CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

Measurement and Instrumentation have become an integral part of all branches of engineering and technology, science and medicine. Measurement of a given quantity is essentially the act or result of comparison between the quantity (whose magnitude is unknown) and a predefined standard. Since two quantities are compared, the result is expressed in numerical values and a unit [1, p.1]. Measurement is a process by which one can convert physical parameters into meaningful numbers. Measuring is the process in which the property of an object or system under consideration is compared to an accepted standard unit, a standard defined for that particular property. Measurement involves the use of instruments as a physical means of determining quantities or variables. “An Instrument can be defined as a device or a system which is designed in such a way that it maintains a functional relationship between a prescribed property of a substance and a physical variable and communicates this relationship to a human observer by some way and means” [2, p.2]. Instruments enable humans to determine the value of an unknown quantity or variable being measured. A generalized instrument or an instrumentation system in the simplest case is a single unit which gives output reading or signal according to the unknown variable (measurand) applied to it [1, p.2].

The use of the proper instrumentation system for the measurement and control requires the knowledge of the nature of application, control parameters, performance of the measuring instrument and sensors under given operating conditions and external interfering inputs (which can cause error in the measurement system). Thus the development of new sensors, measuring instruments and control methods will always continue in order to develop new means for measurement of physical parameters.

Sensors and transducers are the primary sensing elements of an instrumentation system. “A sensor can be defined as a device which has the role of converting a change in the magnitude of one physical parameter into a change in magnitude of a second, different parameter, which can be measured more conveniently and perhaps more accurately” [3]. On the other hand, a transducer is defined as “An element that converts the physical variable to be measured (i.e. a measurand) into a suitable signal, preferably an electrical one” [2, p.2]. A measurement system may, however, use a transducer in addition to a sensor, to convert a physical variable to a usable quantity which can be converted into electrical signals, e.g., a Bourdon tube converts a change in pressure into displacement. This displacement can be converted into electrical voltage with the help of a inductive or capacitive transducer.

1.2 OPTICAL FIBRE SENSOR

With the invention of Laser in 1960’s, a great interest in optical systems for data transmission began. The invention of laser motivated researchers to study the potential of fibre optics for data transmission, sensing, and other applications. Laser systems could send an amount of data much larger than microwave, and other electrical systems. The first experiment with the laser involved the free transmission of a laser beam in the air. Researchers also conducted experiments by transmitting the laser beam through different types of waveguides. Glass fibres soon became the preferred medium for transmission of light. Initially, the existence of large losses in optical fibres prevented coaxial cables from being replaced by optical fibres. Recent advances in fibre-optic technology have significantly changed the telecommunications industry. The ability to carry gigabits of information at the speed of light significantly increased the research and development potential of optical fibres. Simultaneous improvements and cost reductions in optoelectronic components led to similar emergence of new product areas. Sustained research led to integrated development of fibre optics and optoelectronic devices to create a new generation of fibre-optic sensors. Soon it was found that, with internal losses reduced to minimum, and the sensitivity for detection of the losses increasing, one could detect changes in phase, intensity, and wavelength from outside perturbations on the fibre itself. Thus, fibre-optic sensors were born. In parallel with these developments, fibre-optic sensor technology found significant users in the optoelectronic and fibre-optic communication industries. Many of the components associated with these industries were often developed for fibre-optic sensor applications. Fibre-optic sensor technology in turn has often been driven by the developments and subsequent mass production of components to support these industries.

Till date, fibre-optic sensors have been extensively used to monitor a wide range of physical parameters such as position, vibration, strain, temperature, humidity, viscosity, pressure, current, electric field and other environmental factors.

A general block diagram illustrating an optical-fibre sensor system is shown in Figure 1.1

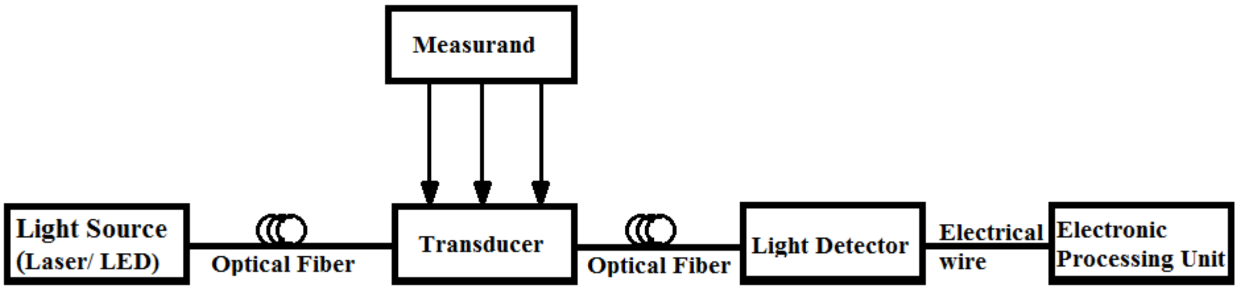

Fig. 1.1: Basic components of an optical-fibre sensor system

The general block-diagram of an optical-fibre sensor system is shown in Figure 1.1. It consists of an optical source (Laser, LED, Laser diode etc), optical fibre, sensing or modulator element (which transduces the measurand to an optical signal), an optical detector and processing electronics (oscilloscope, optical spectrum analyzer etc).

1.3 CLASSIFICATION OF OPTICAL FIBRE SENSORS

Optical sensors can be classified on the basis of their operating principle. The broad classification is given as:

i. Extrinsic type of sensors
ii. Intrinsic type of sensors

1.3.1 Extrinsic Type of Sensors

In the case of an extrinsic sensor, the modulation takes place outside the fibre. The fibre may be used strictly as information carriers that lead up to a black box to impress information on a light beam that propagates to a remote receiver. The black box may contain mirrors, a gas or liquid cell, a cantilevered arm or dozens of other mechanisms that may generate, modulate or transform a light beam [4].

1.3.2 Intrinsic Type of Sensors

In the intrinsic sensor, the physical parameter to be sensed modulates the transmission properties of the sensing fibre. Here one or more physical parameters of the guided light, i.e., intensity, phase, polarization and wavelength/ colour are modulated by the physical parameter to be measured [4].

The classification of Optical Fibre Sensors based on the operating principle is given as-

1.3.3 Fibre-Optic Sensors by Intensity Modulation

Intensity modulated fibre-optic sensors are the simplest of the intrinsic sensors. A large variety of transduction mechanisms has been proposed to produce intensity modulation by the measurand of the guided light that is injected into the sensing fibre [5]. The general configuration of an intensity modulated sensor is shown in Figure 1.2.

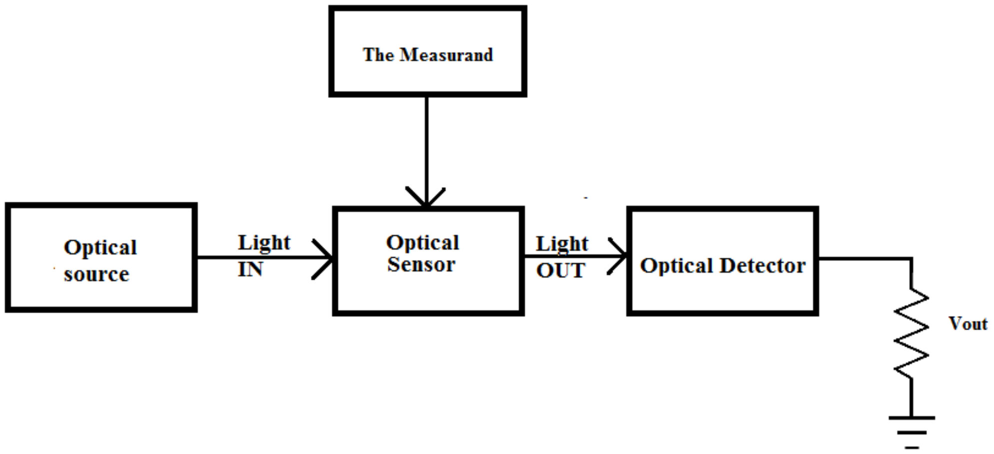

Fig. 1.2: General Configuration of an intensity-modulated sensor

The measurand is a continuously varying quantity which modulates the intensity of the light transmitted through the optical sensor. The modulation is reflected in the voltage output of the detector, which upon calibration gives the magnitude of the measurand. Intensity modulation can be achieved by a variety of schemes like

- displacement of one fibre with respect to another,
- collection of modulated light reflected from a target exposed to the measurand,
- loss modulation in the core or cladding through macro-bending or micro-bending and evanescent coupling into another fibre medium.

1.3.3.1 Intensity Modulation by Light Interruption

A simple light-interrupted intensity-modulated sensor can be assembled by interrupting the direct light from a light source to a light detector [5]. However, coupled light intensity modulation across a fibre joint can be varied by three different types of misalignment between the axes of the two fibres. These three types of misalignments are as follows:

i. Transverse misalignment,
ii. Longitudinal misalignment,
iii. Angular misalignment.

1.3.3.2 Reflective Fibre-Optic Sensor

In the reflective type of fibre-optic sensor, the measurand is used to induce modulation of the light reflected from a reflecting surface. The simplest form of this is the Y-coupler which basically consists of two fused multimode fibres along some portion of their length.

If light from a source enters any one of the unfused potion of the Y-coupler, then the light travels along the fused portion and is reflected back from a reflecting surface and goes out through the other unfused portion of the Y-coupler. The back reflected light intensity is dependent on the distance of the reflecting target from the fibre probe [5]. These types of reflective sensors can be used to detect displacement, pressure and even the position of a float in a variable area flowmeter.

1.3.3.3 Evanescent –Wave Fibre Sensor

When a guided light in a fibre waveguide penetrates into the cladding to a distance then the light wave portion penetrating into the surrounding cladding region is called an evanescent wave. This phenomenon is responsible for the working a fibre optic directional coupler [5]. The coupling intensity between two fibres is a function of the distance between two fibre cores. The closer the distance, the stronger the coupling will be. When light is launched into one of the fibres, and it propagates to a region where a second core is placed in close proximity so that part of the evanescent wave of the first fibre is within the second fibre region. Thus, evanescent wave coupling takes place. The coupling coefficient is directly proportional to the separation distance between the two fibres. When an environmental effect such as a pressure, an acoustic wave, or a temperature change causes the distance to change between two fibres, it results in a change in the coupling coefficient. Thus, the detected light intensity of the second fibre is also changed. Therefore, by monitoring the intensity change of the second fibre, the change in the environment can be sensed [4].

1.3.3.4 Microbend Optical Fibre Sensor

A Microbend is defined to be a sharper bend with a radius of curvature of fibre less than the fibre radius. These sensors are based on microbend induced transmission loss of an optical fibre to detect displacement, pressure, strain and temperature. When a portion of a fibre is exposed to a deformer, that portion of the fibre goes through a continuous succession of small bends on a microscopic scale and the fibre would exhibit excess loss. The fibre is sandwiched between a pair of toothed plates to induce microbending [5]. Such microbending along the axis of the fibre results in the redistribution of the guided power in the fibre waveguide and the coupling of one mode to another.

1.3.3.5 Macrobend Optical Fibre Sensor

A Macrobend is a smoother bend of a length of optical fibre with a bending radius much larger than the fibre radius. If the bend radius is larger than the critical value of bending radius, the fibre is insensitive to the macrobending, which is allowed in communication systems. If the bend radius is reduced below the critical value, the loss increases very rapidly, allowing the construction of a relatively sensitive macrobend fibre-optic sensor. Macrobend losses are generally observed when an optical fibre is bent to a radius of several centimetres.

1.3.4 Phase Modulated Fibre Optic Sensor

The most sensitive fibre optic sensing method is based on the optical phase modulation. The total phase of the light along an optical fibre depends on the properties like the physical length of the fibre, transverse geometrical dimension of the guide, refractive index and the index profile of the waveguide. The refractive index varies with temperature, pressure and longitudinal strain via photo elastic effect. Waveguide dimensions vary with radial strain in a pressure field, longitudinal strain in a pressure field and by thermal expansion. The phase of the light field changes due to the external perturbations so that the fibre optic sensor can also be built based on the light field’s phase changes. This phase change is converted into an intensity change using interferometric schemes like Mach-Zehnder, Michelson, Fabry-Perot or Sagnac forms [4].

1.3.5 Sensors based on effect of Polarization

Optical fibre is mostly made of glass. The refractive index of the fibre can be changed by the application of stress or strain. This phenomenon is called a photo-elastic effect. In addition, in many cases, the stress or strain in different directions is different, so that the induced refractive index change is also different in different directions. Thus, there is an induced phase difference between different polarization directions. In other words, under the external perturbation, such as stress or strain, the optical fibre works like a linear retarder. Therefore, by detecting the change in the output polarization state, the external perturbation can be sensed [4].

For the strain or stress measurement, environmental temperature is unwanted environmental parameter. For the polarization-based fibre-optic sensor, environmentally induced refractive index changes in the two polarization directions are almost the same. Thus, there is almost no induced phase difference between two polarization states.

1.3.6 Sensors based on effect of Wavelength

The sensor based on wavelength/ colour modulation usually employs ratio measurement technique or two colour measurement techniques. One of the wavelengths is affected by the measurand and the other is kept independent from wavelength modulation. In applications like temperature measurement, the fibre tip is coated with phosphor which is excited by the light travelling along the fibre. The intensity of different radiated wavelengths is a function of the probe tip temperature. By comparing the ratio of wavelengths of the two fibres, the noise associated with the measurement system can be eliminated [6].

These type of sensors are used as-

- Chemical analyser
- Analysis of phosphorescence and luminescence
- Analysis of black body radiation.

1.4 ADVANTAGES OF OPTICAL FIBRE SENSOR

Fibre-optic sensors are excellent candidates for monitoring environmental changes and they offer many advantages over conventional electronic sensors. Some of the advantages offered by optical-fibre sensor over conventional sensors are as follows:

- Easy integration into a wide variety of structures, including composite materials, with little interference due to their small size and cylindrical geometry,
- Inability to conduct electric current,
- Immune to electromagnetic interference and radio frequency interference,
- Light weight,
- Robust, more resistant to harsh environments,
- High sensitivity,
- Multiplexing capability to form sensing networks,

- Remote sensing capability,
- Multifunctional sensing capabilities such as strain, pressure, corrosion, temperature and acoustic signals.

Till date, fibre-optic sensors have been widely used to monitor a wide range of environmental parameters such as position, vibration, strain, temperature, humidity, viscosity, pressure, current, electric field and several other environmental factors.

1.5 APPLICATIONS OF OPTICAL FIBRES

Optical fibre sensors find wide applications in sensing various physical, electrical, mechanical, biological and chemical parameters. The different applications of optical fibre sensors have been shown in Table 1.1 based on the different types of optical fibre sensors.

Sl. No.	Type of Optical Fibre Sensor	Applications
01	Intensity based Optical fibre Sensor	Measurement of Displacement, Pressure, acoustic pressure Strain, Force, Vibration, Temperature, liquid level, acceleration, fluorescence and distributed sensing, rotary position sensor, biological sensor, application in medicine, detection of Cataract in human body, distributed and multiplexed sensing, detection of cracks in bridges and dams using microbending and distributed sensing.
02	Phase Modulated Fibre Optic Sensor	Measurement of temperature, pressure, vibration, electric current, electric voltage, load monitoring of power transmission lines, hydrogen sensor, Hydrophone, Gyroscope, Magnetometer, structural monitoring in bridges, dams, tunnel, mines, aircrafts, blood monitoring, monitoring of pipe lines in oil and gas industries.

03	Sensors based on effect of Polarization	Measurement of stress or strain, measurement of magnetic field, transducer of current measurement of high voltage transmission lines.
04	Wavelength based sensors	pH sensor, fluroscence sensor for chemical sensing, medical application and measurement of temperature, viscosity and humidity. Black body sensor, Bragg grating sensor, gas sensor.

Table 1.1: Application of different types of Optical Fibre Sensors

1.6 LITERATURE SURVEY

The determination of refractive index is very important in industries particularly in chemical and pharmaceutical industries. The knowledge of refractive index is required in many industries for quantifying the quality of the industrial products such as oil, liquid chemicals, liquid food, alcohol etc. The measure of refractive index would provide information about the turbidity (lack of clarity) of a liquid. The measurement of refractive index is carried out under the loss of intensity method where the modulation of transmitted light takes place either due to emission, absorption or RI change. Several methods have been used to find the refractive index of solid and liquid samples.

Huang, L., *et al.* [7] showed a novel method to measure refractive index of liquid and curable liquid substances. Planar microlenses with two refracting interfaces facing each other are fabricated with a planar lightwave circuit technology. A liquid, whose refractive index (RI) is to be determined, is filled between the two refracting surfaces and the width of the beam passing through the lens is measured. By comparing the measured beam width with the analytical results, the RI of the liquid can be determined accurately. This method is applicable for measurements of absolute values RI of almost any liquid or curable liquid substances, and can routinely achieve a precision of 1×10^{-4} by using a simple setup with a standard beam profiler.

Allsop, T., *et al.* [8] demonstrated a refractive index sensing system based upon a high-sensitivity long-period grating Mach-Zehnder refractometer. The sensing system had comparable accuracy to laboratory-based techniques used in industry such as high performance liquid chromatography and UV spectroscopy. They reported that their sensor provides the highest refractive index resolution reported for any fibre LPG (Long Period Grating) device.

Possetti, G.R.C., *et al.* [9] showed the applicability of the refractometric measurement system based on an LPG to determine the ethanol concentration in ethanol-gasoline blend. They found that despite the non-linearity of its response curve, the combined and expanded uncertainties associated with LPG measurements are lower than those obtained with the Abbe refractometer.

Measurement of refractive index sensitivity using LPG refractometer was demonstrated by Zhu, Y., *et al.* [10].The principle of operation is based on the use of a long-period grating that is structurally induced by a CO_2 laser, and where the resonance wavelengths are shifted as refractive index of the medium surrounding the cladding of the long-period grating changes. Ethylene glycol, salt, sugar in water solution with the concentration from 0 to l00 per cent, 9.09 to 23.08 per cent, and 6.35 per cent to 54.55 per cent respectively were measured by LPG, and as a refractometer, this fibre-based device not only can differentiate chemicals based on their refractive index, but it can also become a concentration indicator of a particular chemical solution, and could be applied in the oil and petroleum industry.

Calixto, S., *et al.* [11] proposed the use of two optofluidic configurations to measure refractive index and pressure of liquids. As for the measurement of refractive index, the configuration uses two fibres and a capillary. Light is introduced in the set up by means of an optical fibre. This light is focused by the capillary that behaves like a cylindrical lens. Focused light is collected by a second fibre and then this light is sent to a detector. The focusing effect depends on the refractive index of the liquid introduced in the capillary. It was found that light was more focused when refractive index of liquid is higher.

Caucheteur, C., *et al.* [12] proposed a novel demodulation technique based on the monitoring of the polarization-dependent loss in a 1-nm wavelength range to measure the surrounding refractive index by means of weakly tilted fibre Bragg gratings. Resolution of 1×10^{-3} in the determination of the Surrounding Refractive index (SRI) and temperature-insensitive response have been reported in this work.

Wang, S-F., *et al.* [13] proposed a new and simple liquid refractometer based on multiple total-internal reflections in heterodyne interferometry. The sensing unit of the new type liquid refractometer is an elongated prism, i.e., a parallelogram prism. As the length of the elongated prism is longer, the sensitivity and the resolution of this new type liquid refractometer are higher.

Zamarreño, C.R., *et al.* [14] fabricated an optical-fibre refractometer in the infrared region based on the deposition of Indium Tin Oxide (ITO) coatings onto optical-fibre core. ITO coatings act as the resonance supporting layer allowing the coupling of light at specific wavelengths from the waveguide to the ITO-coating/external medium region as a function of the refractive index of the external medium. The utilization of ITO coating allows the fabrication of robust, highly reproducible and easy-to-implement resonance-based refractometers. The results obtained showed an average sensitivity is 3125 nm/refractive index unit. A similar work on refractometer based on the deposition of ITO on the optical-fibre core was again presented by Zamarreño et al [15]. The refractometers showed a sensitivity of 4068-nm/refractive index unit (RIU) in the range 1.333–1.392 RIU.

Li, Y.L., *et al.* [16] proposed the design of a novel refractometer based on a new Electro-Optical detection principle. The group built a mathematical model, and designed the structure of sensing probe; and through detail calculation, key parameters of the refractometer were determined. The simulation results showed that resolution reaches order of 10^{-6}.

Khotiaintsev, S., *et al*. [17] presented a fibre-optic refractometer with intensity-type transducer which can operate remotely via long fibre-optic cables. This version of the refractometer could access the concentration of aqueous solutions of sodium chloride in the range from zero to about 145 per cent ($1.327<n<1.353$ at $\lambda=940$ nm and 25 degree Celsius).

Nath [18] presented a non-intrusive refractometer sensor. The working principle of the sensor is based on intensity modulation of the back-reflected light when output light from an optical fibre end focuses onto air-medium interface. The change in the refractive index of the medium affects the reflectance of the incident light signal and thus modulates the back-reflected light signal. Refractive index variation as small as 0.002 Refractive index unit (RIU) was measured using the technique.

Chaudhari and Shaligram, A.D. [19] proposed an optical-fibre sensor for measuring the refractive index of liquid, based on the measurement of the input and output power of a multimode fibre. The sensor uses two fibres, mirror as reflector and liquid as medium. The light is carried by the illuminating fibre up to modulation zone where the properties of incident light is modulated by modulator. The modulated light is carried by receiving fibre to the detector. The measurement principle is based on reflective intensity modulation. A novel sensing probe is designed with outer ring of fibre acting as illuminating fibre and center fibre acting as read fibre. Using this probe, effect of wavelength on refractive index is studied.

Zhu, Y., *et al.* [20] reported a single long-period fibre-grating refractometer with period up to several millimeters. The principle of operation is based on in the using of a long-period grating that is structurally induced by a CO_2 laser, and where the resonance wavelengths are shifted as the refractive index of medium surrounding the cladding of the long-period grating changes. The different concentrations for three types of solutions (ethylene glycol, salt and sugar) were experimentally measured, and results show that, as a refractometer, this fibre-based device not only can differentiate chemicals based on their refractive index, but it can also become a concentration indicator of a particular chemical solution.

Tian and Yam,S-H. [21] designed, fabricated, and tested a novel in-line single-mode fibre interferometers using Mach–Zehnder and Michelson as refractive index (RI) sensors. Abrupt tapers and connector-offset attenuators have been proposed as alternatives to long period gratings (LPGs) as mode-coupling mechanisms to transfer optical power between core and cladding modes in optical fibre. The coupling coefficients between core and cladding modes in the proposed designs were calculated using numerical packages and the devices were subsequently implemented using commercially available fusion splicer. Three interferometers were realized in the experiment using abrupt taper-Mach–Zehnder and Michelson and connector-offset attenuator—Michelson. They showed large extinction ratios (up to 23 dB) and small insertion losses (smaller than 3 dB). The interferometers were tested as RI sensors using the maximum attenuation wavelength shift. Given that the minimum resolution of optical spectrum analyzer is 10 pm, ~10^{-4} difference of RI can be detected by the proposed interferometric sensors, providing similar performance as LPG-based interferometers at a lower cost and simpler fabrication process.

Ferguson, B., *et al.* [22] proposed a novel means for extracting refractive index information from a surface plasmon resonance (SPR) sensor system. Rather than relying on output wavelength (from a polychromatic light source) or angle of incidence (from a monochromatic wave source) to identify the point of SPR, the system presented uses the spectral shift induced by varying the drive current on a commercially avail-able red LED to identify resonance. Using appropriate, short duty cycle drive electronics and highly sensitive photo detection circuits, the SPR spectroscopic system demonstrates the ability to detect differences in refractive index among air, water, and various sucrose concentrations in water (representing a total dynamic range from 1.0 to 1.4 RI units). Resulting RI resolution of the SPR system is demonstrated at the portable instrument benchmark of 10^{-4} RI units.

1.7 PROBLEM STATEMENT

The problem statement for this research work is- to develop an improved refractometer based on the combination of bare and bent refractometer and bare and tapered refractometer which is more sensitive to the change in refractive index.

1.8 OBJECTIVES OF THE RESEARCH

The main objective of this research work is to use some of the properties of light and optical fibre to achieve specific objectives so that the outcome can be used for the benefit of the society and open avenues for new research and development in some specific fields. The objectives of the study are summerised as follows:

- To design and develop a new optical fibre sensor to measure the refractive index of an unknown liquid. The configuration of the new sensor combines the effect of bare and bent and bare and tapered optical fibre sensor. Therefore this sensor is called bare, tapered and bent multimode optical fibre (BTBMOF).

- The mathematical basis for this new refractometer has been formulated and it is related to the voltage of a LDR based potential divider circuit, so that the advantage of the proposed sensor can be compared with that of bare and tapered refractometer.

1.9 ORGANISATION OF THIS THESIS

The major contribution of this thesis is the presentation of the theoretical basis for the newly developed optical-fibre refractometer and development of the instrumentation system to carry out experimental studies on it to determine its performance. It is organised into six chapters and a bibliography.

Chapter 1 is the Introduction to fibre optics and gives a classification of optical-fibre sensors along with their principle of operation, applications and advantages of optical-fibre. This chapter also presents a brief review of the work done by other researchers in the field, the problem statement and the objectives of the research work.

Chapter 2 is a review of the wave theory of light using Maxwell equation. The chapter also presents the derivation of the mathematical equation of a bent fibre and the bare and tapered refractometer which is the basis of the developed optical-fibre refractometer.

Chapter 3 gives a mathematical model of the bare and bent optical-fibre sensor used in the measurement of moisture in transformer oil, the instrumentation set-up and the experimental work with results and interpretation. The sensor monitors the change in refractive index and temperature of the oil as a measure of its moisture content. Artificial Neural Network (ANN) is used in the instrumentation system to arrive at the result.

Chapter 4 gives the mathematical formulation of a bare, bent and tapered optical- fibre sensor. The performance of the proposed sensor is compared with that of bare and tapered optical fibre sensor using standard sugar solution with different concentration. The proposed sensor confirms better performance compared to than the bare and tapered optical fibre sensor.

Chapter 5 demonstrates the application of the bare, bent and tapered optical-fibre sensor to determine the degree of degradation of lubricating oil of four stroke motor bike engine. A detailed mathematical analysis relating the refractive index with various parameters associated with degradation of lubricating oil is presented. The Instrumentation systems along with the experimental results and their interpretation have also been presented. ANN has been used for the sensor to co-relate the measure of refractive-index, lubricating oil temperature and oil usage to the degradation of the lubricating oil sample.

Chapter 6 is the last chapter which presents the conclusions of the whole research work concentrating on the contribution of each chapter and scope of further work.