Research of M in Optical Materials f uides

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Abstract

Recently, the technology of optical waveguide systems has developed rapidly over the past new years. This progressive research and development have received much attention, due to its potential of offering new capabilities in application such as communication fields, optical sources and detectors and integrated optical circuits. Thus, considering optical materials as one of the major elements in optical waveguide, a study of material dispersion occurred in optical materials and its characteristics must be done seriously. Therefore, in this paper, a relation between Abbe number ν and d-line refractive index n_d for optical materials in optical waveguide are investigated. Then, based on this research, a new approximation method and calculation for an idea of expanding the near-infrared region are proposed.

Chapter 1: Introduction

In this chapter, a briefly introduction about the basic of optical waveguide technology is explained. Then, optical materials, which is one of the major field in optical waveguide study are discussed, by explaining and reviewing the characteristics and the applications of the most commonly used materials.

1.1: Optical Waveguide

Shifting to the world new era, mainstream and micro industrial and also human itself require continuous research and development day by day. Optical waveguide technology; one of the technology field that has received vigorous attention from professionals, due to its potential and considerable promise for networks and communications, optical sources, detectors and integrated optical circuits.

An optical waveguide is a physical structure that guides electromagnetic waves in the optical spectrum. Common types of optical waveguides include optical fiber and rectangular waveguides. Optical waveguides are used as components in integrated optical circuits or as the transmission medium in local and long haul optical communication systems. Briefly, optical waveguide can be classified according to their geometry (planar, strip or fiber waveguides), mode structure (single-mode, multi-mode), refractive index distribution (step or gradient index) and material (glass, polymer, and semiconductor).

Figure 1,2 and 3 below briefly shows optical fiber structure, mode structure are single mode and multi mode fiber, and optical fiber size, respectively.

Figure 1. Core, Cladding, and Coating

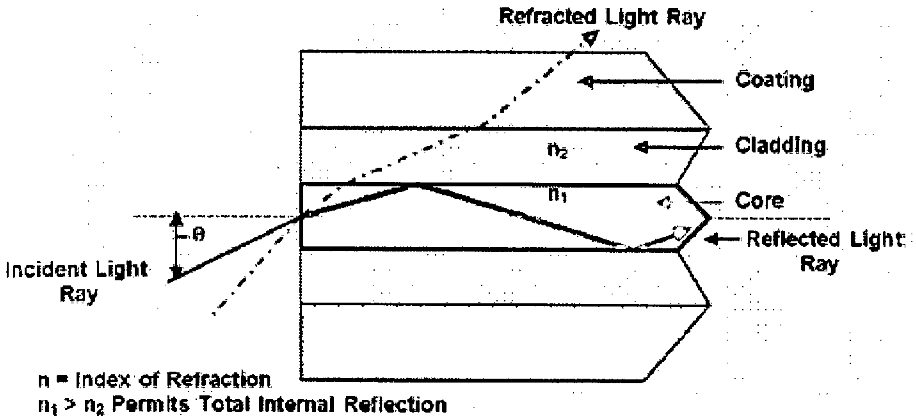


Figure 2. Single-Mode and Multimode Fibers

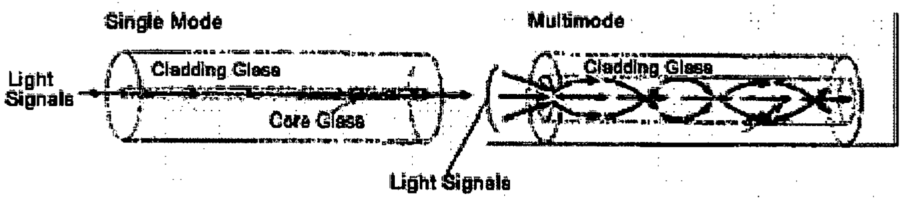
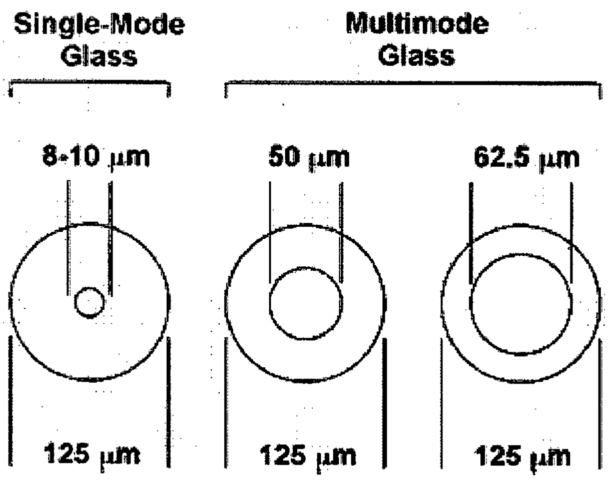


Figure 3. Optical Fiber Sizes



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1.2: Discovering Various Optical Materials and Its Applications

All substances used in the construction of devices or instruments whose function is to alter or control electromagnetic radiation in the ultraviolet, visible, or infrared spectral regions. Optical materials are fabricated into optical elements such as lenses, mirrors, windows, prisms, polarizers, detectors and modulators. These materials serve to refract, reflect, transmit, disperse, polarize, detect and transform light. The term "light" refers here not only to visible light but also to radiation in the adjoining ultraviolet and infrared spectral regions. At the microscopic level, atoms and their electronic configurations in the material interact with the electromagnetic radiation (photons) to determine the material's macroscopic optical properties such as transmission and refraction.

There is a wide range of substances that are useful as optical materials. Most optical elements are fabricated from glass, crystalline materials, polymers, or plastic materials. In the choice of a material, the most important properties are often the degree of transparency and the refractive index, along with each property's spectral dependency. The uniformity of the material, the strength and hardness, temperature limits, hygroscopicity, chemical resistivity, and availability of suitable coatings may also need to be considered.

Glass

Glass technology provided the foundation for classical optical elements, such as lenses, prisms, and filters. Glasses developed for use in the visible region have internal transmittances of over 99% throughout the wavelength range of 380–780 nanometers. However, the silicate structure in glasses limits their transmission to about 2.5 micrometers in the infrared. Chalcogenide glasses, heavy-metal fluoride glasses, and heavy-metal oxide glasses extend this transmission to 8–12 μm.

Advances in the process for manufacturing optical fibers led to the present fiber-optic communication systems that operate in the near-infrared region with windows at wavelengths of 850, 1310, 1550, and 1625 nm. An advanced fiber-optic system, LEAF (Large Effective Area Fiber), was designed to minimize nonlinearities by spreading the optical power over large areas.

Fused-Silica Glasses

The use of photolithography for printing integrated circuits has necessitated the improvement in the transmission of glasses for the ultraviolet region. Fused silica, which transmits to about 180 nm, is well suited for the lithography in the ultraviolet region. However, the crystalline material calcium fluoride, which transmits into the ultraviolet region to about 140 nm, outperforms any glass in printing microchips using fluorine excimer lasers. Deep-ultraviolet applications of fused-silica glasses include high-energy lasers, spacecraft windows, and blanks for large astronomical mirrors, optical imaging, and cancer detection using ultraviolet-laser-induced auto fluorescence.

Plastic Optics

The need for an inexpensive, unbreakable lens that could be easily mass-produced precipitated the introduction of plastic optics in the mid-1930s. Although the variety of plastics suitable for precision optics is limited compared to glass or crystalline materials, plastics are often preferred when difficult or unusual shapes, lightweight elements, or economical mass-production techniques are required.

The softness, inhomogeneity, and susceptibility to abrasion intrinsic to plastics often restrict their application. Haze (which is the light scattering due to microscopic defects) and birefringence (resulting from stresses) are inherent to plastics. Plastics also exhibit large variations in the refractive index with changes in temperature. Shrinkage resulting during the processing must be considered.

Organic Synthetic Polymers

Organic synthetic polymers are emerging as key materials for information technologies. Polymers often have an advantage over inorganic materials because they can be designed and synthesized into compositions and architectures not possible with crystals, glasses, or plastics. They are manufactured to be durable, optically efficient, reliable, and inexpensive. Many uses of polymers in photonic and optoelectronic devices have emerged, including light-emitting diodes, liquid-crystal–polymer photo detectors, polymer-dispersed liquid-crystal devices (for projection television), optical-fiber amplifiers doped with organic dyes (rhodamine), organic thin-film optics, and electro-optic modulators.

Crystal

Although most of the early improvements in optical devices were due to advancements in the production of glasses, the crystalline state has taken on increasing importance. Historically, the naturally occurring crystals such as rock salt, quartz, and fluorite plus suitable detectors permitted the first extension of visible optical techniques to harness the invisible ultraviolet and infrared rays. Synthetic crystal-growing techniques have made available single crystals such as lithium fluoride (of special value in the ultraviolet region, since it transmits at wavelengths down to about 120 nm), calcium fluoride, and potassium bromide (useful as a prism at wavelengths up to about 25 μm in the infrared). Many alkali-halide crystals are important because they transmit into the far-infrared. Following the invention of the transistor, germanium and silicon ushered in the use of semiconductors as infrared optical elements or detectors. Polycrystalline forms of these semiconductors could be fabricated into windows, prisms, lenses, and domes by casting, grinding, and polishing. Compound semiconductors such as gallium arsenide (GaAs), ternary compounds such as gallium aluminum arsenide ($Ga_{1-x}Al_xAs$), and quaternary compounds such as indium gallium arsenide phosphide (InGaAsP) now serve as lasers, light-emitting diodes, and photo detectors.

Non-Linear Crystals

Single crystals are indispensable for transforming, amplifying, and modulating light. Birefringent crystals serve as retarders, or wave plates, which are used to convert the polarization state of the light. In many cases, it is desirable that the crystals not only be birefringent, but also behave nonlinearly when exposed to very large fields such as those generated by intense laser beams. A few examples of such non-linear crystals are ammonium dihydrogen phosphate (ADP), potassium dihydrogen phosphate (KDP), beta barium borate (BBO), lithium borate (LBO), and potassium titanyl phosphate (KTP).

Liquid Crystals

Other optical materials are the liquid crystals used in displays as light valves, materials used in erasable optical disks for computers and in liquid cells (Kerr cells), laser dyes, dielectric multilayer films, filter materials, and the many metals (aluminum, gold, beryllium, and so forth) and alloys that are important as coating materials.

Hence, discovering and study of optical material are one of the major parts in optical waveguide discipline.

Chapter 2: Theory and Principles

In this chapter, some basic theory and principles in the optical waveguide study will be explained and discussed. Firstly, dispersion phenomenon that is occurring in optics is explained, and the discussion will be focused on material dispersion phenomenon in optical materials. Furthering the discussion, the relation between material dispersion with the refractive index is introduced. Hence, Abbe number, which is a measure of the material's dispersion (variation of refractive index with wavelength) in relation to the refractive index, is explained. After that, Cauchy equation, an empirical relationship between the refractive index and wavelength of light for a particular transparent material is explained using its fundamental theory and equation.

2.1: Dispersion

In optics, dispersion is the phenomenon in which the phase velocity of a wave depends on its frequency, or alternatively when the group velocity depends on the frequency. Dispersion is sometimes called chromatic dispersion to emphasize its wavelength-dependent nature, or group-velocity dispersion (GVD) to emphasize the role of the group velocity.

There are generally two sources of dispersion: material dispersion and waveguide dispersion.

Waveguide Dispersion

Waveguide dispersion is chromatic dispersion which arises from waveguide effects: the dispersive phase shifts for a wave in a waveguide differ from those which the wave would experience in a homogeneous medium. The total dispersion is the combination of material dispersion and waveguide dispersion.

The origin of waveguide dispersion can be understood by considering that a guided wave has a frequency-dependent distribution of k vectors, whereas a plain wave (as the reference case) has only a single k vector, which points exactly in the propagation direction. Note that chromatic dispersion for a given propagation mode of a waveguide is calculated from the frequency dependence of the so-called propagation constant, which is the overall phase shift per unit length which the guided wave experiences.

Waveguide dispersion is important in waveguides with small effective mode areas. Examples are optical fibers, in particular certain photonic crystal fibers, but also other single-mode fibers as used in, e.g., optical fiber communications. Waveguide dispersion may be tailored via the fiber design to obtain the desired dispersion properties; see e.g. the article on dispersion-shifted fibers. For fibers with large mode areas, waveguide dispersion is normally negligible, and material dispersion is dominant.

Material Dispersion

Material dispersion comes from a frequency-dependent response of a material to waves. For example, material dispersion leads to undesired chromatic aberration in a lens depends on its frequency for geometric reasons, independent of any frequency dependence of the material from which it is constructed. More generally, waveguide dispersion can occur for waves propagating through any inhomogeneous structure (e.g, a photonic crystal), whether or not the waves are confined to some region. In general, both types of dispersion may be present, although they are not strictly additive. Their combination leads to signal degradation in optical fibers for telecommunications, because the varying delay in arrival time between different components of a signal smears out the signal in time.

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. A type of dispersion that occurs in optical fiber due to the interaction of various wavelengths with the physical matter in the crystalline structure of the glass, i.e., different wavelength travel at different speeds in the medium. The longer the wavelength, the faster the signal travels. No pulse is perfectly defined, i.e., includes a range of wavelengths of lesser power around the center wavelength. The effect of material dispersion is that the various wavelengths comprising the pulse travel at different velocities through the medium. So, the pulse can spread over a distance simply due to the interaction of various wavelengths with the matter in the crystalline core, which causes some portions of a pulse to arrive earlier than the other portions. As the wavelength increases (and frequency decreases), material dispersion decreases. So, optical signal in the 1550nm window suffer less form material dispersion than wavelength in the 1310nm window.

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Material dispersion, which is synonymous with intramodal dispersion and spectral dispersion, is one factor contributing to chromatic dispersion. Material dispersion and chromatic dispersion are issues in long haul fiber optic transmission systems (FOTS) employing single mode-mode fiber (SMF) of step-index construction. Multimode graded-index fibers suffer so much from modal dispersion over short distances that material dispersion and chromatic dispersion never become factors.

Material dispersion can be a desirable or undesirable effect in optical applications. The dispersion of light by glass prisms is used to construct spectrometers and spectroradiometer. Holographic gratings are also used, as they allow more accurate discrimination of wavelength. However, in lenses, dispersion causes chromatic aberration, an undesired effect that may degrade images in microscopes, telescopes and photographic objectives.

The phase velocity, v of a wave in a given uniform medium is given by;

$$v = \frac{c}{n} \quad (1)$$

Where c is the speed of light in a vacuum and n is the refractive index of the medium.

In general, the refractive index is some function of the frequency f of the light, thus n : n(f), or alternatively, with respect to the wave's wavelength n: n(λ). The wavelength dependence of a material's refractive index is usually quantified by its Abbe number or its coefficients in an empirical formula such as the Cauchy equations

For example, figure 3 below shows material dispersion graph, which are the variation of refractive index vs vacuum wavelength for various glasses.

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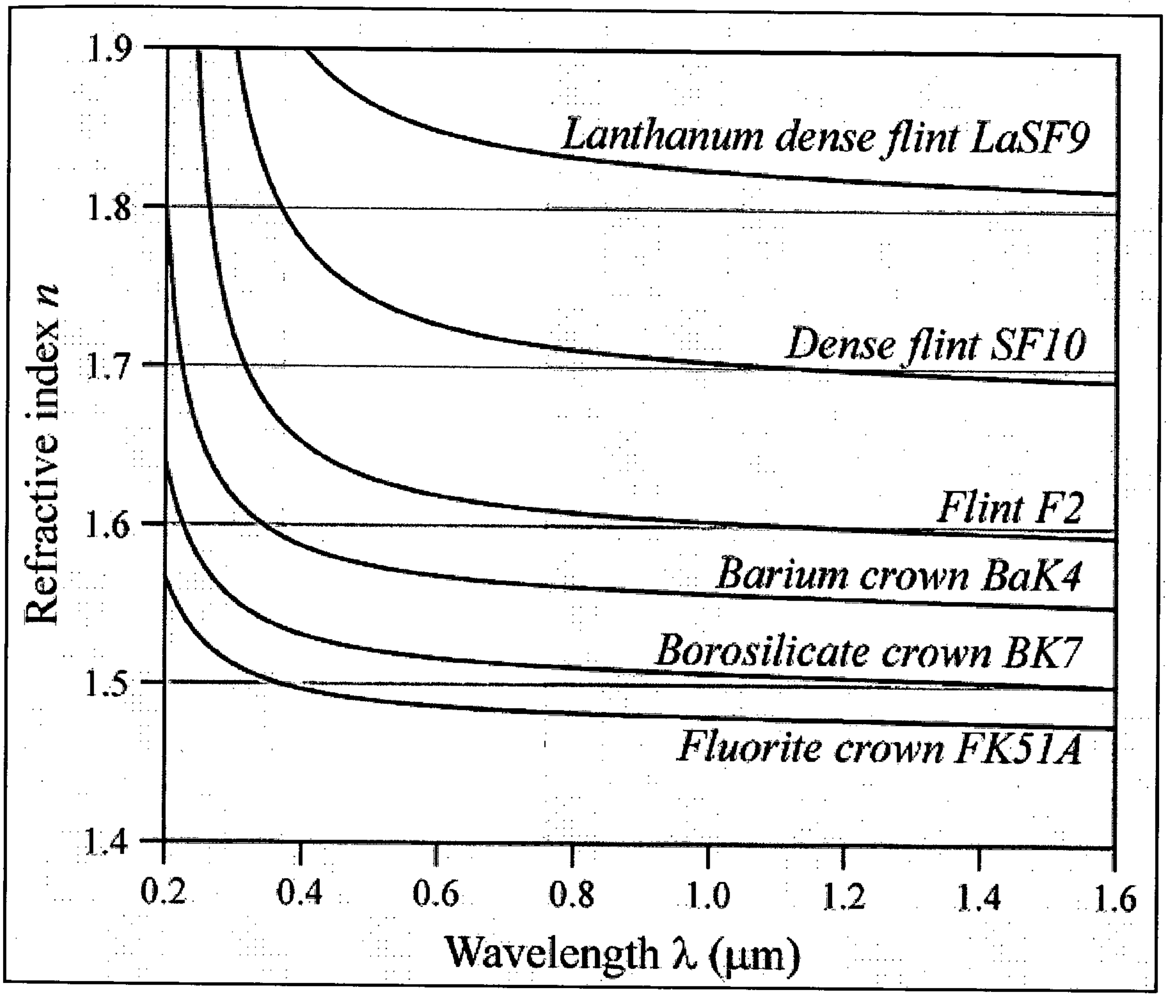

Fig 3: The variation of refractive index vs vacuum wavelength for various glasses. The wavelengths of visible light are shaded in red.

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2.2: Abbe Number

Besides using material dispersion graph to determine the material dispersion of the experimented material, Abbe Number is also used to relate material dispersion with the refractive index. In physics and optics, the Abbe number, also known as the v number or constringence of a transparent material, is a measure of the material's dispersion (variation of refractive index with wavelength) in relation to the refractive index. It is named after Ernst Abbe (1840–1905), the German physicist who defined it.

The Abbe number v of a material is defined as;

$$v_d = \frac{n_d - 1}{n_F - n_C} \quad (2)$$

where n_d, n_F and n_C are the refractive indices of the material at the wavelengths of the Fraunhofer d-, F- and C-spectral lines (587.6 nm, 486.1 nm and 656.3 nm respectively). Low dispersion (low chromatic aberration) materials have high values of v.

Abbe numbers are used to classify glass and other optically transparent materials. For example, crown glass and flint glass. Generally, crown glass is a type of optical glass used in lenses and other optical components. It has relatively low refractive index (≈1.52) and low dispersion (with Abbe number around 60). Meanwhile, flint glass is optical glass that has relatively high refractive index and low Abbe number (high dispersion). Flint glasses are arbitrarily defined as having an Abbe number of 50 to 55 or less. The currently known flint glasses have refractive indices ranging between 1.45 and 2.00. Typical values of *V* range from around 20 for very dense flint glass, around 30 for polycarbonate plastics, and up to 65 for very light crown glass, and up to 85 for fluor-crown glass. Abbe numbers are only a useful measure of dispersion for visible light, and for other wavelengths, or for higher precision work, the group velocity dispersion is used.

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Alternate definitions of the Abbe number are used in some contexts. The value ν_d is given by;

$$\nu_D = \frac{n_D - 1}{n_F - n_C} \quad (3)$$

which defines the Abbe number with respect to the yellow Fraunhofer D (or D3) helium line at 587.5618 nm wavelength.

An Abbe diagram is produced by plotting the Abbe number ν_d of a material versus its refractive index n_d. Glasses can then be categorized by their composition and position on the diagram. This can be a letter-number code, as used in the Schott Glass catalogue, or a 6-digit glass code. Figure 4 below shows an example of Abbe diagram, produced by Schott.

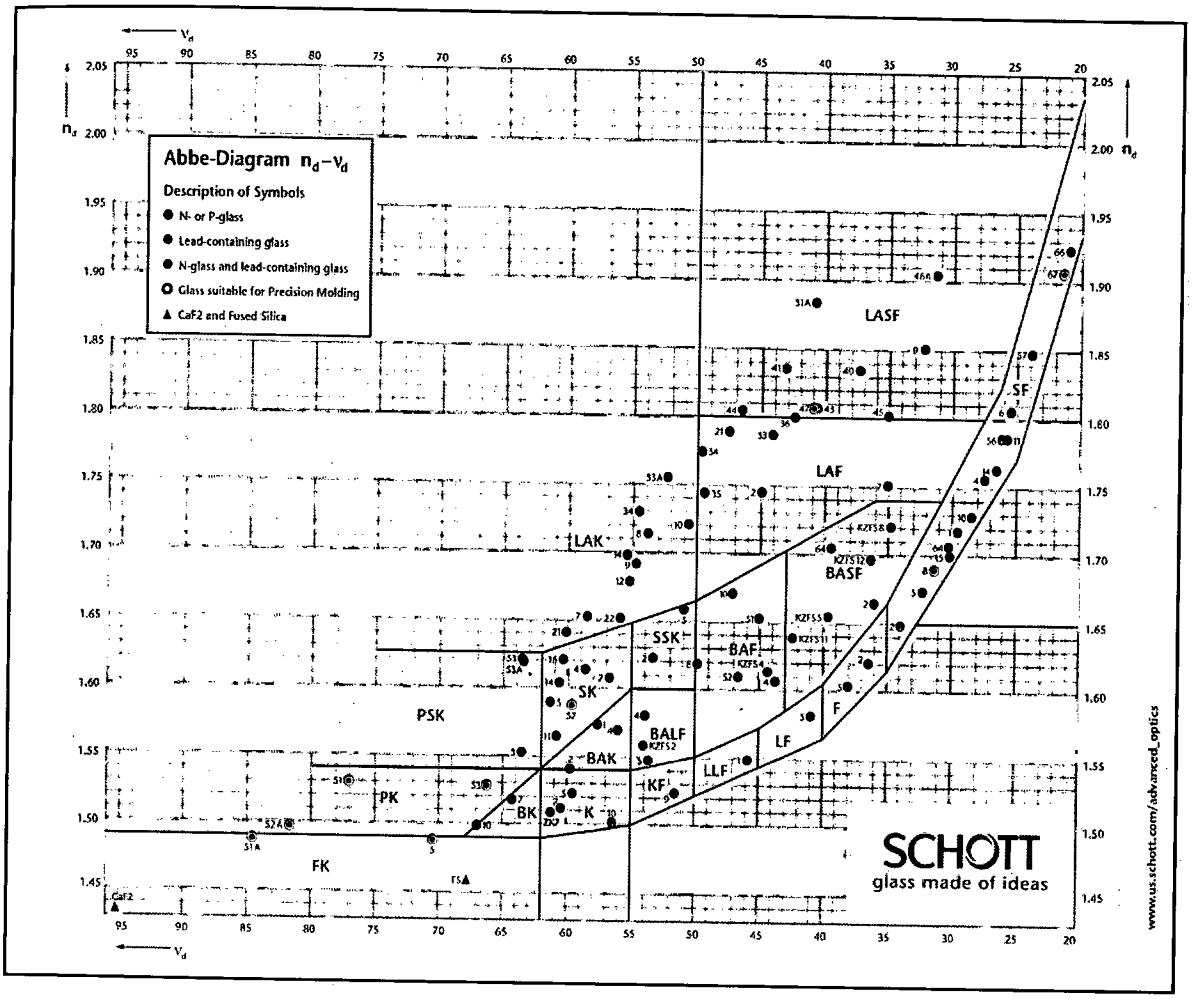

Fig 4: Abbe Diagram Sample (Schott Glass Data)

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2.3: Cauchy Equation

Cauchy equation is an empirical relationship between the refractive index and wavelength of light for a particular transparent material. It is named for the mathematician Augustin Louis Cauchy in 1836.

The most general form of Cauchy's equation is;

$$n(\lambda) = A + \frac{B}{\lambda^2} + \frac{C}{\lambda^4} \ldots\ldots \quad (4)$$

where n is the refractive index, λ is the wavelength, A, B, C etc. are the coefficients that can be determined for a material by fitting the equation to measured refractive indices at known wavelength. The coefficients are usually quoted λ as for the vacuum wavelength in micrometers. Usually, it is sufficient to use a two-term form of the equation which is;

$$n(\lambda) = A + \frac{B}{\lambda^2} \quad (5)$$

where the coefficient A and B are determined specifically for this form of the equation.

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Chapter 3: Methods

In this chapter, the visible wavelength and the near-infrared (NIR) characteristics in material dispersion of the various optical materials are investigated. By using Abbe Number equation and Cauchy equation that have been dicussed in the previous chapter, the idea of defining dispersion curve line by only using Abbe Number and and d-line refractive index data is proposed. Some calculations results are analyzed, and studied.

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3.1: Dispersion Curve

Infrared light (IR) is electromagnetic radiation with longer wavelengths than those visible lights, extending from the nominal red edge of the visible spectrum at 0.74 micrometers to 0.3mm. One of the divisions of the IR is near-infrared (NIR), which has wavelength around 0.75-1.4 micrometers. The NIR are commonly used in fiber optic devices because of low attenuation losses in the SiO_2 glass (silica). Due to its advantages in fiber optics technology, the near-infra red region characteristics in material dispersion that occur among various optical materials are investigated. Firstly, the idea of whether the dispersion curve line could be defined by only using Abbe number v and d-line refractive index n_d data is shown as figure 1.

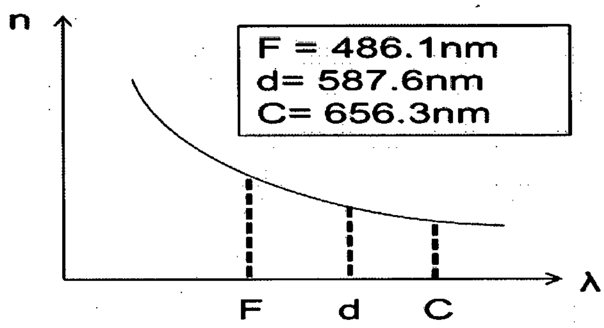

Fig 5: Material Dispersion Graph Sample

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3.2: Cauchy Approximation

To determine the refractive index dispersion characteristics of the optical materials, Cauchy approximation that is related to the wavelength and the refractive index is used. The operation of Cauchy approximation using Abbe Number equation and Cauchy equation are shown in equation below.

Based on Cauchy equation;

$$n = A + \frac{B}{\lambda^2} \quad (6)$$

The value of coefficient A and B should be solved and expressed in refractive index n_d and wavelength λ.

Firstly, the refractive indices of n_d, n_F and n_C will be determined by using Cauchy equation which are;

$$n(d) = A + \frac{B}{(\lambda_d)^2} \quad (7)$$

$$n(F) = A + \frac{B}{(\lambda_F)^2} \quad (8)$$

$$n(C) = A + \frac{B}{(\lambda_C)^2} \quad (9)$$

Then, by referring Abbe number equation;

$$V_d = \frac{n_d - 1}{n_F - n_C} \quad (10)$$

The value of n_F - n_C can be expressed as;

$$n_F - n_C = \frac{B({\lambda_F}^2 - {\lambda_C}^2)}{(\lambda_F \lambda_C)^2} \quad (11)$$

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Therefore;

$$B = \frac{(n_d - 1)(\lambda_F \lambda_C)^2}{V(\lambda_C{}^2 - \lambda_F{}^2)} \quad (12)$$

$$A = n_d - \left(\frac{(n_d - 1)(\lambda_F \lambda_C)^2}{V\lambda_d{}^2(\lambda_C{}^2 - \lambda_F{}^2)} \right) \quad (13)$$

However, the theory of light-matter interaction on which Cauchy based this equation was later found to be incorrect. In particular, the equation is only valid for regions of normal dispersion in the visible wavelength region. In the infrared, the equation becomes inaccurate, and it cannot represent regions of anomalous dispersion.

For example as shown below, it can be seen that the graph error of material dispersion of glass BK7 using Cauchy approximation is increasing when it is over the visible region.

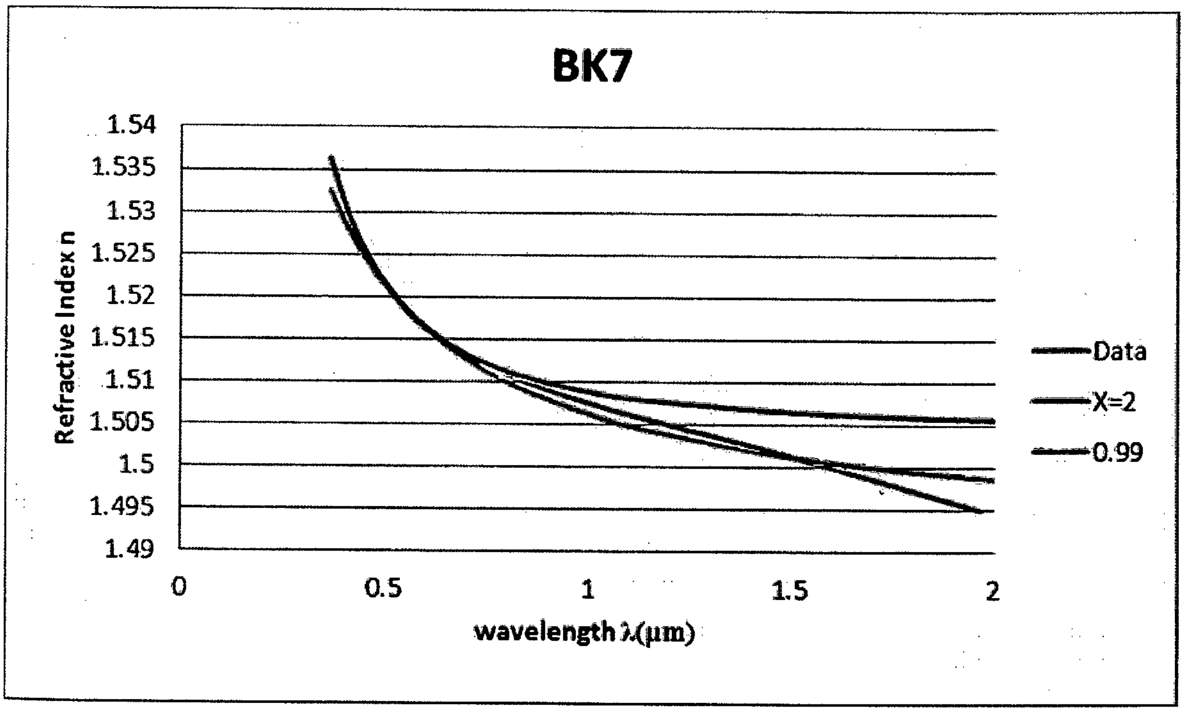

Fig 7: BK7 Material Dispersion with Cauchy Approximation

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