MEASUREMENT OF POLARIZATION MODE DISPERSION IN OPTICAL WAVEGUIDES

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by

Shawn Joseph Dylan Morrison

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MEASUREMENT OF POLARIZATION MODE DISPERSION IN OPTICAL WAVEGUIDES

Student: S. J. Morrison Supervisors: B. L. Daku, H. C. Wood

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ABSTRACT

This thesis is based on the measurement of polarization mode dispersion (PMD) in optical waveguides. The study takes as its starting point a recently reported measurement methodology known as the fixed polarizer wavelength scan technique. A new method of determining the level of PMD from a fixed polarizer wavelength scan is developed. The new method involves the use of Fourier transformation techniques to allow viewing of the PMD as an RMS spread in the time domain. Finally, waveguides from four different processes, modified chemical vapor deposition (MCVD), over-jacketed MCVD, outside vapor deposition (OVD), and dispersion shifted OVD, all cabled in an industry standard loose tube type cable, are characterized for PMD performance. It is believed that this measurement technique will result in a low cost method for fiber and cable process optimization for this important form of dispersion.

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LIST OF ABBREVIATIONS

CVD	Chemical Vapor Deposition
DFT	Discrete Fourier Transform
DOP	Degree of Polarization
DS-OVD	Dispersion Shifted Outside Vapor Deposition
EH, HE	Hybrid Electric
FFT	Fast Fourier Transform
IDFT	Inverse Discrete Fourier Transform
IFT	Inverse Fourier Transform
IR	Infrared
LED	Light Emitting Diode
LP	Linearly Polarized
MCVD	Modified Chemical Vapor Deposition
NA	Numerical Aperture
Nd:YAG	Neodymium:Yttrium-Aluminum-Garnet
NIST	National Institute of Standards and Technology
OJ-MCVD	Over-jacketed Modified Chemical Vapor Deposition
OTDR	Optical Time Domain Reflectometer
OVD	Outside Vapor Deposition
PCVD	Plasma Chemical Vapor Deposition
PIN	Positive Intrinsic Negative
PMD	Polarization Mode Dispersion
SDH	Synchronous Digital Hierarchy

SONET	Synchronous Optical Network
SOP	State of Polarization
TE	Transverse Electric
TM	Transverse Magnetic
UV	Ultraviolet
VAD	Vapor Axial Deposition

1 INTRODUCTION

1.1 Historical Perspective

As what has been termed the Information Age approaches, the already rapid rate of advancement in communications technology appears sometimes to move at a slow pace when compared with the demands for increased speed, mobility, and volume of information. The desire for faster processing speeds, greater information storage capabilities, and faster information channels is relentless, with an advancement in one technology driving the need for improvement in others. The development of the semiconductor laser in the early 1960's, for example, lead to intense research into silica (SiO_2) optical waveguides. Although the idea of a dielectric waveguide had been theorized over 50 years earlier, according to Miller [1], serious consideration was not given to the concept until the prospect of teaming this new semiconductor laser technology with a glass waveguide appeared, offering the potential for a new communications channel with a seemingly limitless capacity. One advancement drove another in this technological courtship, and by 1970 its fruition was evidenced by a semiconductor laser capable of more than a thousand hours of continuous oscillation near room temperature (Bell Labs) [2], and a silica optical waveguide with a loss below 20 dB/km (Corning Glass Works) [3]. These achievements provided the tangible evidence that this communications technology leap, a commercial optical transmission channel, was attainable.

From the first practical implementations of these combined technologies in the early 1970's the development continued but at an even elevated rate, fueled by increasing interest from the scientific community who were naturally intrigued by the potential.

Initially, the system operating wavelengths were dictated by the single component semiconductor laser wavelengths, which fell into the 850 nm region. Waveguide loss was the main focus of the period, and it would soon become apparent that this wavelength region was less than ideal from a transmission loss perspective. The limitation on bandwidth on the other hand seemed of lesser concern, was not well understood, and was caused as much by the fundamental design of the multimode waveguides as it was by the laser's performance. It was not long until improvements in waveguide manufacturing processes presented an opportunity to reduce the system loss by moving to an operating wavelength in the 1300 nm region. This opportunity once again drove the need for advancement in laser technology, and in a few short years (by 1976) [4] tertiary semiconductor compound laser devices, such as indium gallium arsenide phosphorus (InGaAsP), operating in the 1300 nm region were available. It is obvious that the next development should come from the area of the waveguide technology, and that development was the single-mode waveguide.

It had for some time been realized that a major limitation to the system bandwidth was caused by the so called intermodal dispersion of the multimode waveguide. With the lower losses, and longer repeaterless channels offered by the 1300 nm lasers, bandwidth was becoming an area of increased interest. The answer to the large intermodal dispersion penalty was the design of a fiber capable of supporting only one mode. As a bonus, the waveguide designers also tackled the two remaining major dispersion contributors, material dispersion and waveguide dispersion. This was achieved by designing the single-mode fiber such that, at a certain wavelength, the two dispersions canceled each other. It soon became apparent that, even with a so called zero dispersion wavelength now present in the single-mode waveguides, the tolerance of the laser operating frequency and even the width of its output spectrum could generate dispersion which still imposed a stiff bandwidth penalty. The solution was a development in laser technology, known as distributed feedback, which was capable of narrowing laser output spectral widths by orders of magnitude. This topology, the single-mode fiber coupled with an InGaAsP type laser, has remained as the standard in optical communication channels with further research focusing mainly on refinement until recently when the ultimate marriage of the laser and the silica optical waveguide occurred with the invention of the fiber based optical amplifier.

Early optical amplifiers were based on semiconductor devices using laser type structures and special biasing, but there were many problems encountered in this research, and it was not until the discovery that rare earth doped silica fibers were capable of optical amplification that revolutionary advancements in transmission capabilities became attainable. In particular, it was discovered that erbium doped silica waveguides were well suited for operation in the desirable 1550 nm region. This optical amplifier technology had such an array of advantages that it was difficult to imagine any future system that would not employ it. First, erbium doped fiber amplifiers were not limited in frequency, having bandwidths in excess of 1000 GHz. Second, they were capable of amplifying any number of signals simultaneously regardless of the precise wavelength, type of modulation, or bit rate. Third, erbium doped fiber amplifiers could be pumped from readily available diode lasers at levels of only a few milliwatts, which resulted in gain factors which were in the thousands, were insensitive to signal polarization, and were stable over a 100 °C temperature range [5]. Furthermore, because these fiber optical amplifiers were physically just silica waveguides, mechanical integration into a transmission system was simple.

The most startling implication of this new development was that waveguide loss was no longer an issue, it could be countered by inserting optical amplifiers at regular intervals. It has been from this point on that research on silica single-mode optical waveguides has focused mainly on their properties relating to bandwidth limitation. Some of these, which are based on waveguide nonlinearities, delve deep into the physical optics of matter and are only beginning to be understood and may present ultimate capacity limitations, while others such as polarization mode dispersion present a more immediate bandwidth limitation, and are caused by more readily understood phenomena.

At this point a note must be made about the term dispersion. In its classical definition in physical optics, the term dispersion refers to the wavelength dependence of the refractive index of a medium. More often, though, the term is used to refer to the separation of the constituent wavelengths of an optical signal due to the wavelength dependence of the refractive index of a medium. In the optical communications industry the term dispersion takes on an even more general definition of spreading, scattering, or dissemination of an optical signal, not necessarily related to a wavelength dependence of a medium. A common definition of dispersion in the optical communications industry, which uses predominantly digital modulation of the optical carrier, is the spreading of a light pulse incurred in its transition through a transmission medium. This spreading of light pulses causes limitations in transmission capacity through interference between closely spaced pulses, and is referred to as intersymbol interference. As will be seen in Chapter 2, some of the causes of this spreading are related to wavelength dependencies of the transmission medium, while others are not.

1.2 Optical Communication Systems

An optical communication system, though seemingly very different from the more established copper based systems, is very much an extension of these systems. Figure 1.1 shows that the optical communication carrier frequencies fall well above the highest carrier frequencies capable of support in copper based, or even radio wave based communication systems. The frequency range for silica optical waveguide communication systems is typically from about 187 THz to 385 THz. In the optical communications

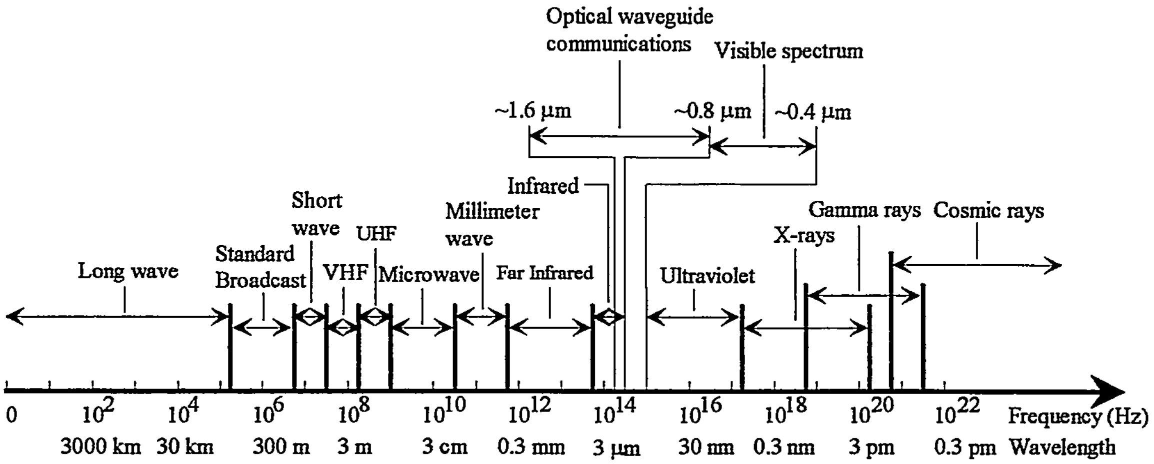

Figure 1.1 The region in the electromagnetic spectrum occupied by optical communication system carrier frequencies.

industry, the carrier frequency is almost without exception referred to in the wavelength domain, where the operating wavelength λ is related to the frequency f by

$$\lambda = \frac{c}{f}, \tag{1.1}$$

where c is the speed of light in free space. The corresponding optical wavelengths are therefore from about 800 nm to 1600 nm, with the 1310 nm and 1550 nm regions being the most predominant in modern systems, as they coincide with windows of low attenuation in silica optical waveguides. The term frequency in the optical communications industry almost universally refers to the modulation frequency, not the optical carrier frequency. These conventions will be adhered to in this thesis.

A block diagram of a typical optical communication system is shown in Figure 1.2. The system, from the information source to and including most of the transmitter, operates essentially identical to a copper based communication system. The conversion to optical carrier frequencies takes place at the very end of the transmitter, and is usually performed by an LED, or more commonly by a laser, most often a semiconductor laser. Lasers such

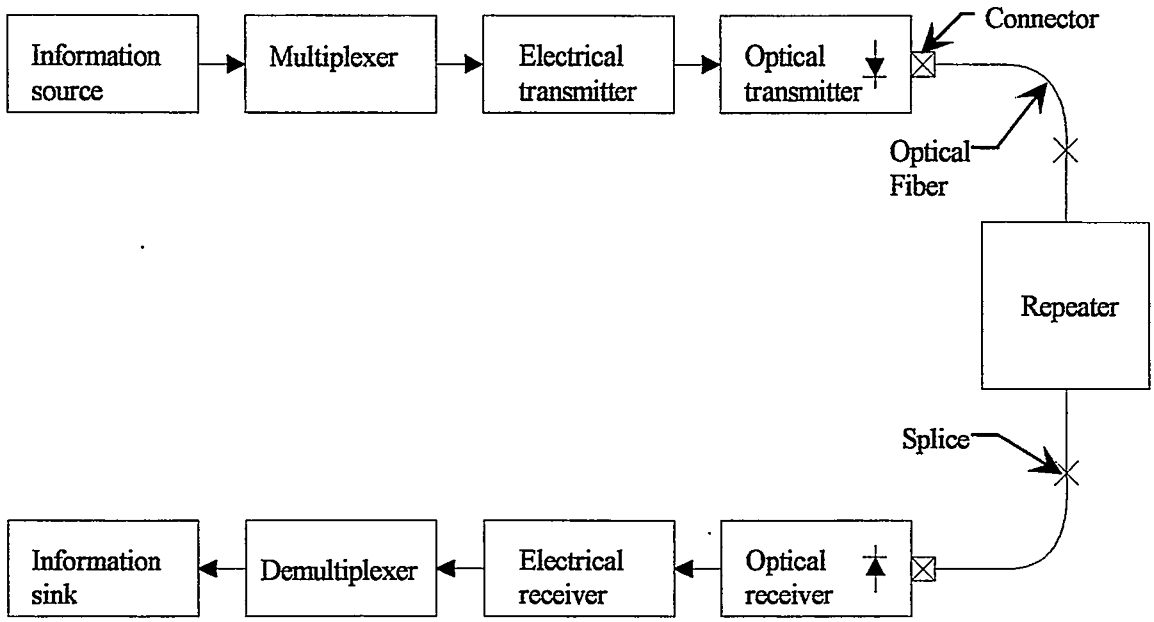

Figure 1.2 The general optical communication system.

as Nd:YAG are also common in analog distribution systems, such as cable TV, which contain many receivers and can take advantage of the higher transmission powers available from the Nd:YAG laser. The modulation of the optical carrier may be obtained by modulating the semiconductor laser directly, or by the use of an external modulator, usually constructed of a piezoelectric crystal such as lithium niobate. The external modulator is becoming an increasingly popular solution to a source of dispersion caused by a phenomenon known as laser chirp, whereby the laser output spectrum changes randomly between two or more states, increasing in severity as the modulation frequency increases. The modulation of the optical signal can be of an analog format, but is more often an on-off digital modulation.

The optical signal from the laser or the electro-optic modulator is coupled directly into the optical waveguide which is, without exception in modern high speed systems, a single-mode optical fiber. The single-mode fiber exits the transmitter card in the form of a protected single fiber cable. This single fiber cable will often go through a number of remateable connection points in what is known as a fiber management system before being connected to the outside plant multi-fiber protected cable which carries the optical fibers in aerial, ducted, or buried installations. The outside plant cable will undergo a number of permanent splices created through thermal fusion of two fiber ends, or through mechanical alignment and retention in permanent, usually deformable, V-grooves before requiring amplification due to signal loss in the fiber and connection points. This amplification block is traditionally known as a repeater, since the signal at this point traditionally undergoes the process of optical to electrical conversion, retiming, and conversion from electrical back to optical, to remove signal dispersion. More often in state of the art systems, though, this block takes the form of a purely optical amplifier as shown in Figure 1.3. This purely optical amplification is only possible when the signal dispersion is low enough such that retiming and regeneration is not required. This type of signal is afforded by lasers of extremely narrow spectral width which essentially eliminates most major forms of dispersion. An exception to this is polarization mode dispersion.

The receiver block of the communication system provides the final conversion from the modulated optical carrier to an equivalent electrical signal. This is usually accomplished through the use of a semiconductor device known as a PIN photodiode, or

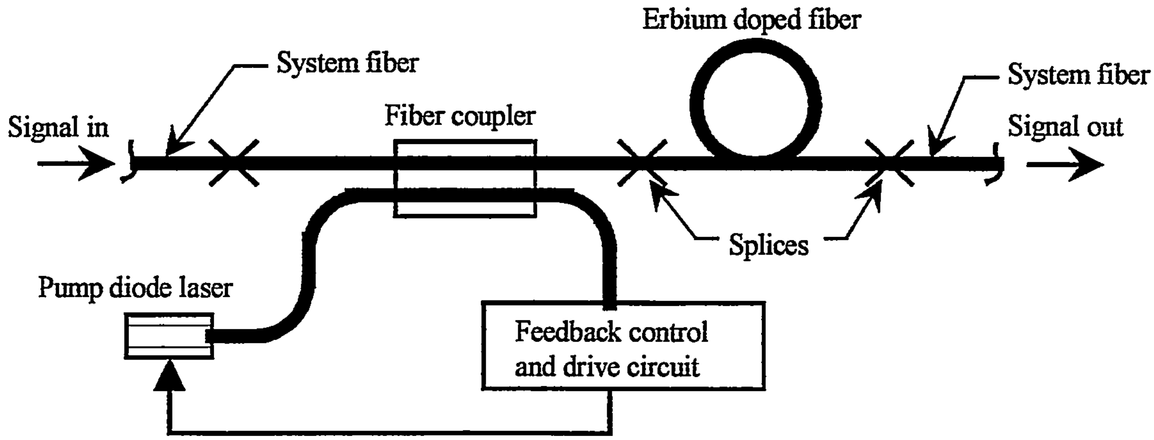

Figure 1.3 An optical repeater based on an Erbium-doped fiber amplifier.

less commonly, an avalanche photodiode. In all commercial systems today, this receive process is non-coherent. Experimental coherent communication systems are still relegated to the laboratory because of the extreme requirement for spectral purity in the laser source.

1.3 Objective of the Thesis

Polarization mode dispersion (PMD) refers to a form of dispersion caused by the presence of birefringence in an optical waveguide. This type of dispersion is of interest primarily in single-mode waveguides where the level of other forms of dispersion is relatively small. Research into PMD in single-mode fibers has appeared in the literature as early as 1978 [6], but the phenomenon was not viewed as very important until it was brought into debate over its impact on analog cable TV distribution systems in 1990 [7], [8]. These analog transmission systems, being more susceptible to signal degradation than digital systems, were the first to exhibit problems caused by this source of dispersion. With the roll-out of products conforming to the international Synchronous Digital Hierarchy (SDH) standard or Synchronous Optical Network (SONET) standard as it is known in North America, the increased presence of digital transmission systems operating well into the gigabit/second region has since made PMD an industry-wide concern.

The approach to eliminating PMD or any unwanted phenomenon involves three general steps. First, an attempt must be made to understand the origins of the phenomenon. In the case of PMD, it is generally accepted that it is caused mainly by variations in the refractive index of the waveguide which are caused by stresses in the glass created during both the manufacture and the cabling of the optical fibers. Second, a method of measuring the phenomenon in research and in production must be found. This test method must accurately represent the extent of the phenomenon and must be repeatable not only from time to time, but also across a variety of equipment which is likely to be assembled in a global industry. The third and final step is to analyze and optimize manufacturing processes to minimize the sources of the phenomenon.

The objective of this thesis is to develop a test system for measuring polarization mode dispersion and to determine the PMD performance of several single-mode fiber types using this system. This thesis takes as its starting point a recently developed measurement methodology known as the fixed polarizer wavelength scan technique. This technique shows great promise due to the low cost of the required equipment, the commonality with existing equipment in the industry, and the simple test procedure. Improvements are still required, though, in the analysis of the data obtained from this test method. It will be shown how the level of PMD can be determined directly from the measurement data through a method referred to as the peak counting method. A new method of analyzing the measurement data to determine the level of PMD will be presented. This new method makes use of Fourier transform techniques to allow time domain analysis of the measurement data which is in the wavelength (frequency) domain, and is being referred to as the time domain RMS spread method. Finally, a test set designed and constructed for the purpose of this research is used to qualify the PMD performance of four modern single-mode fiber designs. It is hoped that this research will help to arrive at an industry standard method of measuring PMD.

2 OPTICAL WAVEGUIDES

2.1 Physical Characteristics

There is a wide variety of optical waveguides existing today with variations including composition materials, physical dimensions, and refractive index profiles, but by far the most popular waveguides are those composed mainly of pure silica glass. The silica fiber is usually given a radially symmetric refractive index profile with inclusion of small amounts of select dopants. All present day commercial manufacturing, without exception, makes use of a process known as chemical vapor deposition (CVD) to generate the fiber core and at least the innermost portion of the cladding. The reason for the popularity of the vapor phase process is the relative ease of maintaining the necessary purity, in comparison with solid phase processes, since the vapor phase reaction can be made selective to the desired chemicals by proper control of temperature and pressure.

Typical chemicals used in the CVD process are $SiCl_4$, $GeCl_4$, $POCl_3$, SF_6, and SiF_4 which react with O_2 to form pure silica glass, SiO_2, or dopant molecules such as GeO_2 or P_2O_5 to raise the core refractive index, and F or B_2O_3 to lower the cladding refractive index. Figure 2.1 indicates the effect that these dopant molecules have on the refractive index of silica glass with increasing mole concentration. GeO_2 is the most common core dopant for modern single-mode fibers due to the susceptibility of phosphorous doped fibers to radiation induced increases in attenuation. Fluorine is the cladding dopant of choice for modern waveguide manufacturing processes.

Optical waveguides are manufactured by one of two basic CVD process, inside deposition and outside deposition. In both of these processes the silica and the dopant

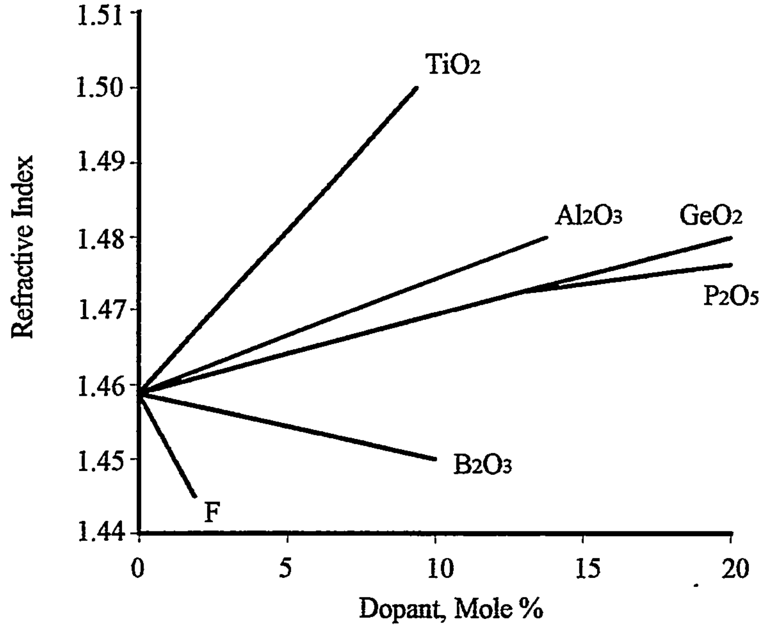

Figure 2.1 Refractive index for doped silica glass [9].

molecules are deposited as a porous soot which is then melted to form solid glass in a process referred to as vitrification, sintering, or consolidation. With inside deposition, the core and a small amount of cladding material are deposited and almost simultaneously vitrified on the inside wall of a silica starting tube which forms the bulk of the fiber cladding. With the outside deposition process, the entire waveguide structure is deposited onto a target mandrel, usually made of ceramic, which is then removed prior to vitrification. These glass tubes are then collapsed into a preform which is later heated and drawn down into a fiber. Modified chemical vapor deposition (MCVD) and plasma chemical vapor deposition (PCVD) are common inside deposition process. Outside vapor deposition (OVD) and vapor axial deposition (VAD) are common outside deposition processes. In North America the MCVD and the OVD processes are most common.

The raw silica fiber must be protected after being drawn to minimize surface abrasion which could lead to fracture and to slow the growth of intrinsic flaws. Coating materials most common in modern manufacturing processes are ultra-violet light cured acrylate polymers which are usually applied in two layers. The inner coating is typically a softer material to protect the fiber from repetitive micro bending caused by such things as a fiber laying on a rough surface. The outer coating is typically of a harder material to give good abrasion resistance. The finished size of this two layer primary coating system is typically 250 μm. A paint is applied to the fiber for color coded identification as a last step prior to cabling.

The various refractive index profiles for optical waveguides can be divided into three general categories:

1) Step index profiles;

2) Graded index profiles;

3) Single-mode profiles.

These index profiles are illustrated in Figure 2.2, where r is the radial distance from the center of the waveguide, n is the refractive index, and n_{clad} and n_{core} are the refractive index values for the waveguide cladding and core respectively. It is noteworthy that the step index profile was the first profile found in early optical waveguide development, but because of its severe bandwidth penalty due to intermodal dispersion, it is virtually nonexistent in communication applications. For the same reason, the graded index profile has declined greatly in popularity, its presence maintained only by its ease of interconnection with LED sources and with other fibers, and is expected to drop out of use in communication applications as precision interconnection components and laser sources continue to decline in cost.

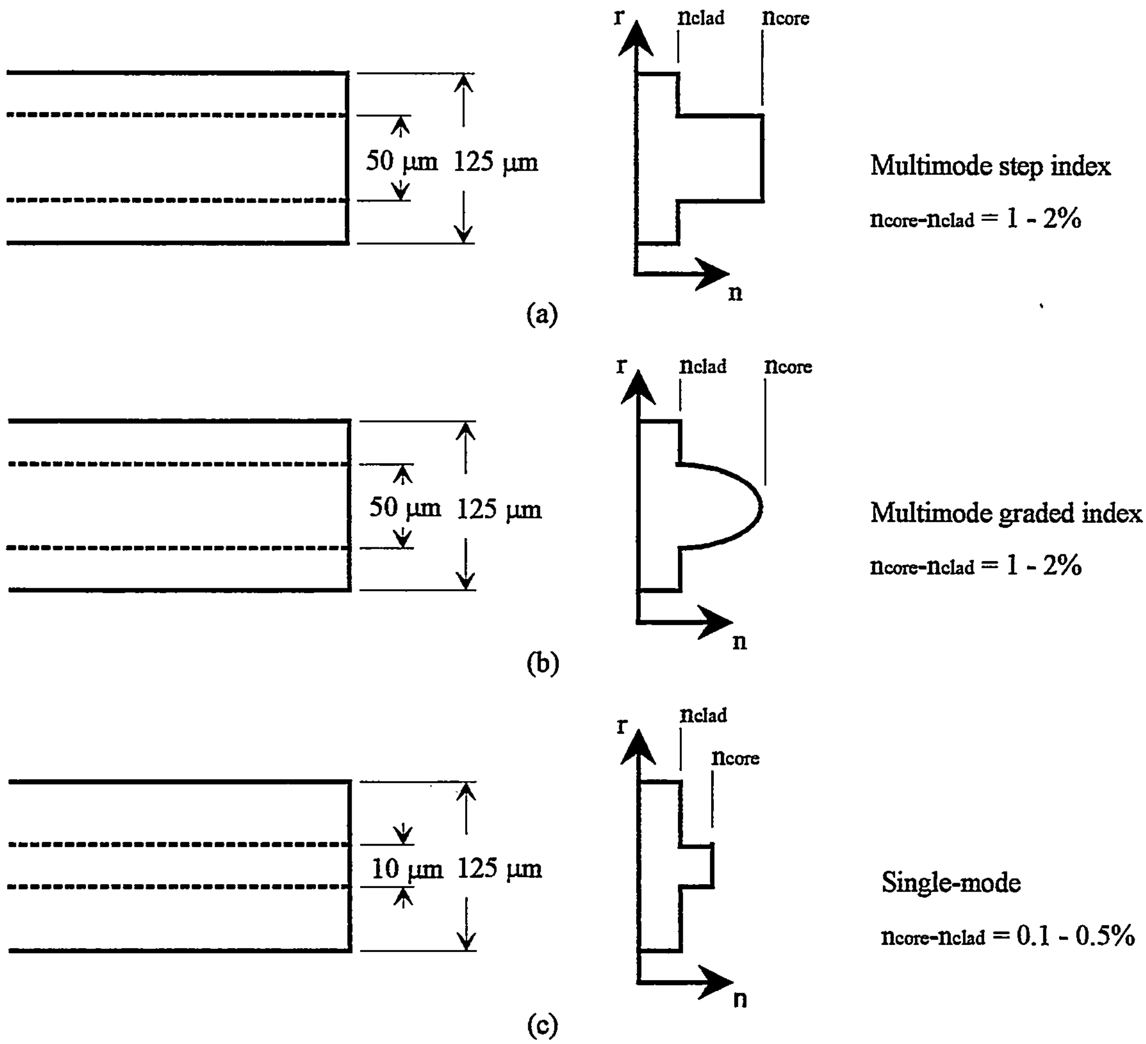

Figure 2.2 Index profiles of waveguides in communication systems. (a) Step index multimode profile. (b) Graded index multimode profile. (c) Single-mode index profile.

2.2 Principles of Operation

2.2.1 Ray Theory

The refractive index n of a medium is defined as the ratio of the velocity of light c in a vacuum to the velocity of light v in that medium, and is given as