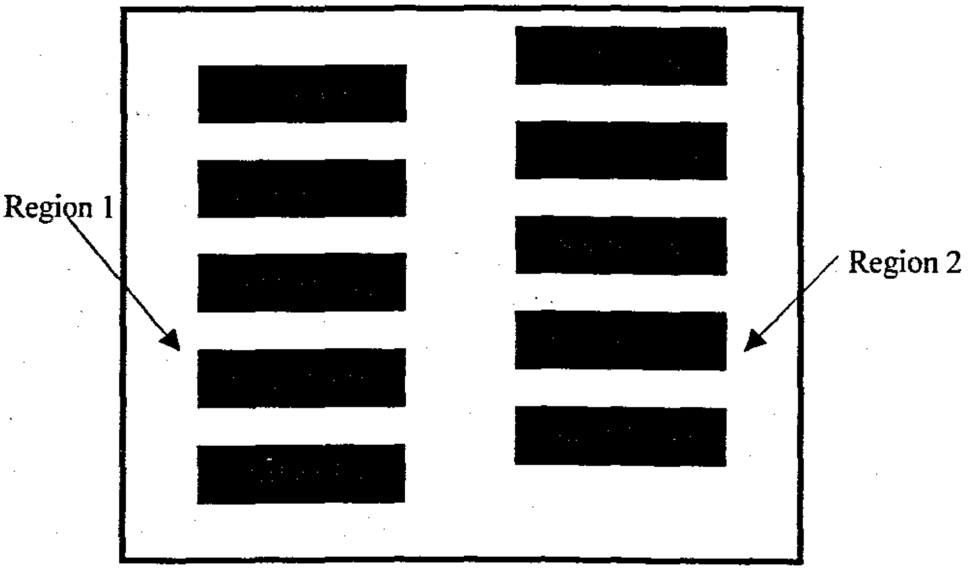


Figure 4.15: Dual grating mask with regions 90 degrees out of phase to support quadrature detection, which allows grating, based sensors to track through multiple lines

When one output is at optimal sensitivity the other is at its lowest sensitivity and vice versa. By using both outputs for tracking, one can scan through multiple grating lines enhancing dynamic range and avoiding signal fade out associated with positions of minimal sensitivity.

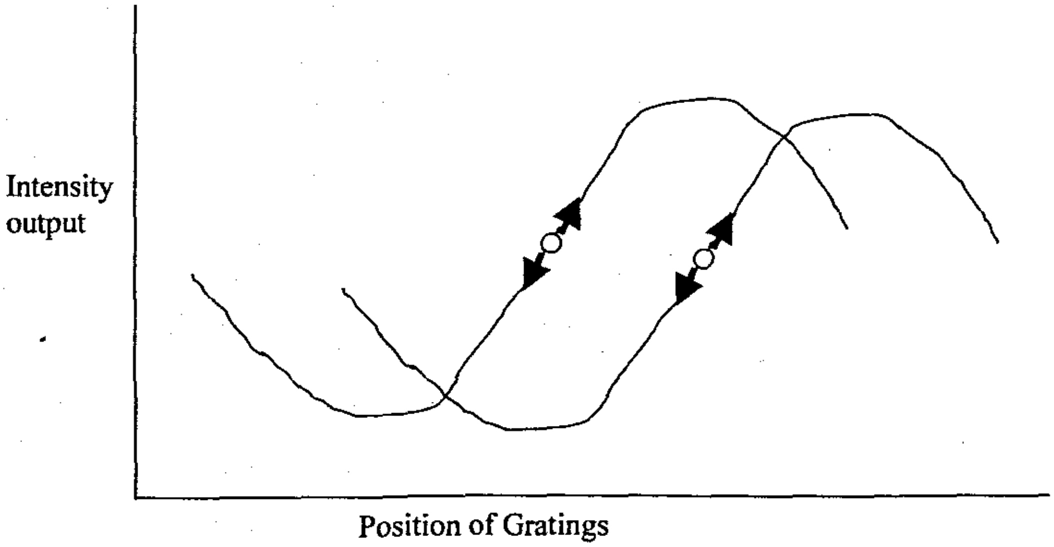


Figure 4.16: Diagram illustrating quadrature detection method that allows one area of maximum sensitivity while the other reaches a minimum and vice versa, allowing uniform sensitivity over a wide dynamic range

Intensity based fiber optic sensors have a series of limitations imposed by variable losses in the system that are not related to the environmental effect to be measured. Potential error sources include, variable losses due to connectors and splices, microbending loss, macrobending loss, and mechanical creep and misalignment of light sources and detectors. To circumvent these problems, many of the successful higher performance intensity based fiber sensors employ dual wavelengths. One of the wavelengths is used to calibrate out all of the errors due to undesired intensity variations by bypassing the sensing region. An alternative approach is to use fiber optic sensors that are inherently resistant to errors induced by intensity variations. In the next section a series of spectrally based fiber sensors that have this characteristic are discussed.

4.3 SPECTRALLY BASED FIBER OPTIC SENSORS

Spectrally based fiber optic sensors depend on a light beam being modulated in wavelength by an environmental effect. Examples of these types of fiber sensors include that based on blackbody radiation, absorption, fluorescence, etalons and dispersive gratings. One of the simplest of these types of sensors is a spectrally based temperature sensor shown in Figure 4.17 and is based on absorption [Christensen and Ives, 1987]. In this case, a Gallium Arsenide (GaAs) sensor probe is used in combination with a broadband light source and input/output optical fibers. The absorption profile of the probe is temperature dependent and may be used to determine temperature.

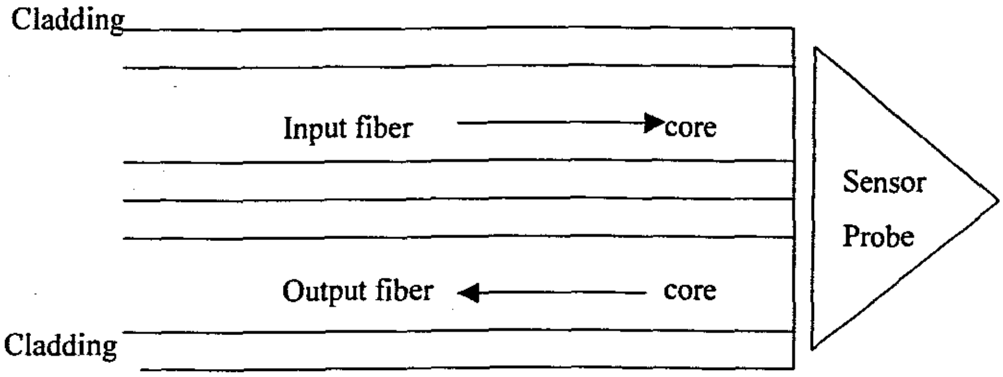


Figure 4.17: Fiber optic sensor based on variable absorption of materials such as GaAs allows the measurement of temperature and pressure

Fluorescent-based fiber sensors [Schwab and Levy, 1989, and Gratten et. al, 1986] are being widely used for medical applications, chemical sensing and can also be used for physical parameter measurements such as temperature, viscosity and humidity. There are a number of configurations for these sensors and Figure 4.18 illustrates two of the most common ones. In the case of the end tip sensor, light propagates down the fiber to a probe of fluorescent material. The resultant fluorescent signal is captured by the same fiber and directed back to an output demodulator. The light sources can be pulsed and probes have been made that depend on the time rate of decay of the light pulse.

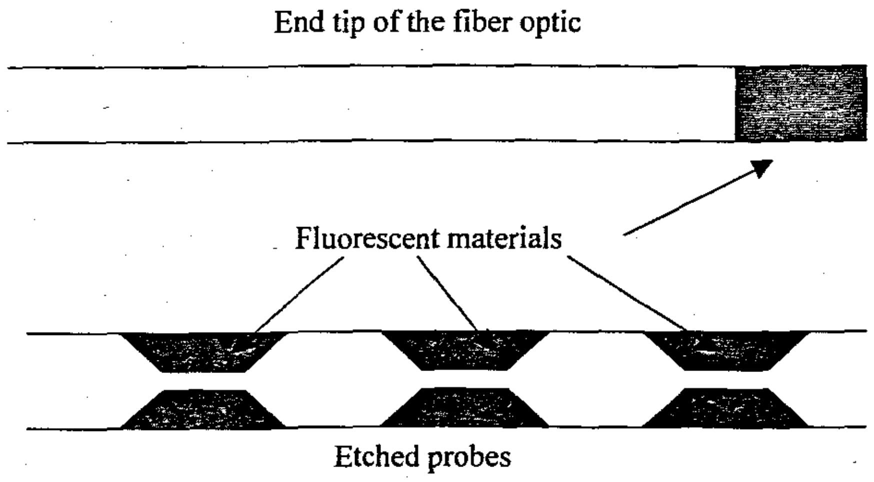


Figure 4.18: Fluorescent fiber optic sensor probe configurations can be used to support the measurement of physical parameters as well as the presence or absence of chemical species. These probes may be configured to be single ended or multipoint by using side etches techniques and attaching the fluorescent material to the fiber

In the continuous mode, parameters such as viscosity, water vapor content and degree of cure in carbon fiber reinforced epoxy and thermoplastic composite materials can be monitored. An alternative is to use the evanescent properties of the fiber and etch regions of the cladding away and refill them with fluorescent material. By sending a light pulse down the fiber and looking at the resulting fluorescence, a series of sensing regions may be time division multiplexed. It is also possible to introduce fluorescent dopants into the optical fiber itself.

This approach would cause the entire optically activated fiber to fluoresce. By using time division multiplexing, various regions of the fiber could be used to make a distributed measurement along the fiber length. In many cases, users of fiber sensors would like to have the fiber optic analog of conventional electronic sensors. An example is the electrical strain gauge that is used widely by structural engineers. Fiber grating sensors

[Morey et. al, 1989, and Morey, 1990] can be configured to have gauge lengths from 1mm to approximately 1cm, with sensitivity comparable to conventional strain gauges. This sensor is fabricated by a fiber grating onto the core of a Germanium doped optical fiber. This can be done in a number of ways. One method, which is illustrated by Figure 4.19, uses two short wavelength laser beams that are angled to form an interference pattern through the side of the optical fiber. The interference pattern consists of bright and dark bands that represent local changes in the index of refraction in the core region of the fiber. Exposure time for making these gratings varies from minutes to hours, depending on the dopant concentration in the fiber, the wavelengths used, the optical power level and the imaging optics.

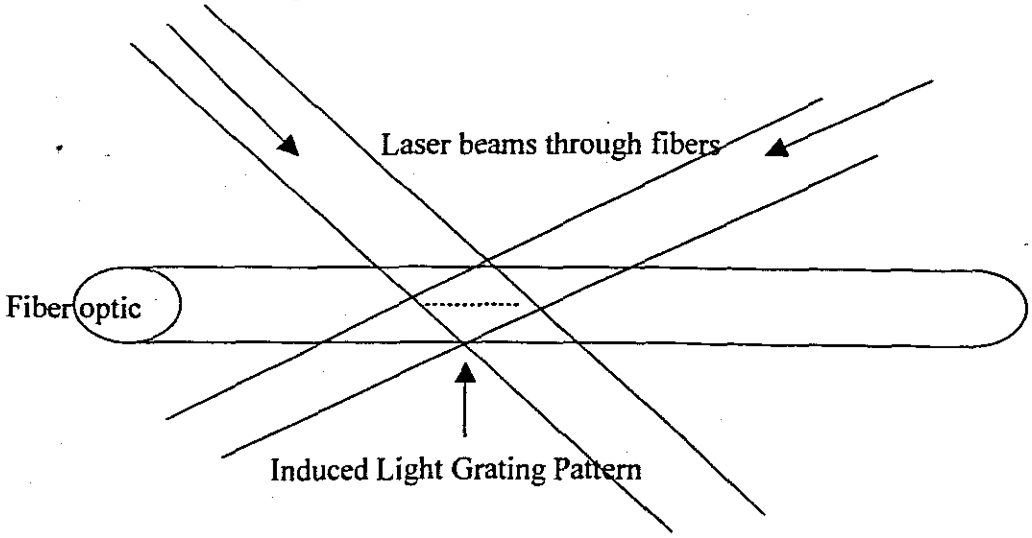


Figure 4.19: Fabrication of a fiber-grating sensor can be accomplished by imaging to short wavelength laser beams through the side of the optical fiber to form an interference pattern. The bright and dark fringes, which are imaged on the core of the optical fiber, induce an index of refraction variation resulting in a grating along the fiber core

Other methods that have been used include the use of phase masks, and interference patterns induced by short high-energy laser pulses. The short duration pulses have the potential to be used to write fiber gratings into the fiber as it is being drawn. Substantial efforts are being made by laboratories around the world to improve the manufacturability of fiber gratings as they have the potential to be used to support optical communication as well as sensing technology.

Once the fiber grating has been fabricated the next major issue is how to extract information. When used as a strain sensor the fiber grating is typically attached to, or embedded in, a structure. As the fiber grating is expanded or compressed, the grating period expands or contracts, changing the gratings spectral response. For a grating operating at 1300nm the change in wavelength is about 10^{-3}nm per microstrain. This type of resolution requires the use of spectral demodulation techniques that are much better than those associated with conventional spectrometers. Several demodulation methods have been suggested using fiber gratings, and interferometers [Kersey et. al, 1992, and Jackson et. al, 1993]. Figure 4.20 illustrates a system that uses a reference fiber grating. The action of the reference fiber grating is to act as a modulator filter. By using similar gratings for the reference and signal gratings and adjusting the reference grating to line up with the active grating, an accurate closed loop demodulation system may be implemented.

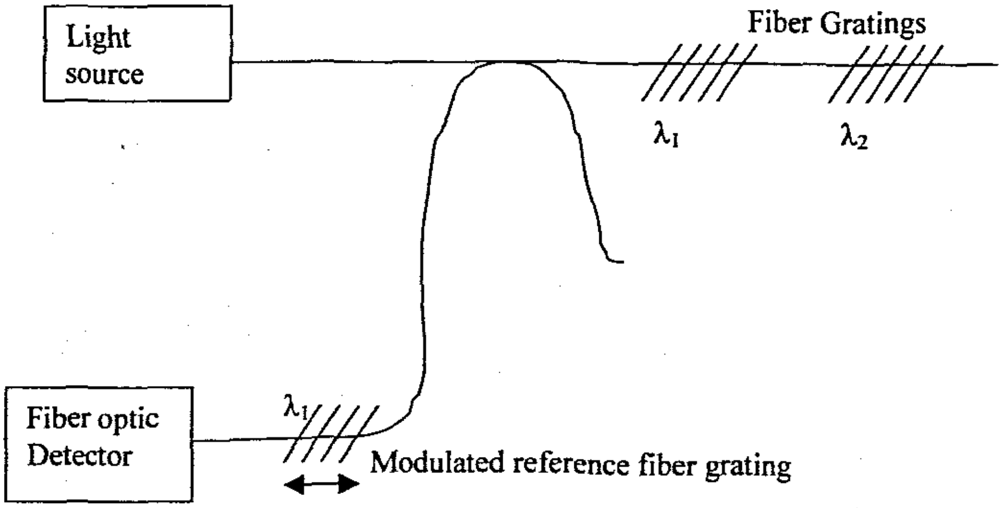


Figure 4.20: Fiber grating demodulation systems require very high-resolution spectral measurements. One way to accomplish this is to beat the spectrum of light reflected by the fiber grating against the light transmission characteristics of a reference grating

An alternative demodulation system would use fiber sensors such as those shown in Figure 4.21. One fiber can be mounted on a piezoelectric and the other moved relative to a second fiber end. The spacing of the fiber ends as well as their reflectivity in turn determines the spectral filtering action of the fiber sensor that is illustrated by Figure 4.22.

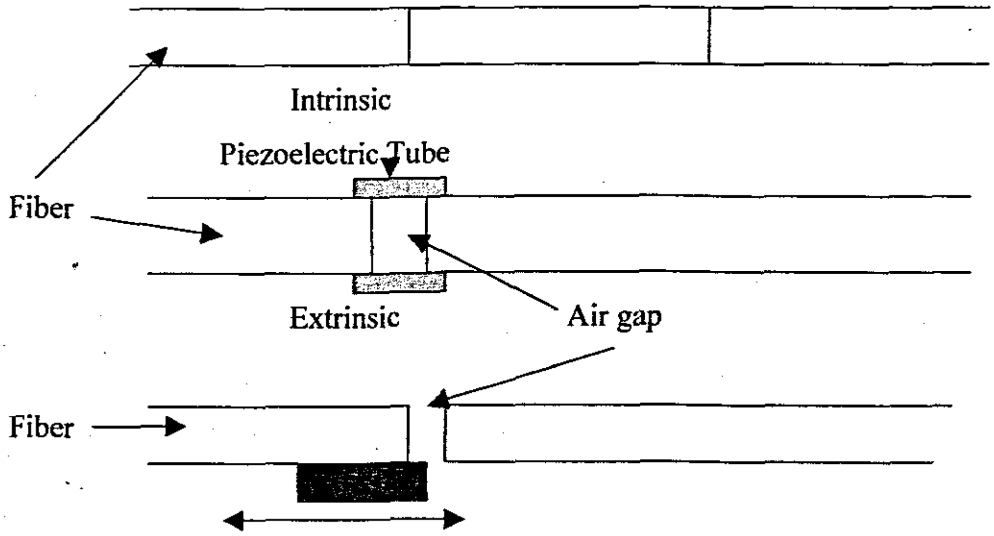


Figure 4.21: Intrinsic fiber sensors are formed by in line reflective mirrors that can be embedded into the optical fiber. Two-mirrored fiber ends in capillary tube form extrinsic fiber sensors. A fiber sensor based spectral filter or two reflective fiber ends that have a variable form demodulator

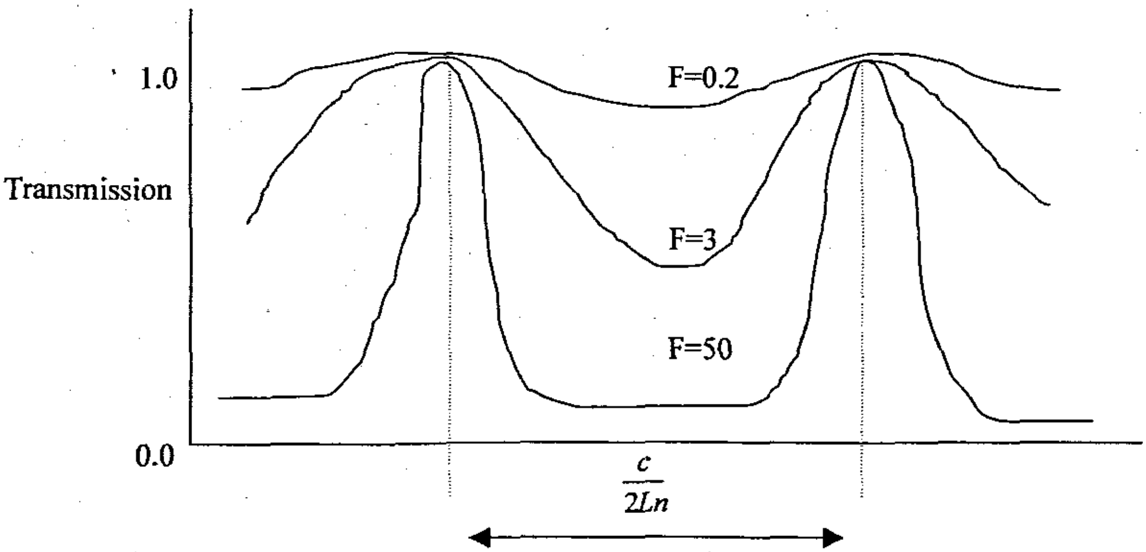


Figure 4.22: Diagram illustrating the transmission characteristics of a fiber sensor as a function of finesse, which increases with mirror reflectivity

The fiber sensor in Figure 4.21 can also be used as sensors [Saaski et. al, 1986, Lee and Taylor, 1988] for measuring strain as the distance between mirrors in the fiber determines their transmission characteristics. The mirrors can be fabricated directly into the fiber by cleaving the fiber, coating the end with titanium dioxide, and then resplicing. An alternative approach is to cleave the fiber ends and insert them into a capillary tube with an air gap. Both of these approaches are being investigated for applications where multiple, in line fiber sensors is required. For many applications a single point sensor is adequate. In these situations, a sensor can be fabricated independently and attached to the end of the fiber. Figure 4.23 shows a series of sensors that have been configured to measure pressure, temperature and refractive index respectively.

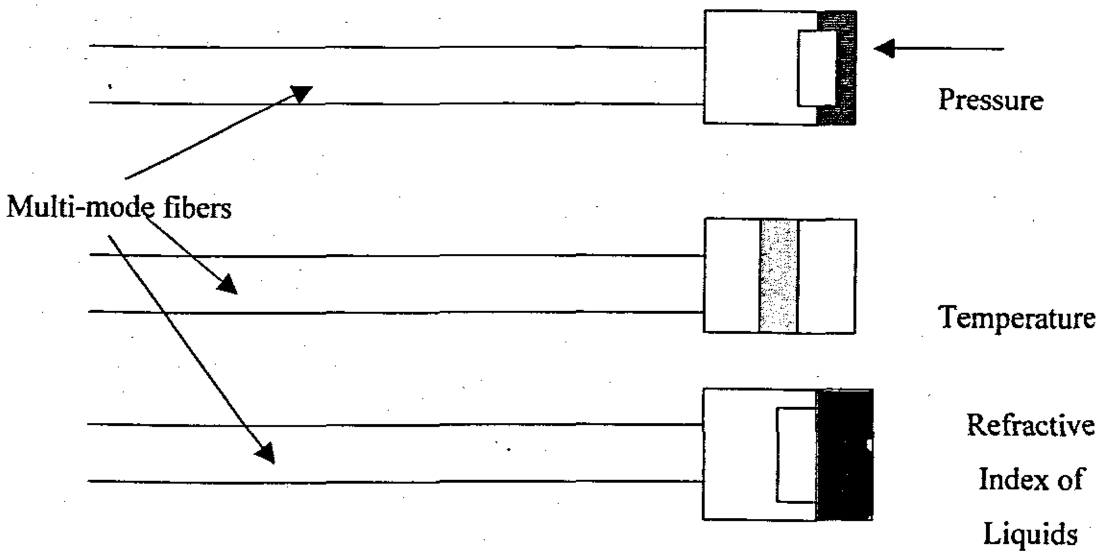


Figure 4.23: Hybrid sensor based fiber optic sensors often consist of micromachined cavities that are placed on the end of optical fibers and can be configured so that sensitivity to one environmental effect is optimized

Much of the current development is devoted to system, which can capitalize on the performance advantage that this technology can offer. This had described the development and implementation of fiber optic sensors and led to a possible use of one sensor type in microwave energy or power measurement. One of the areas of greatest interest in fiber optic has been in the development of high performance Interferometric fiber optic sensors. Substantial efforts have been undertaken on Sagnac interferometers, ring resonators, Mach-Zehnder and Michelson interferometers as well as dual mode, polarimetric, grating and sensor based interferometers.

CHAPTER 5

PRINCIPLES OF INTERFEROMETRIC FIBER OPTIC SENSORS

The previous chapter dealt with non-interferometric sensors. In this chapter, the overviews of the Interferometric fiber optic sensor applications are discussed. Common uses and where they can be found for special different applications are included. It gives a brief description of various common types of Interferometric sensors, and their modulation of the signal measurand, which result in our selection of a suitable sensor for the microwave measurement.

5.1 THE SAGNAC INTERFEROMETER

The Sagnac interferometer has been principally used to measure rotation [Lefevre, 1993, Ezekial and Udd, 1991] and is a replacement for ring laser gyros and mechanical gyros. It may also be employed to measure time varying effects such as acoustics, vibration and slowly varying phenomenon such as strain. By using multiple interferometer configurations it is possible to employ the Sagnac interferometer as a distributed sensor capable of measuring the amplitude and location of a disturbance. The single most important application of fiber optic sensors in terms of commercial value is the fiber optic gyro. It was recognized very early that the fiber optic gyro offered the prospect of an all solid-state inertial sensor with no moving parts, unprecedented reliability, and had the prospect of being very low cost. The potential of the fiber optic gyro is being realized as several manufacturers worldwide are producing them in large quantities to support automobile navigation systems, pointing and tracking of satellite antennas, inertial measurement systems for commuter aircraft and missiles.

Other applications where fiber optic gyros are being used include mining operations, tunneling, altitude control for a radio controlled helicopter, cleaning robots, antenna pointing and tracking, and guidance for unmanned trucks and carriers. Two types of fiber optic gyros are being developed. The first type is an open loop fiber optic gyro. These fiber gyros are generally used for low cost applications where dynamic range and linearity are not the crucial issues. For an example, one have a gyro with a dynamic range of the order of 1000 to 5000, with a scale factor accuracy of about 0.5% and sensitivities that can vary from less than 0.01°/hr and higher. The second type is the closed loop fiber optic gyro that may have a dynamic range of 10^6 and scale factor linearity [Ezekial and Udd, 1991]. These types of fiber optic gyros are primarily targeted at medium to high accuracy navigation applications that have high turning rates and require high linearity and large dynamic ranges.

Figure 5.1 illustrates the basic open loop fiber optic gyro. A broadband light source such as a light emitting diode is used to couple light into an input or output fiber coupler. The input light beam passes through a polarizer that is used to ensure the reciprocity of the counter-propagating light beams through the fiber coil. The second central coupler splits the two light beams into the fiber optic coil where they pass through a modulator that is used to generate a time varying output signal indicative of rotation. The modulator is offset from the center of the coil to impress a relative phase difference between the counter-propagating light beams. After passing through the fiber coil the two light beams recombine and pass back through the polarizer and are directed onto the output detector.

When the fiber gyro is rotated in a clockwise direction, the entire coil is displaced slightly increasing the time it takes light to traverse the fiber optic coil. Remember that the speed of light is invariant with respect to the frame of reference, thus coil rotation increases path length when viewed from outside the fiber. Thus the clockwise propagating light beam has to go through a slightly longer optical path length than the counterclockwise beam, which is moving in a direction opposite to the motion of the fiber coil. The net phase difference between the two beams is proportional to the rotation rate.

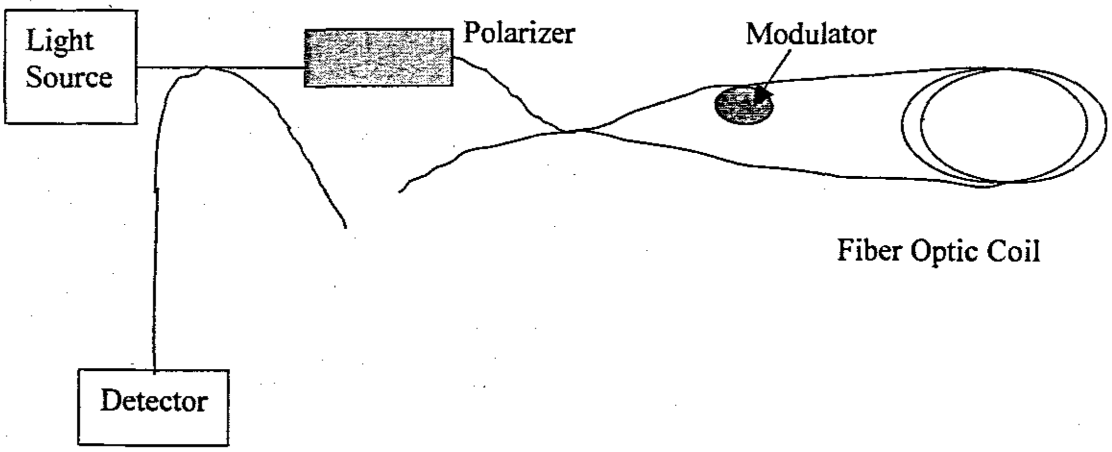


Figure 5.1: Open loop fiber optic gyro is the simplest and lowest cost rotation sensor. They are widely used in commercial applications where their dynamic range and linearity limitations are not constraining

By including a phase modulator loop offset from the fiber coil a time difference in the arrival of the two light beams is introduced, and an optimized demodulation signal can be realized. This is shown on the right side in Figure 5.25. In the absence of the loop the two light beams traverse the same optical path and are in phase with each other and is shown on the left-hand curve of Figure 5.25.

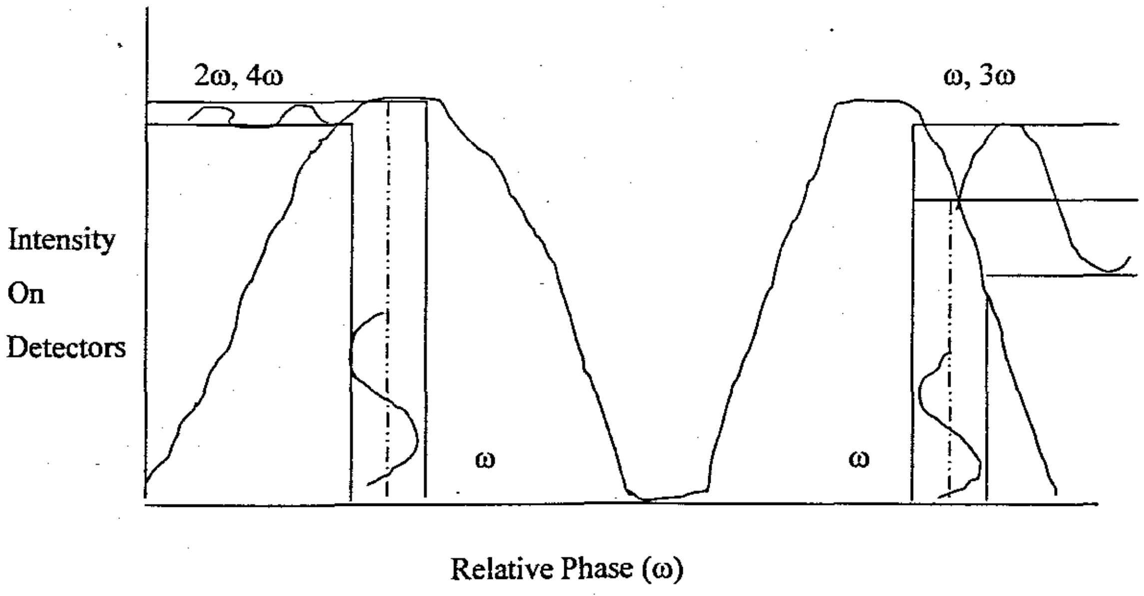


Figure 5.2: An open loop fiber optic gyro has predominantly even order harmonics in the absence of rotation. Upon rotation, the open loop fiber optic gyro has odd harmonic output whose amplitude indicates the magnitude of the rotation rate and phase indicates direction

Another class of fiber optic sensors, based on the Sagnac interferometer, can be used to measure rapidly varying environmental signals such as sound [Dakin et. al, 1987, and Udd, 1991]. Figure 5.26 illustrates two interconnected Sagnac loops that can be used as a distributed acoustic sensor. The WDM (wavelength division multiplexer) in the figure is a device, which either couples two wavelengths (λ_1 and λ_2 in this case) together, or separates them. The sensitivity of this Sagnac acoustic sensor depends on the location of the signal. If the signal is at the center of the loop the amplification is zero, as both counter-propagating of light beams arrive at the center of the loop at the same time. As the signal moves away from the center the output increases. When two Sagnac loops are superposed as in Figure 5.26, the two outputs may be summed to give an indication of the amplitude of the signal and ratioed to determine position. Several other combinations of interferometers have been tried for position and amplitude determinations and the first reported success consisted of a combination of the Mach-Zehnder and Sagnac interferometer [Dakin et. al, 1987].

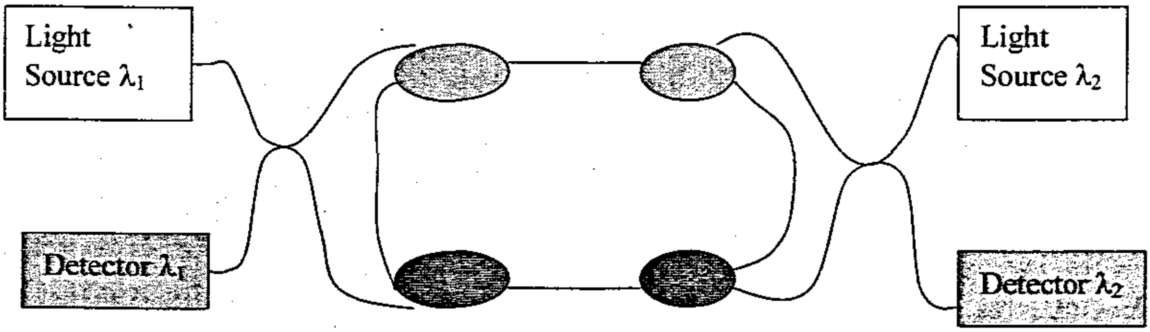
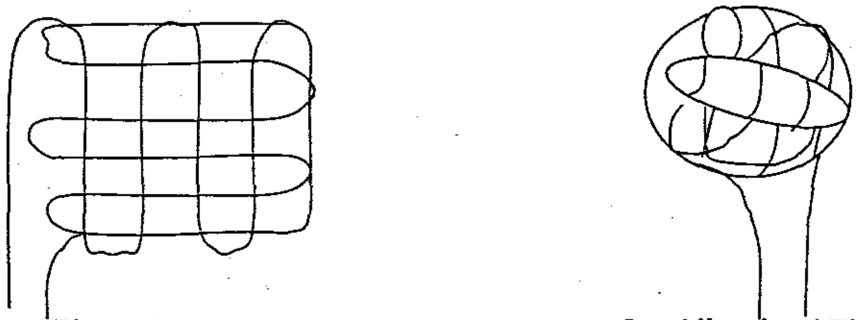


Figure 5.3: Distributed fiber optic acoustic sensor based on interlaced Sagnac loops allows the detection of the location and the measurement of the amplitude along a length of optical fiber that may be many kilometers long

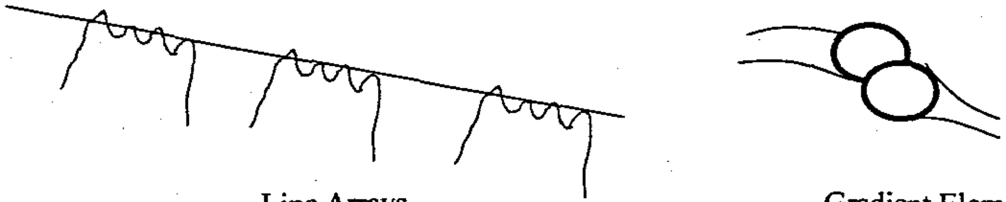
5.2 THE MACH-ZEHNDER AND MICHELSON INTERFEROMETERS

One of the great advantages of all fiber interferometers, such as Mach-Zehnder and Michelson interferometers [Dandridge, 1991] in particular, is that they have extremely flexible geometry's and high sensitivity that allow the possibility of a wide variety of high performance elements and arrays as shown in Figure 5.27.



Planar Arrays

Omnidirectional Elements



Line Arrays

Gradient Elements

Figure 5.4: Flexible geometry's of interferometeric fiber optic sensors transducers are one of the features of fiber sensors that are attractive to designers configuring special purpose sensors

The basic elements of a Mach-Zehnder interferometer are shown in Figure 5.28, which are a light source or coupler module, a transducer and a homodyne demodulator. The light source module usually consists of a long coherence length isolated laser diode, a beam splitter to produce two light beams and a means of coupling the beams to the two legs of the transducer. The transducer is configured to sense an environmental effect by isolating one light beam from the environmental effect and using the action of the environmental effect on the transducer is to induce an optical path length difference between the two light beams. Typically a homodyne demodulator is used to detect the difference in optical path length (various heterodyne schemes have also been used) [Dandridge, 1991].

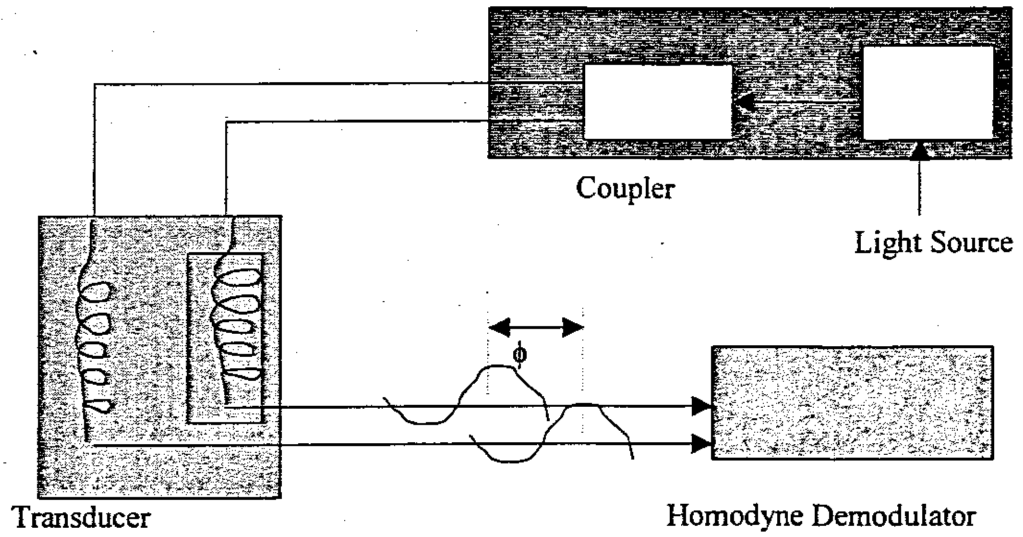


Figure 5.5: The basic elements of the fiber optic Mach-Zehnder interferometer.

Light source is coupled to the 3dB Coupler module, which splits a light beam into two paths. A transducer used to cause an environmentally dependent differential optical path length between the two light beams, and a demodulator that measures the resulting path length difference between the two light beams

One of the basic issues with the Mach-Zehnder interferometer is that the sensitivity will vary as a function of the relative phase of the light beams in the two legs of the interferometer. One way to solve the signal-fading problem is to introduce a piezoelectric fiber stretcher into one of the legs and adjust the relative path length of the two legs for optimum sensitivity.

Figure 5.29 illustrates a homodyne demodulator. The demodulator consists of two parallel optical fibers that feed the light beams from the transducer into a graded index (GRIN) lens. The output from the graded index lens is an interference pattern that rolls with the relative phase of the two input light beams. If a split detector is used with a photo-mask arranged so that the opaque and transparent line pairs on the mask in front of the split detector match the interference pattern periodicity and are 90 degrees out of phase on the detector faces, sine and cosine outputs result.

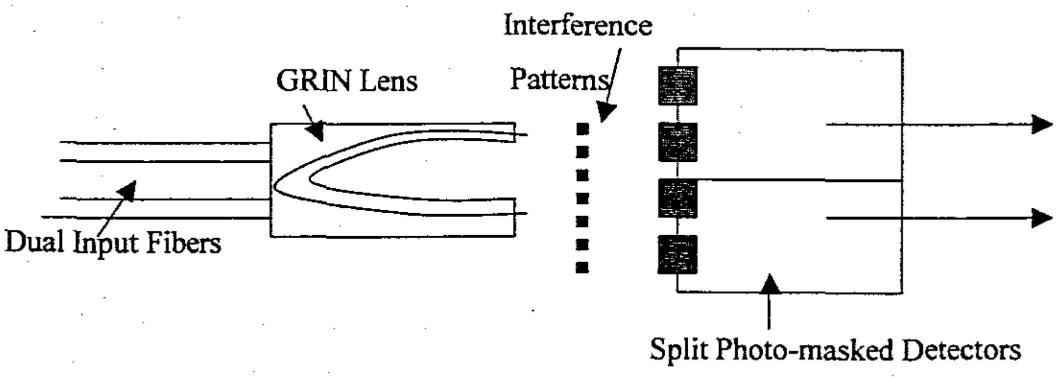


Figure 5.6: Quadrature demodulation avoids signal-fading problems. The method shown here expands the two beams into an interference pattern that is imaged onto a split detector. It gives Sine and Cosine outputs

These outputs may be processed using quadrature demodulation electronics as shown in Figure 5.30. The result is a direct measure of the phase difference.

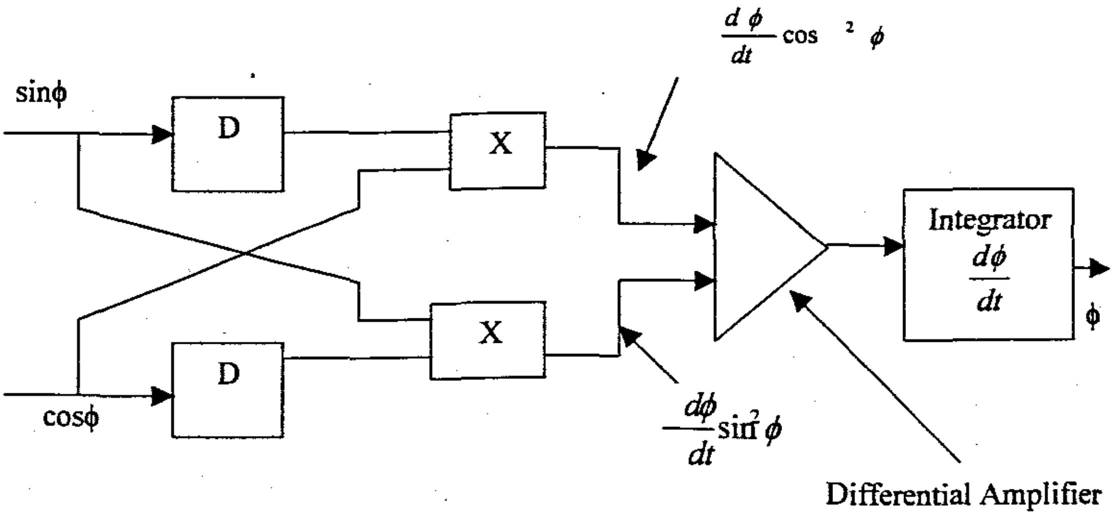


Figure 5.7: Quadrature demodulation electronics take the sinusoidal outputs from the split detector and convert them through cross multiplication and differentiation into an output that can be integrated to form the direct phase difference

Improvements on these techniques have been made; notably the phase generated carrier approach as shown in Figure 5.31. A laser diode is currently modulated, resulting in the output frequency of the laser diode being frequency modulated as well. If a Mach-Zehnder interferometer is arranged so that its reference and signal leg (sensing) differ in length by an amount (L_1-L_2) then the net phase difference between the two light beams is:

$$\phi = \frac{2\pi F(L_1 + L_2)n}{c} \qquad 5.1$$

Where, n, is the index of refraction of the optical fiber, L is the fiber length and c, is the speed of light in vacuum. If the current modulation is at a rate, ω, then relative phase differences are modulated at this rate and the output on the detector will be odd and even harmonics of it. The signals riding on the carrier harmonics of ω and 2ω are in quadrature with respect to each other and can be processed using electronics similar to those of Figure 5.30.

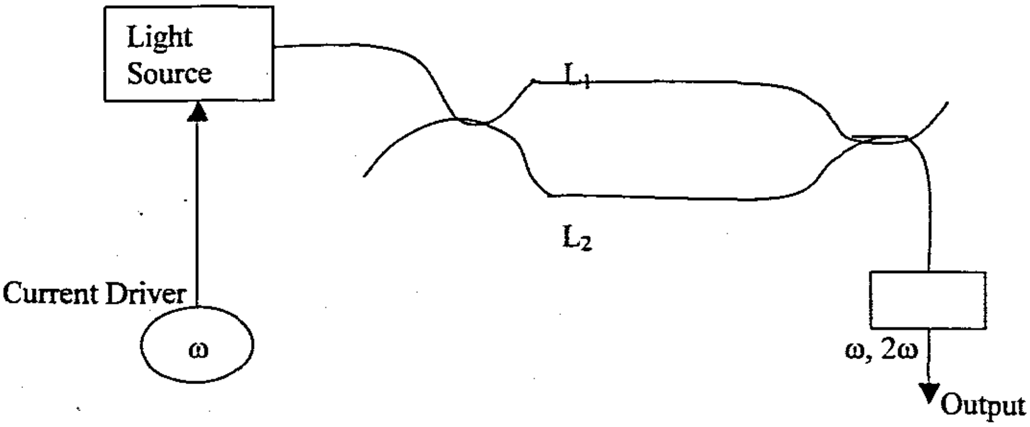


Figure 5.8: The phase generated carrier technique allows quadrature detection via monitoring even and odd harmonics induced by a sinusoidal frequency modulated light source used in combination with a length offset Mach-Zehnder interferometer to generate a modulated phase output whose first and second harmonics correspond to sine and cosine outputs

The Michelson interferometer is shown in Figure 5.32. It is similar to the Mach-Zehnder. The major difference is that mirrors have been put on the ends of the interferometer legs. This results in very high levels of back reflection into the light source greatly degrading the performance of early systems. By using improved diode pumped YAG (Yttrium Aluminum Garnet) ring lasers as light sources these problems can be largely overcome.

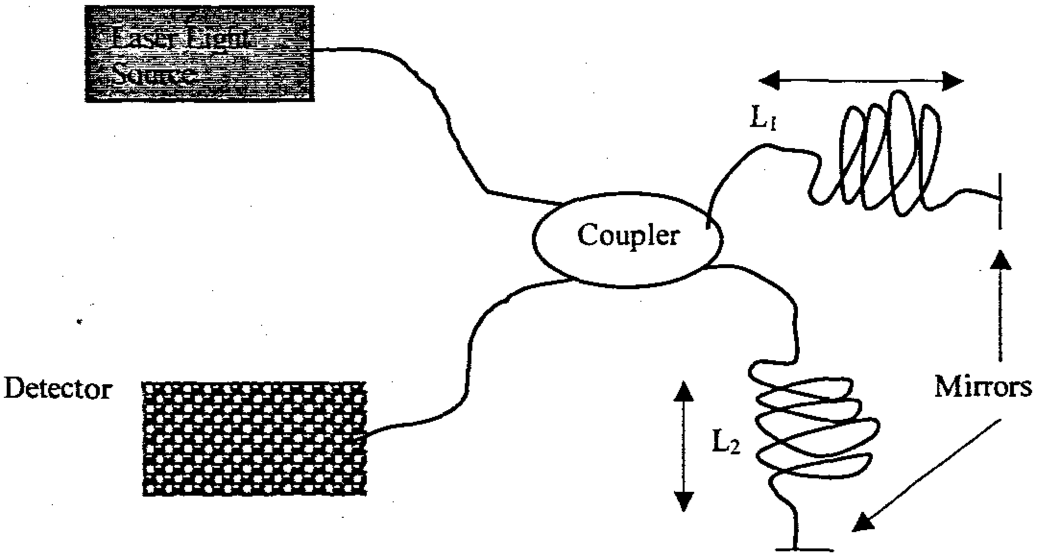


Figure 5.9: The fiber optic Michelson interferometer. It consists of two mirrored fiber ends and can utilize many of the demodulation methods and techniques associated with the Mach-Zehnder

In order to implement an effective Mach-Zehnder or Michelson based on fiber sensor; it is necessary to construct an appropriate transducer. This can involve a fiber coating that could be optimized for acoustic, electric or magnetic field response. In Figure 5.33 a two-part coating is illustrated that consists of a primary and secondary layer. These layers are designed for optimal response to pressure waves and for minimal acoustic mismatches between the medium in which the pressure waves propagate and the optical fiber.

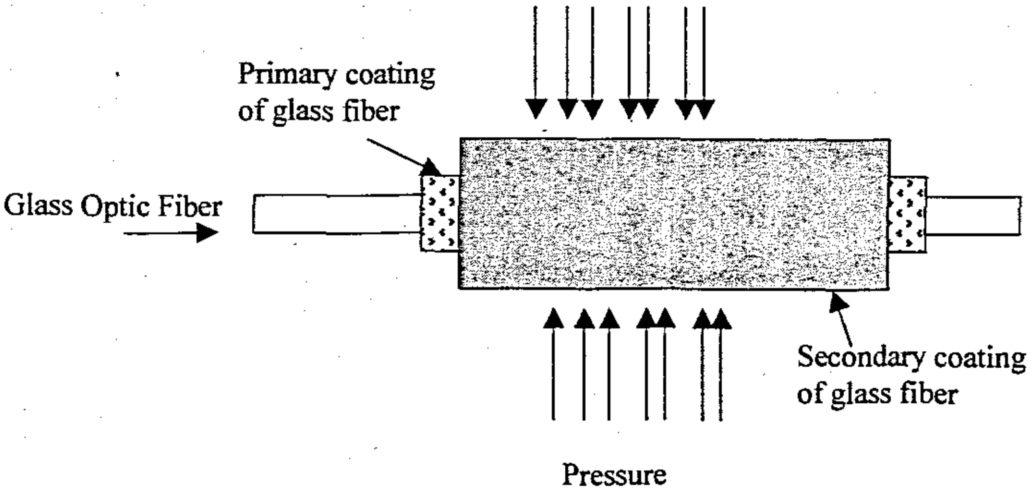


Figure 5.10: Coatings can be used to optimize the sensitivity of fiber sensors. An example would be to use soft and hard coatings over an optical fiber to minimize the acoustic mismatch between acoustic pressure waves in water and the glass optical fiber

These coated fibers are often used in combination with compliant mandrills or strips of material as shown in Figure 5.34 that act to amplify the environmentally induced optical path length difference.

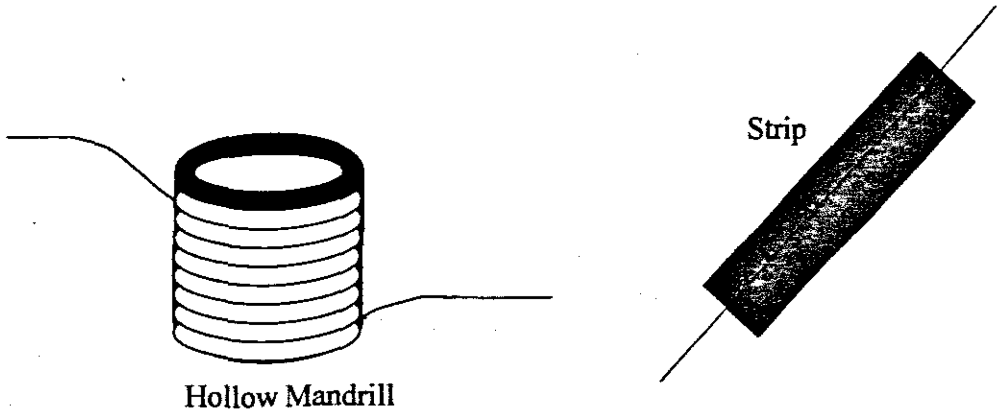


Figure 5.11: Optical fiber bonded to hollow mandrills and strips of environmentally sensitive material are common methods used to mechanically amplify environmental signals for detection by fiber sensors

In many cases the mechanical details of the transducer design are critical to good performance such as the seismic or vibration sensor. Generally the Mach-

Zehnder and Michelson interferometers can be configured with sensitivities that are better than 10^{-6} radians per square root Hertz. For optical receivers, the noise level decreases as a function of frequency. This phenomenon results in specifications in radians per square root Hertz. The best performance for these sensors is usually achieved at higher frequencies because of problems associated with the sensors also picking up environmental signals due to temperature fluctuations, vibrations and acoustics that limit useful low frequency sensitivity.

5.3 MULTIPLEXING AND DISTRIBUTED SENSING

Many of the intrinsic and extrinsic sensors may be multiplexed [Kersey, 1991] offering the possibility of large numbers of sensors being supported by a single fiber optic line. The techniques that are most commonly employed are time, frequency, wavelength, coherence, polarization and spatial multiplexing.

Time division multiplexing employs a pulsed light source launching light into an optical fiber and analyzing the time delay to discriminate between sensors. This technique is commonly employed to support distributed sensors where measurements of strain, temperature or other parameters are collected. Figure 5.35 illustrates a time division multiplexed system that uses microbend sensitive areas on pipe joints.

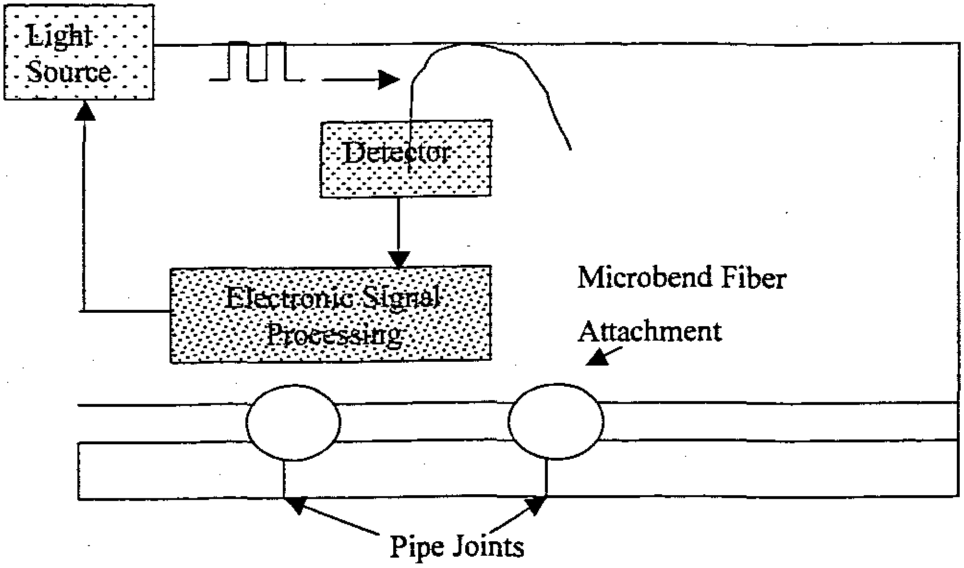


Figure 5.12: Time division multiplexing methods can be used in combination with microbend sensitive optical fiber to locate the position of stress along a pipeline.

As the pipe joints are stressed, microbending loss increases and the time delay associated with these losses allows the location of faulty joints. The entire length of the fiber can be made microbend sensitive and Rayleigh scattering loss used to support a distributed sensor that will predominantly measure strain. Other types of scattering from optical pulses propagating down optical fiber have been used to support distributed sensing. A frequency division multiplexed system is shown in Figure 5.36. In this example a laser diode is frequency chirped by driving it with a sawtooth current drive. Successive Mach-Zehnder interferometers are offset with incremental lengths ($L-L_1$), ($L-L_2$), and ($L-L_3$) which differ sufficiently that the resultant carrier frequency of each sensor (dF/dt)($L-L_n$) is easily separable from the other sensors through electronic filtering of the output of the detector.

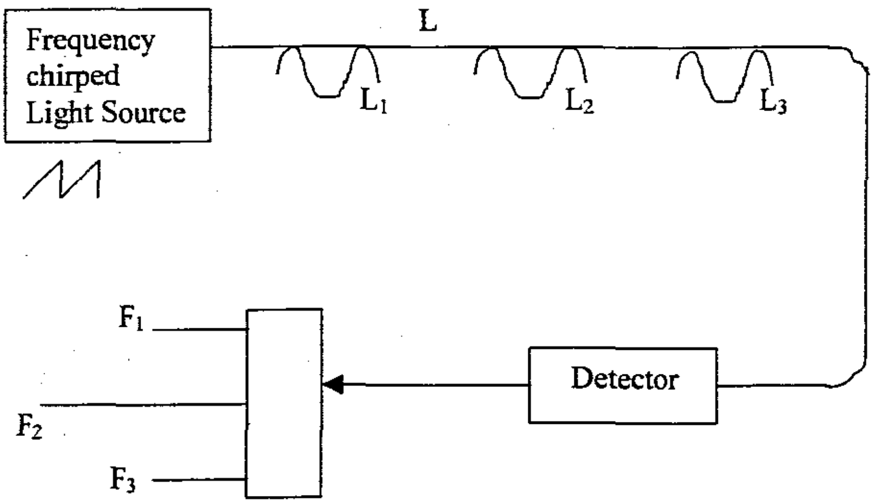


Figure 5.14: Frequency division multiplexing can be used to tag a series of fiber sensors, as in this case the Mach-Zehnder interferometers are shown with a carrier frequency on which the output signal ride.

Wavelength division multiplexing is one of the best methods of multiplexing as it uses optical power very efficiently. It also has the advantage of being easily integrated into other multiplexing systems, allowing the possibility of large numbers of sensors being supported in a single fiber line. Figure 5.37 illustrates a system where a broadband light source, such as a light emitting diode, is coupled into a series of fiber sensors that reflect signals over wavelength bands, that are subsets of the light source spectrum. A dispersive element, such as a grating or prism, is used to separate out the signals from the sensors onto separate detectors.

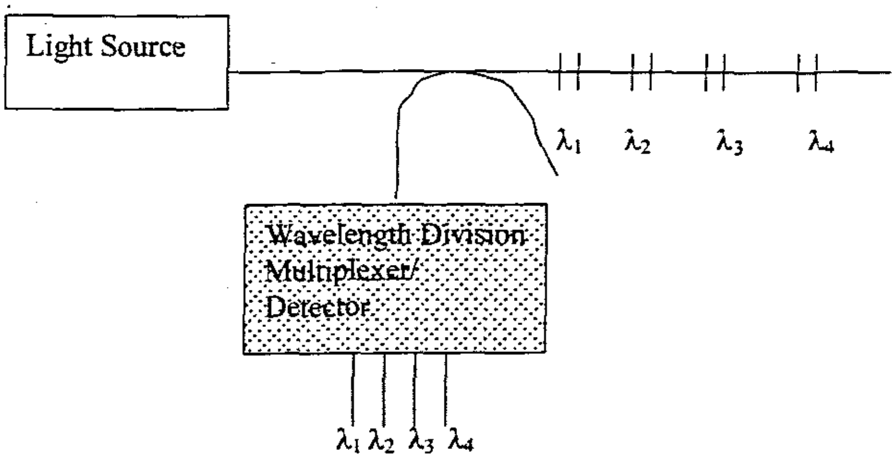


Figure 5.15: Wavelength division multiplexing are often very energy efficient. A series of fiber sensors are multiplexed by being arranged to reflect in a particular spectral band, that is split via a dispersive element onto separate detectors.

Light sources can have widely varying coherence lengths depending on their spectrum. By using light sources that have coherence lengths that are short compared to offsets between the reference and signal legs in Mach-Zehnder interferometers and between successive sensors, coherence multiplexed system similar to Figure 5.38 may be set up. The signal is extracted by putting a rebalancing interferometer in front of each detector so that the sensor signals may be processed. Coherence multiplexing is not as commonly used as time, frequency and wavelength division multiplexing because of optical power budgets and the additional complexities in setting up the optics properly. It is still a potentially powerful technique and may become more widely used as optical component performance and availability continue to improve, especially in the area of integrated optic chips where control of optical pathlength differences is relatively straightforward.

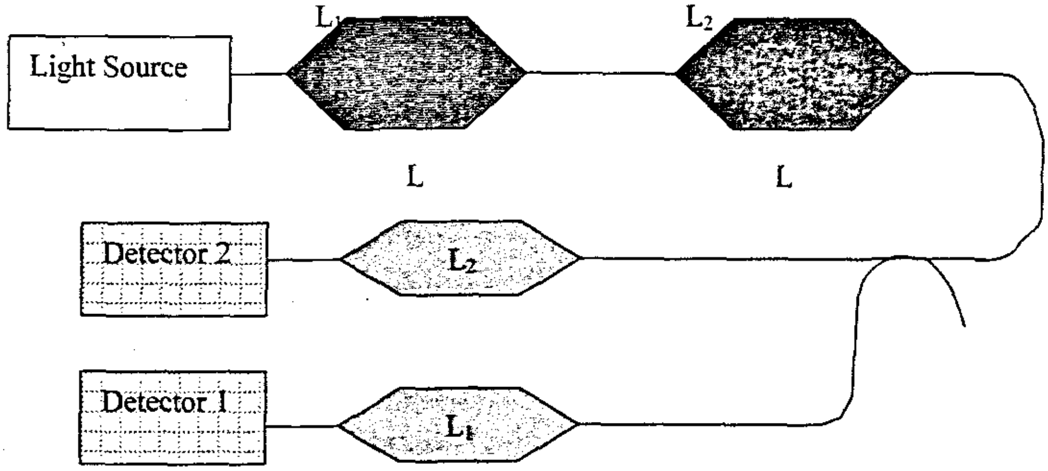


Figure 5.16: Using offset lengths and counterbalancing interferometers uses a low coherence light source to multiplex two Mach-Zehnder interferometers.

All of these multiplexing techniques can be used in combination with one another to form extremely large arrays.

As all sensors have been described, and their topology discussed, these require a good analysis for their operation with a view to choose one for use in or measuring microwave effects with fiber optic, as a sensor for microwave measurement. These lead to description of the different properties of the fiber optic sensors, or fiber optic cable when employed within microwave energy. Comparison of each and selection is made due to the advantages over other sensors, especially looking at the parameters that could be easily monitored, measured or varied for the purpose to change other fiber optic parameters (that is, phase, wavelength, length and refractive index) within the microwave environment.

Table 5.1: - Summaries Of Fiber Optic Sensors

TYPE OF SENSORS	APPLICATIONS	ADVANTAGES	DISADVANTAGES
Microbend Sensors	Measure qualitative information through the loss of light: safety mats in front of rotating machinery that disable machines when operator is at unsafe location, fire detection in large buildings, excess stress locations for pipelines	Low cost; possible Coverage of wide area	Low accuracy
Extrinsic Fabry-Perot Fiber Etalon Sensors	Measure longitudinal component of strain, pressure or temperature through two mirrored surfaces: single point static strain measurements in experiments and manufacturing processes for structures and bridges, pressure measurements	Gauge lengths similar to conventional strain gauges; immunity to electromagnetic interference; high temperature, shock and vibration resistant	Difficulties associated with measuring temperature and strain simultaneously, which may be important for internal measurements in inaccessible areas
Intrinsic Fabry-Perot Fiber Etalon Sensors	Measure longitudinal component of strain, pressure or temperature through two mirrored surfaces: time varying strain measurement applications, including strain on cylinder heads operating at elevated temperatures, vibrating machinery and dynamic loads	Gauge lengths similar to conventional strain gauges; immunity to Electromagnetic interference; high temperature, shock and vibration resistant	Difficulties associated with measuring temperature and strain simultaneously, which may be important for internal measurements in inaccessible areas

	on railway bridges		
Fiber Grating Sensors	Measure an index of refraction Modulation of the fiber core produced by an interference pattern formed through the fiber: strain on bridges, aircraft parts , naval vessel parts and utility poles, compared to the same measurements from Conventional electric strain gauges	Possible future low cost; multi-parameter sensing of transverse and longitudinal strain, Strain gradients, temperature, pressure and corrosion.	Expensive, due to limited production and use. Require specialised equipment to manufacture.
Mach Zehnder and Michelson Interferometric Sensors	Measure acoustic waves and vibration, both the time varying and static quantities, since strain, temperature and pressure all affect their response: Undersea surveillance and geophysical seismic exploration.	Extremely flexible Geometry and high Sensitivity, wide area Distribution sensor possible. Strain induced can be accurately measured.	Medium cost; the long Coherence length lasing light sources required are not as reliable and cannot handle as high temperatures as the light source for the Sagnac sensor.
Sagnac Interferometric Sensors	Filters lower frequency noise components, optimum performance with low coherence light source that has higher reliability and ability to withstand higher temperatures than other interferometers, and distributed sensing capabilities	Rapidly emerging Industrial base for This type of interferometer only; Environmental Ruggedness. Ideally suited for position sensing.	Response at low Frequencies is linearly Proportional to frequency; does not have high sensitivity for detection of low frequency signals

Advantages of these sensors include extremely high sensitivity, wide area distribution, and the ability to be multiplexed in large numbers and combinations of interferometer sensors that allow the measurement of the location and amplitude of time varying events.

Grouping the sensors in this manner helped in making a proper choice of the configuration that should be used or could be easily employed to measure microwaves. The following table is an extract that classifies the fiber optic type with a rating towards microwave measurements.

Table 5.2: Evaluation of fiber optic sensors in use for microwave measurement

Fiber Optic Sensor Type	Ratings of sensors towards microwave			
	N/A	Fair	Good	Excellent
Extrinsic			*	
Intrinsic			*	
Vibration	*			
Numerical Aperture	*			
Rotary	*			
Position		*		
Evanescence	*			
Microbend	*			
Grating		*		
Absorption				*
Fluorescent	*			
Hybrid	*			
Sagnac	*			
Distributed			*	
Interferometry				*

Deducing from Table (5.1) and Table (5.2), we can see that the interferometers are suitable for strain induced sensing and are sensitive enough for testing our microwave measurement theory. Table 5.1 reduces our choice to the Michelson and Mach-Zehnder Interferometer. Since Michelson Interferometers are not a classic optical fiber based topology, but rather a bulk optical sensor approach, our choice of sensor was reduced to the Mach-Zehnder topology.

CHAPTER 6

DEVELOPING A MODEL FOR THE MACH-ZEHNDER INTERFEROMETER FIBER OPTIC SENSOR FOR MICROWAVE MEASUREMENT

6.1 INTRODUCTION

As mentioned before, Phase-modulated sensors operate by detecting measurand and induced optical phase shifts between two or more coherent optical fields. Generally, they are based on fiber implementations of classical interferometers such as the Michelson and *Mach-Zehnder configurations [Udd, 1991]*.

Single-mode fibers are phase-modulated based sensor systems. In this we will discuss primarily phase-modulated sensors based on the two-team interferometer configuration, such as the Mach-Zehnder. When developing a model, basic equations and their principles are required. Therefore, transfer functions of the interferometer are essential to determine relationship between its physical components and environment applied under. This is very important to phase modulated sensor as phase shift generated by the interferometer employ light to current or voltage conversion to virtually display the changes due to the measurand perturbations.

It has been seen that intensity-based sensors have been developed for primarily low-cost process control, or engineering type applications, whereas with interferometric phase-modulated sensors, more emphasis has been directed toward the development of high-performance sensors.

6.2 THE PHASE MODULATED SENSOR

The sensor employs a coherent laser light source and two single mode fibers. The light split and injected into each fiber. If the environment perturbs one fiber relative to the other, a phase shift occurs that can be detected. The phase shift is detected by an interferometer.

6.2.1 PRINCIPLE OF OPERATION

The interferometer allows the measurement of extremely small differential phase shifts in the optical fiber generated by the measurand. The optical phase delay of light passing through a fiber is given by

$$\phi = nkL \qquad 6.1$$

Where n is the refractive index of the fiber core, k is the optical wavenumber in the vacuum ($\frac{2\pi}{\lambda}$, λ being the wavelength), and L is the physical length of the fiber. From the equation, nL is referred to as an optical path length, and small variations in the phase delay could be found by applying differentiation in Equation 6.1.

$$\frac{d\phi}{\phi} = \frac{dL}{L} + \frac{dn}{n} + \frac{dk}{k} \qquad 6.2$$

The first two terms are related to the physical changes in the fiber caused by the perturbation to be measured [Udd, 1987]. Generally, the changes in pressure, temperature, and magnetic field result in different contributions to dϕ through dL and dn. Due to strain optic coefficient of the fiber, an accompanying dn would occur. The last term, dk, takes care of any wavelength (or frequency) variation associated with the light source.

6.2.2 TRANSFER FUNCTIONS OF THE INTERFEROMETER

Each type of interferometer exhibits a characteristic output function with respect to the phase difference in the system employed.

The configuration interferometer to be implemented was a Mach-Zehnder and was designed with the single mode optical fiber to be placed within the microwave field. Its operation is that, the coherent single mode (SM) source is launched into the SM fiber. The light is then split into two beams of nominal equal intensity by the fiber optic coupler (beam splitter), part being sent through the sensing fiber arm, and remainder through the reference arm. The two outputs are recombined by the second coupler after passing through sensing and reference fiber coils. An interference signal between the two beams is then formed, which after propagating the length of output fiber is detected by the photodetectors. The key element of the interferometer is the two fiber couplers. If the power coupling coefficients of the two couplers are k_1 and k_2, there will be certainly an optical loss α_s and α_r associated with the sensing and referencing paths respectively. Therefore, the optical fields at one output of the interferometer from signal and reference arm are [Udd, 1991]

$$E_r = E_o\sqrt{\alpha_r k_1 k_2}(\cos(\omega_o t + \phi_r)) \qquad 6.3$$

and

$$E_s = E_o\sqrt{\alpha_s(1-k_1)(1-k_2)}\cos(\omega_o t + \phi_s) \qquad 6.4$$

Using these formulas, the output intensity is given by

$$I = I_o[\alpha_s k_1 k_2 + \alpha_s(1-k_1)(1-k_2) + 2\sqrt{\alpha_s\alpha_r k_1 k_2(1-k_1)(1-k_2)}\cos(\phi_r - \phi_s)] \qquad 6.5$$

Hence the output fringes visibility of the interferometer is given by the standard definition

$$V = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} \qquad 6.6$$

which forms

$$V = \frac{2\sqrt{\alpha_s \alpha_r k_1 k_2 (1-k_1)(1-k_2)}}{\alpha_s k_1 k_2 + \alpha_s (1-k_1)(1-k_2)} \qquad 6.7$$

Considering the complementary output of the interferometer, this has a similar output:

$$I' = I_o[\alpha_r k_1 (1-k_2) + \alpha_s (1-k_1) k_2 + 2\sqrt{\alpha_s \alpha_r k_1 k_2 (1-k_1)(1-k_2)} \cos(\phi_s - \phi_r) \qquad 6.8$$

The complementary fringe visibility of this output is given by

$$V = \frac{2\sqrt{\alpha_s \alpha_r k_1 k_2 (1-k_1)(1-k_2)}}{\alpha_r k_1 (1-k_2) + \alpha_s (1-k_1) k_2} \qquad 6.9$$

Ignoring the effect of the loss terms, the following commonly encountered cases are of interest: -

- If one of the couplers splitting ratio is fringe, visibilities of each output are the same.
- If both couplers have the same splitting ratio, one output will have unity visibility.

For the case of mathematical manipulation, the equations can be rewritten in the following manner

$$I = I_o \alpha (A + B\cos\Delta\phi) \qquad 6.10$$

$$I' = I_o \alpha (C - B\cos\Delta\phi) \qquad 6.11$$

Where it is assumed that $\alpha_s = \alpha_r = \alpha$ and

$$A = k_1 k_2 + (1-k_1)(1-k_2) \qquad 6.12$$

$$B = 2\sqrt{\alpha_s \alpha_r k_1 k_2 (1-k_1)(1-k_2)} \qquad 6.13$$

$$C = k_1(1-k_2) + (1-k_1)k_2 \qquad 6.14$$

and $\Delta\phi = (\phi_r - \phi_s)$

Further simplification may be if $k_1 = k_2 = 0.5$ (splitting ratio of the couplers) then becomes

$$I = \frac{I_o \alpha}{2}(1 + \cos\Delta\phi) \qquad 6.15$$

$$I' = \frac{I_o \alpha}{2}(1 - \cos\Delta\phi) \qquad 6.16$$

The differential phase shift in the interferometer may be separated into a signal term $d\phi$ of amplitude ϕ_s and frequency ω and a slowly varying phase shift ϕ_d. For simplicity, the interferometer outputs can be equivalent to:

$$I = \frac{I_o \alpha}{2}[1 + \cos(\phi_d + \phi_s \sin\omega t)] \qquad 6.17$$

$$I' = \frac{I_o \alpha}{2}[1 - \cos(\phi_d + \phi_s \sin\omega t)] \qquad 6.18$$

These intensity outputs are then converted to electrical currents by a photodetectors. The differential combination of these photocurrents produces an output:

$$i = \varepsilon I_o \alpha \cos(\phi_d + \phi_s \sin\omega t) \qquad 6.19$$

Where ε is the responsivety of the photodetectors. This equation can be expanded in terms of Bessel function such that the output is of the form

$$\begin{aligned} i = \varepsilon I_o \{ & \cos\phi_d [J_o(\phi_s) \\ & + 2\sum_{n=1}^{\infty} J_{2n}(\phi_s)\cos 2n\omega t] \\ & + \sin\phi_d [2\sum_{n=0}^{\infty} J_{2n+1}(\phi_s)\sin((2n+1)\omega t)]\} \end{aligned} \qquad 6.20$$

Where $J_n(\phi_s)$ is the Bessel function of order n and argument ϕ_s. The processing of this output to retrieve the signal information, d, in the presence of the slowly varying, d, is nontrivial task. The limiting sensitivities (i.e., minimum detectable change) of the detectors thus depend on the desired signal to noise ratio (SNR).

6.3 PHASE DETECTION

The phase angle, ϕ, for a lightwave travelling in a fiber is defined by the equation below, reference to explanation mentioned earlier. The phase angle for a lightwave with a given wavelength, λ, and length, L, is given by

$$\phi = 2\pi \frac{L}{\lambda} = 2\pi n_1 \frac{L}{\lambda_0} \qquad 6.21$$

Where n_1 is the refractive index of the fiber core and λ_0 is the wavelength of light in a vacuum. If L and λ_0 are in the same units, the phase angle is in radians. A change in length and or refractive index will cause a phase change as defined by the following equation.

$$\phi + \Delta\phi = \frac{2\pi}{\lambda_0}[n_1 L + n_1 \Delta L + L\Delta n_1] \qquad 6.22$$

For simplification, considering a phase change associated with changes in length, the above equation is simplified to

$$\phi + \Delta\phi = \frac{2\pi}{\lambda_0}[n_1 L + n_1 \Delta L] \tag{6.23}$$

The phase change of a lightwave through an optical fiber associated with an increase in length, has been stretched by a Length ΔL. The principal attraction of optical phase modulation is its intrinsically high sensitivity to environmental modulation. The advantages of using fibers in interferometric sensors lie both in easing the alignment difficulties inherent in assembling interferometers with long arms, and in increasing the sensitivity of the phase modulation to the environmental parameter, simply by increasing the optical path length exposed to the measurand.

As the basic elements of an optical fibre interferometer are discussed, for reasons, it is usually preferable to operate the interferometer with approximately equal length signal and reference arms to minimize the effects of laser phase noise. The reference arm should be effectively shaded from the influence of the measurand, since both arms are equally sensitive. The modulator could be included in the reference arm to incorporate the 90^0 phase shift in the interferometer.

Therefore, the total phase of the light path along an optical fibre would depend on three properties of the fibre guide:

1. Its total physical length
2. The refractive index and the index profile
3. The geometrical transverse dimensions of the guide.

It would be assumed that the index profile remains constant with environmental variations, so that all the following analysis concentrates on evaluating the depth of phase modulation for variations in length, refractive index and guide dimensions. These variations are then evaluated for a given perturbation applied to the fibre.

6.4 SIGNAL PROCESSING TECHNIQUE

In order to implement the signal processing technique, a means is required to measure changes in one or more of the parameters, describing the optical beam, amplitude, phase direction and frequency of the light beam. Temporal modulation of one, or more, of these parameters enables information to be encoded onto or extracted from the optical wave.

Optical fiber modulation technique is therefore required to encode information, or extract it from the fiber-guided beam. The objectives are to review the techniques for modulating the phase of light waves guided by optical fibers.

To see how phase modulation can be achieved, consider the expression describing the phase change, ϕ, of an optical beam propagating through a fiber of length, L, is

$$\phi = \beta L \qquad 6.24$$

Where β is the propagation constant given by $\beta = \frac{2\pi}{\lambda} n_{ef}$, λ is the free space wavelength of the source and n_{ef} is the effective refractive index of the fiber core. The effective refractive index, also called the effective index is given by $n_{ef} = \frac{\beta}{k}$, where and $k = \frac{2\pi}{\lambda}$. Thus a small change in phase, is described by

$$\Delta\phi = \beta\Delta L + L\Delta\beta \qquad 6.25$$

Where $\beta\Delta L$, is the phase change corresponding to the physical change in length, and $L\Delta\beta$ corresponds to a change in phase produced by a stress-induced change in the fiber propagation constant. Equation 6.26 further describes phase shift as applying differentiation, with respect to n, and r.

$$L\Delta\beta = L\frac{d\beta}{dn}\Delta n + L\frac{d\beta}{d(2r)}\Delta(2r) \qquad 6.26$$

Where r, is the effective radius of the fiber. The first term ($L\frac{d\beta}{dn}\Delta n$) represents a change in the propagation constant due to a change in the refractive index, and second term represents a change due to a change in the fiber diameter. Neglecting the second term (change in radius), the phase change, $\Delta\phi$ results in

$$\Delta\phi = \beta\Delta L + L\frac{d\beta}{dn}n; \quad \beta = \frac{2\pi}{\lambda}n_{ef} \qquad 6.27$$

Therefore, the phase change becomes

$$\Delta\phi = \frac{2\pi}{\lambda}\left[n_{ef}\Delta L + L\Delta n\right] \qquad 6.28$$

With respect to the temperature change (for thermal) of the fiber length, the phase change, will result to this function.

$$\frac{\Delta\phi}{L\Delta T} = \frac{2\pi}{\lambda}\left[\frac{n}{L}\frac{dL}{dT} + \frac{dn}{dT}\right] \qquad 6.29$$

6.5 BASIC EQUATIONS FOR THE DETECTORS

Intensity signals that are recorded by the photodetectors from the circuits would encode the optical phase shift experienced by the sensor, and this phase shift encodes the external loads applied to the sensing fiber, which can be characterized. The equations, which are to be used in the circuits to understand the behaviour of the detectors in the active optical fiber sensors (Mach-Zehnder Interferometer) should have:

1. The relationship between intensity and phase
2. The relationship between phase and strain

3. Relationship between feedback voltage and sensing fiber optical path length change.

Jones' Calculus can be used to derive the intensity functions recorded by the photodetectors in the interferometer [Gialloenzi et. al, 1982]. That is, 1 and 2 of the detectors producing currents, I_1 and I_2.

$$I_1 = E_o^2\left(1-\cos\left(\left(\frac{\Delta\phi_2+\Delta\phi_3}{2}\right)\right)\cos\left(\left(\frac{\Delta\phi_2-\Delta\phi_3}{2}\right)\right)\right) \quad 6.30$$

$$I_2 = E_o^2\left(1+\cos\left(\left(\frac{\Delta\phi_2+\Delta\phi_3}{2}\right)\right)\cos\left(\left(\frac{\Delta\phi_2-\Delta\phi_3}{2}\right)\right)\right) \quad 6.31$$

Where $\Delta\phi_2 = \Delta\phi_2^S - \Delta\phi_2^R$ and $\Delta\phi_3 = \Delta\phi_3^S - \Delta\phi_3^R$ are relative optical phase changes (between sensing, S, and reference, R, fibers) of the light plane polarized along the two principal optical directions in the fiber. As single mode fiber has a low birefringence, equation (6.30) and (6.31) can be reduced to:

$$I_1 = E_o^2(1-\cos(\Delta\phi)) \quad 6.32$$

$$I_2 = E_o^2(1+\cos(\Delta\phi)) \quad 6.33$$

Where $\Delta\phi$ just represents the externally induced phase change. These equations enable to drive or model or calculate the mathematical response of the Mach-Zehnder Interferometer associated with microwave energy measurement, as being represented by one factor (for an example, l, T, or ϕ). It has shown that with the length of fiber used, amount of light source, and its parameters (phase, refractive index), the microwave power can be associated with them in relation to changes within the field.

CHAPTER 7

THE FIBER OPTIC MACH-ZEHNDER INTERFEROMETER FOR MICROWAVE MEASURESEMENT

7.1 INTRODUCTION

As can be seen from the model in Chapter 6, Interferometric optical fiber sensors have proved many orders of magnitude more sensitive than their electrical counterparts, but they suffer from limitations in signal demodulation caused by phase ambiguity, and complex fringe counting, when the output phase difference exceeds one fringe period. Various signal demodulation methods have been developed to overcome some of these drawbacks with limited success.

This chapter gives full details of the new measurement system for the Microwave Fiber Optic Mach-Zehnder Interferometer (MFOMZI) sensor. By investigating a wavelength-modulated source, some of the limitations of interferometric signal demodulation were overcomed. By measuring the output wavelength of a laser diode through current modulation, the MFOMZI output sensor signal was determined by monitoring the phase difference of the multiple fringe patterns. A digital storage oscilloscope (HP 8648B 9KHz – 2000MHz) and Spectrum Analyzer (HP 4396B, 100KHz – 1.8GHz/ 2Hz – 1.8GHz/ 100KHz – 1.8GHz Network/Spectrum/Impedance Analyzer) was used to record the phase change and photodetector circuit outputs. A commercial microwave cavity was used as a microwave source, set on medium and different power levels at instance times in seconds.

7.2 MACH-ZEHNDER INTERFEROMETER

The Mach-Zehnder configuration was an intrinsic sensor based on the interference between a sensing and a reference wave. The two-beam interferometer used a laser diode as the source of coherent light, which was coupled into a single mode fiber (10/125μm). The light was then split equally into two fibers by a 3 dB coupler, as specified later in this chapter. One leg of the Mach-Zehnder interferometer was the sensing leg while the other is the reference. The reference fiber is kept protected from the desired perturbation to be measured and light passes through this leg normally. The sensing fiber was used to monitor the perturbation as immersed in the microwave cavity to observe changes as referred in Figure 7.1. Two complementary outputs were available for signal processing.

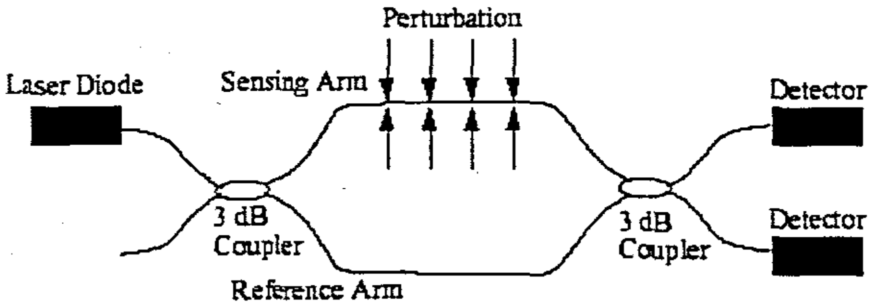


Figure 7.1: Mach-Zehnder Interferometer

The electric fields of the two light waves can be expressed as

$$E_r = E_0 \times e^{i0t} \qquad 7.1$$

$$E_s = E_0 \times e^{i(0t+\Delta\phi)} \qquad 7.2$$

Where E_r is the reference wave, E_s is the sensing wave, and $\Delta\phi$ is the phase difference induced by the sensing fiber as shown in Chapter 6. At the photodetector, the intensity can be simplified as

$$I=E_r^2+\langle E_s^2 \rangle+2\langle E_rE_s \rangle \quad 7.3$$

Where I represent the time integration performed by the photodetector. Equation 7.3 is reduced to

$$I = I_0 (1+ \cos\Delta\phi) \quad 7.4$$

Which is the I_2 term of the Equation (6.33), where, I_0· is proportional to, E_o^2, and we have assumed the ideal conditions of equal splitting ratios, no coherence or polarization effects, and no losses. The information is contained in the phase difference between the two waves. The phase corresponding to a length of fiber L is

$$\phi= kn_eL \quad 7.5$$

Where, $k = 2p\frac{2\pi}{\lambda}$, is the propagation constant in air, l, is the laser diode emitting wavelength, and, n_e is the fiber's effective refractive index. If the desired measurand is X, then the change in ϕ may be represented by [Wilson and Hakes, 1989]

$$\Delta\phi = kL\frac{dn_1}{dX}\Delta X + kn_1\frac{dL}{dX}\Delta X \quad 7.6$$

If the coefficients $\frac{dn_1}{dX}$ and $\frac{dL}{dX}$ for the sensing fiber are known, ϕX, can be found from the output signal, expressed by Equation (7.4) or (6.33).

Quantities such as magnetic field, acoustic pressure, electric field, microwave, and current can be measured indirectly by attaching the sensing fiber to materials that respond to these parameters.

The output of the sensor, Equation (7.4), is sinusoidal and is shown in Figure 7.2. The signal goes through one period for every 2π shifts in $\Delta\phi$. This period is referred to as one fringe. The sensor has maximum sensitivity at the quadrature (Q) point.

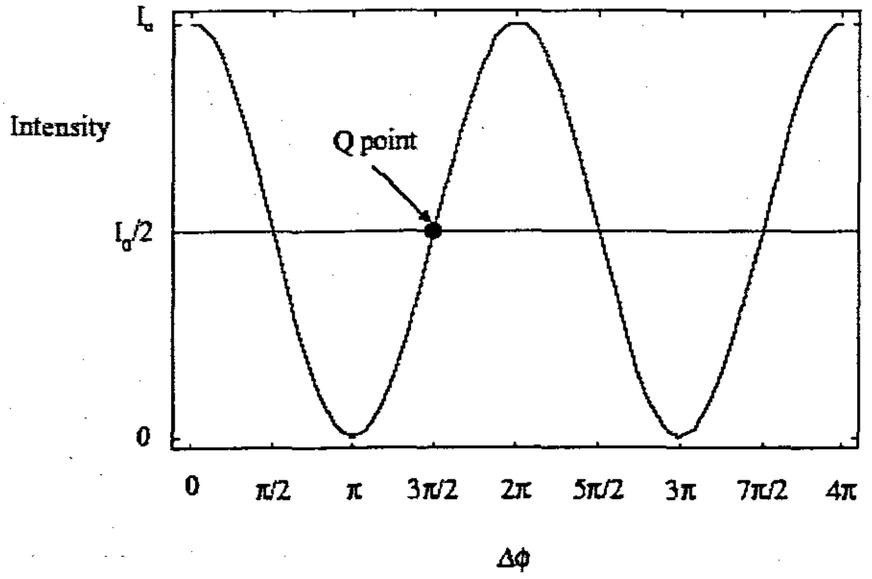


Figure 7.2: Mach-Zehnder Output

The goal of this chapter was to design, and implement a new measurement system for the MFOMZI sensor. Using a wavelength modulated source, 3dB couplers, single mode fibers and photodetectors; some of the limitations of interferometric signal demodulation were overcome. This chapter describes the experimental set-up, some of the limitations encountered, and covers the results and characteristics of the MFOMZI system.

7.3 QUADRATURE PHASE SHIFT MACH-ZEHNDER INTERFEROMETER

The following method was implemented to improve signal demodulation of the MFOMZI. The quadrature phase shift MZI allowed the transmitted signal to be referenced. In this method, the two photodetector sensors circuits were designed to give two signals $\pi/2$ out of phase or in quadrature with each other.

The system consists of two inputs, and output fibers coupled together by 3dB coupler (2×2). The two input and output fibers configurations were designed such that a difference in each sensor causes their signals to be in quadrature. In this way, one sensor was always at the quadrature point; when the other was at a point of minimum sensitivity. By monitoring the phase lead-lag of the two signals, the amplitude of the phase change was referenced to the measurand.

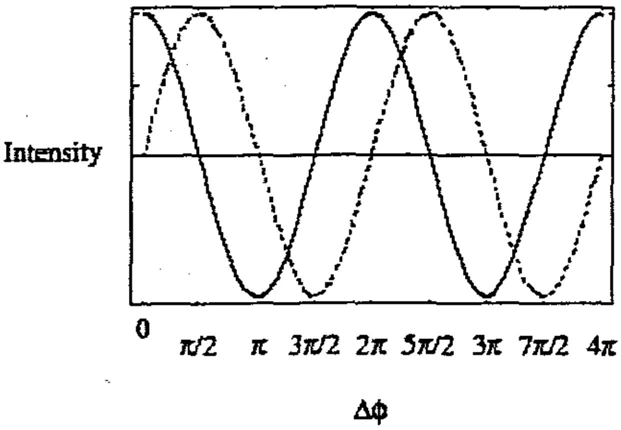


Figure 7.3: Two Photodetector signals in quadrature

To obtain ΔL, complex fringe counting methods still was employed. In addition, sensor design was difficult because the difference in the phase change was very small. For the signals to be in quadrature, Equation (7.7) was used [Bhatia, 1993].

$$L_1 - L_2 = (2n+1)\frac{\lambda}{8} \qquad 7.7$$

Which was difficult to achieve and maintain.

7.4 EXPERIMENTAL RESULTS

We describe further the experimental setup for the testing of the MFOMZI with a wavelength-modulated source. Some of the limitations caused by the set-up are also discussed. Experiments were performed to predict and verify the output interference of the single mode laser diode and the maximum modulation frequency. The performance of the MFOMZI with a wavelength-modulated source was then analyzed.

7.4.1 EXPERIMENTAL SETUP

To test the operation of the MFOMZI with a wavelength-modulated source, the following experiments were performed at the National Laser Centre using the set-up described in Figure 7.4. In addition, a bulk MZI was setup, and tested as described in Appendix 1. For all experiments, the single mode laser diode was used. The source was driven with a current driver that was modulated using a function generator. The current driver was used to set the DC bias point of the laser diode (I_{bias}), and the function generator voltage output was adjusted in amplitude and frequency for the various experiments as shown by Figure 7.4. I_1 and I_2 establish the peak to peak current deviation, defining

$$I_{mod} = I_2 - I_1 \qquad 7.8$$

The laser diode current was modulated at 0.1 mA/mV of input voltage to the current driver. The output was either a saw tooth modulation waveform or a triangular waveform. The sensing arm was a 1m (meter) coiled single mode optical fiber loosely arranged inside the microwave cavity as shown in Figure 7.4. Extra care had to be taken to ensure that microwaves did not escape from the cavity due our sensor arrangement. For this, two 1mm (millimeter) holes were drilled to allow the cable access to the source, and detector electronics of the MFOMZI.

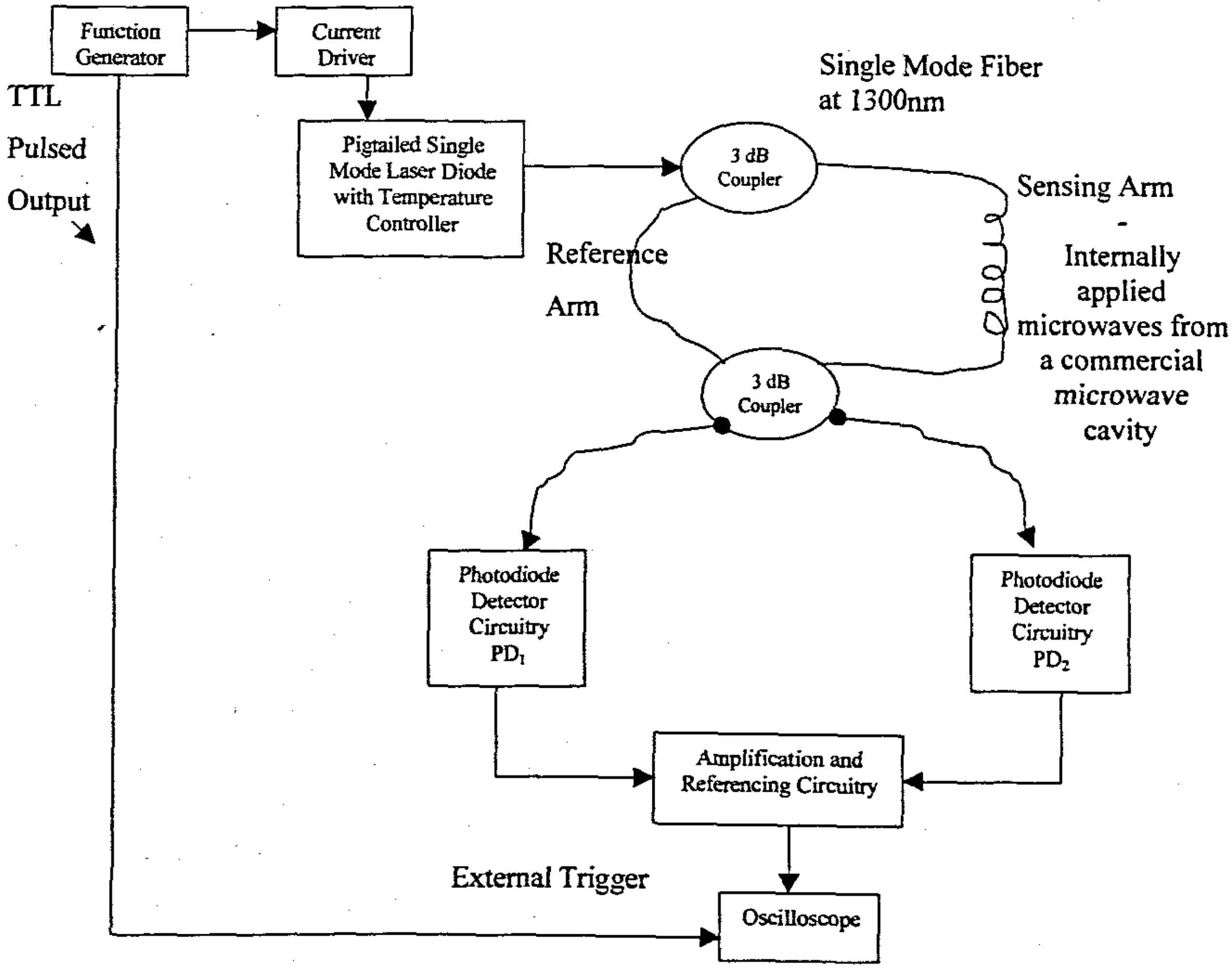


Figure 7.4: Overall experimental setup for testing MFOMZI

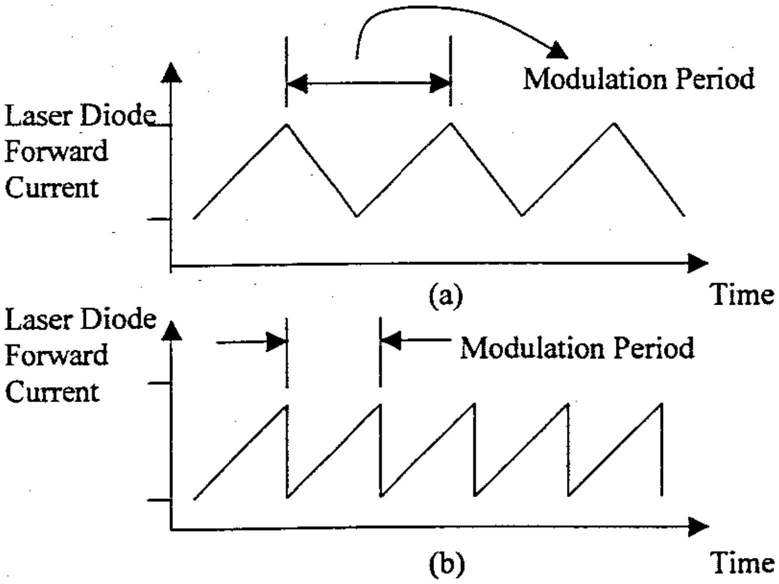


Figure 7.5: Current driver output modulation waveforms, (a) triangular modulation, and (b) saw tooth modulation.

A referencing circuit was employed to remove the unwanted intensity modulation as suggested by Beheim and Fritsch [Beheim and Fritsch, 1985]. Monitoring the intensity modulation with photodetector PD1, and removing the intensity modulation by dividing the PD2 signal by the PD1 signal obtained the response shown by Figure 7.6.

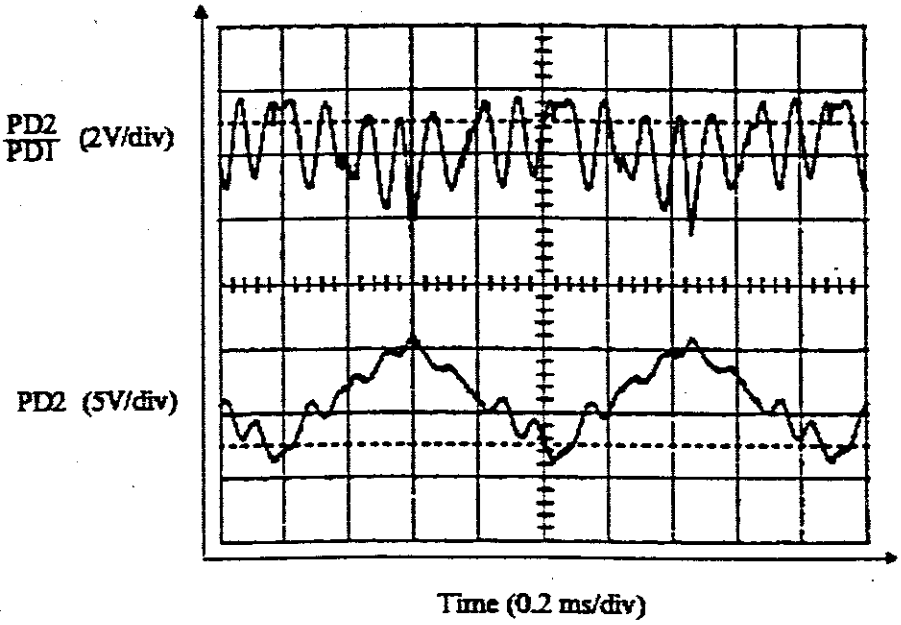


Figure 7.6: Output of PD_2 and PD_2/PD_1

Figure 7.7 shows how the PD1 and PD2 outputs were connected, amplified, and referenced.

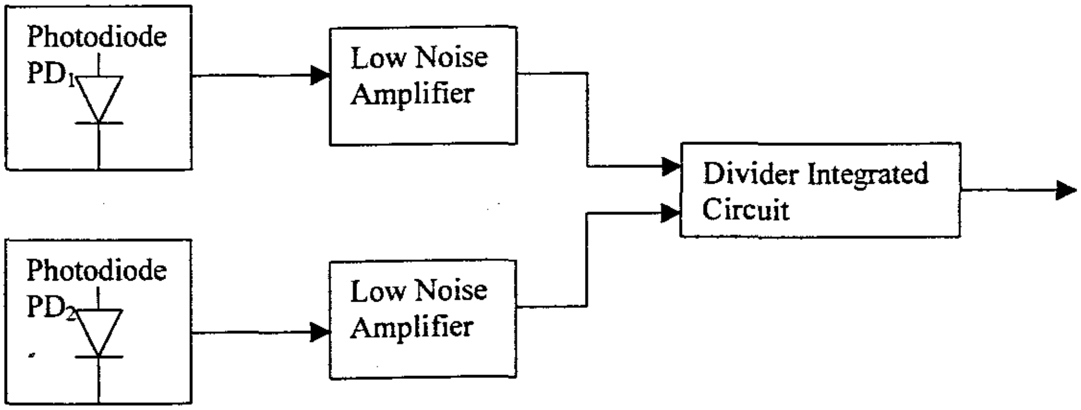


Figure 7.7: Amplification and referencing circuit

7.5 MFOMZI CONFIGURATIONS/ARRANGEMENTS/COMPONENTS USED

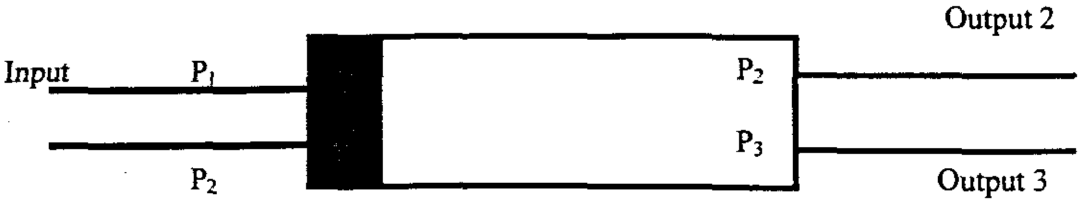
Below are types of MFOMZI configurations, and components used in these experiments. The translation stages, the amplifying, and referencing circuits limited the testing of the MFOMZI with a wavelength-modulated laser source. The frequency response of the amplifying and referencing circuits was also limited.

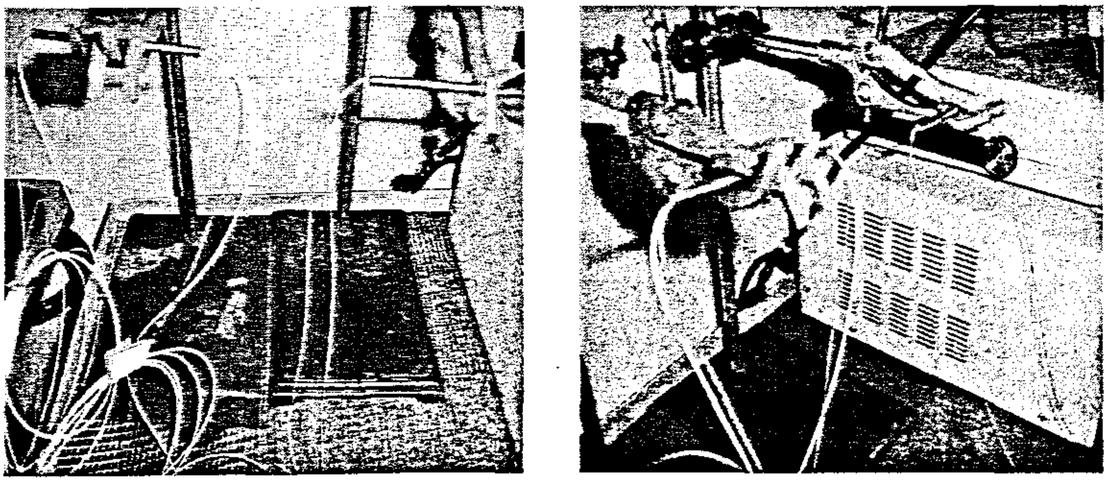
7.5.1 FIBER OPTIC COUPLERS

In this experiment, a 1×2 and 2×2 fiber optic coupler from SAFM Coupler Supplier was used. The first one is a C-NS-AL-50-H-2210-13-NC/NC Coupler. It is 70mm long, 4mm in diameter and is supplied with three single mode step index fibers attached. The second is a combiner (2 × 2 coupler) of the same design. However, it consists of two SMSI (single mode step index) fibers attached on both sides of the same length (2m). A fiber optic coupler is a device that can distribute the optical signal (power) from one fiber among two or more fibers. A fiber optic coupler can also combine the optical signal from two or more fibers into a single fiber. Fiber optic couplers attenuate the signal much more than a connector or splice because the input signal is divided among the output ports. For example, with a 1×2 fiber optic coupler, each output is less than one-half the power of the input signal (over a 3dB loss). Fiber optic couplers can be either active or passive devices.

The difference between active and passive couplers is that a passive coupler redistributes the optical signal without optical-to-electrical conversion. Active couplers are electronic devices that split or combine the signal electrically and use fiber optic detectors and sources for input and output.

With a design concept, a coupler was arranged as show below (the number of input ports and output ports vary depending on the intended application for the coupler). Figure 7.8 illustrates the transfer of optical power in an optical splitter. The input optical power is normally split evenly between the two output fibers.





Fiber optic couplers clamped for being horizontal level

Figure 7.8: Type of optical splitter known as a Y-coupler (1 × 2) and X-coupler (2 × 2).

Table 7.1: Main technical specifications for fiber optic coupler (1 x 2 and 2 × 2)

Internal optical loss, dB:			< 0.2
Coupler parameters are measured at the wavelength, nm:			1300 - 1550
Fiber type:			SM Fiber
1 x 2 Coupler: - Transfer coefficient between coupler ends 1-2, dB Transfer coefficient between coupler ends 1-3, dB Inequality of the division coefficient between ends 2 и 3, dB			 3.15 3.17 0.5
2 x 2 Coupler: - should be equally distributed			
Connector type	ST Connectorized		

Notes:

1. To avoid the damage of the coupler the fibers have not to be excessively stressed.
2. The radius of fiber bending must not to be less than 30 mm.

7.5.2 OPTICAL DETECTORS

The detection of optical perturbation in the sensor was accomplished by converting the optical energy into an electrical signal. Optical detectors may include photon detectors, in which one photon of light energy releases one electron that is detected in the electronic circuitry, and thermal detectors, in which the optical energy is converted into heat, which then generates an electrical signal. We were not so lucky to use such sensitive detectors. Often the detection of optical energy must be performed in the presence of noise sources, which interfere with the detection process. The detector circuitry employed a bias voltage and a load resistor in series with the detector in a typical transimpedance amplifier as shown by Figure 8.1. The incident light changed the characteristics of the detector and causes the current flowing in the circuit to change. The output signal was the change in voltage drop across the load resistor. Initial basic photodetector circuit used is shown in Figure 7.9 for designed purposes. Photodetector output is connected to Digital Storage Oscilloscope (HP 8648B, 9KHz - 2000MHz). The actual specifications of the photodetector module used for the Mach-Zehnder experiment is stated in Table 7.2.

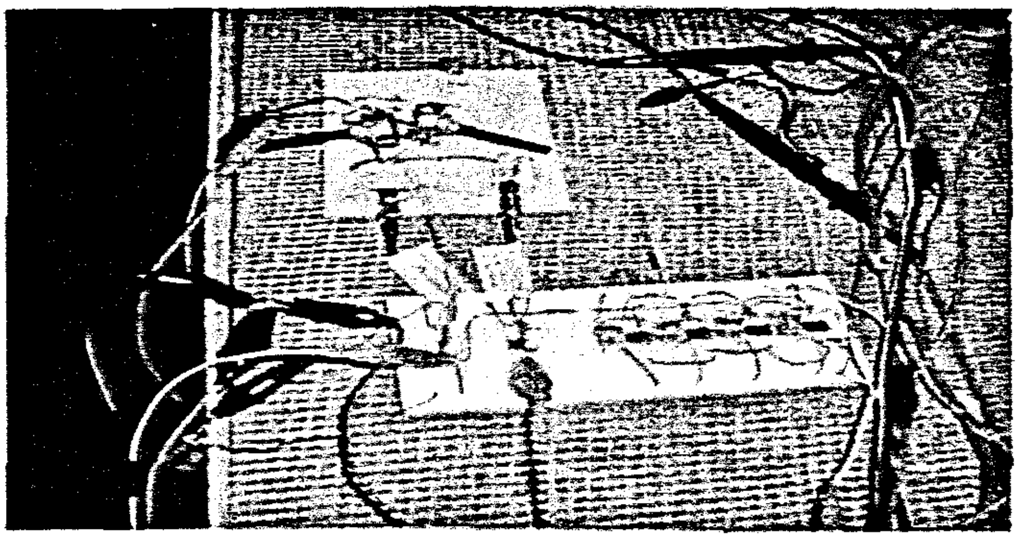


Figure 7.9: Photodetector circuit used for initial testing

Table 7.2: Photodetector module specification

Features:

- single supply 5..15V
- low noise (-83 dBm $Hz^{-1/2}$ at 10 kHz)
- high linearity
- single-mode optical input ST Connectorized

Main specifications:	
Sensitivity - at wavelength 1310 nm: - at wavelength 1550 nm:	 8,4 V/mW 7,2 V/mW
Bandwidth (-3dB):	0-200 kHz
Offset output voltage Uoff:	1.4 mV
Threshold of sensitivity (BW 1.5 Hz..200 kHz):	11 pW
DC supply voltage Usup: (operation at supply voltages below 8.3 V results in degraded performance)	5..15 V
Optical input: single-mode	ST Connectorized
Power supply connector:	Standard
Output:	BNC
Sizes: Length x Height x Width:	170 × 40 × 95 mm

7.5.3 LASER MODULE

Table 7.3 specifies the optical source used in the experiment.

Table 7.3: Single mode light source module (ST connectorized) and its specification

Features:

- stabilization of the temperature
- stabilization of the wavelength with the aid of thermoelectric cooler
- stabilization of the optical power via the use of feedback photodiode

Main specifications:	
Radiation wavelength:	1300 - 1550 nm
Output optical power:	0.35 mW
DC supply voltage:	±10..12 V
Consuming power:	3..5 W
Optical connector:	single-mode ST
Size: Length x Width x Height:	160 x 88 x 40 mm

All setup was powered from external AC – DC adapter through DC – DC converter. The patch cord (FIBERTAIL, ATC "0 – 2" (10/125μm) Fiber Optic Cable 0695M) was attached for measurements of the interferometer parameters. This enabled the interconnections and linking of all the interferometer components together.

7.5.4 PATCH CORD

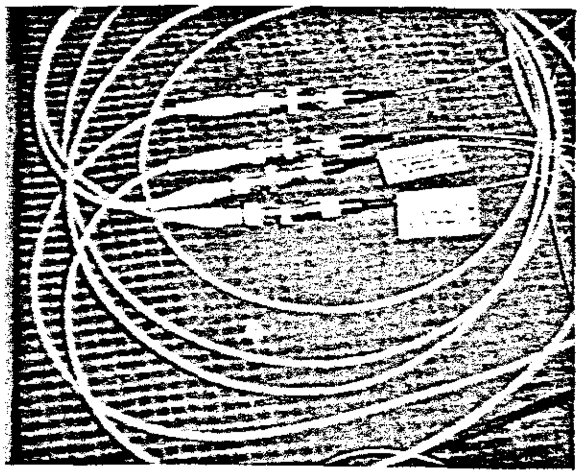


Figure 7.10: 1m and 2m ST connectorized patch cord used for interconnections

Table 7.4: Patch cords and other fiber optic cable specifications

Main specifications:	
Connectors:	ST connectorized
Cable type:	Single-mode 9.5/125 μm
Secondary jacket diameter:	3mm
Cable length:	1m and 2m/others
Insertion loss:	0.13dB (1300nm) – 0.17dB (1500nm)
Return loss:	< 40dB

The total insertion loss in the sensing arm of the experimental set-up was less than 0.4dB.

7.5.5 MINIMUM AND MAXIMUM FREQUENCY CHARACTERISTICS

To determine the maximum modulation frequency, the number of output fringes was monitored for a fixed peak-to-peak, I_{mod} as the current modulation frequency, f_{mod} was increased. As, f_{mod} was increased, the wavelength deviation caused by thermal effects began to subside and the charge carrier induced refractive index change began to dominate. As a result, the number of fringes for the same I_{mod} decreases as illustrated by Figure 7.12.

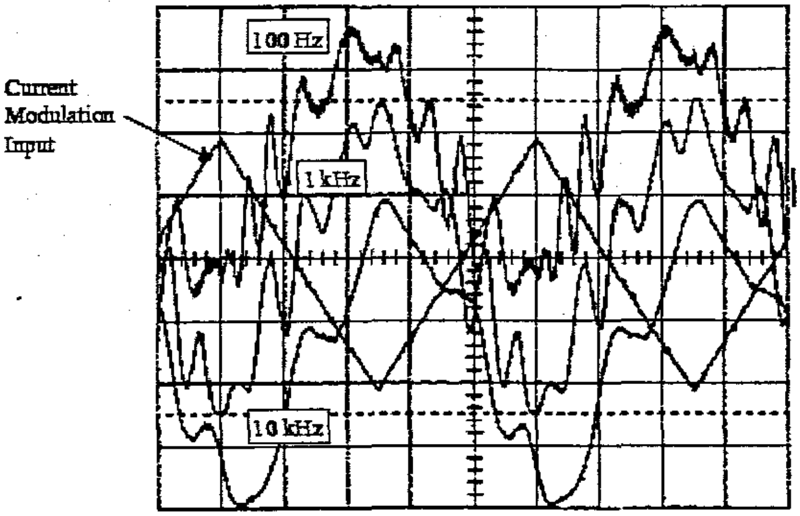


Figure 7.12: Output at photodetectors for three different f_{mod} frequencies: 100 Hz, 1 kHz, and 10 kHz. I_{mod} is 40 mA. The middle graph is the triangular wave input to the current driver.

As the peak moved every 2π, the phase change was recorded versus the change of the two arms (referencing and sensing arm) as shown below.

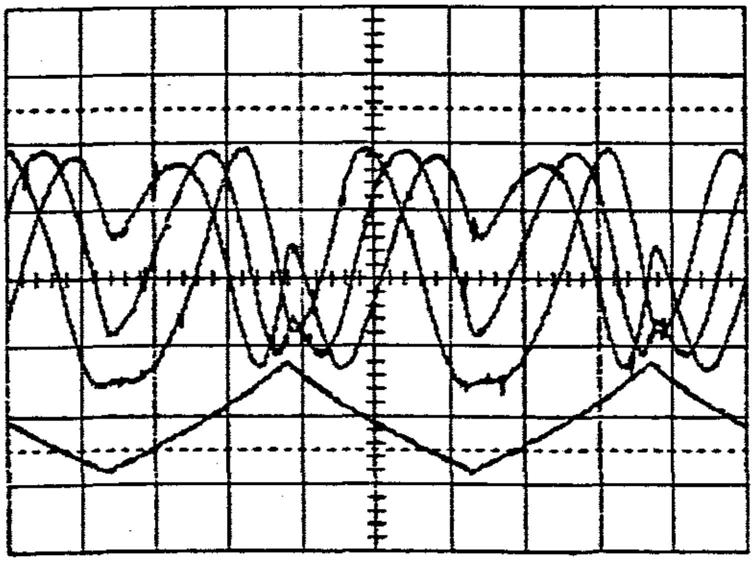


Figure 7.13: Output of the phase movement between the two arms (or photodetectors)

7.6 SPECIFICATIONS AND LIMITATIONS OF THE SYSTEM

The results showed a close correlation between the predicted and measured phase change due to the strain induced by the microwaves on the optical fiber. What wee not clear from the data were the errors caused by phase drift. The signal contained a slow drift in phase of approximately ± $\pi/4$ radians. For static measurements, this caused error and determined the minimum detectable phase change.

This resolution would be significantly reduced in the presence of temperature fluctuations, and therefore a temperature compensation scheme was required. An alternative was using the configuration shown by Figure 7.14 below. The purpose was to use an active homodyne Mach-Zehnder Interferometer to maintain the interferometer at quadrature. This simple circuit compensate for any phase change experienced by the sensing fiber in order to force $\Delta\phi = 0$. Thus the output from the difference amplifier would be a suitable error signal, which would integrated with an integrating amplifier.

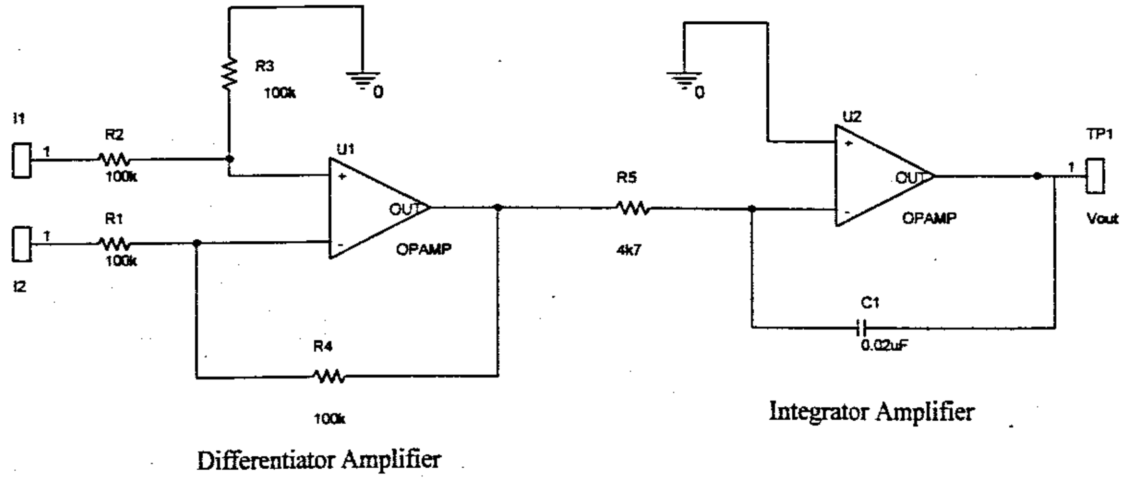


Figure 7.14: The compensator control circuit (the Vout is the same as expressed by Equation)

The present system's dynamic response was limited by the maximum capable, f_{mod} of 10 kHz. Using the present set-up, the dynamic response could not be measured. As long as the phase movement was an order of magnitude less than f_{mod}, the phase change would be measurable if a continuous real time phase shift-tracking scheme was employed. Also the schemes to increase the wavelength deviation at higher, f_{mod} could improve the dynamic response.

7.7 CALCULATIONS

The main aim was to test microwave absorption induced by strain by means of the sensing arm. The microwave power absorbed by the fiber was calculated with: -

1. Assuming that the phase change due to the oscillations aroused from the fiber temperature by virtue of heat transfer, where microwave was absorbed.
2. Considering the microwave power was absorbed uniformly along the fiber length, L in the microwave field.
3. The phase change of the light passing through the core when temperature increases.

Therefore using Equation (6.29) restated here for clarity as

$$\frac{\Delta\phi}{\Delta T}=\frac{2\pi\times L}{\lambda}\left[(n\times\alpha)+\frac{dn}{dT}\right] \qquad 7.9$$

The phase change resulted from both the fiber length change, and the refractive index of the fiber with temperature was calculated.

The thermal linear expansion coefficient, α, of the silica glass fiber = $0.4\times10^{-6}\,/^{0}\,C$

The refractive index change per temperature, $\left[\frac{dn}{dT}\right]$, of silica glass fiber = $1\times10^{-5}\,/^{0}\,C$

The refractive index, n, of the silica glass fiber = 1.4585

The wavelength, λ, of the single mode light source = 1300nm

By substituting values of the parameters in the Equation (7.9), we have

$$\frac{\Delta\phi}{\Delta T}=\frac{2\pi\times L}{\lambda}\left[(n\times\alpha)+\frac{dn}{dT}\right]$$

$$=\frac{2\pi\times 2m}{1300nm}\times\left[\left(1.4585\times(0.4\times10^{-6}\,/^{0}C)\right)+\left(1\times10^{-5}\,/^{0}C\right)\right] \qquad 7.10$$

$$=9666438.934\times\left[0.000000583/^{0}C+(1\times10^{-5}\,/^{0}C)\right]$$

$$=102.30/^{0}C$$

When the temperatures assumed being uniform throughout the fiber cross sectional area, the approximation of the microwave power absorbed per unit length was made relating to the initial heating rate, $\frac{dT}{dt}$.

Power per unit length would be calculated using

$$P_L=L\left[(A\rho s)_c+(A\rho s)_p\right]\frac{dT}{dt} \qquad 7.11$$

Where, A is the cross-sectional area, s is the specific heat and ρ is the density; c denotes the silica glass fiber parameters, and p denotes the primary coatings. Hence the cross sectional area of the primary coating is (the diameter of the silica glass fiber and primary coating used was 10μm and 125μm.): -

$$\begin{aligned} A_c &= 4\times d & A_p &= 4\times d \\ A_c &= 4\times 10\mu m & A_p &= 4\times 125\mu m \\ &= 40\mu m^2 & &= 500\mu m^2 \end{aligned} \qquad 7.12$$

Where, d is the diameter. The length was 2m. Hence power per unit length using Equation (7.11), would be obtained as

$$P_L = 2m\left[\left(200\mu m^2 \times \rho \times s\right)_c + \left(200\mu m^2 \times \rho \times s\right)_p\right]\frac{dT}{dt}$$

$$= 2m\left[\left(40\mu m^2 \times 2100kgm^{-3} \times 840Jkg^{-1}K^{-1}\right) + \left(500\mu m^2 \times 1185kgm^{-3} \times 1500Jkg^{-1}K^{-1}\right)\right]\frac{dT}{dt}$$

$$= 2m[70.56w + 888.75w]\frac{dT}{dt}$$

$$= 1918.62wm\frac{dT}{dt} \qquad 7.13$$

Where, s being the specific heat and ρ being the density would be obtained from the specification table below as given.

With the formula parameters, this made simple assumptions that radial heat transfer within the fiber would be instantaneous and with uniform temperature existing throughout, as relating to the heat capacity of the fiber, and density. Material properties of fiber [Tateda, Tanaka and Sugarawa, 1980] are given in Table 7.5 for reference and use for the calculations.

Table 7.5: Material properties of fiber

Fiber region	**Assumed behaviour**	**Thermal conductivity ($Wm^{-1}K^{-1}$)**	**Specific heat capacity ($Jkg^{-1}K^{-1}$), s**	**Density (kgm^{-3}), ρ**
Core and cladding	As silica	1.6	840	2100
Primary buffer layer	As PMMA	0.25	1500	1185
Secondary coating	As graphite	80	640	1600

Rearranging the Equation (7.9) and (7.11), and assuming k = $\frac{dn}{dT} = 1\times10^{-5}\,/^{0}\,C$, then Equation (7.9) became

$$\Delta\phi = \frac{2\pi \times L}{\lambda}[(n \times \alpha) + k]\Delta T \qquad 7.14$$

and making B = $|(A\rho s)_c + (A\rho s)_p|$, Equation (7.11) became

$$P_L \approx L[B]\frac{\Delta T}{\Delta t} \qquad 7.15$$

Making temperature change, ΔT, the subject of the formula (that is Equation 7.16), and substituting in Equation (7.14) above became

$$\Delta T = \frac{P_L}{L \times [B]}\Delta t \qquad 7.16$$

$$\begin{aligned}\Delta\phi &= \frac{2\pi \times L}{\lambda} \times ((n \times \alpha) + k) \times \frac{P_L}{L \times [B]}\Delta t \\ &= \frac{2\pi}{\lambda} \times ((n \times \alpha) + k)\frac{P_L}{B}\Delta t\end{aligned} \qquad 7.17$$

Where B = $|(A\rho s)_c + (A\rho s)_p|$ = 959.31w, n = 1.4585, α = $0.4 \times 10^{-6} /^0 C$, λ = 1300nm, k = $1 \times 10^{-5} /^0 C$, the phase change was obtained as: -

$$\begin{aligned}\Delta\phi &= \frac{2\pi}{\lambda} \times ((n \times \alpha) + k)\frac{P_L}{B}\Delta t \\ &= \frac{2\pi}{1300nm} \times [(1.4585 \times (0.4 \times 10^{-6} /^0 C) + (1 \times 10^{-5} /^0 C)]\frac{P_L}{B}\Delta t \\ &= \frac{2\pi}{1300nm} \times [0.583 \times 10^{-6} /^0 C + 1 \times 10^{-5} /^0 C]\frac{P_L}{B}\Delta t \\ \Delta\phi &= 51.150^0 / m^0 C \frac{P_L}{B}\Delta t \\ &= 0.0533^0 \times P_L / m\Delta t\end{aligned} \qquad 7.18$$

From the equations above, it was clear that the phase change, Δϕ, is directly proportional to the optical power, P_L, as shown by substitutions in Equation (7.17).

Referring to the table below some results obtained with different power levels, time taken, and power per unit length can be calculated.

Table 7.6: Test results obtained with specific time

Microwave Power Level settings	Time Settings in seconds, Δt	Equivalent Power in cavity, w	Phase Change in Degrees, ^0C	Output voltages measured, $V=V_0\ (1+\cos\Delta\phi)$, where $V_0=1.2V$
Low	10 sec	400 w	213.2	4.20
Medium	20 sec	500 w	533.0	2.40
High Medium	30 sec	650 w	692.9	4.20
High	40 sec	700 w	1119.3	4.20

From Equation (7.4), it can be seen that the photodetector intensity will be influenced by this settings. With reference to the previous chapter, there was a demonstrable proof that microwave energy could be measured by means of Mach-Zehnder Interferometry based on optical fiber sensor. Column 4 presents sample voltages measured with respect to applied power.

CHAPTER 8

CONCLUSIONS AND FUTURE WORK

8.1 CONCLUSIONS

Looking at the experiment as a whole, and the directions in which it was carried, the objectives of designing and constructing the interferometer which is capable of generating the phase shift output on the photodetectors had been achieved. One had achieved a good in-depth knowledge of the electronics involved in the hardware, as well as the workings of the interferometer and the accompanying physics. One element that one wishes; is to alter the new hardware as to observe graphically the output changes of the phase difference incorporated with data acquisition (DAQ). Use of computer analyzes and control on the photodiode outputs and other would give much greater circuitry outputs.

With the new type of signal demodulation system developed for the fiber optic Mach-Zehnder Interferometer, using a wavelength-modulated source, the following goals have been met:

1) Compare the sensing and referencing output signals to obtain the phase shift between the two arms.
2) Reduced the effect of intensity modulations on the signal.
2) Moderate dynamic response.
3) Maintained a simple cost effective design.
4) Results show a close correlation between the predicted and measured phase change.
5) General picture of the interference output pattern of the interferometer.
6) Monitoring the intensity modulation with PD_1, and PD_2 to see the phase difference of the signals.

Although these goals have been met, some system limitations will prevent it from becoming reliable practical design. The limitations are primarily reduced accuracy caused by temperature fluctuations and phase noise from the source as well as fluctuations in the microwave cavity. A high temperature compensation scheme must be utilized in order to make this a viable signal demodulation scheme.

8.2 FUTURE WORK

To solve the problems discovered in this work, a different approach can be implemented using a broadband high-power source. Also, use of the electronic signal processing technique for optical fiber sensor would be essential. That is, with advanced microprocessor system, an analogue quadrature phase shift (QPS) signal processing technique can be implemented for a general-purpose optical fiber interferometer sensor. This would consist of the opto-electronic conversion circuitry, the signal demodulation scheme and the display for interactive changes and control-desired output.

Future work in developing and implementing the basic computer concepts in acquiring the phase detection from the interferometer using electronic and microprocessor system can be done in the techniques proposed by Kahn [Kahn, 2000]. This looks at how the phase changes can be acquired serially using Analogue to Digital Converter and being virtually displayed for further processing and analysis. With this data acquisition (DAQ) method the phase change or difference between the sensing and referencing arms (fibers) of the interferometer can be displayed. This method would involve any virtually graphical software application. Hence, the electronic signal processing system in the optical fiber based sensor system would essentially consist of the opto-electronic conversion circuitry, the signal demodulation scheme and the display. In this concept, analog quadrature phase shift (QPS) signal processing will be advanced as well as microprocessor based techniques for implementation in a general-purpose optical fiber sensor system.

The most important requirement on the interface circuitry will be the accurate reproduction of the optical signal in electrical form (of the same output, making optical to electrical ratio relationship) with the addition of minimal external noise. Figure 8.1 is an example of the circuit diagram of the pre-amplifier circuitry that was developed but not fully tested in the present application.

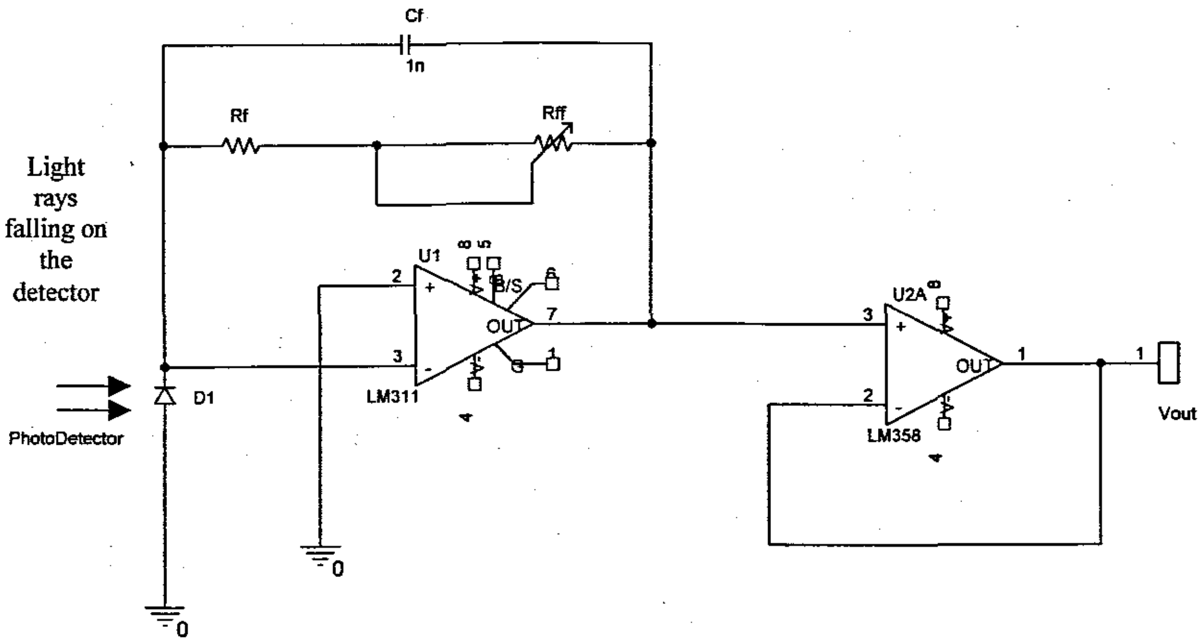


Figure 8.1. Schematic of a single-channel preamplifier circuit.

The optical signal returning from the sensor will be incident on the PIN diode thus inducing a reverse photo current in it. This current flows through the feedback resistor causing a voltage drop across it. The current flowing through the diode will be directly proportional to the intensity of the optical input. Low input current and offset voltage levels are the most important requirements on the operational amplifiers used in such sensitive photodiode applications. The first stage of the preamplifier circuit is thus a current to voltage converter or a transimpedance amplifier. The second stage of the preamplifier circuit is a voltage follower with high input and low output impedance. This stage will prevent subsequent stages from loading the preamplifier circuitry. Equation (8.1) gives the output of the amplifier in Figure 8.1 [Kahn and Thompson, 2000].

$$V_{out} = P_{in} \times R \times R_f \qquad 8.1$$

Where P_{in} is the incident optical power in watts, R_f is the value of the feedback resistor in ohms and R is the responsivity or sensitivity of the PIN photodiode.

Once the sensor output is converted into electrical form, Quadrature Phase Shift (QPS) signal demodulation scheme would be employed in order to detect the phase signal. It should be noted that the MFOMZI interferometer uses two arms. The technique uses two sensors, which are 90^0 out of phase or "in quadrature.

With QPS, the output signal is linearly proportional to the change in phase signal and independent of its initial value, for small phase changes. Figure 8.2 shows the block diagram of the proposed signal demodulation system.

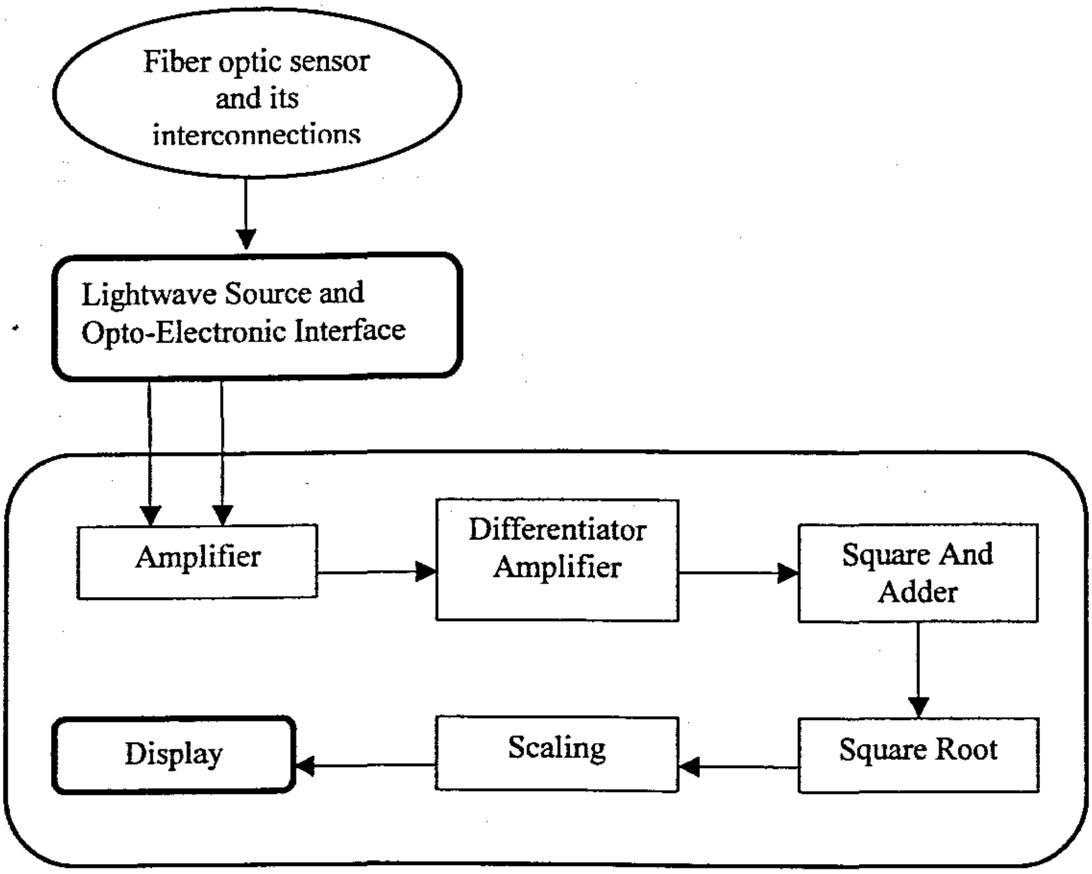


Figure 8.2. The block diagram of QPS signal demodulation scheme.

Although an analog system implementation is simple in design and fabrication, it has several major disadvantages, some of which are stated below.

1. Additional thermal noise generated in the circuit degrades the SNR of the overall system.
2. Components like resistors and capacitors, with precise values, are generally not easily available.
3. Linear integrated circuits like multipliers and dividers have inherent inaccuracy in the computed signal output.

4. Fabrication of the circuit, although simple, is time consuming.
5. The system implementation is not flexible as modification is difficult.

Since signal-to-noise ration (SNR), accuracy, flexibility and speed are critical in the ultra-high sensitivity sensor system, it is clear from the above discussion, that analog implementation of the signal demodulation scheme is not suitable for this particular application. Thus a microprocessor-based, digital signal demodulation scheme could be used in future work in the final measuring system.

Finally this digital optical fiber sensor system although outside the scope of this thesis could be developed for educational purposes at the Technikon and not just microwave measurement, and could find wider application also in optical fiber communications to study optical fiber characteristics.

REFERENCES

Alan Kersey D., Eric Udd, and Anthony Dandridge, (1990): "Applications of Fiber-Optics Sensors," *IEEE Components, Hybrids, and Manufacturing Technology Society*, vol. 13 No. 1, pp137 – 143.

Bailey, A. E. Ed., (1985): "Microwave Measurements," *Electrical Measurement Series*.

Baker, Donald G., (1985): *Fiber Optic Design and Applications*, Reston: Prentice-Hall.

Bansal Narottam P. and Doremus R. H., (1986): *Handbook of Glass Properties*, Harcourt, Bruce, and Jovanovich.

Berthold J. W., Ghering W. L. and Varshneya D., (1987): "Design and Characterization of a High Temperature, Fiber Optic Pressure Transducer," *IEEE J. of Lightwave Tech.*, vol. LT-5, pp1 – 2.

Brookes et.al., (1987): "Time Domain Addressing of Remote Fiber-Optic Interferometric Sensor Arrays," *J. Lightwave Technol*, vol. LT-5, pp1014-1023.

Cameron CB and Garret SL., (1991): "A symetric analog demodulator for optical Fibre interferometric sensor," *Proceedings of the Midwest symposium on circuits and systems*, pp666 – 671.

Cheung Stephen W. and Levien Frederic H., (1985): *Microwave Made Simple: Principles and Applications*, Artech House, Inc, Norwood.

Christensen D. A. and Ives J. T., (1987): "Fiberoptic Temperature Probe Using a Semiconductor Sensor," *Proc. NATO Advanced Studies Institute*, Dordrecht, The Netherlands, pp361 – 362.

Christian Hentschel, (1989): *Fiber Optics Handbook*, Hewlett Packard Company.

Clark T. E. and Burrell M. W., (1988): "Thermally Switched Coupler," *Proceedings of SPIE*, vol. 986, pp164 – 165.

Culshaw B. and Dakin J., (1989): *Optical Fiber Sensors: Systems and Applications*, Artech, Norwood.

Culshaw B., (1986): *Optical Fibre Sensing and Signal Processing*, Peter Peregrinus Ltd., London, UK.

Dakin J. and Culshaw B., (1988): *Optical Fiber Sensors: Principals and Components*, Artech, Boston,.

Dandridge A., (1991): *Fiber Optic Sensors Based on the Mach-Zehnder and Michelson Interferometers, in Fiber Optic Sensors: An Introduction for Engineers and Scientists*, Edited by Eric Udd, Wiley, New York.

Dietrich Marcuse, (1981): *Principles of Optical Fiber Measurements*, Academic Press, New York.

Eric Udd, (1991): *Fiber Optic Sensors: An Application to engineers and Scientists*, John Wiley & Sons, Inc.

Farhad Ansari (ed.), (1993): *Applications of Fiber Optic Sensors in Engineering Mechanics*, American Society of Civil Engineers, New York.

Frank P., and DeWitt, David P., (1996): *Fundamentals of Heat Transfer and Mass Transfer*, 4th Edition, John Wiley & Sons, NY.

Fritsch K. and Beheim G., (1986): "Wavelength Division Multiplexed Digital Optical Position Transducer," *Opt. Lett.*, vol. 11, pp1 – 2.

Fritsch K., (1989): "Digital Angular Position Sensor Using Wavelength Division Multiplexing," *Proceedings of SPIE*, vol. 1169, pp453 – 454.

Giallorenzi Thomas G. et.al., (1982): "Optical Fiber Sensor Technology," *IEEE Journal of Quantum Electronics*, vol. QE-18, pp626 – 665.

Grattan K. T. V., and Meggitt B. T., (1995): *Optical Fiber Sensor Technology*, Chapman & Hall, London.

Hecht Jeff, (1998): *Understanding Fiber Optics*, 3rd Edition, Prentice-Hall, Inc.

Horowitz and Hill, (1989): *The Art of Electronics*, 2nd Edition, Cambridge University Press.

HP Application Notes 64-1A. (1977): "Fundamentals of RF and Microwave Power Measurements," *IEEE*, Inc.

Hutcheson L. D. (Ed.), (1987): *Integrated Optical Circuits and Components*, Marcel Dekkar Inc.

IEEE Communications. February 1996, vol. 34, No.2.

Jackson D. A., Lobo Ribeiro A. B., Reekie L. and Archambault J. L., (1993): "Simple Multiplexing Scheme for a Fiber Optic Grating Sensor Network," *Optics Lett,* vol. 18, pp1192 – 1193.

Jeunhomme, Luc B. (1983): *Single-Mode Fiber Optics Principles and Applications*, New York: Marcel Dekker, Inc.

Kahn MTE, (2000): "Signal demodulation schemes for Fabry-Perot sensors in smart structures," *SAIEE Elektron Journal*, pp13 – 14.

Kahn MTE and Thompson A, (2000): "Programmable Opto-electronic drive and Measurement System," IEEE *Aerospace & Electronic Systems*, pp13 – 16.

Keiser, Gerd., (1993): *Optical Fiber Communications*, McGraw Hill, United States.

Kersey and Dandridge A., (1990): "Applications of Fiber-Sensors," *IEEE Trans. on Comp. Hybrids and Manufact. Technol.* vol.13, pp137 – 143.

Krohn D. A., (1988): *Fiber Optic Sensors: Fundamental and Applications*, Instrument Society of America, Research Triangle Park, North Carolina.

Lagokos N., Litovitz L., Macedo P., and Mohr R., (1981): "Multimode Optical Fiber Displacement Sensor," *Appl. Opt,* vol. 20, pp167 – 168.

Laverghetta Thomas S., (1988): *Modern Microwave Measurements and Techniques*, ArtechHouse, Inc.

Lee C. E. and Taylor H. F., (1990): "Interferometeric Fiber Optic Temperature Sensor Using a Low Coherence Light Source," *Proceedings of SPIE*, vol. 1370, p356 – 357.

Lo Y. L., and Sirkis J. S., (1994): "Active Homodyne Demodulation of Mach-Zehnder Interferometric Optical Fiber Sensors," *Experimental Techniques*, pp33 – 36.

Marten de Vries, (1994): *Optical fiber sensors for advanced civil structures*, Virginia Polytechnic Institute and State University, Blacksburg, VA.

Matasane M., Khan MTE, (1999): "Assessment of Current Commercial Microwave Ovens Operation with a View to Improve Power Measurement Design," *SA Electricity and Control Journal, September Issue*, pp31 – 32.

Melle L. K., and Measures R. M., (1993): "Practical Fiber-Optic Bragg Grating Strain Gauge System," *Appl. Optics*, vol. 32, No. 19, pp3601 – 3609.

Metaxas A. C. and Meredith R. J., (1983): "Industrial Microwave Heating," *IEE Power Engineering Series 4*, Peter Peregrinus Ltd.

Milanovic Veljko, Gaitan Michael, Bowen Edwin D., Tea Nim H., and Zaghloul Mona E., (1997): "Thermoelectric Power Sensor for Microwave Applications by Commercial CMOS Fabrication," *IEEE Electron Device Letter*, vol. 18. No. 9, pp450 – 452.

Kahn MTE and Thompson A, (2000): "Programmable Opto-electronic drive and Measurement System," IEEE *Aerospace & Electronic Systems*, pp13 – 16.

Kahn MTE, (2000): "Signal demodulation schemes for Fabry-Perot sensors in smart structures," *SAIEE Elektron Journal*, pp13 – 14.

Murakami Y. and Sudo S., (1981): "Coupling Characteristics Measurements Between Curved Waveguides Using a Two Core Fiber Coupler," *Appl. Opt*, vol. 20, pp417 – 418.

Nishihara, Haruna M., and Suhaya T., (1989): *Optical Integrated Circuits*, Mc-Graw Hill, New York.

Nolan D. A., Blaszyk P. E. and Udd E., (1991): *Optical Fibers, in Fiber Optic Sensors: An Introduction for Engineers and Scientists, edited by Eric Udd*, Wiley.

Personick, Stewart D., (1985): *Fiber Optics: Technology and Applications*, Plenum, New York.

Pratt Ronald E., (1975): "Very-Low Level Microwave Power Measurements," *Hewlett-Packard Journal*, vol.27, pp8 – 10.

Ranade K. D. Oh, J., et al, (1997): "Optical Fiber Fabry-Perot Interferometric Sensor for Magnetic Field Measurement," *IEEE Photonics Technology Letters*, vol. 9, No. 6, pp797 – 799.

Sander K. F., (1987): *Microwave Components and Systems*, Addision-Wesley Publishing Company, New York.

Snow J. W., (1983): "A Fiber Optic Fluid Level Sensor: Practical Considerations," *Proceedings of SPIE*, vol. 954, pp88 – 89.

Stewart W. J., and Love J. D., (1985): "Design limitation on tapers and couplers in single-mode fibres, in 5th Int. Conf. Integrated Opt. & Opt. Fiber Commun.," *11th European Conf. Opt. Commun., IOOC/ECOC'85*, Instituto Internazionale delle Comunicazioni, Venice, Italy, pp559 – 562.

Tateda M, Tanaka S., and Sugarawa Y., (1980): "Thermal characteristics of phase shift in juckered optical fibers," *Applied Optics*, vol. 19, pp770 – 773.

Thomas Giallorenzi D., and Joseph Bucaro D, Anthony Dradridge, Sigel G. H., JR. James Cole H., Scott Rashleigh C., MEMBER, IEEE, and Richard Priest G., (1982): "Optical Fiber Sensor Technology," *IEEE Journal of Quantum Electronics*, vol. QE-18, No. 4, pp626 – 665.

Tinga . W. R., (1994): "Microwave System Design and Dielectric Property Measurements," *Mater. Res. Soc. Proc.* vol. 347, pp1 – 14.

Udd E. and Turek P. M., (1985): "Single Mode Fiber Optic Vibration Sensor," *Proceedings of SPIE*, vol. *566*, pp135 – 136.

Udd E., (1991): *Fiber Optic Sensors: An Introduction for Engineers and Scientists*, John Wiley and Sons, NY.

Udd E., Michal R. J., Theriault J. P. and Cahill R. F., (1990): "High Accuracy Light Source Wavelength and Optical Fiber Dispersion Measurements Using the Sagnac Interferometer," *Proceedings of the 7th Optical Fiber Sensors Conference*, IREE Australia, pp329 – 330.

Welty J. R., (1978): *Engineering heat transfer*, John Wiley & Sons Inc.

Wilson J. and Hawkes J., (1987): *Lasers, Principles and applications*, Prentice Hall.

Wilson J. and Hawkes J., (1983): *Optoelectronics*, 2nd Edition, Prentice Hall.

Yao S. K. and Asawa C. K., (1983): "Fiber Optical Intensity Sensors," *IEEE J. of Sel. Areas in Communication*, SAC-1 (3).

APPENDIX 1

LABORATORY REPORT FOR UNDERSTANDING THE MACH-ZEHNDER INTERFEROMETER

PURPOSE

The purpose of this lab report was to gain a better understanding of optical fiber and the application in such areas as interferometric sensors. This lab report was also used to obtain experience in laboratory techniques of optical fiber technology. It was preformed to develop the skills necessary in building the interferometric sensor. This report gives a brief theoretical explanation of how an optical fiber interferometer can be used to measure the changes in such physical parameters as temperature and pressure. A summary of the results will also be included. Most importantly, it will give a detailed description of the experimental setup. These details are intended for those who will be attempting to develop the project further. It is hoped that it will save time, as well as help in further refining the set up, to produce more accurate results.

THEORY

The concept behind the interferometric sensor is the property interference. That is, when two electromagnetic light waves are polarized in the same plane, their amplitudes can simply be added together. When two identical fields are 180^0 out of phase the addition of the waves produces a zero field, this is called destructive interference. When the fields are in phase the superposition of these light waves is called constructive interference. Thus a change, in one of the two fields produces a change in the interference of the light waves. The measurement of these changes in the interference as a function of the perturbation of one of the fields is how an interferometer works. There are several types of interferometers, but the Mach-Zehnder interferometer is the one used in this lab report.

A fiber optic Mach-Zehnder interferometer couples a laser into an optical fiber. The beam is split into two fibers, using a bidirectional coupler as shown by the experimental setup. The two output beams are then recombined using a beam splitting cube. The combined beams produce an interference pattern. If there is a change in path length in either arm there is a resulting change in the interference pattern, due to the phase shift between the two waves. A phase shift of 2π causes a displacement of one fringe.

The use of the fiber optic interferometer as a temperature sensor is possible due to the effects of temperature on the length of the fiber and the index of refraction. Both of these change the path length of the light. Equation 1 gives the phase shift as a function of the change in temperature.

$$\frac{\delta\phi}{\delta TL} = 2\pi\lambda\left[\frac{n}{L}\left(\frac{\delta L}{\delta T}\right)+\left(\frac{\delta n}{\delta T}\right)\right] \qquad 1$$

EXPERIMENTAL SET UP

There are several different parts in the sensor, and each need to be given close attention in the setup. Figure 1 shows a diagram of the setup with each part labeled.

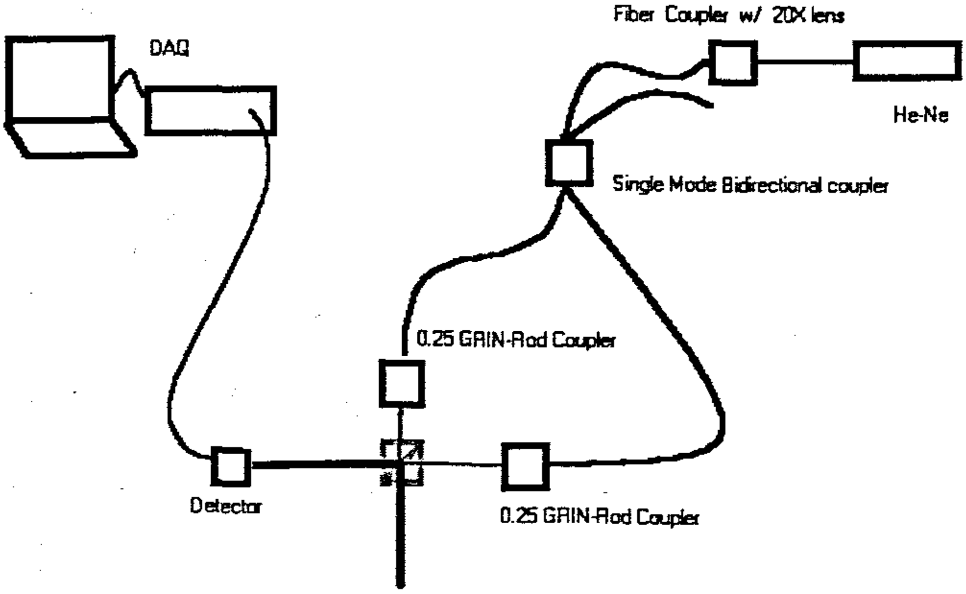


Figure 1. Diagram of the Mach-Zehnder interferometric sensor.

ALIGNING THE LASER

In order to couple the laser into the fiber, the beam needs to be aligned in the direction of the fiber. The suggestion is by using the laser clamp and rod to mount the laser. This would make it very difficult to align the laser precise enough for coupling into the fiber. First, the laser needs to be aligned so that its beam is directly parallel in the X-axis. Place one of the long black optical tracks in front of the laser. Place a mirror on the track at the height of the laser using a mirror mount that is able to slide down the track. Starting close to the laser, adjust the mirror so that the beam is reflected back onto itself. Move the mirror away from the laser, if the beam is no longer reflected back onto itself it is not aligned along the X-axis. Use the micro screw to adjust the laser in the X-Y and X-Z planes. Continue this process until the mirror can be moved from the far end of the track to the near end with the beam being reflected back to the same spot the entire time.

Place the fiber coupler, without the lens, in front of the laser and mount it to the optical table. Adjust the height and its horizontal direction until the laser is aligned with the center of the opening of the coupler. Make sure not to change the adjustment that rotates the laser in the X-Y plane, since it has already been aligned.

COUPLING THE LASER INTO THE FIBER

This is one of the most difficult steps in the setup. Cleave one of the four ends of the bi-directional coupler; place it in the fiber chuck and into the fiber coupler. If the read fiber was chosen, cleave the red output end of the fiber and mount it close to the face of a power meter. The power meter will detect light at intensity levels below what the eye can detect. Slide the fiber chuck towards the microscope objective so that the fiber is approximately 0.5 cm from the objective. With the laser turned on, and using a pair of protective goggles one can observe how close the focused light is from the fiber tip. Use the adjustments on the fiber coupler to move the fiber tip into the beam. When the alignment is close, the fiber exiting the coupler will start to glow red, indicating the higher order modes are escaping the fiber. Once there is enough light exiting the output end of the fiber, the detector can be used to adjust the coupler, and the Y and Z laser direction for maximum transmission.

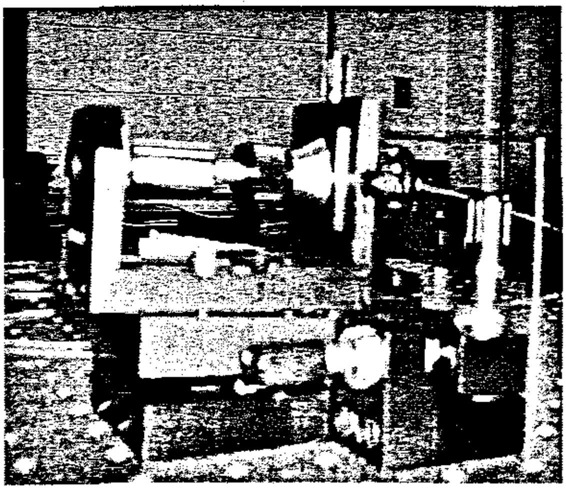


Figure 2: Fiber Coupler

MOUNTING AND ALIGNING THE OUTPUT FIBERS

Mount the GRIN-rod lens couplers so that the outputs of the fibers will intersect perpendicular to one another. It is very helpful to mount the coupler on a translation stage so that it can be adjusted sideways. Cleave both ends of the fiber; insert them into the fiber chucks and then into the couplers. Place the 0.25 pitch GRIN lens into the coupler with out tightening the setscrew. This will keep from damaging the end of the fiber when it is butted against the lens. Move the fiber tip against the GRIN lens so that the lens culminates the diverging beam from the fiber.

In order to obtain a clear interference pattern, the two output beams need to have the same polarization axis. Equipment used for this axial alignment is shown in Figure 3. Place a polarization filter in front of the outputs to determine their polarization axis. Rotate the fibers so that they are both polarized in the same axis.

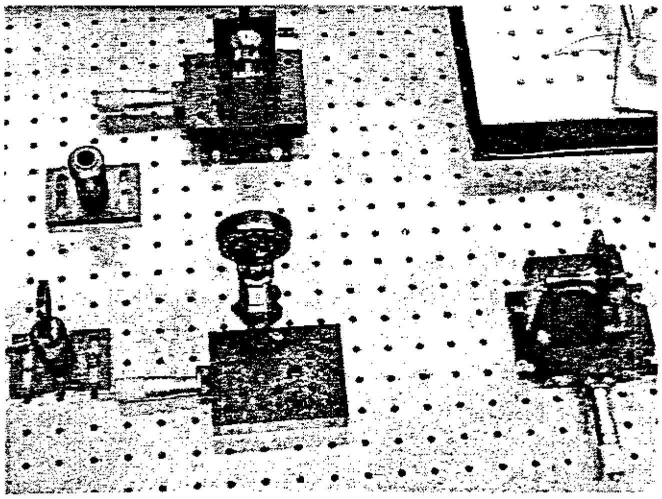


Figure 3: GRIN couplers setup

As with the laser, place an optical tract in front of one of the couplers. Use the same procedure, as outlined above, for aligning the output in the X-Y and X-Z planes. Complete this procedure for the second coupler. This step is very important because in order to obtain an interference pattern both, beams have to be in the same X-Y and X-Z plane.

The beam splitter is affixed at the top of a mirror mount so that it can be adjusted to level. Attach a mirror mount on a translation stage, and mount it on the optical bench so that the beam splitter is centered where the two beams intersect. The combined beams are now leaving the beam splitter in both the X and Y directions. By placing a mirror in the path of one of the combined beams, the beam splitter can be rotated so that the refection from the mirror will travel back and incident on both of the outputs.

After each step of the alignment process is complete an interference pattern should be visible. However, this is unlikely. Much fine-tuning of the output beams will most likely be needed. Pulling the output fibers slightly away from the GRIN lens will enlarge the beams and make the interference pattern more visible.

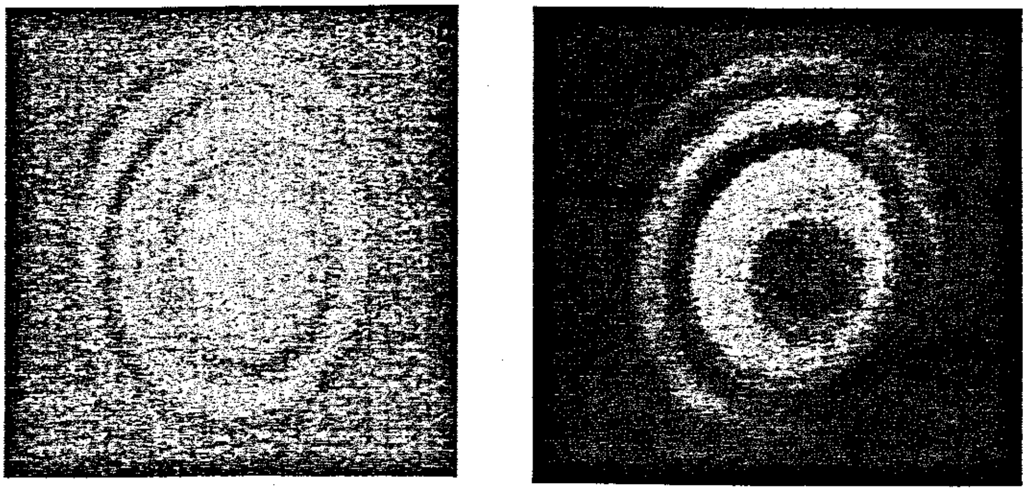
RESULTS

One of the more difficult steps in setting up the sensor was coupling the laser into the fiber. After about two hours I was able to detect light from the output fiber. After another hour I had the maximum output I was able to get.

Measurements using the 2mW laser and the power meter were: -

Laser: 2mW
Red fiber output: 600μW
Blue fiber output: 95μW

After realizing how crucial the alignment of the two beams were, I was finally able to produce the interference pattern as shown below.



Figures 4: Ball Eye interference pattern

TEMPERATURE CHANGE MEASUREMENT

A section of fiber was taped to a plate of glass. An aluminum can was filled with ice and allowed to cool close to 0^0C. The can was then placed on the fiber and the fringe shifts were recorded. The intensity of the central fringe was measured using a photodiode. The output of the photodiode was recorded using a LabView program developed for this experiment and a DAQ board. Shown below is a graph of the intensity of the central fringe of the interference pattern while being cooled from 24°C to approximately 0°C.

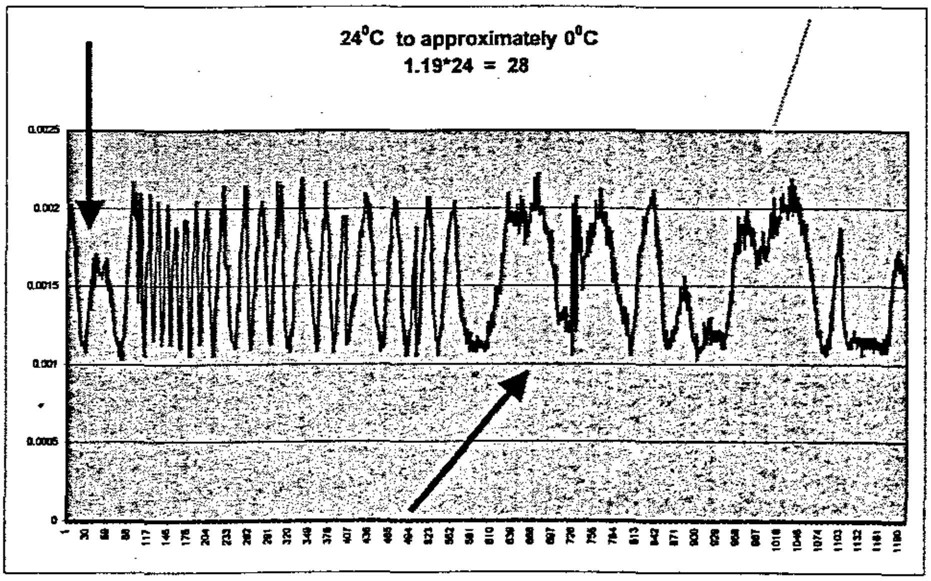


Figure 5: Graph of intensity of interference pattern while fiber is being cooled.

The red arrow shows the disturbance of the fiber when the can was placed on the fiber. After that the fringe shifts are very clear. The black arrow shows the fiber reaching its equilibrium temperature, and the fringes shifting slower. The yellow arrow is where the measurements are no longer accurate. From the graph, it is impossible to tell whether the fringe pattern is shifting outward or inward. However, by visually inspecting the interference pattern while taking data, it is at this point where fringe shifts are unstable.

Shown in Figure 6, is a graph of the intensity of the central fringe of the interference pattern while being warmed from approximately 0°C back to room temperature of 24°C.

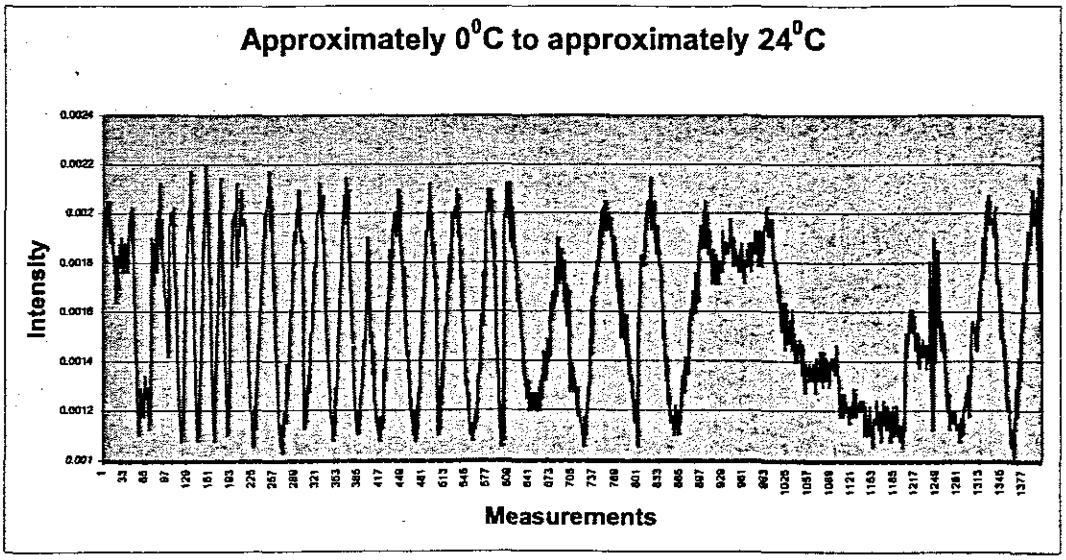


Figure 6: Graph of intensity of interference pattern as fiber is warming.

Again you can see where the can was removed and the temperature started to increase. Towards the end of the graph, the fiber starts to come into equilibrium and the measurements are no longer reliable.

POSSIBLE CORRECTIONS

Because of the sensitivity of the sensor, there were fringe shifts observed while the fibers were not being disturbed. This needed to be fixed, but it was difficult once all the components were setup. This would have kept the components, and the fibers closer together so there would not have been as much temperature difference between them. Second, I would have placed both fibers between insulating materials with only a portion of one fiber sticking out. This would have insulated the fibers from any atmospheric changes such as the air conditioning blowing over them. It would have also reduced the vibration effects on the interference pattern.

CONCLUSION

Even though the results of the temperature sensor were not entirely accurate, it was easy to observe, and record the fringe shifts due to the change in temperature. Due to the sensitivity of the sensor, a much more careful set up is needed to produce accurate results. However, I did obtain a lot of experience in laboratory techniques of optical fibers. Working with this fiber optic sensor has given me a better understanding of the sensitivity of the sensor, and will help when working with other such devices in the future.

APPENDIX 2

INSTALLATION TECHNIQUES FOR FIBER OPTIC SENSORS COMPONENTS AND PROCEDURES FOR CLEANING CONNECTORS

Many of the general procedures for installation, and protection of sensors also apply to fiber optic sensors. The largest concerns are proper surface preparation, mechanical bonding, and providing protection for the sensors and leads. The intent of this document is to characterize the special handling requirements for fiber optic sensor equipment. Surface preparation procedures should be employed with the relevant exceptions for handling fiber cables and fiber based sensors.

Fiber optic sensors may be surface mounted anywhere. Fiber sensors can also be easily embedded into composite materials without significantly impacting the variable to be measured or causing material weakness. Electrical sensors do not embed easily in materials and can cause structural defects.

1 SURFACE PREPARATION

The importance of cleanliness for the bonding surface, as well as the sensor, and fiber cannot be over-stressed. Contaminants can decrease the performance of the sensor, and possibly shorten the useful lifetime of the sensor. All surfaces must be cleaned, and properly prepared for reliable sensor performance. Five main steps are involved in getting a surface ready for bonding the sensor to existing components.

1.1 DEGREASING

The first step should always be to remove any oils, grease, or chemically soluble contaminants. Many methods, and solvents are available depending on the specific materials involved. Always follow the recommended safety, and handling instructions provided with any solvent.

1.2 ABRADING

The surface must be free of any loosely attached materials (such as paint, rust, etc.) that could be a cause of sensing error. In addition, abrasion makes a surface texture suitable for bonding. This step may also include filling of porous materials to maximize bonding area.

1.3 CONDITIONING

An acid is used to help further cleaning of the sensor areas and connectors.

2 BONDING

Some of the adhesives used for installing fiber optic sensor can be used as well.

2.1 ADHESIVE SELECTION

The adhesive chosen will necessarily be driven by the application and materials involved (silica or silicon). Care must be taken to insure that the adhesive will work for the required lifetime of the sensor.

2.2 FIBER JACKET REMOVAL

Some fiber sensors may have a plastic jacket or protective coating over the sensor. This coating must be removed to insure that strain is mechanically transferred to the sensor.
By using special stripping tools (refer Chapter 5) or chemicals, the jacket can be removed, or stripped, from the sensor. Since the jacket has properties that allow for efficient strain transference, the sensors may be directly installed.

2.3 CLAMPING

It is helpful to remember that optical fiber is fabricated from glass. Although seemingly very flexible and strong, glass fibers will not survive strong or excessive clamping. Use soft clamping surfaces, applying lesser pressure only when necessary.

2.4 TERMINATION OF BARE FIBER END

One source of noise in fiber sensors is the *back-reflection at air or glass interfaces* such as the non-connectorized end of the fiber sensor. The simplest method to reduce this noise is to make certain that the end is buried in the adhesive. It turns out that a glass or adhesive interface will have very little back-reflection.

3 PROTECTIONS

Once the fiber sensor is bonded to a surface or placed on the workbench, care must be taken to protect the area, in order to allow operation of the sensor for the expected measurements, and avoid vibration and distortion.

3.1 FIBER STRAIN

A fiber embedded in any material, including epoxy, will tend to break where the fiber comes out of the material. To reduce this possibility, a special protective tube is slid over the fiber before curing. This reinforces the fiber at the critical junction; helping to insure the fiber survives as shown by Figure 1.

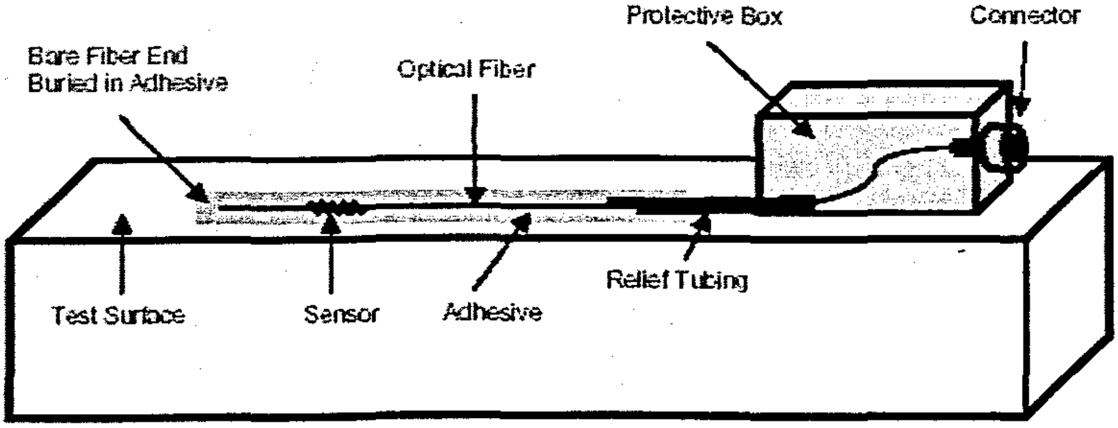


Figure 1: A protective tube and box are recommended for installed sensor and connector

3.2 CONNECTOR MOUNTING AND PROTECTION

It is recommended that the connector be mounted in a protective box similar to what is illustrated above. The box allows for easy connection of a cable to the sensor and helps to protect the lead on the fiber sensor from wear and tear.

3.3 CLEAN CONNECTIONS

Fiber optic connectors are precision optical devices, and require special handling. The recommended cleaning procedures for these connectors are included in this chapter.

3.4 COATINGS OR HOUSINGS

Damage to the sensor, fiber leads, or cable will degrade performance, often to the point of failure. Reasonable protection must be available to all parts of the system. Some suggestions include installing a connector junction box as shown above, over-coating the sensor and exposed fiber with a protective tough coating after installation, running cable, and fiber through conduit. The extent of protection for the fiber sensor, and fiber cable should reflect the environmental extremes the system will be placed.

Paper presented at 5th UICEE Conference, 6 – 9 Feb 2002, Chennai, Madras, India

APPENDIX 3

MONITORING OF MICROWAVE POWER MEASUREMENTS IN MICROWAVE CAVITIES USING OPTICAL TECHNIQUES

M. C. Matasane & MTE Khan

Peninsula Technikon
Bellville, South Africa

ABSTRACT: The technology and applications of optical fibers have progressed very rapidly in recent years. Optical fiber, being a physical medium, is subjected to perturbation of one kind or another at all times. It therefore experiences geometrical (size, shape) and optical (refractive index, mode conversion) changes to a larger or lesser extent depending upon the nature and the magnitude of the perturbation. In this paper the use of fiber optic in microwave measurement will be advanced.

INTRODUCTION

The use of microwave technology in power measurement at laboratory work and commercial has shown increased in recent decades. Since power measurement has important commercial ramifications, this requires reliable equipment and appropriate high accuracy measurement techniques [1,2].

In classical instrumentation, power measurement establishes a means for evaluating the work capacity and efficiency of the device under test [1]. There is continuous effort to design more efficient systems and to increase the work capacity of microwave devices. The concepts lead to higher accuracy requirements in measurement art.

Techniques of microwave power measurement in microwave cavities and as well as use in laboratory work is being challenged by new technologies. One of the new technologies on power measurement is based on fiber optic sensors. Hence, optoelectronics sensing with fiber optics as sensing elements can offer significant advantages over classical instrumentation [2, 3]. It could therefore become a key factor in microwave sensing technology.

With the characteristic behaviour and design of microwave cavities, due to some microwave energy heating effects, it is necessary to measure their output power as to maintain and monitor their power variations, which result on importance to the commercial usage and demand. This requires an in depth look at the operation of a microwave cavity and a study of microwave power measurements to increase the system performance, compared to the previous non-optical power measurement instruments. The study is based on detection of microwave energy within microwave cavities, by virtue of its effects on fiber optics.

MICROWAVE POWER MEASUREMENT

Being a challenge to detect microwave signals, it is necessary to convert the signal power directly or indirectly into some form of mechanical or visible energy [2]. Furthermore, as it is critical when specifying the components that build up the system, the equipment and technique to be used must be accurate and traceable to monitor the absolute magnitude of the output power flowing during operation.

Power measurement here is based on the detection of microwave energy generated by a magnetron into the microwave cavity with respect to its heating and absorption effects. This needs to be measured as to maintain the power changes within the cavity. Definition of power comes with different solutions in systems measurements, as it does have units and definitions. That is, for an example, in measuring the relative power, it is usually expressed in decibels (dB) as stated:

$$\text{dB} = 10 \log \frac{P}{P_{ref}} \qquad 1$$

Where P is the measurable power and P_{ref} is the reference. Apart from this, there is an average power. It is very popular and is also used in specifying almost RF and microwave systems. However, the fundamental definition of power is energy per unit time. But the important question to resolve is over what time is the energy transfer rate to be averaged when measuring or computing power? At RF and microwave devices such views are not common. In a more mathematical approach to power for a continuous wave is to find power at given frequency given.

Above all, this brings a question of why it is important to measure microwave power within cavities. By response, this requires well-behaved equipment, good measurement technique, and common agreement as to what is the standard watt range to indicate when used. Generating significant power at microwave frequency is inherently expensive [3,7]. As one will be looking at the power range from 1watt to 800 watts at frequency of 2450MHz, it is prohibitively costly. Therefore, in all microwave experiments, it is necessary to detect the presence of signal power. Methods, which are useful to indicate the presence of microwave signals, and the measurement of their relative magnitudes, are essential in some cases to determine the absolute magnitude of the power in the system.

The current most devices for sensing and measuring power at Radio Frequencies (RF) and microwave frequencies (2500 MHz), each uses a different kind of device to convert the RF and microwaves power to a measurable DC (Direct Current) or low frequency signal. Such devices are thermistor, thermocouple, and the diode detector. Each device has some advantages or disadvantages over the others and also some measurement uncertainty for power transfer and calibration. Hence these devices need provision for isolation from thermal, or physical shock, and must keep leakage small so that microwave power does not escape from the mount in a shunt path around it. In addition to these, point contact is required on detection regions, and this limits the RF and microwave frequencies for absolute power measurement.

In regard, as many systems are continuously monitored for output power during ordinary operation, large number of power measurements and their importance dictates that measurement equipment must be accurate, repeatable, traceable and convenient, together with the techniques used.

There is currently considerable interest in techniques utilising optical fibers for the different measurements. Also there is a potential advantage in systems using optical fibers as the fiber could both be the transmission medium and the transducer, which is electrically safe, immune to EMI (electromagnetic interference), and chemical inert [4,5,6]. It therefore can be used in adverse environments, especially for particular purpose in use for microwave power measurement in commercial microwave cavities.

FIBER OPTICS SENSORS AND THEIR APPLICATIONS

In fiber optic sensing, the response to external influence is deliberately enhanced so that the resulting change in optical power can be used as a measure of the external perturbation. In communication technology, the signal passing through a fiber is already modulated, while in sensing technology; the fiber acts as a modulator. The fiber therefore serves as a transducer that converts measurands like temperature, stress, strain, rotation or electric and magnetic currents into a corresponding change in the optical power, phase or direction of polarisation of light. The usefulness of the fiber optic sensor therefore depends upon the magnitude of these changes and our ability to measure and quantify these changes. As an example, modulation due to a measurand can be produced in the form of microbend loss modulation by an intensity modulation sensor.

The advantages of fiber optic sensors are freedom from electromagnetic interference (EMI), wide bandwidth, compactness, geometric versatility and economy. In general, fiber optic sensors are characterised by high sensitivity when compared to other types of sensors. They are also passive in nature due to the dielectric construction. Specially prepared fiber optics can withstand high temperature, and other harsh environments. In telemetry and remote sensing applications it is possible to use a segment of the fiber as a sensor gauge, while a long length of the same or another fiber can convey the sensed information to a remote station [4, 5, 7].

Another sensing technique that is popular is the Mach-Zehnder interferometer as Figure 1 illustrates. The configuration uses two photodetectors circuit, which are then amplified and integrated to obtain the phase change with respect to the current difference by the compensator control circuit shown in Figure 2. The purpose of the circuit is being to maintain the interferometer at quadrature.

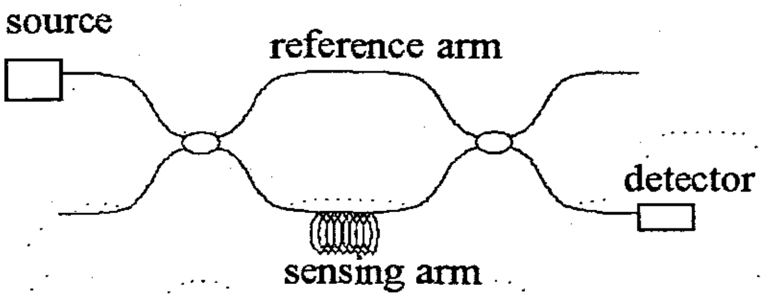


Figure 1: Mach-Zehnder Interferometer [5,6]

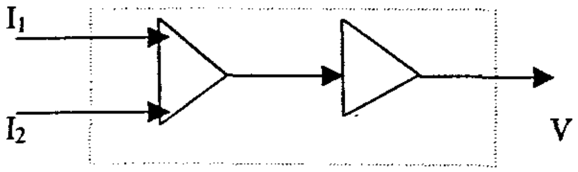


Figure 2(a): Compensator Control Circuit

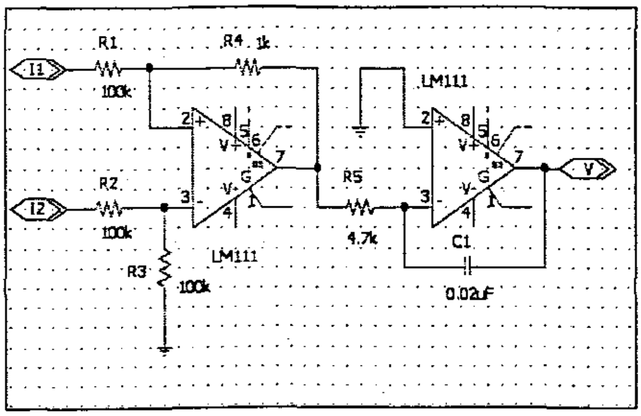


Figure 2(b): Schematic Design for Compensator Circuit

An interferometric sensor is based on the detection of changes in the phase of light emerging out of a single mode fiber. The phase change in general is given by:

$$\Delta\phi=\Delta\phi_L=\Delta\phi_n=\Delta\phi_g \tag{2}$$

Where the three phase terms on the right hand side of Equation 2, are due to the length (L), the index (n) and the guide geometry (g) variations, respectively. The phase change may be converted into an intensity change using interferometric various schemes (for example Mach-Zehnder, Michelson, Fabry-Perot or Sagnac forms and others) [6,7,9]. In a simple scheme, only the sensing and reference arms are made of fibers, while the rest are made of bulk optic components.

However, the use of all-fiber or integrated optic components can provide better stability and compactness compared to their bulk counterparts. Interferometeric fiber optic sensors are by far the most commonly used sensors since they offer the best performance. They have found application as acoustic sensors (e.g. hydrophones), rotation sensors (e.g., gyroscope), strain, temperature, chemical, biological and a host of other types of sensors.

In these techniques, the phase change of light propagating through a fiber of length (l), is obtained with the propagation constant, $\beta = k_o n$, as:

$$\Delta\phi = \Delta\beta = k_0 n l \qquad 3$$

Where n = refractive index, and k_o = longitudinal propagation constant of the fiber. The sensing fiber, which is deformed, will be somehow constrained to bend in a regular pattern (with periodicity of λ). As the perturbation changes, it induces a phase shift, and photodetectors are used at the output of the couplers of the Mach-Zehnder Interferometer to detect an intensity variation and are governed by the current equations given. Using two photodetectors, the currents I_1 and I_2 represent the reference and sensing output current.

By using Jones Calculus [9], one is able to derive the intensity functions generated by the detectors as:

$$\begin{pmatrix} I_1 \\ I_2 \end{pmatrix} = E_0^2 \begin{pmatrix} 1 - \cos((\Delta\phi_2 + \Delta\phi_3)/2)\cos((\Delta\phi_2 - \Delta\phi_3)/2) \\ 1 + \cos((\Delta\phi_2 + \Delta\phi_3)/2)\cos((\Delta\phi_2 - \Delta\phi_3)/2) \end{pmatrix} \qquad 4$$

Where $\Delta\phi_2$ and $\Delta\phi_3$ represents the relative phase changes between the sensing and reference fibers, and E represents the voltage source from the optical power source.

USE OF FIBER OPTICS IN MICROWAVE CAVITIES

The development of distributed, and array sensors covering extensive structure locations are also feasible using fiber optic sensors. Many signal processing devices (splitter, combiner, multiplexer, filter, delay line etc.) can also be made of fiber optic elements; thus enabling the realisation of an all-fiber measuring system. In this paper, optoelectronic techniques using fiber optics as a sensor for measuring magnetron microwaves in commercial microwave cavities has been proposed.

The variations in length, diameter and refractive index that would cause an optical parameter due to microwave change will be investigated. The change in phase of the light through the core when temperature of the fiber increases, will result in the transfer function of phase (ϕ) and temperature, which can be related by Equation 5.

$$\frac{\Delta\phi}{\Delta T}=\frac{2\pi L}{\lambda}[n\alpha+\frac{dn}{dT}] \qquad 5$$

Phase change therefore results from both a changes in fiber length (L) and refractive index (n) with temperature (T). The main aspect of this design will be on a single-mode fiber optic placed in the microwave cavity for power measurement distributed within the cavity. Equation 6 gives us the relationship between microwave power absorption per unit length of the fiber in relation to the initial heating rate, dT/dt [5,7,8].

$$PL=l[(A\rho s)_c+(A\rho s)_p]\frac{dT}{dt} \qquad 6$$

Where A is the cross-sectional area, s is the specific heat and ρ is the density. The parameters relating to the silica glass are denoted by subscript c and those relating to the primary coating are donated by subscript p [8,10,11]. The experimental set-up for the optical fiber microwave sensor is shown in Figure 3.

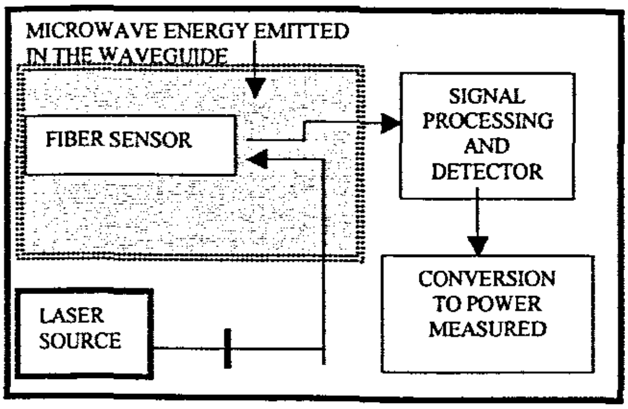


Figure 3: Experimental setup (the pigtailed, HeNe, 2mW, 1300nm, ST-Connectorised laser diode coupled to a wound-length of fiber within the cavity)

Currently, experimental procedures are carried out to achieve the optimal configuration of the sensor to be deployed.

CONCLUSIONS

A system's output power level is frequently the critical factor in the design, and ultimately the purchase and performance of almost all radio frequency and microwave equipment. Also, because signal power is so important to the overall system performance, it is critical when specifying the components that build up the system. Many systems are continuously monitored for output power during ordinary operation. This large number of power measurements, and their importance dictates that the measurement equipment and techniques should be matched with the measurand.

Being a challenge to detect microwave signals optically, it is necessary to convert the signal power directly or indirectly into some form of mechanical or optical perturbation. Furthermore, as it is critical when specifying the components that build up the sensor system, the equipment and techniques to be used must be accurate and traceable to monitor the magnitude of the output power in the cavity.

We hope that optoelectronic sensing with optical fibers as sensing elements can offer significant advantages over classical instrumentation in this field. One of the aims of this research is the mapping of microwave energy within the cavity itself. In this case, we are investigating the possibility of it becoming an important additional tool in microwave characterization within microwave cavities.

Finally as fiber optics has become a very important part of modern day. Although it is still in its infant stages, fiber optics has an enormous amount of potential, and seemingly endless application possibilities. In this millennium, fiber optics will replace all existing communication, and sensing medium standard to achieve better monitoring and signaling devices.

REFERENCES

1. Thomas Laverghetta S., Modern Microwave Measurements and Techniques. Artech House, Inc., (1988).
2. Matasane M., Khan MTE, Assessments of current commercial microwave ovens operation with a view to improve power measurement design. SA Electricity and Control Journal, September Issue, 31 – 32 (1999).
3. RF Engineering, 2.5GHz Power Source. Electronics World, March, 206 – 207 (1997).
4. Jeunhomme, B. Luc., Single-Mode Fiber Optics Principles and Applications. New York: Marcel Dekker, Inc., (1983).
5. Lo Y. L. and Sirkis J. S., Active homodyne demodulation of Mach-Zehnder Interferometeric optical fiber sensors. Experimental Techniques, 33 – 36 (1994).
6. Kao, Charles K., Optical Fiber Systems: Technology, Design, and Applications. New York: McGraw-Hill (1982).
7. Harris & Anchterlonie L. J., Novel means of detecting microwave power using optical fibres. Electronics Letters, Vol. 22, No. 22, 1178 – 1179 (1986).
8. MTE Khan, Peninsula Technikon, "Intelligent structures with opto-electronic sensor systems," Electronic Journal of the SAIEE, July Issue, 34 – 37 (1997).
9. Culshaw B., Optical Fibre Sensing and Signal Processing, Pieregrinus, London (1984).
10. Kersey and Dandridge A., Applications of fiber-sensors. IEEE Trans. on Comp. Hybrids and Manufact. Technol. 13, 137 – 143 (1990).
11. Matasane M. and Khan MTE, Microwave measurement by light: - a new paradigm in instrumentation development. SATCAM 2000 Conference (SATNAC ° COMSIC, AP/BEM ° MTT/EMC), Somerset West - Cape Town, South Africa, 10 – 13 (2000).

Paper presented at SATCAM 2000 Conference (SATNAC ° COMSIC, AP/BEM ° MTT/EMC), Somerset West - Cape Town, 10 - 13 September 2000

APPENDIX 4

MICROWAVE MEASUREMENT BY LIGHT – A NEW PARADIGM IN INSTRUMENTATION DEVELOPMENT

Matasane Clement Matasane, Mohammed Tariq Ekaramodien Khan
Department of Electrical Engineering, Peninsula Technikon
Bellville, 7535, South Africa

ABSTRACT: - The technology and applications of optical fibers have progressed very rapidly in recent years. Optical fiber, being a physical medium, is subjected to perturbation of one kind or another at all times. It therefore experiences geometrical (size, shape) and optical (refractive index, mode conversion) changes to a larger or lesser extent depending upon the nature and the magnitude of the perturbation. In this paper the use of fiber optic in microwave measurement will be advanced.

I. INTRODUCTION

In classical instrumentation, power measurement establishes a means for evaluating the work capacity and efficiency of the device under test [1]. There is continuous effort to design more efficient systems and to increase the work capacity of microwave devices. The concepts lead to higher accuracy requirements in measurement art. Techniques of microwave power measurement in commercial microwave cavities, and as well as use in laboratory work is being challenged by new technologies. One of the new technologies on power measurement is based on fiber optic sensors. Optoelectronics sensing with fiber optics as sensing elements can offer significant advantages over classical instrumentation [2, 3]. It could therefore become a key factor in microwave sensing technology.

Paper presented at SATCAM 2000 Conference (SATNAC ° COMSIC, AP/BEM ° MTT/EMC), Somerset West - Cape Town, 10 - 13 September 2000

II. FIBER OPTICS SENSORS AND THEIR APPLICATIONS

In fiber optic sensing, the response to external influence is deliberately enhanced so that the resulting change in optical power can be used as a measure of the external perturbation. In communication technology, the signal passing through a fiber is already modulated, while in sensing technology, the fiber acts as a modulator. The fiber therefore serves as a transducer that converts measurands like temperature, stress, strain, rotation or electric and magnetic currents into a corresponding change in the optical power, phase or direction of polarization of light. The usefulness of the fiber optic sensor; therefore depends upon the magnitude of these changes, ability to measure and quantify these changes. As an example, modulation due to a measurand can be produced in the form of microbend loss modulation. A microbend sensor is shown by Figure 1. This is a prime example of an intensity modulation sensor.

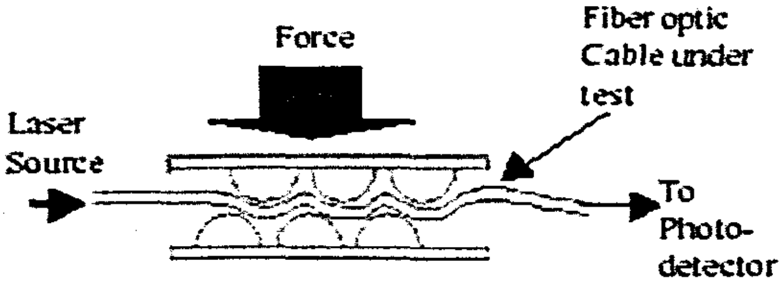


Figure 1: Microbend fiber optic transducer [4]

The advantages of fiber optic sensors are freedom from electromagnetic interference (EMI), wide bandwidth, compactness, geometric versatility and economy. In general, fiber optic sensors are characterized by high sensitivity when compared to other types of sensors. They are also passive in nature due to the dielectric construction. Specially prepared fiber optics can withstand high temperature and other harsh environments. In telemetry, and remote sensing applications it is possible to use a segment of the fiber as a sensor gauge while a long length of the same or another fiber can convey the sensed information to a remote station [4, 5, 7].

Another sensing technique that is popular is the Mach-Zehnder interferometer. The basic interferometer is shown in Figure 2.

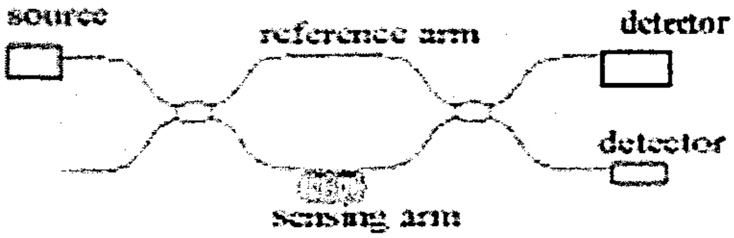


Figure2: Mach-Zehnder Interferometer [5, 6]

An interferometric sensor is based on the detection of changes in the phase of light emerging out of a single mode fiber. The phase change in general is given by Equation 1.

$$\Delta\phi = \Delta\phi_L = \Delta\phi_n = \Delta\phi_g \qquad 1$$

Where the three phase terms on the right hand side of Equation 1, are due to the length (L), the index (n) and the guide geometry (g) variations, respectively.

The phase change may be converted into an intensity change using interferometric various schemes (for example Mach-Zehnder, Michelson, Fabry-Perot or Sagnac forms and others) [7, 8]. In a simple scheme, only the sensing and reference arms are made of fibers, while the rest are made of bulk optic components. However, the use of all-fiber or integrated optic components can provide better stability, and compactness compared to their bulk counterparts. Interferometeric fiber optic sensors are by far the most commonly used sensors, since they offer the best performance. They have found application as acoustic sensors (e.g. hydrophones), rotation sensors (e.g., gyroscope), strain, temperature, chemical, biological and a host of other types of sensors.

In these techniques, the phase change of light propagating through a fiber of length (l), is obtained with the propagation constant $\beta = k_0 n$, as given by Equation 2.

$$\phi = \beta = k_0 \times n \times l \qquad 2$$

As the perturbation changes induce a phase shift, photodetectors are used at the output of the couplers of the Mach-Zehnder Interferometer to detect an intensity variation and are governed by the current equations given below. Using two photodetectors, the currents I_1 and I_2 represent the reference and sensing output current. By using Jones Calculus [9], one is able to derive the intensity functions generated by the detectors as follows:

$$I_1 = E_0^2\left[\left(1-\cos\left(\frac{\Delta\phi_2+\Delta\phi_3}{2}\right)\times\cos\left(\frac{\Delta\phi_2-\Delta\phi_3}{2}\right)\right)\right] \qquad 3$$

$$I_1 = E_0^2\left[\left(1+\cos\left(\frac{\Delta\phi_2+\Delta\phi_3}{2}\right)\times\cos\left(\frac{\Delta\phi_2-\Delta\phi_3}{2}\right)\right)\right] \qquad 4$$

Where $\Delta\phi$ represents the phase changes and E represents the voltage source from the optical power source.

III. USE OF FIBER OPTICS IN MICROWAVE CAVITIES

The development of distributed and array sensors covering extensive structure locations are also feasible using fiber optic sensors. Many signal processing devices (splitter, combiner, multiplexer, filter, delay line etc.) can also be made of fiber optic elements thus enabling the realization of an all-fiber measuring system. In this paper, optoelectronic techniques using fiber optics as a sensor for measuring magnetron microwaves in commercial microwave cavities has been proposed.

The variations in length, diameter and refractive index that would cause an optical parameter due to microwave change will be investigated. The change in phase of the light through the core when temperature of the fiber increases will result in the transfer function of phase (ϕ) and temperature, which can be related by Equation 5.

$$\frac{\Delta\phi}{\Delta T}=\frac{2\pi L}{\lambda}\left[n\alpha+\frac{dn}{dT}\right] \qquad 5$$

Phase change therefore results from both a changes in fiber length (L) and refractive index (n) with temperature (T). The main aspect of this design will be on a single-mode fiber optic placed in the microwave cavity for power measurement distributed within the cavity. Equation 6 gives us the relationship between microwave power absorption per unit length of the fiber in relation to the initial heating rate dT/dt [7, 8].

$$\dot{P}L=L\left[(A\rho s)_c+(A\rho s)_p\right]\frac{dT}{dt} \qquad 6$$

Where A is the cross-sectional area, s is the specific heat and ρ is the density. The parameters relating to the silica glass are denoted by subscript c and those relating to the primary coating are donated by subscript p. The experimental set-up for the optical fiber microwave sensor is shown in Figure 3.

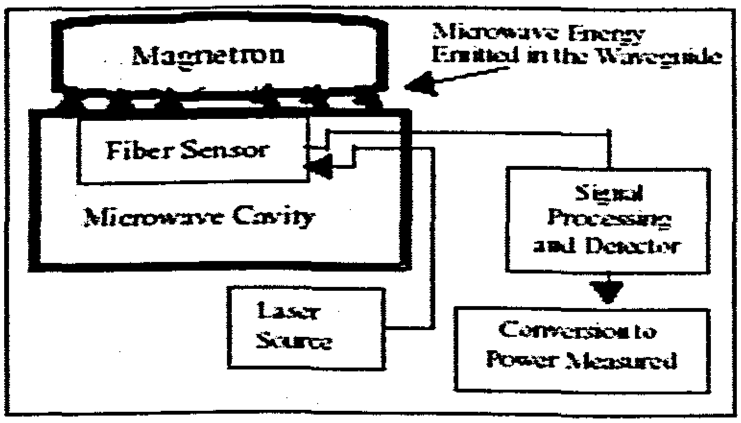


Figure 3: - Experimental Setup

Currently, experimental procedures are carried out to achieve the optimal configuration of the sensor to be deployed.

V. CONCLUSION

Being a challenge to detect microwave signals optically, it is necessary to convert the signal power directly or indirectly into some form of mechanical or optical perturbation. Furthermore, as it is critical when specifying the components that build up the sensor system, the equipment and techniques to be used must be accurate and traceable to monitor the magnitude of the output power in the cavity.

We hope that optoelectronic sensing with optical fibers as sensing elements can offer significant advantages over classical instrumentation in this field. One of the aims of this research is the mapping of microwave energy within the cavity itself. In this case we are investigating the possibility of it becoming an important additional tool in microwave characterization within microwave cavities.

REFERENCES

[1] Thomas S. Laverghetta, "Modern Microwave Measurements and Techniques," Artech House, Inc. 1988, Chp7 & 9.

[2] M. Matasane, MTE Khan, "Assessments of current commercial microwave ovens operation with a view to improve power measurement design," SA Electricity and Control Journal, September Issue, 1999.

[3] RF Engineering, "2.5GHz Power Source," pp206 – pp207, March 1997, Electronics World.

[4] Jeunhomme, B. Luc, "Single-Mode Fiber Optics Principles and Applications," New York: Marcel Dekker, Inc., 1983.

[5] Y. L. Lo and J. S. Sirkis, "Active Homodyne Demodulation of Mach-Zehnder Interferometeric Optical Fiber Sensors," Nov/Dec 1994, pp33 – pp36, Experimental Techniques.

[6] Kao, K. Charles, "Optical Fiber Systems: Technology, Design, and Applications," New York: McGraw-Hill, 1982.

Paper presented at SATCAM 2000 Conference (SATNAC ° COMSIC, AP/BEM ° MTT/EMC), Somerset West - Cape Town, 10 - 13 September 2000

[7] Harris & L. J. Anchterlonie, "Novel Means of Detecting Microwave Power using Optical Fibres," Electronics Letters, Vol. 22, No. 22, 23rd October 1986, pp1178 – pp1179.

[8] B. Culshaw, "Optical Fibre Sensing and Signal Processing," Pieregrinus, London 1984, Chap 7.

[9] Kersey and A. Dandridge, "Applications of Fiber-Sensors," IEEE Trans. on Comp. Hybrids and Manufact. Technol. 13,1990, pp137 - pp143.