PERFORMANCE INVESTIGATION OF FIBER BRAGG GRATING TEMPERATURE SENSOR FOR INDUSTRIAL APPLICATION

A Dissertation Submitted in Fulfillment of the Requirement for the Award of the Degree

of

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Submitted by

Tamanna Jain

Roll No: 801661026

Supervisor

Dr. R.S.Kaler

Senior Professor, ECED

ELECTRONICS AND COMMUNICATION ENGINEERING DEPARTMENT

THAPAR INSTITUTE OF ENGINEERING AND TECHNOLOGY

(A DEEMED TO BE UNIVERSITY), PATIALA, PUNJAB

JULY, 2018

DECLARATION

I, Tamanna hereby declare that the work presented in this thesis entitled " Performance Investigation of Fiber Bragg Grating Temperature Sensor for Industrial Application" in fulfilment of the requirement for the award of degree of Master of Engineering (ECE) submitted at Electronics and Communication Engineering Department, T.I.E.T., Patiala is an authentic record of work carried out under supervision of **Dr. R.S.Kaler** (Senior Professor), Electronics and Communication Department, T.I.E.T., Patiala from July 2017 to July 2018.

The matter presented in this thesis has not been submitted either in part or full to any other university or institute for the award of any other degree.

Tamanna

Tamanna Jain

Date: 13 · August · 2018

Roll no: 801661026

It is certified that the above statement made by the candidate is correct to the best of my knowledge and belief.

Date: 13 · August · 2018

Dr. R.S.Kaler

Senior Professor, ECED

T.I.E.T. (A Deemed to be University)

Patiala, Punjab

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ABSTRACT

Monitoring the temperature in industrial applications is a crucial factor which decides the stability of the system. In high temperature industrial applications conventional sensors have not proved to be beneficial due to their malfunction around 150 degree Celsius temperature. These conventional sensors are replaced by the Fiber Bragg Grating FBG sensors due to their inherent features of EMI immunity, compact size and light in weight. In this research, we propose a model which use FBG sensor to measure temperature for industrial applications. The maximum temperature that can be sensed by this proposed sensor model is up to 900 degree Celsius and the system is stable. In this research relation between wavelength and temperature is considered and result shows FBG sensor has high sensitivity than conventional sensors. If temperature goes beyond that a particular range it will affect the stability. Some systems work for a particular temperature range and some of the system work at high temperature range. High temperature value can be detected by the sensor which can be done through optimizing the dimension of the design. In this research we have also present the result which shows how much temperature gets affect due to change in the dimension of the design. This research can be used where high temperature accurate monitoring and sensing is required. In this research work optimization of design model is also done on the basis of its dimensions.

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LIST OF ABBREVIATIONS

OF	Optical Fiber
TIR	Total internal reflection in Optical Fiber
SOF	Step Index Optical Fiber Profiles
GOF	Graded Index Optical Fiber Profiles
OT	Optical Transmitter
SMF	Single mode step index optical fiber
MMF	Multimode step index optical fiber

CHAPTER 1

INTRODUCTION

The impact of the remarkable developments done by the industries of fiber optic communications and optoelectronics led the optical sensor that is fiber-optic sensor one of the most successful technologies. The innovation of lasers in 1960's opened a new area for researchers to study the optical fibers for data communication, sensing and other applications. Charles Kao [1] who won the Nobel Prize award in 2009 was first who planned the idea of optical fiber for the communication of data and has revolutionized modern communication and optical science. As coated by C. Kao, compared with existing coaxial cable and radio systems, the fibers with glass of high purity has a larger information capacity. With improved technologies of manufacturing, nowadays light attenuation in fibers is below 0.2 dB/km is possible at a wavelength of around 1550 nm [2]. Today optical fiber material loss almost disappeared and the sensitivity for sensing is increased.

1.1 Optical Fiber

An optical fiber (OF) [3] is cylindrical waveguide of dielectric material made up from low-loss materials, commonly silicon dioxide. The core is made up of glass which is in cylindrical shape of dielectric material. Propagation of light is done along the fiber core. The fiber cladding is too in shape of cylindrical and has less refractive index than core refractive index. The cladding is of glass or plastic in material. The clad adds mechanical strength to the fiber, prevents from surface contamination and losses due to scattering is also prevented at the interface of core clad. To prevent the fiber from abrasions and damaged the fiber is coated with a plastic coating. Schematic representation of Optical Fiber is shown in Figure 1.1.

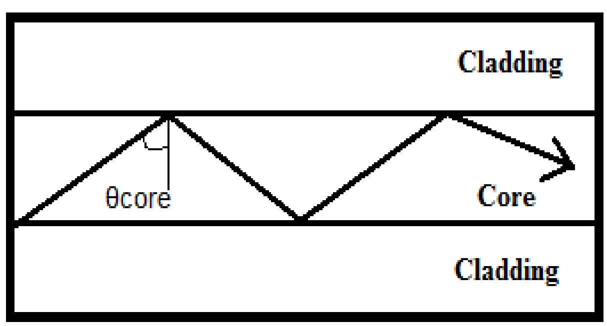


Figure 1.1: Optical Fiber (OF) [4]

Light propagates in the fiber through Total Internal Reflection (TIR) principle [3-5] and this happens as refractive index of the core is higher than the refractive index of the clad of the fiber and light propagates along the core of the fiber. Figure 1.2 shows light propagation through TIR principle (Total Internal reflection).

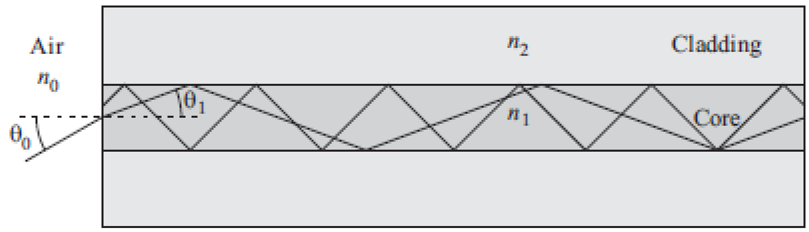


Figure 1.2: Total internal reflection (TIR) in optical fiber [5]

1.2 Basic Fiber Optical Communication System

Figure 1.3 shows a basic model of fiber optic system (FOS). The fiber optic system [4] comprises:

- For transmission along the fiber requires a function of converting electrical signal into optical form through Optical Transmitter (OT).
- Cable provides a guiding medium as it contain bundles of optical fibers.
- For transmission at a greater distance boosting of the signal is done through Optical Amplifiers.
- Optical Receivers are those elements used to convert the incoming signal into original form.

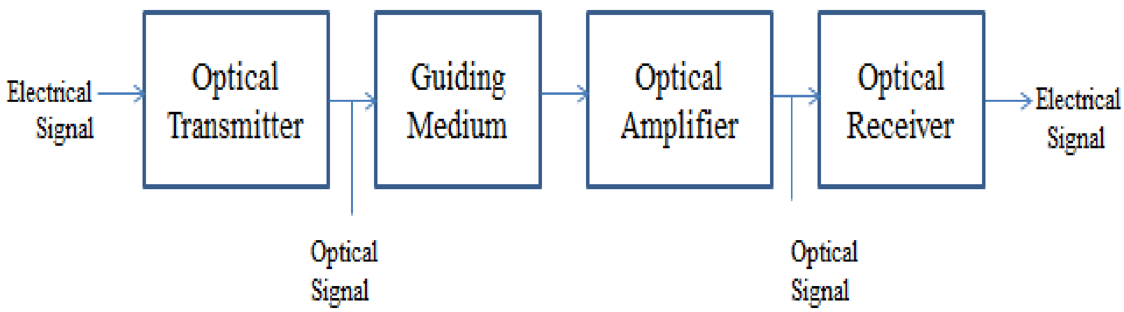


Figure 1.3: Basic Fibers Optical System (FOS)

1.3 Classification of Optical Fiber

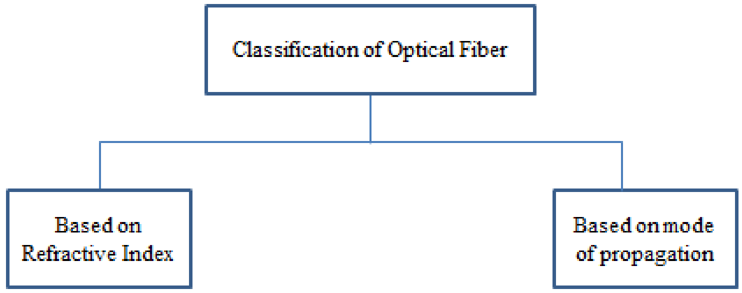


Figure 1.4: Classification of Optical Fiber

1.3.1 Based on Refractive index

1.3.1.1 Step Index Optical Fiber

Those fibers whose refractive index remains constant from core center to the interface of core-cladding, those optical fibers OF are Step Index Optical Fiber (SOF) [7]. Figure 1.5 shows that the refractive index endures the same from fiber center to the interface of core-cladding.

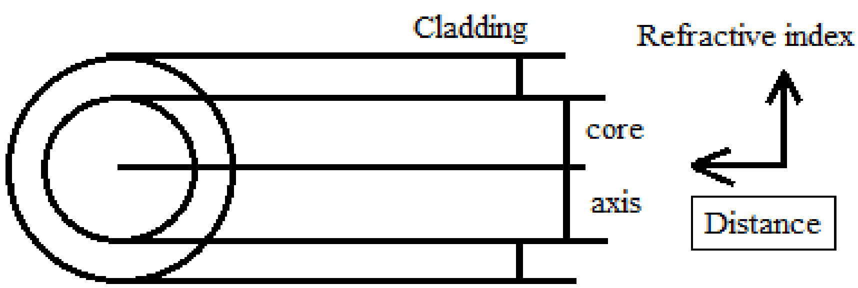


Figure 1.5: Step Index Optical Fiber (SOF) Profiles [4]

1.3.1.2 Graded Index Optical Fiber.

Fibers whose refractive index varying from the core center to the interface of core cladding, those optical fibers OF are Graded Index type Optical Fiber known as Graded Index Optical Fiber (GOF) [8]. The refractive index does not remain constant it changes according to the distance from core center to core cladding interface as shown in Figure 1.6.

GOF profile describes how refractive index changes, it attains maximum value at core center and then decreases till interface of core cladding. Graded index optical fiber helps in reducing the dispersion problem because all the light rays reached at the same time at the receiver end as speed of light rays gets slow due to maximum value of refractive index at core center of the fiber.

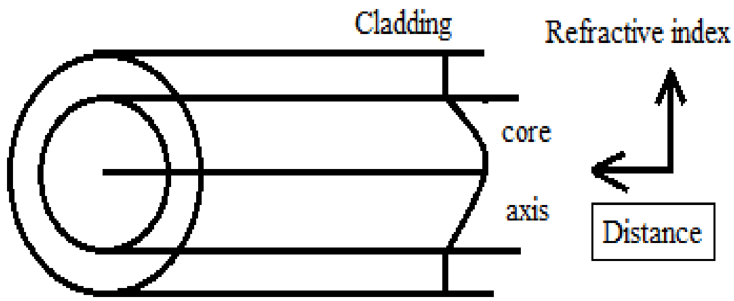


Figure 1.6: Graded Index Optical Fiber (GOF) Profiles

1.3.2 Modes of propagation based Optical Fiber

1.3.2.1 Single mode: An optical fiber whose core diameter less than 10 micrometers are single mode step index optical fiber (SMF) and it allows only one light path [8].

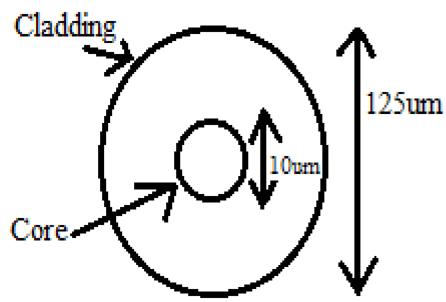


Figure 1.7: Single Mode Step Index Fibers

1.3.2.2 Multimode: An optical fiber whose core to cladding diameter ratio is greater 50 micrometers to 125 micrometers those optical fiber are multimode step index optical fiber (MMF). It leads to intermodal dispersion [8] as it carry several rays each with different angle of reflection hence each ray reached at different times at the receiver end which lead to this kind of dispersion.

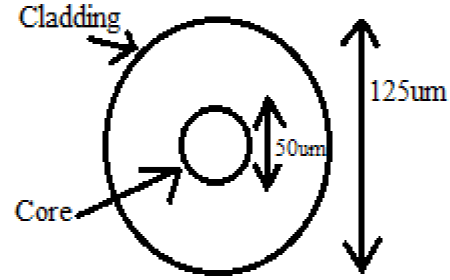
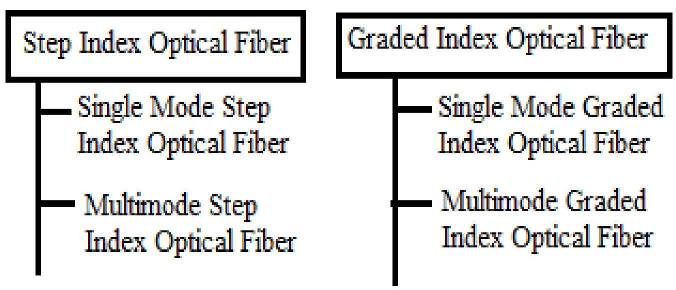


Figure 1.8 Multimode Step Index Optical Fibers

Combination of Optical Fiber: Different combinations of Optical Fiber can be formed by considering refractive index of optical fiber core and propagation modes of light rays in the optical fiber.



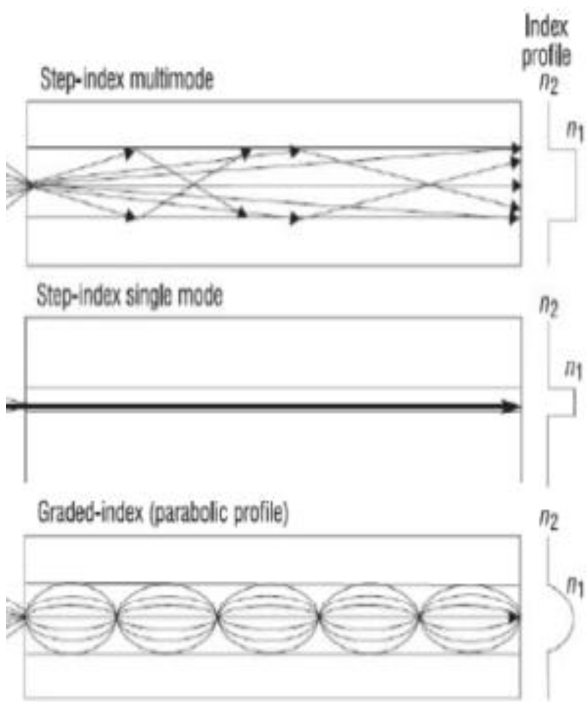


Figure 1.9: Different modes in Optical Fiber [6]

1.4 Optical Fiber Sensors

The optical fiber sensing process is multidisciplinary art based on various physical and chemical processes [9]. For sensing and recording process the main function of sensor is to convert one form of signal into another form electrical or optical to become that signal compatible for next stage to get the desired result in output. Fiber optic sensor [10] act as a transducer which performs the conversion of the measured data (parameters such as temperature, strain, stress, pressure, electrical or magnetic currents, etc.) in wavelength coded form. For detection applications sensors are able to communicate with each other through fiber or with the help of fiber channel medium.

Optical fiber sensors offer many benefits over conventional sensors [11]

- Optical sensors can be integration into a wide variety of structures, including composite materials
- Optical sensors have a small size and cylindrical geometry and it produce little interference in structure.
- Optical sensors have high resistivity and do not conduct electric current.
- Optical sensors are free from al type of electromagnetic interference and radio frequency interference. Optical sensors are very robust to sustain any harsh environments.
- Optical sensors have high sensitivity to selective parameters.
- Optical sensors offer easy multiplexing capability to form sensing networks.
- Optical sensors use wireless communication for any remote sensing application
- Optical sensors are true multifunctional and can sense simultaneously several parameters such as strain, pressure, corrosion, temperature and acoustic signals.
- Optical sensors are light weight, low cost and easy to fabricate.

1.5 Optical Fiber Sensor System

The Optical Fiber Sensor system [12] comprises of

- Optical source: It is a source which provides illumination to any fiber optic system. Laser light amplification by stimulated emission of radiation and LED light emitting diode are popular optical sources.
- Optic Fiber: Transmission is possible through optic fiber and serves as a communication medium.
- Modulator as sensing element: modulator works as a transducer and converts the measurand to an optical signal.
- Detector: Optical detector transduces optical energy into electrical signals.

- Processing electronic devices: End processing electronics are of high speed systems which provide us meaningful data. Processing devices that can be used for detection are Oscilloscope and OSA Optical Spectrum Analyzer.

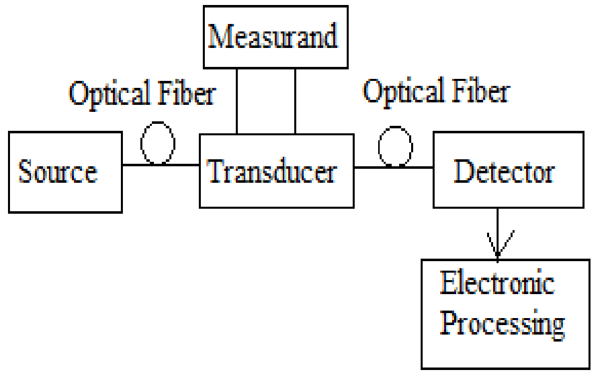


Figure 1.10: System of Optical Fiber Sensor

1.6 Classification of Fiber Optics Sensor Systems

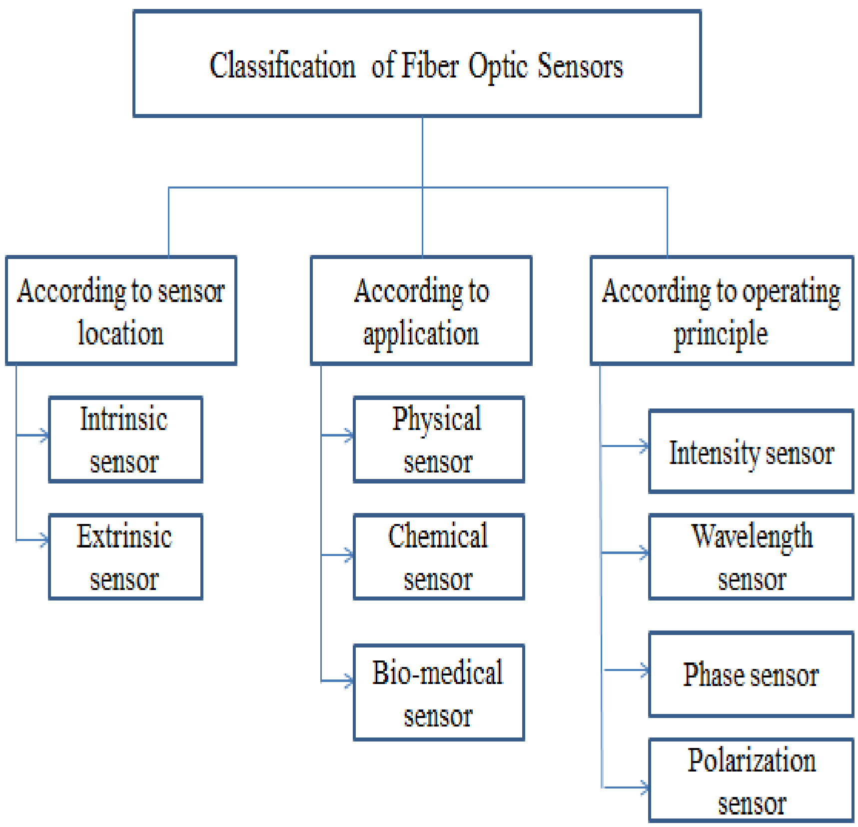


Figure 1.11: Classifications of Fiber Optics Sensor Systems

1.6.1 Based on the sensing location

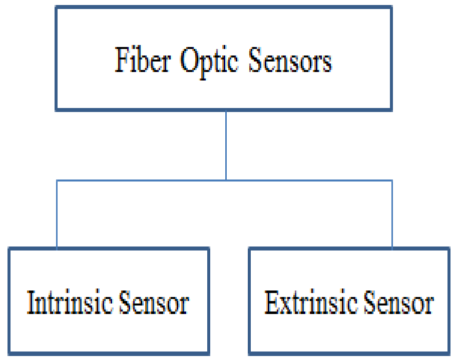


Figure 1.12: Classification on the basis of Sensing Location

1.6.1.1 Intrinsic type optical sensor: Intrinsic Fiber Optic sensor has an inherent quality that directly converts the changes occurred by environment into modulated signal. This modulated signal can be in the form of intensity, frequency, phase or polarization.

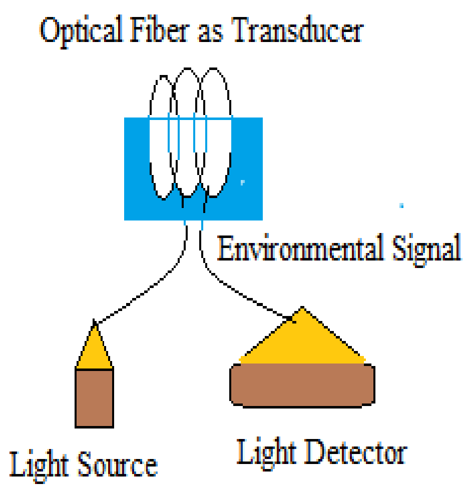


Figure 1.13: Intrinsic Optical Fiber Sensors

1.6.1.2 Extrinsic type optical sensor: In Extrinsic Optical Fiber sensor the fiber is for the transmission purpose only that is its function is to provide the signal to the sensing location. The external device may be made up of mirrors, glass or any other mechanism which only function to generate the optical signal.

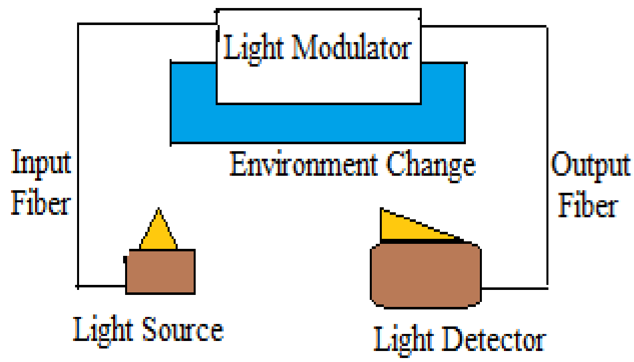


Figure 1.14: Extrinsic Optical Fiber Sensors

1.6.2 Based on the Application

An optical fiber sensor can be categorized on the application basis as:

- Physical optical fiber sensors: These sensors measures physical parameters like temperature, stress, etc.
- Chemical optical fiber sensors: These sensors provide the measurement of pH level, analysis of gas, studies of spectroscopic, etc.
- Bio-medical optical fiber sensors: These optical fiber sensors are used in the field of bio-medical for the measurement of flow, cardiac problems measurement, etc.

1.6.3 On the basis of Operating Principles

On the base of operating principle an optical fiber sensor can be categorized which depends on the process of modulation and demodulation.

These sensors are classified as

- Intensity based optical fiber sensor
- Polarization based optical fiber sensor
- Phase based optical fiber sensor
- Wavelength based optical fiber sensor

Due to the external disturbances these parameters are subject to changes producing change in its properties so by detecting the change that occurred in these parameters the external perturbations measurement is done.

1.6.3.1 Intensity based optical fiber sensor: Intensity based type of modulation is generally used as an extrinsic sensor. Light intensity can be used as a sensing parameter. Figure 1.13 [12] is a vibration sensor which basically intensity modulation type fiber optic sensor. It works on the principle of application of vibration will induce the change in the injected light in turn which used to measure the vibration amplitude.

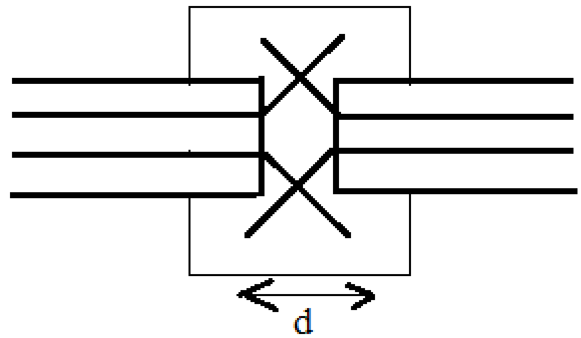


Figure1.15: Vibration based Fiber Optic Sensor

Limitations of these intensity optical sensors are connection losses at joints, splicing problem, losses due to bending of macro and micro type, mechanical creep, etc.

1.6.3.2 Polarization based optical fiber sensor: The electrical field polarization is defined by the polarization based optical fiber sensor.

Polarization optical fiber sensor can be categorized as follows:

- Linear polarization optical fiber sensor: During the propagation of the light rays, the electrical field of the rays remains in the same line of propagation.
- Elliptical polarization optical fiber sensor: The electrical field of the light ray changes at the time of propagation and take the shape of an ellipse, these optical fiber sensors are known as elliptical polarization type optical fiber sensor.
- Circular polarization optical fiber sensor: In this polarization type of optical fiber sensor the electrical field of the light ray remains at constant amplitude but its direction rotates with time at a steady rate and perpendicular to the direction of the wave that is light ray.

Figure 1.14 is a polarization optical fiber sensor: Polarization based optical fiber sensor produce change in the refractive index of the sensor which is due to the photo elastic effect. In photo elastic effect, when strain or stress is applied on the sensor it will produce a phase difference in both the direction of polarization which in turn produce change in its refractive index. By the measurement of the refractive index the external perturbation can be measured.

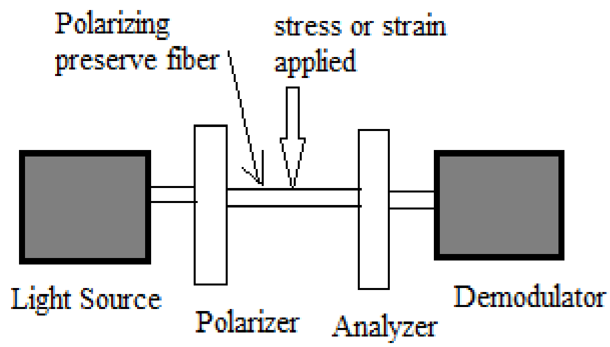


Figure 1.16: Polarization based Optical Fiber Sensor

1.6.3.3 Phase based optical fiber sensor: In phase modulated optical fiber sensor the phase of the signal is changes according to the message signal. Example of phase based optical fiber sensor is Mach Zehnder optical fiber sensor.

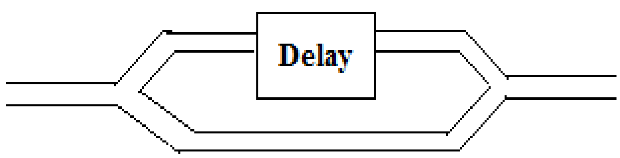


Figure 1.17 Mach Zehnder Optical Fiber Sensors

It comprises of:

- Splitter: It is a device which splits the signal into two waveguides.
- Delay block: Delay function is to maintain the path length of the fiber by introducing phase difference between the signals at the output end when they recombine.
- Combiner: Combiner act as a filter by just giving the output of those signals whose phase difference of 180 degrees. It basically recombines both the signals at the output.

1.6.3.4 Wavelength based optical fiber sensor: The measurement of humidity, strain, temperature, stress and viscosity is possible through wavelength based optical fiber sensor. These sensors produce the change in measurand signal in the wavelength coded form. Black body optical fiber sensor, Bragg Grating sensor and Fluorescent optical fiber sensor comes under the category of wavelength based optical fiber sensor.

Fluorescent Optical Fiber Sensor: Light has to be propagating till end of the beam so for this end tip sensor is used. Due to the presence of fluorescent material the light ray comes out from the end tip and this emitted light is sensed by the optical fiber and then tied up back to the demodulator.

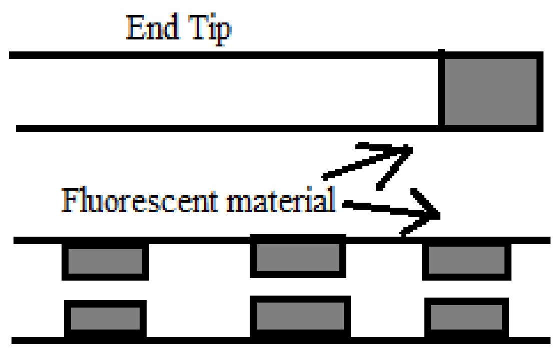


Figure 1.18: Fluorescent Optical Fiber Sensor

Blackbody Optical Fiber Sensor: Black body optical fiber sensors as shown in Figure 1.17 are used for RF field applications for temperature measurements up to few degrees Celsius. A blackbody cavity is placed at the end of the fiber. This blackbody cavity functions as a light source when temperature rises. Now this light is sensed by the detector circuitry. The detector circuitry is used along with the combinations of lens and narrow-band filters, their main function is to sense the blackbody profile curve.

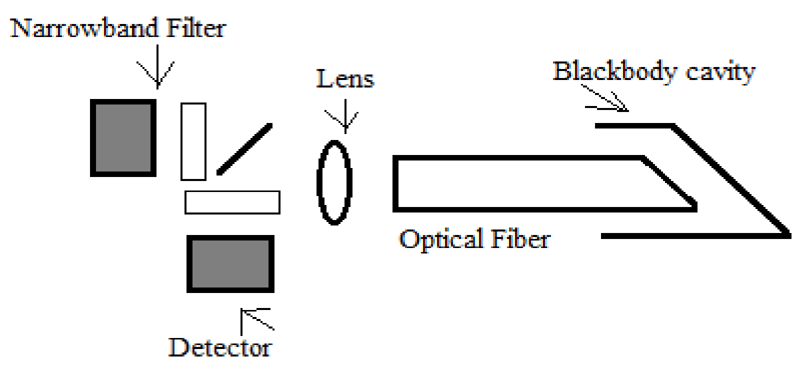


Figure 1.19 Blackbody Optical Fiber Sensors

Bragg grating sensor: Fiber Bragg gratings (FBG) [13] are framed by establishing periodic changes in core refractive index of a single mode SMF optical fiber. This periodic disturbance in refractive index is normally achieved by exposing the core of optical fiber to a concentrated interference pattern of UV rays energy. The variation in core refractive index so formed, develops an interference pattern which represents as a grating.

1.7 Fiber Gratings

For various applications, integration of optical elements (wavelength filters, partial reflectors, mirrors, etc.) to optical fibers was a challenging task in late 1970's. All these hurdles were disappeared with the invention of fiber grating. Hill [14] was the inventor of fiber grating where he observed that by optical absorption of the UV rays can altered core refractive index of SMF single mode fiber which leads to invention of Gratings.

1.7.1 Fabrication of Fiber Grating

The manufacture of Fiber gratings rely on the introducing of a periodic variant of the optical properties of the optical fiber. This may be proficient by permanently alter the refractive index of core of the optical fiber or another approach is physical buckling/deformation of the fiber [15]. The modulation of core refractive index has been achieved by bright ultraviolet (UV) irradiation, ion establishment and treatment of infrared by carbon dioxide CO2 lasers, dopants dissemination into the core, reduction of mechanical stress and lessening electrical discharges. The fiber deformation has been achieved by a mechanically, by fiber thinning or by warp of the core or cladding.

1.7.2 Photosensitivity

The photosensitivity process offers

- A novel methodology for revising the properties of flawlessness in glasses.
- It also offers a pragmatic method for engraving of enduring refractive index gratings in glass crystal fiber. Gratings are beneficial in the building of optical fiber based devices for communications in optical domain and also for sensing applications in the field of optical.

Photosensitivity [16] permits fabrication of the phase structure by allowing the modification in core refractive index of the OF optical fiber. By permanently altering the core refractive index in an occasionally periodic pattern alongside the fiber core is used to attained these phase erections or phase gratings. It functions as Bragg narrow band filter.

Parameters which define value of reflectivity in the gratings is depend on:

- Wavelength
- The period of the gratings
- The length of the gratings
- Modulation index strength

1.7.3 Transverse Holographic Technique

The photosensitivity issue was overcome by Meltz that it could be made more prominent by using one photon process [16] at a wavelength of 244nm Germania oxygen vacancy defect bands. Instead of using blue argon laser wavelength of 488nm used wavelength of the ultraviolet radiation (UV) rays of 244 nm which is one half of the blue argon laser wavelength.

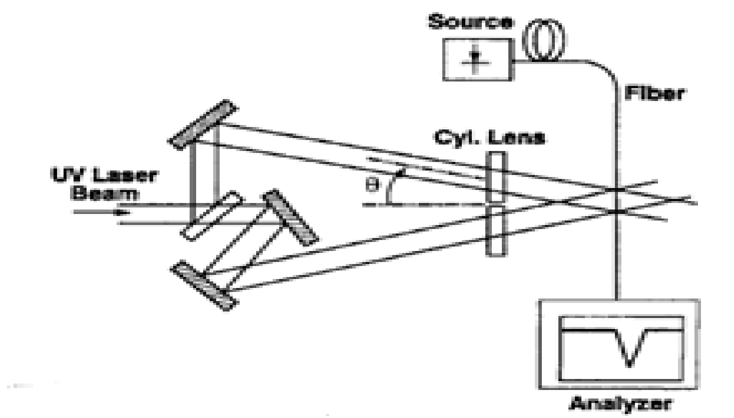


Figure 1.20: Two beam interferometer setup

The 244 nm of wavelength provides more prominent and high intensity of reflected wavelength light by the process of interfering two overlapping UV light beams in the core of the fiber which generates a periodic perturbation interference pattern which gives constant index of the modulation, this is transverse holographic technique.

1.7.4 Fiber Bragg Grating FBG Sensor

Fiber Bragg grating FBG sensor have been used in solutions of monitoring in widespread range for industrial domain such as going from health monitoring of industries to conveyance to structural/civil health monitoring level from production to gas/oil [18]. The sensor framework likewise needs the utilization of a readout unit skilled to remotely cross examine various multiplexed FBGs with highlights, for example, high affectability, speed and unwavering quality and which ought to likewise be suitable to address applications where parameters like size, weight and power utilization are intense for task. Figure 1.20 shows the schematic diagram showing Fiber Bragg grating FBG.

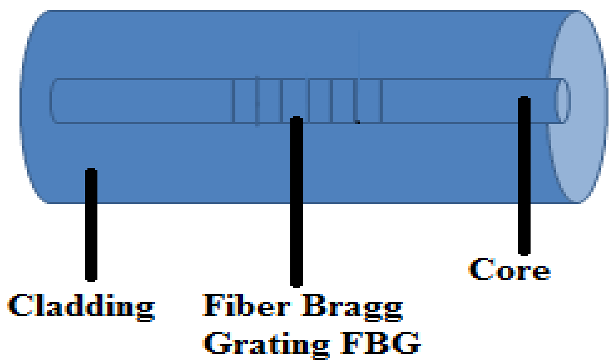


Figure 1.21: Schematic diagram showing Fiber Bragg grating FBG

1.7.4.1 Principle of operation

The basic process of the FBG Fiber Bragg grating sensor structure is to sense the shift in the wavelength of the returned reflected Bragg light signal which depends on the measurand, can be stress, temperature, viscosity, strain, pressure, vibrations, etc. and the emitted output is in the wavelength coded form.

A light source of multiple wavelengths when encountered a Bragg grating, a small portion of one wavelength is sequentially reflected while propagating through the fiber. These small reflections can interfere constructively and destructively. Those which interfere constructively produce a single wavelength at the output from the multiple wavelengths of the original light source.

In other words broadband source of light when passed through the fiber, it reflects a particular wavelength and acts as a wavelength selective mirror. Figure 1.21 shows the perturbation in the small segment of the optical fiber which acts as a distributed reflector. Distributed reflector performs the coupling of forward propagation mode to the regressive propagating mode.

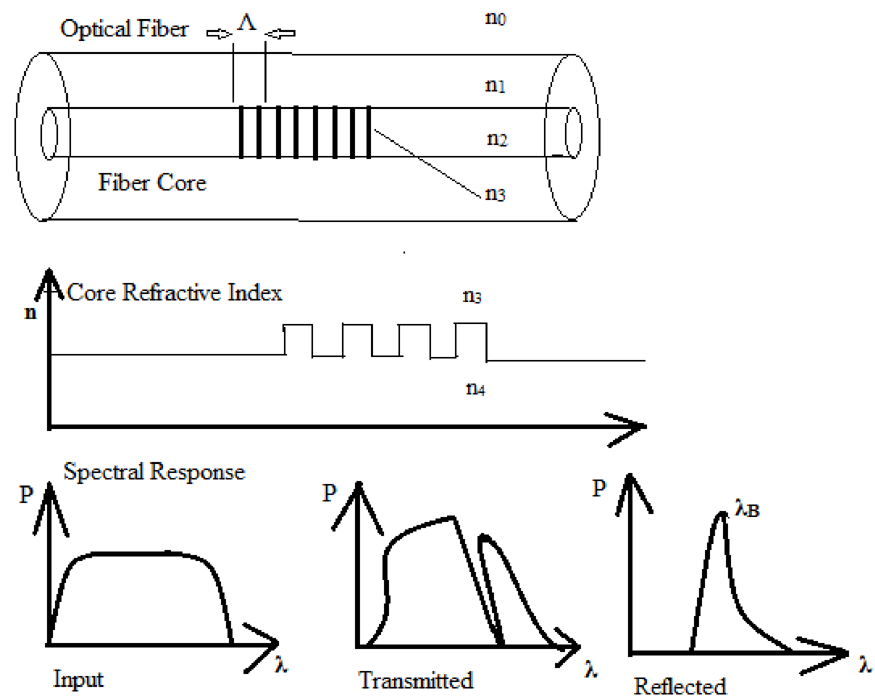


Figure 1.22 FBG Fiber Bragg Grating Sensors as a Selective Mirror

The Bragg wavelength λ_B is associated to the grating period Δ and the effective refractive index of the fiber η_{eff} by the following equation

$$\lambda_B = 2\Delta\ \eta_{eff} \qquad (1.1)$$

Equation 1 [19] describes that the Bragg wavelength is a function of the grating Period (Δ) and effective refractive index (η_{eff}) of a Fiber Bragg grating that result in a shift in the reflected wavelength.

This Bragg wavelength can be changed due to both strain and temperature and this is shown in Equation 2 [19].

$$\Delta\ \lambda_B = \lambda_B\ ((1 - \rho_e)\ \varepsilon_z + (\alpha + \eta)\ \Delta T) \qquad (1.2)$$

This shows the combined effect of both parameters on reflected Bragg wavelength where λ_B is the initial wavelength and $\Delta\ \lambda_B$ is the wavelength shift. This Equation 2 defines the effect of strain and temperature on the Bragg wavelength where ρ_e is the strain optic coefficient, ε_z is strain experienced by the grating, η is fiber thermo coefficient, α is thermo expansion coefficient and ΔT is temperature coefficient.

As FBG respond to both parameters strain and temperature, one has to account for both parameter effects and be acquainted with how to differentiate them. For measuring temperature FBG stay unstrained and this is how we can distinguish between both the affects.

For sensing temperature

$$\Delta \lambda_B = \lambda_B (\alpha + \eta) \Delta T \quad (1.3)$$

One can use package FBG sensor so that package FBG is not coupled by effects of bending, compression and tension or torsion forces.

In above Equation 3, η thermo optic coefficient is due to expansion in grating because of temperature and α thermo expansion coefficient is describes the change in refractive index. The glass expansion coefficient is negligible hence change in reflected Bragg wavelength can be defined only by modification in refractive index of the fiber.

Thermal sensitivity can be enhanced by coating the package with a material of high thermal expansion coefficient such as polymer material as shown in Figure 1.22 showing polymer on the FBG enhances its thermal sensitivity.

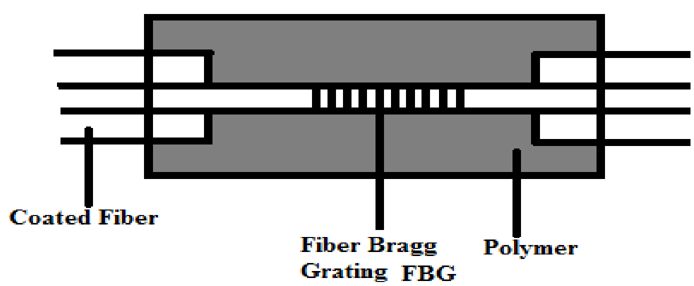


Figure 1.23: Polymer on the FBG enhances its thermal sensitivity

1.8. Applications of Fiber Bragg grating Sensor

Susceptibility to interference and transmission loss is the major challenges which was overcome by the optical fiber sensing that is through optical sensors and the best solution for that is Fiber Bragg grating sensor (FBG) and can be used in various applications.

1.8.1 FBG sensor for industries

FBG sensors are untouchable for utilize in the industries [20] because of the fortification to EMI electro-magnetic interference. In addition transmission loss in the optical fiber is low so its operation is possible for long-distance distant. With the help of Fiber Bragg Grating sensors calculations of winding temperature of power transformers, power transmission lines loading and electrical currents is possible.

1.8.2 FBG sensor for winding temperature measurement

In high voltage and high power applications knowledge of distribution of the localized temperature is must where equipment such as transformers and generators are used to understand the operation of overall process. By observing the fluctuations in the winding temperature detection of degraded and defective instruments can be identified. This periodic monitoring of winding temperature is monitored using FBG sensor. With the help of dual combo of 1550 nm FBGs, one sensor act as sensing sensor and other one as reference that is interrogated through optical spectrum analyzer for the monitoring of winding temperature.

1.8.3 FBG sensor for applications in oil and gas industry

Feature of multiplexed and distributed sensing make FBG sensor an ideal option for monitoring parameters at spatial locations in oil and gas industry. This become possible because of inherent features of FBG sensor of being intrinsically safe, immune to electromagnetic interference, multiplexing capability, working at high temperature application and invasive nature.

1.8.4 FBG sensor for monitoring pipeline

FBG sensors can be an ideal option for monitoring of temperature in the pipe and pressure at the joints as these fiber sensor refractive index is sensitive to both temperature and pressure. With the help of multiplexing methods parameters like temperature and pressure can be monitored along the length of the fiber.

1.8.5 FBG sensor for bridge

In steel and concrete structures steel based tendons are not proven to be efficient one for sensing the strain and monitoring the deformation. For this Fiber Bragg grating sensor used for optical sensing that employ carbon fiber-based compound pre-stressing tendons for achieving such a goal in the highway bridge. To achieve this goal FBG Fiber Bragg grating temperature sensor was fitted in the each iron beam that allows the rectification of thermally generated strain.

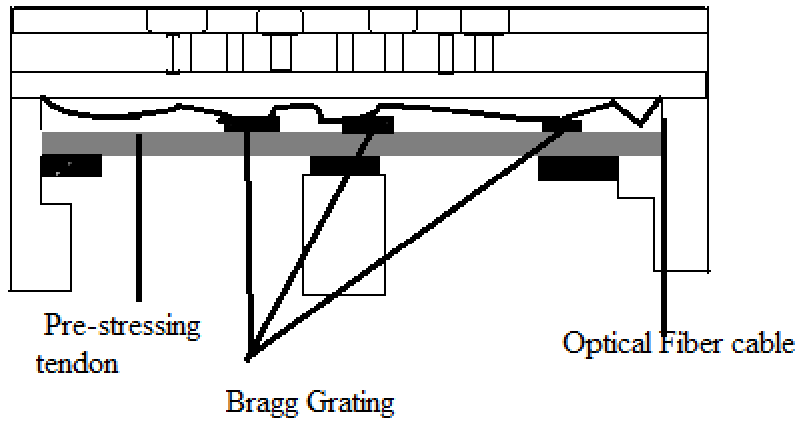


Figure 1.24: Strain monitoring of a bridge

1.8.6 FBG sensor for Aircraft

In aerospace structures advanced composite materials [21] are used because of advanced fatigue resistance, not heavy in weight, corrosion resistant, ability of obtaining complex shapes and higher strength to weight ratio in comparison with metallic materials. For improved performance and to reduce the maintenance cost FBG sensor is used along with these advanced materials in the aircraft for monitoring the service and recognizing real time health practice with on-board sensor system which is an important challenge that only be achieved with the FBG sensor. Through FBG sensor rectification of the thermal strain and static strain is possible because FBG Fiber Bragg grating sensors are profound to both strain and temperature.

1.8.7 FBG sensor for Mines

Underground excavation of coalmines and channels, it is very important to measure the load and monitor the displacement changes. For conventional electrical sensors (load cells and strain gauge) it is a challenging task as they cannot performed well on a multiplexed fashion type of system and efficiency is poor as cannot handle risky environment because of strong electromagnetic field. Multiplexed Fiber Bragg Grating sensors can work in high risky environment which is generated by excavating machinery and even with simple multiplexed fashion type of system.

1.8.8 FBG sensor for Power Transmission Lines

There is no simple assessment in the hilly areas for the monitoring of mechanical load on the power transmission line at the time of heavy snow. This shows an online measurement to monitor the alteration in load which can be possible by FBG sensor. Figure 1.22 shows the FBG sensor for measuring altering cargo on the power transmission lines. By introducing strain on load through a metal plate onto FBG is bonded and this whole is attached to the line. Multiple sensors can be placed at the spatial locations for such application.

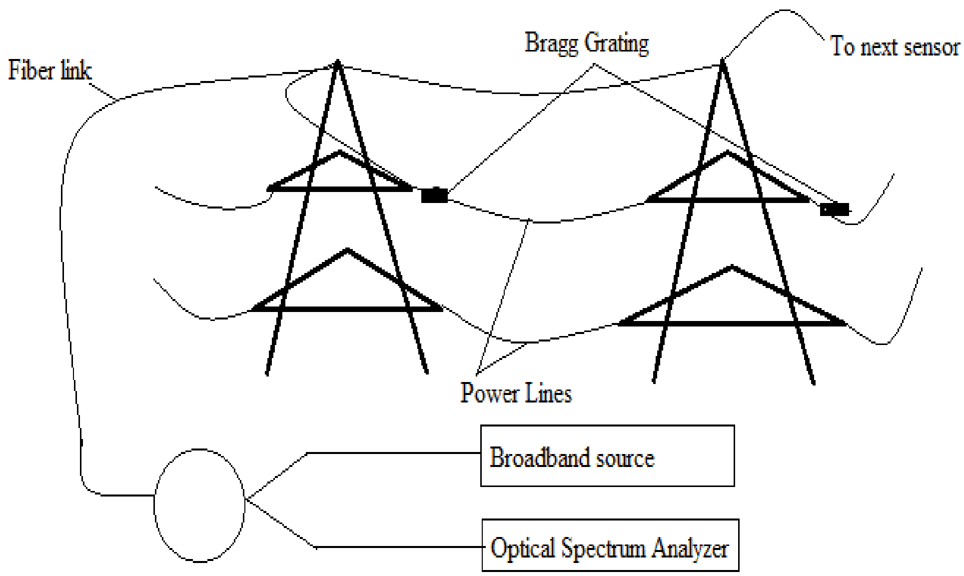


Figure 1.25: FBG sensor for measuring altering load on the power transmission lines

1.2 THESIS OUTLINE

The dissertation is divided into chapters and rest of the elements of the dissertation are organized in the following manner

CHAPTER 1

The chapter begins with the introduction of optical fiber sensors and its types on the basis of various parameters. It describe the need of FBG sensor and how it is beneficial than optical fiber sensors. It is then followed with the technique of fabrication of FBG and the application areas.

CHAPTER 2

This chapter presents the literature survey about the existing techniques for the temperature measurement. Researches done by various authors are analyzed and practice is done to achieve the desired results. Based on the researches research gaps are found and aimed to enhance the design model to obtain the desired enhanced results. In the end motivation and research objectives are defined.

CHAPTER 3

This chapter focused on the proposed methodology and presents the model of FBG sensor for the industrial applications. In this chapter simulation work is presented which shows the FBG sensor for industrial applications for different industrial temperature. Then later we have characterized this working temperature to measure the wavelength. Multiple wavelength bands are obtained which shows better they can be used for different communication applications. In the end we have showed the optimized the design on the basis of dimensions and results are presented which shows the monochromatic nature, good sensitivity and linearity of the model is also achieved.

CHAPTER 4

This chapter summarized the whole work conducted in the dissertation and in the end future aspects are defined to extend the thesis work further.

CHAPTER-2

LITERATURE SURVEY

Cristian Vendittozzi *et al.* [22] in 2018, demonstrate a model for enhancing temperature sensitivity. Simple Fiber Bragg grating sensor shows significant drop in temperature sensitivity as temperature decreases due to low thermal optic coefficient and thermal expansion coefficient (CTE). He showed that temperature sensitivity can be enhanced by coating the Fiber Bragg grating with a metal. The temperature sensitivity now depends upon material and its thickness. It takes into account the elongation in cryogenic range with temperature variations.

Francisco J *et al.* [23] in 2002, demonstrate a dual sensor model to detect humidity and temperature simultaneously using optical fiber waveguide. In this he showed a dual sensor which consists of a Fiber Bragg grating sensor along with Fabry-Perot interferometer. The Fabry-Perot interferometer is using EASM (electro static self-assembled monolayer process) to coating of different layers. A layer of coat of 85nm thickness is obtained by this method which helps in measuring highest humidity and temperature is measured through Fiber Bragg grating. In this way it simultaneously measured temperature and humidity.

B. Torres Gorroz *et al.* [24] in 2017 proposed a model by using regenerated Fiber Bragg grating optical sensor to measure the temperature in concrete structures in case of fire. He demonstrated a model in which a long beam of 5.8m long is used which contains total nine sensors in their mid-span section of the beam. Accurate placement and installation of sensors is required with proper insulation otherwise in case of concrete spalling at the site will destroy the wiring and simultaneously distort the result and even damaged the fiber optic sensor. So proper installation and precautionary measures is to be take into account for this kind of work where measurement of temperature in case of fire is done. The maximum temperature that is measured is 935 degree Celsius by FBG fiber optic sensor.

Ying-gang Liu *et al.* [25] in 2018 proposed a more convenient model for simultaneously measuring different physical quantities. His proposed model proves to a cost effective. A process of laser excimer is used to fabricate two holes at certain distance on single mode Fiber Bragg grating sensor. Now this dual micro hole fabrication make this single mode Fiber Bragg grating sensor as Fabry-Perot Fiber Bragg grating fiber interferometric sensor for simultaneously measuring liquid refraction index along with the change in temperature.

Rajini Kumar Ramalingam *et al.* [26] in 2011 demonstrate a model to measure the distribution of temperature at various insulation layers. He took four array of fibers in which through wavelength division multiplexing scheme fabrication of Fiber Bragg grating FBG sensors is done. This multilayer insulation scheme has temperature distributed which is measured through FBG sensors as they give output in wavelength coded form which is analogous to temperature distribution. Each temperature distribution in each insulated layer is different from the other this proves that insulation is not affected FBG sensor and the temperature distribution in each layer is independent. For a good quality of insulation the vacuum should be around 10^{-4} mbar or lower than that.

Aashia Rahman *et al.* [27] in 2010 proposed a model which provides the discrimination between strain and temperature. This discrimination is very much important in order to discriminate between strain and temperature measurement. Packaging FBG does not prove to be an essential method where measurement of temperature is also needed. For this he demonstrated a novel method of sensing sensor which is a Fabry-Perrot integrator which is used to measure strain and temperature simultaneously and due to different properties of grating discrimination is possible between the two physical quantities.

Dr. Shehab A. Kadhim *et al.* [28] in 2015 demonstrated a method for the measurement for strain free temperature using Optical Spectrum Analyzer (OSA). He showed the differentiation in the properties of Fiber Bragg grating sensor and Mach-Zehnder theoretically and experimentally too. It also proves that temperature sensitivity is higher in Fiber Bragg grating sensor and showed that wavelength and temperature has linear relation which is experimentally proved and sensitivity obtained from 1550nm FBG sensor is comes around 13.7pm/degree Celsius.

Noritomo Hirayama *et al.* [29] proposed a model in which he showed how sensitivity of a temperature sensor can be enhanced. For this he assembled the modeling by taking a U shaped fiber which is spliced to Fiber Bragg grating sensor which is bonded to a ceramic case. To enhance the operating temperature range polyimide coating is used and enclosed in the thermocouple housing. He presented graphs through experimentally performing this model which shows heat resistance of 230 degree centigrade and bending loss at U turn shaped side is 0.05dB and total loss of 0.9dB is obtained experimentally.

Madrakhim Zaynetdinov *et al.* [30] presented a multiplexible sensing of temperature which focused on the sensitivity of temperature at cryogenic temperature. To improve the sensitivity at cryogenic temperature is achieved by using a Fiber Bragg grating sensor with optical fiber implemented on a polytetrafloroethylene coupon. Experimentally he demonstrated this with Micron Optics interrogator which allowed 12 FBG optical sensors at a time on a single fiber. Graphs are achieves which shows for temperature range less than 285 degree Celsius has greater sensitivity better than 2.73 degree Celsius.

Joao Batista Rosolem *et al.* [31] demonstrated a water level optical fiber sensor. This work is useful in reservoirs, dams and tanks to detect the water level. In this he experimentally demonstrated where seven optical fiber sensors are installed in the tank to detect the water level with the membrane technique. It uses an elastomeric membrane is used between the fiber and water. Water pressure compressed this membrane produce a fiber bending effect in the optical fiber and this fiber bending effect is used to measure the water level.

Marlen A. Gonzalez-Reyna *et al.* [32] presented a fiber laser temperature sensor along with Mach Zehnder Interferometer (MZI). It can measure temperature changes effectively due to the narrow liner width of the laser. MZI is fabricated by splicing a photonic crystal fiber between two single mode fibers. In this temperature change produce change in refractive index and grating period of the photonic crystal fiber which in turn make MZI act as a wavelength selective filter. This used for a temperature range of 20 degree Celsius to 90 degree Celsius and observed temperature sensitivity of 18.8 ppm per degree Celsius for 1550 nm wavelength.

Diego Fernandes *et al.* [33] proposed a model showing cross sensitivity between refractive index and temperature of Fiber Bragg Grating sensor using wave optics module of Comsol Multiphysics software. He proposed a nonlinear equation showing relation between refractive index, temperature and the effective index, by calculating the Bragg wavelength we can find effective index and in turn both parameters can be measured. When applied this to a multimode Fiber Bragg grating it produce a system of equations in order to calculate temperature and refractive index for different ranges.

Feng Xiang *et al.* [34] demonstrated a model of optical fiber hydrogen sensor with enhanced sensitivity. Its principle used a composite film made up of Pd/Ni whose ratio has to be in controlled manner during sputtering process which should be around 91:0. This film is sputtered by Pd/Ni atoms and heating is induced through 980nm pump laser at one percent of hydrogen concentration. Experimental result shows its response time remains stable under different concentration of hydrogen and it is around 2 minutes.

Li Xu *et al.* [35] demonstrated a temperature insensitive optical sensor of contact force in Bidirectional Catheter. In this he used two Fiber Bragg grating FBG sensor at different arcs of the catheter but with same center wavelength. Force applied on the contact of bidirectional catheter produce bifurcation at the FBG sensors. Result shows a linear relation between bifurcation and contact force applied at the contact which is temperature insensitive. This measurement of spectral bifurcation in turn leads to the measurement of the contact force. This temperature insensitive contact sensor can be used in the medical field for implant delivery, Electrophysiology mapping (EP) and ablation procedures.

Daniela Lo Presti *et al.* [36] proposed model of using array of Fiber Bragg grating sensor for applications of vital signal monitoring. This fabrication of smart modeling is done using an array of twelve Fiber Bragg Grating sensors for monitoring parameters of respiratory such as respiratory period, respiratory rate and expiratory periods. It can also be used for measuring heart rate. Further testing is also performed to show how useful the proposed model is in medical field. The more number of FBG sensors the more will be the enhanced performance without calibration and prove best for cardio-respiratory performances.

Ning Zhang *et al.* [37] demonstrated model for steel monitoring process. He uses sputtering process to sputtered iron film on the etched Fiber Bragg grating sensor. The change in the center wavelength of the optical sensor has linear relation with the corrosion. So measurement of center wavelength of the fiber gives us the amount of corrosion occurred in iron film. Even this sensor is capable enough to measure the iron status in the corrosion process. The uneven distribution of corrosion can also be detected as it produced variation in refractive index which showed effect in center wavelength of the Fiber Bragg grating sensor.

Yufeng Zhang *et al.* [38] demonstrated a Mach Zehnder Interferometer based on suspended core fiber. He presented this optical sensor for high temperature measurements. He took a short segment of suspended core fiber and sandwiched them between single mode fibers to make this modeling of Mach Zehnder Interferometer. It shows high sensitivity up to 1000 degree Celsius where maximum sensitivity obtained is 53.87 pm/degree Celsius. This obtained sensitivity is not dependent on fiber length.

Raffaella Di Sante *et al.* [39] proposed an optical fiber sensor model for industrial applications with thermal compensation. In this he uses a thermal compensation block which is attached to the fiber and surrounded by a fluid of damping type. Due to this modeling it can easily withstand shocks and vibrations under different conditions. In the temperature range of -20 to 80 degree Celsius with a standard wavelength, the thermal sensitivity is obtained is 8.45 pm/degree Celsius and this sensor is best for harsh conditions.

Z. C. Zhuo *et al.* [40] proposed a cost effective temperature insensitive optical sensor to detect tension in the instruments used in industrial applications. In this one segment of the grating is attached to a plate (crystal plate) and other section with an etched HF acid. One of the biggest advantage is the power variation is detected by photo detector only, no need for any other demodulator or for an OSA. This can also be used to measure the intensity parameter and can be treated as intensity based temperature insensitive optical fiber sensor.

Lifang Xue *et al.* [41] designed a model to enhance temperature sensitivity of the optical fiber sensor which is based on bimetallic sheets. The two edges of this bimetallic sheets were bonded to bolts and the Fiber Bragg grating sensor is placed a longitudinally on one of the sheets and this is ensure that the thermal expansion coefficient of the sensor is larger than the other one. Excellent features like linearity, reversibility is achieved which is proved by the experimental results.

Yun Jiang Rao *et al.* [42] provide a strain free Fiber Bragg grating sensor for medical applications. This can be used for the treatment of hyper thermia. It is enclosed by a sleeve hence it is strain free temperature sensor. Temperature changes produce wavelength shift which is detected with high resolution using a drift compensation interferometric type detector. The wavelength multiplexing of cross talk free type is also achieved by multiplexing the return signals of Fiber Bragg grating sensor with a simple monochromator.

Yaofei Chen *et al.* [43] designed a model for simultaneously measurement of the dual parameters that is magnetic field and temperature. This can be possible by taking closely concatenated Fiber Bragg grating FBG with macro bending single mode fiber structures. The entire structure is coated with a magnetic fluid. Experiment result shows two dips in the transmission spectrum and both have different sensitivities which made this dual parameter measurement possible using FBG sensor.

Dandan Pang *et al.* [44] proposed a novel method of designing an optical fiber sensor for high temperature with acoustic emission sensing technology. Experimentally results showed acoustic emission type of sensor has showed more excellent features than a normal FBG Fiber Bragg grating sensor. The result shows good relationship between output response and sensing lengths. The graphs are obtained which take account parameters of sensing length, bandwidth and resonance frequency. He also achieved high speed of detection by using demodulation technique of narrow band laser.

Wolfgang Wildner *et al.* [45] presented an optical fiber temperature sensor which is fabricated by taking material combination of compound epoxy and glass particles. This combination of compound material optical sensor has excellent performance for temperature applications and achieved greater optical transmission because of this combination of materials as both the materials combinations have different thermal optic coefficients. Results are discussed which show relation between fiber sensor length and material characterization. Greater temperature sensitivity is achieved when small particle size and larger fiber sensing length is taken into account.

Shaomin Li *et al.* [46] demonstrated an optical fiber temperature sensor based on grating which showed brilliant characteristics in temperature measurement in oil/gas down-hole. In this he presented different topologies such as time division multiplexing, spatial and wavelength techniques. It also showed how this sensor can be used for multipoint sensing for sensing temperature, strain and pressure. Experiment analysis is done which shows cross sensitivity between strain and temperature and proves measurement method validity too.

Minfu Liang *et al.* [47] presented an optical temperature sensor to improve cross sensitivity of temperature with physical parameter that is pressure. He demonstrated a model which comprise of a plane diaphragm, temperature compensation Fiber Bragg grating TC-FBG sensor and pressure sensitivity Fiber Bragg grating PS-FBG sensor. He showed experimentally the relation between central wavelength shift, temperature and pressure. Due to advantage of low frequency chirp and larger stability they are best suited for complex environment applications.

Ruiya Li et al. [48] realized an optical sensor to improve the robustness of the sensor by incorporating temperature compensation block. By adjusting the diaphragm thickness excellent sensitivity is achieved. To achieved dynamic sensitivity property of diaphragm and optical sensor is taken into account and by experimentally prove that circular property of diaphragm and axial properties of optical sensor should consider for excellent sensitivity characteristics.

Guoyu Tang et al. [49] designed temperature Fiber Bragg grating sensor based on power changes of grating structure. This is used to obtain the segmental measurement of the temperature. For this a dual grating structure is used which consists of two Fiber Bragg grating sensors. The transmission spectrum achieved by second FBG sensor is power difference of two peaks. The reflected signal of second FBG is obtained from the modulation by the temperature around first FBG.

Ye Tian et al. [50] proposed a novel method for the measurement of strain and temperature which is cavity based method. To fit the shape of the cavity Gaussian function is used and overlap value decides the maximum value. This method helps to discriminate the measurements of strain and temperature which is proved experimentally. Overlap splicing method improve the strain sensitivity.

Long Jin et al. [51] presented an embedded optical sensor. This sensor simultaneously measure stress and temperature. It took a tapered polymer in which the uniform Fiber Bragg grating sensor is encapsulated so that grating gets chirped. With the help of coefficient matrix calculate the chirp and the center wavelength of the FBG sensor. By measuring the chirp and center wavelength calculation of stress and temperature is done. Experiment result shows 0.108 nm/ degree Celsius temperature sensitivity and 2.62 x 10-3 nm/N stress sensitivity.

2.2 RESEARCH GAP

1. Potential of optical sensors to provide accurate sensing with optimized results in an open area of research.
2. Effective techniques for FBG temperature sensor used in long term monitoring have to be investigated.
3. Sensitivity enhancement techniques have to be achieved for the sensing systems.
4. Designing the temperature sensor that can provide us wide wavelength bands for optical communication field to overawed the capacity limits.

2.3 METHODOLOGY

Designing of FBG temperature sensor for industrial application has been realized with the help of COMSOL Multiphysics 5.2 version software. A concise introduction allied to this software is described as follows -

COMSOL MULTIPHYSICS 5.2 defines the complete picture of our model by performing the simulation work. In this software modeling is possible of complex to complex problem. It offers wide features to provide us the overall overview of the model. Two dimension and three dimension modeling is possible in this software with different parameters settings. Study of the design can be done with various features such as time dependent study, static study, etc. Physics is also decided in the beginning of the modeling. Desktop of the software provide us a tab of model builder where you can get the overall idea of the design as it specify the geometry, material selection information, parameters that has been used, boundary conditions information, meshing and final results of the study. It actual present the modeling just the way it appears in the real time environment. It provides various windows such as model builder, graphics, setting and material selection. It also has one inherent feature for creating the applications through application builder options and the model can be linked with the application.

2.3 OBJECTIVES

1. To design optical Fiber Bragg Grating sensor for monitoring the temperature for industrial applications.
2. To characterize working temperature and measured wavelength of the designed FBG model.
3. To optimize the designed FBG model on the basis of its dimensions.

CHAPTER 3

FIBER BRAGG GRATING TEMPERATURE SENSOR FOR INDUSTRIAL APPLICATIONS

Measuring the temperature in high temperature industrial application is an important and challenging task where sensors have to withstand high temperature without destruction [52]. Nowadays, the monitoring and control of infrastructure equipment are subjects to changes and have received increasing attention. Conventional electronic sensors like thermocouple, bimetal switches etc. cannot withstand high temperature, easily pick up by electromagnetic interference (EMI) and malfunction due to overheating. That is the reason nowadays conventional sensor has been replaced by Fiber optical sensor [53].

Fiber Bragg Grating (FBG) sensor have been widely used in high temperature industrial applications. Optical fiber sensor can be produced by photo inscription the core of the optical fiber by ultra violet rays [54]. Such optical fiber sensor is known as Fiber Bragg Grating sensor. Photo engraving the core with UV radiations is a photo mask technology. It creates periodic perturbations in the refractive index of the fiber core. The refractive index of the fiber is transformed according to the intensity of light to which it is exposed, depending upon the photosensitivity of the fiber. This resulting periodic variant in the refractive index is known as thermo-optic properties of Fiber Bragg grating. FBG proves to be efficient one of the fiber-based sensor. The information sensed by FBG sensor is in the form of wavelength encoded.

In industrial applications thermal expansion has a crucial influence on reliability and expected working life of instruments to be used. To associate value of the temperature with location an accurate and reliable method is mandatory. For assessing the hot-spot temperature fiber-optic sensors (FBG) can be used to obtain temperature from any surface or internal position of the devices [55].

Thermal processes can introduce large non liner optical effects. When incident laser is passed through an optical medium, some fraction of the incident light is absorbed which lead to the origin of thermal nonlinearity. In the similar way when temperature is assigned to a material then the illuminated portion will reflect the heat in form of some parameter, can be in wavelength coded form which can be of a particular band of wavelength. This occurs because the temperature of the illuminated material consequently increases, which produce a change in the refractive index of the material [56].

Thermal expansion is an important factor in all types of high temperature industrial application where differential heating may occur either from environmental effects or from service conditions. The thermal expansion coefficient ξ will be a variable quantity depending on materials [57]. This thermal expansion coefficient has a strong correlation to optical parameters. The Bragg wavelength λ_B is related to the grating period Δ, and the effective refractive index of the fiber η_{eff} by the following equation

$$\lambda_B = 2\Delta\ \eta_{eff} \tag{3.1}$$

Where, λ_B = Bragg wavelength

Δ = grating period

η_{eff} = effective refractive index

Subjecting the fiber to a change of temperature will cause $\Delta\ \eta_{eff}$ and therefore λ to change. By determining the wavelength of the reflectivity, the temperature to which the fiber is subjected may be found [58].

The shift in the wavelength of the FGB sensor is measured from the following equation [55]

$$\Delta\lambda_B = \lambda_B\ (1+\xi)\ \Delta T. \tag{3.2}$$

Where, $\Delta\lambda_B$ = change in Bragg wavelength

λ_B= Bragg wavelength

ξ = thermo-optic coefficient

ΔT = change in Temperature

The temperature sensitivity can be improved by using an SOI interferometer sensor with waveguide Bragg reflective grating which enhance the temperature sensitivity. It was emerged as an attractive proposal as its thermal expansion coefficient has larger than grating sensor which shows in this way we can enhance the sensitivity [59]. Temperature sensitivity can be enhanced three times by using a polymer coated Fiber Bragg Grating sensor [60]. He proposed that coated Fiber Bragg Grating sensor (FBG) by using Teflon coating of 20 to 40 um of thickness.

3.1 MODELING OPTICAL FIBER BRAGG GRATING SENSOR FOR INDUSTRIAL APPLICATIONS AND MONITORING FOR DIFFERENT INDUSTRIAL TEMPERATURE

In this paper we developed a model in which domain probe points are analogous to our FBG sensor to sense the temperature at various instances and the temperature can be monitored and measure regularly in high temperature application regions. Therefore we designed the temperature sensor by adopting domain probe points using software COMSOL Multiphysics 5.2.

3.1.1 SENSOR DESIGN

A 2D model is designed using COMSOL 5.2 Multiphysics. In this model a rectangle shape slab of length 0.6m and breadth 0.2m is chosen as shown in Figure 3.1. Mainly in high temperature industrial applications various materials like aluminium, borosilicate, tungsten titanium alloy, silicon etc. are used. Among them aluminium [61] has high thermal conductivity and that is the reason we have chosen this material for our model.

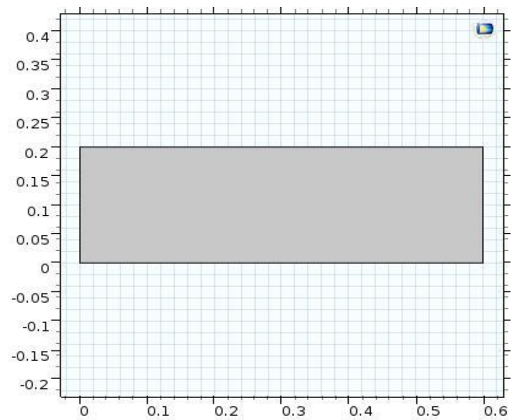


Figure 3.1: Schematic of 2D model (furnace dimensions in meters)

The temperature is assigned at one side (left hand side) of the model which is conducted throughout according to the material conductivity as shown in Figure 3.2. The blue line indicates the temperature is assigned to the model. This is done from the boundary selection tab option. The value is inserted in the T_0 block option in terms of Kelvin (K).

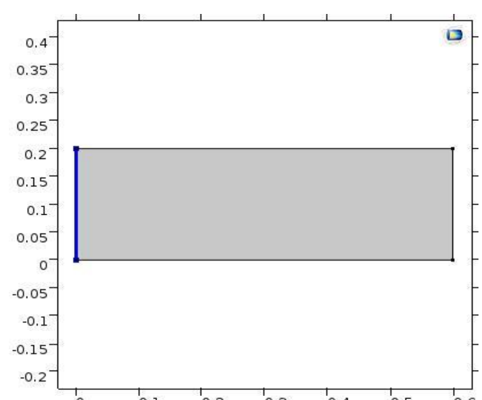


Figure 3.2: Schematic of 2D model showing temperature

3.1.2 TEMPERATURE MEASUREMENT

This is a heat transfer model in which temperature is assigned at the left side of the slab as shown in Figure 3.2. Thermal conductivity is assigned to the model according to the material. Thermal conductivity outlines the degree to which a quantified material conducts electricity. Heat flux which states flow of energy per unit of area per unit of time is also defined in the model.

3.1.3 PROBE POINT AS SENSOR

Domain probe point is selected from Definitions tab which is available in the Comsol Multiphysics 5.2. Domain probe point is analogous to FBG sensor is used to sense the temperature. The probe points are applied at arbitrary positions and temperature is sensed at various time instants as shown in Figure 3.3. These probe points are analogous to the FBG sensor. We know that change in temperature will produce change in wavelength which has linear relation.

Figure 3.3: The 2D model showing domain probe point

3.1.4 BOUNDARY CONDITIONS

In this modeling after assigning the material to the slab few parameters are set from the tab of Heat Transfer in Solids (ht). These parameters are thermal conductivity (k) in unit of W (m.K) which is set to user defined, density (ρ) in unit of kg/m^3 and heat capacity at constant pressure C_ρ in unit of J/(kg.K).

Initial value of temperature is set from the Initial value tab in the Heat Transfer in Solids physics. This is generally set at the room temperature that is 293.15 Kelvin (K).Thermal insulation is done at the necessary sides and this boundary condition defines that no heat flux is there across the boundary means the domain boundary are well insulated which is shown from equation 3.3.

$$n. (k.\nabla T) = 0 \tag{3.3}$$

Where, n = normal vector of the boundary k = thermal conductivity

∇T = temperature gradient

After this the temperature is assigned at the left most side of the slab which is denoted by T_0 external temperature to be applied. In this paper we have taken different temperature value which comes under the industrial temperature range to show the change in the range of wavelength and to know different spectrum of wavelength for different applications zone.

Heat flux tab is selected and its main function is to add heat to the domain that is to the sides of the slab which is selected from the selection list from the boundary conditions tab. Select the Inward heat flux option and enter the values of heat transfer coefficient (h) in $W/(m^2.K)$ which is by default set at 0, external temperature value in SI unit Kelvin (K). Inward Heat Flux is given by the equation

$$q_0 = h\,(T_{ext} - T) \qquad (3.4)$$

Where, q_0 = inward heat flux

h = heat transfer coefficient

T_{ext} = external temperature

T = initial temperature

Boundary heat source defines how much heat is generated within the domain. This option is also selected from the selection list tab in the boundary conditions. In this we have define the value of power source P_b in terms of Watt (W) SI unit. In this chapter general heat source Q_b is selected. This general source of heat Q_b, positive and negative value defines about heating and cooling. The positive value of heat source defines heating and the negative value defines cooling. Its default value is zero. The general heat source Q_b is defines in the SI unit of W/m^2. The overall rate of heat Q_b is defined by power per unit area (A).

$$Q_b = P_b/A \qquad (3.5)$$

Where, Q_b= general heat source

P_b = total power

A = area

3.1.5 GENERATION OF MESH

From the mesh mode setting window click on Mesh node. Then element size selection is done from the element size list. From this fine element size is clicked. To create this mesh select build all option from the toolbar window.

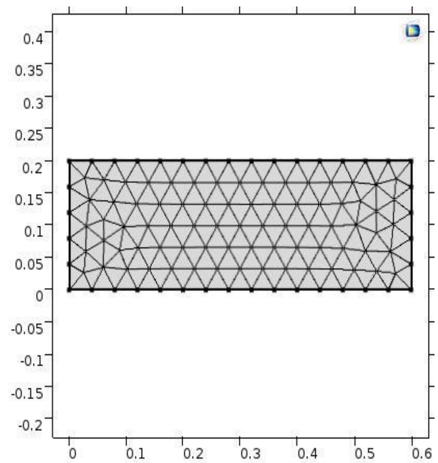


Figure 3.4: Meshing of 2D model

3.1.6 SIMULATION RESULTS

The design discussed above is simulated by utilizing Comsol Multiphysics 5.2 version. Simulation results in terms of temperature and wavelength by each FBG sensor probes at arbitrary instances are discussed in the next subsections.

3.1.6.1 Surface Plot

The heat transfer is defined by the surface plot diagram. Figure 3.5 shows the surface plot at the 300 degree Celsius temperature that shows the heat transfer along the design model. This clearly shows it has a dependent variable that is temperature (T) which means that may be changed. The maximum temperature reached at the design is 570 (K).

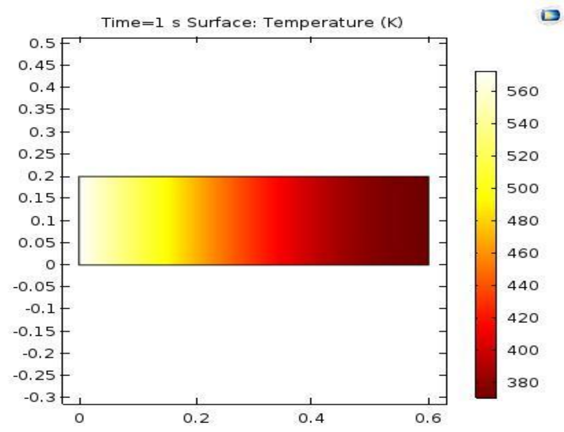


Figure 3.5: Surface Plot

3.1.6.2 Temperature versus Time plot at 300 degree Celsius

Sensor domain point probes are placed at arbitrary instances and plot the change in temperature with time. At same instance of time each probe sensed different value of temperature.

- ***Probe 1***

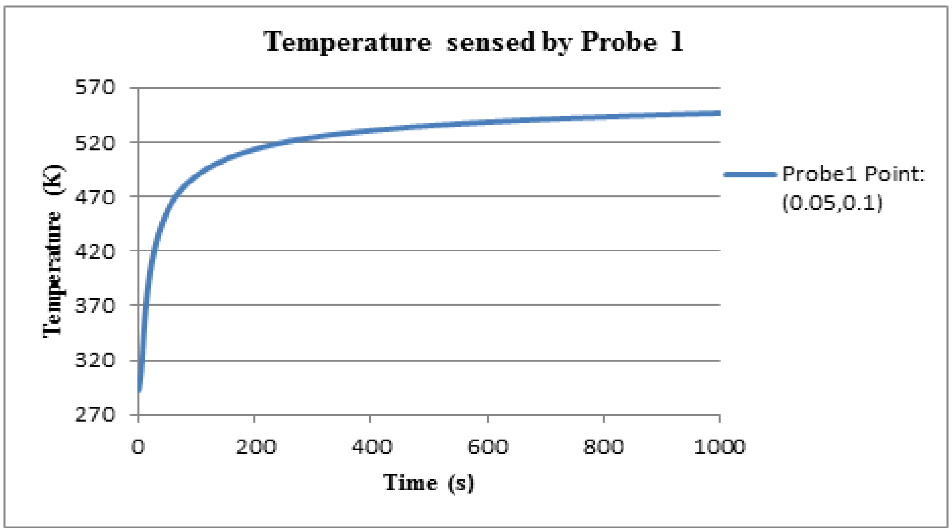


Figure 3.6: Temperature sensed by Probe1

- ***Probe 2***

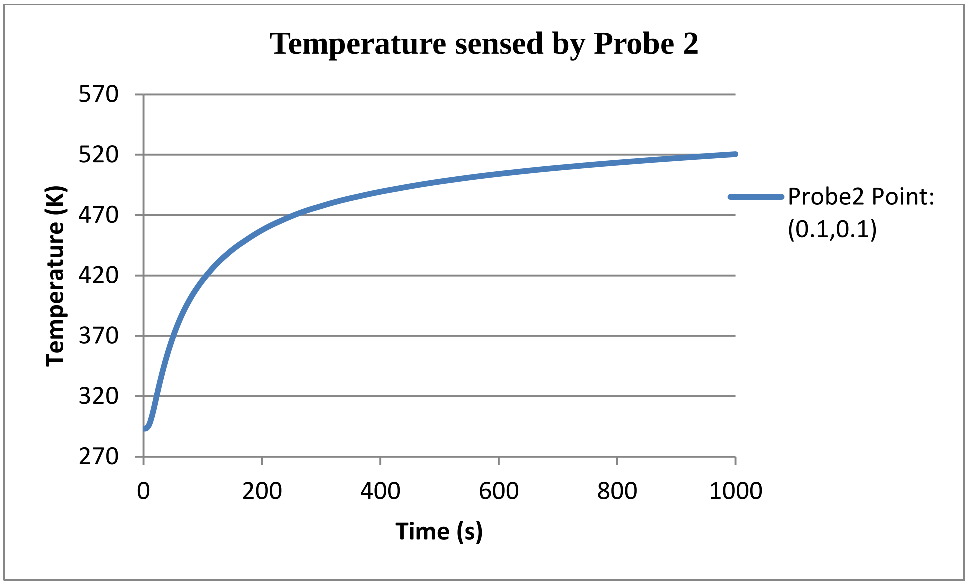


Figure 3.7: Temperature sensed by Probe 2

- ***Probe 3***

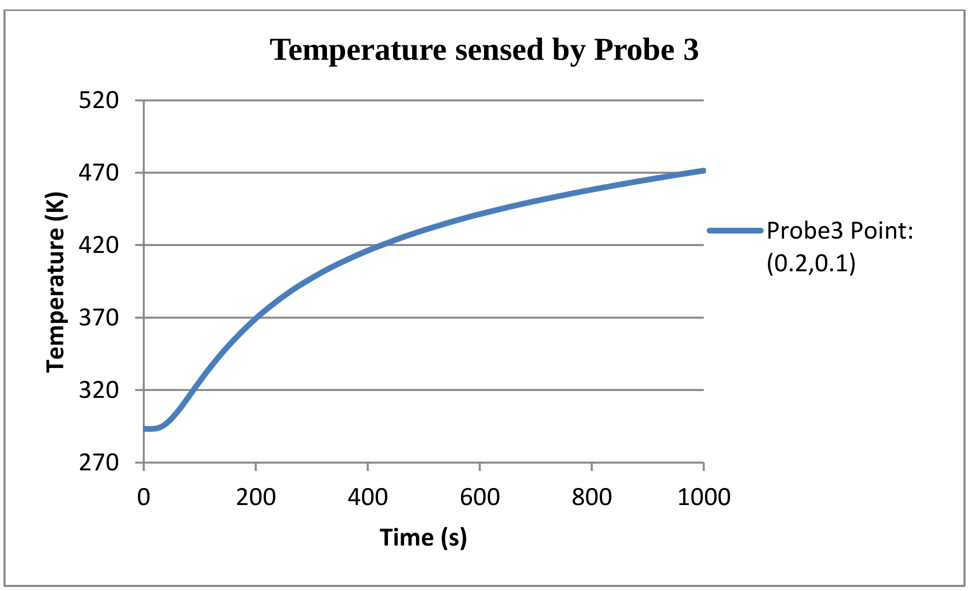


Figure 3.8: Temperature sensed by Probe3

- ***Probe 4***

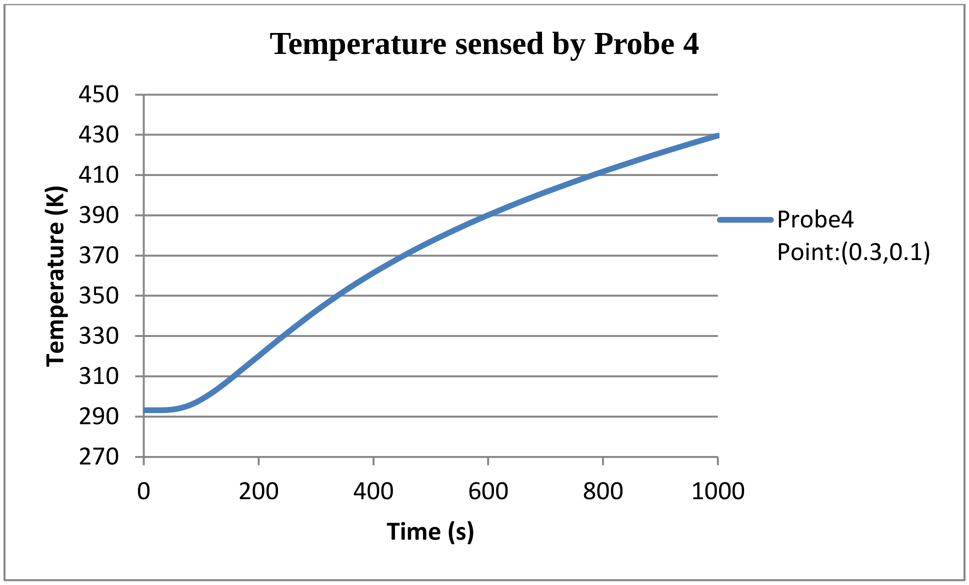


Figure 3.9: Temperature sensed by Probe4

- ***Probe 5***

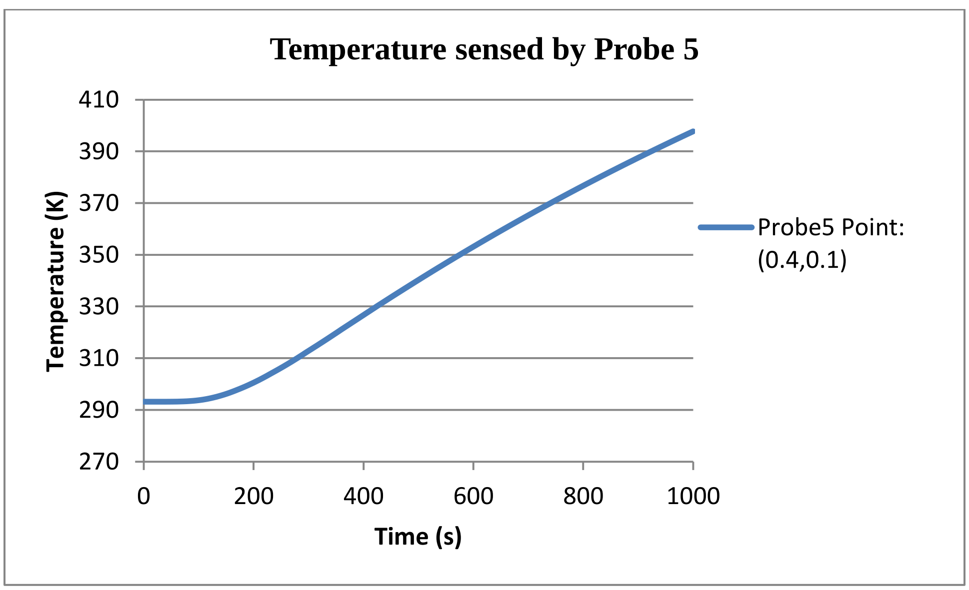


Figure 3.10: Temperature sensed by Probe5

- ***Probe 6***

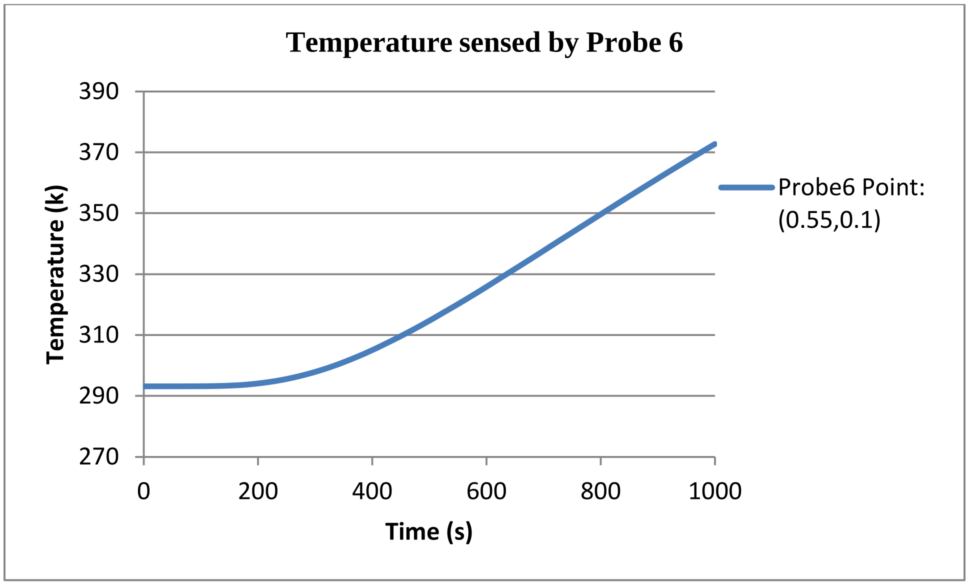


Figure 3.11: Temperature sensed by Probe6

Comparision of temperature probes by all the domain point probes has been submarized in the graph below.

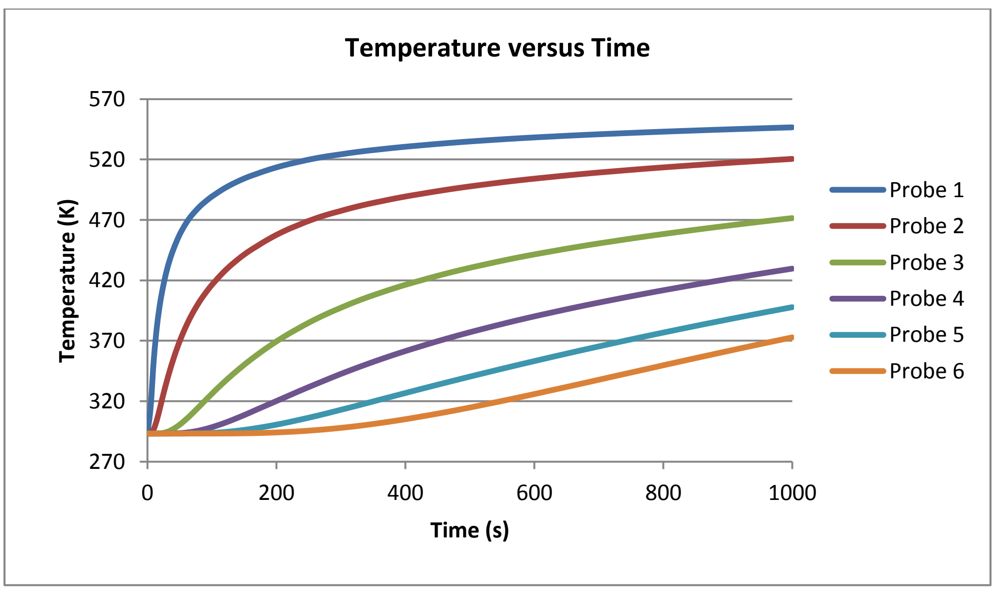


Figure 3.12: The Temperature sensed by all the probes

The combined graph of temperature by all the six probes is shown in Figure 3.12. This shows that the change in temperature is highest at the front end. As the distance increases the temperature value increases as the heat is transfered along the design. Highest temperature is achieved at the right most side and lowest temperature at left most side. This change in temperature is because of the thermal conductivity of the choosen material.

3.1.6.2.1 Wavelength versus Temperature at 300 degree Celsius

Wavelength and Temperature has linear relation which is shown by the graphs taken by domain point probes. Range of wavelength can be decided by the sensor locations.

- ***Probe 1***

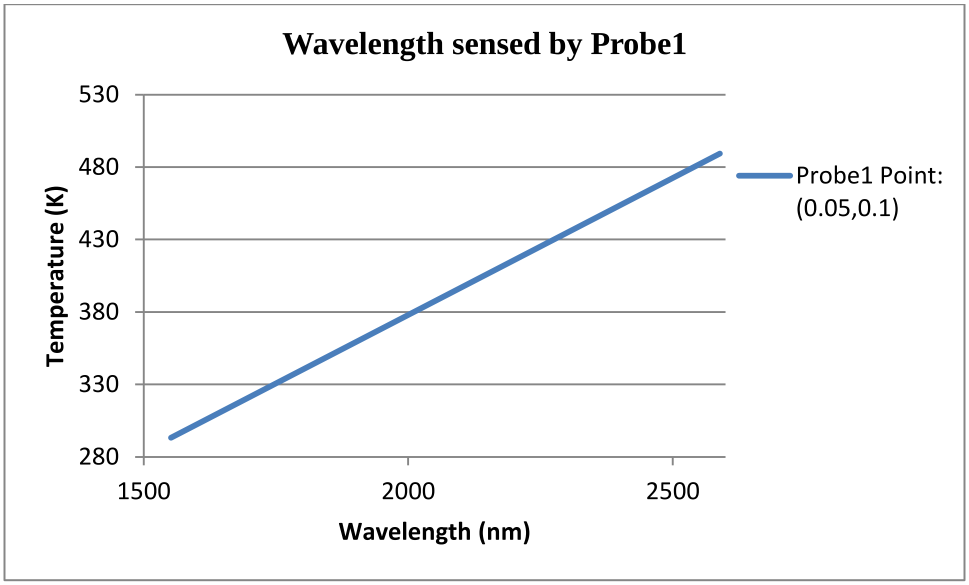


Figure 3.13: Wavelength sensed by Probe1

- ***Probe 2***

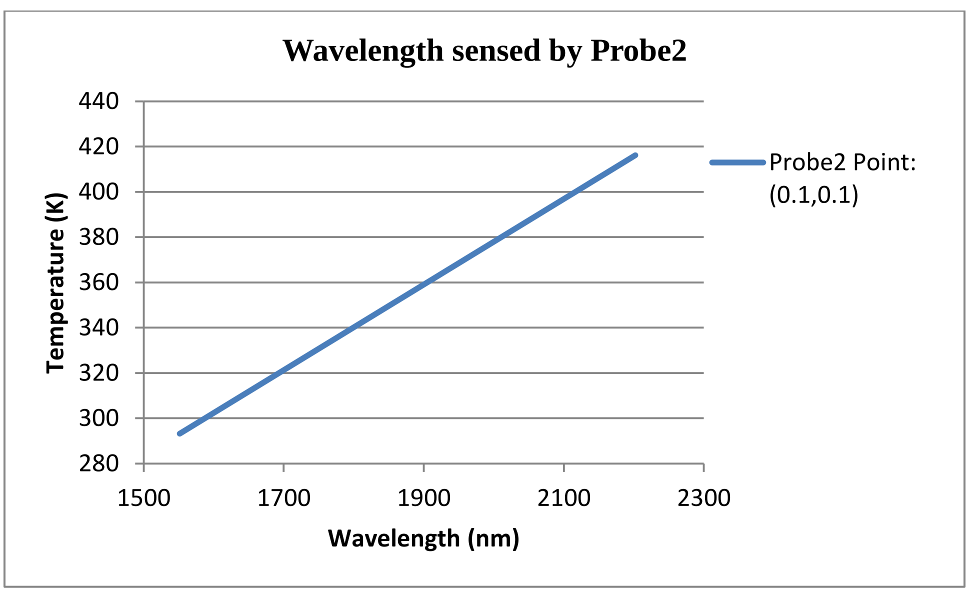


Figure 3.14: Wavelength sensed by Probe2

- ***Probe 3***

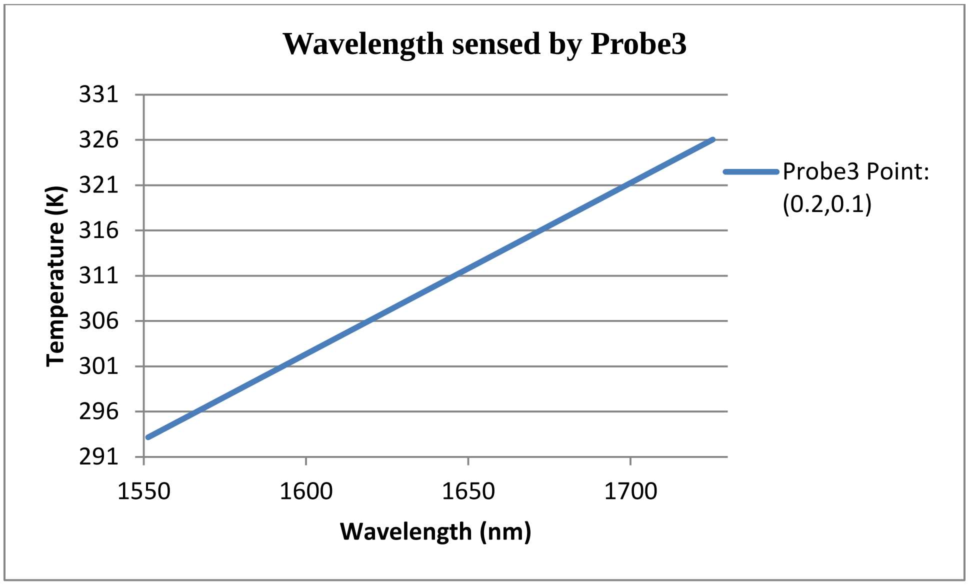


Figure 3.15: Wavelength sensed by Probe3

- ***Probe 4***

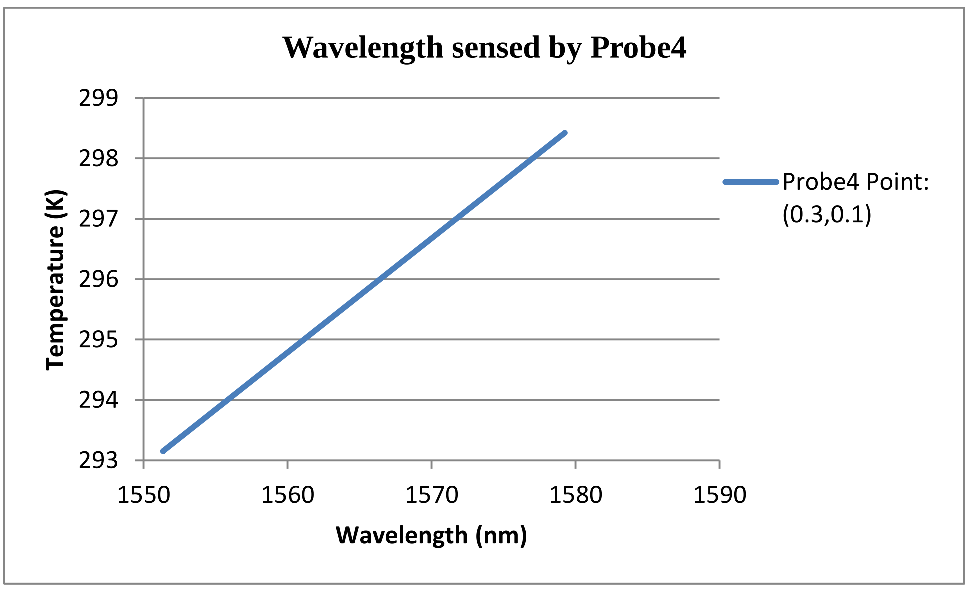


Figure 3.16: Wavelength sensed by Probe4

- ***Probe 5***

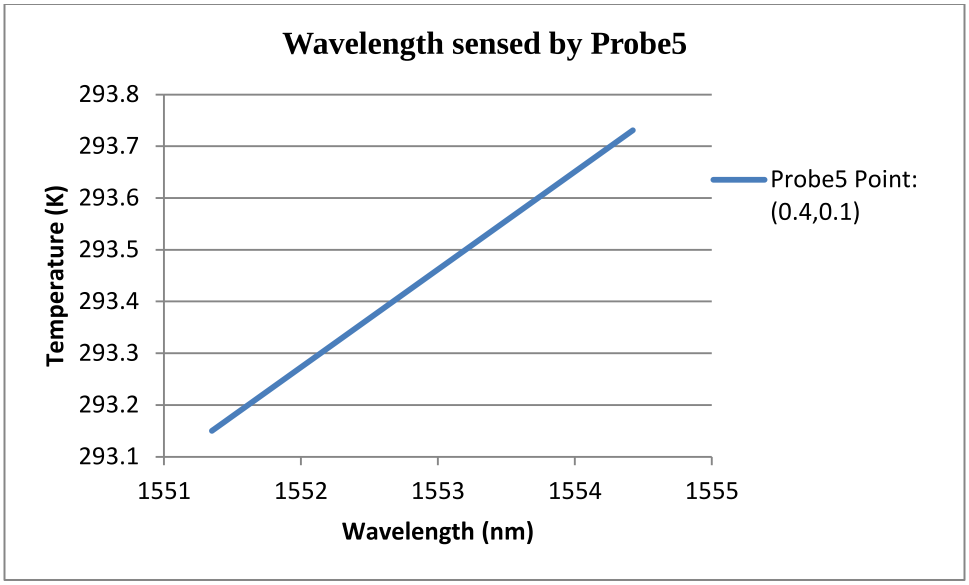


Figure 3.17: Wavelength sensed by Probe5

- ***Probe 6***

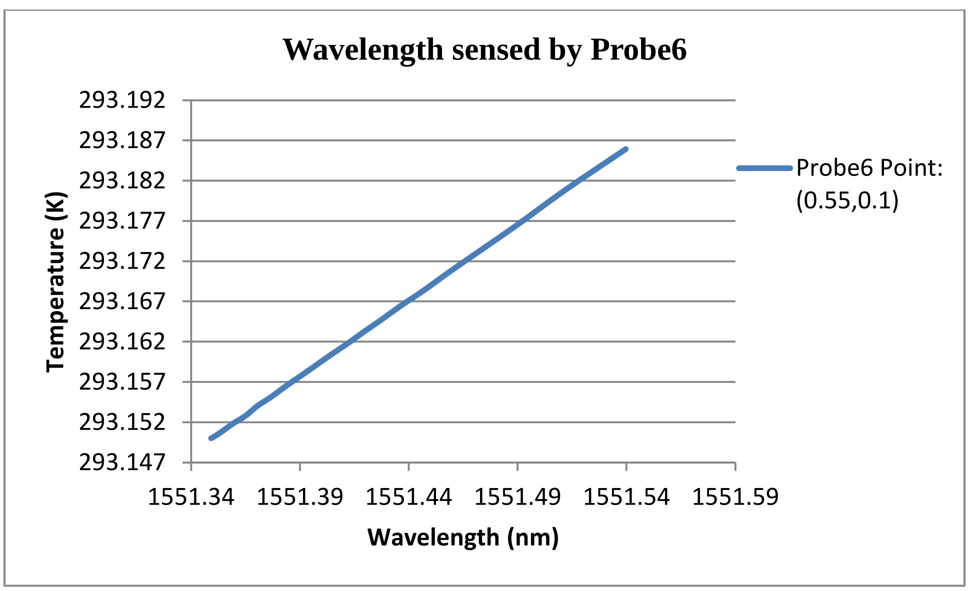


Figure 3.18: Wavelength sensed by Probe6

3.1.6.2.2 Wavelength versus Temperature of last three domain probes at 300 degree Celsius

Figure 3.19 shows the graph between Wavelengths (nm) versus Temperature (K). In this at every change in value of temperature the probe points reflect a light of a particular wavelength. As the distance increases the change in wavelength achieve is small which means after a particular temperature change it will reflect a particular wavelength. This means that at this temperature we can standardize the probe sensors. Different wavelength that is achieved provides us the sensor range.

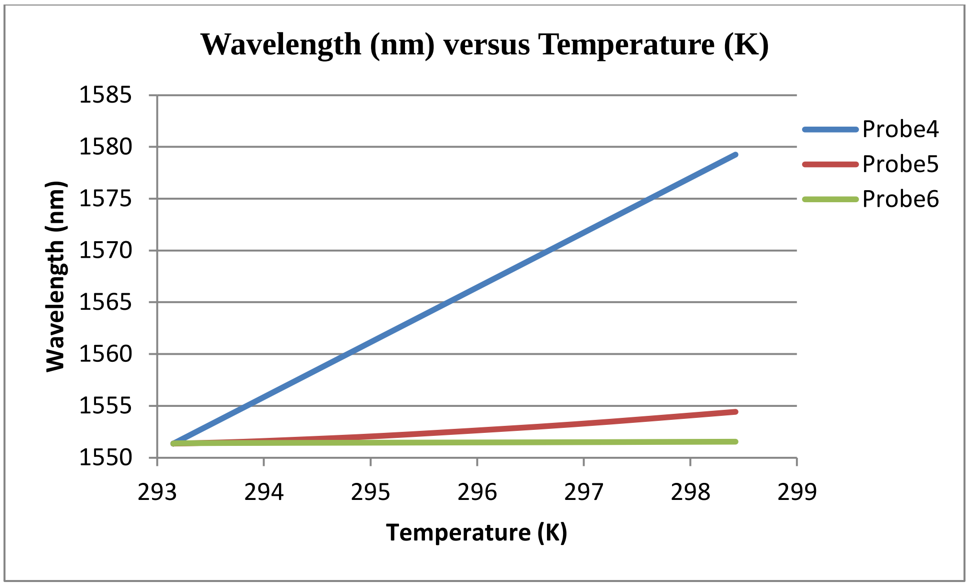


Figure 3.19: Wavelength versus Temperature of last three domain probes

3.1.6.2.3 Wavelength versus Time at 300 degree Celsius temperature

Figure 3.20 shows the wavelength versus time graph by all the domain probe points. We can have range of wavelength that can be used in different optical fiber communication fields. The dimension of domains probe points are same the only difference is in their placed locations.

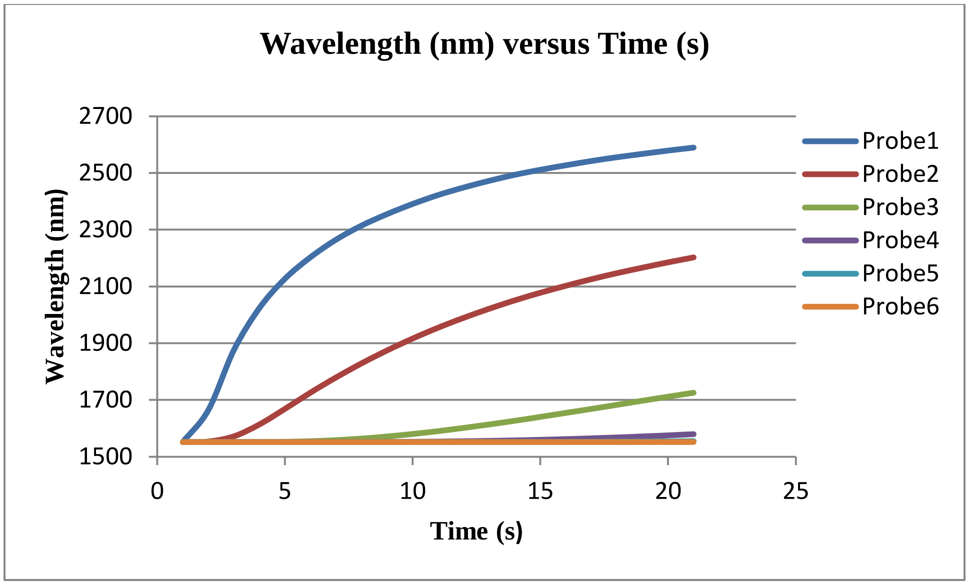


Figure 3.20: Wavelength versus Time at 300 degree Celsius temperature

CONCLUSION

Figure 3.21 shows the graph which states that we have standardized the sensor. At different location of probe points we have achieved a same wavelength. In this we have achieved a particular wavelength of 1551nm with different sensor placing locations. In a way standardization of designing is done. Monochromatic nature appears.

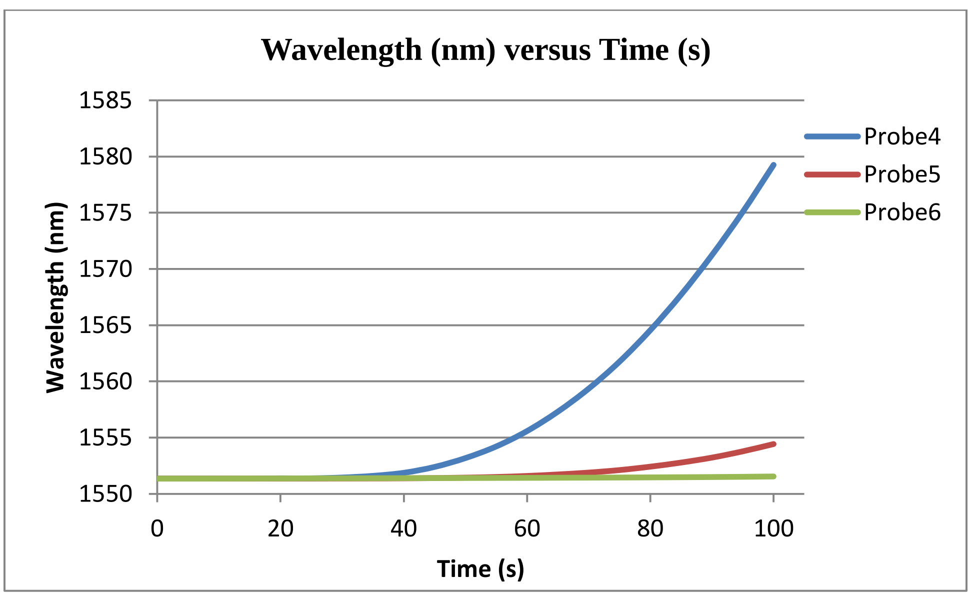


Figure 3.21: Wavelength versus Time of last three probes at 300 degree Celsius temperature

3.1.6.3 Temperature versus Time at 500 degree Celsius

- ***Probe 1***

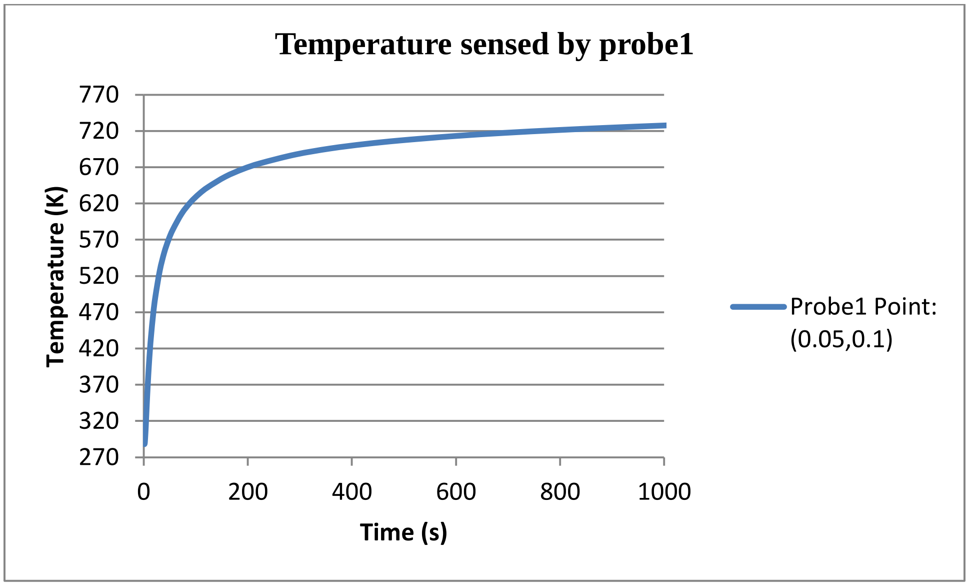


Figure 3.22: Temperature sensed by Probe1

- ***Probe 2***

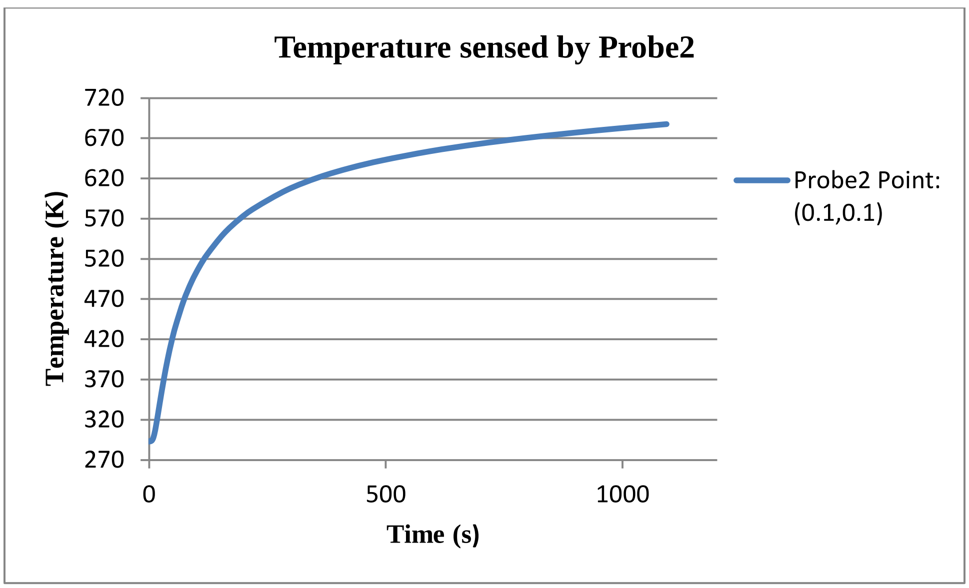


Figure 3.23: Temperature sensed by Probe2

- ***Probe 3***

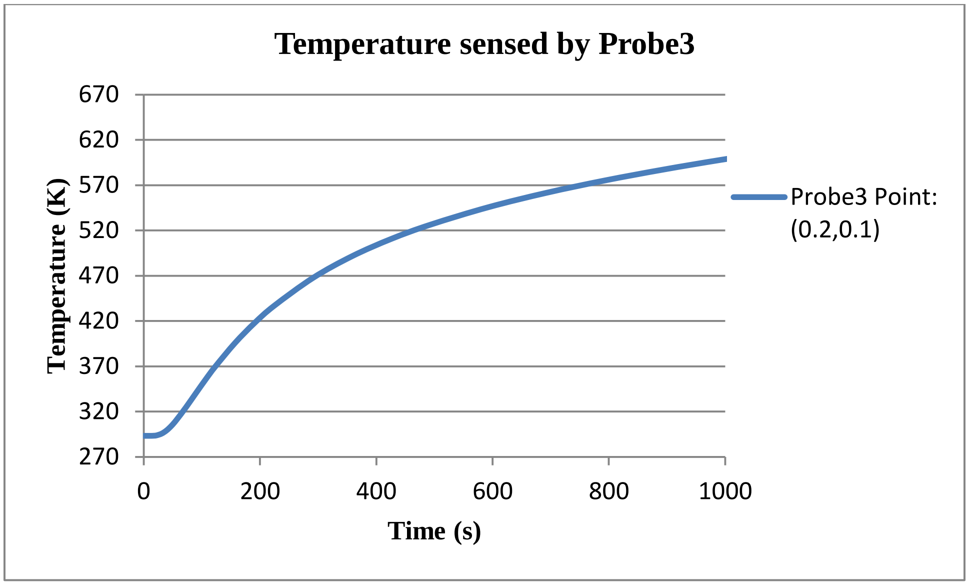


Figure 3.24: Temperature sensed by Probe3

- ***Probe 4***

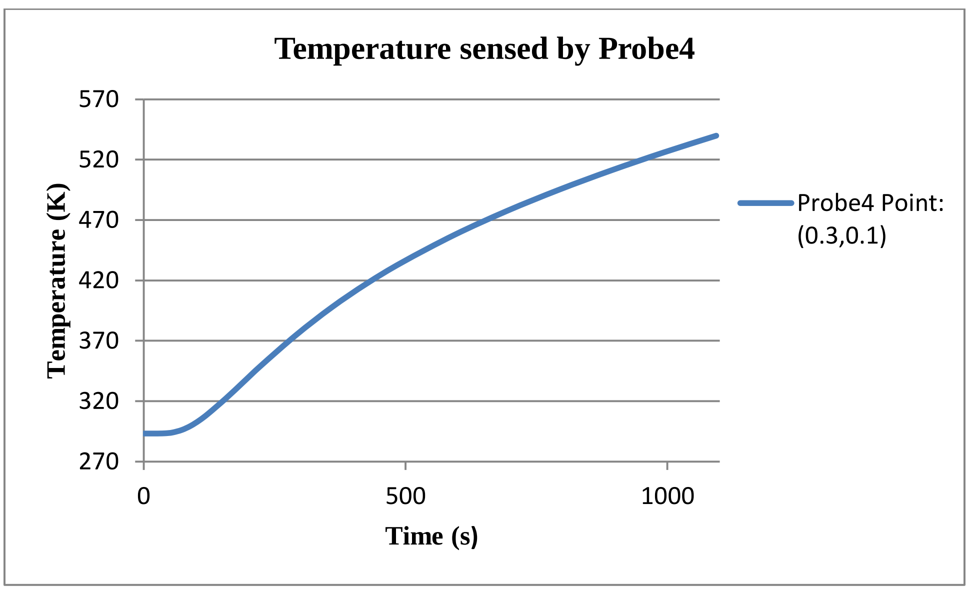


Figure 3.25: Temperature sensed by Probe4

- ***Probe 5***

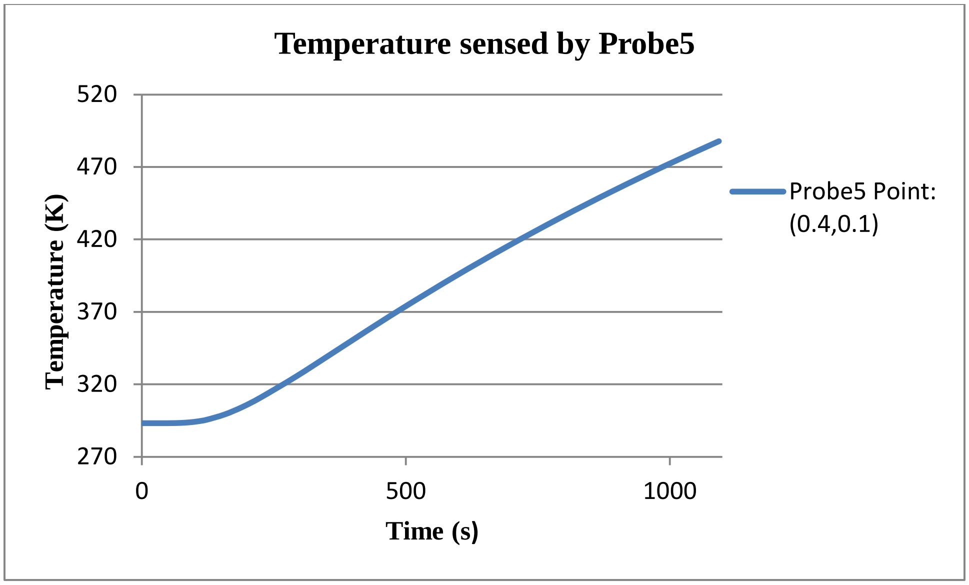


Figure 3.26: Temperature sensed by Probe5

- ***Probe 6***

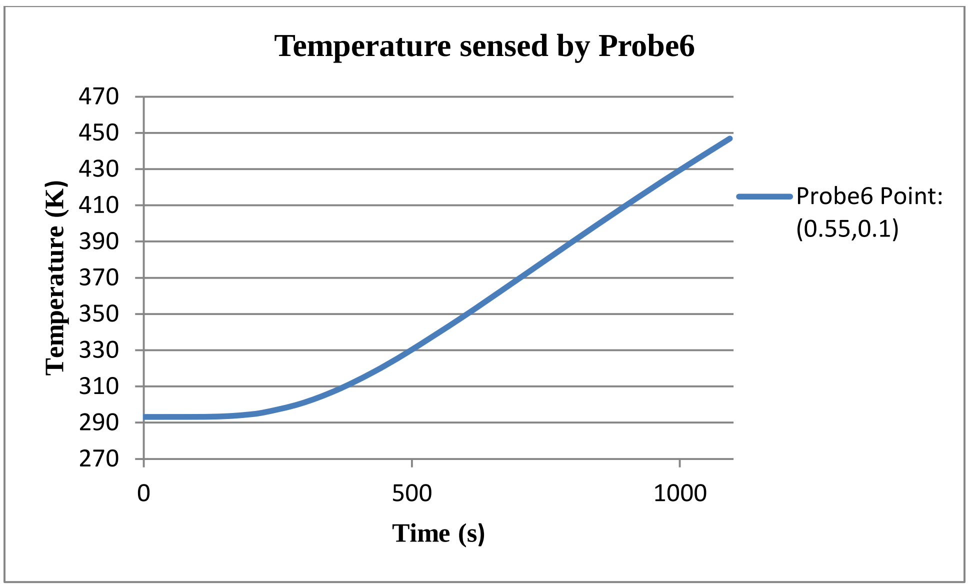


Figure 3.27: Temperature sensed by Probe6

The range of temperature is increased when the applied temperature is 500 degree Celsius at the left most side of the slab. This happens because higher the temperature applied greater will be the heat transfer along the design. Hence enhance temperature range is achieved.

Comparision of temperature probes by all the domain point probes has been submarized in the graph below.

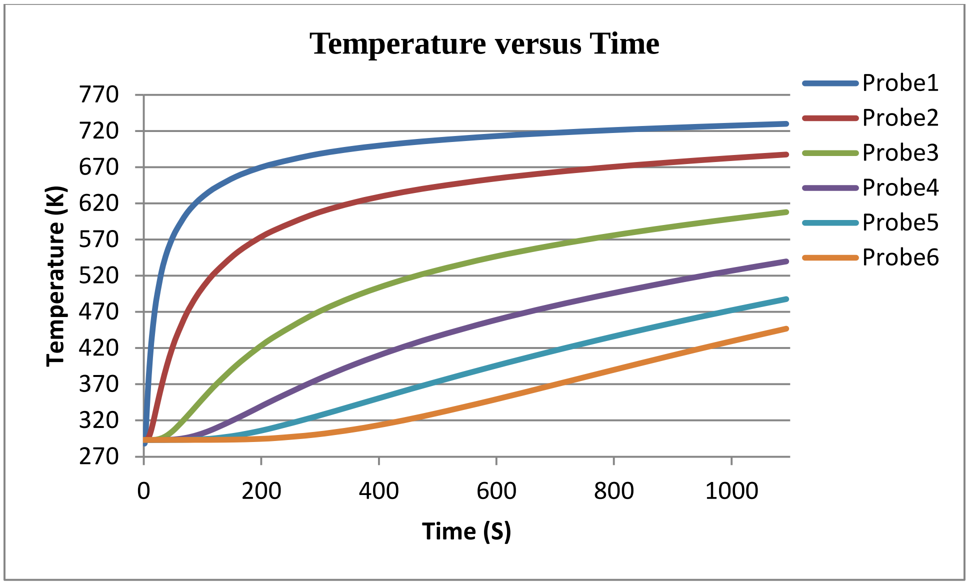


Figure 3.28: Temperature sensed by all the probes

High value of temperature is obtained with 500 degree Celsius applied temperature in comparison with 500 degree Celsius applied temperature. The range obtained is 270 degree Celsius to 770 degree Celsius.

3.1.6.3.1 Wavelength versus Temperature at 500 degree Celsius

Wavelength and Temperature has linear relation which is shown by the graphs taken by domain point probes. Range of wavelength can be decided by the sensor locations.

- ***Probe 1***

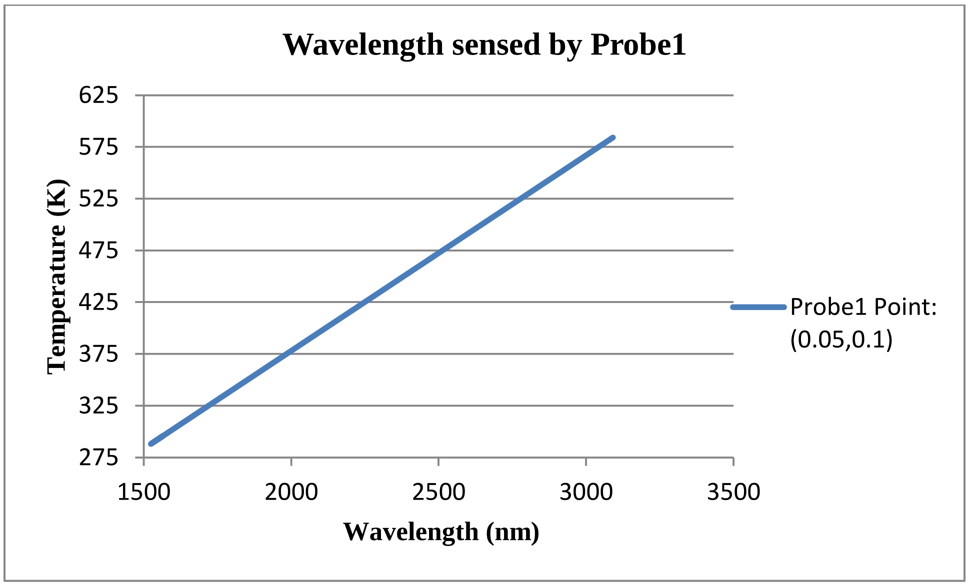


Figure 3.29: Wavelength sensed by Probe1

- ***Probe 2***

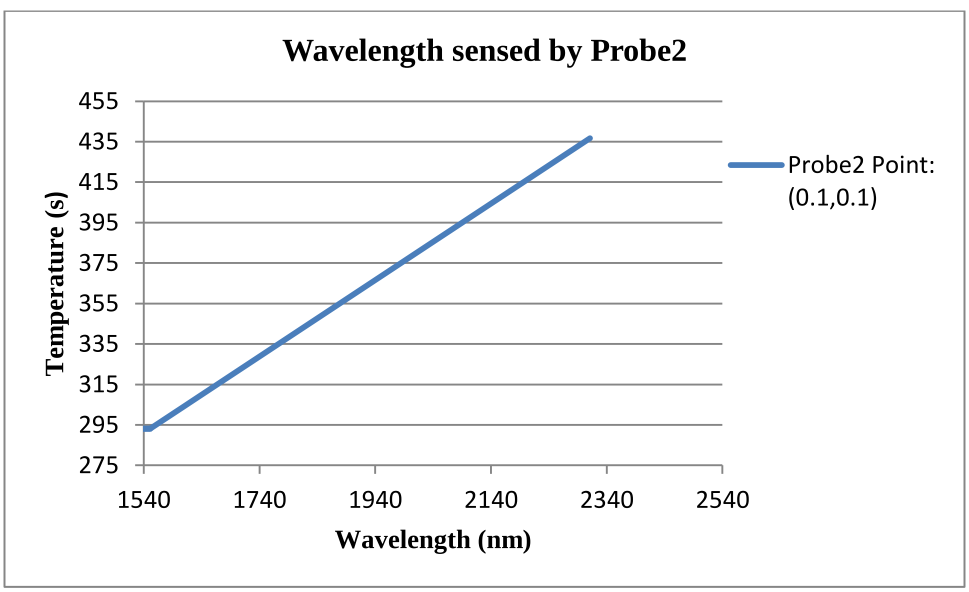


Figure 3.30: Wavelength sensed by Probe2

- ***Probe 3***

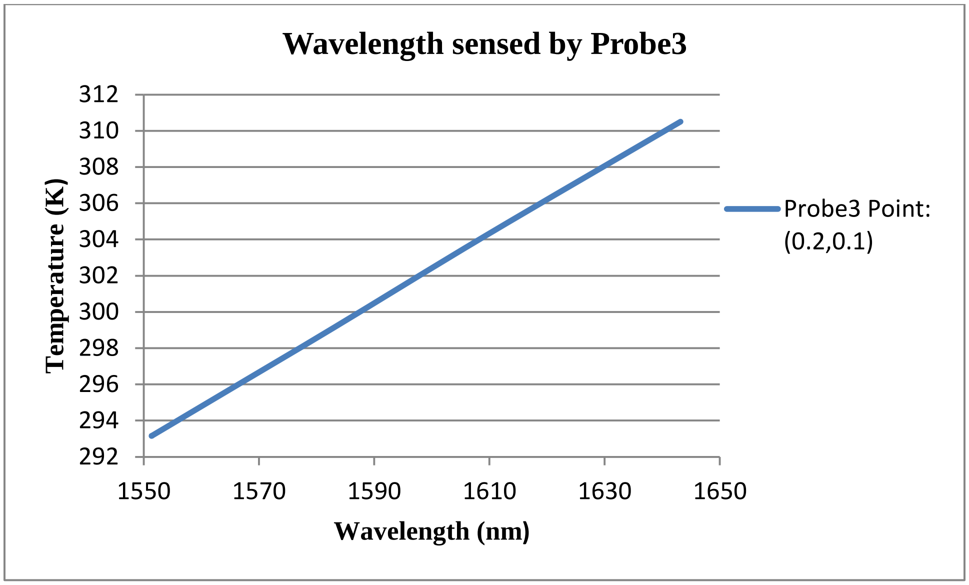


Figure 3.31: Wavelength sensed by Probe3

- ***Probe 4***

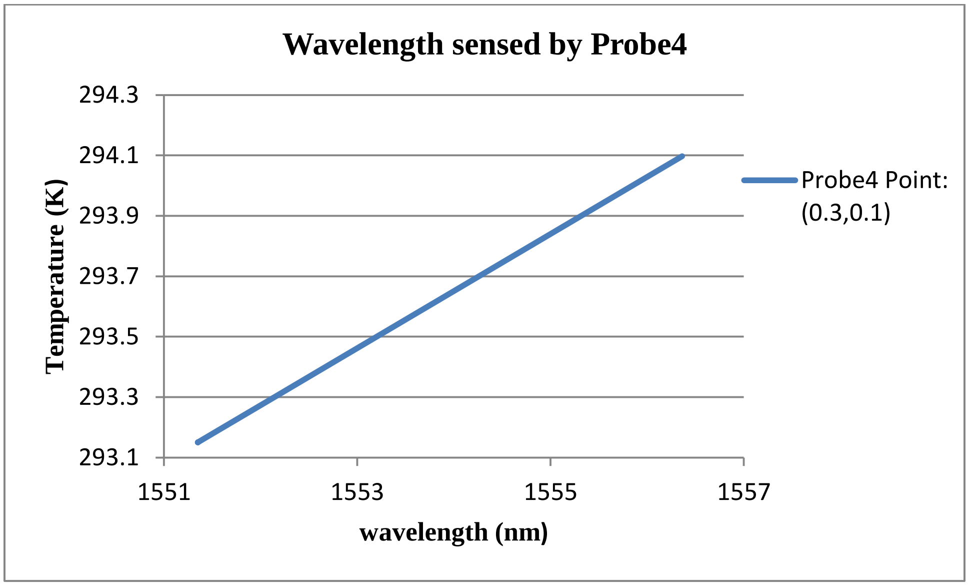


Figure 3.32: Wavelength sensed by Probe4

- ***Probe 5***

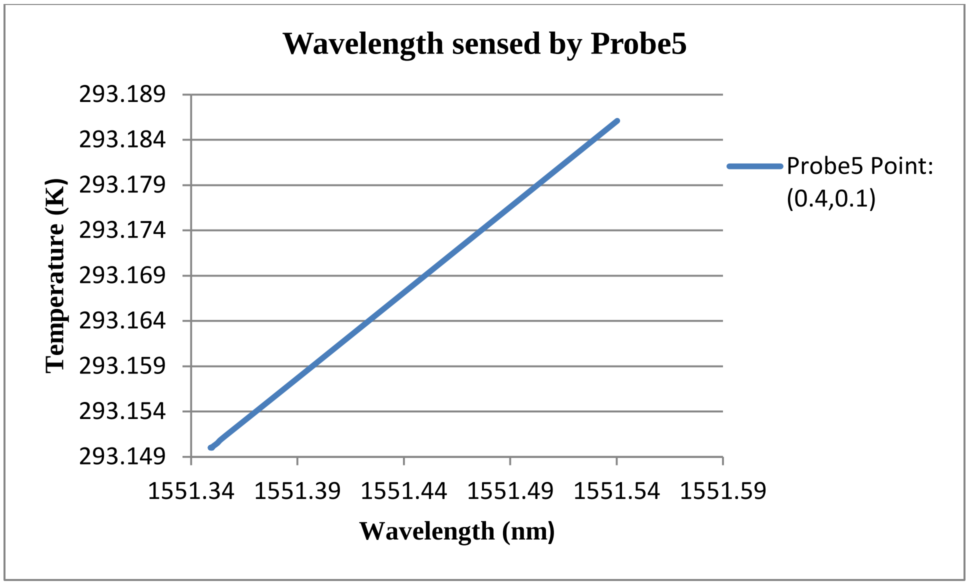


Figure 3.33: Wavelength sensed by Probe5

- ***Probe 6***

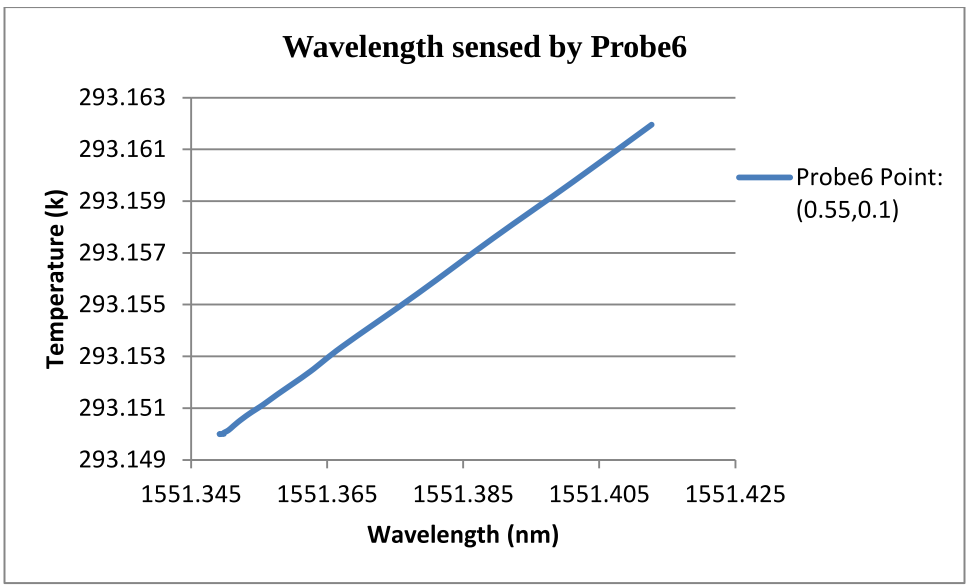


Figure 3.34: Wavelength sensed by Probe6

3.1.6.3.2 Wavelength versus Temperature of last three domain probes at 500 degree Celsius

Figure 3.35 shows the graph between Wavelengths (nm) versus Temperature (K). In this at every change in value of temperature the probe points reflect a light of a particular wavelength. As the distance increases the change in wavelength achieve is small which means after a particular temperature change it will reflect a particular wavelength. This means that at this temperature we can standardize the probe sensors. Different wavelength that is achieved provides us the sensor range. A particular wavelength is observed for the temperature range.

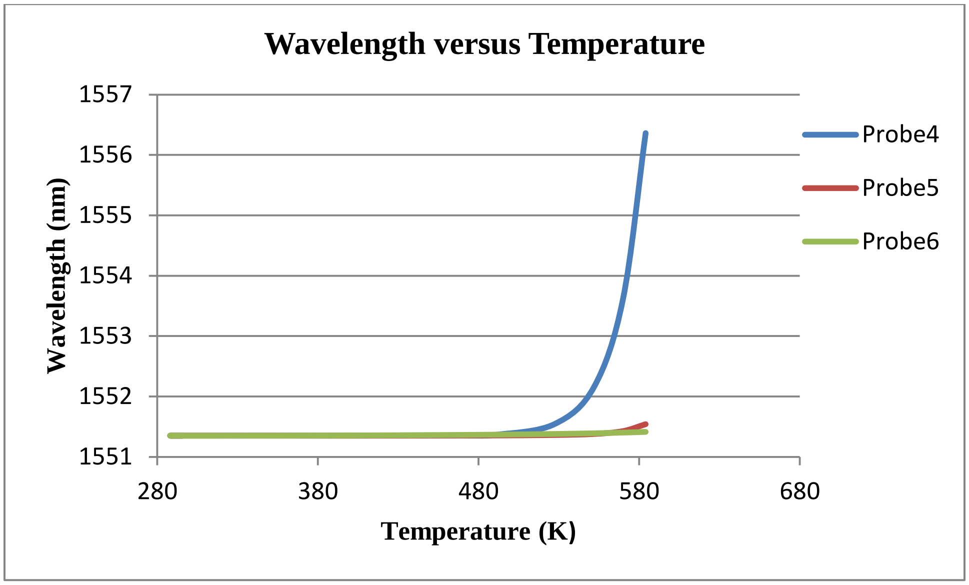


Figure 3.35: Wavelength versus Temperature of last three domain probes

3.1.6.3.3 Wavelength versus Time at 500 degree Celsius temperature

Figure 3.36 shows the wavelength versus time graph by all the domain probe points. We can have range of wavelength that can be used in different optical fiber communication fields. The dimension of domains probe points are same the only difference is in their placed locations.

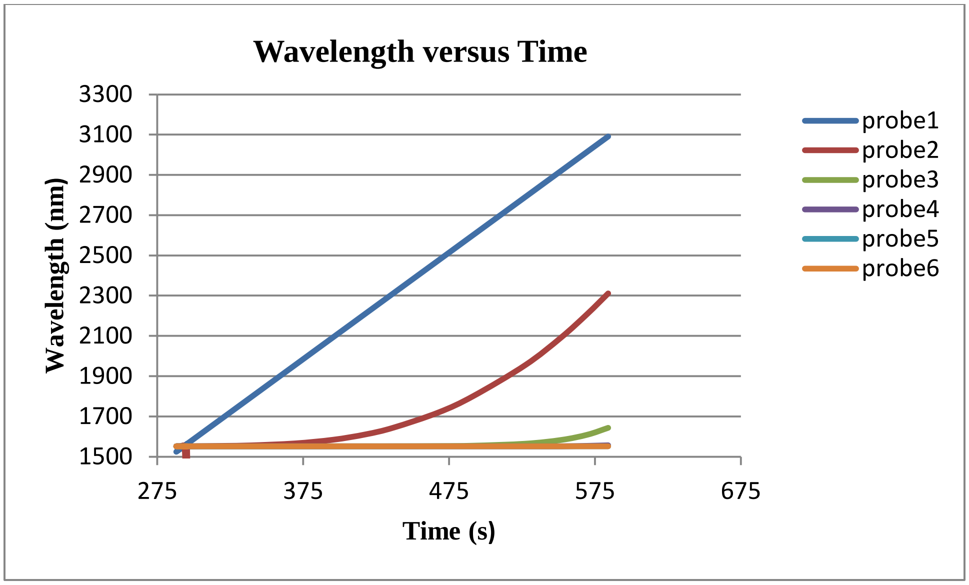


Figure 3.36: Wavelength versus Time at 500 degree Celsius temperature

CONCLUSION

Figure 3.37 shows the graph which states that we have standardized the sensor. At different location of probe points we have achieved a same wavelength. In this we have achieved a particular wavelength of 1551nm with different sensor placing locations. In a way standardization of designing is done. Monochromatic nature appears.

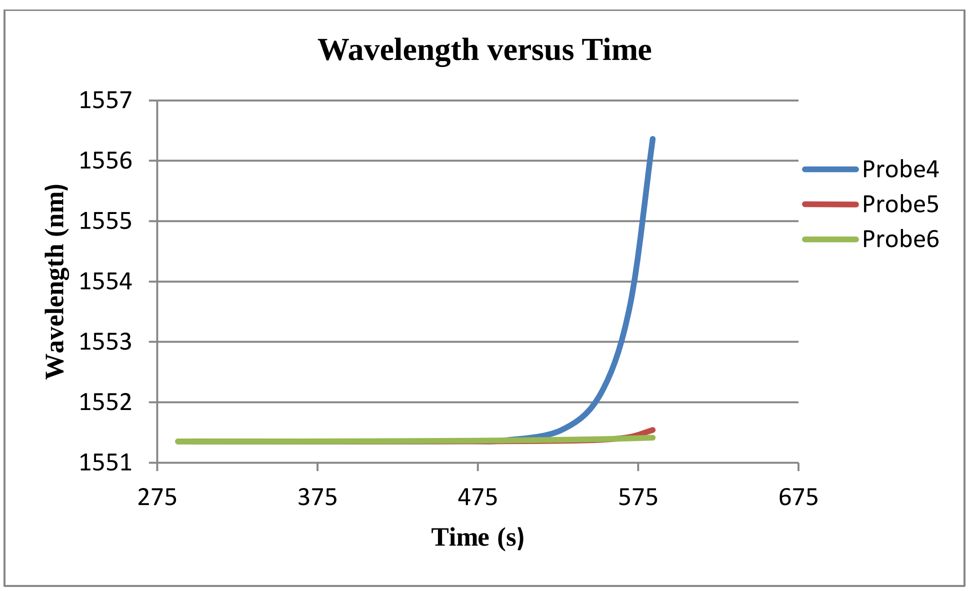


Figure 3.37: Wavelength versus Time of last three probes at 500 degree Celsius temperature

3.1.6.4 Temperature versus Time plot at 700 degree Celsius

Sensor domain point probes are placed at arbitrary instances and plot the change in temperature with time. At same instance of time each probe sensed different value of temperature.

- ***Probe 1***

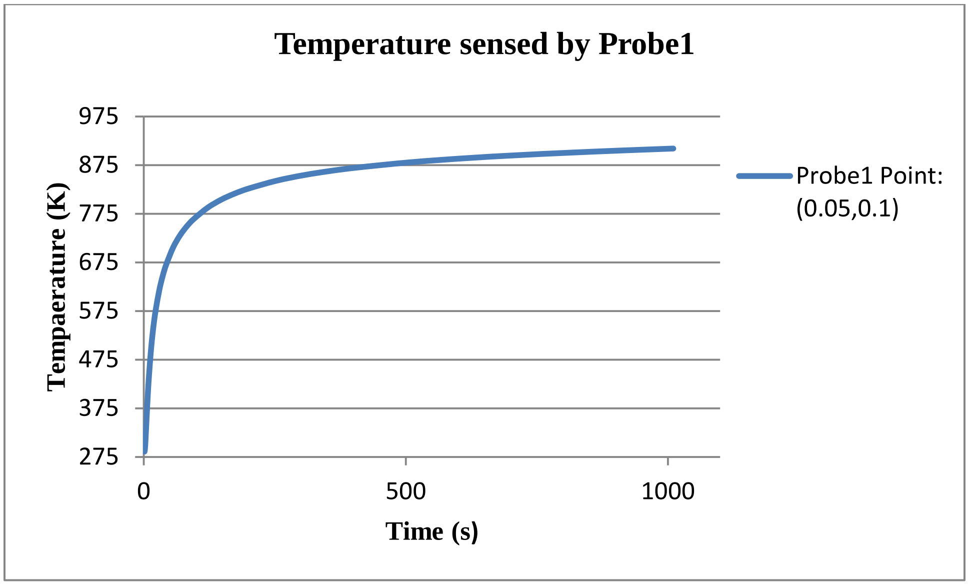


Figure 3.38: Temperature sensed by Probe1

- ***Probe 2***

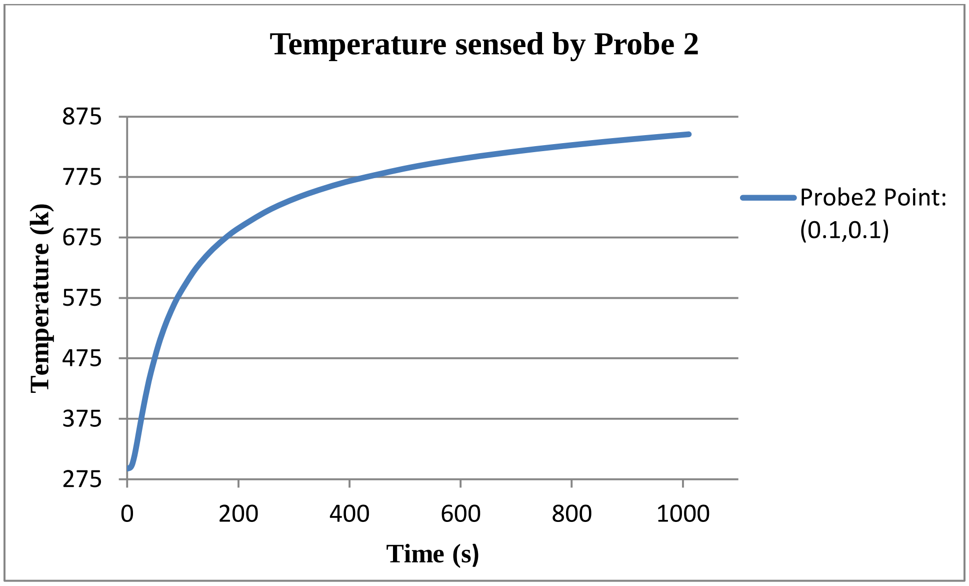


Figure 3.39: Temperature sensed by Probe2

- ***Probe 3***

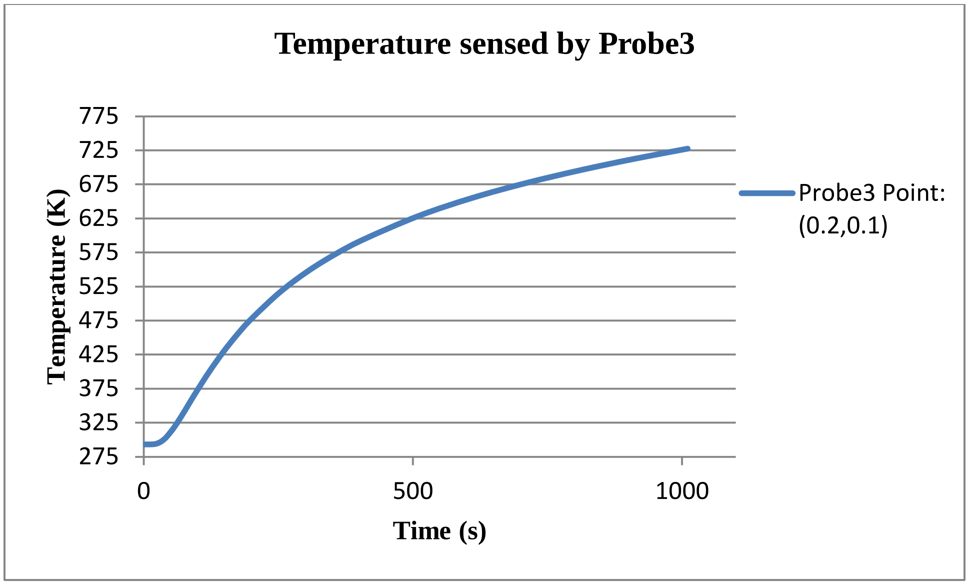


Figure 3.40: Temperature sensed by Probe3

- ***Probe 4***

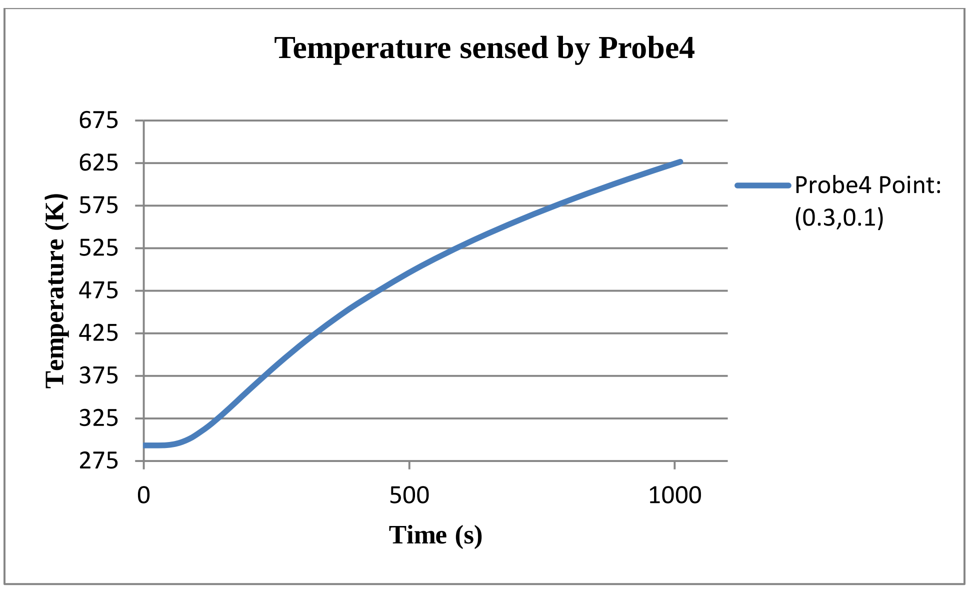


Figure 3.41: Temperature sensed by Probe4

- ***Probe 5***

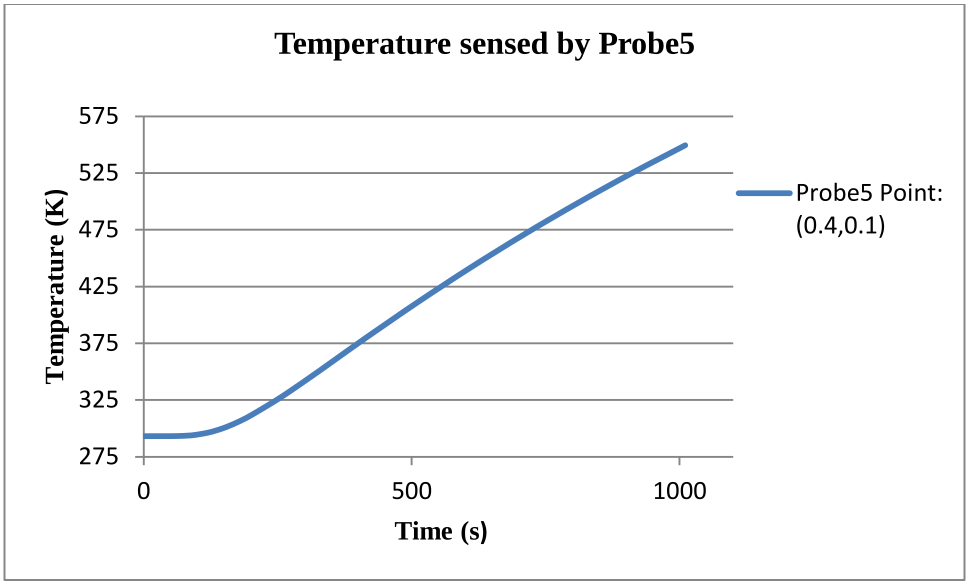


Figure 3.42: Temperature sensed by Probe5

- ***Probe 6***

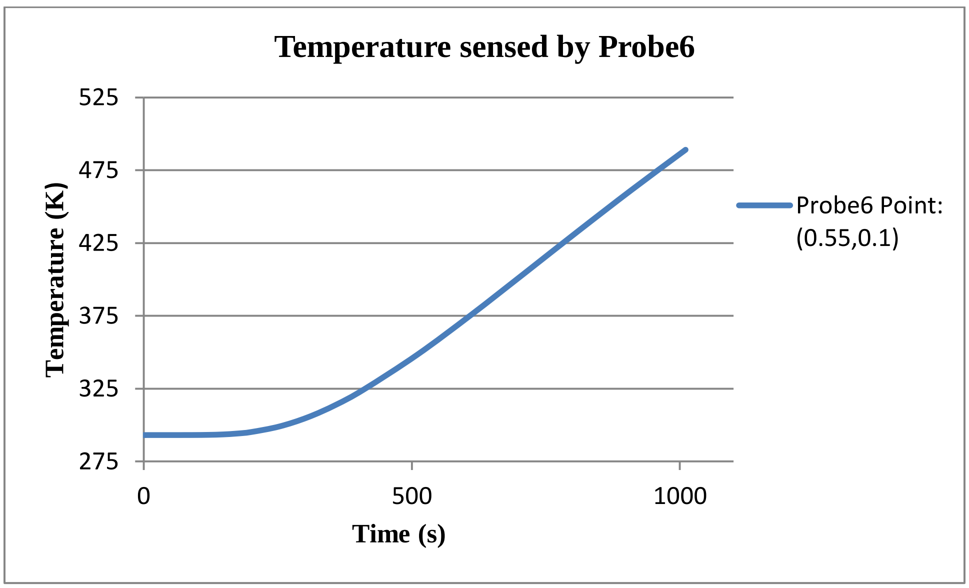


Figure 3.43: Temperature sensed by Probe6

Comparision of temperature probes by all the domain point probes has been submarized in the graph below.

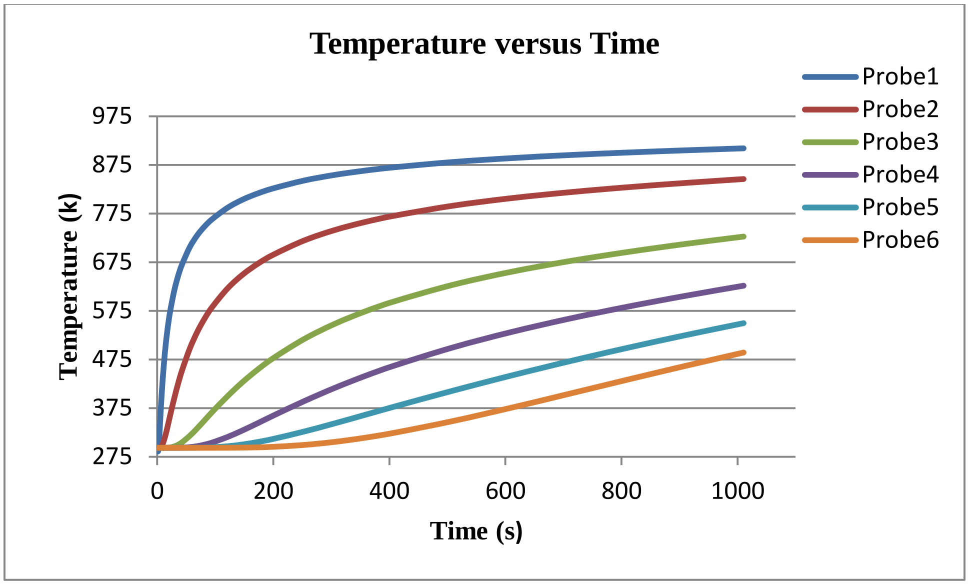


Figure 3.44: Temperature sensed by all the probes

High value of temperature is obtained with 700 degree Celsius applied temperature in comparison with 500 degree Celsius applied temperature. The range obtained is 275 degree Celsius to 975 degree Celsius.

3.1.6.4.1 Wavelength versus Temperature at 700 degree Celsius

- ***Probe 1***

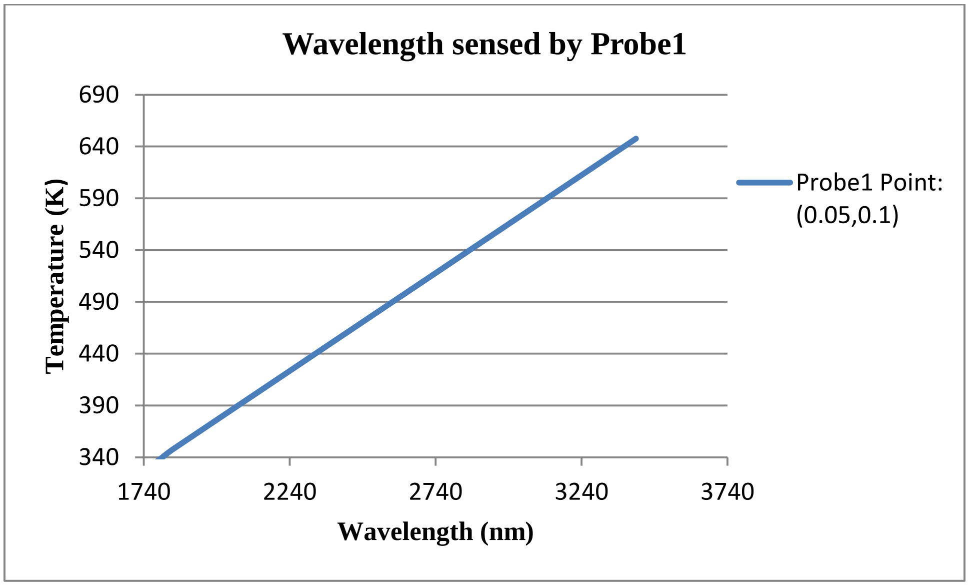


Figure 3.45: Wavelength sensed by Probe1

- ***Probe 2***

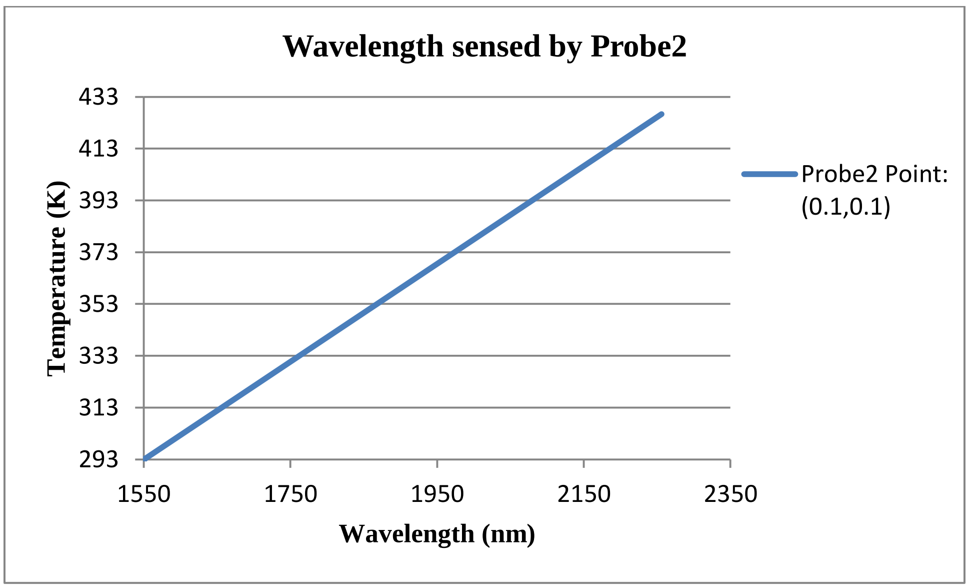


Figure 3.46: Wavelength sensed by Probe2

- ***Probe 3***

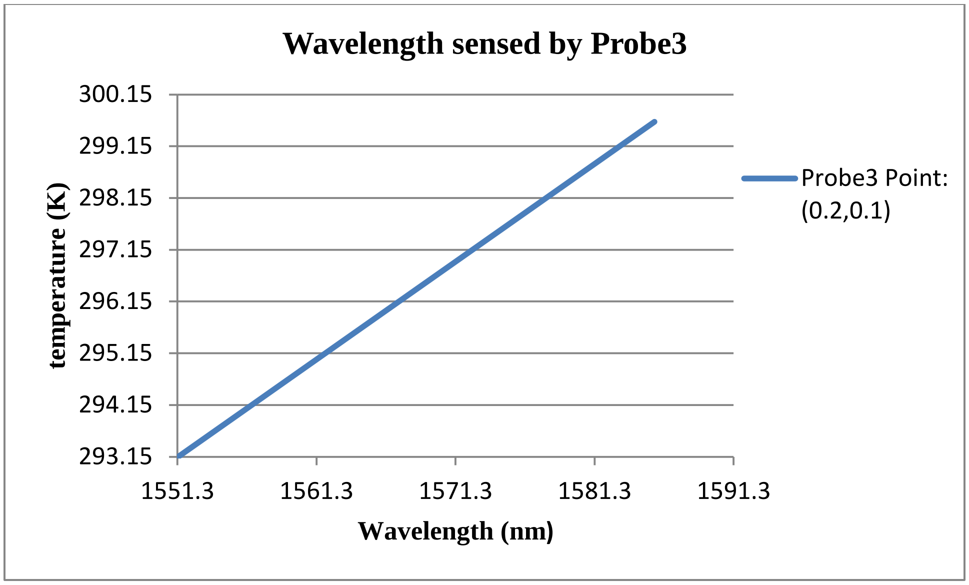


Figure 3.47: Wavelength sensed by Probe3

- ***Probe 4***

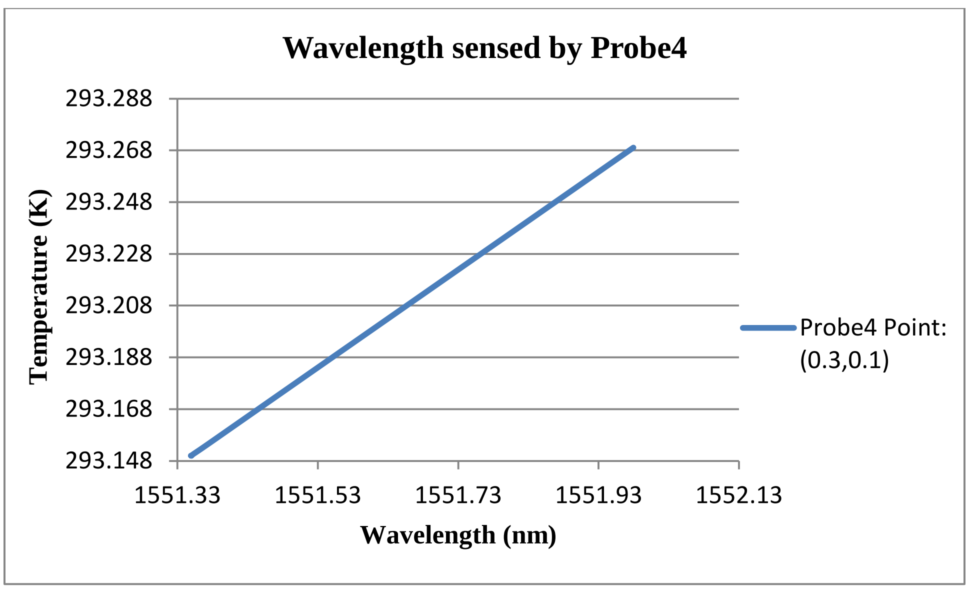


Figure 3.48: Wavelength sensed by Probe4

- ***Probe 5***

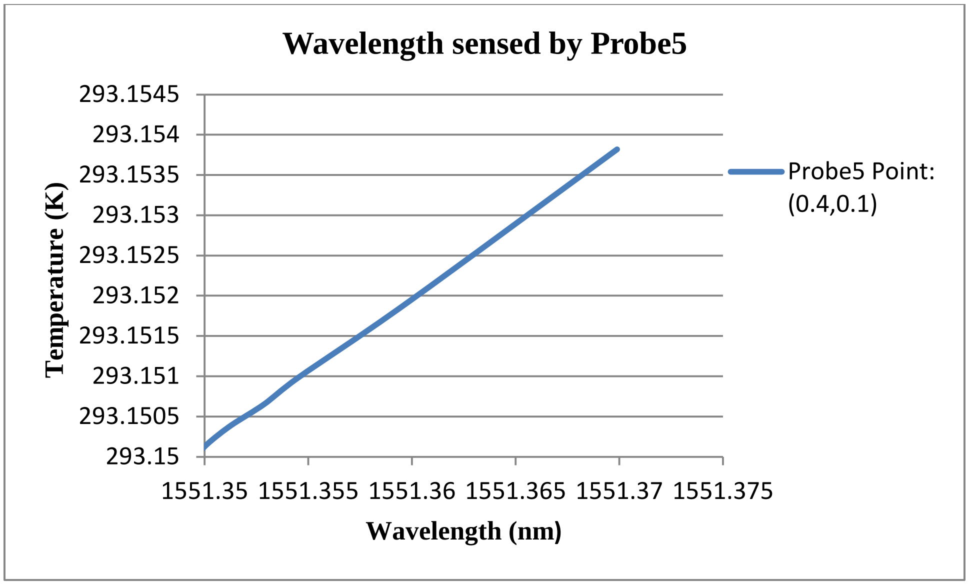


Figure 3.49: Wavelength sensed by Probe5

- ***Probe 6***

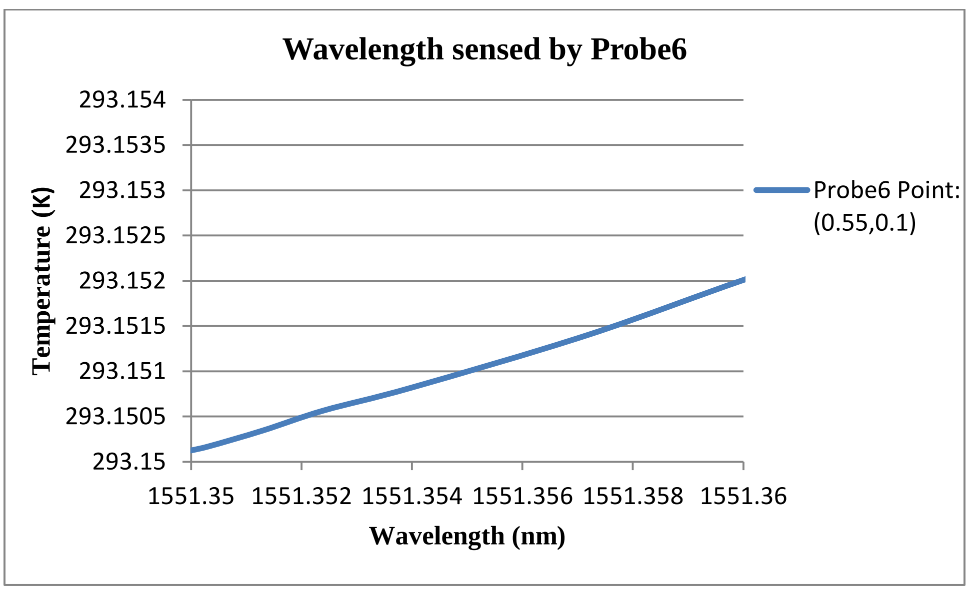


Figure 3.50: Wavelength sensed by Probe6

3.1.6.4.2 Wavelength versus Temperature of last three domain probes at 700 degree Celsius

In this at every change in value of temperature the probe points reflect a light of a particular wavelength. As the distance increases the change in wavelength achieve is small which means after a particular temperature change it will reflect a particular wavelength. This means that at this temperature we can standardize the probe sensors. Different wavelength that is achieved provides us the sensor range.

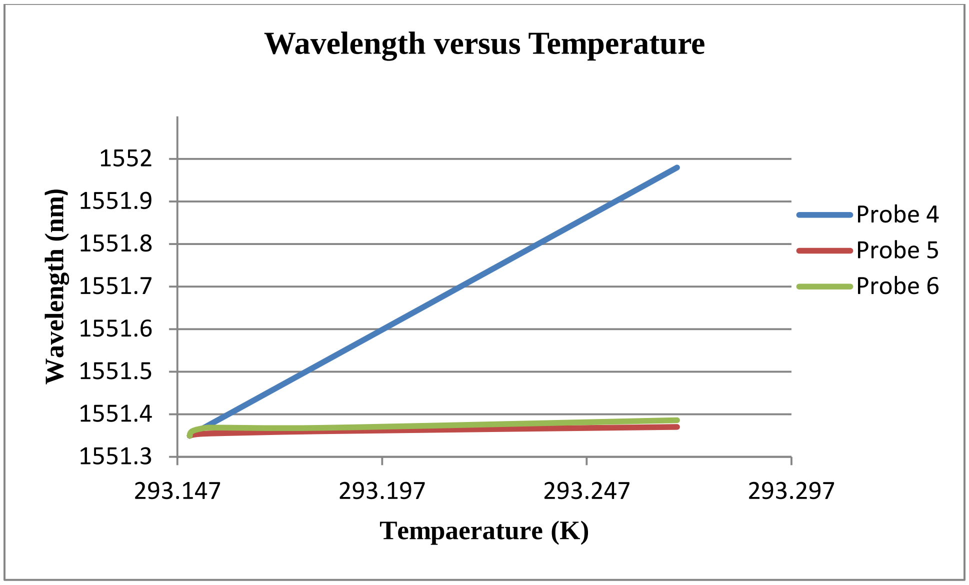


Figure 3.51: Wavelength versus Temperature of last three domain probes at 700 degree Celsius temperature

3.1.6.4.3 Wavelength versus Time at 500 degree Celsius temperature

Figure 3.52 shows the wavelength versus time graph by all the domain probe points. We can have range of wavelength that can be used in different optical fiber communication fields. The dimension of domains probe points are same the only difference is in their placed locations.

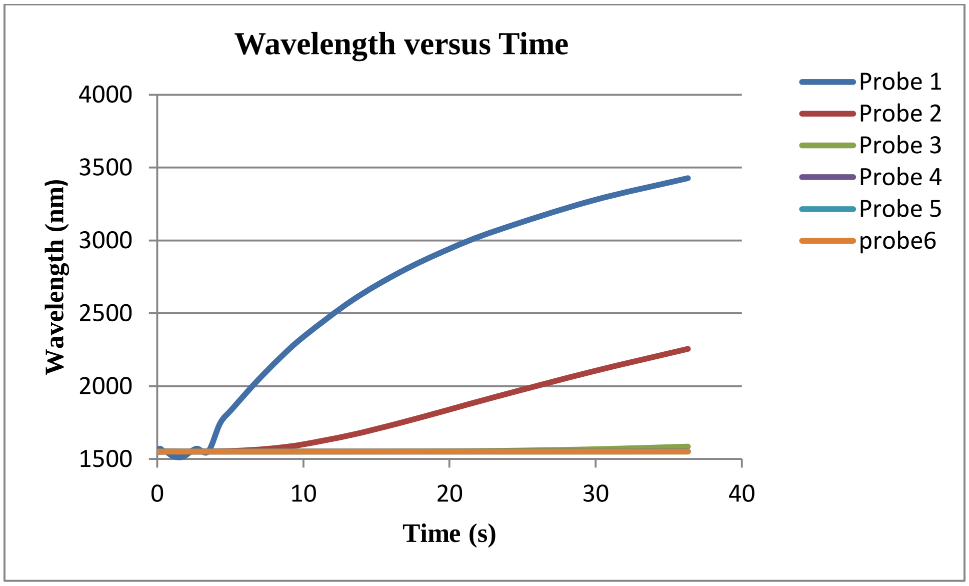


Figure 3.52: Wavelength versus Time at 700 degree Celsius temperature

As the graph shows last four domain probe sensors reflect a particular wavelength for range of temperature values. This shows monochromatic behavior. For the applications same wavelength has to use for that purpose this modeling design can be preferred.

CONCLUSION

Figure 3.53 shows the graph which states that we have standardized the sensor. At different location of probe points we have achieved a same wavelength. In this we have achieved a particular wavelength of 1551nm with different sensor placing locations. In a way standardization of designing is done. Monochromatic nature appears.

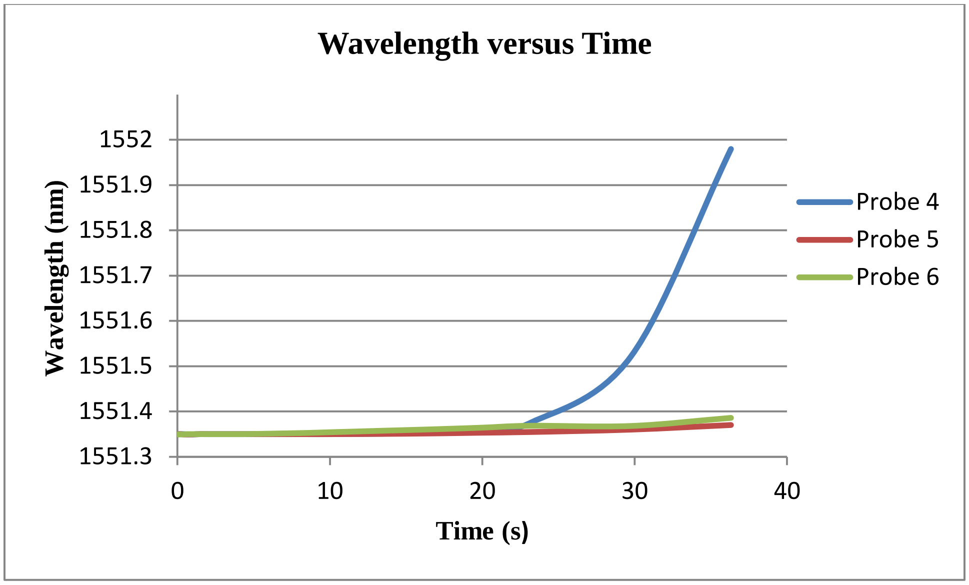


Figure 3.53: Wavelength versus Time of last three probes at 500 degree Celsius temperature

3.1.6.5 Temperature versus Time plot at 900 degree Celsius

Sensor domain point probes are placed at arbitrary instances and plot the change in temperature with time. At same instance of time each probe sensed different value of temperature.

- ***Probe 1***

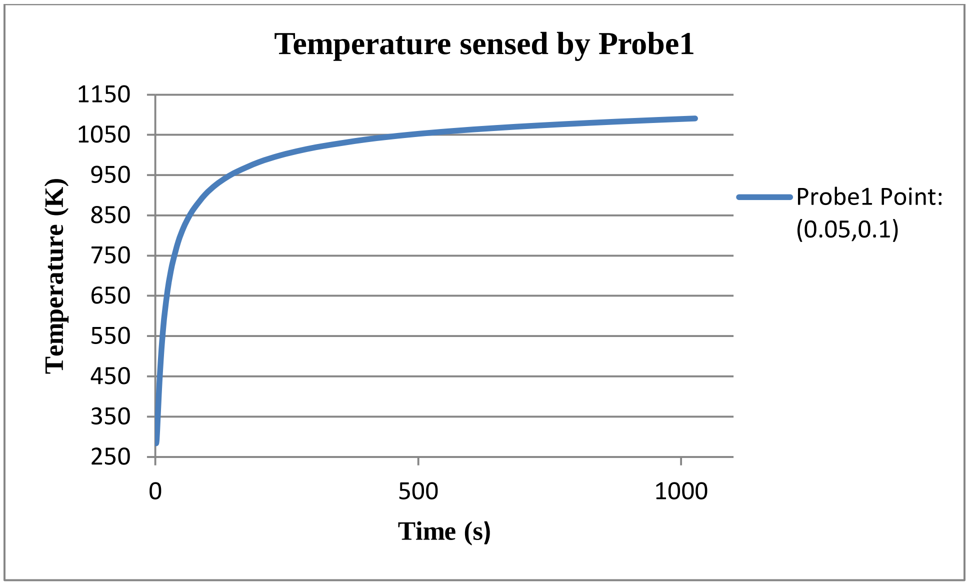


Figure 3.54: Temperature sensed by Probe1

- ***Probe 2***

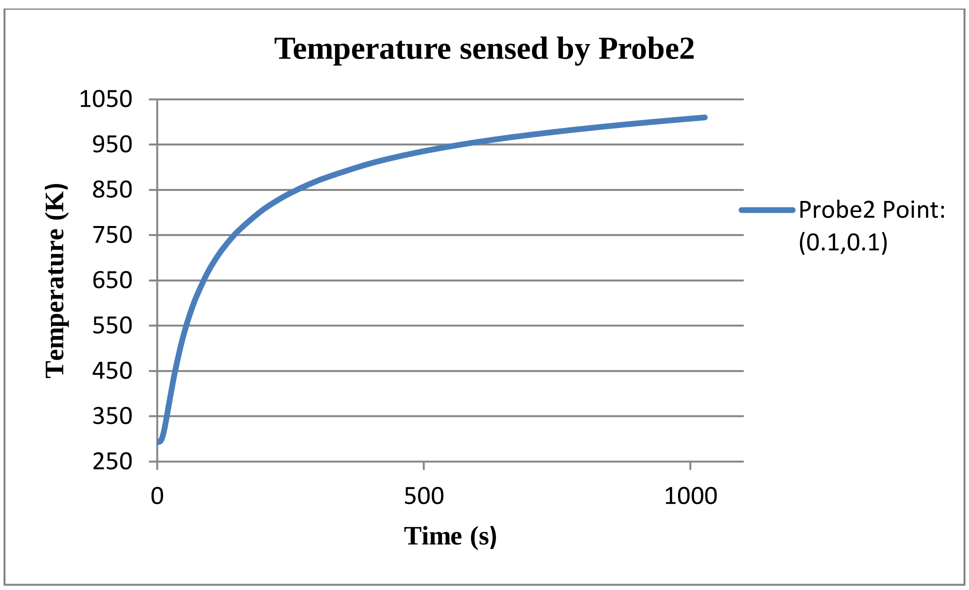


Figure 3.55: Temperature sensed by Probe2

- ***Probe 3***

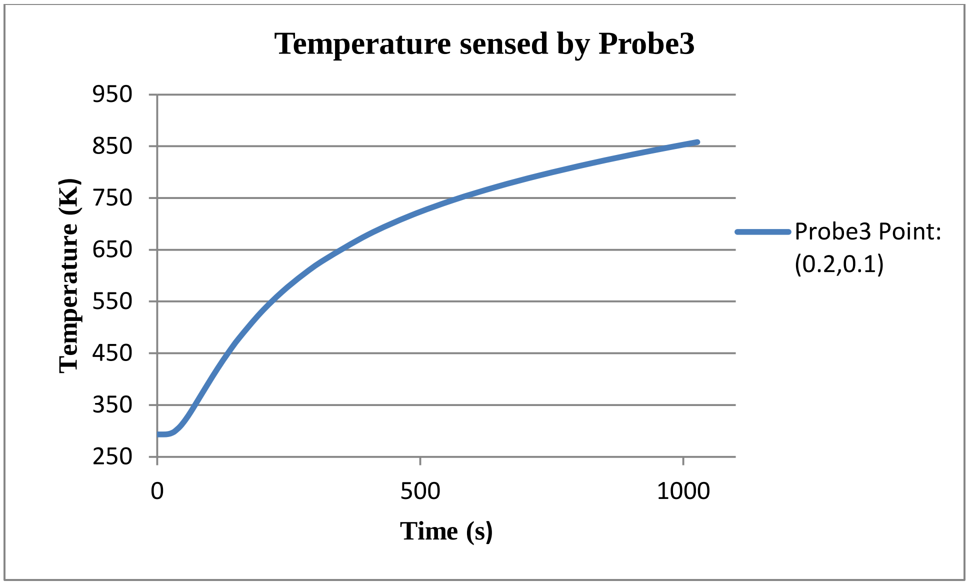


Figure 3.56: Temperature sensed by Probe3

- ***Probe 4***

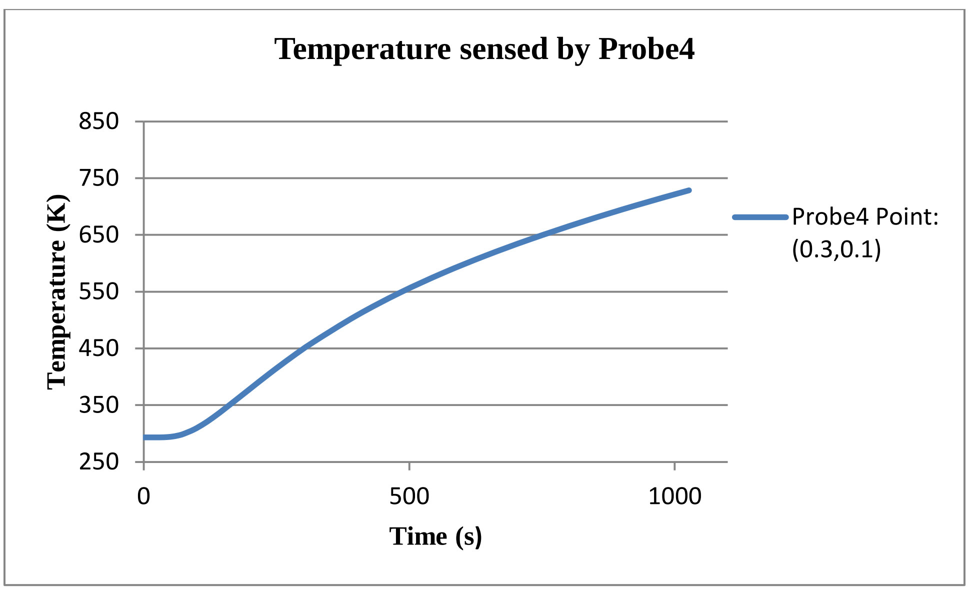


Figure 3.57: Temperature sensed by Probe4

- ***Probe 5***

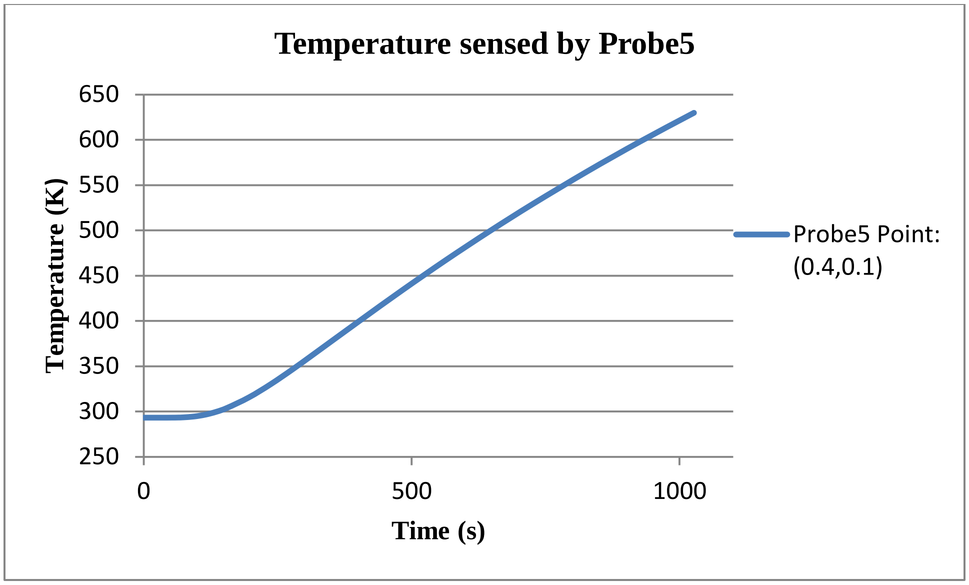


Figure 3.58: Temperature sensed by Probe5

- ***Probe 6***

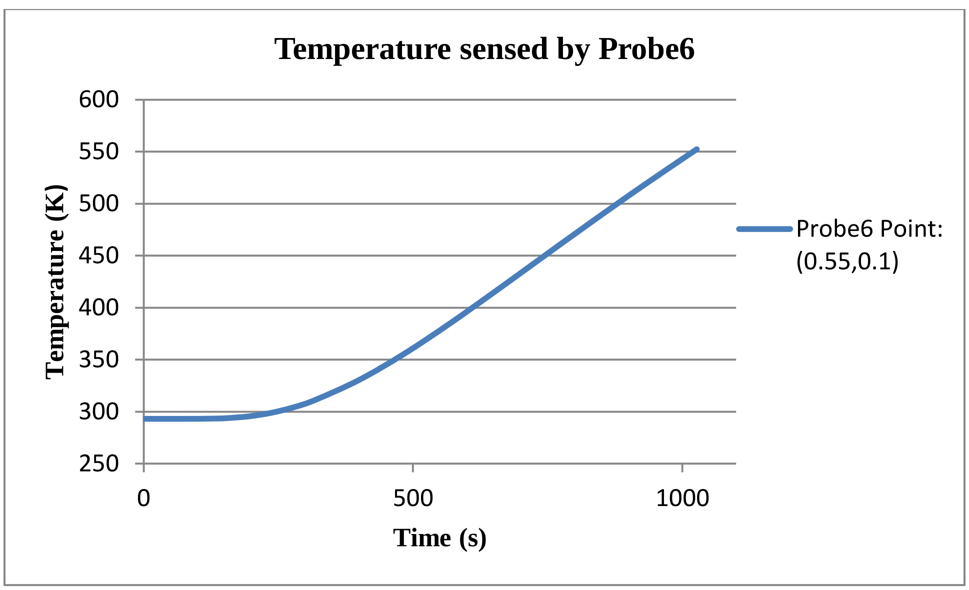


Figure 3.59: Temperature sensed by Probe6

Comparision of temperature probes by all the domain point probes has been submarized in the graph below.

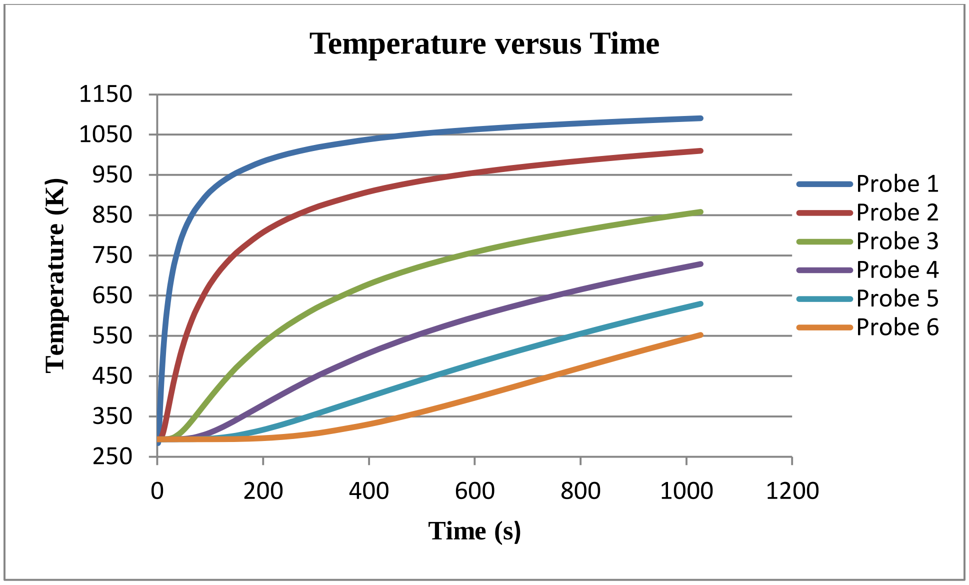


Figure 3.60: Temperature sensed by all the probes

High value of temperature is obtained with 900 degree Celsius applied temperature in comparison with 500 degree Celsius applied temperature. The range obtained is 250 degree Celsius to 1150 degree Celsius.

3.1.6.5.1 Wavelength versus Temperature at 900 degree Celsius

- ***Probe 1***

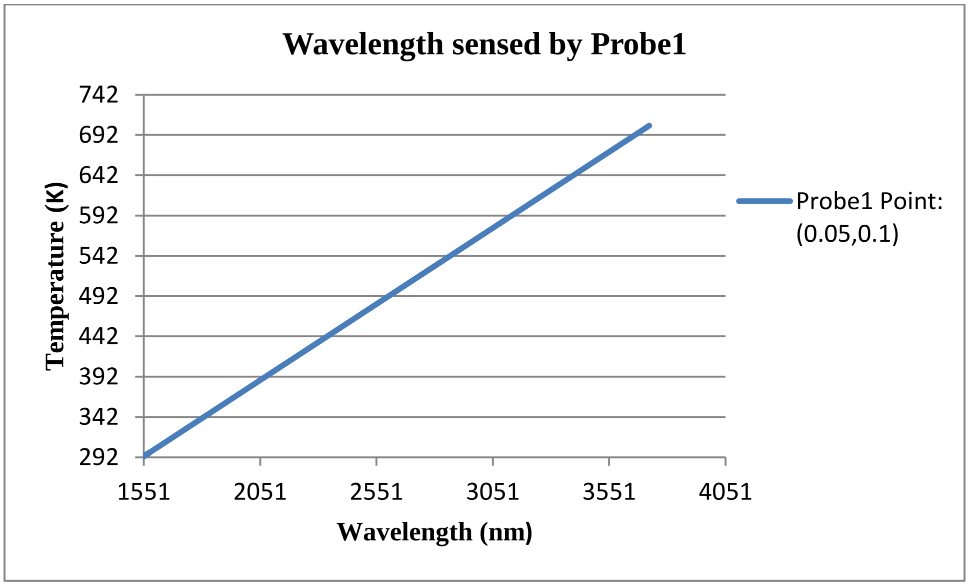


Figure 3.61: Wavelength sensed by Probe1

- ***Probe 2***

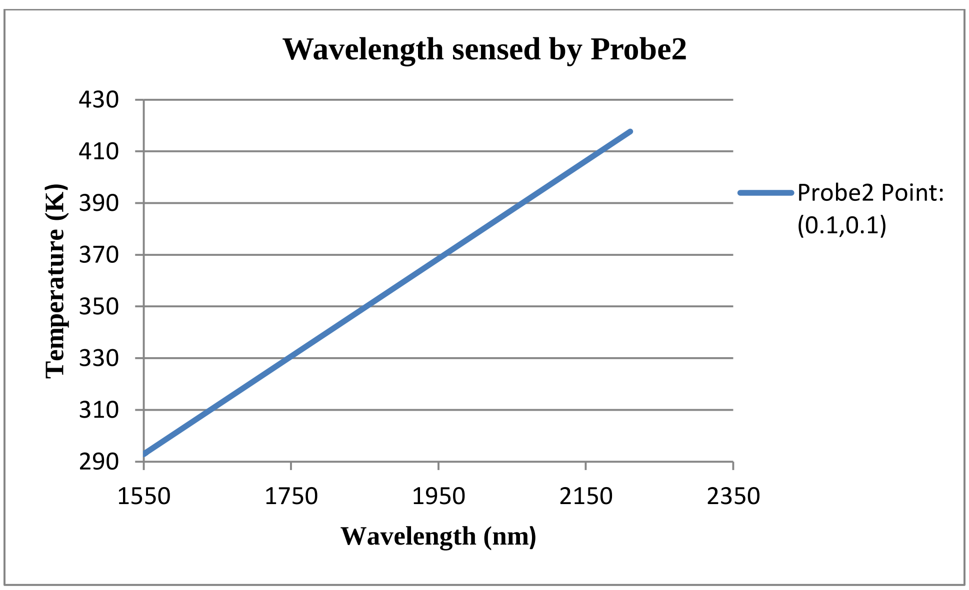


Figure 3.62: Wavelength sensed by Probe2

- ***Probe 3***

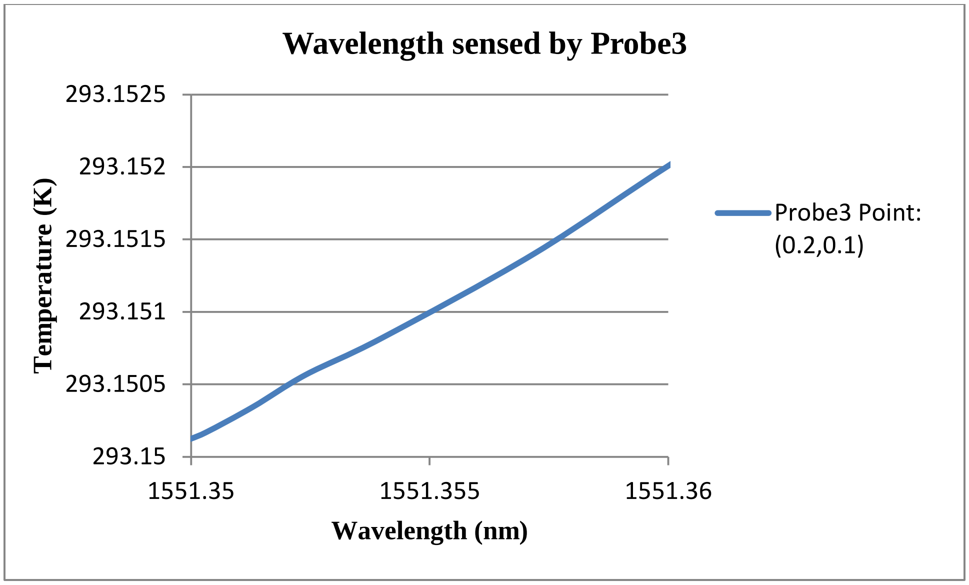


Figure 3.63: Wavelength sensed by Probe3

- ***Probe 4***

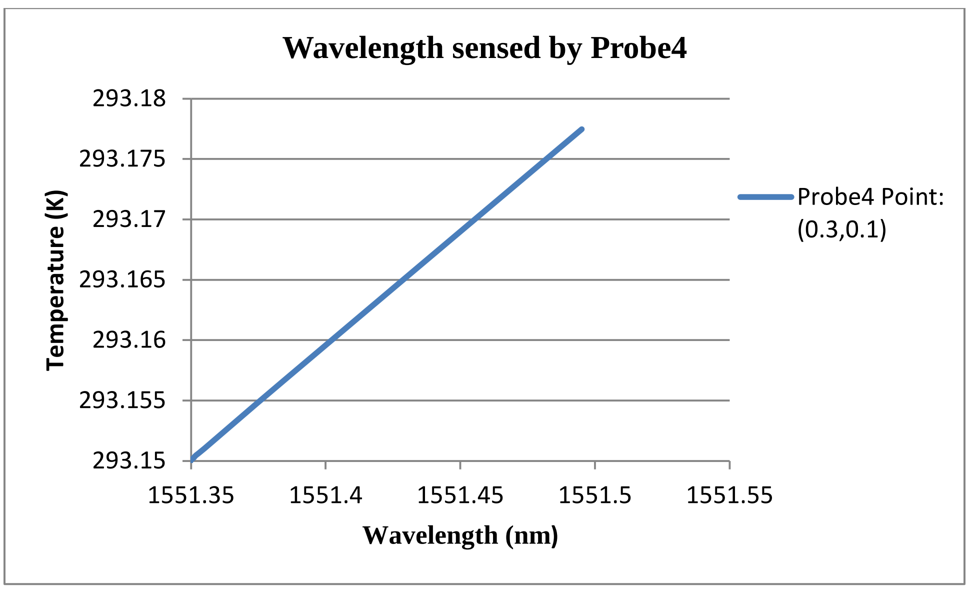


Figure 3.64: Wavelength sensed by Probe4

- ***Probe 5***

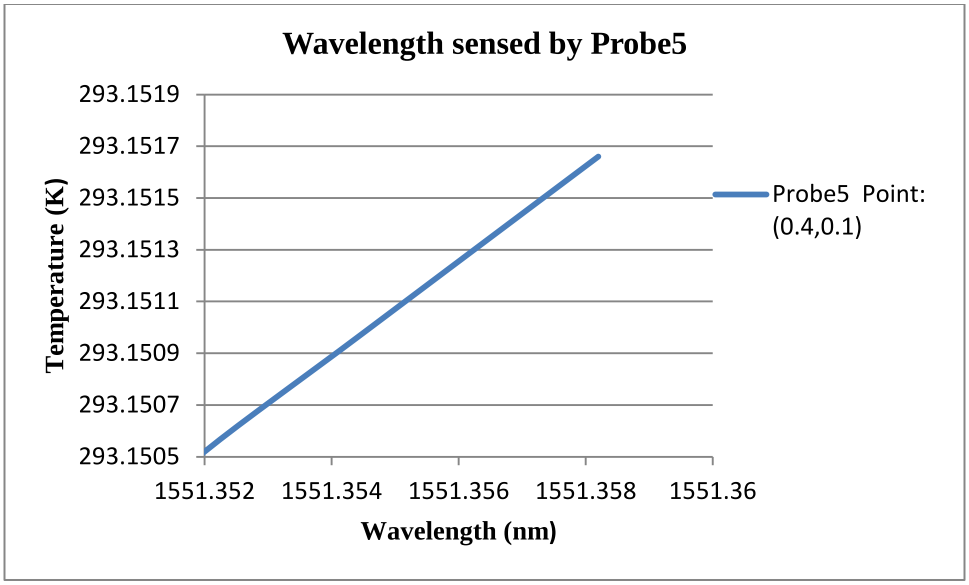


Figure 3.65: Wavelength sensed by Probe5

- ***Probe 6***

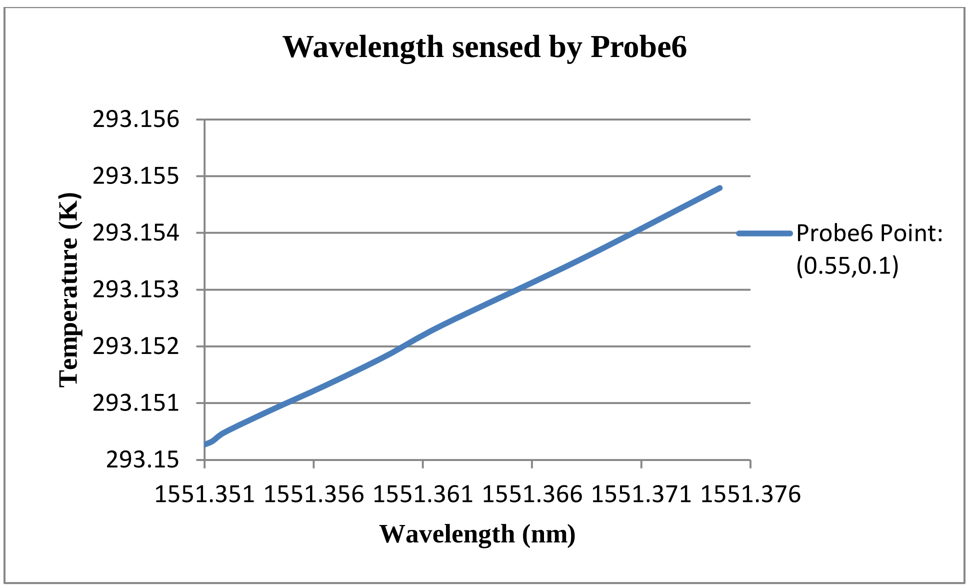


Figure 3.66: Wavelength sensed by Probe6

3.1.6.4.2 Wavelength versus Temperature of last three domain probes at 900 degree Celsius

Figure 3.51 shows the graph between Wavelengths (nm) versus Temperature (K). Different wavelength that is achieved provides us the sensor range. In this at every change in value of temperature the probe points reflect a light of a particular wavelength. As the distance increases the change in wavelength achieve is small which means after a particular temperature change it will reflect a particular wavelength. At a point of time instance all the last three probes reflect same wavelength.

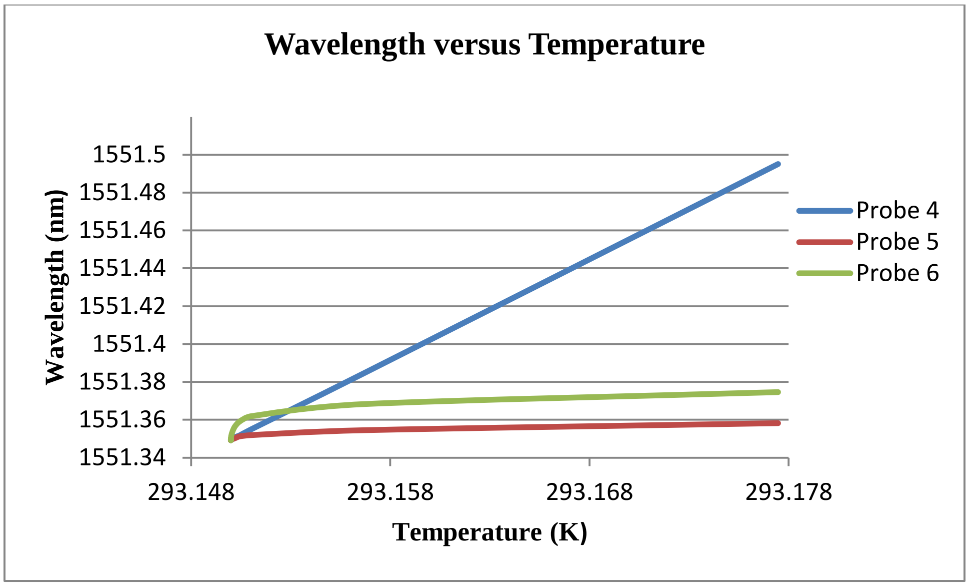


Figure 3.67: Wavelength versus Temperature of last three domain probes

3.1.6.3.3 Wavelength versus Time at 900 degree Celsius temperature

Figure 3.68 shows the wavelength versus time graph by all the domain probe points. We can have range of wavelength that can be used in different optical fiber communication fields. The dimension of domains probe points are same the only difference is in their placed locations.

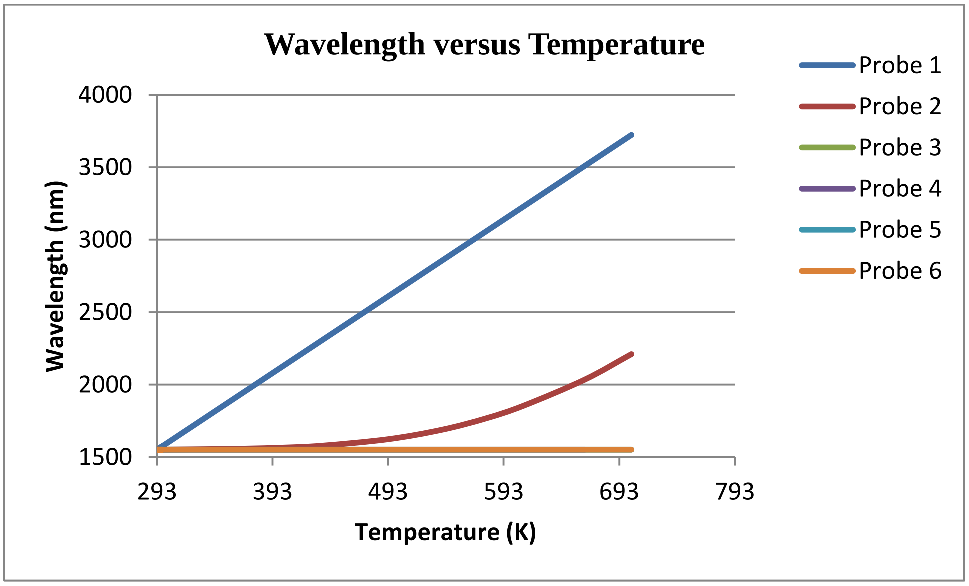


Figure 3.68: Wavelength versus Time of last three probes at 500 degree Celsius temperature

3.2 TO OPTIMIZE THE DESIGNED FBG MODEL ON THE BASIS OF ITS DIMENSIONS

Modeling of the designed FBG model is optimized on the basis of its dimensions by changing the length of the designed model or by changing the width of the designed model and measured the change in temperature by domain probe points.

3.2.1 By changing the length parameter and width remains constant

Width W=0.2m	Temperature at L=0.6m	Temperature at L=0.9m	Temperature at L=1.2m	Temperature at L=1.5m
Domain probe point (0.05,0.1)	523.936 K	532.615 K	538.228 K	546.591 K
Domain probe point (0.1,0.1)	476.824 K	493.271 K	504.116 K	520.371 K
Domain probe point (0.2,0.1)	396.363 K	422.425 K	441.186 K	470.457 K
Domain probe point (0.3,0.1)	341.694 K	367.504 K	389.140 K	425.806 K

Table 3.1: Showing obtained temperature values when parameter of length is varied

In this case study width remains constant at a particular value. The change in temperature is measured by varying the length. Above tabulated data shows length parameter and probe point locations plays a very important role. Length parameter shows that as the length increases the temperature value obtained is also of high value but as the heat is transferred with the distance, the increased distance decreases the value of the temperature to be measured. The reason behind that is this result is depend on the distance between temperature source and the probe points.

Simulation work results: Graphs are obtained when parameter length is varied and probe location and width is fixed.

- ***Domain probe point (0.05,0.1)***

In this the change in temperature is measured at point (0.05, 0.1) by domain probe point by changing the length and width remains constant at W=0.2m.

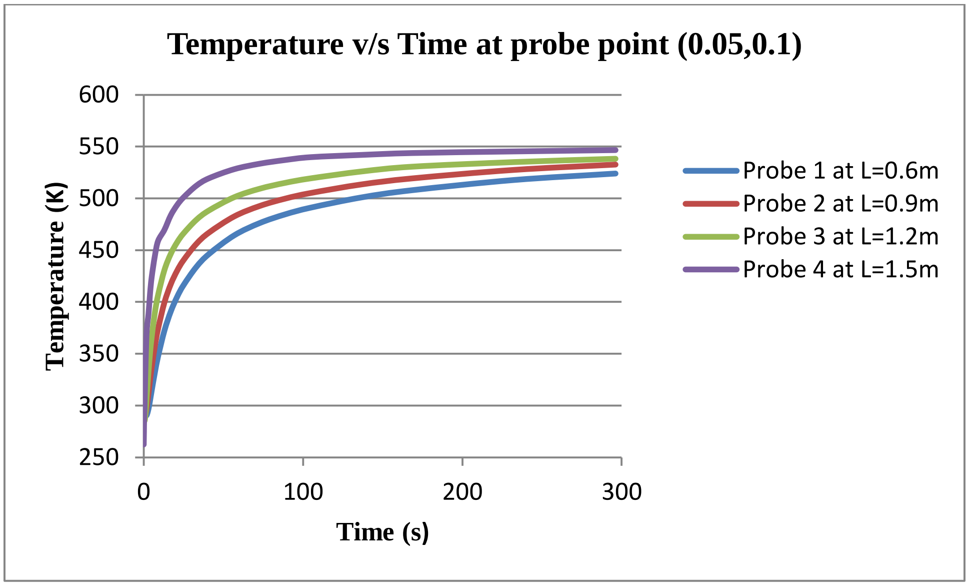


Figure 3.69: Temperature v/s Time at probe point (0.05, 0.1)

- ***Domain probe point (0.1,0.1)***

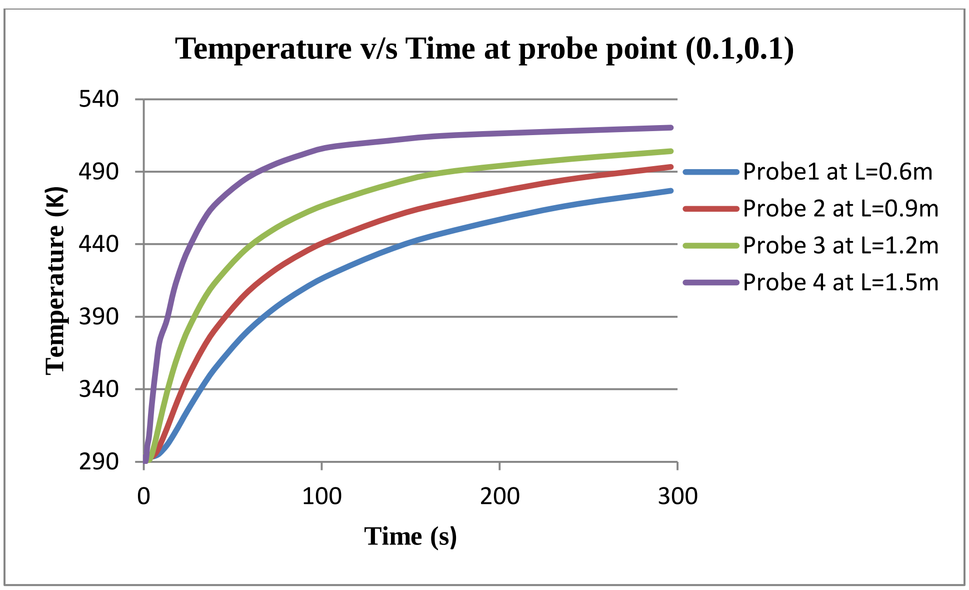


Figure 3.70: Temperature v/s Time at probe point (0.1, 0.1)

- ***Domain probe point (0.2,0.1)***

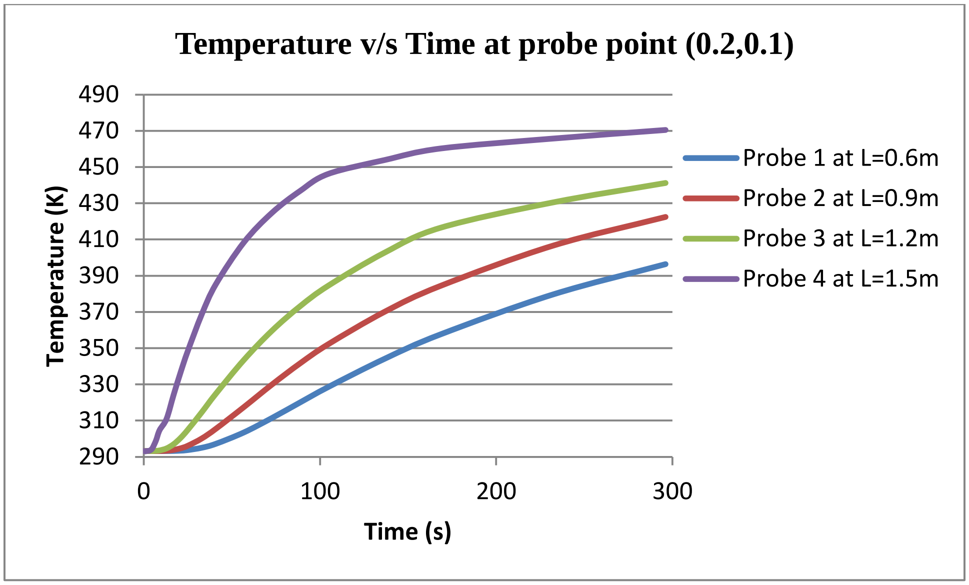


Figure 3.71: Temperature v/s Time at probe point (0.2, 0.1)

- ***Domain probe point (0.3,0.1)***

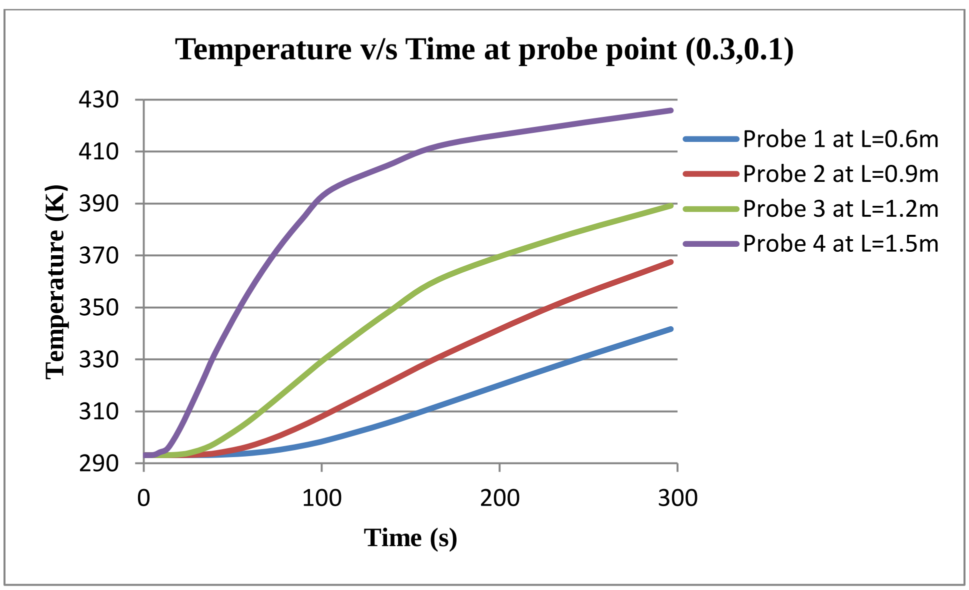


Figure 3.72: Temperature v/s Time at probe point (0.3, 0.1)

3.2.2 By changing the width parameter and length remains constant

Length at L=0.6m	Temperature at W=0.2m	Temperature at W=0.4m	Temperature at W=0.8m	Temperature at W=1.0m
Domain probe point (0.05,0.1)	541.422 K	541.721 K	545.186 K	546.928 K
Domain probe point (0.1,0.1)	510.354 K	510.939 K	517.741 K	521.175 K
Domain probe point (0.2,0.1)	452.687 K	453.752 K	466.357 K	472.885 K
Domain probe point (0.3,0.1)	404.439 K	401.768 K	422.635 K	431.629 K

Table 3.2: Showing obtained temperature values when parameter of width is varied

In this tabulated data shows that the change in width does produce a change in temperature that too in a small number. So this concludes that the major change in temperature is achieved due to the length parameter variation.

- ***Domain probe point (0.05,0.1)***

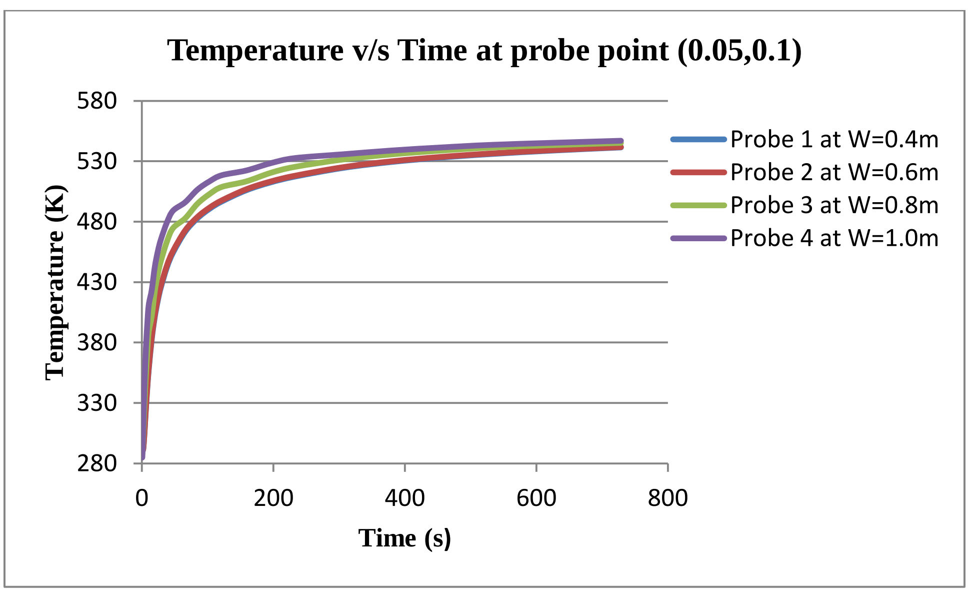


Figure 3.73: Temperature v/s Time at probe point (0.05, 0.1)

- ***Domain probe point (0.1,0.1)***

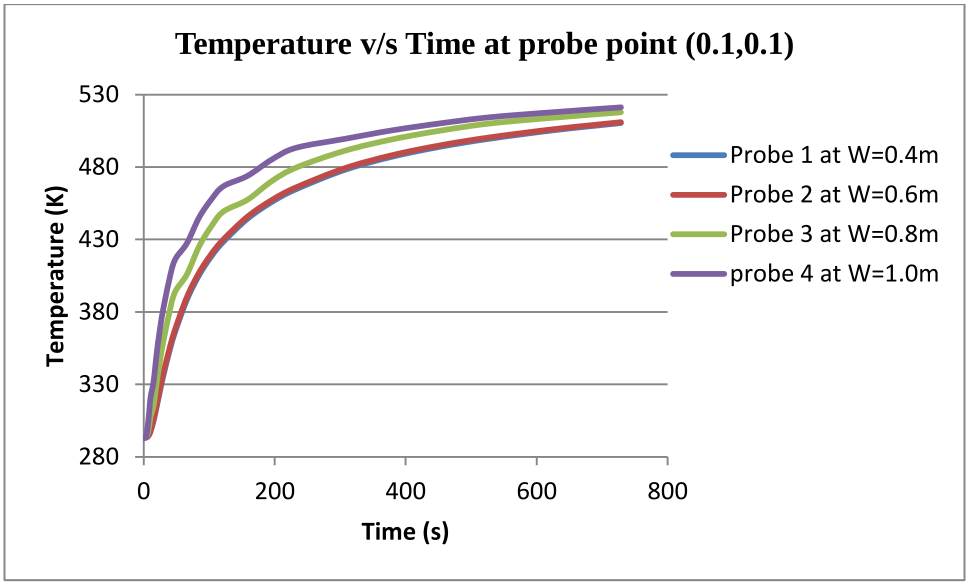


Figure 3.74: Temperature v/s Time at probe point (0.1, 0.1)

- ***Domain probe point (0.2,0.1)***

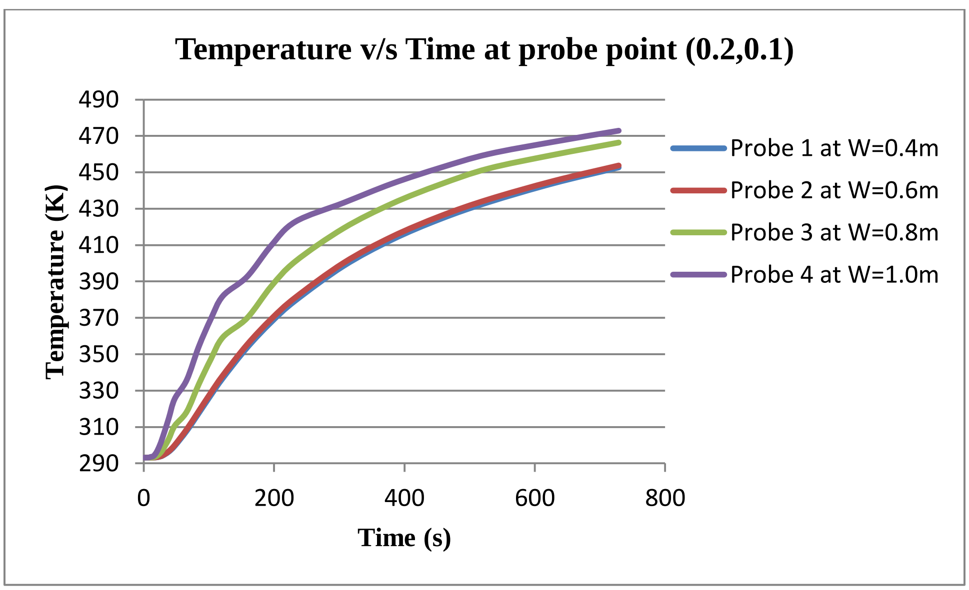


Figure 3.75: Temperature v/s Time at probe point (0.2, 0.1)

- ***Domain probe point (0.3,0.1)***

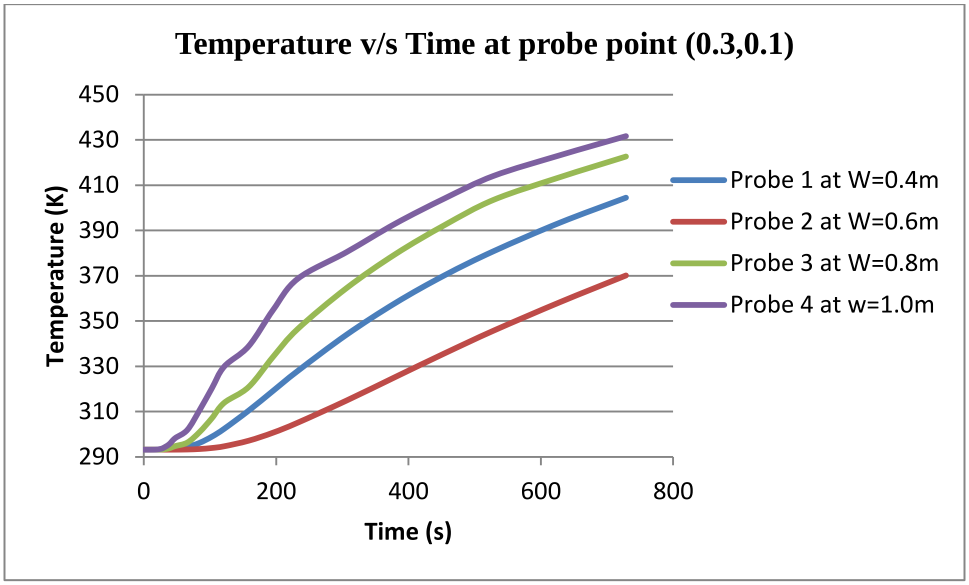


Figure 3.76: Temperature v/s Time at probe point (0.3, 0.1)

In the end we can conclude that heat is transferred along the model and the change in temperature is measured. The results shows that the temperature change is higher at the beginning and as the heat transferred and the distance between the temperature source and probe point is increased the change in temperature is small. Dimension variation can optimized the result and enhance sensitivity is obtained by changing the length of the model as change in the width do produce a change but that too is small.

CHAPTER 4

CONCLUDING REMARKS AND FUTURE SCOPE

CONCLUSION

The optical fiber technologies have been proved to be the best for monitoring and sensing process of the smart industrial structures. The real time monitoring is very essential for industrial applications. Temperature and strain are two parameters to be taken into account which affect the smart industrial systems. In this research relation between wavelength and temperature is considered for the high temperature industrial applications. The temperature changes play a very crucial role as it affects the system accuracy. FBG temperature sensors have been widely used to detect the changes that occurring in the system and have better sensitivity than the conventional sensors. It is also capable of dealing with the practical problems that occurring in the implementation and installation of the sensor. The overall research results have given us the encouragement for the continued study of the development and use of FBG sensor for accurate sensing and monitoring purposes.

FUTURE SCOPE

In the duration of this course work, many concepts of advanced technologies came into mind for the further enhancement in the study. Few of them are listed below..

1. Their inherent features such as immunity from EMI, small size, compact, light in weight made possible the remote sensing for long term monitoring.
2. In this research work results are saturating after a point which is a system constraint. By proper material selection we can reach the temperature beyond 2000 degree Celsius and can be best application in industries.

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