Interferometric Weight & Displacement Sensor and Pollution Monitoring Sensors for Fe$^{3+}$ & Mn$^{2+}$ Detection

Introduction

Fiber optic sensors are extensively used for pollution monitoring and environmental sensing [1-25]. Moreover, they find extensive applications in various physical parameter measurement when used in the fiber interferometric configuration [26-56]. In the present chapter, we concentrate on the development of phase modulated sensors for displacement and weight measurement, and intensity modulated sensors for aqueous iron and manganese detection. In addition, a new referencing technique for intensity modulated sensors is also proposed.

4.1 Phase modulated optical fiber sensors

Phase modulation of light has been increasingly exploited as a highly sensitive technique for monitoring environmental changes over the past hundred years. The principal attraction of optical phase modulation is its intrinsically high sensitivity to environmental modulation, so that very high-resolution measurements are feasible. 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. A suitably designed fiber interferometer takes optical interferometry from the laboratory optical bench into a compact and mechanically rugged piece of instrumentation. Optical fiber interferometric sensors are among the most sensitive measurement devices yet developed.

Hydrophones, magnetometers, accelerometers, strain gauges, and thermometers have all been fabricated around the fiber interferometer, and all have achieved sensitivities exceeding that available from other technologies. Moreover, the dynamic range of fiber interferometers is as high as 150 dB. How much of this is actually available depends on the detection technique used to convert the phase modulation to a usable electrical signal.

The basic elements of an optical fiber interferometer are shown in fig 4.1. The modulator in included in the reference arm either to incorporate the required $90^\circ$ imbalance for homodyne detection or to provide frequency offset for heterodyne detection. The beam splitters are most conveniently optical fiber 3 dB couplers, thereby, eliminating mechanical noise common with discrete optical components. However, the use of couplers does limit the scope of the modulation function to phase modulators based on mechanical stretching of the fiber using piezoelectric elements.

Figure 4.1: Schematic sketch of a Mach-Zehnder interferometer
4.1.1 Phase modulation mechanisms in optical fibers

The total phase of the light path along an optical fiber depends on three properties of the fiber guide:

- Its total physical length
- The refractive index and the index profile
- The geometrical transverse dimensions of the guide

It is 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 alone. These variations may then be evaluated for a given perturbation applied to the fiber, and hence the phase sensitivity of the fiber to this perturbation can be estimated. The total physical length of an optical fiber may be modulated by:

- Amplitude of a longitudinal strain
- Thermal expansion
- Application of a hydrostatic pressure causing expansion via Poisson's ratio

The refractive index varies with:

- Temperature
- Pressure and longitudinal strain via photoelastic effect

And the guidance dimensions with:

- Radial strain in a pressure field
- Longitudinal strain through Poisson's ratio
- Thermal expansion

The effect of a pure change in length, $\delta L$, on the phase of light propagating in the guide is readily determined:

$$\delta \phi_L = \frac{2\pi \delta L}{\lambda_g} = \frac{2\pi L}{\lambda_g} \varepsilon_l$$

where $\lambda_g = \frac{\lambda_0}{n} \sin \theta$, $\lambda_0$ is the wavelength of light in the guide, $\theta$ is the angle of incidence of a ray on the core-cladding interface and $\varepsilon_l$ is the
longitudinal strain. The effect of a change in refractive index $\Delta n$ is equally readily derived to be:

$$\delta \phi_n = \frac{2\pi}{\lambda_g} L \Delta n \quad (4.1)$$

in the limit that the change in $\lambda_g$ is negligible. The change in guide wavelength with core diameter is a little more complicated to derive, but the general expression:

$$\Delta \phi_d = \frac{2\pi L}{\lambda_g^2} \frac{\partial \lambda_g}{\partial d} \Delta d \quad (4.2)$$

is clear from simple geometrical considerations. Temperature changes the refractive index and the geometrical dimensions of the fiber. The change in phase is thus

$$\Delta \phi = \frac{2\pi L}{\lambda_g'} \left\{ \alpha + \frac{\partial n}{\partial T} \right\} \Delta T \quad (4.3)$$

where $\alpha$ is the temperature coefficient of expansion. The effect of a pressure variation on the optical phase path may be written in the most general form as

$$\Delta \phi = \frac{2\pi L}{\lambda_g} \left\{ \kappa - \frac{n^2}{2} (P_{11} + P_{12}) \varepsilon_r + P_{12} \varepsilon_l \right\} \quad (4.4)$$

where $\varepsilon_l$ is the longitudinal strain and $\varepsilon_r$ the radial strain. $P_{11}$ and $P_{12}$ are the photoelastic constants of the silica fiber.

4.1.2 Experimental setup

![Figure 4.2: Sensing Shell]
The sensing arm of the interferometer consists of a fiber wound over a hollow, elastic, cylindrical structure made of thin rubber of thickness 1 mm as shown in fig 4.2. It has been experimentally observed that the rubber tube is more sensitive and reversible than a polymer film or a paper of appropriate thickness.

The light emitted from a diode pumped solid-state laser (B&W TEK, BWT-50) operating at 532 nm and 50 mW is coupled to a fiber optic 3dB coupler using a microscope objective of NA 0.25. One arm at the output end of the coupler may be treated as the reference arm and the other as the sensing arm (sensing shell) as shown in Fig 4.3. Finally, these two arms are brought near to each other laterally and the light coming out is allowed to interfere. The interference pattern is allowed to fall on a photodiode and the signal is amplified and fed to a fringe counting system, which is used to count the number of fringes shifted when the rubber tube gets deformed. This amount of deformation is proportional to the amount of force applied on it.

Figure 4.3: Experimental Setup

Figure 4.4: The block diagram of the photo-detector
The block diagram of the detector-fringe counter system is shown in Fig 4.4.

Fig 4.5: Electronic circuit for a detector-fringe counter system.
The weak signal coming from a commercially available photodiode (commercially known as photo-receiver) is amplified using a low noise operational amplifier (TL071). The amplified signal is then fed to a double OPAMP (TL082) operating as a difference amplifier and a voltage amplifier, which nullifies the effects of ambient light intensity. The reference signal for this difference amplifier is provided by a zener diode driving a transistor (BC547) in combination with a potentiometer (trimport 203). This output is again amplified and fed to a comparator (OP07CP). Depending on the voltage set at the second trimport 203, the output of this comparator switches between +9V and -9V. Finally, the output of this third stage is fed to a standard counter IC (MM74C926N) which in turn drives a set of 4 seven segment displays through 4 transistors. Using this fringe counter 0-9999 fringes can be counted.

A compact detector-fringe counting system using the above circuit is developed and is shown in fig 4.6
4.1.3 Results and Discussion

For the displacement measurement, the rubber tube that serves as the sensing shell is held in between a platform and a micrometer screw. The displacements with a resolution of 10 µm are made using the screw which applies a pressure in the transverse direction of the shell and the corresponding number of fringes shifted is noted. The experiment is carried out using rubber tubes of varying radii and different fiber turns. Fig 4.7 shows the sensor response curve with shell diameter of 20 mm and varying fiber turns. It can be seen that the sensitivity is a function of number of turns of the fiber. This is in agreement with the theoretically predicted results (4.1), because as the number of turns increases the total sensing length increases.

Figure 4.7: Shows the response of the displacement sensor with shell radius 20 mm for various fiber turns, a = 1 fiber turn, b = 3 turns and c = 5 turns
Chapter IV: Interferometric Weight and...

Figure 4.8: Shows the response of a single turn displacement sensor with various shell radii. Here the response of the sensor is inversely proportional to the bending radius. Even

Fig 4.8 shows the response of a single turn of the fiber for various shell radii. Here the response of the sensor is inversely proportional to the bending radius. Even
though the total sensing length decreases with the bending radius, the loss due to power coupling to radiation modes will be stronger for smaller bending radius. This may be the reason for the observed effect.

Fig 4.9 shows the response of the weight sensor response with different fiber turns for a constant fiber radius of 20 mm. It is obvious from the figure that as the number of turns increases the sensitivity correspondingly increases which is understandable on the basis of (4.1). The response of the weight sensor also varies in a similar fashion with shell radius just as in the case of the displacement sensor.

4.2 Fiber optic Fe$^{3+}$ and Mn$^{2+}$ detection in aqueous environments

The ever-expanding industrialization and concomitant domestic waste generation causes the release of steadily growing number of pollutants into the environment. Therefore, a great deal of attention must be paid to the pollution of natural freshwater and seawater reserves. Standards for drinking water have evolved over the years as knowledge of the nature and effects of various contaminants has grown. It is considered desirable that drinking water be free of suspended solids and turbidity. In addition, it should be tasteless, odourless and dissolved inorganic solids be in moderate quantities, and toxic substances and pathogens be absent. With further improvements in water quality standards, additional requirement may be added to this list, making drinking water quality requirements even more stringent.

Iron and manganese are minerals found in drinking water supplies. Water percolating through soil and rock can dissolve minerals containing iron and manganese and hold them in solution. Occasionally, iron pipes also may be a source of iron in water. Several factors that cause iron contamination of piped drinking water are, low chlorine residual, infrequent and insufficient hydrant flushing, low water usage, breakage of water pipes by tree roots, frost or pipe corrosion, galvanic or bacterial corrosion, presence of dissolved organic matter and heterotrophic bacteria. Iron and manganese are chemically similar and cause similar problems. Iron is the more frequent of the two contaminants in water supplies; manganese is typically found in iron-bearing water.
Iron and manganese can affect the flavor and color of food and water. In fact, vegetables cooked in iron-contaminated water turn dark and look unappetizing. In addition, they may react with tannins in coffee, tea and some alcoholic beverages to produce a black sludge, which affects both taste and appearance. Iron will cause reddish-brown staining of laundry, porcelain, dishes, utensils and even glassware. Manganese acts in a similar way but causes a brownish-black stain. Soaps and detergents do not remove these stains, and use of chlorine bleach and alkaline builders (such as sodium and carbonate) may intensify the stains. Iron and manganese deposits will build up in pipelines, pressure tanks, water heaters and water softeners. This reduces the available quantity and pressure of the water supply. Iron and manganese accumulations become an economic problem when water supply or water softening equipment must be replaced. There also are associated increases in energy costs from pumping water through constricted pipes or heating water with heating rods coated with iron or manganese mineral deposits.

Oxidation of dissolved iron particles in water changes the iron to white, then yellow and finally to red-brown solid particles that settle out of the water. Iron that does not form particles large enough to settle out and that remains suspended (colloidal iron) leaves the water with a red tint. The four forms of iron commonly found in drinking water are ferrous, ferric, organic and iron bacteria. Ferric iron precipitates or settles out. Organic iron does not settle out. In well water, insoluble iron oxide is converted to a soluble form of ferrous (dissolved) iron. In deep wells, where oxygen content is low, the iron/manganese-bearing water is clear and colorless (the iron and manganese are dissolved). Water from the tap may be clear, but when exposed to air, iron and manganese are oxidized and change from colorless, dissolved forms to colored, solid forms. Iron bacteria (a harmless bacteria), occur in soil, groundwater, and some surface waters. They thrive on iron in the sink or metal parts of the water system and are most easily seen on the inside surface of the toilet tank.

Manganese is similar to iron but forms a brownish-black precipitate and stains. Manganese is less commonly found in groundwater than iron, rarely found
alone in a water source, and generally found with dissolved iron. In fact, manganese is objectionable in water even when present in smaller concentrations than iron. Manganese usually is dissolved in water, although some shallow wells contain colloidal manganese (black tint).

The presence of iron and manganese in water is not considered a health problem. In fact, small concentrations are essential to human health. However, high concentrations of iron may give the water an unpleasant metallic taste while still being safe to drink. Under guidelines for public water supplies set by the Environmental Protection Agency (EPA), iron and manganese are considered secondary contaminants. Secondary standards apply to substances in water that cause offensive taste, odor, color, corrosion, foaming, or staining but have no direct affect on health. Secondary standards set by World Health Organization [57] as well as Kerala State Pollution Control Board [58] specifies secondary contaminant level for iron as 0.3 milligram per litre (300 ppb) and manganese as 0.05 mg/L (50 ppb). Conventional methods of iron detection are generally based on spectrophotometry and fluorescence quenching [59-63]. In addition, a few works related to fiber optic iron detection have also been reported [64-67].

In this context, it is worthwhile to develop fiber optic sensors for Fe$^{3+}$ and Mn$^{2+}$ detection. The characterization of the sensors is carried out using an automated data acquisition system by setting up a LabVIEW environment in the lab.

4.2.1 LabVIEW fundamentals

LabVIEW is a graphical programming language that uses icons instead of lines of text to create applications. In contrast to text-based programming languages, where instructions determine program execution, LabVIEW uses dataflow programming, where data determine execution. In LabVIEW, a user interface is built by using a set of tools and objects. The user interface is known as the front panel. One then adds code using graphical representations of functions to control the front panel objects. The block diagram contains this code. If organized properly, the block diagram resembles a flowchart. LabVIEW is integrated fully for communication with
hardware such as GPIB, VXI, PXI, RS-232, RS-485, and plug-in data acquisition devices. LabVIEW also has built-in features for connecting one’s application to the Internet using the LabVIEW web server and software standards such as TCP/IP networking and ActiveX.

LabVIEW programs are called virtual instruments, or VIs, because their appearance and operation imitate physical instruments, such as oscilloscopes and multimeters. Every VI uses functions that manipulate input from the user interface or other sources and display that information or move it to other files or other computers.

A VI contains the following three components:

- **Front panel**—Serves as the user interface.
- **Block diagram**—Contains the graphical source code of the VI that defines its functionality.
- **Icon and connector pane**—Identifies the VI so that one can use the VI in another VI. A VI within another VI is called a subVI. A subVI corresponds to a subroutine in text-based programming languages.

### 4.2.1.1 Front Panel

The front panel is the user interface of the VI. One can build the front panel with controls and indicators, which are the interactive input and output terminals of the VI, respectively. Controls are knobs, push buttons, dials, and other input devices. Indicators are graphs, LEDs, and other displays. Controls simulate instrument input devices and supply data to the block diagram of the VI. Indicators simulate instrument output devices and display data which the block diagram acquires or generates.

### 4.2.1.2 Block Diagram

After one builds the front panel, he can add code using graphical representations of functions to control the front panel objects. The block diagram contains this graphical source code. Front panel objects appear as terminals on the block diagram. However, one cannot delete a terminal from the block diagram. The terminal disappears only
after one deletes its corresponding object on the front panel. Moreover, every control or indicator on the front panel has a corresponding terminal on the block diagram. Additionally, the block diagram contains functions and structures from built-in LabVIEW VI libraries. Wires connect each of the nodes on the block diagram, including control and indicator terminals, functions, and structures. LabVIEW communicates with most instruments through instrument drivers, which are libraries of VIs that control programmable instruments.

LabVIEW instrument drivers simplify instrument control and reduce test development time by eliminating the need to learn the low-level programming protocol for each application. The foundation for LabVIEW drivers is the VISA (Virtual Instrument Software Architecture) VI library, a single interface library for controlling GPIB, VXI, RS-232, and other types of instruments. Drivers using VISA are scalable across instrument I/O interfaces.

4.2.2 Experimental

For developing the sensor probe a plastic clad silica (PCS) fiber with core diameter 200μm and numerical aperture (NA), 0.22 is unclad over a length of 12 cm. This is done by first removing the sheath of the fiber with a sharp razor and then removing the cladding by immersing the unsheathed portion in pure HF for a minute. The bent fiber sensor uses a bare plastic fiber of core diameter 380 μm and NA 0.3. The permanent microbents are written on the plastic fiber by pressing the fiber in between a pair of corrugation plates each having a length of 60mm and pitch 1 mm.

To calibrate the sensor standard solutions of Fe³⁺ are prepared by the thiocyanate method in which Fe³⁺ reacts with thiocyanate to give a series of intensely red-colored compounds, which remain in true solution [68]. The potassium thiocyanate solution is prepared by dissolving 20 gm of A.R. potassium thiocyanate in 100 ml distilled water. 0.864 gm of Ferric Ammonium Sulphate is dissolved in 10 ml concentrated HCl, which is further diluted to 1 liter. 1 ml of such a solution is = 0.1 mg of Fe. Knowing this value, test solutions of different concentrations are prepared by again diluting the above solution as required. 40 ml of the test solution is
mixed with 5 ml of 2 M potassium thiocyanate solution and 3 ml of 4 M nitric acid, and the resultant solution is diluted to 50 ml. Fig 4.10 shows the absorption spectra of the solution with various concentrations of Fe$^{3+}$. It is clearly visible from the plot that the peak absorption of the solution is at 480 nm. The sensitivity of the sensor will be high if the operating wavelength is near this wavelength. This is the motivation for using the 488 nm output of an Ar$^+$ laser to power the sensor.

![Absorption spectrum](image)

Figure 4.10: Absorption spectrum of the resulting solution containing various concentrations of Fe$^{3+}$ (a = 1 ppm, b = 2.5 ppm, c = 5 ppm, d = 10 ppm and e = 25 ppm)

Small quantities of manganese are usually determined calorimetrically by oxidation to permanganic acid. Here an oxidizing agent like potassium periodate is used to oxidize the manganese iron. Standard potassium permanganate (Qualigens, India) solution is reduced with a little sulphite after the addition of dilute sulphuric acid (Merck, India), and the sulphur dioxide is removed by boiling. The resulting Mn$^{2+}$ solution is diluted and oxidized with potassium periodate (Qualigens, India) to give a coloured solution with absorption peaks at 526 nm and 546 nm as shown in fig 4.11.
Chapter IV: Interferometric Weight and...

Figure 4.11: Absorption spectrum of the resulting solution containing various concentrations of Mn$^{2+}$ (a = 3 ppm, b = 5 ppm, c = 7 ppm, d = 10 ppm and e = 30 ppm)

The schematic diagram of the experimental set-up used to characterize the iron sensor is shown in fig 4.12. The laser radiation at 488 nm from an Ar$^+$ laser (Spectra Physics, model 171) is coupled to the optical fiber using two mirrors M$_1$ and M$_2$ and a microscope objective having a numerical aperture 0.25. The optical fiber is fixed on a pair of x-y translators, with the unclad/microbent portion of the fiber passing through a glass cell. A laser power meter (Metrologic 545-45) is used to measure the light guided through the fiber, which in tum is connected to a PC using the GPIB (IEEE-488) card of a digital multimeter (DMM, HP-34410). Another laser power meter (Newport 1815-C) is used with the microbent fiber to measure the optical power in the cladding modes. Fig 4.13 shows the program used to continuously take the values from the DMM, which is plotted to give the graph. The front panel of the basic LabVIEW program of the DMM is shown in the fig 4.14 and its block diagram is shown in fig 4.15. It may be noted that the front panel is almost similar to the front view of the DMM. The total number of samples and the delay between each sample can be adjusted. The data is taken as a block of samples which also can be controlled.
Chapter IV: Interferometric Weight and...

Fig 4.12: Schematic of the experimental set-up for iron sensing. A—$\text{Ar}^+$ laser, $M_1$—Mirror1, $M_2$—Mirror2, L—Lens, $T_x$—X-Y translator, $T_y$—X-Y translator, C—Glass Cell, $D_1$—Detector1 (Metrologic 45-545), $D_2$—Detector2 (Newport 1815-C), $H$—Multimeter & $P$—Personal Computer

Figure 4.13: Front panel of the LabVIEW program used to continuously take readings
Figure 4.14: Front panel of the built-in LabVIEW program of the multimeter
Figure 4.15: front panel of the LabVIEW program used to continuously take readings
The schematic diagram of the experimental set-up used to characterize the manganese sensor is shown in fig 4.16. The light coming from a green He-Ne laser (JDS Uniphase) operating at 543.5 is coupled to the unclad or microbent fiber whose sensing region is in a cell containing Mn^{2+} solution. A detector (Newport 1815-C) measures the light intensity coming at the output end of the fiber.

![Figure 4.16: Schematic sketch of the experimental setup for Mn^{2+} sensing](image)

In order to make the sensor cost effective, laser is replaced with a green super bright LED whose modulating circuit is shown in the fig 4.17. The value of the variable resistance 200 KΩ determines the output frequency of the astable multivibrator, which is adjusted to oscillate at one KHz. The output of the multivibrator is given to the LED for its modulation.

![Figure 4.17: Diagram of the LED modulation circuit](image)
Chapter IV: Interferometric Weight and...

The expensive commercial detector is replaced with an inexpensive photodiode and an amplifying circuit which is shown in fig 4.18.

![Diagram of the photodetector circuit](image)

The amplifying circuit consists of two stages using low noise FET OPAMPs (LN 356); the first stage is a current to voltage converter and the second stage is a voltage amplifier.

4.2.3 Results and Discussion

Fig. 4.17 shows the variation of output power from a 12 cm unclad multimode PCS fiber for various concentrations of Fe$^{3+}$ surrounding the unclad portion. It is evident from the plot that the present device can measure even a few ppb of Fe$^{3+}$. In addition, the sensor responds in a logarithmic fashion, which makes the device to cover a large dynamic range of 4 – 5 orders of magnitude, though sacrificing its sensitivity at higher concentrations. This is not the case with conventional spectrophotometric detection where the absorbance varies linearly with concentration. Moreover, it should be noted that with a standard spectrophotometer (Jasco UV-570) the range of detection is limited with a minimum detectable concentration of 1 ppm and the maximum 25 ppm. However, according to the drinking water standards of the World Health Organization and Kerala State Pollution Control Board the permissible limit of
iron content in water is 0.3 ppm which is well below the detection limit of the spectrophotometric method.

![Variation of guided mode power in an unclad multimode plastic clad silica fiber with respect to Fe³⁺ concentration](image)

*Figure 4.19: Variation of guided mode power in an unclad multimode plastic clad silica fiber with respect to Fe³⁺ concentration*

Figs 4.20 and 4.21 shows the experimental graphs obtained with a plastic FOS whose sensing region is 6 cm long microbent portion at the middle of the fiber. Fig 4.18 corresponds to the change in core mode (guided mode) power with the variation in concentration of Fe³⁺ surrounding the bent portion of a plastic fiber. It is observed that the sensitivity of a 6 cm microbent fiber is almost same as that of a 12 cm unclad PCS fiber. This reduction in the sensing length is obviously an advantage of the former over the unclad fiber sensor.

Fig 4.21 represents the change in cladding mode power with the change in concentration of Fe³⁺ surrounding the bent portion of the fiber. Contrary to the curve obtained for guided modes, here the graph in this case is not linear throughout the range of measurements. This is similar to our earlier observation with the generic sensor using microbent fiber. The non-linearity is mainly attributed to the azimuthal anisotropy in microbending that in turn is restricted to a single plane only. But it
should be noted that this detection of cladding modes is very sensitive above 1-ppm level of $\text{Fe}^{3+}$ concentration.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{Figure4.20}
\caption{Variation of guided mode power in a microbent plastic fiber with respect to $\text{Fe}^{3+}$ concentration}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{Figure4.21}
\caption{Variation of cladding mode power in a microbent plastic fiber with respect to $\text{Fe}^{3+}$ concentration}
\end{figure}
Comparing the results obtained with the unclad PCS fiber sensor and microbent plastic fiber sensor, the latter is found to be more useful, because of the following reasons. 1) The sensing length can be reduced considerably without any loss of sensitivity, 2) it is a double detection scheme utilizing both cladding and core modes which enables a cross checking of the readings and hence the reliability of measurements is high, 3) the sensitivity of detection of cladding mode variation in ppm range is higher than the core mode power variation corresponding to both microbent and unclad fibers and 4) it uses inexpensive plastic fiber and hence is cost effective. It can be seen that both type of sensors are of the intensity modulated type and hence requires only a few optical components which will significantly reduce their cost, from the device point of view.

The response time of the present device is measured by taking the readings continuously in the block data collection mode of LabVIEW as shown in fig 22. The valleys in the graph correspond to the removal of standard solutions from the glass vessel. The response time is found to be approximately 2 minutes which is the time needed for the reading to get stabilized. Nevertheless, during our measurements we have observed that 90% of the stabilized power meter reading is reached within a relatively short time of 3 seconds.
Chapter IV: Interferometric Weight and...

Figure 4.22: Temporal response of the PCS fiber Fe$^{3+}$ sensor (a=water, b=2.5 ppb, c=air, d=10 ppb, e=25 ppb, f=100 ppb, g=250 ppb, h=1 ppm, i=2.5 ppm, j=10 ppm, k=25 ppm, l=50 ppm)

Figure 4.23: Variation of guided mode power in an unclad multimode plastic clad silica fiber with respect to Fe$^{3+}$ concentration (a=response time of 3 seconds, b=response time of 2 minutes)
Chapter IV: Interferometric Weight and...

Fig 4.23 gives a comparison between the readings taken after two minutes/three seconds of addition of the various Fe$^{3+}$ test solutions. It can be clearly seen that the response time can be considerably reduced without much sacrificing the sensitivity. Fig 4.24 & 4.25 shows the characteristic curves of the Mn$^{2+}$ sensor with a microbent fiber and an unclad fiber respectively; the source is a laser, and the detector is a power meter (Metrologic).

![Graph showing the variation of guided mode power in a microbent plastic fiber with respect to Mn$^{2+}$ concentration.]

*Figure 4.24: Variation of guided mode power in a microbent plastic fiber with respect to Mn$^{2+}$ concentration*

![Graph showing the variation of guided mode power in an unclad multimode plastic clad silica fiber with respect to Mn$^{2+}$ concentration.]

*Figure 4.25: Variation of guided mode power in an unclad multimode plastic clad silica fiber with respect to Mn$^{2+}$ concentration*
Fig 4.26 shows the characteristic curve of the sensor with an unclad fiber as the sensor head, the source is an LED, and the detector is a photodiode. Comparison of the above three figs shows that the sensor with LED and the inexpensive detector circuit is as sensitive as that obtained with the laser and expensive detector.

![Graph showing LED with PCS fiber 60 mm](image)

*Figure 4.264: Variation of guided mode power in an unclad multimode plastic clad silica fiber with respect to Mn²⁺ concentration*

**4.3. Referencing strategies for intensity modulated fiber optic sensors (IMFOS)**

Considerable amount of research has been carried out for the fabrication of myriad varieties of FOS. However, only a few of them have come to the market. One reason for this may be the restricted precision of IMFOS which are the most economic ones. In continuous analogue measurement applications of IM-FOS there is the requirement that the output from a system should be truly related to the measurand alone. In practice, this condition cannot be easily satisfied due to the variable losses within optical components such as fiber leads, optical couplers and connectors. Furthermore, additional measurement unreliability can arise from the instability of the optoelectronic components, such as optical sources and detectors. It is impossible to eliminate these variations in any optical fiber systems design but compensation may be applied by monitoring the undesirable optical signal losses. The usual approach is
to generate at least one additional (reference) signal which may then, in conjunction with the measurand signal, be used to make a relative measurement that is free from these so-called common mode variation. Both signals need be separately identified which is normally achieved by employing either spatial separation, wavelength separation, frequency separation, temporal separation or a combination of these methods [69-76].

Spatial separation is required when the optical signals have the same spectral constitution as in the case where they are generated from a single LED source used in conjunction with a Y-coupler or from two similar LED sources. In the case when each signals contained within a separate spectral band both signals can be transmitted on the same optical fiber link. The presence of spectral spacing between the signal channels enables wavelength separation by the use of simple wavelength demultiplexing elements. Temporal separation can be employed when the signals are generated from, separate optical sources by time division multiplexing (TDM). The optical signals are transmitted with separate time slots and therefore they can be separately identified from their time of arrival at the point of detection. In the frequency separation technique by frequency division multiplexing (FDM) the optical source is modulated at different frequencies. The optical signals are then separated by the use of electrical filtering of the photocurrent into the respective frequency components. An advantage of both TDM and FDM signals is that they can be allowed to propagate into the same fiber as well as enabling detection with common photodetector.

Here we propose and develop a new reference strategy that can take care of source fluctuations, by placing an index matching liquid on the cladding at a distance of 1.5 cm from the input side of the optical fiber and detecting this optical power which is used to normalize the fiber output. Light is launched into the optical fiber as both core and cladding modes and the power carried in the latter decays off very quickly. When there is source intensity variation, corresponding changes occur for core and cladding mode power. In the conventionally used IMFOS, the core mode
power at the fiber output end alone is measured and used for sensing applications. However, here we detect both core mode and cladding mode power and the former is normalized by the latter. The schematic of the experimental set-up is shown in Fig 4.27. The source used is a Ar⁺ laser operating in the current control mode so that its output power can be varied.

![Figure 4.27: D₁, detector for measuring source power, D₂, detector for measuring cladding mode power, D₃, for measuring core mode power. R, index matching liquid](image)

![Figure 4.28: Variation of cladding mode power with respect to source power](image)
The variation of the cladding mode power with respect to source power and core mode power are shown in fig 28 and fig 29 respectively. From the graphs, it is clear that the present referencing scheme can be used in various IMFOS for nullifying the effect of source fluctuations.

As first part of this chapter, development of sensors for weight and displacement measurement based on interferometry has been discussed. In the second part, fabrication of intensity modulated sensors for Fe$^{3+}$ and Mn$^{2+}$ detection in aqueous environments has been detailed. The sensors are evaluated in terms of the findings of the experimental results. Finally a new referencing strategy has been developed.
References:

52. A B Buckman, J. Lightwave Technol. 8, 1456 (1990)
57. Howard S Peavy, Donald R Rowe, George Tchobaloglous, Environmental Engineering, McGraw Hill, 1985
58. Kerala State Pollution Control Board – STANDARDS & GUIDELINES.
65. P Pulido, J M Barrero, M C Perez-Conde and C Camara, Quim. Anal. 12, 45 (1993)
66. M Feraldos, M C Moreno and C Camara, Analusis, 16, 87 (1988)

120