International Journal of Instrumentation Electrical Electronics Engineering
p- ISSN: 2321 – 0621 e- ISSN: 2321- 063X

Optical Time Domain Reflectometry Technology an efficient tool for sensors in Industrial Applications

Ravinder Gaur[1], H M Padhy[2], Pranati Mishra[3], Deepanjita Sahoo[4]
[1] Department of Science & Technology, New Delhi, [2,3,4] Sophitorium Group of Institutions, Bhubaneswar

Abstract Fiber optic sensors offer an all-passive dielectric approach that is often crucial to successful applications, inclusion the electrical isolation of patients in medicine, elimination of conductive path in high voltage environments, and compatibility within materials. The lightweight and small size of these devices is critical in such areas as aerospace and provides substantial advantages to many products. Coupled to the issue of size and weight is immunity to the electromagnetic interference. Conventional electrical sensors often require heavy shielding, significantly increasing the cost, size, and weight. Environmental ruggedness provides key opportunities for fiber optic sensors, including high-temperature operation and all solid state configurations capable of withstanding extreme vibrations and shock levels. Completing these attributes are high sensitivity and bandwidth of fiber optic sensors. When multiplexed into arrays of sensors the large bandwidth of the optical fibers themselves offer distinct advantages in their ability to transport resultant data.

1. Introduction

Fiber Optic Technology is a well known technology for the telecommunication purpose as of now. This technology has almost replaced the so called wired telecommunications technology and has given a big boom to the telecommunication network with the 2G/3G and other technologies. This revolution became a route as mass production techniques coupled with technical improvements resulted in superior performance at lower costs than those of alternative approaches. Next to this revolution emerged another one as a result of combination of the fiber optic telecommunication product outgrowths with optoelectronic devices to create fiber optic sensors. These areas of opportunities include the potential of replacing the majority of environmental sensors in existence today as well as opening up entire markets where sensors with comparable capability do not exist.

The fiber optic sensors that can be basically divided in two groups extrinsic and intrinsic fiber optic sensors. Extrinsic fiber optic sensors are distinguished by the characteristic that sensing takes place in a region outside the fiber. There are also hybrid fiber optic sensors that are similar to extrinsic ones and can be thought of as a sensors for which fiber are used to carry light to the box and back. Frequently the two terms are applied interchangeably. Intrinsic indicate that the sensing takes place within the fiber itself. It is apparent that virtually any environmental effect that can be conceived of can be converted to an optical signal to be interpreted. Fiber optic sensors offer an all-passive dielectric approach that is often crucial to successful applications, inclusion the electrical isolation of patients in medicine, elimination of conductive path in high voltage environments, and compatibility within materials. The lightweight and small size of these devices is critical in such areas as aerospace and provides substantial advantages to many products. Coupled to the issue of size and weight is immunity to the electromagnetic interference. Conventional electrical sensors often require heavy shielding, significantly increasing the cost, size, and weight. Environmental ruggedness provides key opportunities for fiber optic sensors, including high-temperature operation and all solid state configurations capable of withstanding extreme vibrations and shock levels. Completing these attributes are high sensitivity and bandwidth of fiber optic sensors. When multiplexed into arrays of sensors the large bandwidth of the optical fibers themselves offer distinct advantages in their ability to transport resultant data.

Optical Fiber as a tool for sensor

In the present work the Optical fiber technology is utilized for designing a sensor. The said technology can be utilized for the sensing of various physical parameters like temperature, pressure, strain etc.

In the present work, intrinsic distributed sensors are developed by monitoring of a single measurand at a large number of points or continuously over the path of fiber. The sensor so designed has the application areas as:

- Stress monitoring of large structures such as buildings, bridges, storage tanks etc.
- Temperature profiling along the length of the optical fiber.
- Leakage detection systems in pipelines, fault detection and diagnostics.
- Embedded sensors in composite materials for use in the real-time evaluation of stress, vibration, and temperature for different applications.

In quasi distributed sensors configuration, the measurand is not monitored continuously along the fiber path, but at a finite number of locations. This is

International Journal of Instrumentation Electrical Electronics Engineering
p- ISSN: 2321 – 0621 e- ISSN: 2321- 063X

accomplished by sensing the fiber locally to a particular field of interest or by using extrinsic (bulk) sensing elements. This type of system can be used in single-measurand monitoring applications, but it is also capable of multimeasurand monitoring by sensitizing each sensor element to specific measurand field of interest. Application areas for this form of sensors include those listed above, and various multimeasurand monitoring applications such as those found in chemical, power and manufacturing industries.

2. Theory behind the Design Fiber optic technology for sensing mechanism

Velocity of light in optical medium: The light pulse can be launched by a laser source on an optical media. This light pulse is typically at a wavelength of between about 800 to 1600 nm, in the infrared and just beyond the visible spectrum*. When this light enters the fiber, it is slowed down somewhat. The degree to which it is slowed is related to the refractive index of the fiber. The velocity of light in the fiber, v, is related to the speed of light in a vacuum, c, and the fiber refractive index through the following equation.

$$v = c/n = (3 \times 10^{+8}) / 1.5 = 2 \times 10^{+8} \text{ m/s}$$

Most optical media has a value of n between 1.5 and 1.7. Using a value of n=1.5, the velocity of light in a fiber is determined to be about $2 \times 10^{+8}$ m/s. If the fiber has a larger refractive index than the surroundings, then light within the fiber may be trapped and forced to propagate through the fiber. This occurs when the angle of incidence between the light ray within the fiber and its interface with the surroundings is less than some critical value. This is the principle of "total internal reflection" based on Snell's Law.*

Length of the Laser Pulse: The laser light pulse typically has duration of about 10 ns (nanoseconds) or less. When that pulse enters the fiber, it is said to be "launched". The length of a 10 ns pulse in the fiber, assuming that the refractive index of the fiber is 1.5, is given by multiplying the velocity of light in the fiber, c/n, times the pulse duration of 10ns.

Light pulse length in fiber = $((3. \times 10^{+8}) / 1.5)$ m/s x (10x10-9)s = 2 m

This light pulse is, in effect, a travelling sensor moving through the fiber line and relaying back temperature information (See Figure1). The length of this pulse is one factor in resolution along the fiber length.

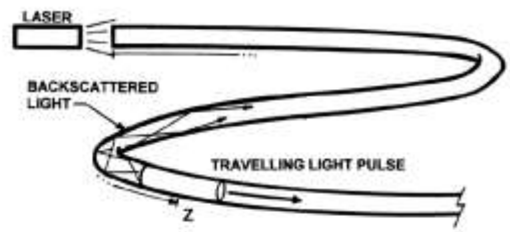

Figure1: Travelling light pulse sending backscattered light back

Travel time and distance along the fiber and detecting the backscattered signal: The refractive index of the fiber is usually well known before installation. It determines the speed of light in the fiber. When the light pulse travels to some point along the fiber, z, the backscattered light must return along that same path, and the total two-way path length for the signal is 2z. If the velocity of light in the fiber is v, a window can be opened at some time t to capture that backscattered light. The time t for this window is

$$t = 2z/v$$

The window size required to achieve a one meter length resolution along the fiber (Δz = 1m) is

$$\Delta t = 2\Delta z/v = 2 \times 1/(2 \times 10^{+8}) = 10^{-8} = 10 \text{ ns}$$

The Laser source used in the above system must be capable of providing series of laser 10 ns pulses.

Spatial and sampling resolution: In the previous section it was shown that the samples can be gathered in depth increments of one meter if the backscatter detecting windows are set for 10 ns duration. This would be called the "sampling resolution", i.e., the depth increment at which temperature data is gathered. This, however, is not the same as the depth or "spatial resolution" of a DTS system. The difference is easily illustrated by looking at the system's response to a short (.5m) temperature anomaly.

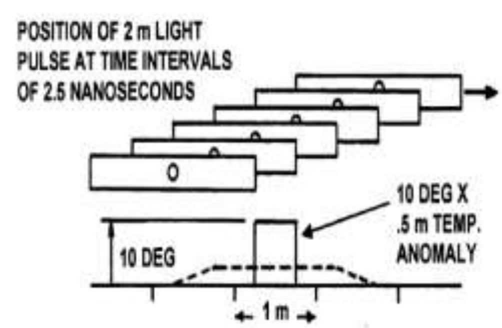

Figure 2: Response of a 2m light pulse to a .5m x 10 deg temperature anomaly

A temperature anomaly of 10 deg along .5 meter of the fiber is shown. The response from the

International Journal of Instrumentation Electrical Electronics Engineering
p- ISSN: 2321 – 0621 e- ISSN: 2321- 063X

laser pulse is seen to spread the .5 meter step in temperature over about 2.5 meters and reduce the temperature detected to about 2.5 degrees. The reduction of the temperature anomaly measured is roughly equal to the hot spot width divided by the "spatial resolution", i.e., the 2 meter length of the light pulse. Shorter laser pulses and smaller time windows are required to better detect short length high temperature anomalies.

"Spatial Resolution" is more or less defined as the distance it takes a system to fully respond to a sudden or step change in temperature. Considering the circumstances similar as stated above,the spatial resolution to a step temperature anomaly would be 2 meters.

Of course, in real world conditions, with variations in backscattered light, filtering, and electronics, the actual transition across a step would not be linear, but would follow a shape like that shown in figure below. Under such circumstances, the Spatial Resolution may be defined as the distance between the 10% and 90% points on the temperature ramp.*** This definition is not Universal and other definitions are also exist to study the issue.

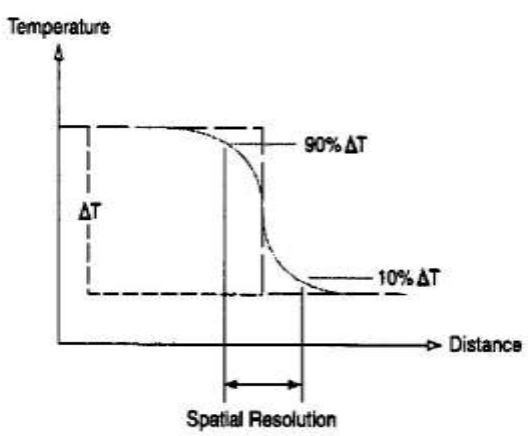

Figure 3: Backscattered Spectrum : The Rayleigh, Brillouin and Raman Spectra:

As the light pulse propagates along the fiber, it energizes the glass, lattice structure, and molecules. At first glance, the waves which return appear like reflections. They are not. The energized lattice and molecules then give off light having wavelengths at, just above, and just below the wavelength of the incident wave. The main backscattered wave is at the wavelength of the launched wave and is called the Rayleigh peak or band. This is by far the strongest signal returned. Except for certain special quality control tests, this signal is usually filtered and suppressed. Those waves associated with the lattice vibrations show up as Brillouin lines or peaks on the backscatter spectrum. The Brillouin lines are very close to and difficult to separate from the main Rayleigh band. Finally, the weakest of the backscattered waves, resulting from molecular and atomic vibrations, are the Raman Bands. The Backscatter Spectrum can be shown as below.

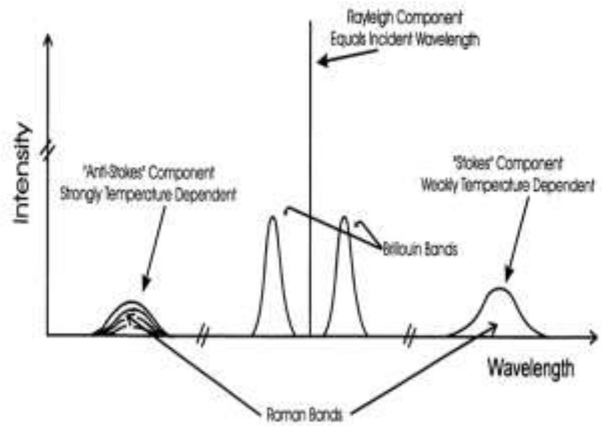

Figure 4: Backscatter spectrum with Rayleigh, Brillouin, and Raman bands as well as the Stokes and anti-Stokes bands

Temperature from the Anti Strokes/ Stroke Ratio :

The Raman signal is the signal used for evaluation of temperature. It is sufficiently strong and has a unique temperature dependence. Its wavelength is also shifted substantially (about 40/Nm) from the main Rayleigh peak, thereby allowing the dominant Rayleigh and Brillouin peaks to be filtered out.

The Raman signal is comprised of the so-called "Stokes" and "anti-Stokes" bands. The Stokes band at the higher wavelengths is stable with little temperature sensitivity. The anti-Stokes band at the lower wavelengths exhibits a temperature sensitivity, where the higher the energy within the band, the higher the temperature and vice versa. A ratio of the energy or area within the Anti-Stokes band to that of the Stokes band can be simply related to the temperature of the fiber optic line at the depth where the signal originated.

The temperature, T(z) (deg K), can be related to the ratio of anti-Stokes to Stokes signals by the equation :

$$\mathbf{T(z) = Tref\ (1+ \Delta\alpha z/ln(C+/C-) + ln(I+/I-)/ln(C+/C-))}$$

3. Experimental Set Up

Growing public concern over the environmental implications of hazardous liquid spills from pipelines and refinery storage facilities has resulted in increased government regulation in many countries. A simple sensing system capable of rapidly detecting such events would greatly reduce the potential risk and damage caused. Fiber optic sensors interrogated using optical time domain reflectometry techniques have recently been developed for these applications. The sensors are non-invasive, do not require an electrical supply at the sensing location and

International Journal of Instrumentation Electrical Electronics Engineering
p- ISSN: 2321 – 0621 e- ISSN: 2321- 063X

provide the capability of locating spill events anywhere along a sensor length that may extend to 10 km. These features offer distinct advantages over electrical point sensors where many individual points are monitored and the electrical nature of the sensors cause a risk of explosion. Using the technology explained above the experimental set up is done for the study of optical fiber as a sensor.

The sensor was interrogated using an optical time domain reflectometer (OTDR) operating at a wavelength of 850 nm. The OTDR is an instrument commonly used for optical fiber network analysis in the communications industry. It operates by sending a short high power laser pulse into the fiber and monitoring as a function of time the small amount of light that is scattered back to the detector. Knowing the propagation speed of the pulse along the fiber, the intensity of the returned light may then be displayed as a function of position along the optical fiber. The OTDR can locate many separate events on a single optical fiber, sensor as shown in the schematic of an instrument with typical trace. The OTDR can thus be used to provide a distributed measurement capability on a single sensor that may be manufactured to any desired length, the flexibility of the GRP rod allowing the sensor to be coiled onto standard storage reels. The range of the OTDR instrument and the dry attenuation of the sensor limit the maximum length that can be effectively monitored. Currently the maximum length is 2 km, although it has been estimated from analysis of OTDR theory that this can potentially be increased to 100 km or greater. This could be readily achieved with the use of a 1300 nm wavelength source and minimising the inherent attenuation of the sensor to a level equivalent to that of the optical fiber itself.

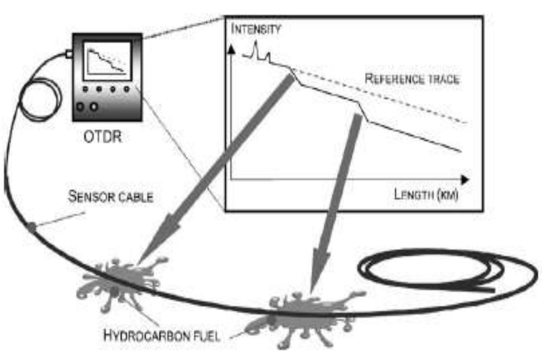

Figure 5: Experimental set up for the studies

4. Experimental results

The experimental set up designed for hydrocarbon detection was tested with various chemicals. The graphical table shows the variation of the hydrocarbon content as a function of distance. Laboratory tests were conducted on sensors using optical fiber approximately 50 cm long using the experimental set up with optical fiber and OTDR instrument operating at 850 nm.

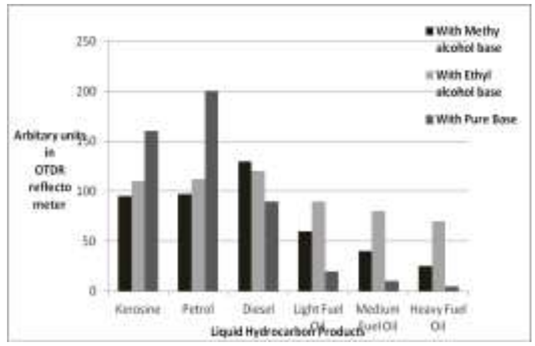

Figure 6: Arbitrary units in the OTDR reflectometer in Liquid Hydrocarbons

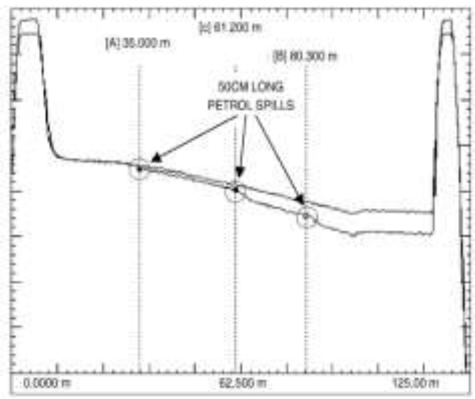

Figure 7: OTDR Trace of 3 nos of petroleum exposures along the 50 cm fiber.

5. Conclusions

A distributed fibre optic sensor with the potential to detect and locate the presence of hydrocarbon fluids over its entire length has been described. The sensor incorporates a standard optical fibre that is subject to multi sensor feature for the total length of the fiber. Evaluation was carried on several different materials as suitable for incorporation into the sensor design. It was observed that the reflectometer gives the information in regard to the distance and the kind of chemical in touch along the length of the fiber.

During extensive laboratory tests using prototype sensors, the location of three simultaneous 50 cm long gasoline exposures was demonstrated using a standard OTDR instrument. Additional testing confirmed that a variety of other fluids such as condensate and kerosene could readily be detected using the standard sensor design.

Reference

- Pranati Mishra, H.M.Padhy “Detection of liquefied and gaseous form of CO2 implementing new method in Non-

dispersive infrared spectroscopy sensor system" Global Journal of Science Frontier Research, ISSN : 0975-5896, Volume 12, Issue 2.
- Pranati Mishra, Himansu Mohan Padhy, R Sridevi and P Jagannadha Rao "ICT enabled techniques in Bio-Medical Instrumentation with simple graphic tools" Global Journal of Medical Research, ISSN : 0975-5888, Vol. 12, Issue 10.
- Pranati Mishra, Dr H M Padhy and N Suresh Kumar "Infrared rays are green energy in Medical Science helps increasing blood flow" by International Journal of Electronics Communication and Computer Engineering" ISSN:2249-071X, Volume 3, Issue 5.
- J.N. Fields, Attenuation of a parabolic index fibre with periodic bends, App. Phys. Lett. 36 (1979) 779–801.
- M.B.J. Diemeer, E.S. Trommel, Fibre optic sensors: sensitivity as a function of distortion wavelength, Opt. Lett. 9 (6) (1994) 260– 262.
- W. Michie, et al., Distributed pH and water detection using fibre optics sensors and hydrogels, J. Lightwave Technol. 13 (7) (1995) 1415–1421.
- A. MacLean, et al, Hydrogel/fibre optic sensor for Distributed Measurement of Humidity and pH Value, in: Proceedings of the Fifth Annual International Symposium on Smart Structures and Materials, San Diego, March 1998, pp. 134–144.
- Leslie A. Liu, "The Net Environmental Effects of Carbon Dioxide Reduction Policies", reportsubmitted to to the Department of Electrical Engineering and Computer Science in Requirements for the Degree of Master of science in Technology and Policy at the Massachusetts Institute of Technology, May, 1994.
- Th. Lang, H.-D.Wiemhöferand W. Göpel, Carbonate Based CO2 Sensors with High Performance, Conf.Proc.Eurosensors IX, Stockholm (S) (1995); Sensors and Actuators B, 34, 1996, 383–387.
- R. Zhou, S. Vaihinger, K.E. Geckeler and W. Göpel, Reliable CO2 Sensors Based with Silicon-based Polymers on Quartz Microbalance Transducers, Conf.Proc.Eurosensors VII, Budapest (H) (1993); Sensors and Actuators B, 18–19, 1994, 415–420.
- Airgas, Material Safety Data sheet Prepared to U.S. OSHA, CMA, ANSI and Canadian WHMIS Standards.
- SylvainHerminjard et al., "Surface Plasmon Resonance sensor showing enhanced sensitivity for CO2 detection in the mid-infrared range", Optical Society of America. 5 January 2009 / Vol. 17, No. 1 / Optics express 293.
- Theory an Operations of NDIR Sensors, Technical Note-TN169 by RAE system Inc, www.raesystem.com.
- Ernie Perkins, "Fundamental Geochemical Processes Between CO2, Water and Minerals",Alberta Innovates – Technology Futures,
- C. Gouveia et al., "Measurement of CO2 using refractometric fiber optic sensors", Advances in sensors, signals and materials, ISSN: 1792-6211,ISBN: 978-960-474-248-6.
- H. Raether, "Surface plasmons on smooth andrough surfaces and on gratings," Springer tracts in moderns physics 111, Springer, Berlin (1988).
- N. Suresh Kumar et al."Digital frequency meter using DMATerminal Count stop method", International Journal of Engineering and Technology Vol.2(2), 2010, 34-37.
- MilanProkin," DMA transfer method for wide range andfrequency measurement", IEEE transactions on instrumentation and measurement, VOL. 42, NO.4,

Biographies

	**Er. Ravinder Gaur** is Masters Degree Holder in Electronics Engineering. He is working as Scientist in the Department of Science & Technology, Govt of India. He has contributed significantly in different project work related to technology development in different thrust areas having importance for the nation . His current research interests include development of indegenous electrical instrument , microprocessor application , advanced sensor networks and optical fiber as sensor for industrial applications.
	**Dr. Himansu Mohan Padhy**, is a Ph. D. Degree holder in Electronics. Currently he is working as Professor in Sophitorium Group of Institutions, Bhubaneswar, Odisha. He is the Principal Investigator of Major Research Projects sponsored by DST, Govt of India, NRSC, Hyderabad and OSDMA, Govt of Odisha. He has published many papers in National and International journals. His area of research is optical fiber as sensors.
	**Pranati Mishra**, received her Bachelor's Degree from Berhampur University in Electronics & Instrumentation Engg in 2001 and Master's Degree in Electronics and Communication Engg from Biju Pattanaik University of Technology in 2008. Currently she is working as the Asso. Professor in Sophitorium Group of Institutions, Bhubaneswar, Odisha. She is the Principal Investigator of the R & D Projects sponsored by DST, New Delhi. She has published many papers in National and International journals. Her area of research is sensors and image processing.

International Journal of Instrumentation Electrical Electronics Engineering
p- ISSN: 2321 – 0621 e- ISSN: 2321- 063X

	**Deepanjita Sahoo**, is Master's degree holder in Physics. She is working as Research Scholar in a DST funded major project at Sophitorium Group of Institutions. She is working on optical fiber as sensors.