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Investigation on Material Dispersion as a Function of Pressure and Temperature for Sensor Design

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INVESTIGATION ON MATERIAL DISPERSION AS A FUNCTION OF
PRESSURE AND TEMPERATURE FOR SENSOR DESIGN

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ABSTRACT

The concept of material dispersion is an important factor in analyzing the performance of an optical fiber system. The thesis presents an analysis of the material dispersion as a function of any pressure (in Mega Newton's per square meter) and temperature (in degrees Celsius). The pressure dependent and temperature dependent Sellmeier coefficients are considered for the analysis. The results obtained can be used in building a sensor that can be used for measuring dispersion as a function of pressure or temperature.

Introduction

Material dispersion is the phenomena whereby materials cause light to spread out as it propagates. Material dispersion occurs because the index of refraction varies as a function of the optical wavelength. Since the group velocity of a mode is a function of the index of refraction, the various spectral components of a given mode will travel at different speeds, depending on wavelength. As the distance increases, the pulse becomes broader as a result.

Material dispersion is present in graded index fibers and also single mode fibers, but this is of particular importance in the single mode waveguides and any system, which has a broader output spectrum such as LED. This phenomenon is not helpful in optical communications. On the contrary, material dispersion limits how much data can be sent, as the pulses will overlap and information will be lost. Ongoing research is attempting to reduce the effects of material dispersion.

In optics, the Sellmeier equation is an empirical relationship between refractive index n and wavelength λ for a particular transparent medium. The refractive index of any optical material is determined mainly by the two types of resonance absorption: one is due to the electronic transitions of oscillators, i.e., the average resonance of electronic absorption in the UV region and the other is due to the lattice vibrations of the material in the IR region. The refractive index n is related to the wavelength λ using the two-pole

Sellmeier equation with the consideration of the effective electronic transition and lattice vibration as $n^2 = A + \dfrac{B\lambda^2}{\lambda^2 - C} + \dfrac{D\lambda^2}{\lambda^2 - E}$, where A, B, C, D, E are the optical constants. C and E represent the effective resonance absorption wavelengths in the UV and IR region respectively. λ is the wavelength in microns.

In this thesis, an examination of the Sellmeier equation is done for calculating material dispersion of optical fibers at different pressures and temperatures. The second derivative of the refractive index with respect to wavelength gives the material dispersion. The refractive index, n, in the Sellmeier equation is considered for double differentiating with respect to wavelength λ, which in turn is multiplied with wavelength over velocity of light. Substituting the values of Sellmeier constants A, B, C, D, E, wavelength, velocity of light being constant, at desired pressure/temperature yields us the material dispersion at the desired value.

The material dispersion for silica at different pressures and temperatures are calculated. The pressure dependent Sellmeier constants for silica at any operating pressure have also been calculated. These optical constants help in determining the optical design parameters at different pressures and also to predict the operating features of optical fiber as a function of pressure.

Chapter 1: Overview of Optical Networks

1.1 Introduction

Telecommunications networks based on optical fiber technology have become a major information-transmission system, with high capacity optical fiber links encircling the globe in both terrestrial and undersea applications (1). Optical fiber communications technology has been extensively employed and deployed in global communications networks and throughout terrestrial systems, from fiber-to-the-home schemes in several countries to internetworking between countries and major cities. Optical networking uses optical fiber to carry data, voice, or video signals from one place to another. Those signals travel as pulses of infrared light, which are created by a light-emitting diode (LED) or a laser at one end of the fiber.

Optical networks are high-capacity telecommunications networks based on optical technologies and components that provide routing, grooming, and restoration at the wavelength level as well as wavelength based services. Most optical networks are used to carry enterprise data over substantial distances, such as between two buildings or between two cities, rather than to individual computers. Optical fiber has tremendous bandwidth and this helps them carry much more data over greater distances than copper wire of equivalent size (2). Because of this, optical networks can carry many forms of information simultaneously. For example, Internet Protocol (IP) data, ESCON (computer storage) traffic, and telephone calls can coexist on an optical network. The optical fiber immunity to electromagnetic interference that can affect copper wire is an added

advantage over copper, a quality that is especially desired in some medical, security, and national-defense applications.

Several innovative configurations for optical transmission systems and distribution networks have been made possible due to the enormous bandwidth of optical fibers and the advancements in optical communications technology. Current deployments of optical signals over single mode optical fibers are only based on single channels either at 1310 nm or 1550 nm windows, except in some field trail systems and networks. It is essential that these enormous bandwidth regions should be used extensively. Intense investigation and experiments of ultra-long and ultra-high speed optical communication systems have been carried out together with interests in the multiplexing of optical carriers in the same fiber channel.

1.2 Optical Networks

Telecommunication networks have evolved during a century-long history of technological advances and social changes. The networks that once provided basic telephone service are now capable of transmitting the equivalent of thousands of encyclopedias per second. Throughout, the digital network has evolved in three fundamental stages: asynchronous, synchronous, and optical (3).

1.2(a) Asynchronous

The first digital networks were asynchronous networks. In asynchronous networks, each network element's internal clock source timed its transmitted signal. Because each clock had a certain amount of variation, signals arriving and transmitting could have a large variation in timing, which often resulted in bit errors.

More importantly, as optical-fiber deployment increased, no standards existed to mandate how network elements should format the optical signal. A myriad of proprietary methods appeared, making it difficult for network providers to interconnect equipment from different vendors.

1.2(b) Synchronous

The need for optical standards led to the creation of the synchronous optical network (SONET). SONET standardized line rates, coding schemes, bit-rate hierarchies, and operations and maintenance functionality. SONET also defined the types of network elements required, network architectures and the functionality that each node must perform. Network providers were now able to use different vendor's optical equipment with the confidence of at least basic interoperability.

1.2(c) Optical

The one aspect of SONET that has allowed it to survive during a time of tremendous changes in network capacity needs is its scalability. Based on its open-ended growth plan for higher bit rates, theoretically no upper limit exists for SONET bit rates. However, as the bit rates increased, the physical limitations of laser sources and optical fiber made the increasing bit rate on each signal an impractical solution. Additionally, connection to the networks through access rings has also had increased requirements. To provide full end-to-end connectivity, a new paradigm was needed to meet all the high-capacity and varied needs. Optical networks provided the required bandwidth and flexibility to enable end-to-end wavelength services.

Optical networks began with wavelength division multiplexing (WDM), which provided additional capacity on existing fibers. Like SONET, defined network elements and

architectures provided the basis of the optical network. However, unlike SONET, rather than using a defined bit-rate and frame structure as its basic building block, the optical network was based on wavelengths. The components of the optical network were defined according to transmission, grooming implementation of wavelengths in the network.

1.3 Driving Factors behind Optical Networks:

Here the factors that are the driving factors behind the optical networks are described.

1.3(a) Fiber Capacity:

The first implementation of what has emerged as the optical network began on routes that were fiber-limited. When providers needed more capacity between two sites, higher bit rates or fibers were not available. The only option in these situations was either to install more fiber, which is an expensive and labor-intensive chore, or place more time division multiplexed (TDM) signals on the same fiber. WDM provided many "virtual" fibers on a single physical fiber. By transmitting each signal at a different frequency, network providers could send many signals on one fiber just as though they were each traveling on their own fiber.

1.3(b) Restoration Capability:

As network planners use more network elements to increase fiber capacity, a fiber cut can have massive implications. In current electrical architectures, each network element performs its own restoration. For a WDM system with many channels on a single fiber, a fiber cut would initiate multiple failures, causing many independent systems to fail. By performing restoration in the optical layer rather than the electrical layer, optical networks can perform protection switching faster and more economically. Additionally,

the optical layer can provide restoration in networks that currently do not have a protection scheme. By implementing optical networks, providers can add restoration capabilities to embedded asynchronous systems without first upgrading to an electrical protection scheme.

1.3(c) Reduced Costs:

In systems using only WDM, each location that demultiplexes signals needs an electrical network element for each channel, even if no traffic is dropping at that site. By implementing an optical network, only those wavelengths that add or drop traffic at a site need corresponding electrical nodes. Other channels can simply pass through optically, which provides tremendous cost savings in equipment and network management. In addition, performing space and wavelength routing of traffic avoids the high cost of electronic cross-connects, and network management is simplified.

1.3(d) Wavelength Services:

One of the great revenue-producing aspects of optical networks is the ability to resell bandwidth rather than fiber. By maximizing capacity available on a fiber, service providers can improve revenue by selling wavelengths, regardless of the data rate required. To customers, this service provides the same bandwidth as a dedicated fiber.

1.4 Types of Transmission Networks

The evolution to the optical layer in telecommunications networks will occur in stages in different markets because the traffic types and capacity demands for each are different. Overall, the growth is predicted to be enormous (see the figure below). There are mainly

two different types of transmission networks: one for long-haul environment and the other for metro-inter office environment.
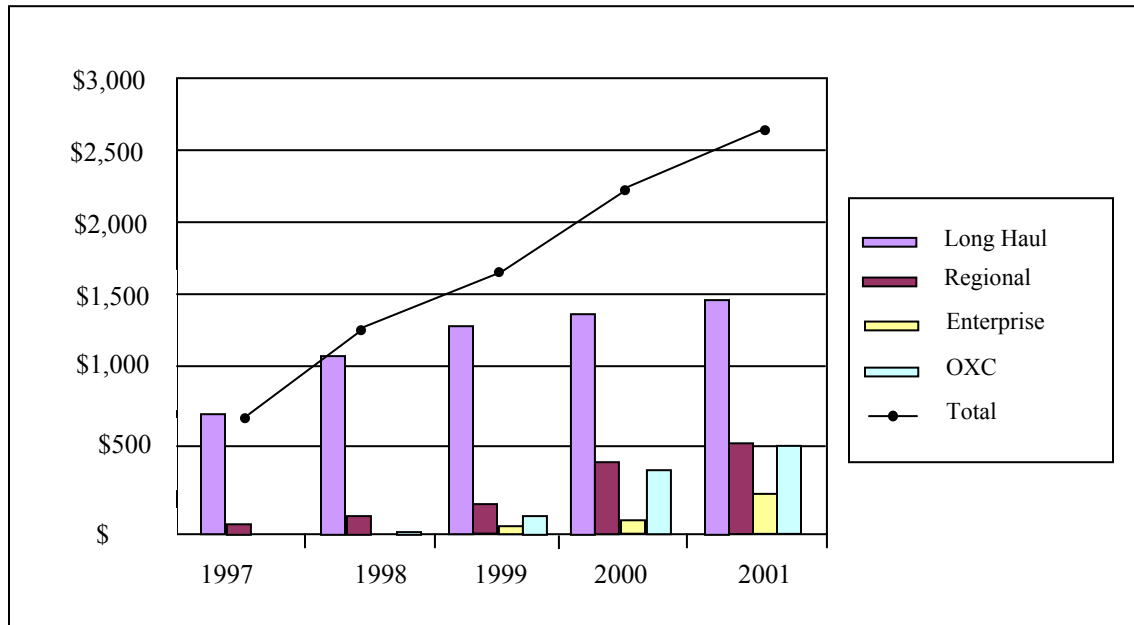
Figure 1.1: Optical Network Market (in Millions of Dollars)

1.4(a) Long-Haul Environment

Spanning in many cases for thousands of miles, long-haul networks are different from all other markets in several important regards: long spans between nodes and extremely high-bandwidth requirements.

Long-haul optics refers to the transmission of visible light signals over optical fiber cable for great distances, especially without or with minimal use of repeaters. Normally, repeaters are necessary at intervals in a length of fiber optic cable to keep the signal quality from deteriorating to the point of non-usability. In long-haul optical systems, the

goal is to minimize the number of repeaters per unit distance, and ideally, to render repeaters unnecessary.

The backbone network is the traditional long-haul network that has been around for many years. Typical backbone networks have the following characteristics:

- There are an extensive number of points where traffic is going onto or leaving the network.

- Distances of a circuit (a service) transported on this network are less than 600 km.

Long-haul networks were the first to have large-scale deployment of optical amplifiers and wideband WDM systems mainly because of cost reductions. Optical amplifiers are a cheaper alternative to a large number of electrical regenerators in a span. In addition, using WDM, inter exchange carriers increased the fiber capacity by using WDM, which avoids the large expenditures of installing new fiber.

Optical networking technologies have brought about radical changes and revolutionary possibilities for long-haul optical transport. Service providers are driven to continually lower the cost per bit per kilometer while maximizing fiber usage and increasing service velocity to meet customer demand. Service providers continually evaluate solutions that lengthen spans, increase capacity, and enhance performance.

While technological advancements overcome the constraints that previously hindered cost-effective long-haul optical transport, market drivers in today's complex optical core are converging to form distinct segments around which service providers are designing their networks. These segments include:

- Conventional Long-Haul (LH), which serves spans of fiber between signal regeneration devices of up to 600 km.

- Extended Long-Haul (ELH), supporting spans of 600 to 2,000 km while reducing network costs.

- Ultra Long-Haul (ULH), which supports spans of over 2,000 km and is best, suited for the all-photonic network of the future in which photonic switching plays a key role in the backbone.

While traditional views have broken the core transport market into two segments, the LH and ULH, the third -- the Extended Long-Haul -- is emerging as the sweet spot for long-haul transport where service providers can maximize channel count, speed, and distance.

As end-to-end transport becomes the mantra of ever more carriers, long-haul optical technology is revolutionizing approaches to overall network design with promises of improvements in capacity, flexibility and cost- efficiency at the regional and metro levels as well as dramatic gains in signal reach over great distances. The expanding impact of techniques typically associated with ultra-long-haul (ULH) performance ties directly into the fact that as optical wavelength switching gains traction among carriers that operate end-to-end networks. Network designers will have to plan for how each aspect of the optical architecture affects every other aspect across traditional topological boundaries. According to some vendors, the driving force behind the roll out of optical platforms employing innovations such as solitons, Raman amplifiers and so-called "super" forward error correction (FEC) has at least as much to do with this perspective on network design as it does with any demand for systems that can deliver a terabit payload

in a straight shot over a single fiber for a distance of 3,000 kilometers, which is the performance level now being reached by some ULH systems.

Forward Error Correction (FEC) -- serves to synchronize the reading of the bit stream in accord with how the stream has been distorted as it travels over the network, resulting in a net code gain of several decibels once the coding penalty associated with synchronization is subtracted from the amount of recovered code.

Raman pump lasers -- deliver a stream of photons into the fiber core or into a Raman-optimized erbium-doped fiber amplifiers where, as they travel through the fiber and lose energy from collisions with atoms in the glass, they drop to lower frequencies and assume the wavelength and signal pattern of the primary light wave in the 1550 nm waveband, resulting in a great boost in the signal power without the addition of spurious signals or noise.

Solitons -- Concentrations of multiple light pulses that capitalize on the fact that when such pulses are in precise phase with each other they combine into a single, high-energy pulse that is more resistant to degradation as it travels through fiber than any of the original pulses would be.

1.4(b) Metro-Inter Office (IOF) Environment:

Networks in the metro interoffice (IOF) have different needs for optical technologies. IOF networks are typically more interconnected and geographically localized. Because of the traffic patterns and distances between offices, optical rings and optical cross-connects will be required much earlier. IOF networks not only need to distribute traffic throughout a region, they must also connect to the long-haul network. As the optical network

evolves, Wavelength add/drop and interconnections add flexibility and value that IOF networks require.

1.4(c) Business Access Networks:

The "last mile" of the network to business customers has gone by many names: Wide-Area Networks (WANs), Metropolitan-Area Networks (MANs), and Business-Access Networks. Regardless of the name, these networks provide businesses with connections to the telecommunications infrastructure. It is these networks where the application of optical networks is not so clear. Many more complexities arise in these networks, including variable bit-rate interfaces, different cost structures, and different capacity needs. Similar in architecture to IOF networks, business-access network sites are much closer together, so fiber amplification is not as important.

An important component for optical networks in business-access networks is the asynchronous transponder, which allows a variety of bit-rate signals to enter the optical network. Optical networks designed for the business access environment will need to incorporate lower-cost systems to be cost-effective and enable true wavelength services. The challenge will be proving when and where DWDM is effective in access networks.

1.5 Optical Fiber Performance Characteristics:

The key optical performance parameters for fibers are attenuation and dispersion. Dispersion is discussed in detail in the next chapter.

1.5(a): Attenuation:

The reduction in signal strength is measured as attenuation. Attenuation measurements are made in decibels (dB). The decibel is a logarithmic unit that indicates the ratio of

output power to input power. Each optical fiber has a characteristic attenuation that is normally measured in decibels per kilometer (dB/km) (4).
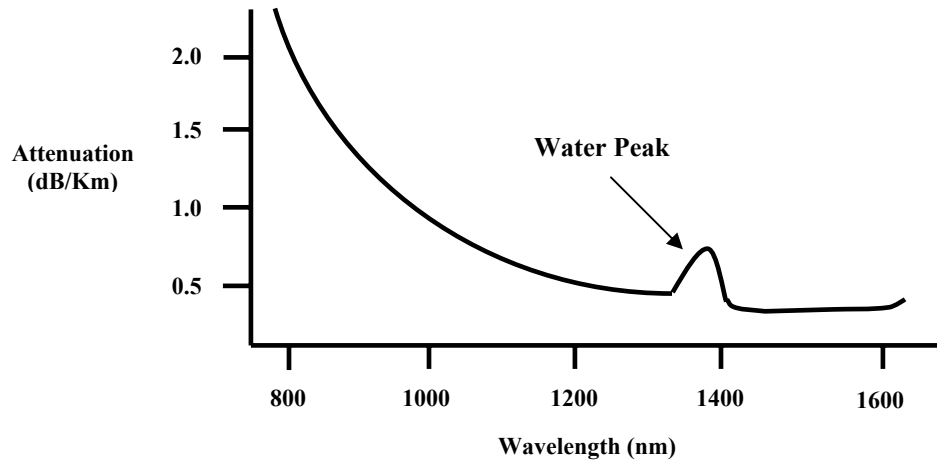
Figure 1.2: Typical Attenuation vs. Wavelength

Optical fibers are distinctive in that they allow high-speed transmission with low attenuation. Attenuation can be caused by several factors, but is generally placed in one of two categories: intrinsic or extrinsic.

1.5 (a-1): Intrinsic Attenuation:

Intrinsic attenuation occurs due to something inside or inherent to the fiber. It is caused by impurities in the glass during the manufacturing process. As precise as manufacturing is, there is no way to eliminate all impurities, though technological advances have caused attenuation to decrease dramatically since the first optical fiber in 1970.

When a light signal hits an impurity in the fiber, one of two things will occur: it will be either scattered or absorbed.

Scattering

Rayleigh scattering accounts for the majority (about 96%) of attenuation in optical fiber. Light travels in the core and interacts with the atoms in the glass. The light waves elastically collide with the atoms, and light is scattered as a result. Rayleigh scattering is the result of these elastic collisions between the light wave and the atoms in the fiber. If the scattered light maintains an angle that supports forward travel within the core, no attenuation occurs. If the light is scattered at an angle that does not support continued forward travel, the light is diverted out of the core and attenuation occurs.

Some scattered light is reflected back toward the light source (input end). This is a property that is used in an Optical Time Domain Reflectometer (OTDR) to test fibers. This same principle applies to analyzing loss associated with localized events in the fiber, such as splices.

Absorption

The second type of intrinsic attenuation in fiber is absorption. Absorption accounts for 3-5% of fiber attenuation. This phenomenon causes a light signal to be absorbed by natural impurities in the glass, and converted to vibrational energy or some other form of energy.

Unlike scattering, absorption can be limited by controlling the amount of impurities during the manufacturing process.

1.5(a-2): Extrinsic Absorption:

The second category of attenuation is extrinsic attenuation. Extrinsic attenuation can be caused by two external mechanisms: macrobending and microbending. Both cause a reduction of optical power (5).

Macrobending:

If a bend is imposed on an optical fiber, strain is placed on the fiber along the region that is bent. The bending strain will affect the refractive index and the critical angle of the light ray in that specific area. As a result, light traveling in the core can refract out, and loss occurs. A macrobend is a large-scale bend that is visible; for example, a fiber wrapped around a person's finger. This loss is generally reversible once bends are corrected.

To prevent macrobends, all optical fiber (and optical fiber cable) has a minimum bend radius specification that should not be exceeded. This is a restriction on how much bend a fiber can withstand before experiencing problems in optical performance or mechanical reliability. The rule of thumb for minimum bend radius is 1 1/2" for bare, single-mode fiber; 10 times the cable's outside diameter (O.D.) for non-armored cable; and 15 times the cable's O.D. for armored cable.

Microbending:

The second extrinsic cause of attenuation is a microbend. This is a small-scale distortion, generally indicative of pressure on the fiber. Microbending may be related to temperature, tensile stress, or crushing force. Like macrobending, microbending will cause a reduction of optical power in the glass.

Microbending is much localized, and the bend may not be clearly visible upon inspection. With bare fiber, microbending may be reversible; in the cabling process, it may not.

1.6 Different Types of Single Mode Fibers:

Although we have got several different types of fibers, we shall only deal with single mode fibers in this section, as we shall be concentrating on them in the future sections. We shall only deal with the dispersion in the single mode fibers. There are four different types of single-mode fiber in use today. These are standardized by the IEC (International Electrotechnical Commission) and ITU (International Telecommunications Union). The ITU-T Series G.652 recommendation, commonly referred to as standard single-mode fiber, represents the majority of the installed base of single-mode fiber. The G.652 recommendation describes both standard single-mode fiber (IEC type B1.1) and low water-peak standard single-mode fiber (IEC type B1.3).

1.6(a-1): Standard Single-Mode Fiber (IEC 60793-2 B1.1 & B1.3 / ITU G.652):
Standard single-mode fiber is essentially a thin core (5-8 microns) of Silicon/Germanium-doped glass surrounded by a thicker layer of pure glass and is the workhorse of the optical communications infrastructure. Nearly any application can be addressed with standard single-mode fiber, but it is optimized to support transmission at 1310 nm. Performance issues with standard single-mode fiber can become more significant as higher data rates (such as 10 Gbps) and longer distances (>40 km) are encountered. Low water-peak standard single-mode fiber (IEC type B1.3) has the same dispersion characteristics as standard single-mode fiber (IEC type B1.1), but has reduced attenuation in the region of the water peak (nominally 1383 nm). As no specification is given for water-peak attenuation in standard single-mode fiber, attenuation in the region

of 1383 nm can be significantly higher than that at 1310 nm. By reducing the water impurities introduced in this region during the time of manufacture, low water-peak standard single-mode fiber provides identical support to standard single mode fiber, plus can support additional wavelengths between 1360 and 1460 nm.

1.6(a-2): Dispersion Shifted Fiber (DSF) (IEC 60793-2 B2 / ITU G.653):

Dispersion shifted fiber (DSF) was introduced in the mid 80's and represents a very small percentage of the installed base of single-mode fiber. The need for DSF was driven by the development of 1550 nm lasers which have much less fiber attenuation than 1310 nm lasers. DSF allowed optical signals to travel significantly farther without the need for regeneration or compensation due to reduced chromatic dispersion characteristics, effectively allowing an optical pulse to maintain its integrity over longer distances. DSF was well suited to meet these needs for single-channel optical transmission systems. However, with the advent of broadband optical amplifiers and wavelength division multiplexing (WDM) the chromatic dispersion characteristics of DSF presented detrimental effects to multiple wavelength signal integrity. As a result, a new type of fiber was introduced, namely non-zero dispersion shifted fiber (NZDSF).

1.6(a-3): Cutoff Shifted Single-Mode Fiber (IEC 60793-2 B1.2 / ITU G.654):

Cutoff shifted single-mode fiber is designed to allow for extended transmission distances through lower attenuation and the ability to support higher power signals. This fiber is typically used only for transmission in the 1550 nm region due to a high cutoff wavelength around 1500 nm. Due to significant manufacturing complexity, cutoff shifted single-mode fiber is typically much more expensive than other single-mode fiber types. It

is commonly found only in submarine applications due to the stringent requirements in such an environment.

1.6(a-4):Non-Zero Dispersion Shifted Fiber (NZDSF) (IEC 60793-2 B4 / ITU G.655):

Non-zero dispersion shifted fiber (NZDSF) was introduced in the mid 90's to address issues encountered with multiple wavelength transmission over DSF by maintaining a finite amount of chromatic dispersion across the optical window (typically 1530-1625 nm) commonly exploited by wavelength division multiplexing (WDM). The primary concern addressed by NZDSF is a nonlinear effect known as four wave mixing (FWM). In simple terms, three wavelengths carrying different information can generate signals at another wavelength. In the regularly spaced channel plan of most WDM systems (usually 1.6 nm or less between adjacent wavelengths); the newly generated noise signals can overlap with a wavelength carrying live traffic. NZDSF mitigates this effect by ensuring that all wavelengths in the region of interest (1530-1625 nm) encounter some finite dispersion and thus signals on adjacent wavelengths will not overlap in time for extended periods. Four wave mixing is reduced as the time during which adjacent wavelength signals overlap is shortened. The reduced chromatic dispersion of NZDSF can also reduce the detrimental contributions of other nonlinear effects such as self-phase modulation (SPM) and cross-phase modulation (XPM). NZDSF is optimized for transmission in the 1530-1625 nm window, but can support some 1310 nm configurations with proper consideration given to laser type and system configurations.

Name	ITU-T	IEC	Optimized Dispersion Range (in nm)
Standard Single Mode Fiber (Dispersion Unshifted Fiber)	G.652	IEC 60793-2 (B1.1,B1.3)	1300-1324
Dispersion Shifted Fiber (DSF)	G.653	IEC 60793-2 (B2)	1500-1600
Cutoff Shifted Fiber	G.654	IEC 60793-2 (B 1.2)	1550-1625
Non-Zero Dispersion Shifted Fiber (NZDSF)	G.655	IEC 60793-2 (B4)	1530-1565 (C-band) 1555-1625 (L-band)

Table 1.1: Different Types of Fibers

1.7 Conclusion:

The above discussions presented a brief idea on the present optical networks scenario and also put forth the basic concepts of optical fibers. In this chapter, we have reviewed the performance characteristics of the optical fibers along with the various parameters affecting them. The proceeding chapters mainly deal with one of the main characteristics of optical fibers – dispersion.

Chapter 2: Concepts of Dispersion

2.1 Introduction

This chapter deals with the dispersion. A study of dispersion is made here as this is a key characteristic in analyzing the performance of a fiber.

Dispersion is the "spreading" of a light pulse as it travels down a fiber. As the pulses spread, or broaden, they tend to overlap, and are no longer distinguishable by the receiver as 0s and 1s. Light pulses launched close together (high data rates) that spread too much (high dispersion) result in errors and loss of information.
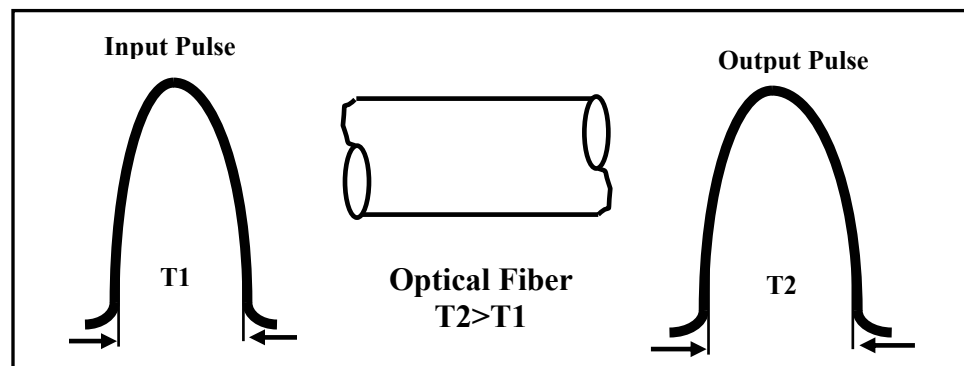
Figure 2.1: Dispersion in Optical Fiber

There are two different types of dispersion in optical fibers.

They are:

1. Intramodal Dispersion

2. Intermodal Dispersion

Intramodal, or chromatic, dispersion occurs in all types of fibers. Intermodal or modal dispersion occurs only in multimode fibers. Each type of dispersion mechanism leads to pulse spreading. As a pulse spreads, energy is overlapped. The spreading of the optical pulse as it travels along the fiber limits the information capacity of the fiber.
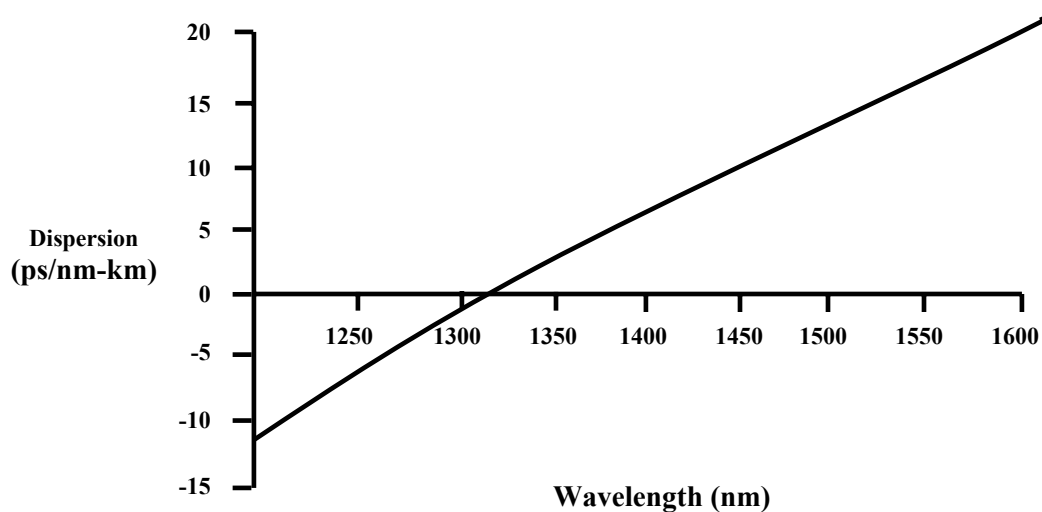
Figure 2.2: Typical Dispersion vs. Wavelength curve

Intramodal Dispersion:

Intramodal, or chromatic, dispersion depends primarily on fiber materials. There are two types of intramodal dispersion. The first type is material dispersion. The second type is waveguide dispersion. Intramodal dispersion occurs because different colors of light travel through different materials and different waveguide structures at different speeds.

2.2 Refractive Index:

Light travels slower within a medium than in a vacuum. The speed at which light travels in the medium is determined by its refractive index. In an ideal situation, the refractive index would not depend on the wavelength of the light. However, this is not the case which results in different wavelengths traveling at different speeds within an optical fiber.

Environmental conditions, such as variations in temperature can change the refractive index of the optical fiber. As temperature increases, so will the refractive index, however, the increase is not uniform over all wavelengths resulting in differing wavelength speeds. In addition, stress, such as the pressure experienced by a submarine cable, can affect the refractive index of an optical fiber.

2.3 Chromatic Dispersion:

Chromatic dispersion is a broadening of the input signal as it travels down the length of the fiber. Chromatic dispersion consists of both material dispersion and waveguide dispersion as illustrated:
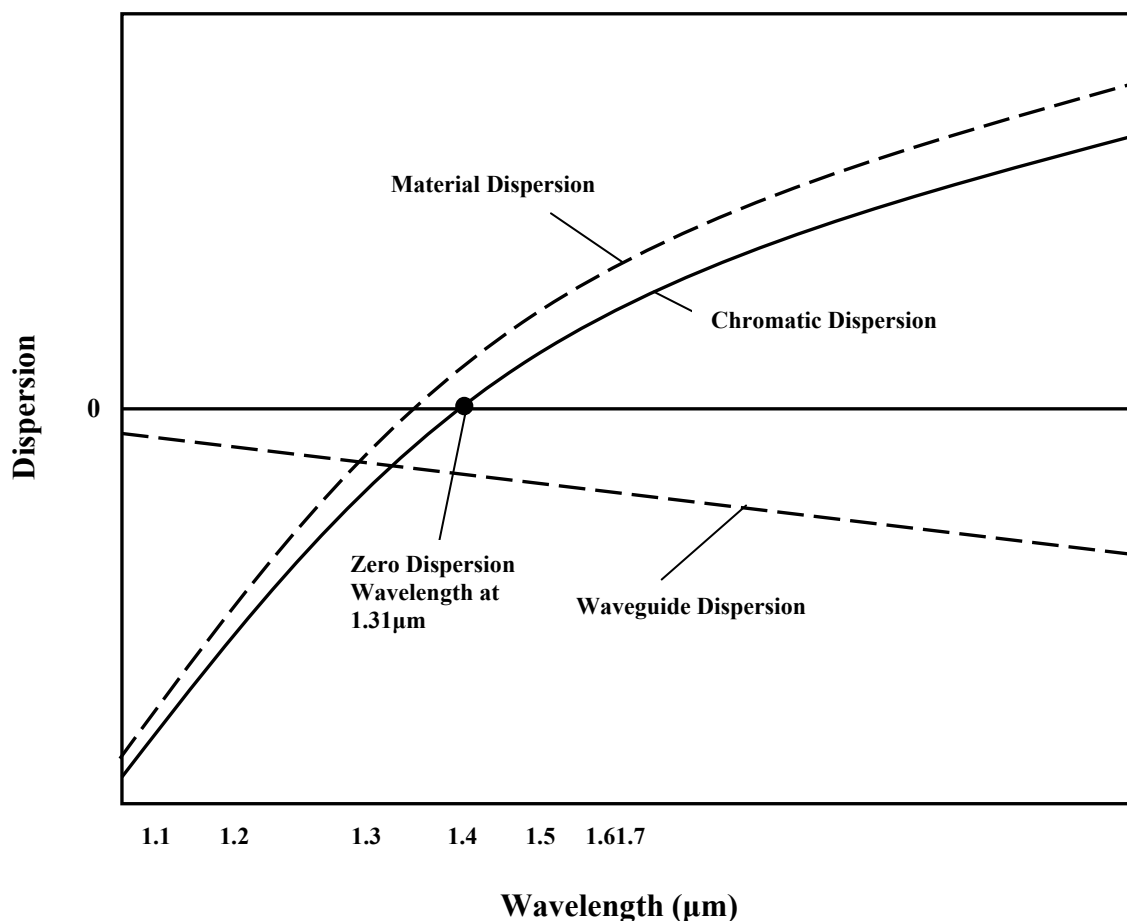
Figure 2.3: Dispersion versus Wavelength Characteristics

When a series of pulses travel down an optical fiber, the pulses broaden or disperse

making them indistinguishable, creating an effect called intersymbol interference. The

source of intersymbol interference arises from the waveguide and material properties of

the optical fiber. One of the dispersive effects caused by the properties of the waveguide

and the material is called chromatic dispersion and is measured in units of ps/nm-km.

A pulse is not monochromatic, but is comprised of several wavelengths. The

amount of broadeninga pulse experiences is a function of the refractive index difference

between the wavelengths contained within the pulse. The difference in the refractive

index results in the wavelengths comprising the pulse to travel at different speeds,

causing some wavelengths to travel faster than others. This phenomenon is known as material dispersion. The detrimental effects of material dispersion result in the slower wavelengths of one pulse intermixing with the faster wavelengths of an adjacent pulse, causing intersymbol interference.

Optical fiber is composed of a core and cladding layer where the refractive index of the core is greater than the refractive index of the cladding. The difference in the refractive index causes most of the light to be confined within the core of the fiber. However, some of the light propagates within the cladding. The difference in the refractive index causes the light in the core traveling slower than the light in the cladding, resulting in a spreading of the pulse. This phenomenon is known as waveguide dispersion. Waveguide dispersion is a function of the wavelength of light, the refractive index difference between the core and cladding layers and the diameter of the core. Changes in the core diameter, the wavelength or the refractive index of the core and cladding will result in a change in the waveguide dispersion. The time between pulses, or bit rate, determines the amount of pulse broadening an optical system can handle. The chromatic dispersion limit, the amount of acceptable dispersion, is inversely proportional to the bit rate squared. This implies higher bit rates can tolerate smaller amounts of dispersion. For instance, a 2.5 Gbps system can experience 16 times more dispersion than a 10 Gbps system and 250 times more dispersion than a 40 Gbps system.

Changes in the refractive index due to temperature variations will result in modifying the amount of chromatic dispersion the pulse experiences. Varying the temperature results in a change of the zero-dispersion wavelength, the wavelength of the least amount of dispersion. The change in the zero dispersion wavelength results in a shift

of the dispersion curve by $\Delta \lambda_0$, either increasing or decreasing the amount of dispersion experienced by the pulse. Not only does the temperature affect the zero dispersion wavelength, pressure and strain also shifts the zero dispersion wavelength. This results from changes in the waveguide properties of the fiber due to pressure or strain. The resultant pressure related change in zero-dispersion wavelength for unshifted fiber is -0.007 nm/MPa, respectively.

2.3 (a) Material Dispersion:

Material dispersion occurs because the spreading of a light pulse is dependent on the wavelengths' interaction with the refractive index of the fiber core. Different wavelengths travel at different speeds in the fiber material. Different wavelengths of a light pulse that enter a fiber at one time exit the fiber at different times. Material dispersion is a function of the source spectral width. The spectral width specifies the range of wavelengths that can propagate in the fiber. Material dispersion is less at longer wavelengths.

2.3 (b) Waveguide Dispersion:

Waveguide dispersion occurs because the mode propagation constant is a function of the size of the fiber's core relative to the wavelength of operation. Waveguide dispersion also occurs because light propagates differently in the core than in the cladding. In multimode fibers, waveguide dispersion and material dispersion are basically separate properties. Multimode waveguide dispersion is generally small compared to material dispersion. Waveguide dispersion is usually neglected. However, in single mode fibers, material and waveguide dispersion are interrelated. The total dispersion present in

single mode fibers may be minimized by trading material and waveguide properties depending on the wavelength of operation.

2.4 Intermodal Dispersion:

Intermodal or modal dispersion causes the input light pulse to spread. The input light pulse is made up of a group of modes. As the modes propagate along the fiber, light energy distributed among the modes is delayed by different amounts. The pulse spreads because each mode propagates along the fiber at different speeds. Since modes travel in different directions, some modes travel longer distances.

Modal dispersion occurs because each mode travels a different distance over the same time span. The modes of a light pulse that enter the fiber at one time exit the fiber at different times. This condition causes the light pulse to spread. As the length of the fiber increases, modal dispersion increases. Modal dispersion is the dominant source of dispersion in multimode fibers. Modal dispersion does not exist in single mode fibers. Single mode fibers propagate only the fundamental mode. Therefore, single mode fibers exhibit the lowest amount of total dispersion. Single mode fibers also exhibit the highest possible bandwidth.

2.5 Conclusion:

In this chapter, an overview of the concepts of dispersion has been presented. The chapter mainly focused on the various types of dispersion, its occurrence and effects. The next chapter deals with the Sellmeier coefficients and its dependence on pressure and temperature along with a brief review of the technical papers used. The chapter also gives an insight into the material dispersion equations.

Chapter 3: Sellmeier Coefficients

3.1 Introduction:

As dispersion is an important characteristic in the transmission of optical fibers, much work is being carried out to minimize it during the transmission. For analyzing the refractive indices of optical materials, the two-pole Sellmeier dispersion formula, is the most accurate of the dispersion formulas, and can fit index data to accuracy consistent with the measurements and the accuracy needed for most optoelectronic applications. The analyses of papers that have been used for this thesis work have also been analyzed.

Fiber lasers and amplifiers are considered the initial step in the replacement of the older electronic regenerators leading to an all-optic complete photonics future. The basic component in the fiber lasers, amplifiers and various kinds of optical fibers is Silica glass. Characteristics of silica glass such as refractive index (RI), dispersion, chromatic dispersion and its variation as a function of temperature and pressure play an important role in the evaluation of optical fiber transmission system. Characterization of refractive indexes with sufficient accuracy is important in the ultrafast optical fiber communication systems (OCFS) and in other optical devices.

Owing to its sound physical basis, Sellmeier method is considered to be one of the most common techniques for the measurement for the above mentioned desirable characteristics of silica, and its suitable interpolation/extrapolation technique is the state of art. Chromatic dispersions play a vital role in the optical fiber communication system (OFCS), especially for undersea submarine optical fiber cables used to transmit optical

signals from one continent to other Evaluation of chromatic dispersion, at different

temperatures and different pressures requires knowledge of refractive index as a function

of temperature and pressure respectively. The two-pole Sellmeier formula has been

considered a physically meaningful model that is capable of representing the refractive

indices (RIs) with wavelengths for all optical materials satisfactorily. One pole is due to

electronic resonance absorption, and the other is due to lattice/ionic absorption. The

refractive index of any optical material is determined by two types of resonance

absorption – one due to electronic transitions of oscillators and the other due to the lattice

vibrations of the material in the IR region.

3.2 Wavelength Dependent Sellmeier Equation:

The wavelength dependent Sellmeier Equation is of the form

$$n^2 = A + \frac{B\lambda^2}{\lambda^2 - C} + \frac{D\lambda^2}{\lambda^2 - E}$$

Where, λ is the wavelength in μm. The last term accounts for the decrease in the

refractive indexes due to lattice absorption, where as the first and second terms represent

the contribution to refractive indexes due to higher energy and lower energy gaps of

electronic absorption. The method of fitting a refractive index data for low refractive

index materials to a Sellmeier in order to evaluate constants was first described by

Maltison. More about the Sellmeier equation is described in the section to follow.

3.3 Temperature Dependence:

Of the two factors determining temperature dependence, electronic effect is more

dominant than lattice/ionic effect in diamond-like semiconductor crystals. An observation

on the physical origin of chromatic dispersion in fused silica presented that all

manifestations of chromatic dispersion in the silica optic window possess a temperature modulation dominated by temperature derivative of the Sellmeier valence to conduction band energy gap. Here the temperature derivative of the average energy gap is considered and since in such glasses the variation of energy gap with temperature is much larger than that of thermal expansion a positive dn/dT is observed. Then they allowed variations in the electronic energy gap, keeping lattice absorption frequency constant while evaluating temperature dependency of Sellmeier coefficients. A negligible shift of lattice absorption gap was observed when temperature was changed. The authors succeeded in formulating the temperature dependent Sellmeier coefficients of optical fiber glasses to calculate the RIs at any wavelength and at any operating temperature. These were not only useful in the determination of optical design parameters but also were capable of predicting the operating features of fiber optics as a function of temperature.

3.4 Pressure Dependence:

Here, a physically meaningful two-pole Sellmeier equation that is capable of representing the RIs for all optical materials satisfactorily to account for the change of RIs against pressure in silica glass. The dispersion is analyzed in a physically meaningful Sellmeier-type equation by considering a constant dn/dP at the measured pressure increments/intervals for the silica glass. The optical constants can be used to calculate the Sellmeier coefficients at any operating pressure. The authors successfully formulated the pressure-dependent Sellmeier coefficients to calculate RIs at any wavelength and at any operating pressure. These were not only useful in the determination of optical design parameters but also were capable of predicting the operating features of fiber optics as a function of pressure

3.5 Refractive Index and Sellmeier Equation:

The refractive indices are the fundamental parameters of the optical materials. There are many dispersive relations accounting for the refractive indices. Normally the measured refractive indices are fitted with the desired dispersive relation. However, the fitting accuracy should be the dominant consideration in choosing a dispersion formula having fewer optical parameters. For analyzing the refractive indices of optical materials, the two-pole Sellmeier dispersion formula, is the most accurate of the dispersion formulas, and can fit index data to accuracy consistent with the measurements and the accuracy needed for most optoelectronic applications.

The room temperature values of refractive indices are used to evaluate the Sellmeier coefficients A, B, C, D and E for mostly all optical materials. Sometimes, other forms of Sellmeier equations are used to evaluate the Sellmeier coefficients. The five evaluated Sellmeier coefficients are used to calculate the refractive index for any wavelength lying within the normal transmission region of the optical materials.

3.6 Different Dispersive relations for Refractive Index:

The dielectric constant and refractive index are function of wavelength and hence frequency. The variation of wavelength or frequency of refractive index is dispersion. Dispersion is an important optical design parameter in correcting chromatic aberration and this of much importance for ultra fast optical fiber communication systems.

Refractive indices are measured at discrete wavelengths within the transmission region of the optical materials with sufficient accuracy. It is desirable to have a functional form for the dispersion of the refractive index to have interpolated or extrapolated values.

Many formulae are used to represent the refractive index. One of them is the Sellmeier equation.

The Sellmeier equation was first proposed by Sellmeier in 1871 and hence it is so called. The equation is:

$$n^2(\lambda) = 1 + \sum_{i=1}^{m} \frac{a_i \lambda^2}{(\lambda^2 - \lambda_i^2)} \qquad \text{............................ (Equation 1)}$$

where λ is the wavelength of the incident radiation and a_i is a constant that depends on the number of oscillations per unit volume and is called the oscillator strength of the oscillators resonant at the wavelength λ_i and m is a collection of number of harmonic oscillators resonant to a radiation of various wavelengths λ_i

It was believed that the dispersion formula of the Sellmeier type best fits the refractive indices of the alkali halide crystals in their transmission region. As a result, most of the early experimental researchers adopted the above equation 1 with λ_i's and a_i's as adjustable empirical constants chosen only to fit data without any theoretical or experimental basis or explanation. Nevertheless, if the equation used correctly, gives a good deal of explanation concerning the position of absorption band, oscillator strength and the dielectric constant for static field.

The above equation 1 can be rewritten for the transparent region as:

$$\varepsilon = n^2(\lambda) = 1 + \sum_{i=1} \frac{b_i \lambda^2}{(\lambda^2 - \lambda_i^2)} + \sum_{j=1} \frac{c_j \lambda^2}{(\lambda^2 - \lambda_j^2)} \qquad \text{...... (Equation 2)}$$

The first summations are contributions from ultraviolet absorption bands and the second summations are due to infrared absorption bands. But at $\lambda_1 = 0$, equating the wavelength of the shortest wavelength resonance to zero makes the first term constant. The constant

term represents contributions to the refractive index from electronic transitions at energies far above the band gap. Sellmeier terms with small λ_i (representing electronic transitions), can be expanded a power series:

$$\frac{a_i \lambda^2}{(\lambda^2 - \lambda_i^2)} = a_i \sum_{j=0}^{\infty} \left(\frac{\lambda_i^2}{\lambda^2}\right)^j = a_i + \frac{a_i \lambda_i^2}{\lambda^2} + \frac{a_i \lambda_i^4}{\lambda^4} + \ldots\ldots\ldots\ldots \quad \ldots \text{(Equation 3)}$$

and the terms with large λ_i (representing vibrational transitions) are expanded as:

$$\frac{a_i \lambda^2}{(\lambda^2 - \lambda_i^2)} = -a_i \sum_{j=1}^{\infty} \left(\frac{\lambda^2}{\lambda_i^2}\right)^j = -a_i \frac{\lambda^2}{\lambda_i^2} - a_i \frac{\lambda^4}{\lambda_i^4} + \ldots\ldots\ldots\ldots \quad \ldots\ldots \text{(Equation 4)}$$

The power-series approximations of the Sellmeier equation are expressed in many forms. The equations 3 and 4 were used to represent the index of refraction for Schott and Ohara optical glasses as the power series approximation to the Sellmeier equation. One common form was used by Schott and Ohara is given by:

$$n^2 = A_0 + A_1 \lambda^2 + A_2 \lambda^{-2} + A_3 \lambda^{-4} + A_4 \lambda^{-6} + A_5 \lambda^{-8} \ldots\ldots\ldots\ldots \text{(Equation 5)}$$

A comparison of the Schott power-series formula with a three-term Sellmeier formula showed equivalent accuracy of the range of the Schott fit, but the Sellmeier model was accurate over a much wider wavelength range. A generalized form of the short-wavelength approximation to the Sellmeier equation is the Cauchy formula developed in 1836. This was the first successful attempt to represent dispersion by an empirical equation. The equation is:

$$n = A_0 + \sum_{i=1} \frac{A_i}{\lambda_i^2} \quad \text{............................} \quad \text{(Equation 6)}$$

The Hartmann formula is also commonly used for the index of refraction. This is related

to the Sellmeier equation for a limited spectral region as:

$$n = A + \frac{B}{(\lambda - \lambda_0)} \quad \text{...........................} \quad \text{(Equation 7)}$$

Among all these dispersion equations, Equation 2 is the most significant and can be

transformed to

$$\varepsilon = \varepsilon_{uv} + \sum \frac{c_j \lambda^2}{(\lambda^2 - \lambda_j^2)},$$

where $\varepsilon_{uv} = 1 + \sum b_i = \varepsilon_s - \sum c_j$ is the high-frequency dielectric constant. In the

transparent wavelength region, the damping effects are negligibly small. It is

scientifically useful and physically acceptable to use an average absorption band gap and

also an average lattice absorption band gap.

$$n^2 = A + \frac{B\lambda^2}{\lambda^2 - C} + \frac{D\lambda^2}{\lambda^2 - E}$$

3.7 Material Dispersion Equation:

The propagation loss of single mode fibers has been reduced to the most intrinsic

limit of the material by proper fiber design and by OH radical reduction in both core and

cladding. As intermodal dispersion can be removed in the single mode fiber, only

material dispersion and waveguide dispersion, which are much smaller than the

multimode dispersion, remains resulting in broad bandwidth characteristics.

Wavelength dispersion arises from variation of group delay per unit length τ with

wavelength λ. That is

$$s = \frac{d\tau}{d\lambda} \quad \ldots\ldots\ldots \text{ (1)}$$

$$\tau = \frac{\lambda^2}{2\pi c} \frac{d\beta}{d\lambda} \quad \ldots\ldots\ldots \text{ (2)}$$

Where c is the speed of light in vacuum and β is the propagating constant. Wavelength

dispersion is separated into material dispersion s_m and waveguide dispersion s_w. That is

$s = s_m + s_w$. The analysis of material dispersion is as follows:

The scalar wave equation in the weakly guiding fiber, with the arbitrary refractive index

profile n(r), is written as:

$$\nabla^2 \psi(r) + \left(\frac{\omega^2}{c^2} n^2(r) - \beta^2 \right) \psi(r) = 0 \text{ ..(3)}$$

Where $\psi(r)$ represents transverse components of the electric or magnetic field, β, c and

ω are propagation constants of the guided wave, light speed in vacuum and angular

frequency respectively. Normalized frequency is defined as:

$$v = (2\Pi a / \lambda)\sqrt{\left(n_{max}^2 - n_{clad}^2\right)} \ldots \text{ (4)}$$

Here, n_{max} is the maximum value of the refractive index in the core, n_{clad} is the cladding

refractive index, λ is the wavelength in vacuum and a is the effective core radius. The

scalar equation is rewritten by using v as:

$$\nabla'^2 \psi(r') + [v^2 f(r') - v^2 b]\psi(r') = 0 \dots (5)$$

Where

$$b = \left(\beta^2 / k^2 - n_{clad}^2\right) / \left(n_{max}^2 - n_{clad}^2\right)$$

$$f(r') = \left(n^2(r') - n_{clad}^2\right) / \left(n_{max}^2 - n_{clad}^2\right)$$

$$r' = r / a$$

$$\nabla' = a\nabla \dots \dots \dots (6)$$

Here, b and $f(r')$ are the normalized propagation constant and the normalized refractive index profile respectively. Equation (5) indicates that b depends only on v where $f(r')$ is assumed to be independent of the wavelength.

The propagation constant β is expressed from equation (6) as:

$$\beta^2 = k^2[n_{clad}^2 + \left(n_{max}^2 - n_{clad}^2\right)b] \dots \dots \dots (7)$$

Putting equation (7) into (2), τ is obtained as:

$$\tau = -\frac{1}{c}\left[n_{clad}N_{clad} + \left(b + \frac{v}{2}\frac{db}{dv}\right).\left(n_{max}N_{max} - n_{clad}N_{clad}\right)\right] \Big/ \left(n_{clad}^2 + \left(n_{max}^2 - n_{clad}^2\right)b\right)^{1/2} \dots (8)$$

Where N_{max} and N_{clad} are the group indexes. Then s is obtained by differentiating equation (8) with respect to λ, without any approximation, as:

$$s = s_m^c + s_w^c + s_d^c$$

Where

$$s_m^c = -\frac{\lambda n_{max}}{c n_{clad}}\frac{d^2 n_{max}}{d\lambda^2}H(v) + \left(1 - H(v)\right)\frac{2}{c}\frac{d^2 n_{clad}}{d\lambda^2}\bigg/[1 + 2\nabla b]^{1/2}$$

$$s_w^c = \frac{-n_{clad}\Delta}{\lambda c(1 + 2\Delta b)^{1/2}}\left(1 - \frac{\lambda}{n_{clad}}\frac{dn_{clad}}{d\lambda}\right)^2 G(v) - \frac{n_{clad}\Delta^2}{\lambda c(1 + 2\Delta b)^{3/2}}\left(1 - \frac{\lambda}{n_{clad}}\frac{dn_{clad}}{d\lambda} - \frac{\lambda}{2\Delta}\frac{d\Delta}{d\lambda}\right)^2 .(F(v) - b)$$

$$s_d^c = \frac{-n_{clad}\lambda(d\Delta/d\lambda)}{\lambda c\left((1 + 2\Delta b)^{1/2}\right)}\left(1 - \frac{\lambda}{n_{clad}}\frac{dn_{clad}}{d\lambda} - \frac{\lambda}{4\Delta}\frac{d\Delta}{d\lambda}\right) * \left[G(v) + (F(v) - b)\left(1 - \frac{2\Delta b}{(1 + 2\Delta b)^{1/2}}\right)\right]$$
$$+ \frac{n_{clad}^3(\lambda d\Delta)}{\lambda c(1 + 2\Delta b)^{1/2}}H(v)(1 - b)$$

$$F(v) = \frac{d(vb)}{dv}$$

$$G(v) = v\frac{d^2(vb)}{dv^2}$$

$$H(v) = (F(v) + b)/2$$

$$\Delta = \frac{n_{max}^2 - n_{clad}^2}{2n_{clad}^2}....................(9)$$

Since Δ and $\lambda d\Delta/d\lambda$ are smaller than unity in the weakly guiding optical fiber, higher order terms with respect to these parameters may be neglected. Furthermore, the absolute values of $(\lambda/n_{clad})(dn_{clad}/d\lambda)$ and $(\lambda/\Delta)(d\Delta/d\lambda)$ in the Ge doped silica optical fiber in the 0.9-1.6 μm region may be evaluated, by using the parameters below, to be less than

0.02 and 0.05 respectively, which may also be neglected when compared to unity. Then equation (9) becomes:

$$s = s_m + s_w + s_d$$

$$s_m = -\left(\frac{\lambda}{c}\frac{d^2 n_{max}}{d\lambda^2}H(v) + (1-H(v))\frac{\lambda}{c}\frac{d^2 n_{clad}}{d\lambda^2}\right)$$

$$s_w = -\frac{n_{clad}\Delta}{c}G(v)$$

$$s_d = -\frac{n_{clad}}{\lambda c}\frac{d\Delta}{d\lambda}(G(v) + F(v) - b) \quad\ldots\ldots\ldots\ldots\ldots\ldots \text{(10)}$$

In equation 10, $-(\lambda/c)(d^2 n_{max}/d\lambda^2)$ and $-(\lambda/c)(d^2 n_{clad}/d\lambda^2)$ indicate the material dispersion the material dispersions corresponding to the maximum refractive index and the cladding index, respectively. Material dispersion s_m is the linear combination of $-(\lambda/c)(d^2 n_{max}/d\lambda^2)$ and $-(\lambda/c)(d^2 n_{clad}/d\lambda^2)$ with a weighting factor $H(v)$.

The meaning of $H(v)$ is discussed. The relation between the group velocity v_g or τ and the phase velocity v_p for the wave propagation in the inhomogeneous and the nondispersive media may be generalized to the dispersive case as

$$1/(v_g v_p) = \left[\int n(x,y)N(x,y)|\psi|^2 \, ds \Big/ c^2 \int |\psi|^2 \, ds\right] \ldots\ldots \text{(11)}$$

by introducing the dispersive refractive index into the variation expression for the angular frequency . Here $n(x,y), N(x,y)$ and ψ are the refractive index, the group index and the wave function respectively. The integration is performed over the cross section of the

propagating wave. Since the velocities v_p and v_g are expressed as ω/β and $1/(d\beta/d\omega)$, respectively. $1/(v_g v_p)$ may be rewritten using equations (7) and (9) as

$$1/(v_g v_p) = \left[n_{clad} N_{clad} + (n_{max} N_{max} - n_{clad} N_{clad}) \left(b + \frac{v}{2} \frac{db}{dv} \right) \right] \cdot \frac{1}{c^2} \quad \ldots \ldots (12)$$

then   equation   (11)   can   be   rewritten   as

$$n_{clad} N_{clad} + (n_{max} N_{max} - n_{clad} N_{clad}) H(v) = \left[\int_{core} n(x,y)N(x,y)|\psi|^2 \, ds + n_{clad} N_{clad} \int_{clad} |\psi|^2 \, ds \Big/ \int |\psi|^2 \, ds \right]$$

$\ldots\ldots\ldots$ (13)

by separating the integration of the numerator $\int ds$, and the cladding part $\int_{clad} ds$, and by

the relation $H(v) = b + (v/2)[db/dv]$. Thus,

$H(v) = k' P_c$, where P_c expresses the fractional field power in the core. In the

homogeneous core fiber, the fractional field power is unity. Therefore H(v) in the

homogeneous core fiber is the fractional power in the core.

Waveguide dispersion s_w is determined only by waveguide parameters. The main part of

waveguide dispersion is governed by G(v), which depends only on the v value. So,

dispersion values depend on the refractive index profile. This fact may be utilized during

the manufacture of the optical fibers.

The third term in equation (10) indicates the dispersion effect caused by $\lambda d\Delta/d\lambda$. The

total dispersion therefore is expressed as $s = s_m + s_w$.

3.8 Conclusion:

The thesis mainly focuses on the pressure dependent Sellmeier coefficients and temperature dependent Sellmeier Coefficients, as an important factor to optimize optical design parameters of the optical fiber transmission system. A study of Sellmeier equations and the coefficients have been done. The next chapter deals with the simulations and the dispersion characteristics for different pressures and temperatures.

Chapter 4: Simulation Results

4.1 Introduction:

The dispersion characteristics are important in analyzing the optical fiber characteristics.
This chapter helps in understanding the material dispersion characteristics and zero
dispersion wavelength characteristics of silica fibers at various pressures and
temperatures.

4.2 Simulation Program:

The Matlab program can be explained as a process of three steps. Initially the values for
refractive index and wavelength are plotted against each other. In the next step the values
of material dispersion and wavelength are plotted against each other. This is considered
to be the important part of the program. Finally, the zero dispersion values are calculated
for different wavelengths for different pressures and temperatures.

For the initial step, the Sellmeier equation which relates refractive index and different
Sellmeier coefficients is considered. The equation is:

$$n^2 = A + \frac{B\lambda^2}{\lambda^2 - C} + \frac{D\lambda^2}{\lambda^2 - E}$$

This equation is the building block on which the whole program is based on. Then the
values of different Sellmeier coefficients are taken. The values of Sellmeier coefficients
are different for pressure and temperature. From the above equation, refractive index, n,
is calculated by taking the square root on the equation. Changing the Sellmeier
coefficients for different pressure and temperatures at the desired wavelength λ, the

refractive index is obtained at the desired pressure/temperature and wavelength. Thus the obtained values of refractive index are plotted against wavelength. Since the Sellmeier coefficients don't change hugely for different values of pressure/temperature, a noticeable change isn't noticed in the graphs.

The second step in the program is to find the material dispersion at a desired wavelength with the use of Sellmeier coefficients. For obtaining the material dispersion, the Sellmeier equation which is considered is double differentiated with respect to wavelength, and the result of this equation is multiplied with wavelength over velocity of light. Material dispersion is defined as:

$$M(\lambda) = -\frac{\lambda}{c}\left(\frac{d^2 n(\lambda)}{d\lambda^2}\right).$$

In this step, the material dispersion is found at a specific pressure/temperature, varying the wavelength. For doing so, an array of 10 is declared for both material dispersion M, and wavelength λ. The value of array produces the specific number of iterations. By varying the size of array, precise values can be obtained. The values of material dispersion obtained at the particular wavelengths are stored in their respective arrays and are plotted against each other.

In this thesis, the values of Sellmeier coefficients for pressure and temperature are obtained from a technical paper. In order to have the values for any pressure or temperature, the current set of values are extrapolated and a new set of values are obtained. Likewise, the Sellmeier coefficient values can be obtained for any pressure or temperature.

Finally the zero dispersion wavelengths are calculated using the Sellmeier constants and also with the extrapolated coefficients. The zero dispersion wavelength plots are linear.
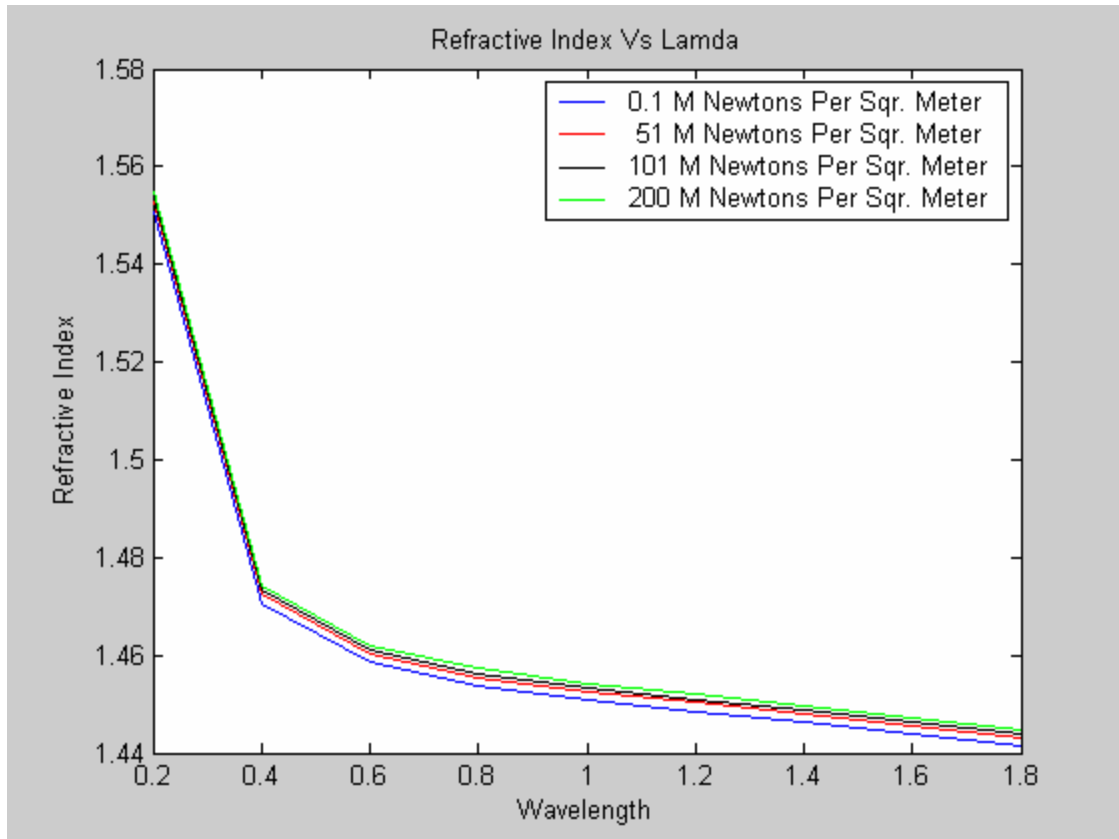
4.3 Results:

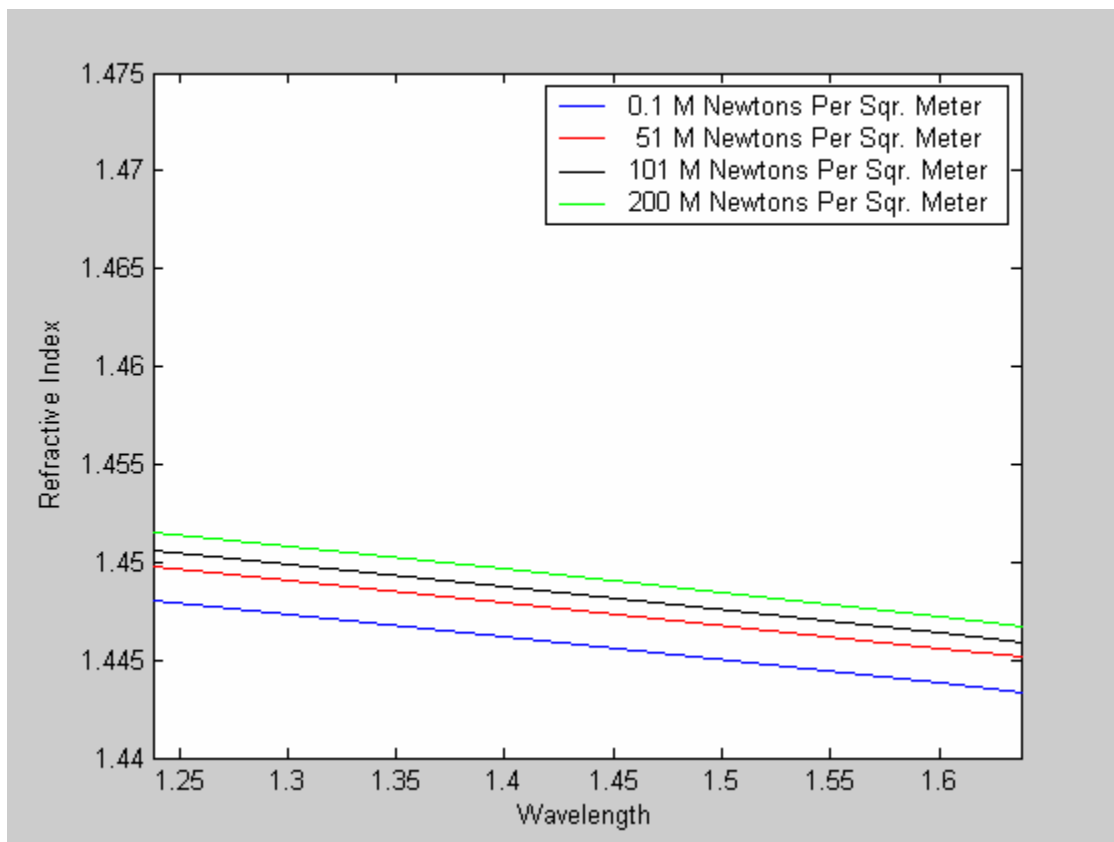Figure 4.1: Refractive Index Versus Material Dispersion for Various Pressures

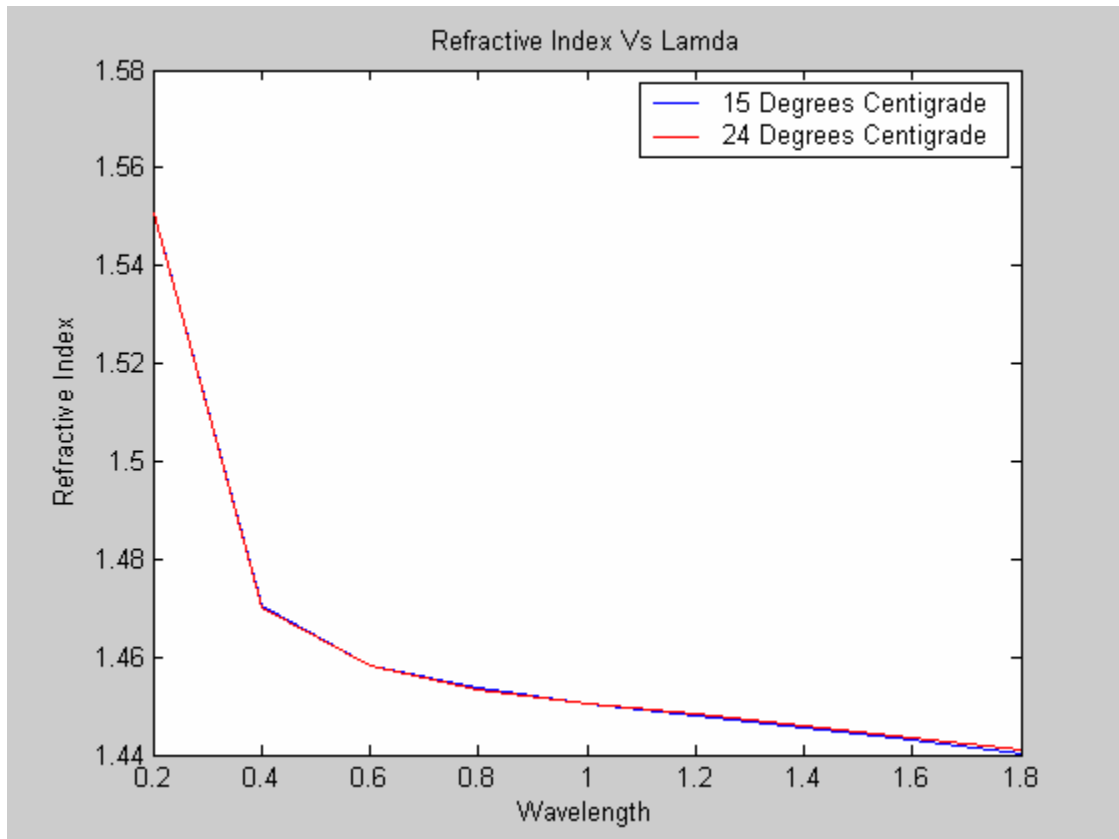Figure 4.2: Enlarged Section of Previous graph from 1.3µm to 1.55µm

Figure 4.3: Refractive Index Versus Wavelength for Different Values of Temperature
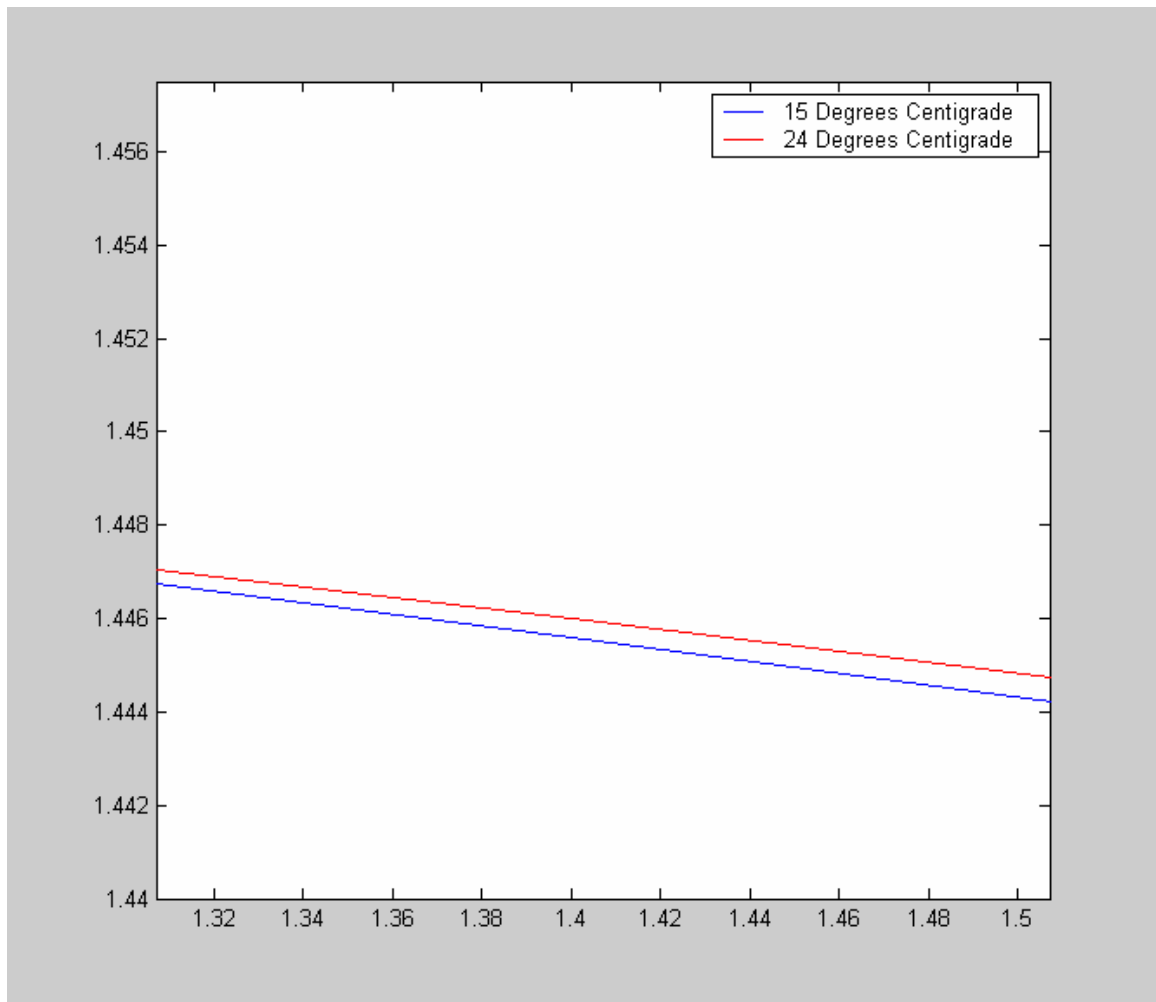
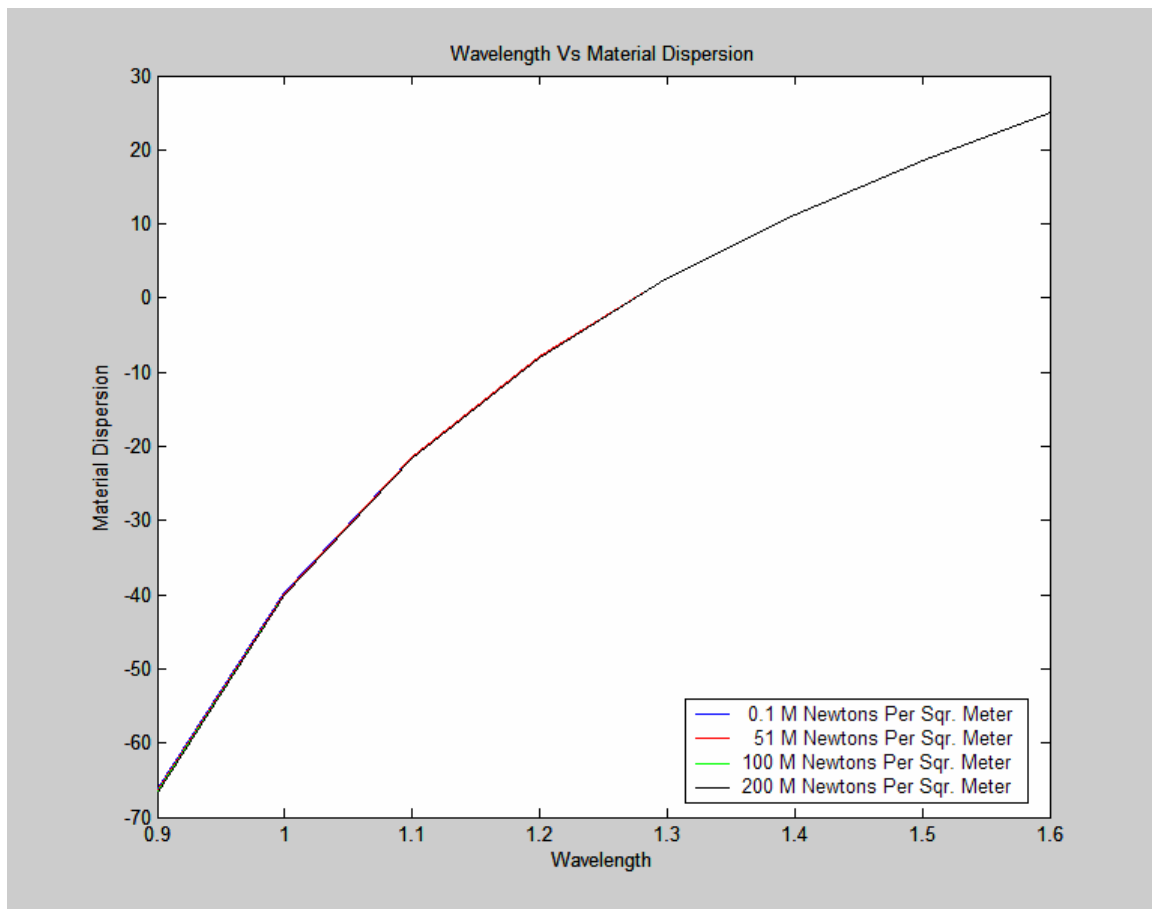Figure 4.4: Enlarged Section of Previous graph from 1.3µm to 1.5µm

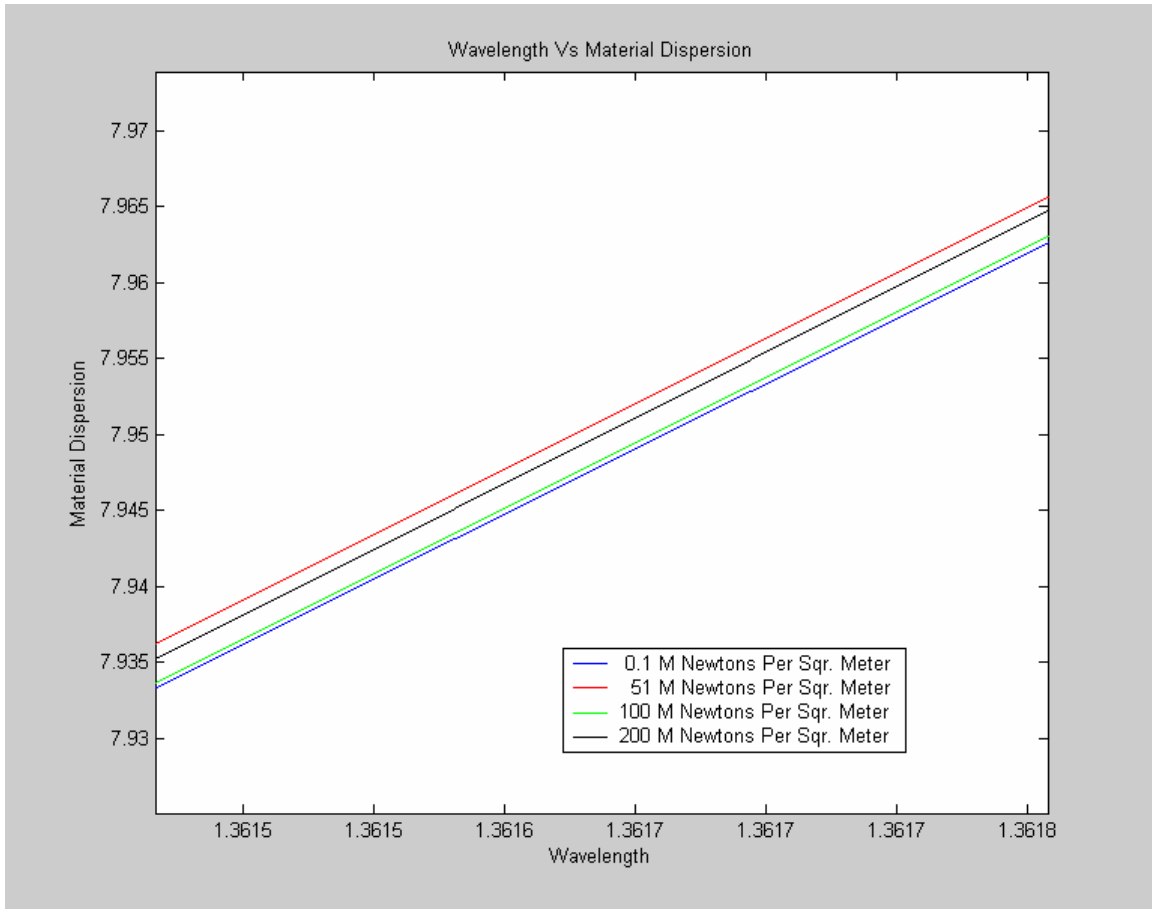Figure 4.5: Wavelength Versus Material Dispersion for Various Values of Pressure

Figure 4.6: Enlarged View of a Section of Previous Graph

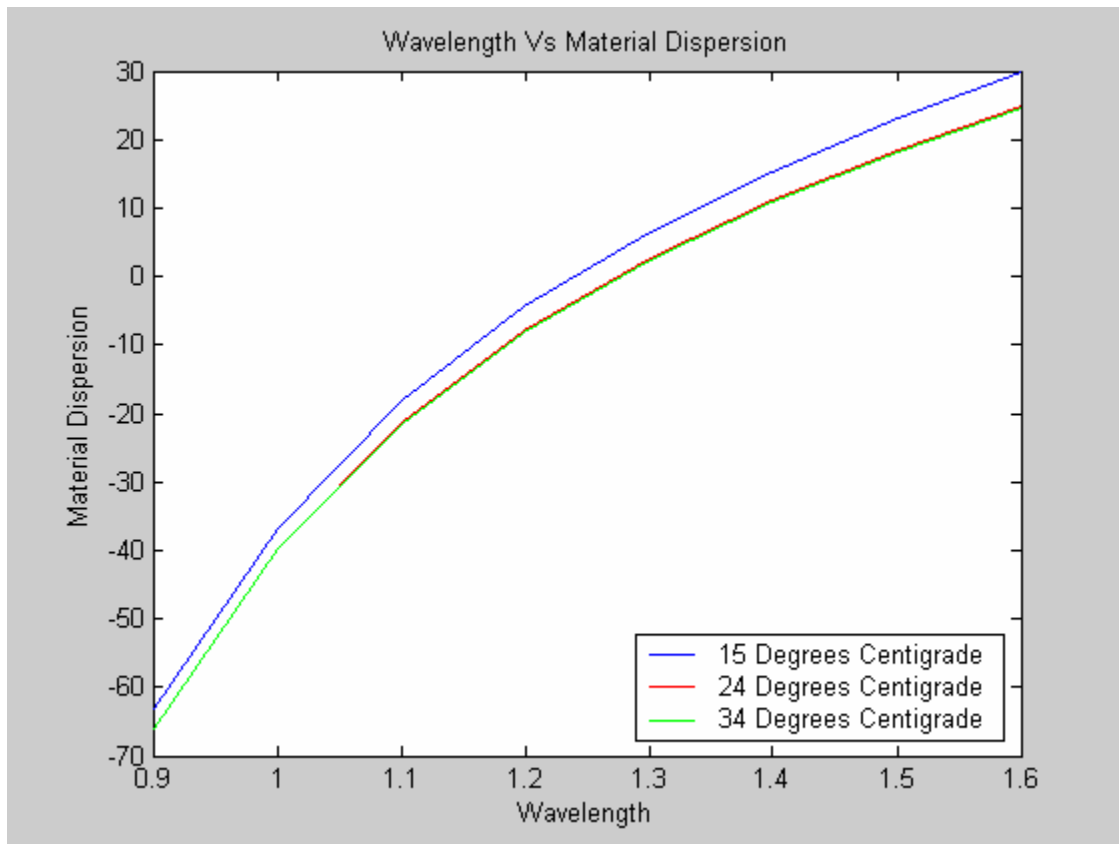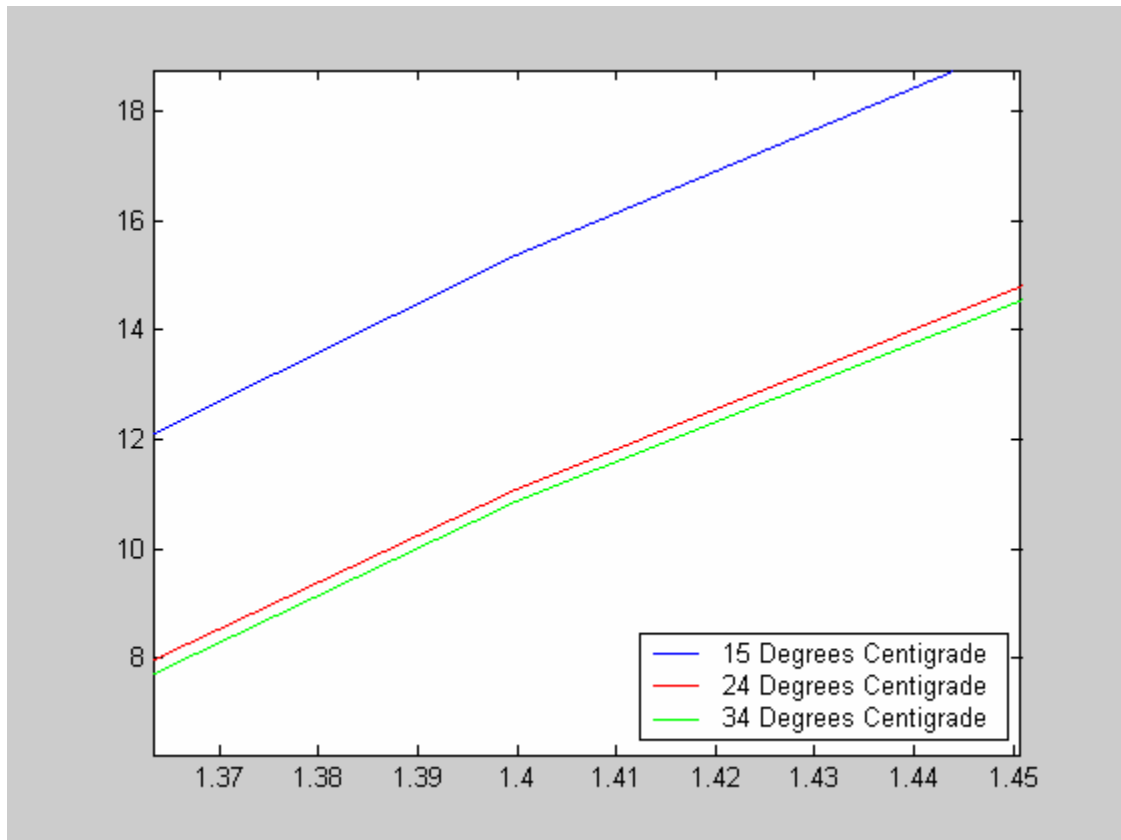Figure 4.7: Wavelength Versus Material Dispersion for Values of Temperature

Figure 4.8: Enlarged View of a Section for the previous graph
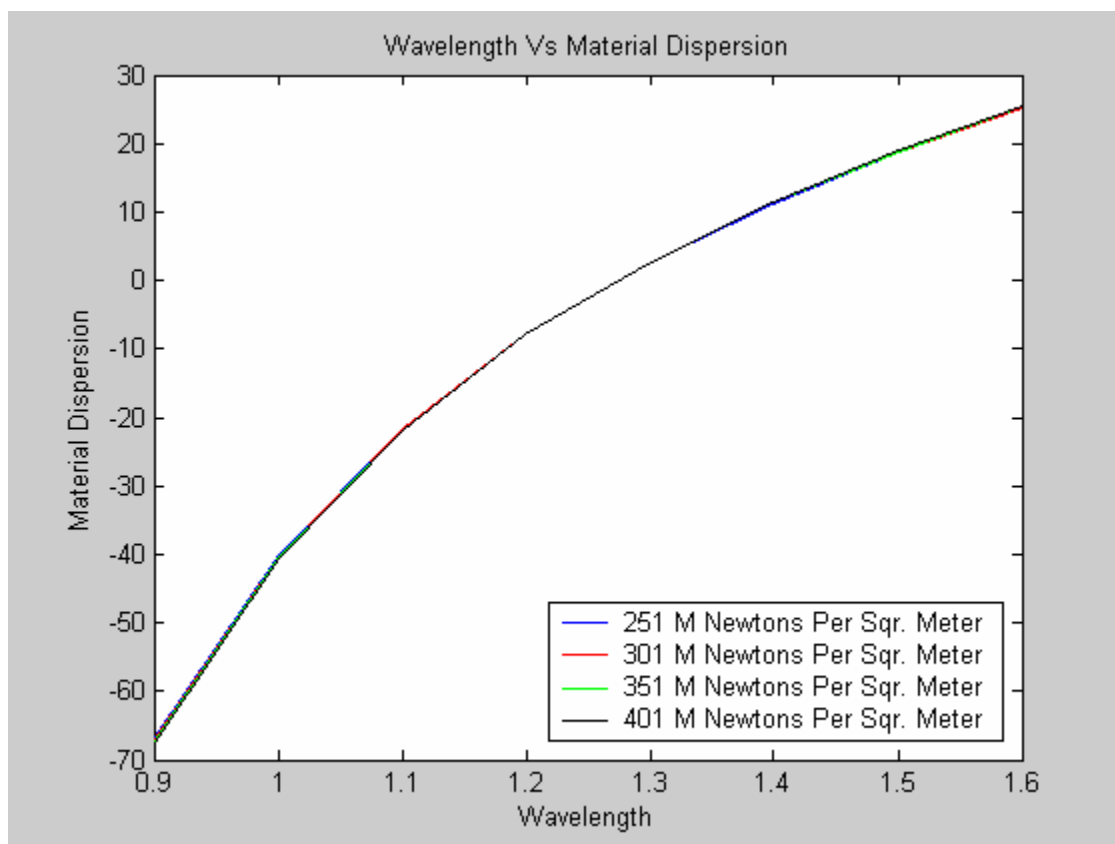
Figure 4.9: Wavelength Versus Material Dispersion for Different Extrapolated Values of Pressure
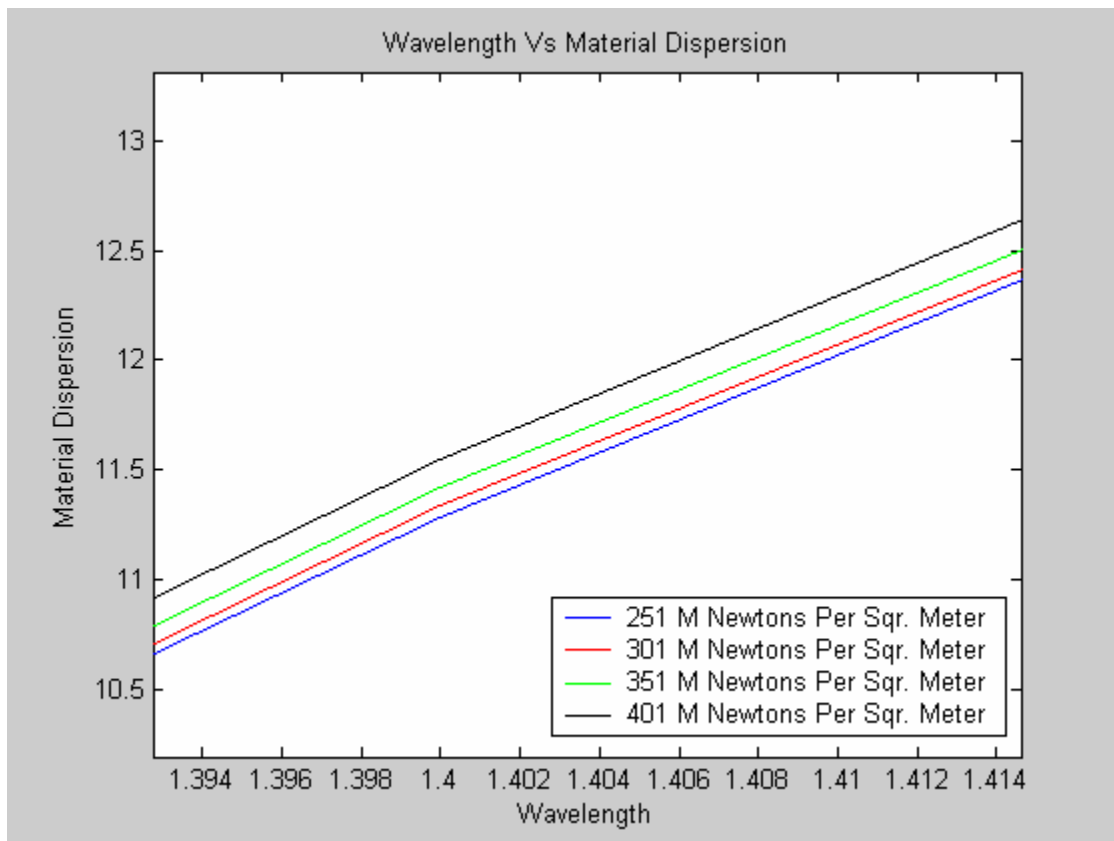
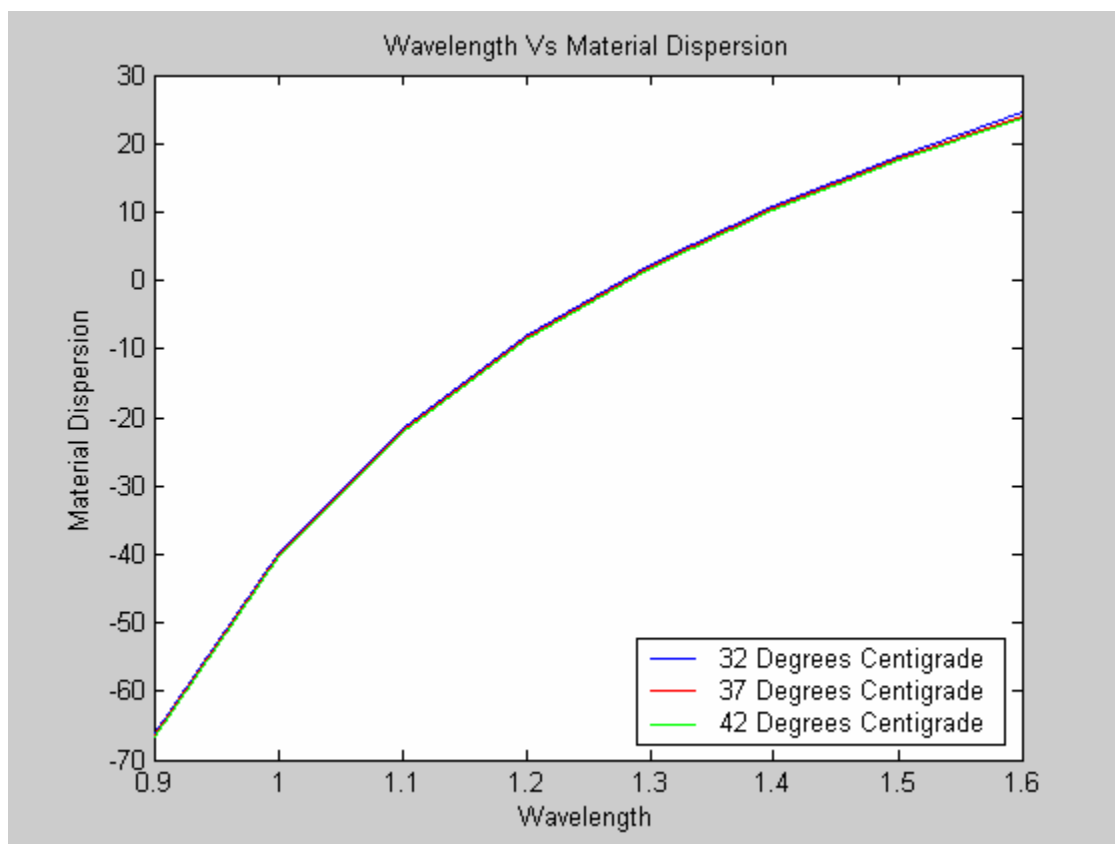Figure 4.10: Enlarged View of a Section for the previous graph

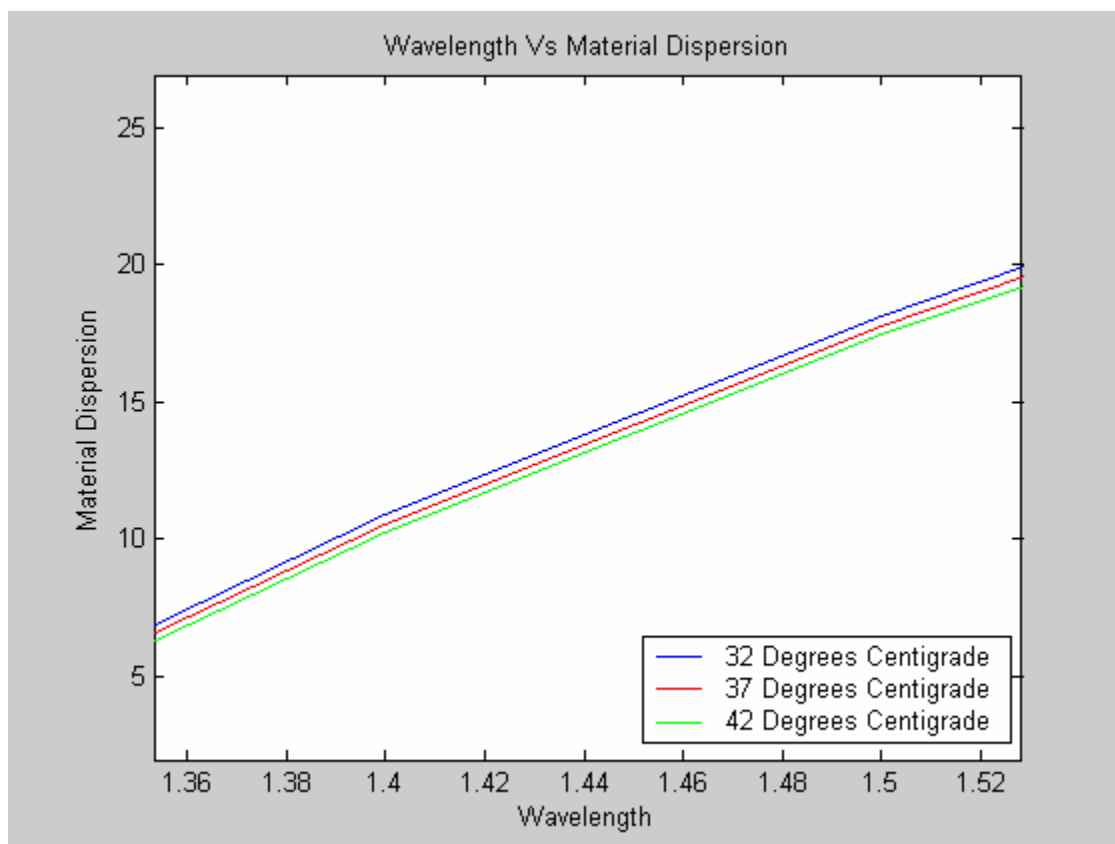Figure 4.11: Wavelength Versus Material Dispersion for Different Extrapolated Values of Temperature

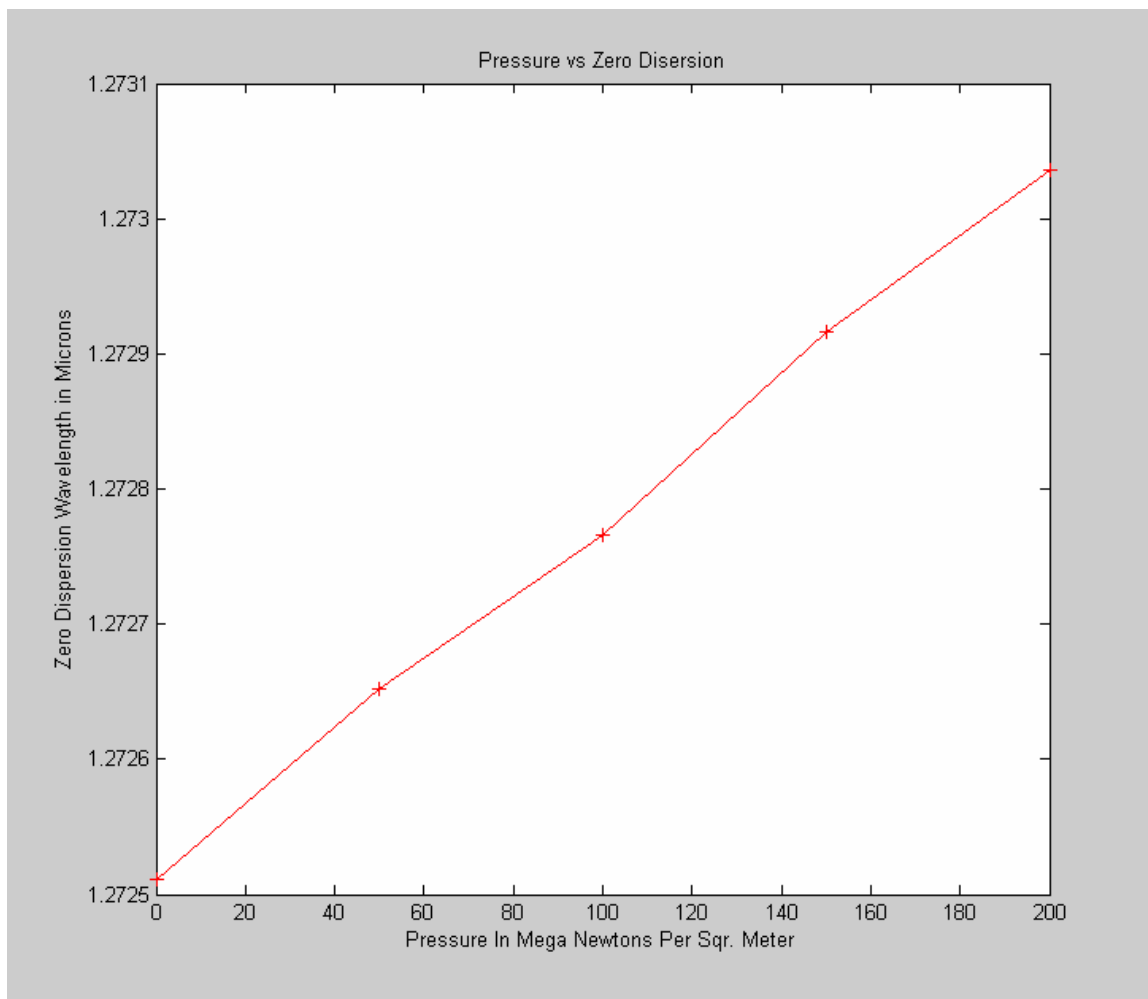Figure 4.12: Enlarged View of a Section of previous figure

Figure 4.13: Zero Dispersion Wavelengths for Different Values of Pressure

4.4 Discussions:

The refractive index and material dispersion is calculated for various pressures and temperatures. An analysis of the results is done in the proceeding section.

Figure 4.1: The refractive index is plotted against for various pressures. The refractive index decreases with the increase in pressure, although with not much variation.

Figure 4.2: The plot shows an enlarged view of the previous graph

Figure 4.3: The refractive index is plotted against wavelength for various temperatures. Here, the refractive index also decreases with increase in temperature, as like in pressure.

Figure 4.4: The graph shows an enlarged view of the previous graph

Figure 4.5: The wavelength is plotted against material dispersion for different values of pressure. Here the material dispersion decreases with increase in pressure. The change is shown using an enlarged view of the plot in the next figure.

Figure 4.6: This plot shows the enlarged view of a part of figure 4.5.

Figure 4.7: This plot shows the wavelength plotted against material dispersion for various values of temperature. Here the material dispersion decreases, similar to pressure, with increase in temperature. The change is shown using a enlarged view of the plot in the next figure.

Figure 4.8: This plot shows an enlarged view of a part of figure 4.7.

Figure 4.9: This plot shows material dispersion plotted against different values of wavelength using the extrapolated values of pressure coefficients. Here also, the change is shown using an enlarged view of the plot in the next figure.

Figure 4.10: This plot shows an enlarged view of a section in figure 4.9.

Figure 4.11: this plot shows the material dispersion plotted against different values of wavelength using the extrapolated values for temperature coefficients. Here the change is also shown using an enlarged view of a portion in the next figure.

Figure 4.12: This plot shows an enlarged view of a section in figure 4.11.

Figure 13: This plot shows the zero-dispersion values for at various values of pressure.

4.5 Conclusion:
The plots of dispersion for different pressures and temperatures are studied. The next chapter deals with the conclusion and future work.

Chapter 5: Conclusions

5.1 Conclusion:

The material dispersions are computed at different pressures and temperatures using the

Sellmeier coefficients.

The pressure dependence of material dispersion at 0.85 μm is -83.865 ps/ (nm-km) at 0.1

Mega Newton's pressure and 21.846 ps/ (nm-km) at 1.55 μm at the same pressure. There

is a little variance with the experimental value of 18.3 ps/ (nm-km) of pure-silica at

1.55 μm. The dispersion characteristics are not linear for the spectral range considered

and the plots showing the dispersion variations with pressure overlap since the pressure

coefficients vary at decimal places. The zero dispersion wavelengths for the glass are also

calculated using different pressure coefficients.

The temperature dependence of material dispersion is calculated at 1.55 μm and is

-1.5*10^ (-3) ps/nm-km at 25 degrees Celsius and is same as the experimental value. The

zero-dispersion wavelengths are calculated and plotted and are linear.

The refractive indices of silica fibers can be calculated from UV region to 1.7 μm for any

temperature or pressure. These are not only useful to determine the optical design

parameters at different pressures/temperatures but for also predicting the operating

features of optical fibers as a function of pressure/temperature.

5.2 Future Work

This thesis is an extended work to various previous papers that propose Sellmeier

coefficients for calculation of refractive index at any temperature and pressure for any

wavelength. As could be observed refractive index is one important factor in any fiber

optic material and the calculation of refractive index plays an important role considering

factors like pressure and temperature. By double differentiating the refractive index,

material dispersion, could be calculated which is a primary factor in analyzing the

performance of a fiber. Here we propose to build a sensor that could be able to calculate

the material dispersion as a function of pressure or temperature for any wavelength or

given the wavelength and the values of material dispersion, the sensor can be able to find

the values of pressure and temperature.

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VITA

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