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ANALYSIS, DESIGN AND PERFOMANCE EVALUATION OF MULTI LAYER SINGLE MODE OPTICAL FIBER

A Thesis Submitted to
The Laser and Optoelectronics Engineering Department, University of Technology in Partial Fulfillment of the Requirements for the Degree of Master of Science in Optoelectronics Engineering

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جمهورية العراق
وزارة التعليم العالي والبحث العلمي
الجامعة التكنولوجية
قسم هندسة الليزر والبصريات الالكترونية

تحليل وتصميم وتقيّم اداء الليف البصري احادي النمط المتعدد الطبقات

رسالة مقدمة الى
قسم هندسة الليزر والبصريات الالكترونية الجامعة التكنولوجية
كجزء من متطلبات نيل درجة الماجستير علوم في هندسة البصريات الالكترونية

تقدم بها المهندس

وسام حامد عبد الحسين

بإشراف

الدكتور وليد ياسين حسين

Appendix A

Table (A-1): Number designation for pure and doped silica glasses.

Material	**Composition**
M_1	*SiO_2 Pure Silica*
M_2	13.5 %GeO_2 , 86.5 %SiO_2
M_3	7.0 % GeO_2 ,93.0 % SiO_2
M_4	4.1 % GeO_2 , 95.9 % SiO_2
M_5	9.1 % GeO_2 , 7.7 % B_2O_3 , 83.2 %SiO_2
M_6	4.03 % GeO_2 , 9.7 % B_2O_3 , 86.27 % SiO_2
M_7	0.1 % GeO_2 , 5.4 % B_2O_3 , 94.5 % SiO_2
M_8	13.5 % B_2O_3 , 86.5 % SiO_2
M_9	13.5 % B_2O_3 , 86.5 % SiO_2 (Chilled)
M_{10}	3.1 % GeO_2 , 96.9 % SiO_2
M_{11}	3.5 % GeO_2 , 96.5 % SiO_2
M_{12}	5.8 % GeO_2 , 94.2 % SiO_2
M_{13}	7.9 % GeO_2 , 92.1 % SiO_2
M_{14}	3.0 % B_2O_2 , 97.0 % SiO_2
M_{15}	3.5 % B_2O_2 , 96.5 % SiO_2
M_{16}	3.3 % GeO_2 , 9.2 % B_2O_3 , 87.5 % SiO_2
M_{17}	2.2 % GeO_2 , 3.3 % B_2O_3 , 94.5 % SiO_2
M_{18}	*Quenched* SiO_2
M_{19}	13.5% GeO_2 , 86.5 %SiO_2
M_{20}	9.1 % P_2O_5 , 90.9 % SiO_2
M_{21}	13.3 % B_2O_3 , 86.7 % SiO_2
M_{22}	1.0 % F , 99.0 %SiO_2
M_{23}	16.9 % Na_2O , 32.5 % B_2O_3 , 50.6%SiO_2

Table (A-2): Sellmeier's coefficients for the materials of Table 1.

Material	A_1	A_2	A_3	λ_1 (μm)	λ_2 (μm)	λ_3 (μm)
M_1	0.696166	0.4079426	0.8974794	0.0684043	0.1162414	9.896161
M_2	0.73454395	0.42710828	0.82103399	0.08697693	0.11195191	10.846540
M3	0.68698290	0.44479505	0.79073512	0.078087582	0.11551840	10.436628
M_4	0.68671749	0.43481505	0.89656582	0.072675189	0.11514351	10.002398
M_5	0.72393884	0.41129541	0.79292034	0.085826532	0.10705260	9.3772959
M_6	0.70420420	0.41289413	0.95238253	0.067974973	0.12147738	9.6436219
M_7	0.69681388	0.40865177	0.89374039	0.070555513	0.11765660	9.8754801
M_8	0.70724622	0.39412616	0.63301929	0.080478054	0.10925792	7.8908063
M_9	0.67626834	0.42213113	0.58339770	0.076053015	0.11329618	7.8486094
M_{10}	0.7028554	0.4146307	0.8974540	0.0727723	0.1143085	9.896161
M_{11}	0.7042038	0.4160032	0.9074049	0.0514415	0.1291600	9.896156
M_{12}	0.7088876	0.4206803	0.8956551	0.0609053	0.1254514	9.896162
M_{13}	0.7136824	0.4254807	0.8964226	0.0617167	0.1270814	9.896161
M_{14}	0.6935408	0.4052977	0.9111432	0.0717021	0.1256396	9.896154
M_{15}	0.6929642	0.4047468	0.9154064	0.0604843	0.1239609	9.896152
M_{16}	0.6958807	0.4076588	0.9401093	0.0665654	0.1211422	9.896140
M_{17}	0.6993390	0.4111269	0.9035275	0.0617482	0.1242404	9.896158
M_{18}	0.696750	0.408218	0.890815	0.069066	0.115662	9.900559
M_{19}	0.711040	0.451885	0.704048	0.064270	0.129408	9.425478
M_{20}	0.695790	0.452497	0.712513	0.061568	0.119921	8.656641
M_{21}	0.690618	0.401996	0.898817	0.061900	0.123662	9.098960
M_{22}	0.691116	0.399166	0.890423	0.068227	0.116460	9.993707
M_{23}	0.796468	0.497614	0.358924	0.094359	0.093386	5.999652

Appendix B

The Bessel and modified Bessel Equations of the first and second kinds used in them formulations described in Chapter three was calculated using MATLAB program 7.

- Bessel Equation of the first kind

$$x^2 \frac{d^2 y}{dx^2} + x\frac{dy}{dx} + \left(x^2 - v^2\right)y = 0$$

Where ν is a real constant, is called Bessel's equation, and its solutions are known as Bessel functions.

$$J_v(x) = \left(\frac{x}{2}\right)^v \sum_{k=0}^{\infty} \frac{\left(-\frac{x^2}{4}\right)^k}{ki\Gamma\left(v+k+1\right)}$$

Where Γ(α) is the gamma function

- Bessel Equation of the second kind

$$x^2 \frac{d^2 y}{dx^2} + x\frac{dy}{dx} + \left(x^2 - v^2\right)y = 0$$

A solution $Y_v(x)$ of the second kind can be expressed as

$$Y_v(x) = \frac{J_v(x)\cos(v\pi) - J_{-v}(x)}{\sin(v\pi)}$$

- Modified Bessel Equation of the first kind

$$x^2 \frac{d^2 y}{dx^2} + x\frac{dy}{dx} - \left(x^2 + v^2\right)y = 0$$

Its solutions are known as modified Bessel functions.

$$I_v(x) = \left(\frac{x}{2}\right)^v \sum_{k=0}^{\infty} \frac{\left(\frac{x^2}{4}\right)^k}{ki\Gamma\left(v + k + 1\right)}$$

- Modified Bessel Equation of the second kind

$$x^2 \frac{d^2 y}{dx^2} + x\frac{dy}{dx} - \left(x^2 + v^2\right)y = 0$$

Its solutions are known as modified Bessel functions. A solution K $_v$(x) of the second kind can be expressed as

$$K_v(x) = \left(\frac{\pi}{2}\right)\frac{I_{-v}(x) - I_v(x)}{\sin(v\pi)}$$

Chapter One

Introduction and Literature Survey

1.1. Introduction

Optical fiber is the backbone component in long-distance and high capacity optical communication systems. The choice of fiber depends on where and how it is applied and what one kind of fiber can offer over the other. Optical fibers are found in a variety of important applications such as sensors, communication systems, and telecommunication networks, etc.

A clear understanding of the fundamental properties of fibers is needed not only to support the current optical networks, but to ensure the development of more powerful networks in the future too. An understanding of fiber optics is also important for the development of the fiber components found not only in communication systems but also in the many types of fiber sensors. Modern optical fiber system design typically requires the use of mathematical numerical computer models to estimate system performance.

The optical signal through transmission it in optical fiber suffers distortions from dispersion and nonlinearities. Dispersion can be avoided by using two optical fiber dispersion-shifted or dispersion-flattened fibers, but effects of nonlinearities remain a limiting factor for long distance transmission.

Optical fibers with modified dispersion characteristics, such as dispersion-shifted, dispersion-flattened, and dispersion compensating fibers are of considerable interest in broadband fiber-optic communication systems. Dispersion-shifted fibers offer a very small dispersion at the wavelength of λ=1.55μm. This wavelength corresponds to the minimum attenuation wavelength of silica-based optical fibers. Dispersion-flattened fibers provide small dispersion over an extended range of wavelengths.

These fibers have application in wavelength-division multiplexed systems in which several optical channels are simultaneously transmitted on the same fibers. With a flattened dispersion characteristic, all channels suffer small signal distortions comparison to Dispersion-shifted fibers. This feature makes dispersion-flattened fibers useful for applications in broadband communication systems, particularly those incorporating WDM (Wavelength Division Multiplexing). Both dispersion-shifted and dispersion-flattened fibers must be single-mode in the wavelength range of operation to avoid inter-modal dispersion.

With wavelength division multiplexing systems, dispersion and nonlinearity are the major limiting factors for transmission over very long distance. There are several design requirements for low nonlinearity single mode fibers, including low dispersion in the wavelength range of operation, larger effective-area than in conventional fibers, low losses (intrinsic, splice, microbending, and bending losses) and cutoff wavelength well below the wavelength of operation. However, the design requirements cannot be satisfied independently; for example, a larger effective-area generally implies a larger mode field diameter which leads to a large bending loss.

The design of multi-layer structure fibers is analyzed via using the weakly guiding approximation, which has small refractive index differences. The electromagnetic fields are quasi-transverse electromagnetic, with longitudinal components of the fields being very small compared with the transverse components. Boundary conditions result in a characteristic equation from which the propagation constant and the field solutions are then obtained by solving the scalar wave equation instead of vector wave equation at a certain wavelength. The wavelength dependence of the refractive index is calculated by Sellmeier equation. As the propagation constant and field solutions are known, dispersion,

dispersion slope, effective area, mode field diameter and cutoff wavelength can be calculated.

1.2. Historical background of Optical Communication Systems

Fiber optics telecommunication systems are nowadays the major component of terrestrial and submarine long distance networks. This is the result of intensive research and the situation is still in progress currently.

Although uncladded glass fibers were fabricated in the 1920s, the field of fiber optics was not born until the 1950s when the use of a cladding layer led to considerable improvement in the fiber characteristics, The idea that optical fibers would benefit from a dielectric cladding was not obvious and has a remarkable history The field of fiber optics developed rapidly during the 1960s, mainly for the purpose of image transmission through a bundle of glass fibers. These early fibers were extremely lossy (loss >1000 dB/km) from the modern standard. However, the situation changed drastically in 1970 when, following an earlier suggestion, losses of silica fibers were reduced to below 20 dB/km [1].

In years 1970 to 1980, communication networks were based on two key medias: the coaxial cable and radio systems (using electromagnetic wave). This double choice was motivated by the possibility of mutual help between cable and radio which are linked to different risks: for cable, an accidental breaking of the cable requires an intervention whereas an outage linked to the wave propagation for radio systems is intrinsically repaired automatically. The apparition of the first optical transmission systems is the result of many years of research in order to achieve good quality of fibers (presenting attenuation compatible with the needs of a telecommunication network) and also high-performance components or devices (in particular laser sources) which must be reliable.

These important evolutions had a great impact in the first years of optical communications:

• The use of monomode fiber instead of multimode fiber. Monomode fiber is leading to more difficult problems in terms of connector industry but it offers a much bigger potential capacity and reach.

• The change of telecommunication window from 800 nm wavelength to 1300 nm wavelength and to 1550 nm, which presents a minimal attenuation [2].

First optical systems are installed during years of the 80s with a bit rate of a few Mbit/s to 560 Mbit/s. The capacity of these systems is comparable to capacity of coaxial cable systems but they present a key advantage, which is the distance between regenerators (typically around 70 km for terrestrial transmissions). The consequence is the diminution of the number of optical repeaters, which is a major issue for submarine transmission. The first transatlantic cable, TAT 8, is installed in 1988 and operates at 1300 nm wavelength. Its reach is 6740 km and its capacity is 280 Mbit/s per fiber. In 1991, TAT 9 is installed and operates at 1550 nm wavelength allowing transmission of 560 Mbit/s per fibre.

In the beginning of 90s, first high capacity optical systems were born. They are characterized by a bit rate of 2,5 Gbit/s at 1550 nm with a repeater spacing of 90 km .From this period, optical systems present more capacity and much higher quality than radio systems. Between 1992 and 1996, optical transport networks will be built using standard fiber G.652 in France. Each fiber is equipped with a transmission system delivering 2.5Gbit/s with a typical repeater spacing of 90 km. In 1993, the accumulate length of optical fiber in the communication network is around 170000 km in France and in 2005 achieved 40 Gbit/s with 80 WDM channels unregenerate reach 3000 km [3].

The rapid expansion of worldwide networks is due to the development of the Web and of its online applications. This results in a need for increasing capacity in order to ensure data transmission. The technical context, essentially based on optical technologies, is full of hopes for this development as a major breakthrough occurs with the apparition of WDM transmission and new optical amplifiers [2,4].

Laser diodes operating at 1550nm were developed. These lasers allowed optical systems to operate at the fiber with minimum losses especially in single mode optical fiber see figure (1.2). 1550nm systems are the current standard system. Modern Distributed Feedback Lasers (DFB) can be fabricated to operate in the 1550nm region at precise wavelengths. International standards for WDM systems assume DFB lasers can be fabricated to launch specific wavelengths in 100GHz steps. In fact, some companies are designing WDM systems which assume that lasers can provide 25GHz steps between WDM carriers.

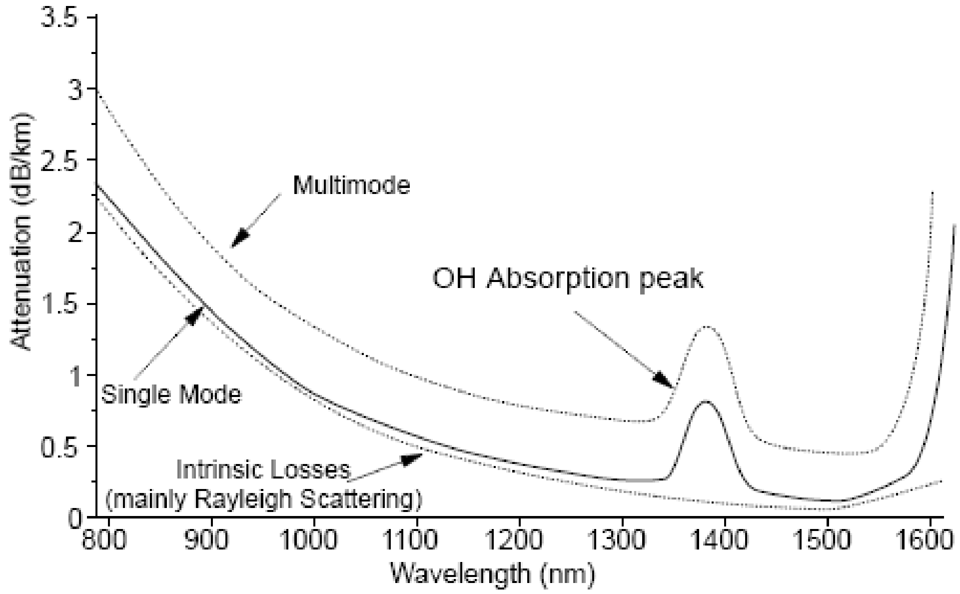


Figure1.1: Attenuation coefficient of a single-mode fiber [5].

Given the fact that the 1550nm region is the minimum loss region of optical fibers, future developments in optical systems will most likely focus on increasing the number of WDM channels which can be squeezed into

the 1550nm window, rather than moving to a new operating wavelength region. Research and development allowed to extend the 1550nm window to the wavelength range was used [5,3].

1.3. Optical Multiplexing.

Multiplexing is a term that is used to describe the concept of bringing together several independent communication streams (such as telephone calls or computer data streams) into a single stream

In which several optical carriers are transmitted in a single fiber and increases in data rate can be achieved by adding more carriers. In this case, each optical carrier in the single fiber may be modulated at a lower rate, but by having many such carriers in a single fiber (new commercial systems have up to 160 carriers), the overall data rate for the fiber can be extremely high. WDM assigns incoming optical signals to specific frequencies of light (wavelengths) within a certain frequency band. This multiplexing closely resembles the way radio stations broadcast on different wavelengths without interfering with each other because each channel is transmitted at a different frequency, we can select from them using a tuner. Another way to think about WDM is that each channel is a different color of light; several channels then make up a “rainbow.” [6,7].

Dense Wavelength Division Multiplexing (DWDM), are dramatically increasing both the numbers of links available and the per link transmission speeds [7]. The capacity of the modern optical communication reached at (10.92-terra bit/sec) through Dense Wavelength Division Multiplexing, and the conventional fiber is no longer sufficient for this modern optical communication. There are many reasons for that, such as dispersion and nonlinearity [3].

The nonlinear effect considers one of the important problems in the transmission of optical fiber by using WDM. Where two or more wave propagates in the same direction in single mode optical fiber. The signals mix to produce new signals. Therefore the nonlinear effect considers the limit factor to use the WDM.

1.4. Literature Survey

Several research groups have investigated low-nonlinearity dispersion-flattened fibers.

In 1998, H. J. Dutton [5], had presented effective-areas ranging from 55μm^2 to 80μm^2 and the mode field diameter standard SMF at 1550 nm are between 10.5μm and 11μm. have been reported in the literature.

In 1998, Hattori[8], obtained dispersion flattened fiber, an effective area as large as 93.4 μm^2 with mode field diameter 10.48 μm, dispersion less than 0.3847 ps/km.nm, and dispersion slope of about -3.95×10^{-3} ps/km.nm^2.

In 1999, according the national physical laboratory [9], presented the mode field diameter of 8.00 um and effective-areas 50.3 μm^2.

In 2003, Sub Hur, and his group [10] evaluated in their paper for single mode fiber dispersion 17 ps/km.nm , dispersion slope 0.05936 ps/km.nm^2 and effective area 78 μm^2.

In 2003, Ravi K. Varshney, et al [11], given designs which provide large mode field diameter 8.3 μm at λ=1550μm leading to the relatively large effective area (A_{eff} = 56.1μm). The total dispersion of the proposed fiber is in the range of (2.7-3.4) ps/km.nm and the dispersion slope at λ=1550μm is 0.01 ps/km.nm.

In 2005, H. R Sahu and S. Kant [12], present dispersion compensate fiber where dispersion -86.59 ps/km.nm , dispersion slope -0.135 ps/km.nm^2 and effective area 35 μm^2

Kant present effective-areas 72 μm^2, mode field diameter 9.6 μm, dispersion (2-11.2) ps/km.nm and dispersion slope less 0.09 ps/km.nm^2 and this group present effective-areas 55 μm^2, mode field diameter 8.4 μm, dispersion (2.6-8.9) ps/km.nm and dispersion slope less 0.05 ps/km.nm^2

In 2006, Soan Kim [13], obtained low dispersion slope of less than $1 \cdot 10-3$ ps/(km.nm^2) with an ultra-flattened dispersion of 0 ± 0.5 ps/(km.nm) from wavelengths of 1.36 μm to 1.75 μm and for an effective mode area as large as 100 μm^2 in the same spectral range.

1.5. Aim of This Work

The purpose of this work is to:

1. 1.Analysis, design and enhancement multi layer optical fiber to reduce the attenuation and distortion in single mode optical fiber. By using mathematical model and computer simulations for multi-layer optical fibers with various constructed layers which help to explain the characteristics of such optical fibers.
2. Performance evaluation of transmission properties and Investigate the effects of nonlinearity due to Kerr effect on parameters design of single mode fiber.

1.6. Thesis Layout

Chapter two introduces a formulation of the principal propagation characteristics of the optical fibers. Expressions for refractive index as a function of wavelength, effective refractive index, propagation constant, effective-area and mode-field-diameter are derived, cutoff wavelength, dispersion, dispersion slope and explanation of the nonlinear effects on optical fibers are also presented.

Chapter three discusses the analysis of electromagnetic wave propagation in optical fibers; starting with Maxwell's equations, wave equations are derived based on weakly guiding approximation, which are used in the analysis of fibers with an arbitrary index profile

Chapter four explains the propagation characteristics of optical fibers having multi-layer with three different profiles. A tolerance analysis for the design parameters such as effective area, mode field diameter dispersion and dispersion slope is carried out. Also the effects of nonlinearity are investigated within this chapter.

Chapter five presents the summary conclusions of the work in addition to the suggested future work.

Chapter Two

Transmission Properties of Optical Fiber and Nonlinearity

2.1. Introduction

In this chapter, the principal transmission properties of an optical fiber are addressed. These properties describe how pulses are attenuated and distorted in optical fibers. In particular, dispersion, cutoff wavelength, effective area, mode-field-diameter

The nonlinearity is undesired and contributes to signal distortion. However, in special case nonlinearity counterbalance dispersion and the pulses propagate without distortion over very long distance. This nonlinearity described in this chapter.

2.2. Fiber Types

An optical fiber is a dielectric waveguide that operates at optical frequencies. This fiber waveguide is normally cylindrical in form. It confines electromagnetic energy in the form of light to within its surfaces and guides the light in a direction parallel to its axis. The transmission properties of an optical waveguide are dictated by its structural characteristics, which have a major effect in determining how an optical Signal is affected as it propagates along the fiber. The structure basically establishes the information-carrying capacity of the fiber and also Influences the response of the waveguide to environmental.

Variation in the material composition of the core gives rise to the two commonly used fiber types. In the *first case*, the refractive index of the core is uniform throughout and undergoes an abrupt (or step) at the cladding boundary This is called a step-index fiber and can be divided into Multimode fiber and Single-Mode.

- Multimode fiber allows an infinite number of possible paths to be transmitted. These paths are called “modes” and identify the general characteristic of the light transmission system being used. Fiber that has a core diameter large enough for the light used to find multiple paths is called “multimode” fiber see figure (2.1).

-Single-Mode, if the fiber core is very narrow compared to the wavelength of the light in use then the light cannot travel in different modes and thus the fiber is called “single-mode” or “monomode” as show in figure (2.2).

In the *second case*, the core refractive index is made to vary as a function of the radial distance from center the of the fiber. This type is called graded-index fiber see figure (2.3) [5,15,16].

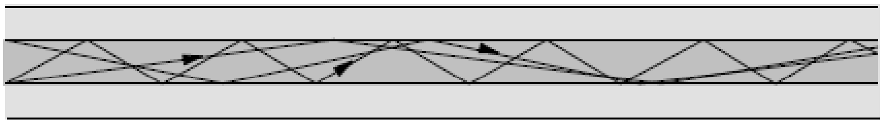


Figure 2.1: Multimode Step-Index Fiber

Figure 2.2: Single-Mode Fiber.

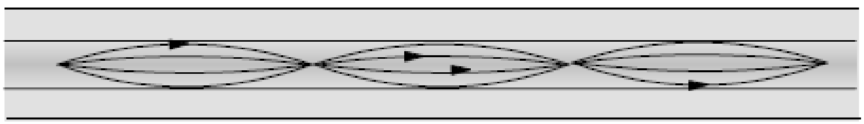


Figure 2.3: Multimode Graded index Fiber

2.3. Multi-layer Optical Fiber

To obtain special feature other than that in the conventional step index fiber, it is possible to design a fiber with multiple concentric layers of arbitrary refractive indices. The most benefit features of such fiber are to reduce the dispersion over a wide range of wavelengths and other losses. In spite of all fabrication problems of multi-layer fibers, the design of such fiber becomes very essential in many scientific industrial aspects.

2.4. Fiber Modes

The concept of the mode is a general concept in optics occurring also, for example, in the theory of lasers. An optical mode refers to a specific solution of the wave equation (electromagnetic wave) that satisfies the appropriate boundary conditions and has the property that its spatial distribution does not change with propagation. The fiber modes can be classified [5], as:

2.4.1 Transverse Electric (TE) Modes

TE modes exist when the electric field is perpendicular to the direction of propagation (the z-direction) but there is a small z-component of the magnetic field. Here most of the magnetic field is also perpendicular to the z-direction but a small z-component exists. This implies that the wave is not traveling quite straight but is reflecting from the sides of the waveguide. However, this also implies that the “ray” path is meridional (it passes through the centre or axis of the waveguide). It is not circular or skewed.

2.4.2 Transverse Magnetic (TM) Modes

In a TM mode the magnetic field is perpendicular to the direction of propagation (z) but there is a small component of the electric field in this direction. Again this is only a small component of the electric field and most of it is perpendicular to the z-axis. Rather than talk about field components here it might be better to say that the orientation of the electric field is only a few degrees away from being perpendicular to the z-axis.

2.4.3 Transverse ElectroMagnetic (TEM) Modes

In the TEM mode both the electric and magnetic fields are perpendicular to the z-direction. The TEM mode is the only mode of a single-mode fiber.

2.4.4 Helical (Skew) Modes (HE and EH)

In a fiber, most modes actually travel in a circular path of some kind. In this case components of both magnetic and electric fields are in the z-direction (the direction of propagation). These modes are designated as either HE or EH (H = magnetic) depending on which field contributes the most to the z-direction.

2.4.5 Linearly Polarized (LP) Modes

It turns out that because the refractive index difference between core and cladding is quite small much can be simplified in the way we look at modes. The TE, TM, HE and EH modes can all be summarized and explained using only a single set of LP modes. It is conventional to number the TE and TM modes according to the number of nulls in their energy pattern across the waveguide. Thus mode TE00 would have a single energy spot in the centre of the waveguide and no others. (This would be the same mode as TEM.) Mode TE21 would have two nulls (three energy spots) in one direction and a single null (two energy spots) in the other. This is illustrated in figure (2.4).

When the subscript numbers are low (0, 1, 2) the modes are often referred to as "low order" modes. When the subscripts are high numbers the modes are referred to as "high order" modes.

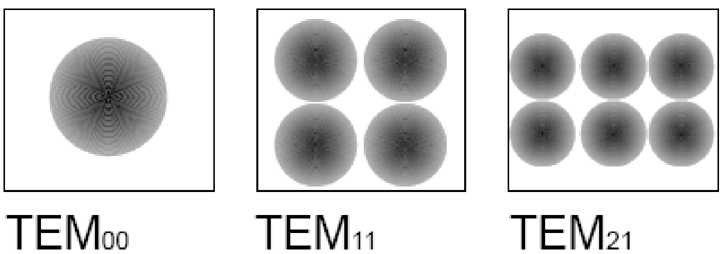


Figure 2.4: Energy Distribution of Some TEM Modes. The numbering system used here applies to TE, TM and TEM modes.

LP mode numbering is different from TE or TM mode numbering. This is illustrated in figure (2.5). LP modes are designated LP_{vm} where m is

the number of maxima along a radius of the fiber (note here the number of maxima rather than the number of nulls as before). v here is half the number of maxima around the circumference. LP is used when discussing multi-mode or single mode fiber propagation. In practice, TE and TM designations are usually used when discussing lasers and planar waveguides. [5].

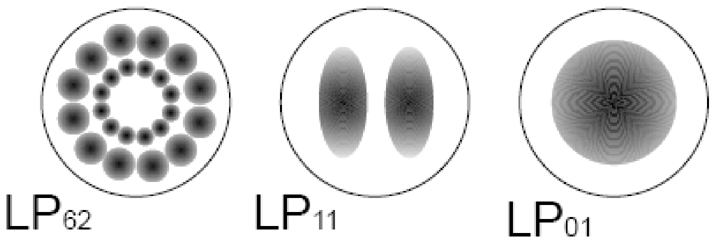


Figure 2.5: Energy Distribution of Some LP Modes in Fiber

2.5. Fiber Optic Parameters

2.5.1. Numerical Aperture (NA)

It is a measure of the ability of fiber to gather light at the input end, and it is a measure of the contrast of refractive index between core and cladding. It is a good measure of the light guiding properties of the fiber. The higher the NA is the smaller radius we can have bent in the fiber before loss of light becomes a problem [7,17].

$$NA = \sqrt{n^2{}_{\max} - n^2{}_{clad}} \tag{2.1}$$

Where:

n_{max} max. refractive index

n_{clad} cladding refractive index

2.5.2. Normalized Frequency - "V"

One often quoted and very useful measure of a fiber is usually called the "V". In some texts it is called the "normalized frequency" and in others just the "dimensionless fiber parameter". V summarizes all of the important characteristics of a fiber in a single number. It can be used directly to

determine if the fiber will be single-mode or not at a particular wavelength and also to calculate the number of possible bound modes. In addition it can be used to calculate the spot size, the cutoff wavelength and even chromatic dispersion. However it is important to note that V incorporates the wavelength that we are using on the fiber and so to some extent it is a measure of a fiber within the context of a system rather than the fiber alone.

$$V = \frac{2\pi d}{\lambda}\sqrt{n^2{}_{\max} - n^2{}_{clad}} \qquad (2.2)$$

d is the core radius

λ is the wavelength.

n is the refractive index.

If $V \leq 2.405$ the fiber will be single mode at specific wavelength [7,18].

2.5.3. Phase Velocity (n_{phase}) and Group Velocity (n_g)

The phase velocity is the speed of propagation of an electromagnetic wave in some medium. In fiber it is the speed of planar phase front of the mode as it propagates along the fiber [19].

$$V_{phase} = \frac{c}{n_{eff}} \qquad (2.3)$$

Group velocity is the usual way of discussing the speed of propagation on fiber. It is the speed of propagation of modulation along the fiber. It is generally a little less than the phase velocity. The reason why the group velocity is different from the phase velocity is related to the amount of dispersion in the medium. If there is no dispersion in the medium the group velocity and the phase velocity are the same [7].

2.5.4. Effective Refractive Index (n_{eff})

It is a single number situated between the refractive index of the core (max. refractive index) and cladding refractive index, which summarizes the effect of them.

$$n_{eff} = \frac{\beta}{k} \tag{2.4}$$

Where β is propagation constant and $k=2\pi/\lambda$.

k is wave number

2.5.5. Propagation Constant (β)

The wave is guided in the specific mode if (β) the "propagation constant" satisfies:

$$n_{clad}.k < \beta < n_{max}k \tag{2.5}$$

and the normalized propagation constant b is[7,20]

$$b = \frac{(n^2{}_{eff} - n^2{}_{clad})^{1/2}}{(n^2{}_{\max} - n^2{}_{clad})^{1/2}} \tag{2.6}$$

It is lies in the range $0 \leq b \leq 1$

The propagation constant β is the ratio between angular frequency ω and phase velocity (ν_{phase})

$$\beta = \frac{\omega}{v_{phase}} \qquad \text{where} \qquad k = \frac{\omega}{c_0} = \frac{2\pi}{\lambda} \tag{2.7}$$

2.6. Parameters of Low Nonlinearity Single-Mode Fiber

There are several design requirements for low nonlinearity and single mode fiber, such as low dispersion in the operation wavelength, large effective area, small mode field diameter and cutoff wavelength below the operation wavelength.

2.6.1. Mode Field Diameter (MFD)

As we have seen optical power (in single-mode fiber) travels in both the core and the cladding. In many situations, not the least being when we join fiber, we need a number that will give us a measure of the extent of the region that carries the optical signal. In single-mode fiber the core diameter is not sufficient. And from figure (2.6) a significant proportion (up to 20%) of light in a single – mode fiber actually travels in cladding [4,10]. For this reason the apparent diameter of the core (the region in which most of the light travels) is somewhat wider than the core itself. The region in which light travels in a single–mode fiber is often called the “mode field”.

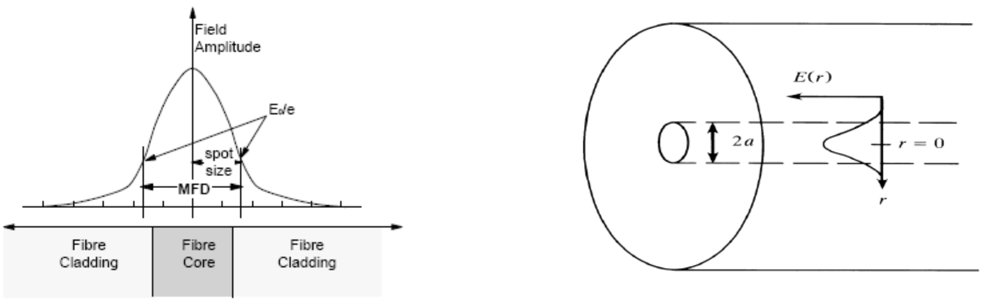


Figure 2.6: MFD represents how the light is actually distributed in the single mode fiber [5,15].

Mode Field Diameter (MFD), instead of the core diameter, the mode field varies in diameter depending on the relative refractive indices of core and cladding.As the optical power in “single mode fiber” travels in both core and cladding, MFD is representing the distribution of light through the core and the cladding of a particular fiber. It is used to calculate power losses due to fiber bending and splicing. MFD can be calculated from the following relation [5,21]:

$$MFD = \left[8 \frac{\int_0^\infty |E(r)|^2 \, rdr}{\int_0^\infty \left| \frac{dE}{dr} \right|^2 rdr} \right]^{1/2} \qquad (2.8)$$

2.6.2. Effective Area [8]

The effective-area is a property of optical fibers that appears when the nonlinear equation is derived. Intuitively, the power divided by the effective-area is a measure of power density inside the fiber.

$$I = P / A_{eff} \qquad (2.9)$$

Where (I) intensity distribution, (P) power lunching to the fiber, A_{eff} effective area.

The larger the effective-area, the lower is the power density inside a fiber. Fiber nonlinearities strongly depend on the power density inside a fiber, thus an increase in the effective-area results in a decrease in fiber nonlinearities and their effects on signal transmission. As mentioned before, fiber nonlinearities are detrimental for very long links, even a moderate power levels. For this reason, it is important to design optical fibers with large effective-areas.The effective-area is defined as.

$$A_{eff} = 2\pi \frac{\left[\int_0^\infty |E(r)|^2 \, rdr \right]^2}{\int_0^\infty |E(r)|^4 \, rdr} \qquad (2.10)$$

$$A_{eff} = 2\pi \frac{\left[\int_0^\infty I(r) rdr \right]^2}{\int_0^\infty I(r)^2 \, rdr} \qquad (2.11)$$

Where *E(r)* is the amplitude and *I(r)* is the intensity of the fundamental mode at radius r from the axis of the fiber.

2.6.3. Cutoff Wavelength. [8].

Cutoff wavelength of a guided mode occurs when the mode becomes a radiation mode and its power leaks out the fiber and is absorbed by the jacket. In simple terms, this means that total reflection at the most external boundary of the fiber ceases to exist and the wave is partially transmitted into the external cladding region.

All fiber designs presented in Chapter four are required to be single-mode. This means that a fiber must support only one propagating mode in the wavelength range of operation, $\lambda_1 < \lambda < \lambda_2$. This is accomplished if the first propagating mode has a cutoff wavelength greater than λ_2 and the second propagating mode has a cutoff wavelength less than λ_1. The first mode to propagate in a multi-clad structure is the LP_{01} mode and the second one is the LP_{11} mode. Then, single-mode operation is guaranteed if $\lambda_{c,11} < \lambda < \lambda_{c,01}$, where $\lambda_{c,01}$ and $\lambda_{c,11}$ are cutoff wavelengths of LP_{01} and LP_{11} modes, respectively.

The cutoff occurs at the wavelength that the effective refractive index becomes equal to the refractive index of the most external layer (for specific mode) [7].

2.6.4. Dispersion:

The width (duration) of the pulse propagating in an optical fiber increases with distance of propagation. The pulse of light is composed of wavelengths. The propagation velocity is not the same for all wavelengths. This phenomenon is called dispersion see figure (2.7).

The two modes must travel at different distances to arrive at their destinations. The disparity between the times that the light rays arrive is called as modal dispersion [5,22,32].

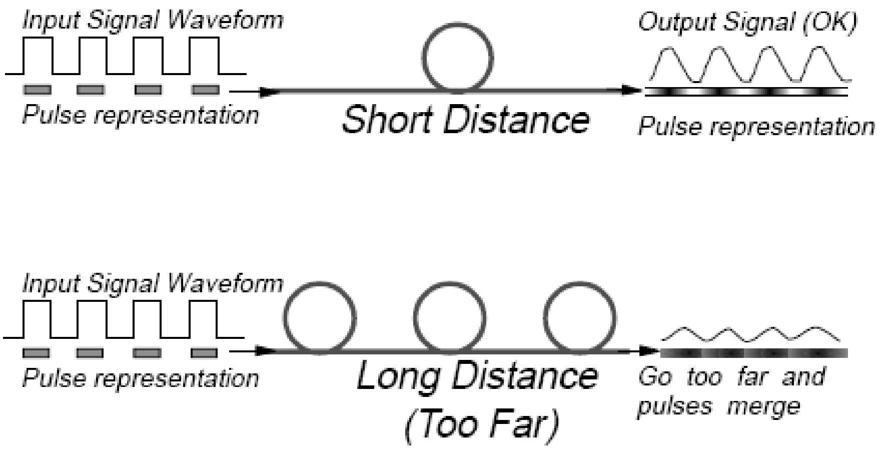


Figure 2.7: The effect of dispersion on short distance and long distance.

i. Dispersion in Single-Mode and Multimode Fibers

Intermodal dispersion does not occur in single-mode fibers, but is a significant effect in multimode fibers. It occurs as a result of different modes having different group velocities at the same frequency. Graded-index fibers with nearly parabolic-index profile were developed mainly to reduce the effect of intermodal dispersion. Here, bound rays deviating from the axis of the fiber travel a longer distance but at larger velocities, reaching the receiving end of the fiber at about the same time with the other rays, thus in graded-index fibers pulse spreading is significantly reduced. The main advantage of single-mode fibers is that intermodal dispersion is absent simply because the energy of the injected pulse is transported by a single mode. However, pulse broadening does not disappear altogether. The group velocity associated with the fundamental mode is frequency dependent because of chromatic dispersion. Three mechanisms contribute to intramodal dispersion: material dispersion, waveguide dispersion, and polarization-mode dispersion see figure (2.8) [23,24,25].

$$D = DM + DW \tag{2.12}$$

D is Dispersion

DM is Material Dispersion

DW is Waveguide dispersion

a. Material Dispersion

Material dispersion is caused by variations of refractive index of the fiber material with respect to wavelength. Since the group velocity is a function of the refractive index, the spectral components of any given signal will travel at different speeds causing deformation of the pulse. Variations of refractive index with respect to wavelength are described by the Sellmeier equation which is expressed as Sellmeier's Eq. [22,25,26,36].

$$n(\lambda) = \left[1 + \sum_{i=1}^{3} \frac{A_i \lambda^2}{\lambda^2 - \lambda^2_i}\right]^{1/2} \tag{2.13}$$

λ is the operating wavelength and λ_i, A_i (i = 1, 2, 3) are the Sellmeier's coefficients whose measured values are available for a number of silica–based materials used for fiber fabrication. The materials used in our designs are summarized in table (Appendix A). In this table, M is assigned to each material. The corresponding Sellmeier's coefficients for the materials shown in Table 1 are given in Table 2. These data are extracted from [7,8].

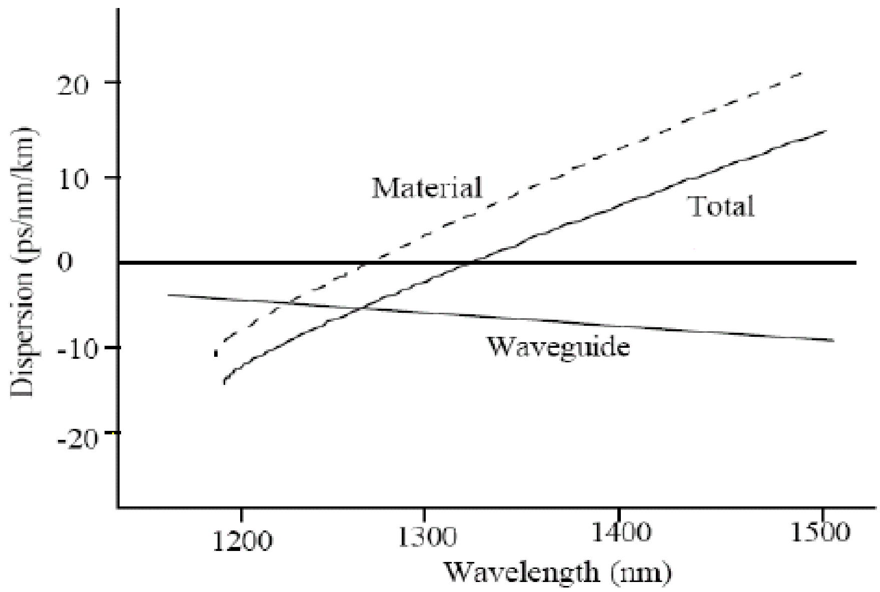


Figure 2.8: Dispersion variation with Wavelength for standard single mode fiber.

b. Waveguide Dispersion

Waveguide dispersion occurs because different spectral components of a pulse travel with different velocities by the fundamental mode of the fiber. It is as a result of axial propagation constant b being a function of wavelength due to the existence of one or more boundaries in the structure of the fiber. Without such boundaries, the fiber reduces to a homogeneous medium, the fundamental mode becomes a uniform plane-wave, and the waveguide dispersion effect is eliminated [25,27].

c. Polarization Mode Dispersion (PMD)

Within a single mode fiber, the linear polarization light really has two components: x-component and y-component each of them perpendicular to each other. The two components exhibit a different refractive index to the different birefringence. This may happen in a normal single mode fiber such that there is usually a very slight difference in refractive index for each polarization (component), see figure (2.9). In addition there is another effect to cause a circular or elliptical polarization due to unperfected circular shape of the fiber [7,28].

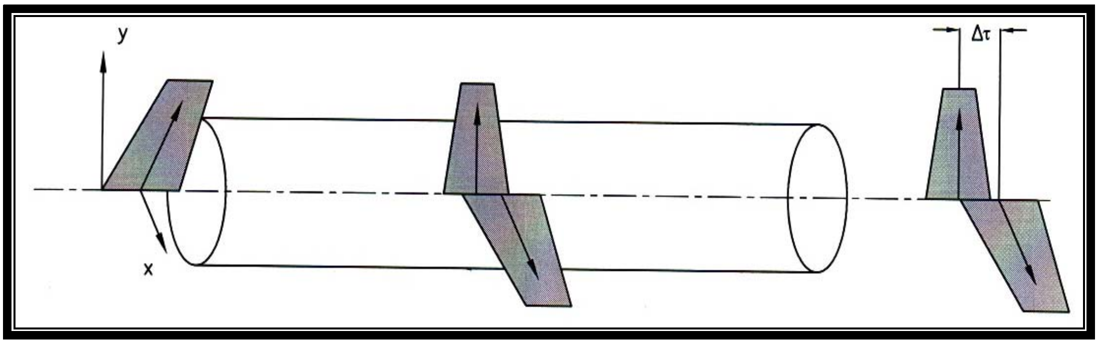


Figure 2.9: the effect of PMD

ii. Dispersion-Altered Fibers

The objective in the optimum design of an optical fiber is to achieve the lowest attenuation and dispersion at the wavelength of operation. In ordinary single-mode fibers, total dispersion vanishes at a wavelength of about 1.3 µm. However, the lowest attenuation for glass fibers occurs at 1.55 µm. Alteration of dispersion in a fiber is attained by manipulating the index profile and geometry of the fiber. Dispersion-altered fibers include dispersion-shifted, dispersion-flattened, and dispersion compensating fibers discussed below.

a. Dispersion Shifted Fiber (DSF)

In a single mode fiber there is a point for zero dispersion where the material and waveguide dispersion cancel each other at a wavelength of 1.31 µm. For this reason most of the current long distance fiber networks operate at that wavelength.

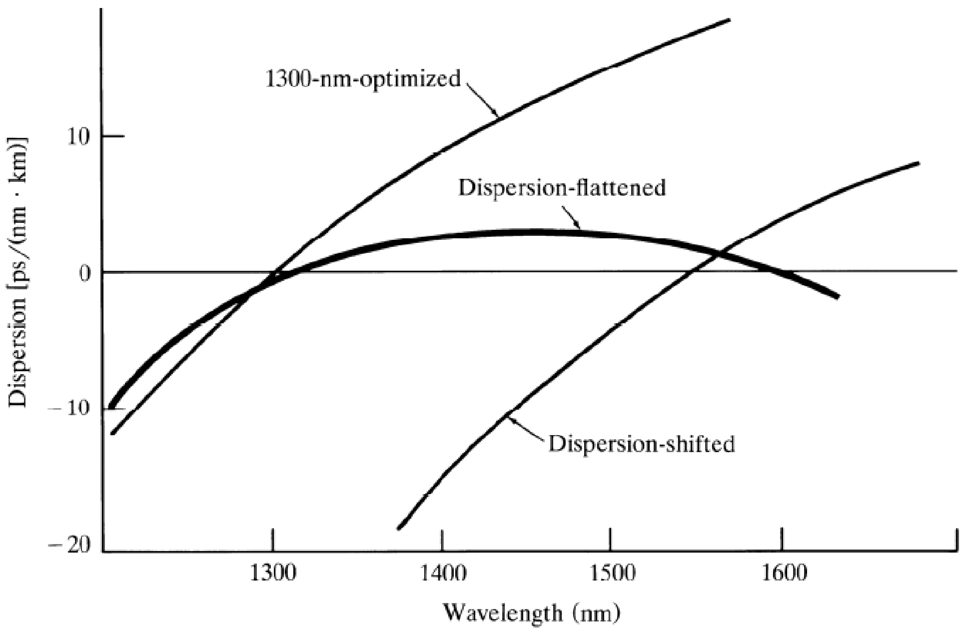


Figure 2.10: Dispersion Flattened Fiber. and Shifted Fiber and Optimized Fiber

However, there are many reasons to work in 1.55 µm band. These reasons are: the fiber attenuation is much lower in 1.55 µm band, EDFA operates in this band and WDM system requires a large amplified

bandwidth, and this means that we have to use 1.55 μm window and optical amplifier. With a single mode fiber (conventional type) the dispersion is about 17 psec/km.nm, this is very comparatively large, however, by using lasers with a very narrow line-width we can reduce the dispersion effect but the problem is still there [7] see figure (2.10).

b. Dispersion Flattened Fiber (DFF)

Dispersion flattening occurs by partial cancellation of waveguide dispersion by material dispersion in the wavelength range of operation. In some applications such as wavelength division multiplexing, where a number of signals with different wavelengths are carried by one fiber, it is desired to design the fiber optic system such that all optical signals experience relatively the same low distortion. The information capacity of fiber-optic systems using dispersion flattened fibers and wavelength division multiplexing (WDM) schemes can be increased many folds. Multi clad fibers, including double, triple, and quadruple-clad fibers can be used to design dispersion-flattened fibers [25], as shown in figure (2.10).

c. Dispersion Compensating Fiber (DCF)

It is possible to construct fiber profile where the total dispersion is about 100 ps/km.nm in the opposite direction to the dispersion caused by material. This can be placed in series with exist fiber link to the signal without dispersion [7,29].

iii. Dispersion Calculation

When energy propagates from a non monochromatic source, such as light emitting diode or laser through a dispersive dielectric-medium, which is concerned with the group velocity or the group delay of the energy being transmitted. One may consider a component of monochromatic electric

field, say the y component, the propagation in the z direction in a dielectric medium [7,15,19].

$$E_y = A\cos(\omega t - kz) \tag{2.14}$$

The phase velocity is obtained by setting the phase of this wave equal to a constant then finding dz/dt.

$$v = \frac{dz}{dt} = \frac{\omega}{k} \tag{2.15}$$

$$\omega t - kz = const$$

now consider that the wave has two frequencies of equal amplitude

$$\omega + \Delta\omega$$

$$\omega - \Delta\omega$$

and the wave numbers corresponding to the two frequencies are:

$$k + \Delta k$$

$$k - \Delta k$$

For frequency 1

$$E_y^1 = A\cos[(\omega + \Delta\omega)t - (k + \Delta k)z]$$

For frequency 2

$$E_y^2 = A\cos[(\omega - \Delta\omega)t - (k - \Delta k)z]$$

$$E_y = E_y^1 + E_y^2$$

$$E_y = A\{\cos[(\omega + \Delta\omega)t - (k + \Delta k)z] + \cos[(\omega - \Delta\omega)t - (k - \Delta k)z]\}$$

$$E_y = 2A\cos(\omega t - kz)\cos(\Delta\omega t - kz) \tag{2.16}$$

To obtain the phase velocity of this wave for a constant phase point

$$\omega t - kz = const$$

The phase velocity is

$$v = \frac{dz}{dt} = \frac{\omega}{k}$$

$$\Delta\omega t - \Delta kz = const$$

Then the group velocity

$$v_g = \frac{dz}{dt} = \frac{\Delta\omega}{\Delta k} \tag{2.17}$$

Taking the limit as $\Delta\omega > 0, v_g$ becomes the group delay τ_g is defined as

$$v_g = \lim_{\Delta\omega \to 0} \frac{\Delta\omega}{\Delta k} = \frac{d\omega}{dk} \tag{2.18}$$

$$\tau_g = \frac{1}{v_g} = \frac{dk}{d\omega} \tag{2.19}$$

$$k = nk_0 = n\left(\frac{\omega}{c}\right)$$

$$v = \frac{\omega}{k} = \frac{c}{n}$$

$$\tau_g = \frac{dk}{d\omega} = \frac{1}{c}\frac{d(n\omega)}{d\omega} \tag{2.20}$$

As the medium is dispersive whose refractive index is a function of ω and

$$\tau_g = \frac{1}{c}\left(n + \frac{\omega dn}{d\omega}\right) \tag{2.21}$$

$$N_g = n + \frac{\omega dn}{d\omega} \tag{2.22}$$

$$\tau_g = \frac{1}{c}N_g$$

$$v_g = \frac{c}{N_g}$$

The group index N_g is

$$N_g = n + \omega\frac{dn}{d\lambda}\frac{d\lambda}{d\omega} \tag{2.23}$$

Finally the dispersion is defined as:

$$D = \frac{d\tau_g}{d\lambda} = -\frac{\lambda}{c}\frac{d^2 n}{d\lambda^2} \tag{2.24}$$

2.6.5. Dispersion Slope (Second Order Dispersion)

Dispersion slope is the rate of change of dispersion with a wavelength (must be less than 0.095 ps/ km. $(nm)^2$. In WDM it is desirable to have all the channels experience a similar dispersion coefficient in order to reduce the costs associated with dispersion management. For this reason fibers with reduced slope have been developed for multi–channel application (DFF). Dispersion slope is [7,20]:

$$\frac{dD}{d\lambda} = \frac{1}{c}\left[\frac{d^2 n}{d\lambda^2} + \lambda \frac{d^3 n}{d\lambda^3}\right] \qquad (2.25)$$

2.7. The Effect of High Power (Nonlinearity) with Optical Fiber

Optical waveguide does not always behave as completely linear channels whose increase in output optical power is directly proportional to the optical power. Nonlinear effects are the ones that increase in significance exponentially as the level of optical power in fiber is increased, at low power levels there is little or no effect. As the power is increased the effects appear and can then become very significant [17,30].

Nonlinear effects in optical fibers can be divided into elastic and inelastic processes. Elastic processes do not exchange energy between the electromagnetic fields and the dielectric medium and are generally caused by the nonlinear refractive index. On the other hand, inelastic processes exchange energy with the medium and are caused by stimulated scattering. The prime example of elastic scattering is four wave mixing. Stimulated Brillouin scattering and stimulated Raman scattering is examples of inelastic processes

The nonlinear effects as a result of transmission in fiber almost undesirable give rise to signal distortion, interference, and signal to noise ratio (SNR), degradation and attenuation. On the other hand high injection power is required in order to enhance the system performance, such as bit

rate transmission distance and increasing the number of channels. The major nonlinear effect causing degradation in optical system is explained in the following sections [5,7].

2.7.1 Stimulated Brillouin Scattering (SBS)

Brillouin scattering inelastic processes where is a scattering of light backwards towards the transmitter caused by mechanical (acoustic) vibrations in the transmission medium (fiber). SBS is usually trivial but can be very important in the situation where a high quality, narrow line width laser is used at a relatively high power level.

This effect is caused by the presence of the optical signal itself, even though a signal level of a few milliwatt, with very small core radius of single mode fiber core, the field can be very intense. An optical signal is in reality has a very strong electromagnetic field; this field causes mechanical vibration in the fiber which produces a regularly varying pattern of very slight differences in the refractive index. The Brillouin scattering effect is caused by light being reflected by the diffraction grating created by the regular pattern of refractive index changes. The light is reflected backward from moving grating then its frequency is shifted by Doppler Effect. This effect is non-linear and in practical system requires a power level of about 3mW for any serious effect to be observable [5,14].

2.7.2. Stimulated Raman Scattering (SRS)

Stimulated Raman scattering interaction basically caused by inelastic collisions, high power light in the small fiber core reacts with molecular vibrations of fiber material to radiate light at a wavelength longer than that of incident light. Thus energy is transferred from shorter to longer wavelengths. Scattered light can appear in both the forward and backward directions. In a single channel system, the power level at which Raman scattering begins to take effect is very high [5,31].

2.7.3. Phase Modulation

The refractive index is dependent on power, this is because the electromagnetic field acts on the atoms and molecules of the fiber. This is called Kerr effect, at low intensities the effect is linear, the change in refractive index varies linearly with light intensity. At high intensities the effect is highly nonlinear the change in refractive index caused by a particular amount of intensity change is much greater than the change in refractive index caused by the same amount of intensity change at lower total levels. This is called non-linear Kerr effect [3,32]. Kerr nonlinearities are characterized by the power-dependent refractive index of the fiber

$$n = n_0 + n_{non} I \tag{2.26}$$

$$n = n_0 + n_{non} \left(\frac{P}{A_{eff}} \right) \tag{2.27}$$

Where n_o is the linear refractive index of the material,

n_{non} is nonlinear coefficient which is about $3.4 \times 10^{-8} \mu m^2/w$,

P is the power, and A_{eff} is the effective area.

At a very high power, Kerr nonlinearities can be used to balance the effect of chromatic dispersion in the fiber and at low power levels the results of Kerr effect are self-phase modulation and cross–phase modulation [15].

i. Self–Phase Modulation (SPM)

Because of Kerr effect, the refractive index of the fiber affected by a pulse of light, the effect depending on the points within the pulse that the refractive index is affected. At different points within a single pulse of light in the fiber the refractive index of the glass is different, so there is a small difference between the refractive indices at the leading, middle and trailing. This changes the phase of the light-waves, which is consisted of the pulses.

Changes in phase lead to changes in frequency, which lead to broaden the pulse. SPM usually has a very small effect and it can be ignored [3,7].

ii. Cross-Phase Modulation (XPM)

With multi-channel at different wavelength WDM in the same fiber, Kerr effect caused by one signal can result in phase modulation of the other signals, this is called cross–phase modulation XPM because it acts among multiple channels rather than within a single signal. In XPM effect there is no power transfer among signals. The result of XPM is a symmetric spectral broadening and distortion of the pulse shape. Finally XPM is associated with SPM [7].

2.7.4. Four Wave Mixing (FWM)

This effect is related to WDM systems. It occurs when two or more waves propagate in the same direction in the single mode fiber. The signals mix to produce new signals. Four-wave mixing occurs because of high power leading to variation of refractive index of the fiber core, which produces an interaction among the signals that are closely spaced in wavelength [7,33,34]. new frequencies (wavelengths) are produced according to

$$f_{fwm} = f_1 + f_2 - f_3 \tag{2.28}$$

Where f_{fwm} corresponds to operating frequencies at three closely spaced channels 1, 2 and 3. See figure (2.11).

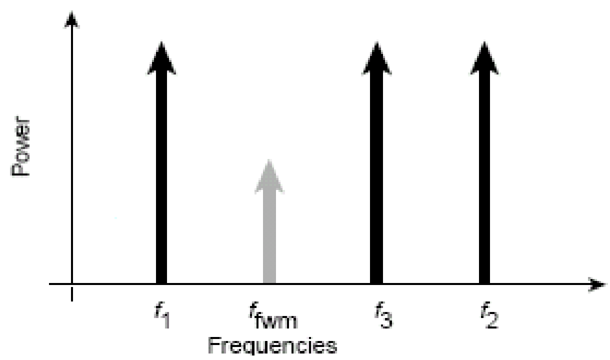


Figure 2.11: Four Wave Mixing Effects.

Chapter Three

Mathematical Representation and Modelling of Multilayer Optical Fiber

3.1. Introduction

In this chapter, a generalized analysis of multi layer fibers is presented. The geometry considered here is limited to a four-layer cylindrical dielectric structure and investigations of electromagnetic (EM) wave propagation in multi–layer optical fiber are taken into consideration. The present work proposes an effective numerical approach based on scalar wave equation method.

To solve the wave equation taking into account the weakly guiding approximation to compute the propagation constant (β) as well as the field distribution. All programs that represent the proposed algorithm are written by MATLAB7.

3.2. Analysis of Waveguiding and Scalar-Wave

Electromagnetic fields in multi layer fibers are solutions in Maxwell's equations subject to boundary conditions [15]. In deriving these solutions, we focus attention on guided modes only and take advantage of weakly guiding conditions, which are always met for optical fibers of practical interest, in order to simplify the solutions.

It is well known that the constituent materials of practical optical fibers have nearly equal refractive indices, so that the waveguiding region of a fiber appears like a nearly homogeneous medium. In this case, the fields inside the optical fiber are quasi-TEM (Transverse ElectroMagnetic) and have only small components along the direction of propagation.The polarization effects due to different layers are small and the fields may be described as a linear combination of scalar modes oriented along transverse

Cartesian coordinates (x or y direction). These considerations allow us to examine the propagation properties inside a fiber based on the scalar wave analysis [8].

Initially, it is assumed that fiber is a linear medium and nonlinearities will be accounted for as a perturbation to the "linear state" in a later chapter. These nonlinearities are weak in general and the principal nonlinearity to be considered here is the Kerr effect [7,8].

3.3. Considerations of the Multi-Layer Fiber Optic Design

1. The fiber has a multi-layer of an arbitrary refractive index.
2. The materials constituting the fiber are assumed to be homogeneous, linear, isotropic dielectric materials having no currents and free charges.
3. The fiber under test is considered as a waveguide having a circularly symmetric, dielectric and homogenous cross section.
4. The direction of propagation of electromagnetic field is in positive z – direction
5. The fiber is a waveguide, free from any perturbation such as bend or twists that cause an asymmetry in the index profile of the fiber.
6. The fiber has an infinite long waveguide, then the discontinuities at fiber and faces are neglected.
7. The fiber is loss-less, this means that the propagation constant is real.
8. The effects of nonlinearities are ignored (at the beginning).
9. The outer final cladding layer extends to infinity this means that the electromagnetic field within the single mode fiber decays rapidly outside the core.
10. Weakly guiding conditions imply that the index difference between two neighboring layers is very small; (Relative Refractive Index (Δ)) that is, $\Delta_i = (n_{i+1} - n_i)/ n_i << 1,\ i = 1$, 2, for layer fibers [35].

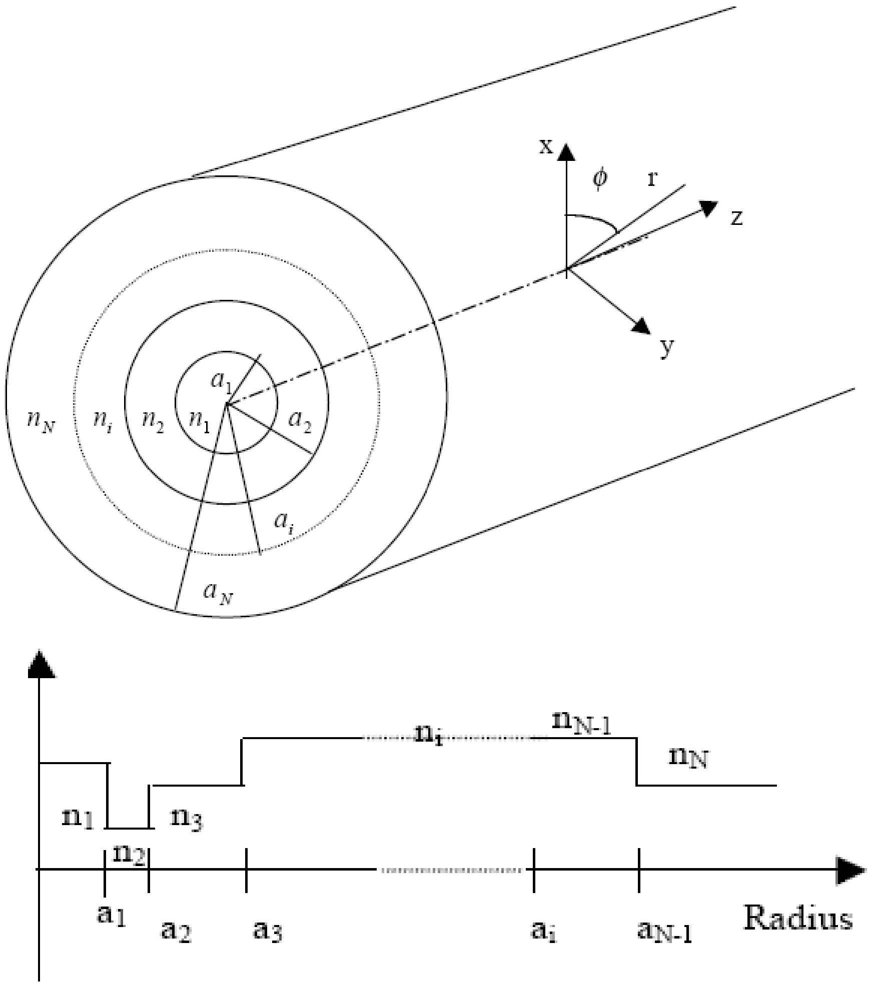


Figure 3.1: Geometry and dimensions of a cylindrical multi-layer optical fiber [8].

3.4. Analysis of Multi-Layer Optical Fiber

Firstly, a derivation of wave equations of multi–layer circular wave-guide of arbitrary refraction indexes profile is shown in figure (3.1). Approximations and assumption have been used with a wave-guide analysis.

1- To analyze the optical waveguide we need to consider Maxwell's equations that give the relationships between the electric and magnetic field. Assuming linear, isotropic dielectric materials having no currents and free charges [15,17].

$$\nabla \times E = -\frac{\partial B}{\partial t} \tag{3.1}$$

$$\nabla \times H = \frac{\partial D}{\partial t} \tag{3.2}$$

$$\nabla \cdot D = 0 \tag{3.3}$$

$$\nabla \cdot B = 0 \tag{3.4}$$

Where

D=εE and B=μH

E is the electric field.

H is the magnetic field.

D is the electric flux density.

B is the magnetic flux density.

μ is the permeability of free space.

ε is the material permittivity.

A relationship defining the wave phenomena of electromagnetic fields can be derived from Maxwell's equations. Taking the curl of Eq. (3.1) and making use of equation (3.2) yields

$$\nabla \times (\nabla \times E) = -\mu \frac{\partial}{\partial t}(\nabla \times H) = -\varepsilon\mu \frac{\partial^2 E}{\partial t^2} \tag{3.5}$$

Using the vector identity.

$$\nabla \times (\nabla \times E) = \nabla(\nabla \cdot E) - \nabla^2 E \tag{3.6}$$

And using Eq. (4.3) (i.e., $\nabla \cdot E = 0$), equation (3.5) becomes

$$\nabla^2 E = \varepsilon\mu \frac{\partial^2 E}{\partial t^2} \tag{3.7}$$

Similarly, by taking the curl of Eq. (3.2), it can be shown that

$$\nabla^2 H = \varepsilon\mu \frac{\partial^2 H}{\partial t^2} \tag{3.8}$$

The equations (3.7) and (3.8) are the standard wave equations.

2- Then equations (4.1) and (3.2) become:

$$\nabla^2 E + \mu\varepsilon E = -\nabla\left[\frac{\nabla\varepsilon}{\varepsilon} E\right] \tag{3.9}$$

$$\nabla^2 H + \mu\varepsilon H = -\frac{\nabla\varepsilon}{\varepsilon} \times (\nabla \times H) \tag{3.10}$$

The above two equations represent nonhomogeneous vector wave equations for electrical and magnetic field. The refractive index of the material (n) is related to material permittivity.

$\varepsilon = \varepsilon_o \varepsilon_r = \varepsilon_o n^2$

Where ε_o is the free space permittivity, ε_r is the dielectric constant of material.

$c_o=(\mu_o \varepsilon_o)^{1/2}$, $n=c_o/v_{phase}$

$v_{phase}= \omega/k$ and $k_0=2\pi/\lambda_0$.

n and ε_r are not constants but are functions of position, this is because of the optical fiber consists of multi-layer with different refractive index values.

The multi-layer has approximately equal refractive index values. There are many reasons for that [7,25].

i. Material with different refractive index will have different thermal expansion coefficients. If the refractive index between layers is too large, then any change in the ambient temperature in the fiber environment will cause stress at the interface between layers and can cause a defect in the fiber.

ii. The difference in the refractive index between layers is less than 1%.

iii. High contrast refractive index between layers means high doping to the cladding layers, which leads to more attenuation.

iv. Since (n) and (ε) change only very slightly over the cross section of the fiber, their derivative can be approximated to zero in equations (3.9) and (3.10).

3- Then the nonhomogeneous vector wave equations become homogeneous vector equations:

$$\nabla^2 E + k_0^{\,2} n^2 E = 0 \tag{3.11}$$

$$\nabla^2 H + k_0{}^2 n^2 H = 0 \tag{3.12}$$

4- By using the cylindrical coordinates *(r, ϕ, z)*, the homogeneous vector wave equation for E and H fields of equations (3.11, 3.12), can be written in cylindrical coordinates as

$$\frac{\partial^2 \psi}{\partial r^2} + \frac{1}{r}\frac{\partial \psi}{\partial r} + \frac{1}{r^2}\frac{\partial \psi^2}{\partial \varphi^2} + q^2 \psi = 0 \tag{3.13}$$

Where $q^2 = (k^2 n^2 - \beta^2)$

The field propagates in positive z direction and has a form:

$\psi = \psi(r, \phi)\exp(-i\beta z)$

β is the modal propagation constant.

The vector of electric field E consists of three scalar components (E_r, E_ϕ, E_z) and similarly the vector of magnetic field H consists of three scalar components (H_r, H_ϕ, H_z). The type of mode under analysis determines which of the six scalars (E_r, E_ϕ, E_z) and (H_r, H_ϕ, H_z) are used [7].

We have a circularly symmetric fiber which can be classified into transverse electric (TE), transverse magnetic (TM) and hybrid modes (HE) or (EH). TE modes consist of the (h_r, e_ϕ, h_z) fields and TM modes consist of (e_r, h_ϕ, e_z). Hybrid modes consist of all six fields. The analysis waveguide of the with multi-layer structure by using full vector wave equations becomes very complicated [1,15].

5- The fiber modes can be classified as guided modes, leaky modes, and radiation modes. By using weakly guided approximation, as the refractive index of the layers are nearly equal, the longitudinal field component (e_z, h_z) are very small compared to the transverse ones, and then can be neglected. In this case the field inside the optical fiber is quasi (TEM) (TEM: Transverse Electro-Magnetic), then the field can be described as linear combination of scalar modes oriented along transverse (x,y) plane. By these approximations, it is possible to examine the propagation

properties inside the fiber and leads to construct a set of scalar equations with negligible error comparing with vector wave equations [1].

As we consider equation (3.13), which represents the scalar cylindrical wave equation, the terms ψ becomes ψ scalar quantity. By looking at the refractive index profile and the effective refractive index we can get from equation (3.13) one of the following solutions: -

- If n_i which is the refractive index of the i^{th} layer is greater than the effective refractive index β/k, then q^2 should be positive, and accordingly the zero order solution (ν=0) of this scalar wave equation consists of Bessel function of 1st kind and 2nd kind see appendix B. [1,7,32].

$$y''+\frac{y'}{x}+\left(1-\frac{v^2}{x^2}\right)y=0$$

$$y=A_1J_O(x)+A_2Y_O(x)$$

- If n_i is less than β/k, q^2 should be negative, the zero order solution (ν=0) consists of modified Bessel of 1st kind and 2nd kind.

$$y''+\frac{y'}{x}-\left(1+\frac{v^2}{x^2}\right)y=0$$

$$y=A_1I_O(x)+A_2K_O(x)$$

6- Using the method of separation of variables and dropping the common term $\Phi(\varphi)$ and the solution of equation (3.13) is becomes.

$$\psi(r,\varphi)=[A_iJ_v(u_ir)+B_iY_v(u_ir)]\Phi(\varphi) \quad n_{eff}<n_i \tag{3.14}$$

$$\psi(r,\varphi)=[A_iI_v(u_ir)+B_iK_v(u_ir)]\Phi(\varphi) \quad n_{eff}>n_i \tag{3.15}$$

A_i, B_i are constants (amplitude coefficients),

Accordingly the zero order solution *(ν=0)* of this scalar wave equations (4.14) and (4.15) will become.

$$\psi(r,\varphi)=[A_iJ_o(u_ir)+B_iY_o(u_ir)]\Phi(\varphi) \quad n_{eff}<n_i \tag{3.16}$$

$$\psi(r,\varphi) = [A_i I_o(u_i r) + B_i K_o(u_i r)]\Phi(\varphi) \quad n_{eff} > n_i \tag{3.17}$$

Where

$$u_i = \left(\left|n_i^{\,2} - n_{eff}^{\;\;2}\right|\right)^{1/2}$$

i = 1, 2, 3,….. N; N: number of layers

and A_i and B_i are constants (amplitude coefficients), v is an integer, J_v is the Bessel function of first kind of order v, Y_v is the Bessel function of second kind of order v, I_v is the modified Bessel function of first kind of order v, and K_v is the modified Bessel function of second kind of order v.

In the region that includes the origin ($r=0$), Y_v and K_v functions must be excluded from the solution because they are undefined at the origin. Also, in the outer cladding layer the solutions involve only K_v functions to ensure that fields remain bounded as r approaches infinity. This is simply considered by equation (3.16-3.17) as shown in figures. (3.2) and (3.3).

The discrete "approximate solutions" derived from the scalar wave equation are called linearly polarized modes and are designated as LP_{vm}, where m is the order of mode for a given value of v; m=1, 2, 3, …. The fundamental mode is the LP_{01} mode, while the next propagating mode is the LP_{11} mode.

7- The tangential field component among the various successive layers should be continuous, i.e. $\psi(r,\varphi)$ and its derivative $\partial\Psi/\partial r$ are continuous at the boundaries. Depending on this condition, it is possible to write down the general relationship of the field and its derivative by the following relation for the i^{th} laye

$$A_i M_0(u_i a_i) + B_i N_0(u_i a_i) = A_{i+1} M_0(u_{i+1} a_i) + B_{i+1} N_0(u_{i+1} a_i) \tag{3.18}$$

$$A_i \frac{d}{dr} M_0(u_i a_i) + \frac{d}{dr} B_i N_0(u_i a_i) = A_{i+1} \frac{d}{dr} M_0(u_{i+1} a_i) + B_{i+1} \frac{d}{dr} N_0(u_{i+1} a_i) \tag{3.19}$$

where a_i :is the radius of i^{th} layer.$M_0(u_i a_i)$ which could be either the Bessel function of 1^{st} kind $J_0(u_i a_i)$; or the modified Bessel function of 1^{st} kind $I_0(u_i a_i)$. $N_0(u_i a_i)$ is the Bessel function of 2^{nd} kind $Y_0(u_i a_i)$; or the modified Bessel of 2^{nd} kind $K_0(u_i a_i)$.Note the following special cases:

i. At the boundary between the core and 1^{st} layer, equations (3.18) and (3.19) become:

$$A_1 M_0(u_1 a_1) - A_2 M_0(u_2 a_1) - B_2 N_0(u_2 a_1) = 0 \tag{3.20}$$

$$A_1 \frac{d}{dr} M_0(u_1 a_1) - A_2 \frac{d}{dr} M_0(u_2 a_1) - B_2 \frac{d}{dr} N_0(u_2 a_1) = 0 \tag{3.21}$$

ii. At the boundary between the layer (N-1) and (N), equations (3.18) and (3.19) become:

$$A_{N-1} M_0(u_{N-1} a_{N-1}) + B_{N-1} N_0(u_{N-1} a_{N-1}) - B_N K_0(u_N a_{N-1}) = 0 \tag{3.22}$$

$$A_{N-1} \frac{d}{dr} M_0(u_{N-1} a_{N-1}) + \frac{d}{dr} B_{N-1} N_0(u_{N-1} a_{N-1}) - B_N \frac{d}{dr} K_0(u_N a_{N-1}) = 0 \tag{3.23}$$

According to the set of equations (3.18), (3.19), (3.20) (3.21), (3.22) and (3.23) a system of (2N-2) (matrix) equations with (2N–2) unknowns was obtained. Avoiding a trivial solution, the determinant of coefficients for this system of equations must be equal to zero. Hence normalized propagation constant for a given range of wavelength and a specific mode for a given fiber will be obtained.

$$\begin{bmatrix} X_j(u_1a) & -X_j(u_2a) & -Z(u_2a) & 0 & 0 & 0 \\ \overline{X}_j(u_1a) & -\overline{X}_j(u_2a) & -\overline{Z}_j(u_2a) & 0 & 0 & 0 \\ 0 & X_j(u_2a) & Z_j(u_2a) & -X_j(u_3a) & -Z_j(u_3a) & 0 \\ 0 & \overline{X}_j(u_2a) & \overline{Z}_j(u_2a) & -\overline{X}_j(u_3a) & -\overline{Z}_j(u_3a) & 0 \\ 0 & 0 & 0 & X_j(u_3a) & Z_j(u_3a) & -Z_j(u_4a) \\ 0 & 0 & 0 & \overline{X}_j(u_3a) & \overline{Z}_j(u_3a) & -\overline{Z}_j(u_4a) \end{bmatrix} \times \begin{bmatrix} A_1 \\ A_2 \\ B_2 \\ A_3 \\ B_3 \\ B_4 \end{bmatrix} = 0$$

(3.24),

Number of layers (4), A_i and B_i are constants, i is the layer number, a is the radius of layer and j is the order of the mode.

$X_j(u_ia) = J_j(u_ia)$ if $n_i > n_{eff}$

$X_j(u_ia) = I_j(u_ia)$ if $n_i < n_{eff}$

$Z_j(u_ia) = Y_j(u_ia)$ if $n_i > n_{eff}$

$Z_j(u_ia) = K_j(u_ia)$ if $n_i < n_{eff}$

$\overline{X}_j(u_ia)$ the derivative of $X_j(u_ia)$

$\overline{Z}_j(u_ia)$ the derivative of $Z_j(u_ia)$

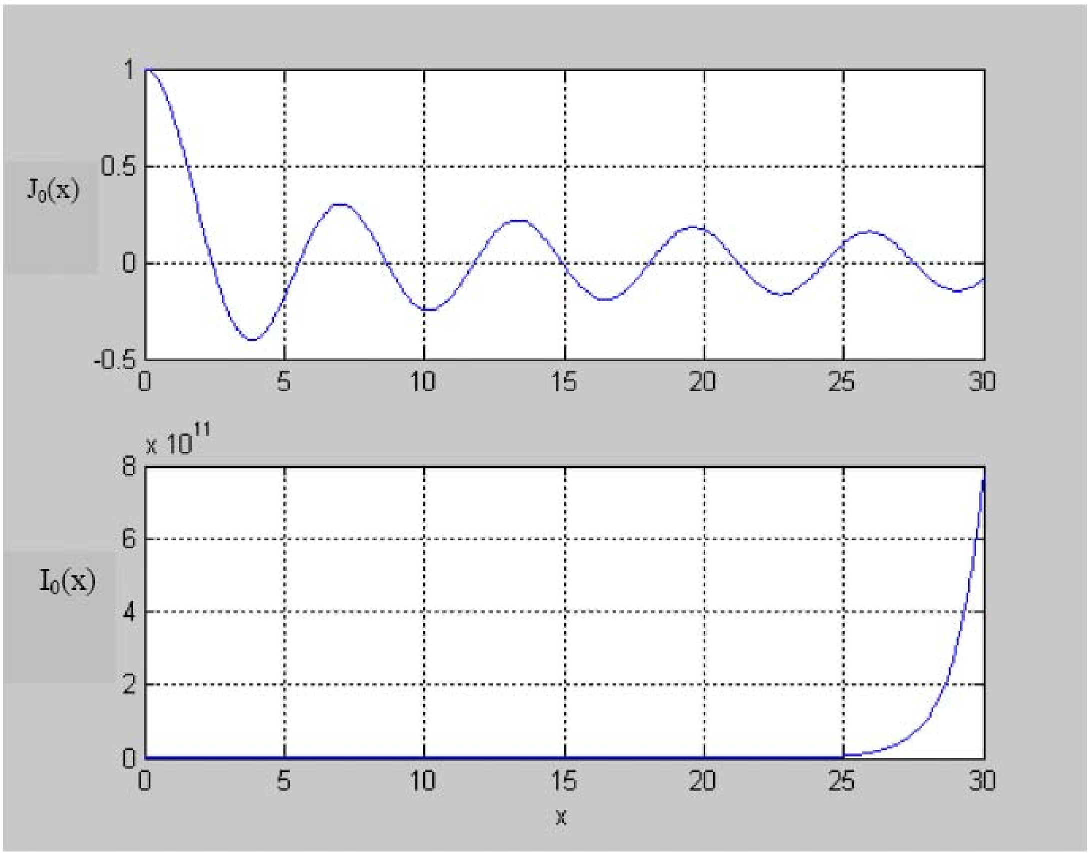


Figure 3.2: Bessel function of the first kind and Modified Bessel function of the first kind.

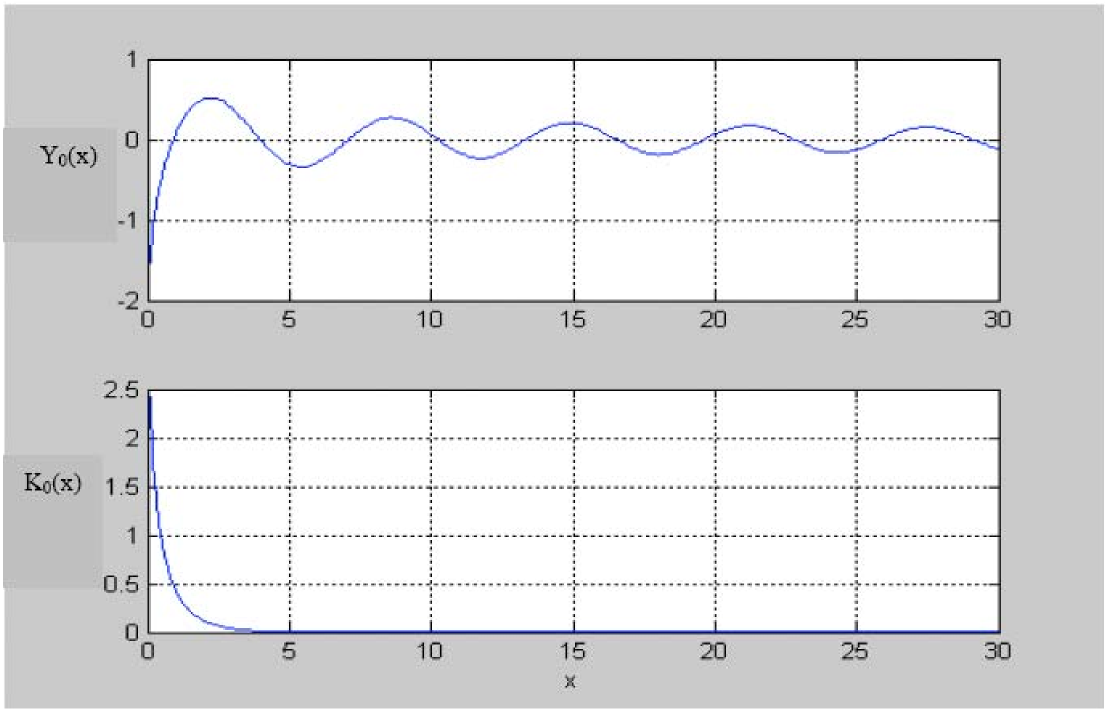


Figure 3.3: Bessel function of the second kind and the Modified Bessel function of the second kind

Chapter Four

Design of Low Nonlinearity Dispersion- Flattened Fibers and Numerical Results

4.1 Introduction

In this chapter, the numerical results of designed large effective area (low-nonlinearity) dispersion-flattened fibers based on multi layer profiles are presented. A systematic approach for designing these fibers, using a reference W-index profile to initiate the design, is adopted. Where presented group (A) with three different profile index to show behavior of these profile and chose optimum design. Also, study the characteristics of the transmission properties as a dispersion, dispersion slope, mode field diameter, effective area and cutoff wavelength.

This chapter will show examples of fiber design with parameters listed on figures namely; a_i (the dimension of the i^{th} layer), n_i (the refractive index of the i^{th} layer) and M the material type, which is listed in table (A-1, 2)

4.2. Design Considerations of Optical Fiber for WDM System

Silica fiber has the lower attenuation with a band of wavelength around 1.55μm, and the optical amplifiers work over this band. These two features lead WDM systems to work in this band. However, the dispersion is large within this band and the effective area is less than that of conventional fiber (about 55μm^2). These two problems play an important role in long distance applications and cause several kinds of signal distortion. Inter-modal dispersion and tolerable bending and splicing losses must be avoided.

4.3. Design Procedure.

To design multi layer fiber optic and calculation of transmission properties use flow chart as a shown in figure (4.1). A computer program (matlab version (7)) was developed for the numerical solution of the field distribution (equation (3.24)). The input data to this program include material compositions and radii of various layers of the waveguide, the wavelength, and the mode numbers for the desired mode. A listing of silica-based materials, commonly used in optical fiber fabrication, is provided in appendix A. The Sellmeier coefficients of the materials are stored in the program and are used for specified materials to calculate the refractive indices. After the input, these data obtain on the transmission properties as function of wavelength. For the materials of tables appendix A, it can be easily verified that the refractive indices vary slightly from one material to another; hence scalar field analysis is justified as discussed earlier in chapter three.

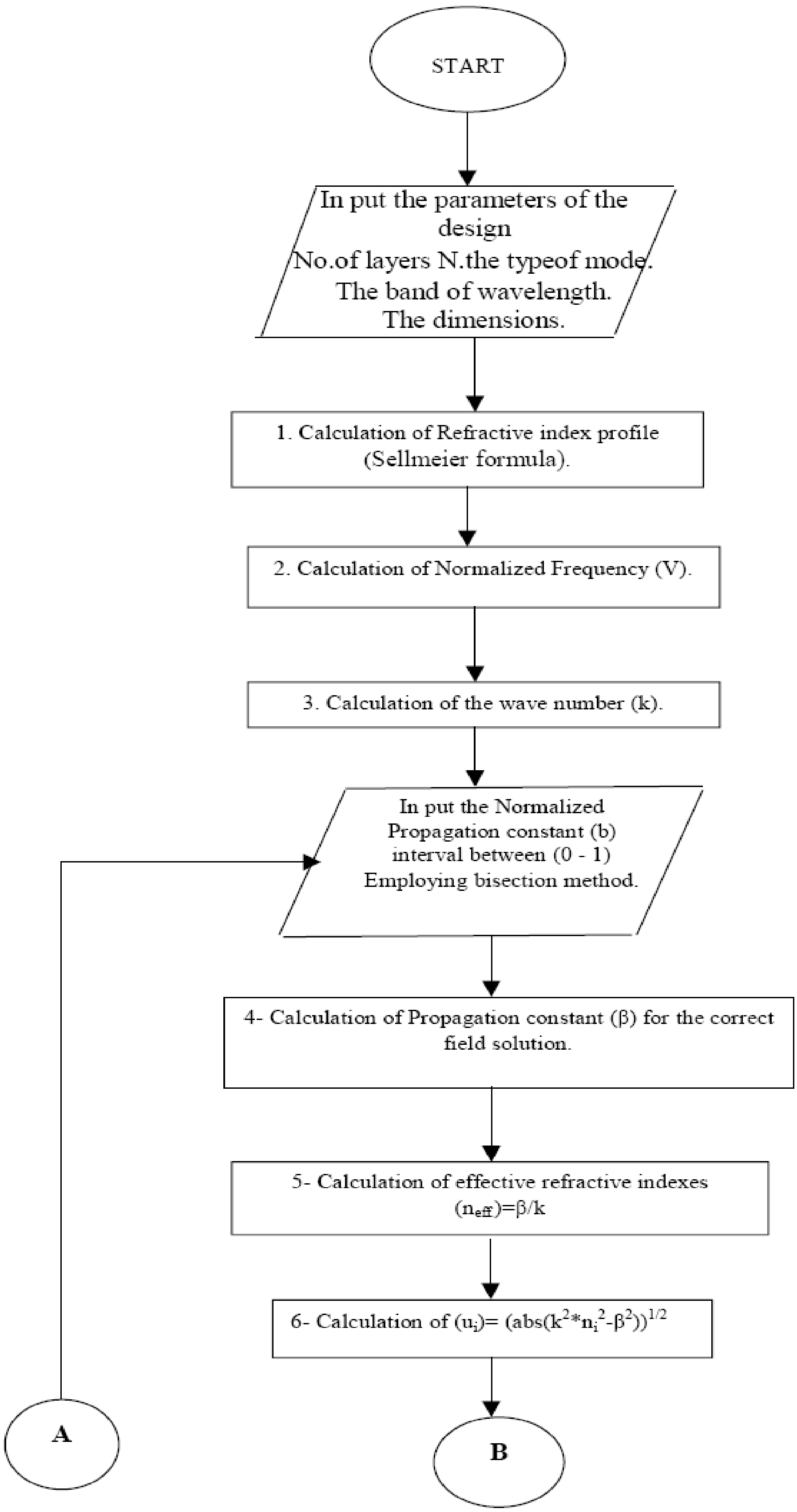


Figure (4.1): show the design of multi layer of fiber optic and calculation of transmission properties

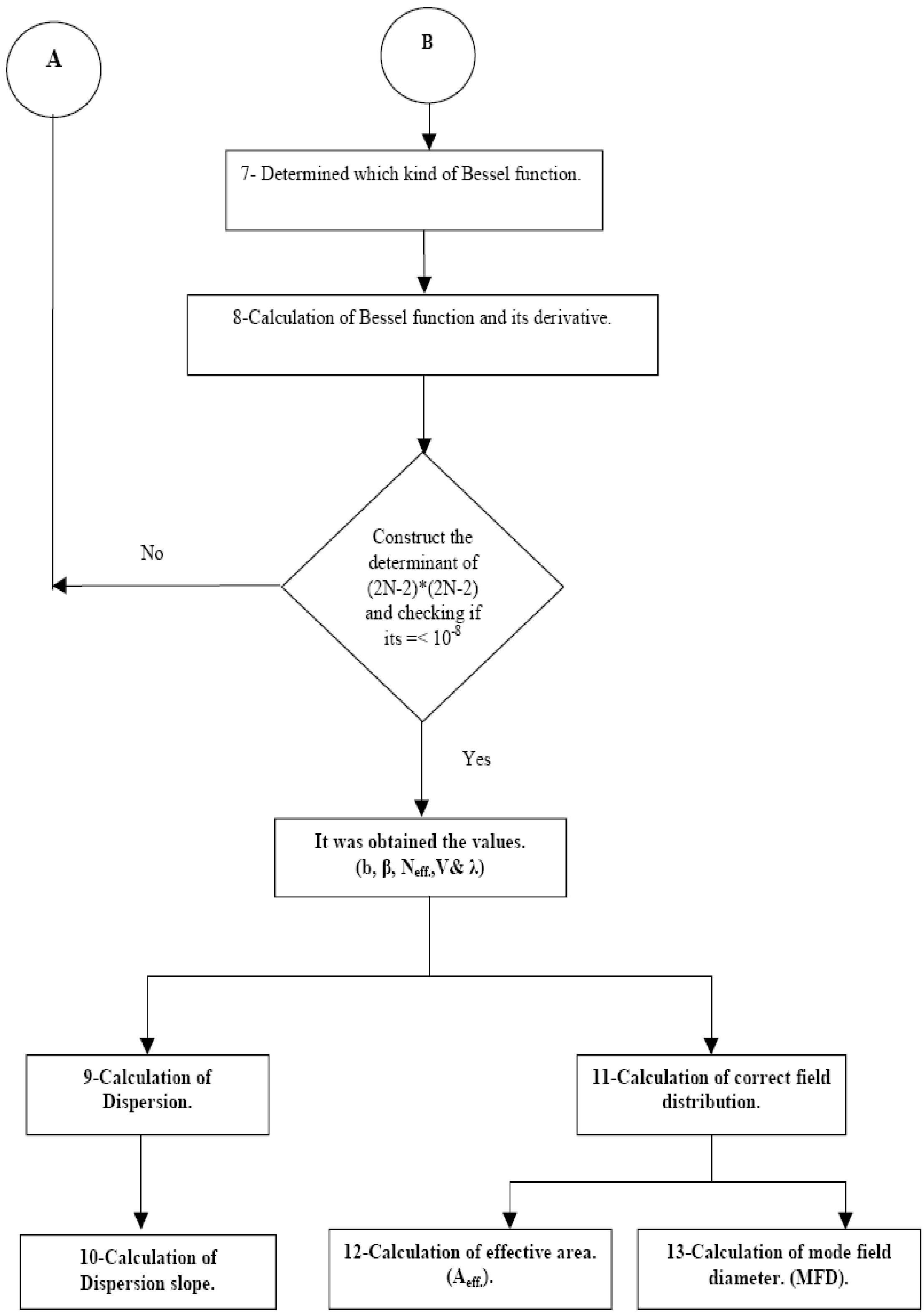


Figure (4.1): continued

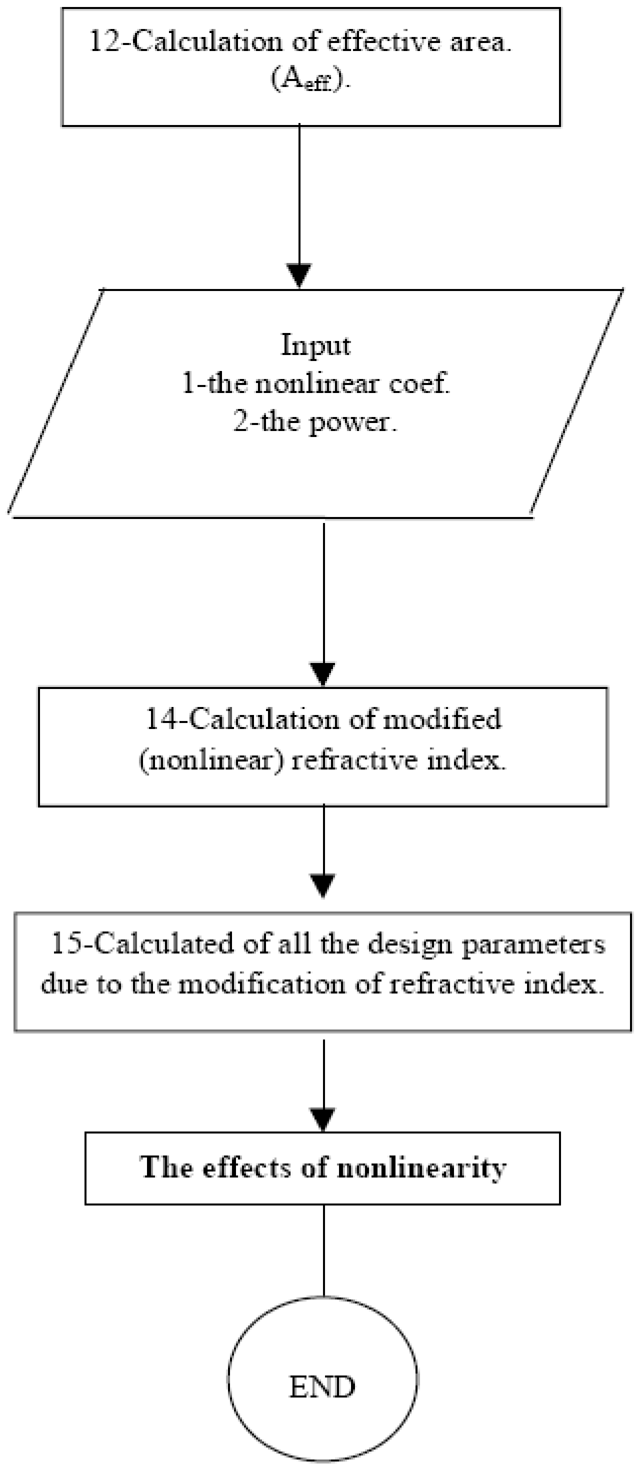
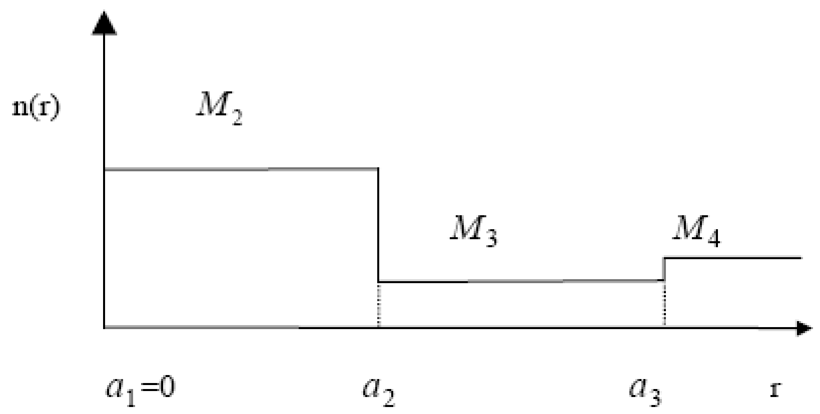


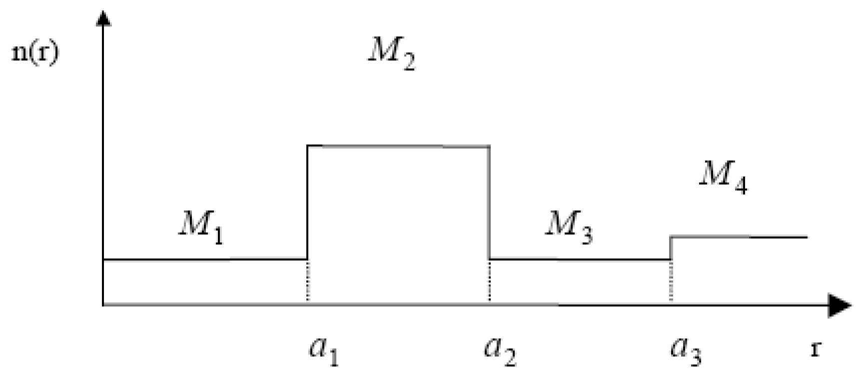
Figure (4.1): continued

4.4. Optimal Design

In order to obtain the most promising design, the multi-layer fiber parameters should be selected to get: (i) a single mode (ii) a zero or near zero dispersion flattened over some specific range of wavelength (iii) a large effective area (minimum nonlinearity) (iv) a small mode field diameter (minimum losses). The dispersion-flattened fibers discussed here must exhibit larger effective-areas than conventional dispersion-flattened fibers and have low losses. The large effective-area can be very useful to broadband WDM (Wavelength Division Multiplexing) systems involving very long distances. To achieve a larger effective-area, the index profile of the fiber is modified such that the fields become less confined to its central core region. The approach adopted is to start with a reference fiber that provides zero dispersion at (1.55 μm) and reduce the refractive index of a central portion of the core region. Here, a W-index fiber is chosen as the reference fiber (group A) [8]. Reducing the index of a portion of its core region, a four layers structure is created in which the first inner cladding assumes the highest refractive index. This modification of index profile moves the zero-dispersion wavelength away from (1.55μm). Then, indices and dimensions of different layers are adjusted so that the zero-dispersion wavelength is shifted back to (1.55μm). The design of large effective area dispersion-flattened fibers may evolve from known profiles, which provide zero dispersion at (λ= 1.55μm). Here, a simple profile as that shown in figure (4.2a) is chosen as the reference profile. Obviously, this choice is not unique and other profiles might be considered in initiating the design. Material compositions for the reference W-fiber and other profiles in figure 4.2 (M_1, M_2, etc.) are given in Appendix A. where table 4.1(A) and table 4.2(A) represented group A use as reference design, see figure 4.2a. The reference W-fiber (group A) with provides a negligible -0.0713 ps/nm.km dispersion and an effective-area of about 32 μm^2 at λ = 1.55μm see table



(a)



(b)

Figure: 4.2 Refractive index profiles for (a) a reference-fiber, and (b) depressed-core large effective-area dispersion-flattened fibers.

Although lowering the index of a portion of the core of reference fiber brings the benefit of larger effective area, but moves the zero-dispersion wavelength away from (1.55μm). To bring the zero-dispersion wavelength to (1.55μm), the dimensions and/or the indices of the layer regions must be altered. To what extent and which dimensions or indices

need to be modified are dictated by several factors, including the size and index of the core region, the requirement that the fiber remain single-mode in the (1.55 μm).

We now present three groups biased on W-index fiber (group A) as reference. Where; group (B): the refractive index of a central portion of the core region is smaller than the layer three. Group (C): the refractive index of a central portion of the core region is larger than the layer three. Group (D): the refractive index of a central portion of the core region is equal the layer three, and we take optimal design one from every group and create group (E) to compare between there groups. See figure (4.2-b) as reference design for four layer dispersion-flattened fiber.

4.4.1. Group A

Tables 4.1(A) and 4.2(A) represent group (A). Table 4.1(A) represents material compositions (M) and dimensions (a) of layer from the center core radius of fibers for group B. table 4.2(A) contains effective-area (A_{eff}), mode-field-diameter (MFD), dispersion (D), dispersion slope (DS) (all at λ = 1.55μm), cutoff wavelength (λc) and quality factor (Q).This is group use to reference design.

Table 4.1(A): Parameters and material compositions for the designed fiber

Fiber number	1^{st} Layer	2^{nd} Layer	3^{rd} Layer
1	M_2 a=2.58	M_{12} a=5	M_3 a=20

Table 4.2(A): Effective-area, mode-field-diameter, dispersion, dispersion slope (all at λ = 1.55 μm), cutoff wavelength and quality factor.

Fiber number	A_{eff} μm^2	MFD μm	D Ps/nm.km	DS Ps/nm^2.km	λc μm	Q
1	31.97	6.47	0.029	0.035	1.08	0.764

4.4.2. Group B

Tables 4.3(B) and 4.4(B) represent group (B). Table 4.3(B) represents material compositions (M) and dimensions (a) of layer from the center core radius of fibers for group B. Table 4.4(B) contains effective-area (A_{eff}), mode-field-diameter (MFD), dispersion (D), dispersion slope (DS) (all at $\lambda = 1.55\mu m$), cutoff wavelength (λc) and quality factor (Q).

Data of three first designs from group (B), will be illustrated to show the behavior of dispersion flattened fiber for this group.

The profile index of group B ($n_1<n_2<n_3<n_4$) is shown in figure (4.3) for fibers 1, 2, and 3 from group B, this profile index demonstrates the refractive index versus with center core radius. Figure (4.4) shows the variations of the normalized propagation constant versus wavelength for fibers of group B, are clarified the cutoff wavelength (λc) of the fundamental mode PL_{01}, at which the PL_{11} can no longer propagate, and the wavelength range for single mode operation is determined from the cutoff wavelength (λc) of the second propagating mode. From this figure, it possible to note the relation between the wavelength and the propagation constant and could estimate the cutoff of the mode. In figure (4.5) shows, the variations of the normalized propagation constant versus the normalized frequency for the same fiber presented. It is clear that within the operating band (1.1-1.65) μm, the normalized frequency is less than 2.405, this means that the fiber is single mode LP_{01} [15,18]. Figure (4.6) illustrates normalized radial field distributions, $\Psi(r)$, at ($\lambda = 1.55\mu m$) in layers of optical fibers.

Figure (4.7) shows the variations of the effective refractive index versus wavelength. It is clear that the effective refractive index value lies between the maximum refractive index and refractive index of the outer cladding layer. Figure (4.8) for fibers 1, 2, and 3 from group B shows

variations of effective-area versus wavelength in the 1.55 μm window for these fibers.

Table 4.3(B): Parameters and material compositions for the designed fibers

Fiber number	1st Layer	2nd Layer	3rd Layer	4th Layer
1	M_{15} a=1.48	M_4 a=3.41	M_9 a=6.36	M_1 a=16.5
2	M_{15} a=1.41	M_4 a=3.24	M_8 a=6	M_1 a=16.5
3	M_9 a=1.2	M_4 a=3.35	M_8 a=6	M_7 a=16.5
4	M_9 a=1.1	M_4 a=3.1	M_{14} a=7.3	M_1 a=16.5
5	M_8 a=1.05	M_{11} a=3.26	M_{14} a=6.5	M_1 a=16.5
6	M_9 a=1.2	M_4 a=2.8	M_8 a=6.87	M_{16} a=16.5
7	M_9 a=1	M_{11} a=3.19	M_8 a=6.03	M_1 a=16.5
8	M_{15} a=1	M_4 a=3	M_8 a=6.6	M_1 a=16.5

Table 4.4(B): Effective-area, mode-field-diameter, dispersion, dispersion slope (all at λ = 1.55 μm), cutoff wavelength and quality factor.

Fiber number	A_{eff} μm^2	MFD μm	D Ps/nm.km	DS Ps/nm^2.km	λcμm	Q
1	109.6	10.77	-0.008864	-0.00379	0.99	0.94488
2	121.7	11.6	-0.004395	-0.008498	0.98	0.9044
3	105.6	10.89	-0.03539	-0.01224	0.96	0.89044
4	81.06	9.705	0.03745	-0.05487	0.95	0.8606
5	93.21	10.48	0.01547	-0.004049	0.94	0.84867
6	109.9	11.42	0.02051	-0.01422	0.88	0.8426
7	101.1	11	0.01649	-0.01649	0.94	0.8355
8	84.29	10.14	0.005946	-0.01999	0.94	0.81978

From this group it is observed that the effective-area at λ = 1.55 μm varies from (81.06-121.7) μm^2, see table 4.4(B) .As expected, fiber '2' provides the largest effective-area. Figure (4.9) was shown the mode-field-

diameter versus with wavelength, the mode-field-diameter at $\lambda = 1.55\mu m$ varies from about 9.07 μm for fiber '4' to 11.42 μm for fiber '6'.

Finally, the fundamental requirement of nearly zero dispersion at $\lambda = 1.55$ μm met by fibers 1, 2, and 3 from group (B). This seen in figure (4.10) which depicts variations of dispersion versus wavelength the dispersion is very important property in studying characteristics of single mode fiber, see table 4.4(B). The dispersion slope for fibers 1, 2, and 3 from group (B) shows in figure (4.11). Observed from group (B) the larger effective-area achieved at the expense of a larger mode-field-diameter. It is now clear that a satisfactory design should maintain a balance between the effective-area and mode-field diameter. Data in Table 4.4(B) clearly indicate that many possibilities exist to achieving both large effective-area and small mode field diameter at $\lambda = 1.55\mu m$. Now, the question is which fiber offers a better performance; namely, less signal distortion and less loss. The data in these tables clearly indicate the trade-off between the effective-area that provides a measure of signal distortion due to nonlinearity and the mode-field-diameter that is an indicator for bending loss. Assuming that all other losses such as intrinsic and microbending losses are about the same for all fibers in tables 4.4(B),the performance of a design may be assessed in terms of a quality factor defined $Q = A_{eff}/(MFD)^2$ [8]. This factor is a dimensionless quantity that can be used to determine the tradeoff between mode-field-diameter and effective-area. Then, among several designs, satisfying certain limits on effective-area and mode-field-diameter fiber that provides the largest quality factor is the best design. Accordingly, group 'B' among all fibers in Tables 4.4(B) meets the design requirements for maximum effective-area and minimum mode-field-diameter and provides the largest quality factor (Q=0.944885). The quality factor for conventional fibers is about 0.741. [8].

In summary, the trade-off between effective-area and mode-field-diameter is an important deciding factor in selection of a design.

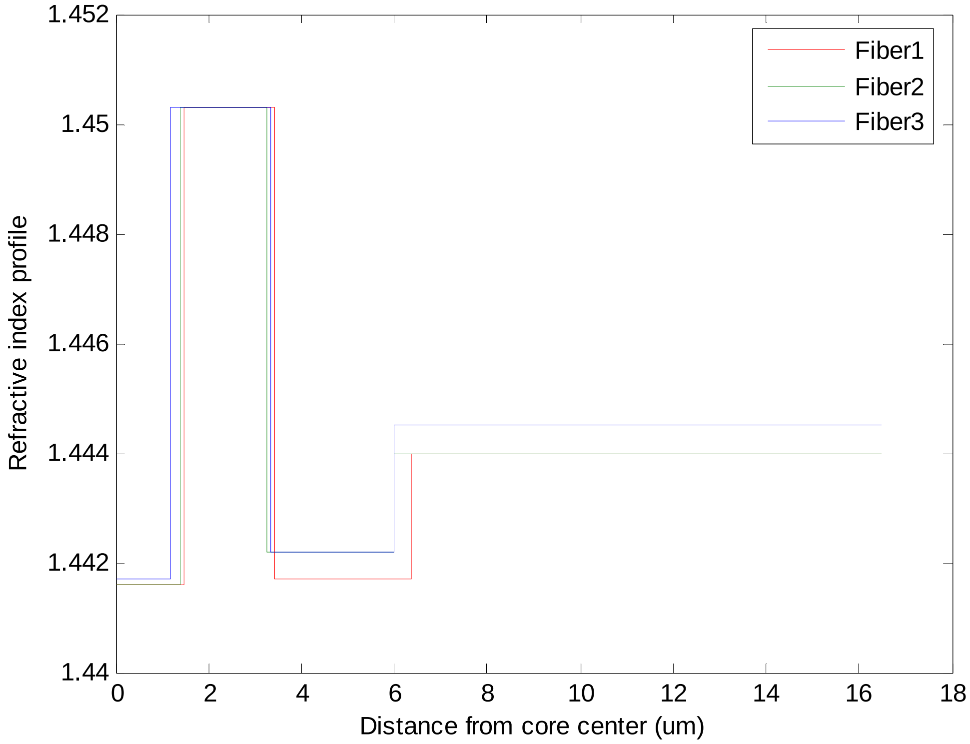


Figure 4.3: Refractive index profiles for fiber1, 2, and3 from group B

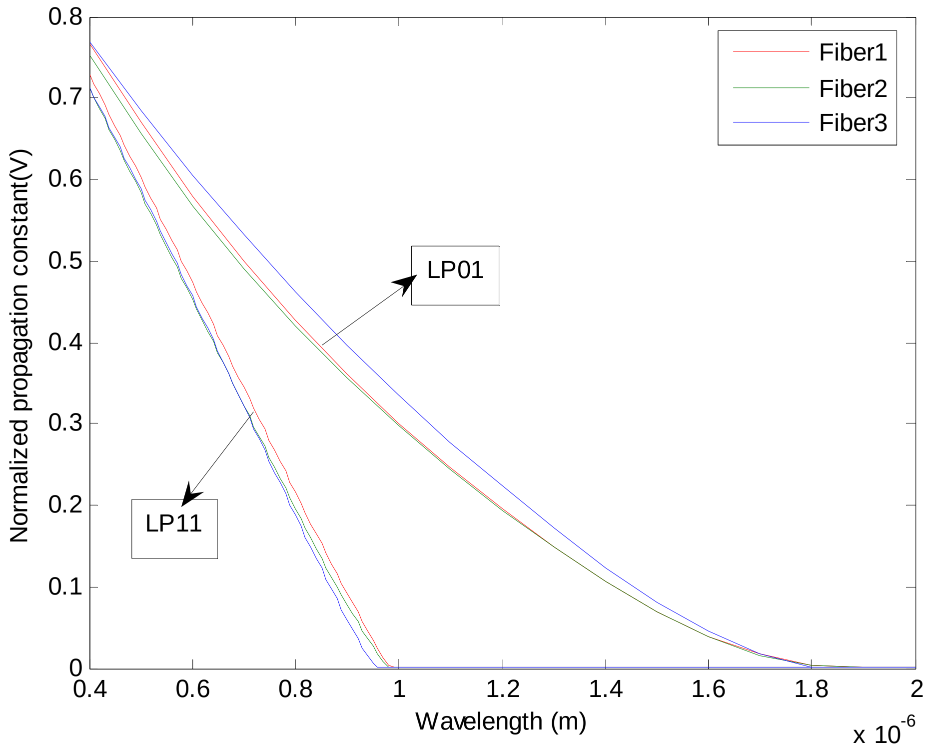


Figure 4.4: The variation of normalized propagation constant with wavelength for fiber1, 2, and3 from group B.

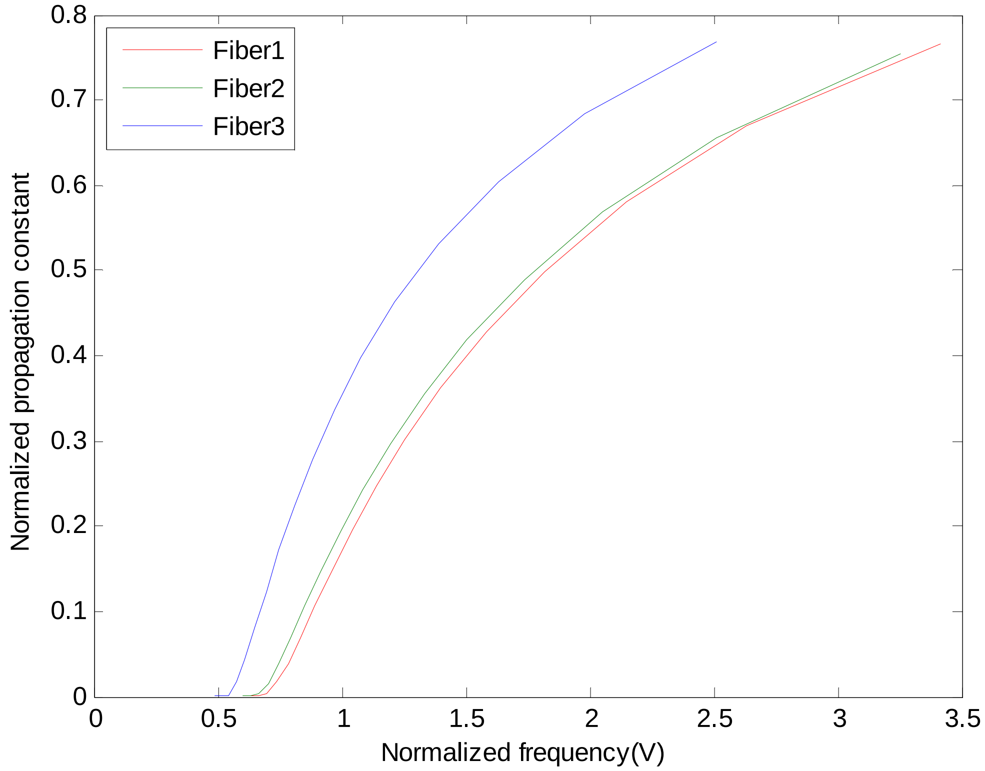


Figure 4.5: The variation of normalized propagation constant with normalized frequency (V) for fiber1, 2, and3 from group B.

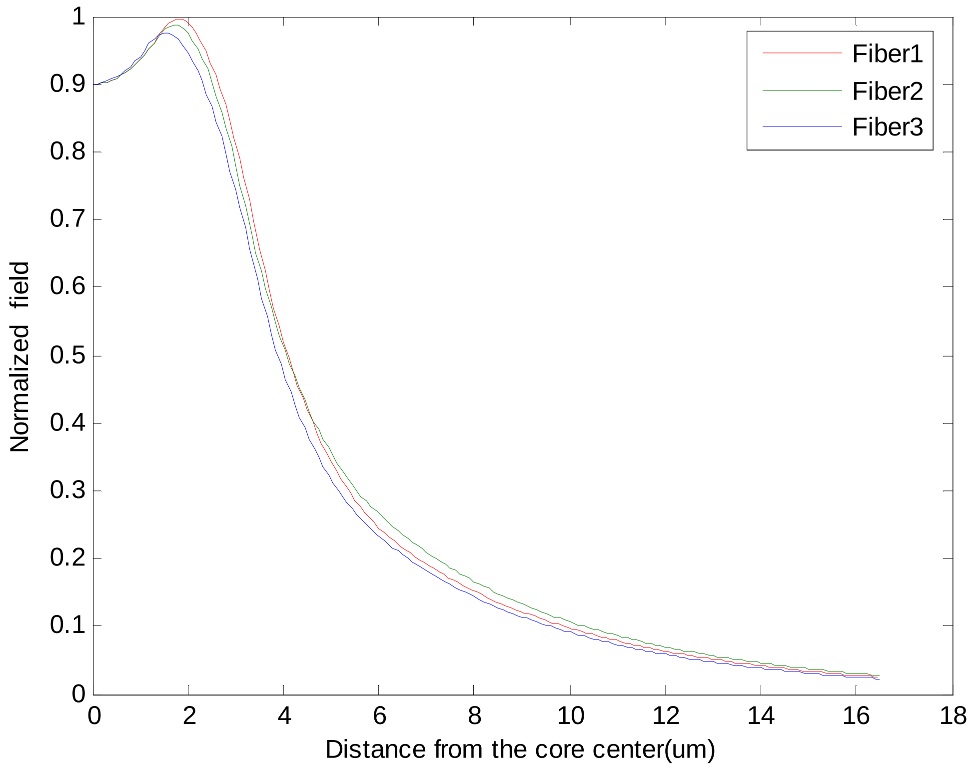


Figure 4.6: Variation of field distribution versus distance from the core center for fiber1, 2, and3 from group B.

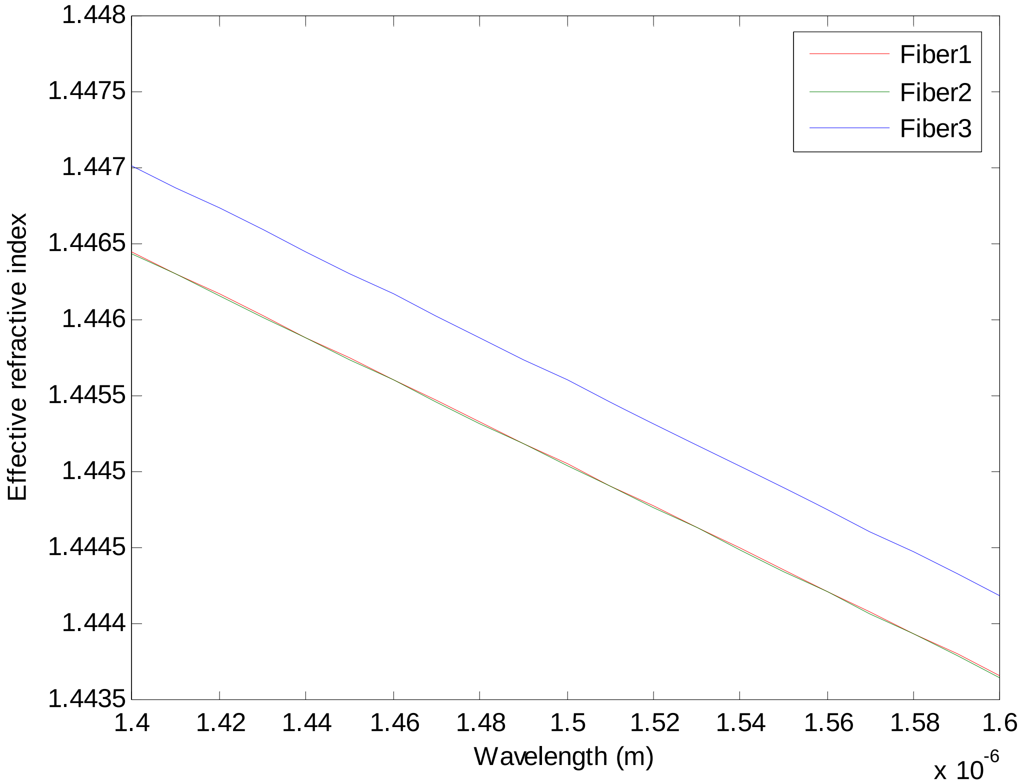


Figure 4.7: The variation of effective refractive index with wavelength for fiber1, 2, and3 from group B.

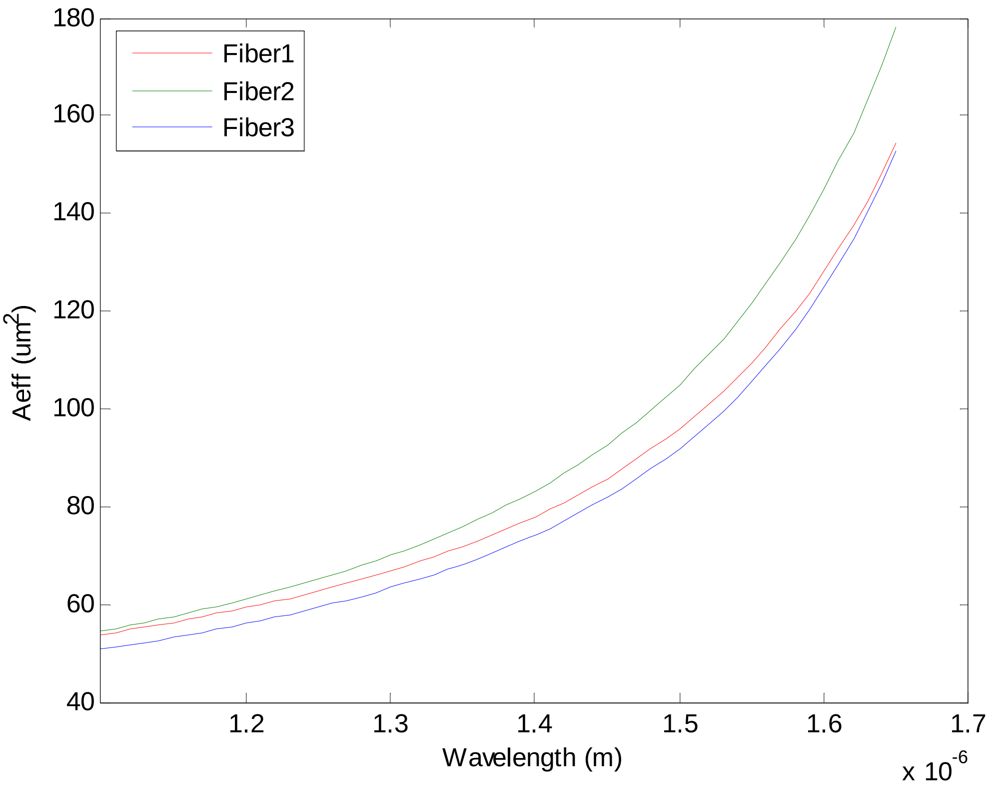


Figure 4.8: Variation of A_{eff} with wavelength for fiber1, 2, and3 from group B.

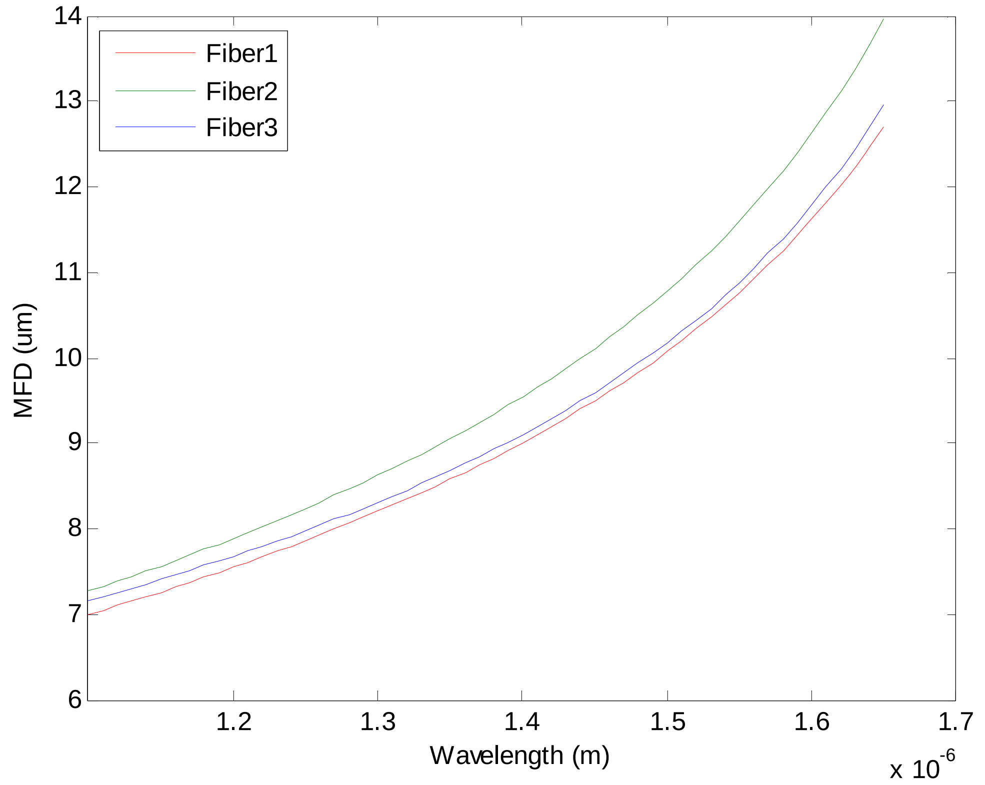


Figure 4.9: Variation of MFD with wavelength for fiber1, 2, and3 from group B.

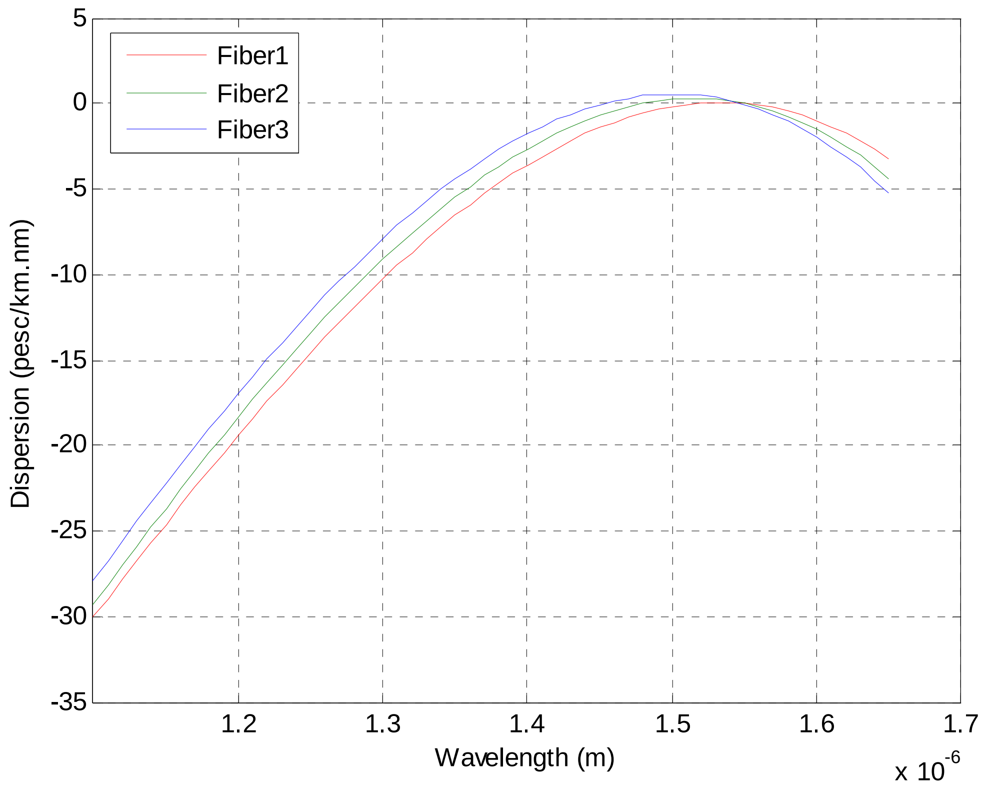


Figure 4.10: Variation of dispersion with wavelength for fiber1, 2, and3 from group B.

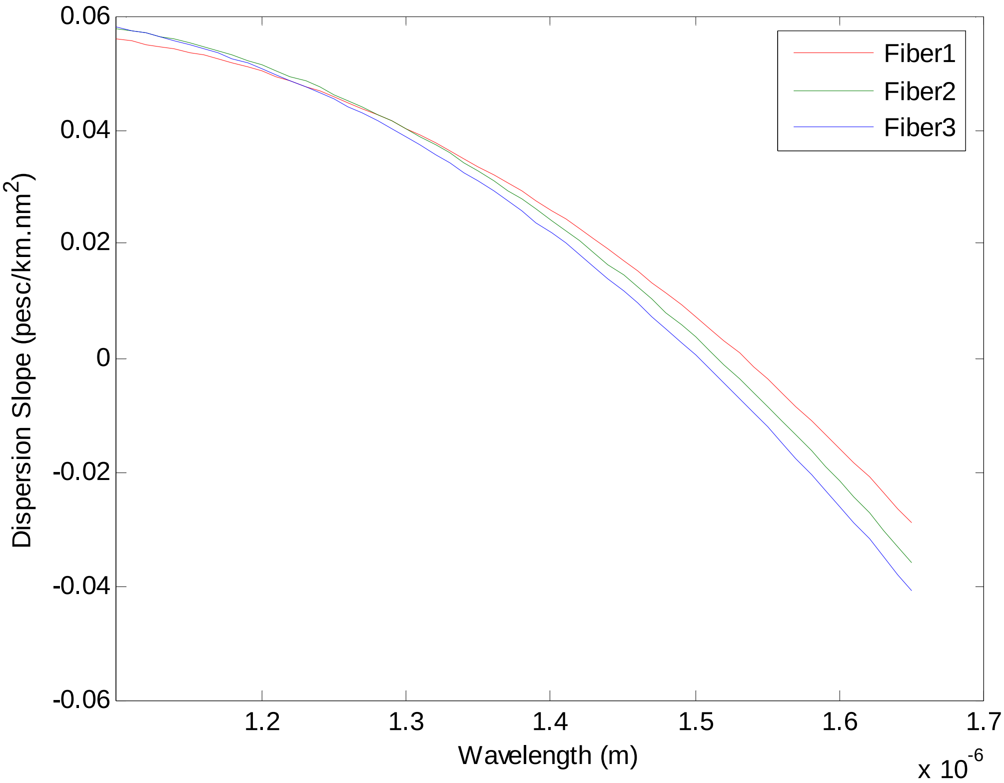


Figure 4.11: Variation of dispersion slope with wavelength for fiber1, 2, and3 from group B.

4.4.3. Group C.

Tables 4.5(C) and 4.6(C) represent group (C). Where table 4.5(C) represent material compositions (M) and dimensions (a) of layer from the Center core radius of fibers for group (C). Table 4.6(C) contains effective-area (A_{eff}), mode-field-diameter (MFD), dispersion (D), dispersion slope (DS) (all at $\lambda = 1.55\mu m$), cutoff wavelength (λc) and quality factor (Q).

Group (C) considers another profile is deferent from group (B) where ($n_3<n_1<n_4<n_2$), as shown in figure (4.12) for fibers 1, 2, and 3 from group (C). This profile index demonstrates the refractive index versus with center of core radius.

Fibers 1, 2, and 3 from group (C) will be study to know behavior and characteristics of dispersion flattened fiber for this group. Figure (4.13) shows the variations of the normalized propagation constant versus wavelength for fibers of group (C), to determined the cutoff wavelength

(λc) for this group and indicated the wavelength range(1.1-1.65) for single mode operation. Figure (4.14) shows the normalized propagation constant varies normalized frequency for fibers of group (C), the normalized frequency must be less than 2.405, for the single mode LP_{01}. In figure (4.15) shows the variations of effective-area versus wavelength for fibers in group (C).

Table 4.5(C): Parameters and material compositions for the designed fibers

Fiber number	1st Layer	2nd Layer	3rd Layer	4th Layer
1	M_8 a=1.2	M_4 a=3.47	M_9 a=7	M_7 a=16.5
2	M_8 a=1.3	M_4 a=3.34	M_{15} a=6.95	M_1 a=16.5
3	M_{14} a=1.3	M_4 a=3.17	M_8 a=6.46	M_1 a=16.5
4	M_8 a=1.33	M_4 a=3	M_9 a=7	M_{16} a=16.5
5	M_8 a=1	M_{11} a=3.31	M_9 a=6.32	M_1 a=16.5

Table 4.6(C): Effective-area, mode-field-diameter, dispersion, dispersion slope (all at λ = 1.55 µm), cutoff wavelength and quality factor.

Fiber number	A_{eff} µm^2	MFD µm	D Ps/nm.km	DS Ps/nm^2.km	λc µm	Q
1	82.32	9.409	0.01366	-0.02161	0.96	0.92986
2	82.53	9.504	0.01636	-0.00921	0.97	0.91369
3	100.1	10.69	0.003489	-0.01604	0.97	0.8759
4	96.11	10.54	-0.03143	-0.004659	0.89	0.86514
5	87.06	10.14	-0.007705	-0.01328	0.94	0.84672

From this group it observed, the effective-area at (λ = 1.55µm) varies from (82.32) µm^{2}for fibers 1, to (100.1) µm^2 for fibers 3, see table 4.6(C). Figure (4.16) shows the mode-field-diameter versus with wavelength, the mode-field-diameter for this group at (λ = 1.55µm) varies from about (9.409 µm) for fiber '1' to (10.69µm) for fiber '3'. Figure (4.17) shows the dispersion

versus with wavelength. The dispersion slope shown in table 4.6(C) and it seen that largest quality factor (Q) fiber ‘1’equal (0.92986).

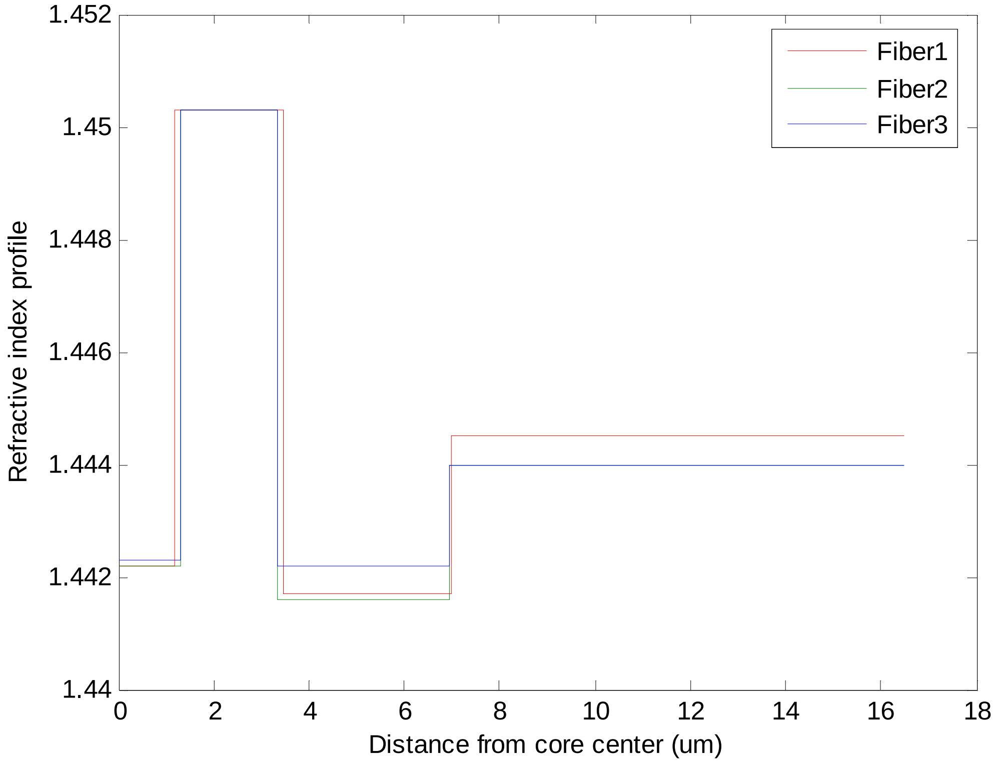


Figure 4.12: Refractive index profiles for fiber1, 2, and3 from group C

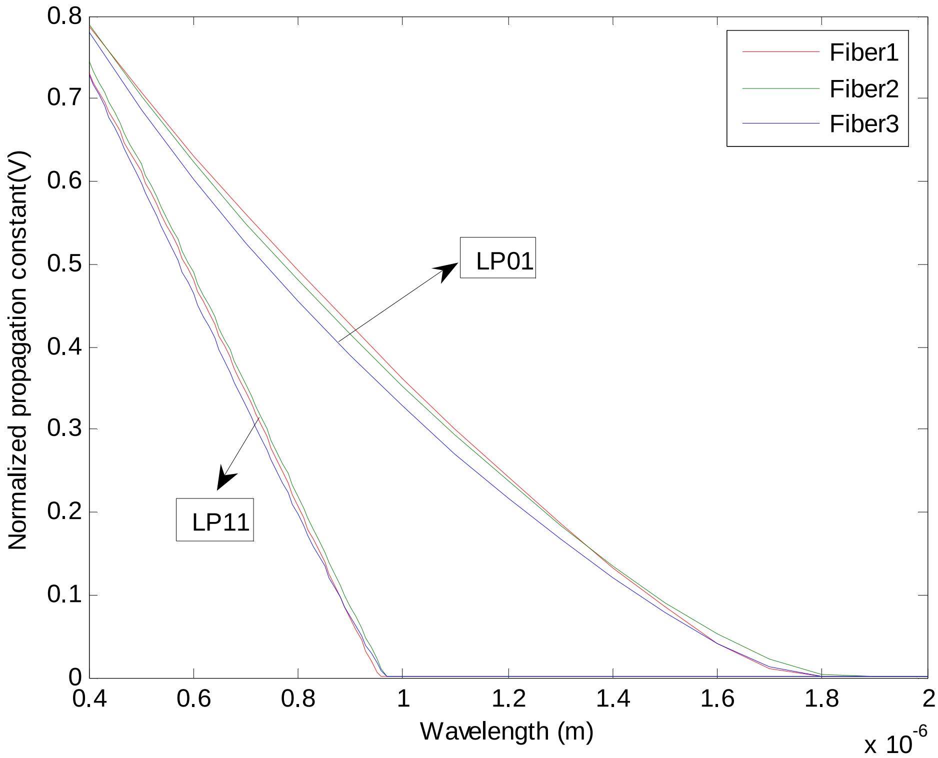


Figure 4.13: The variation of normalized propagation constant with wavelength for fiber1, 2, and3 from group C.

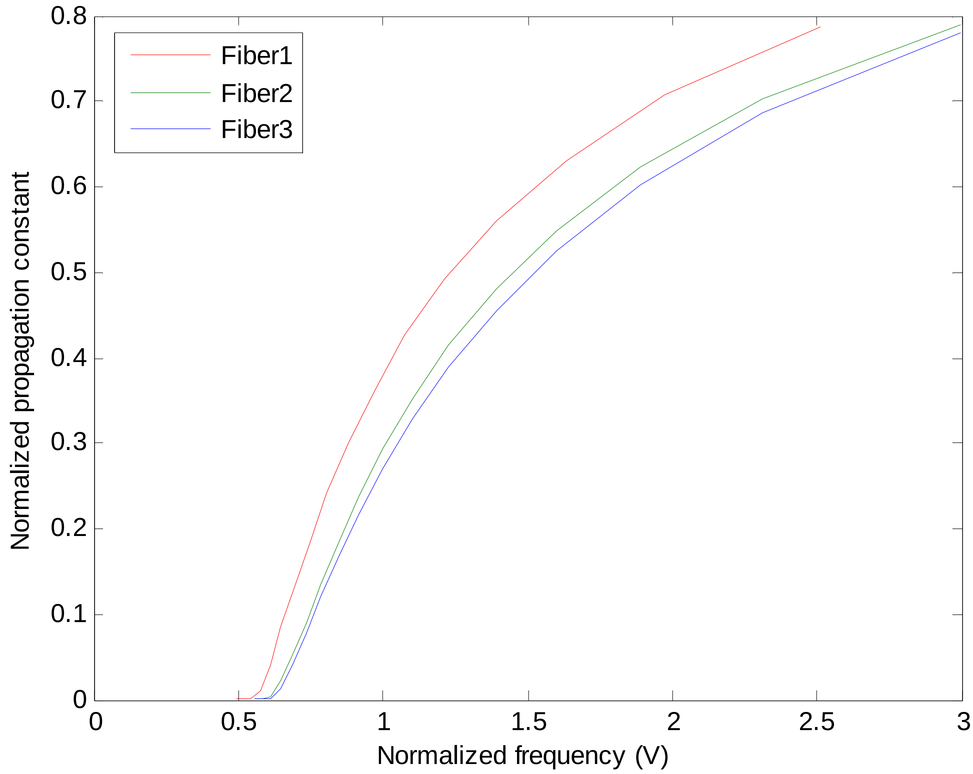


Figure 4.14: The variation of normalized propagation constant with normalized frequency (V) for fiber1, 2, and3 from group C.

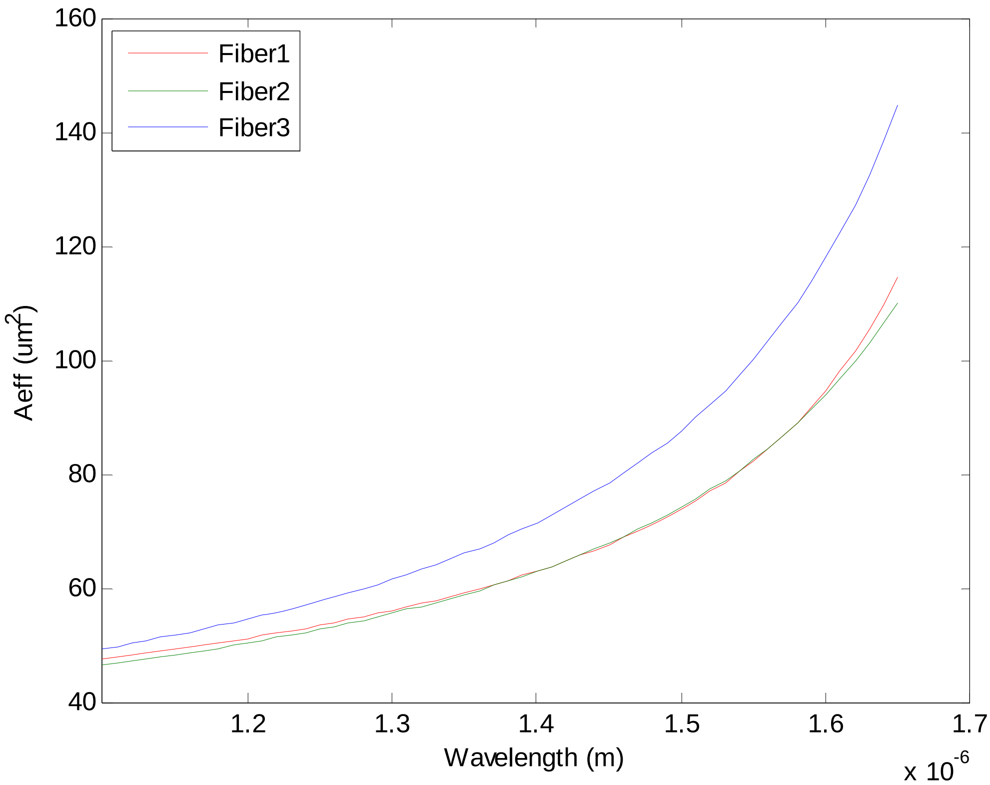


Figure 4.15: Variation of A_{eff} with wavelength for fiber1, 2, and3 from group C

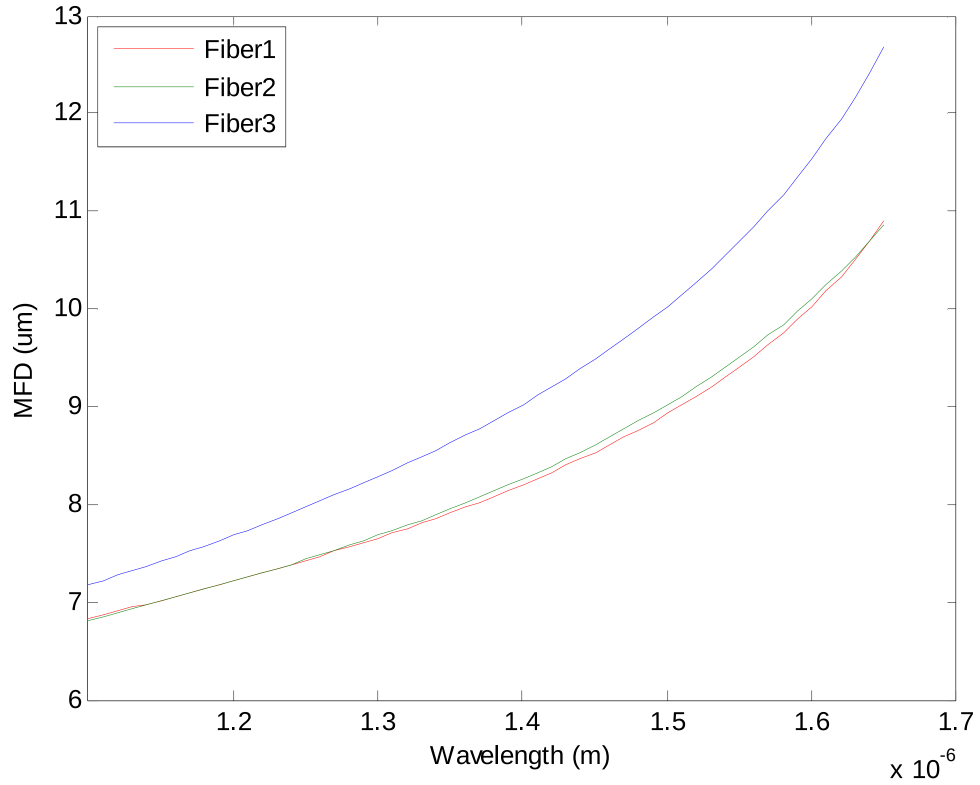


Figure 4.16: Variation of MFD with wavelength for fiber1, 2, and3 from group C.

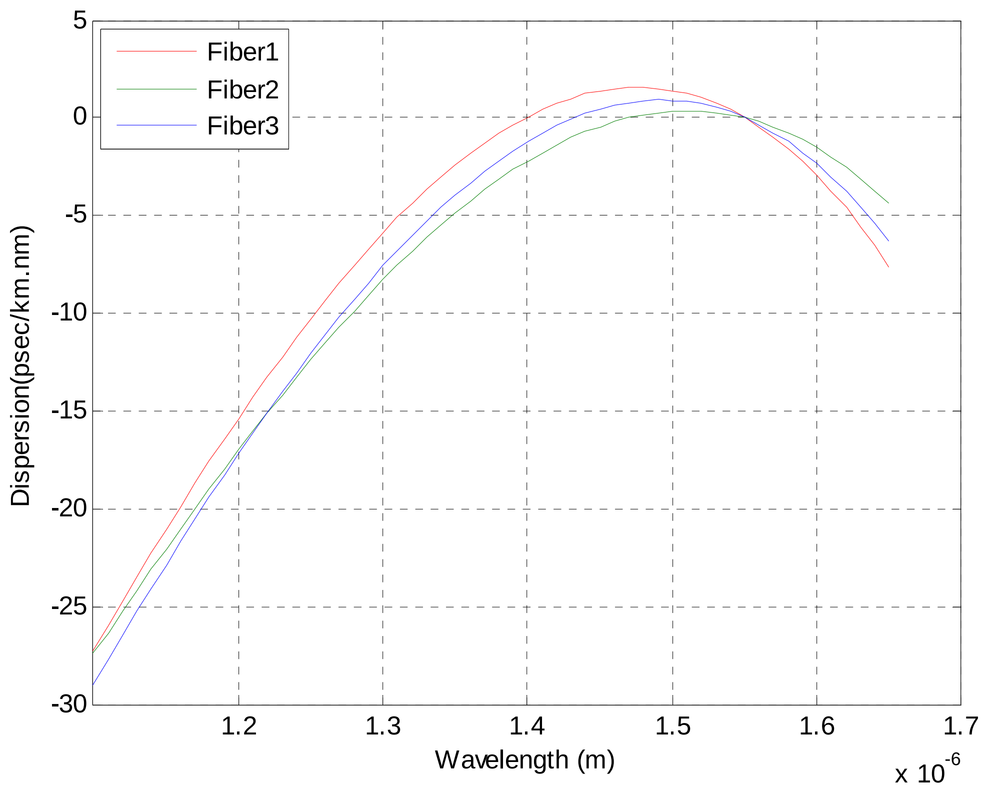


Figure 4.17: Variation of dispersion with wavelength for fiber1, 2, and3 from group C

4.4.4. Group D

Tables 4.7(D) and 4.8(D) represent group (D). Where table 4.7(D) represent material compositions (M) and dimensions of layer from the Center core radius (a) of fibers for group D. Table 4.8(D) contains effective-area (A_{eff}), mode-field-diameter (MFD), dispersion (D), dispersion slope (DS) (all at λ = 1.55μm), cutoff wavelength(λc) and quality factor (Q).

Group (D) considers another profile that is deferent from groups (B, C) ($n_1=n_3<n_4<n_2$), as shown in figure (4.18) for fibers 1, 2, and 3 from group (D). This profile index, is demonstrates the refractive index is versus with center of core radius.

Fibers 1, 2, and 3 from group D will be study to know behavior and characteristics of dispersion flattened fiber for this group. In figure (4.19) the variations of the normalized propagation constant versus wavelength for mode LP_{01} and LP_{11}, to show cutoff wavelength (λc) and show the wavelength range (1.1-1.65) μm for single mode operation is determined from the cutoff wavelength (λc). Figure (4.20) shown the normalized propagation constant varies normalized frequency.

Table 4.7(D): Parameters and material compositions for the designed fibers

Fiber number	1^{st} Layer	2^{nd} Layer	3^{rd} Layer	4^{th} Layer
1	M_9 a=1.48	M_4 a=3.41	M_9 a=6.24	M_1 a=16.5
2	M_{15} a=1.15	M_4 a=3.24	M_{15} a=6.9	M_1 a=16.5
3	M_8 a=1	M_4 a=3	M_8 a=6.5	M_1 a=16.5
4	M_9 a=0.8	M_4 a=3	M_9 a=6.4	M_1 a=16.5
5	M_{15} a=0.7	M_4 a=3	M_9 a=6.6	M_1 a=16.5

Table 4.8(D): Effective-area, mode-field-diameter, dispersion, dispersion slope (all at λ = 1.55=μm), cutoff wavelength and quality factor

Fiber number	A_{eff} μm^2	MFDμm	D Ps/nm.km	DS Ps/nm^2.km	λc μm	Q
1	109.4	10.8	0.03017	-0.003121	0.99	0.93792
2	78.86	9.487	0.02853	-0.006881	0.95	0.87619
3	82.01	10.07	0.0155	-0.01941	0.94	0.80873
4	68.88	9.434	0.008631	-0.008537	0.92	0.7739
5	62.45	9.057	0.02338	-0.004947	0.91	0.76131

In figure (4.21) for fibers 1, 2, and 3 from group D shows variations of effective-area versus wavelength for these fibers. From this group is observed the effective-area at λ= 1.55μm varies from (62.45)μm^2 for fiber 5, to (109.4)μm^2 for fibers 1 see table 4.8(D). Figure (4.22) shows the mode-field-diameter versus with wavelength, the mode-field-diameter for this group at λc = 1.55μm varies from about (9.057) μm for fiber '5' to (10.8) μm for fiber '1'. Figure (4.23) for a fiber 1, 2, and 3 from group (D) shows the dispersion versus with wavelength. The table 4.8(D) shows the largest quality factor (Q) fiber '1'equal (0.9379

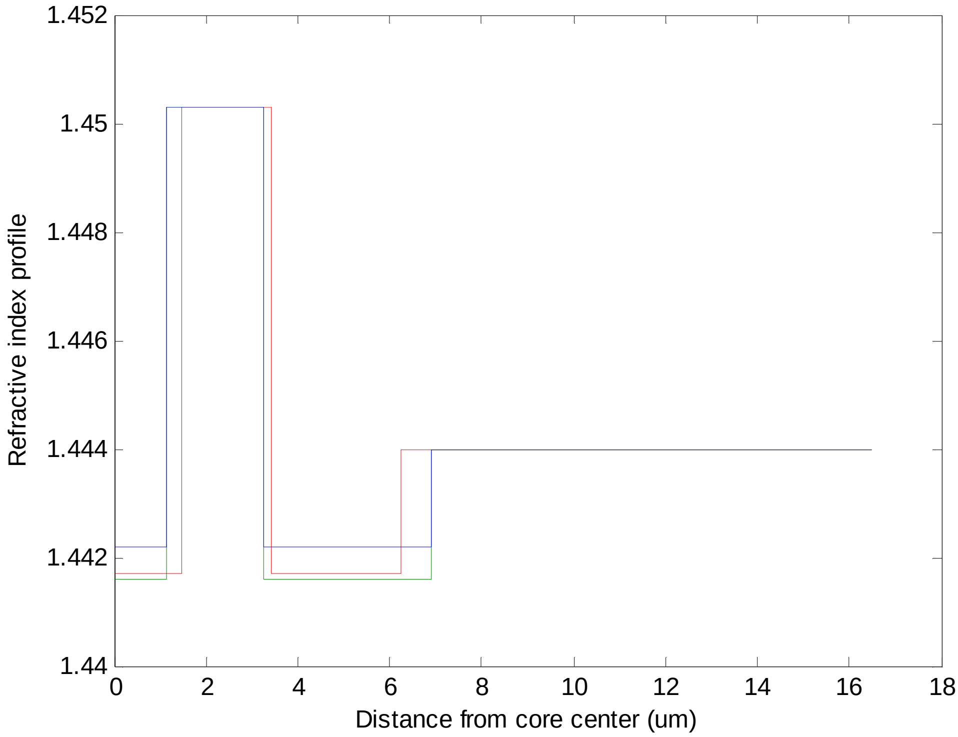


Figure 4.18: Refractive index profiles for fiber1, 2, and3 from group D

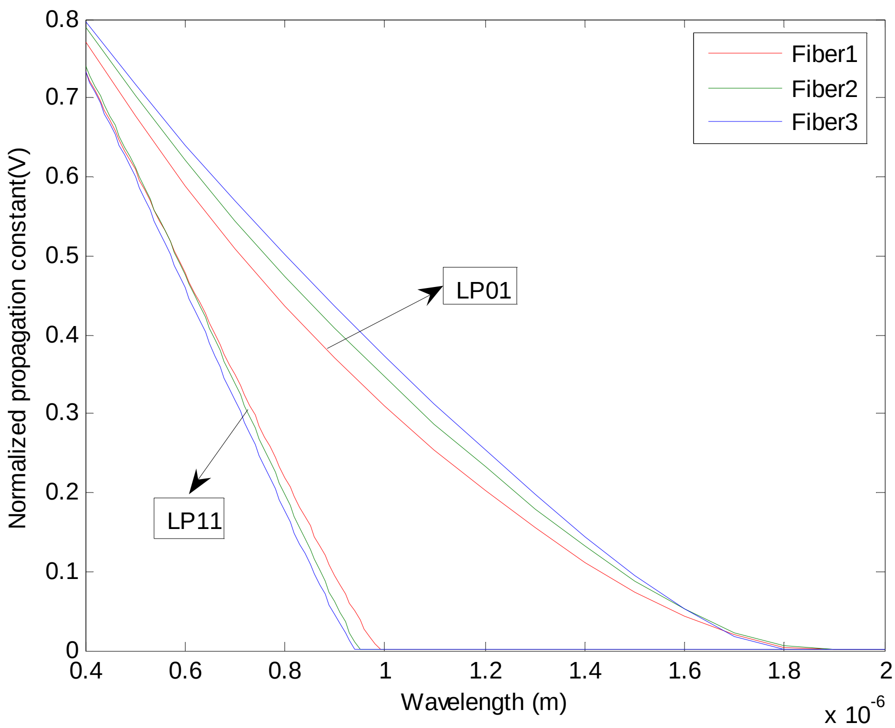


Figure 4.19: The variation of normalized propagation constant with wavelength for fiber1, 2, and3 from group D.

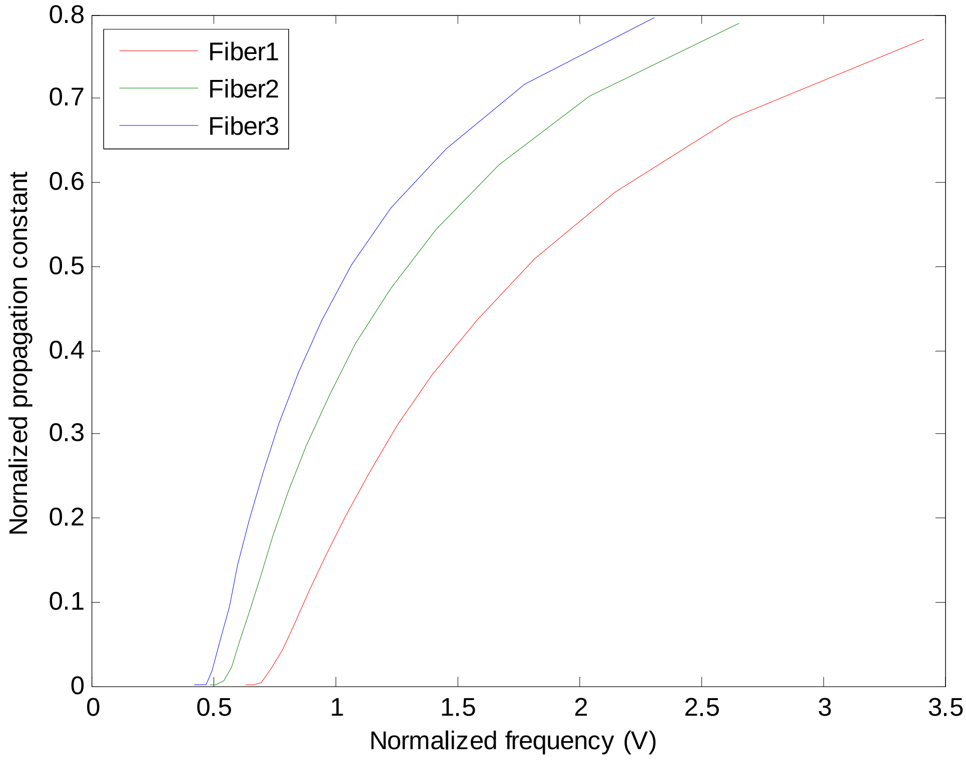


Figure 4.20: The variation of normalized propagation constant with normalized frequency (V) for fiber1, 2, and3 from group D.

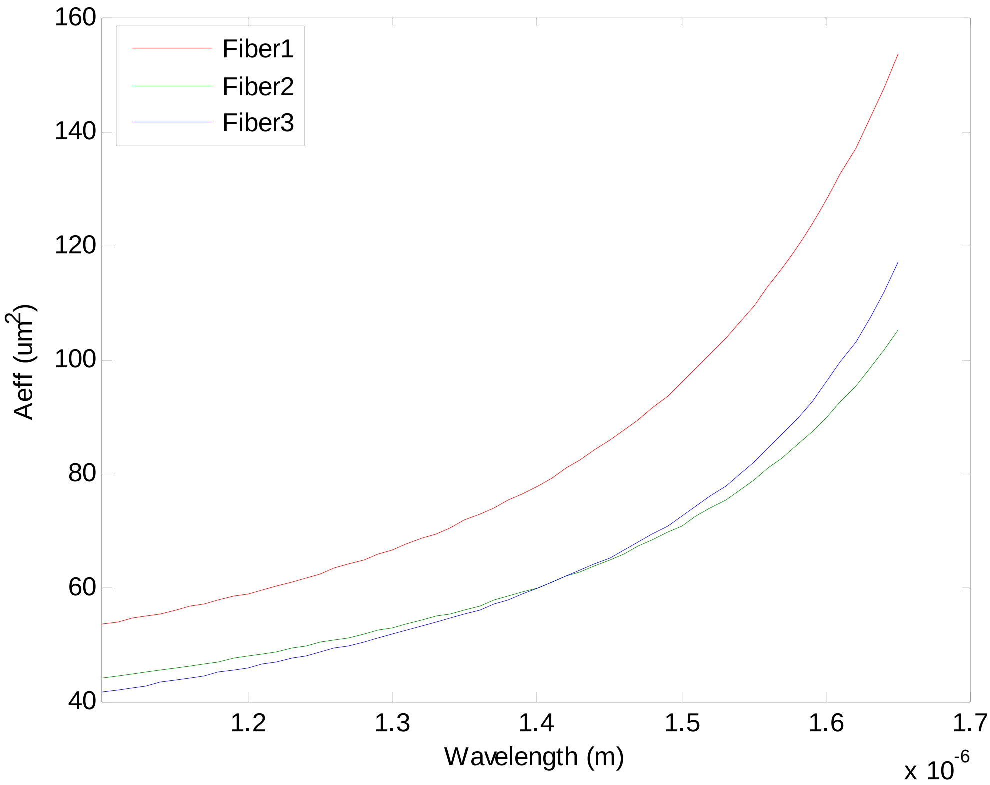


Figure 4.21: Variation of A_{eff} with wavelength for fiber1, 2, and3 from group D.

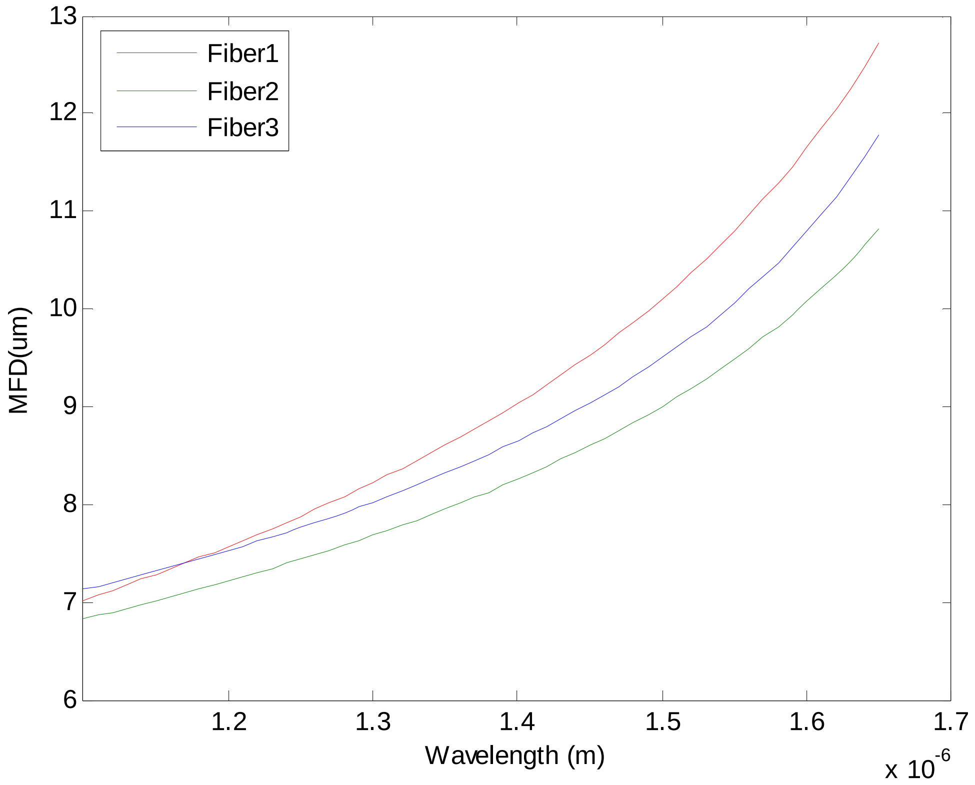


Figure 4.22: Variation of MFD with wavelength for fiber1, 2, and3 from group D.

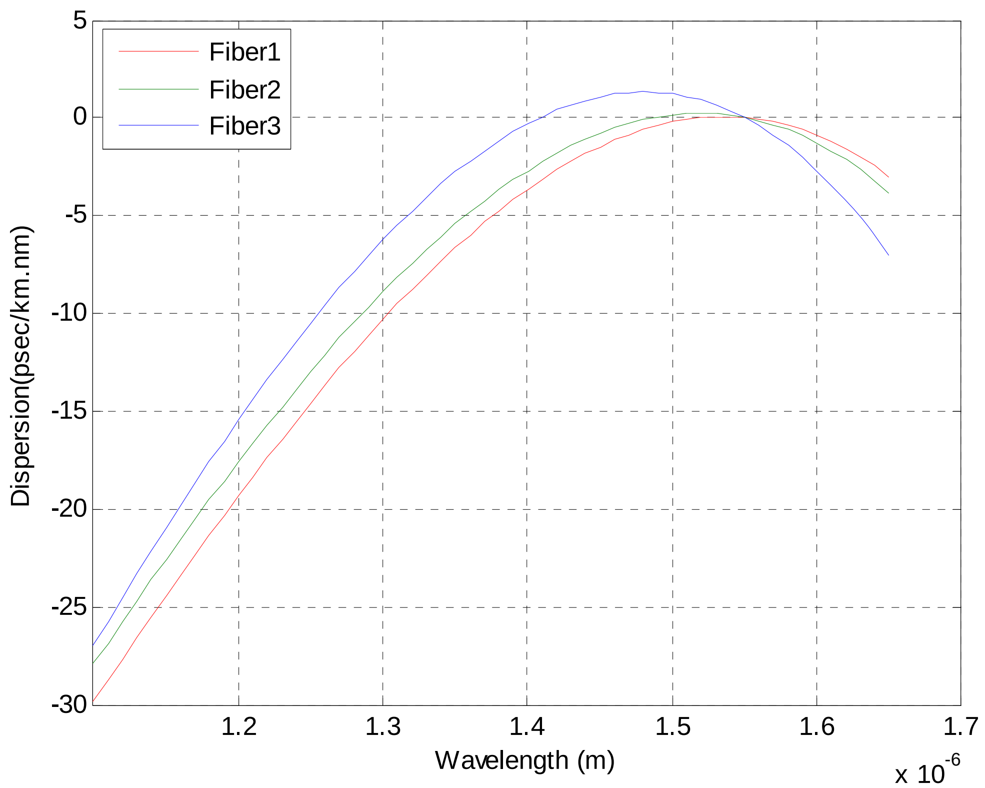


Figure 4.23: Variation of dispersion with wavelength for fiber1, 2, and3 from group D.

4.4.5. Group E

This group designed from the combination of groups B, C and D to obtain a new optimum group, in this group the tolerance and nonlinear effect will studied and compare with groups B, C and D.

By using the criterion of quality factor (Q) to chosen optimal design from (i) Group B, fiber1, (ii) group C, fiber1 (iii) group D, fiber1, to represent group E.

Tables 4.9(E) and 4.10(E) represent group (E). Where table 4.9(E) represent material compositions (M) and dimensions of layer from the center core radius(a) of fibers for group E.

Tables 5.10(E) contains effective-area (A_{eff}), mode-field-diameter (MFD), dispersion (D), dispersion slope (DS) (all at λ= 1.55μm), cutoff wavelength and quality factor (Q).

Table 4.9(E): Parameters and material compositions for the designed fibers

Fiber number	1^{st} Layer	2^{nd} Layer	3^{rd} Layer	4^{th} Layer
1	M_{15} a=1.48	M_4 a=3.41	M_9 a=6.36	M_1 a=16.5
2	M_9 a=1.48	M_4 a=3.41	M_9 a=6.24	M_1 a=16.5
3	M_8 a=1.2	M_4 a=3.47	M_9 a=7	M_7 a=16.5

Table 4.10(E): Effective-area, mode-field-diameter, dispersion, dispersion slope (all at λ = 1.55μm), cutoff wavelength and quality factor.

Fiber number	A_{eff} μm^2	MFDμm	D Ps/nm.km	DS Ps/nm^2.km	λc μm	Q
1	109.6	10.77	-0.008864	-0.00379	0.99	0.94488
2	109.4	10.8	0.03017	-0.003121	0.99	0.93792
3	82.32	9.409	0.01366	-0.02161	0.96	0.92986

Figure (4.24) illustrates normalized radial field distributions, $\Psi(r)$, at λ=1.55μm in layers of optical fibers. Figure (4.25) shows the variations of the effective refractive index versus wavelength. In figure (4.26) shows variations of effective-area versus wavelength. From this group is observed the effective-area at λ= 1.55μm varies from (82.32μm^2) for fibers 3, to (109.6μm^2) for fibers 1 see table 4.10(E). Figure (4.27) shows the mode-field-diameter versus with wavelength, the mode-field-diameter for this group at λ= 1.55μm varies from about (9.409μm) for fiber '3' to (10.8μm) for fiber '2'. Figure (4.28) shows the Dispersion versus with wavelength. The dispersion slope versus with wavelength shown in figure (4.29). noted table 4.10(E) and from this table show the largest quality factor (Q) fiber '1'equal (0.944885).

From the study, group E illustrate fiber1, and 2, is very near values as shown the effective area (A_{eff}), mode-field-diameter (MFD), dispersion (D), dispersion slope (DS) (all at λ= 1.55μm), cutoff wavelength(λc) and quality factor (Q) because that refractive index of material and radius core of layer for both fibers is very near values, this lead two fibers is approximately of quality factor (Q) and similarity of design.

In summary, from study on three profile index of group E from figures and tables we obtained one optimal design and this design did not dependent only on thickness of radius core center, but dependent on refractive index profile and radius core together, see fiber 1and fiber 4 from group D, the same refractive index profile but different in thickness of layer the result of this fibers is different. Therefore, the changing the profile index (material), thickness of layer to obtain a large effective area (A_{eff}), small field diameter (MFD), and low desperation (D) for optimum design.

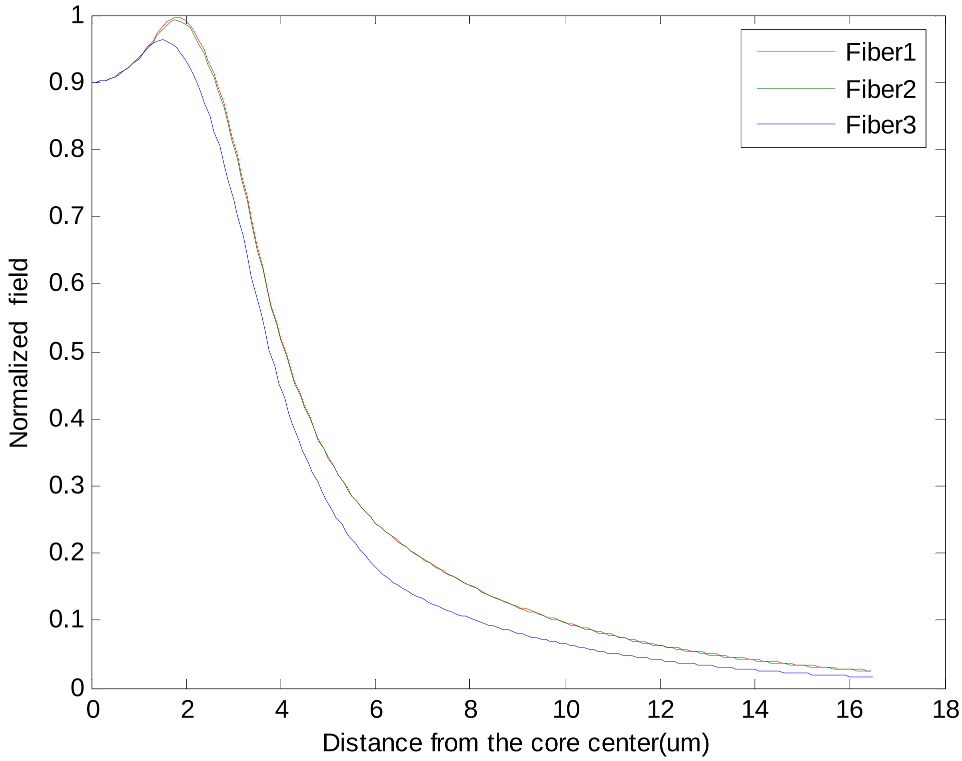


Figure 4.24: Variation of field distribution versus distance from the core center for fiber1, 2, and3 from group E.

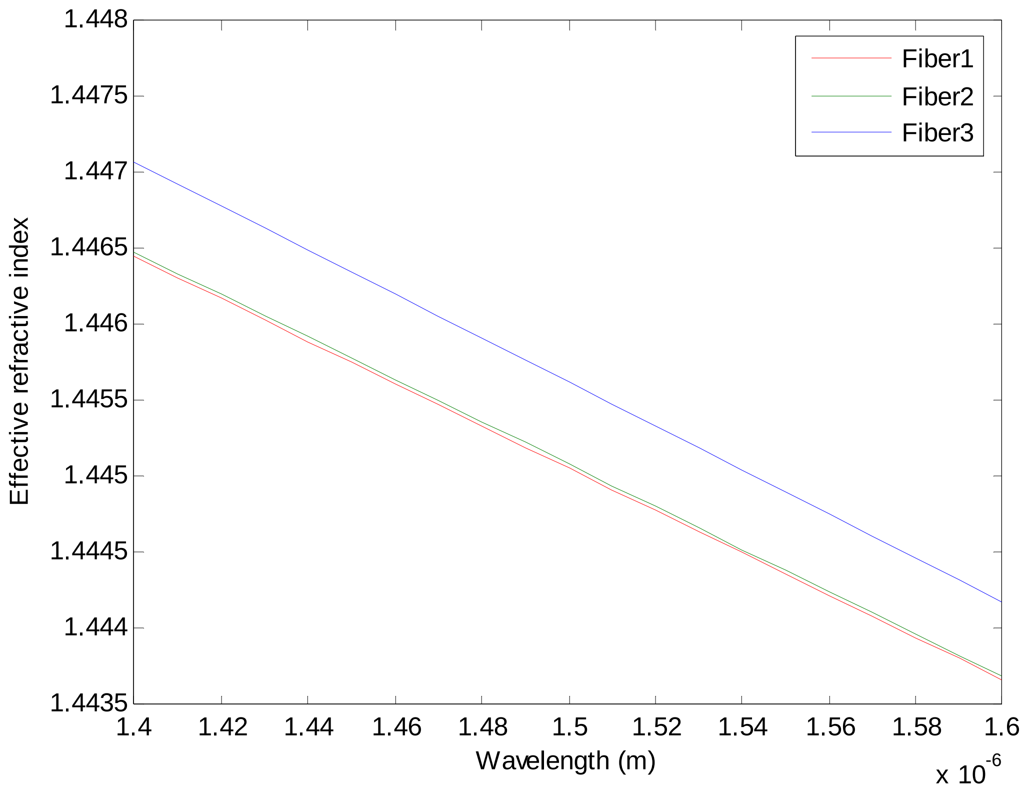


Figure 4.25: The variation of effective refractive index with wavelength for fiber1, 2, and3 from group E

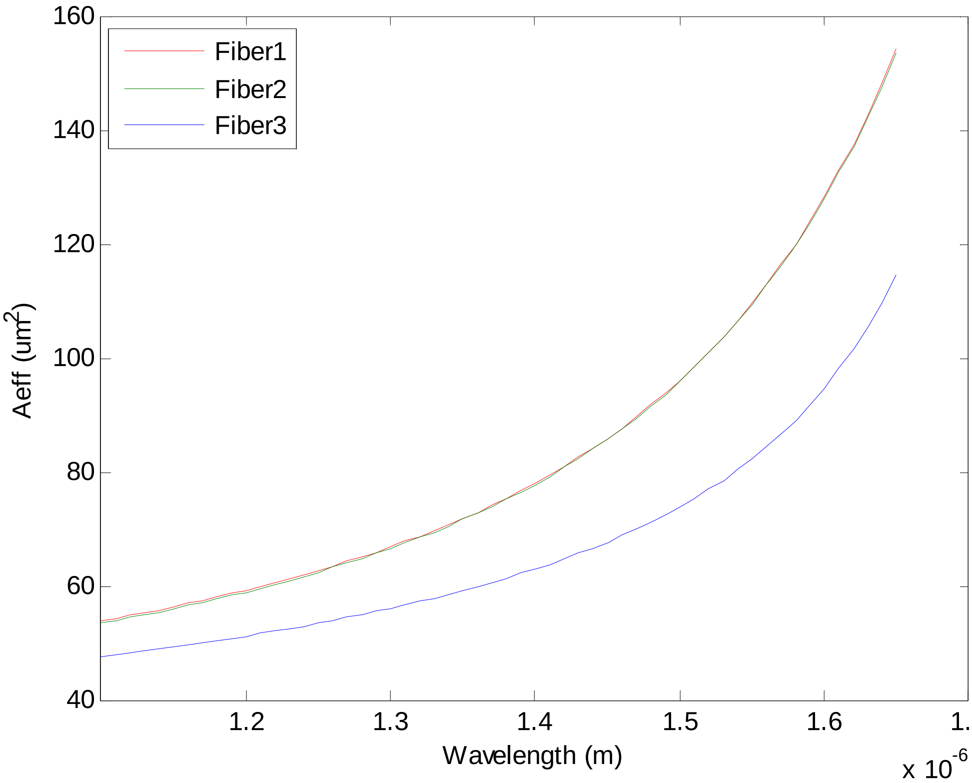


Figure 4.26: Variation of A_{eff} with wavelength for fiber1, 2, and3 from group E.

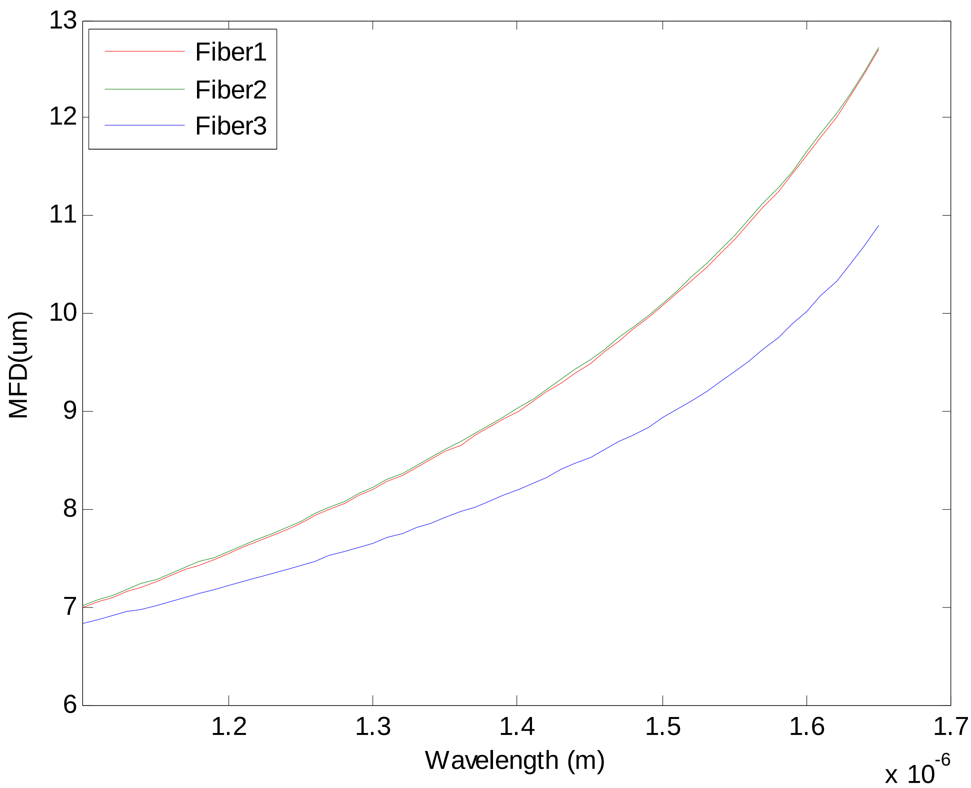


Figure 4.27: Variation of MFD with wavelength for fiber1, 2, and3 from group E.

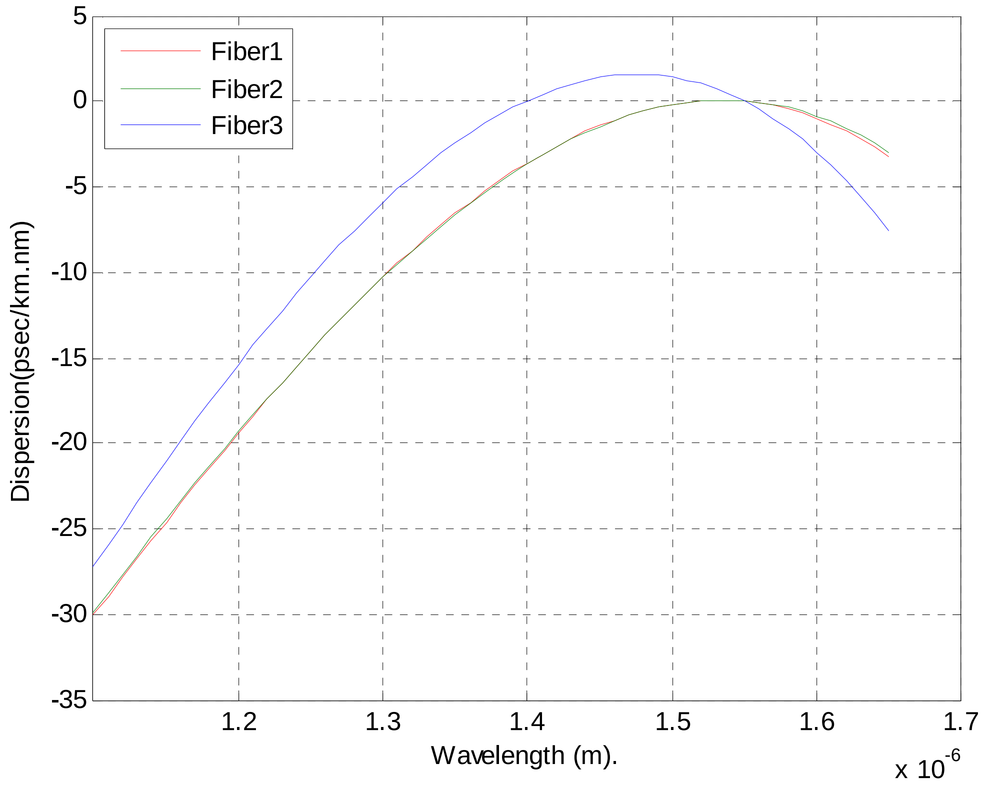


Figure 4.28: Variation of dispersion with wavelength for fiber1, 2, and3 from group E.

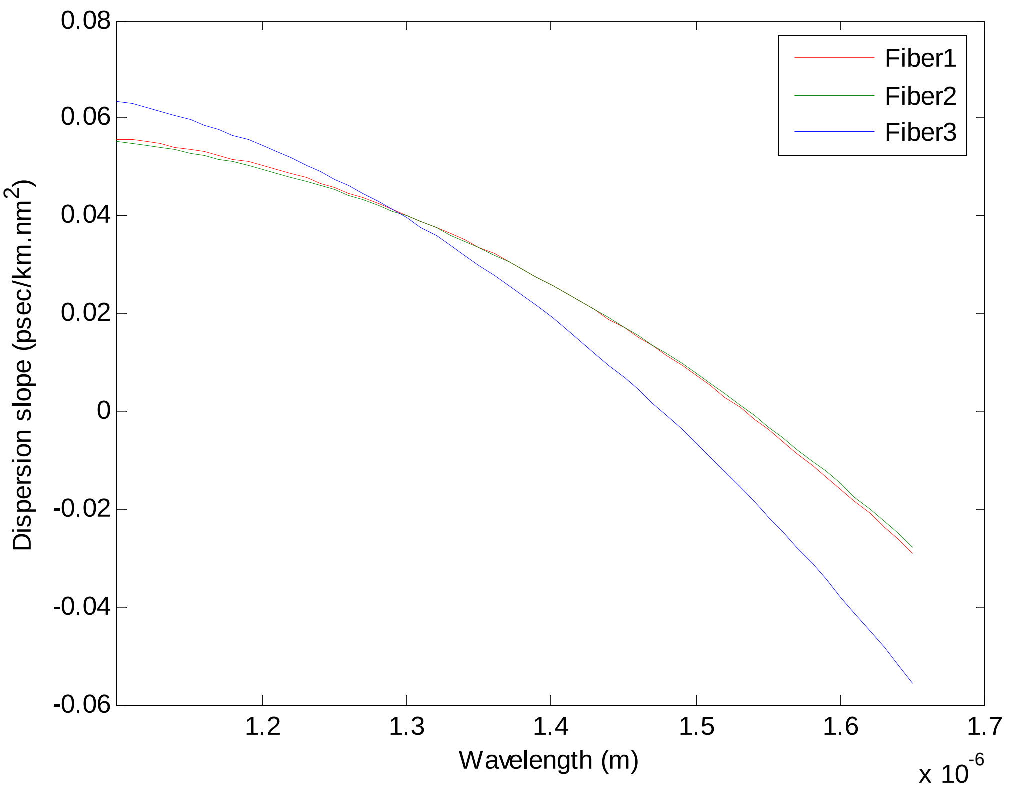


Figure 4.29: Variation of dispersion slope with wavelength for fiber1, 2, and3 from group E.

4.5. Study Designs with other Range of Wavelength

Now study designs with other range of wavelength where Taha Barake study with wavelength (1.31-1.67)µm to obtain on dispersion less than 1ps/nm.km[25].

Will study with range of wavelength (1.3-1.6) µm and (1.4-1.6) µm for group E because this group represented optimum design for three profiles for about 18 fibers to know ability of designs operates with other range of wavelength and what happen on the parameters designs.

Putting the range wavelength (1.3-1.6) µm then (1.4-1.6) µm instead the range of wavelength (1.1-1.65) µm in the system designs (program MATLAB7) by using group E to show the behavior change in the parameters designs.

Table (4.11) shows the parameters designs of group E with range of wavelength (1.1-1.65) µm. Table (4.12) shows the parameters designs of group E with range of wavelength (1.3-1.6) µm and Table (4.13) shows the parameters designs of group E with range of wavelength (1.4-1.6) µm. Figure (4.30) shows the variation of effective area (A_{eff}) with wavelength for fiber 1 from group E. Figure (4.31) shows the variation of mode field diameter (MFD) with wavelength for fiber 1 from group E. Figure (4.32) shows the variation dispersion with wavelength for fiber 1 from group E. In figure (4.33) shows the variation dispersion slope with wavelength, figures from (4.30) to figure (4.33) operate with range of wavelength (1.3-1.6) µm and (1.4-1.6).

From these tables and figures, it shown that is no change in the cutoff wavelength. This means that this design is single mode fiber and with no changes in the effective area (A_{eff}) no change in the mode field diameter (MFD) but of small change in the dispersion and dispersion slope. This change is reasonable for such designs.

This result indicates the ability of these designs to operate with other range of wavelength which leads to the ability of these designs to operate with more type of WDM and DWDM according to operation this type.

Table 4.11: Effective-area, mode-field-diameter, dispersion, dispersion slope (all at λ = 1.55μm), cutoff wavelength and quality factor with range wavelength (1.1-1.65)μm for group E

Fiber number	A_{eff} μm^2	MFDμm	D Ps/nm.km	DS Ps/nm^2.km	λc μm	Q
1	109.6	10.77	-0.008864	-0.00379	0.99	0.944885
2	109.4	10.8	0.03017	-0.003121	0.99	0.93792
3	82.32	9.409	0.01366	-0.02161	0.96	0.92986

Table 4.12: Effective-area, mode-field-diameter, dispersion, dispersion slope (all at λ = 1.55μm), cutoff wavelength and quality factor with range wavelength (1.3-1.6)μm for group E

Fiber number	A_{eff} μm^2	MFDμm	D Ps/nm.km	DS Ps/nm^2.km	λc μm	Q
1	109.6	10.77	0.04204	-0.001496	0.99	0.944885
2	109.4	10.8	0.2546	0.001969	0.99	0.93792
3	82.32	9.409	0.4231	-0.01957	0.96	0.92986

Table 4.13: Effective-area, mode-field-diameter, dispersion, dispersion slope (all at λ = 1.55μm), cutoff wavelength and quality factor with range wavelength (1.4-1.6)μm for group E

Fiber number	A_{eff} μm^2	MFDμm	D Ps/nm.km	DS Ps/nm^2.km	λc μm	Q
1	109.6	10.77	0.05532	-0.003686	0.99	0.944885
2	109.4	10.8	0.2541	0.001969	0.99	0.93792
3	82.32	9.409	0.3167	-0.02311	0.96	0.92986

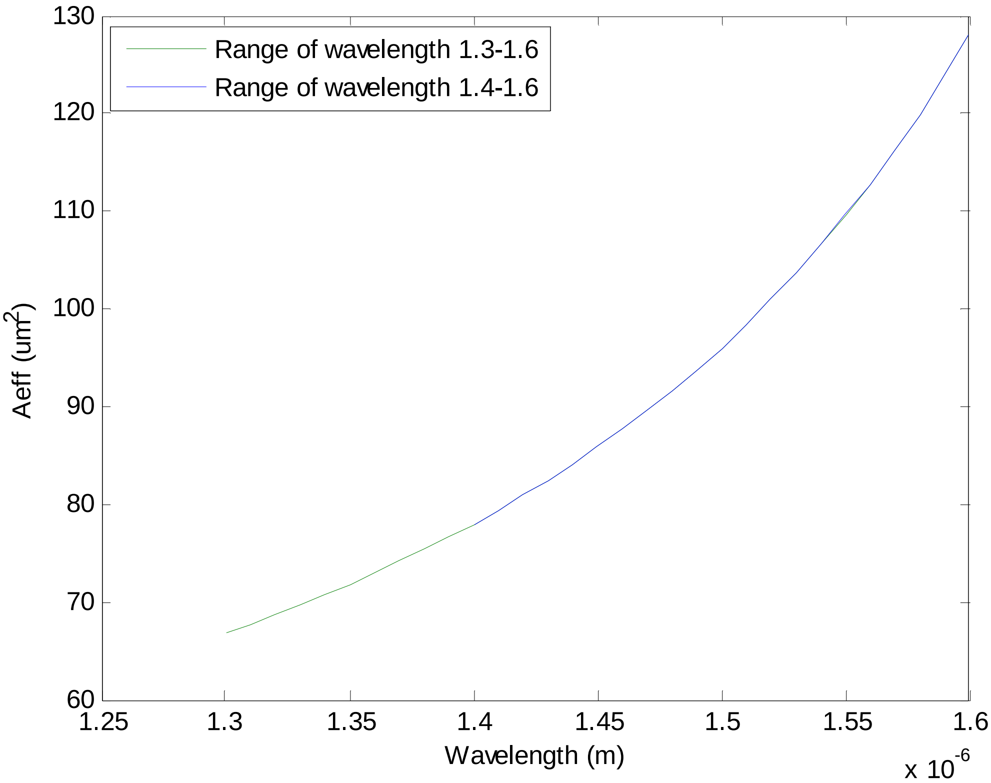


Figure 4.30: Variation of A_{eff} with wavelength for fiber1 from group E, with range wavelength (1.3-1.6)µm and with range wavelength (1.4-1.6)µm

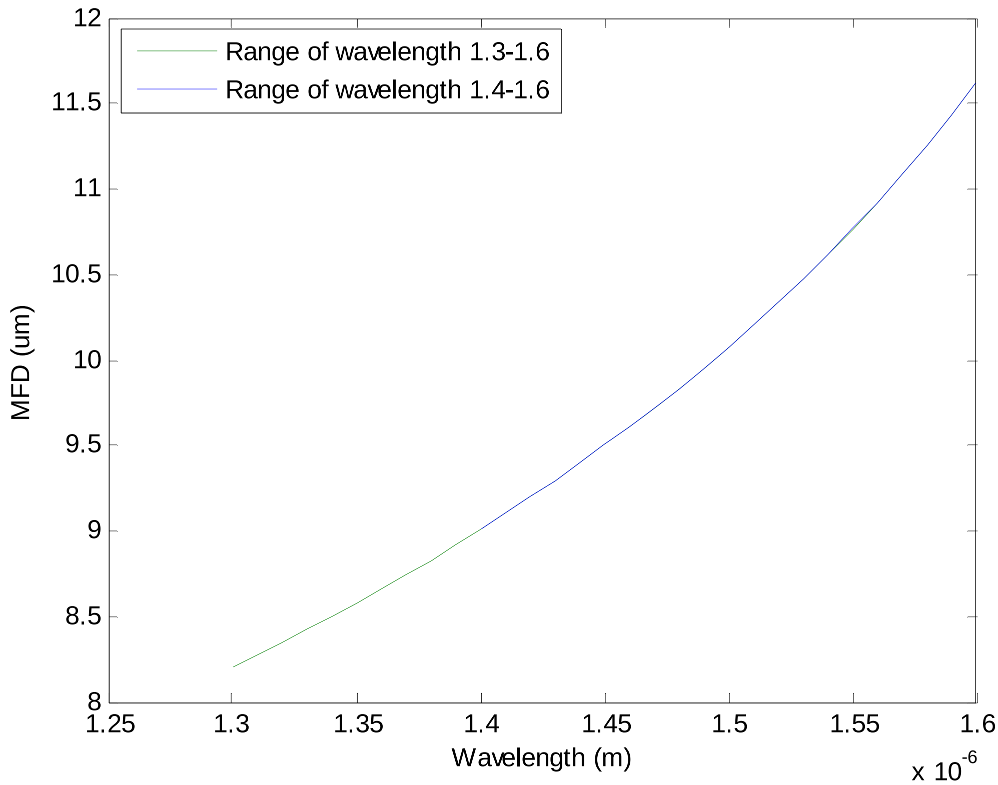


Figure 4.31: Variation of MFD with wavelength for fiber1 from group E, with range wavelength (1.3-1.6)µm and with range wavelength (1.4-1.6)µm

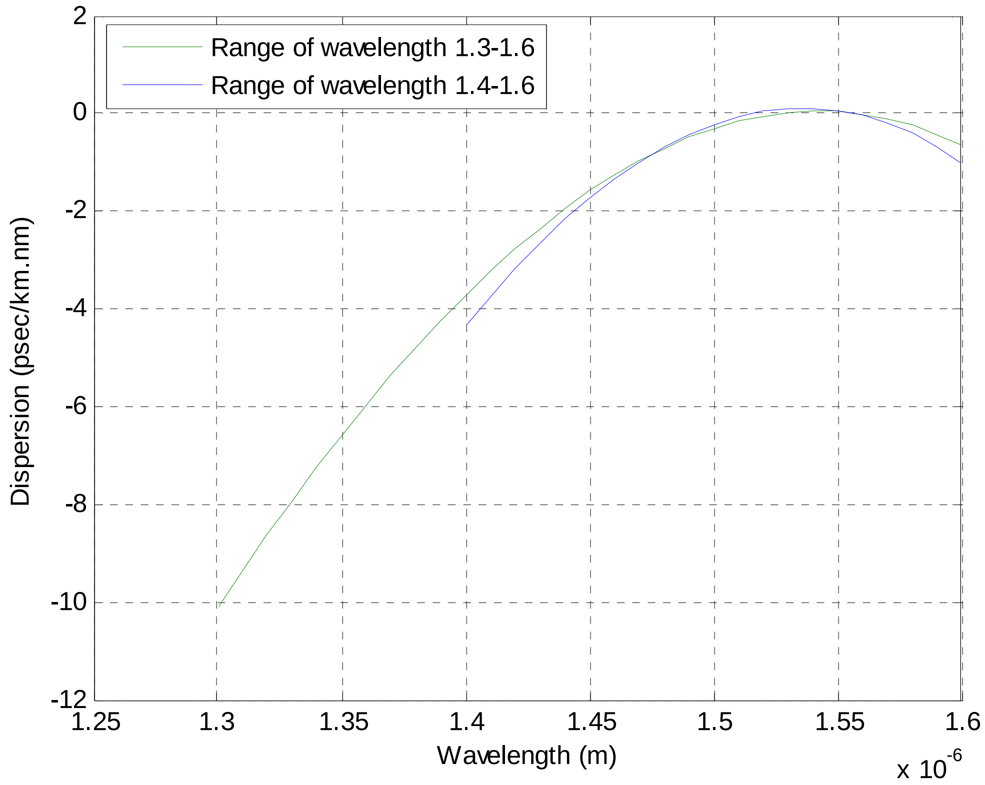


Figure 4.32: Variation of Dispersion with wavelength for fiber1 from group E, with range wavelength (1.3-1.6)µm and with range wavelength (1.4-1.6)µm

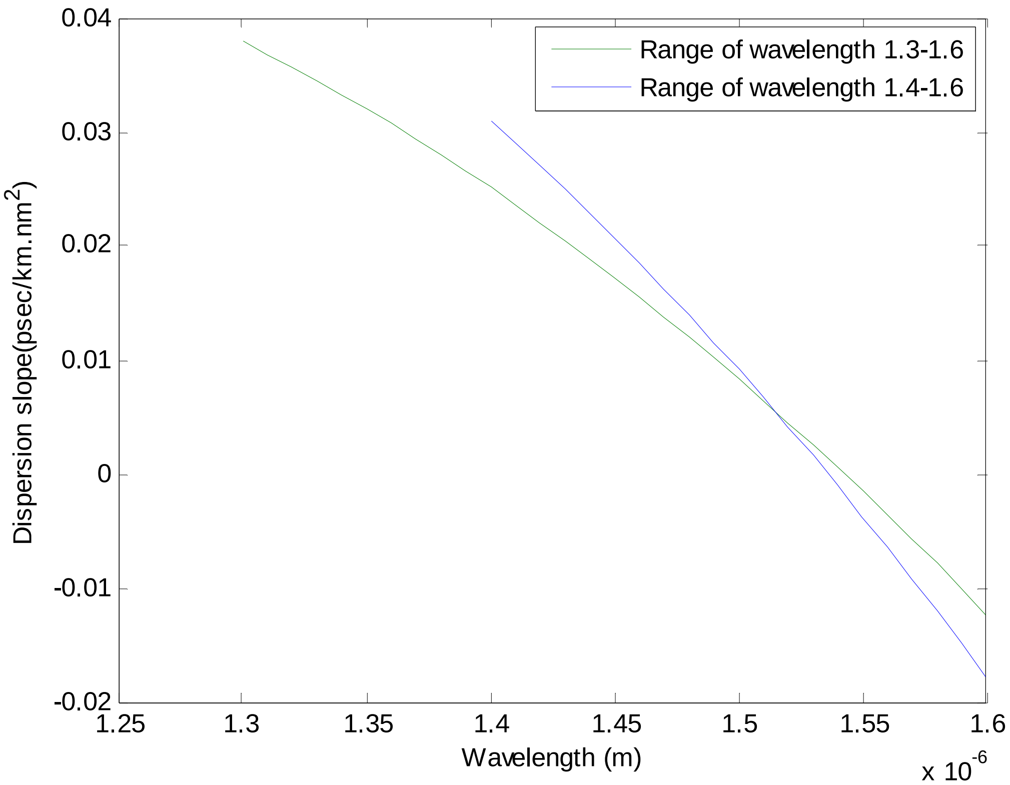


Figure 4.33: Variation of Dispersion slope with wavelength for fiber1 from group E, with range wavelength (1.3-1.6)µm and with range wavelength (1.4-1.6)µm

4.6. Tolerance Analysis

In groups B, C and D, various designs for dispersion-flattened fibers were presented. However, every design involves tolerances in the manufacturing process. These tolerances are important and determine if a given design is feasible or not. In this chapter, variations of second-order dispersion, effective-area and mode-field-diameter with respect to small changes in the radii, wavelength (–2% to +2%) and refractive indices (− 0.02 % to + 0.02) will be analyzed. This analysis will establish that the proposed designs can indeed be manufactured, using the available fiber fabrication technology.

Among the dispersion-flattened fibers presented in this chapter, fiber 1from group (B) chosen as a representative case for tolerance analysis. This is because this fiber has a large effective-area and small mode-field diameter according the quality factor (Q). Besides, all designed fibers exhibit similar behavior versus variations of design parameters, and thus a representative case is sufficient for tolerance analysis.

4.6.1. Tolerance dimensions of layers radius

Tables 4.14, 4.15, 4.16, and table 4.17 show changes in the radii of layers 1, 2,3and 4 respectively at 1.55 μm (–2% to +2%) for fiber1 from group B.

Figures (4.34, 4.35, 4.36, 4.37) show variations of dispersion versus wavelength when radii layer1, layer2, layer3 and layer4, for fiber 1 from group B are varied, one at a time, by the amounts ±1% and ± 2%. Noted from figure 4.37 that radius layer4 has less influence on dispersion than the other radii, while radius layer2 has the strongest influence see figure 4.35. This means that special care should be taken with respect to radius layer2 in manufacturing process. The largest variation in dispersion at 1.55 μm is –5.02 to 3.348 ps/nm.km, resulting from variation of layer2 from –2% to

2% .Figures 4.38, 4.39, 4.40 and 4.41 shows variations of effective-area as a function of wavelength when radii layer1, layer2, layer3 and layer4, for fiber 1from group B are varied ±1% and ± 2%. Again, layer2 has the strongest influence on the effective-area, while layer4 has little effect. The largest variation in effective-area at 1.55μm is from 101.9 to 121.9 μm^2, which results from variation of layer2 by –2% to +2%.

Tables show variations of mode-field-diameter as a function of wavelength for variations of layer1, layer2, layer3 and layer4, for fiber 1 from group B are varied ±1% and ± 2%. The same conclusions can be deduced in this case too. The largest variation in the mode-field-diameter at 1.55μm is from 10.37 to 11.34 μm. Again, this variation is due to changes in layer2 by +2% and –2%. In summary, it is concluded that the most sensitive radius is layer2 and the least sensitive is layer4. This expected because the fields at the outer layer are much smaller than in the inner layers.

Table 4.14: changes in the radii of layer 1 at 1.55 μm (–2% to +2%) for fiber1 from group B

Tolerance	A_{eff} μm^2	MFD μm	D Ps/nm.km	DS $Ps/nm^2.km$	λc μm
+2%	115.2	10.97	-1.283	-0.00655	0.99
+1%	112.3	10.88	-0.6418	-0.005224	0.99
0%	109.6	10.77	-0.008864	-0.00397	0.99
-1%	107	10.65	0.58618	-0.002397	0.99
-2%	104.6	10.55	1.103	-0.001437	0.99

Table 4.15: changes in the radii of layer 2 at 1.55 μm (–2% to +2%) for fiber1 from group B

Tolerance	A_{eff} μm	MFD μm	D Ps/nm.km	DS $Ps/nm^2.km$	λc μm
+2%	101.9	10.37	3.348	0.004293	1.01
+1%	105.3	10.54	1.832	0.0007654	1
0%	109.6	10.77	-0.008864	-0.00397	0.99
-1%	114.9	11.04	-2.243	-0.00947	0.98
-2%	121.9	11.34	-5.02	-0.01691	0.97

Table 4.16: changes in the radii of layer 3 at 1.55 μm (–2% to +2%) for fiber1 from group B

Tolerance	A_{eff} µm^2	MFD µm	D Ps/nm.km	DS Ps/nm^2.km	λc µm
+2%	108.2	10.68	-0.5547	-0.007088	0.99
+1%	108.9	10.7	-0.3014	-0.005596	0.99
0%	109.6	10.77	-0.008864	-0.00397	0.99
-1%	110.2	10.83	0.2931	-0.00196	0.99
-2%	110.8	10.85	0.5784	-0.000403	0.99

Table 4.17: changes in the radii of layer 4 at 1.55 µm (–2% to +2%) for fiber1 from group B

Tolerance	A_{eff} µm^2	MFD µm	D Ps/nm.km	DS Ps/nm^2.km	λc µm
+2%	109.8	10.86	-0.008864	-0.00397	0.99
+1%	109.7	10.83	-0.008864	-0.00397	0.99
0%	109.6	10.77	-0.008864	-0.00397	0.99
-1%	109.5	10.71	-0.008864	-0.00397	0.99
-2%	109.4	10.68	-0.008864	-0.00397	0.99

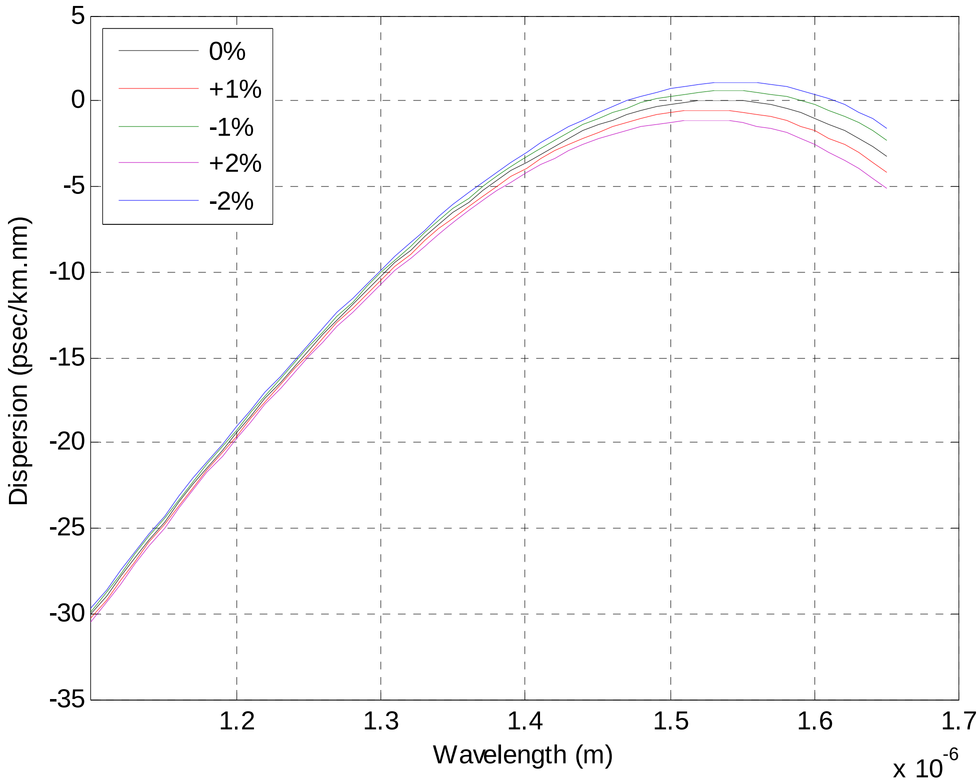


Figure 4.34: Variations of dispersion versus wavelength for fiber 1 from group B. Radius of layer1 is varied ±1% and ±2%

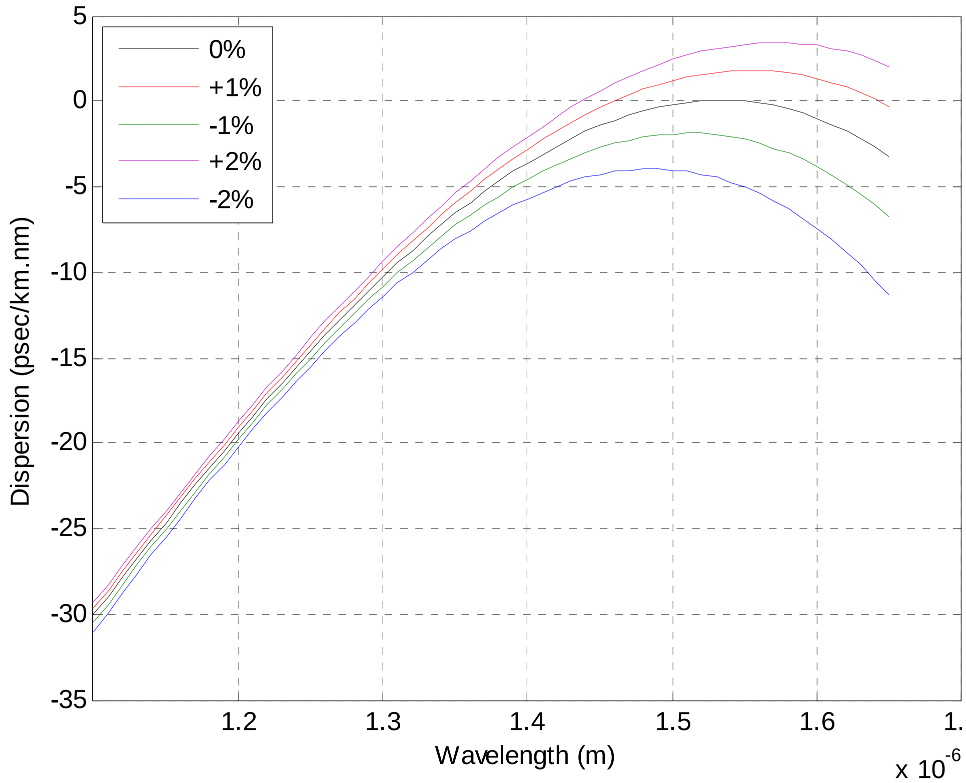


Figure 4.35: Variations of dispersion versus wavelength for fiber 1 from group B. Radius of layer2 is varied ±1% and ±2%

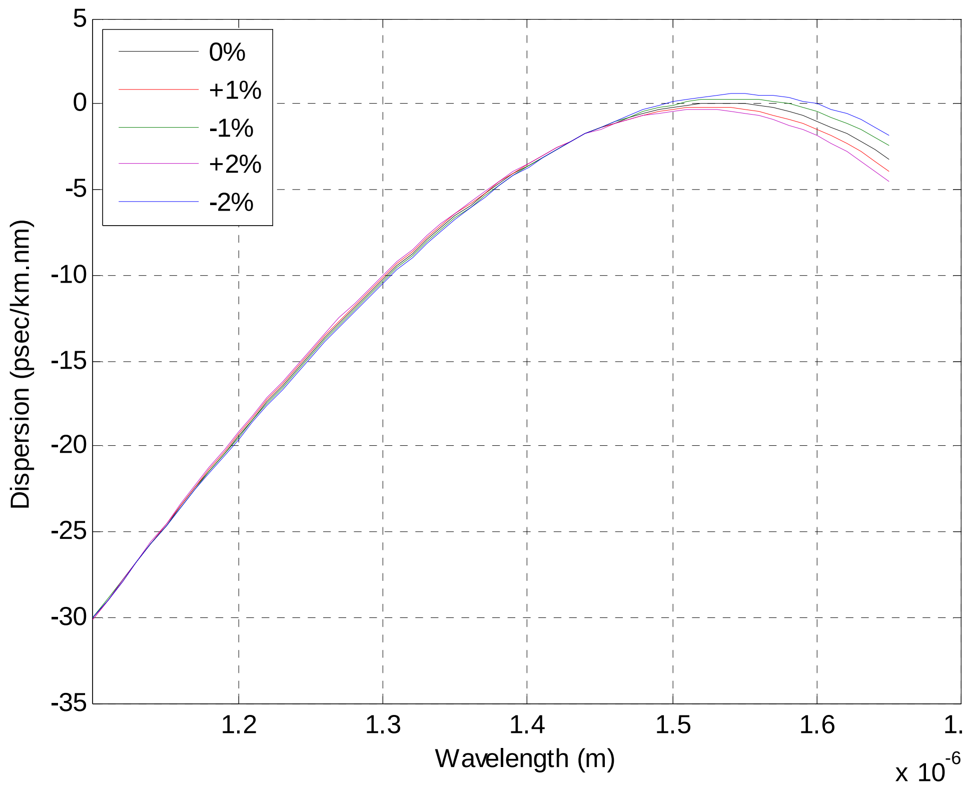


Figure 4.36: Variations of dispersion versus wavelength for fiber 1 from group B. Radius of layer3 is varied ±1% and ±2%

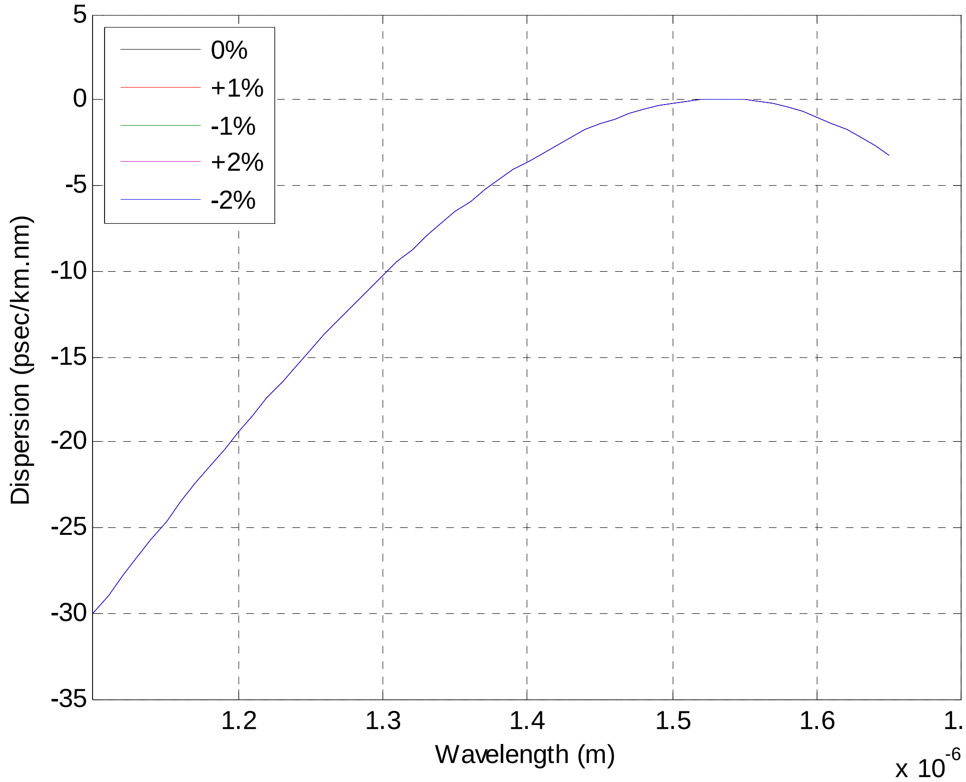


Figure 4.37: Variations of dispersion versus wavelength for fiber 1 from group B. Radius of layer4 is varied ±1% and ±2%

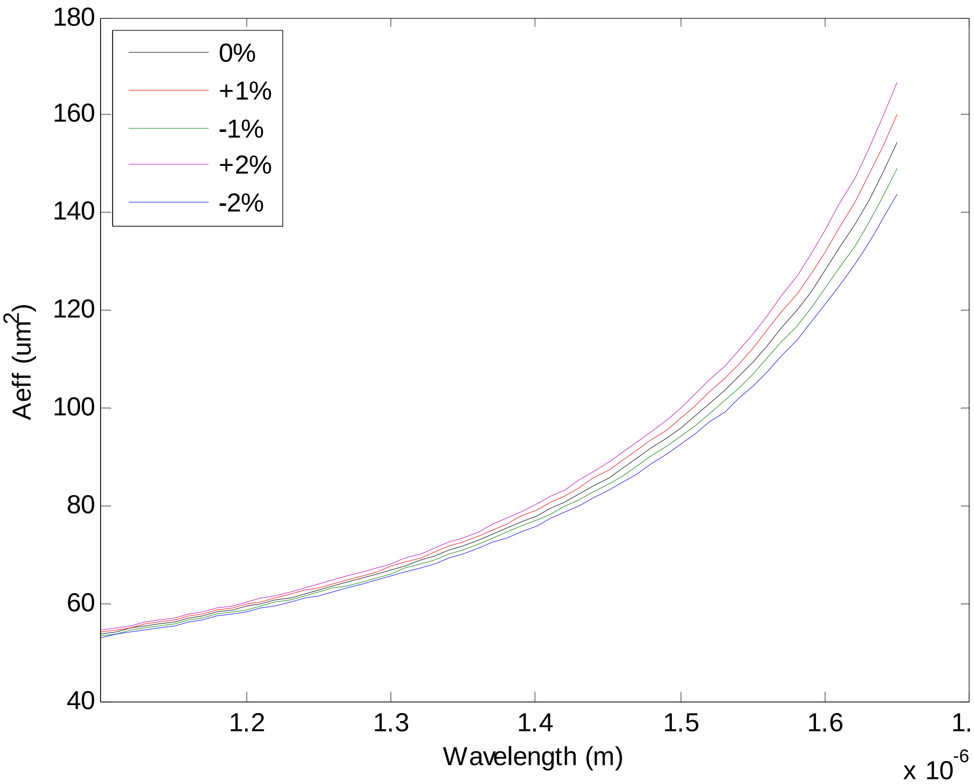


Figure 4.38: Variations of effective-area versus wavelength for fiber 1 from group B. Radius of layer1 is varied ±1% and ±2%

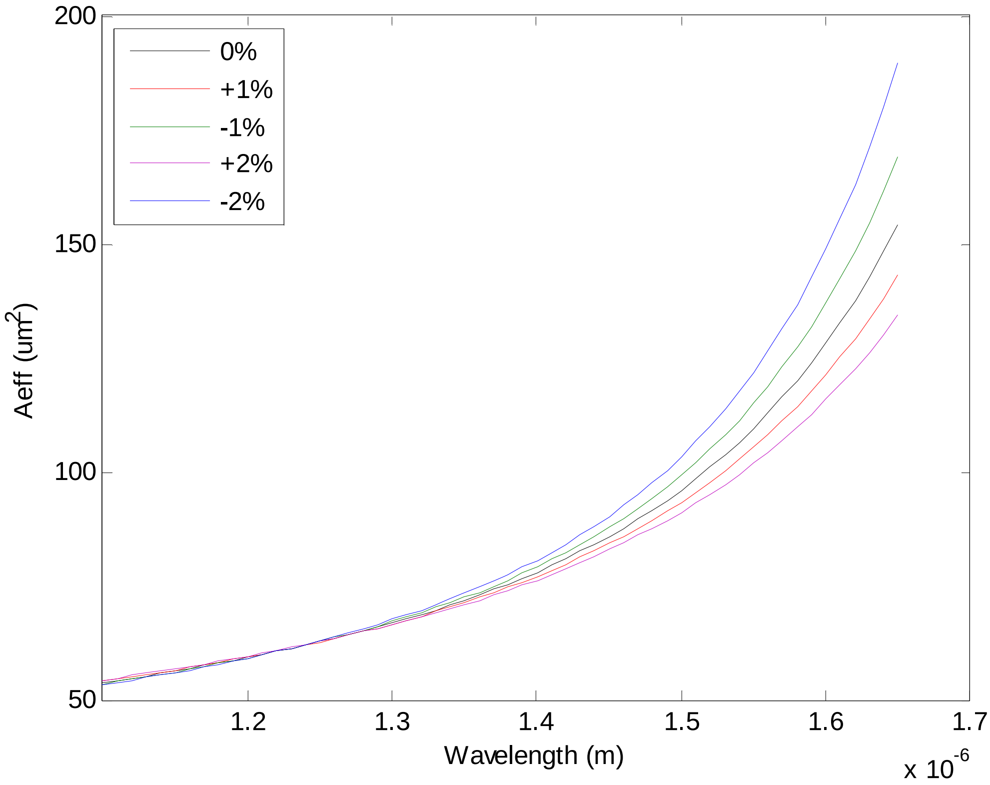


Figure 4.39: Variations of effective-area versus wavelength for fiber 1 from group B. Radius of ayer2 is varied ±1% and ±2%

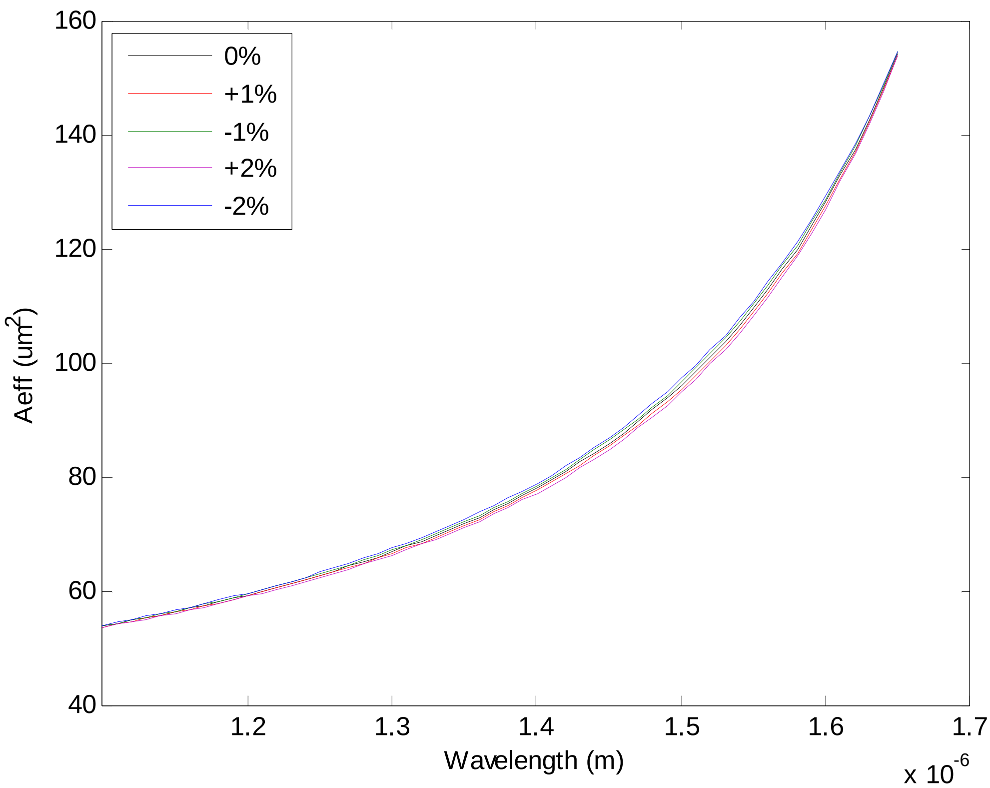


Figure 4.340: Variations of effective-area versus wavelength for fiber 1 from group B. Radius of ayer3 is varied ±1% and ±2%

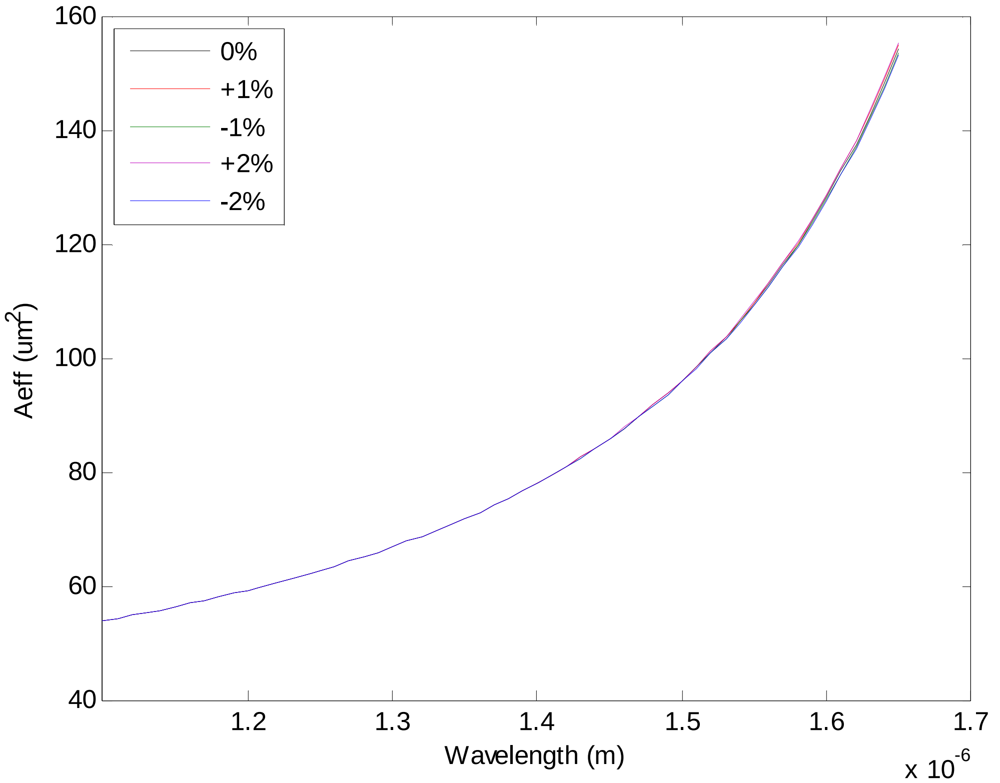


Figure 4.41: Variations of effective-area versus wavelength for fiber 1 from group B. Radius of ayer4 is varied ±1% and ±2%

4.6.2. Tolerance refractive indices

The examination of the effects of varying the refractive indices on dispersion, dispersion slope, effective-area and mode-field-diameter of layer1, layer2, layer3 and layer4, for fiber 1 from group B seen in tables 4.18 ,4.19 ,4.20 ,4.21.

This refractive index will be changed ± 0.01 %, typical variations that may occur in an actual fiber manufacturing process. In addition, we study changing ± 0.02 %, to test ability of this fiber if increase this percentage of tolerance for manufacturing. Fiber 1 from group B includes four refractive indices, layer1, layer2, layer3 and layer4 that are varied, one at a time by the amounts ± 0.02% and ±0.01%. Figures 4.42, 4.43, 4.44 and 4.45 for dispersion and figures 4.46, 4.47, 4.48 and 4.49 for effective-area. From these figures and tables as expected, transmission properties are most sensitive to layer4 and least sensitive to layer1.Values dispersion about

5.627to -14.75 ps/nm.km at 1.55 µm, which results from variation of layer4 by –0.02% to +0.02%.

Figures 4.46 to 4.49 illustrate variations of effective-area versus wavelength for changes of refractive indices in fiber1. The effective-area changes considerably for changes of layer1, layer2, layer3 and layer4, however, changes in layer4 are much more critical than changes in layer1. Variations in radius layer4 have an insignificant effect on the effective area. At 1.55 µm, the effective-area changes from 95.59 to 144.4 µm^2, when layer4 varies by –0.02% to +0.02%. From these tables it observed that variations in refractive indices cause significant changes in the mode-field-diameter, while changes in refractive indices layer1 cause small changes in this parameter. At 1.55µm, the mode-field-diameter changes from 10.13 to 12.8 µm when layer4 varied from – 0.02% to +0.02%, there for the layer4 in manufacturing process to avoid distortion was shown in tables and figures. Tables that effect percentage – 0.02%, and +0.02% is larger than percentage – 0.01% and +0.01% .This means that special care should be taken with respect to – 0.02% and +0.02% in the manufacturing process.

Table 4.18 changes in the Refractive index of layer 1(–0.02% to +0.02%) for fiber1 from group B.

Tolerance	A_{eff} µm^2	MFD µm	D Ps/nm.km	DS Ps/nm2.km	λc µm
+0.02%	105.5	10.62	1.024	-0.001698	0.99
+0.01%	107.5	10.69	0.5273	-0.002534	0.99
0.00%	109.6	10.77	-0.008864	-0.00397	0.99
-0.01%	111.7	10.84	-0.5325	-0.004679	0.99
-0.02%	113.9	10.92	-1.08	-0.005788	0.99

Table 4.19 changes in the Refractive index of layer 2(–0.02% to +0.02%) for fiber1 from group B.

Tolerance	A_{eff} µm^2	MFD µm	D Ps/nm.km	DS Ps/nm2.km	λc µm
+0.02%	98.35	10.22	2.818	0.003457	1.01
+0.01%	103.4	10.47	1.541	0.0002143	1
0.00%	109.6	10.77	-0.008864	-0.00397	0.99
-0.01%	117.1	11.11	-1.831	-0.008102	0.98
-0.02%	126.8	11.52	-4.197	-0.01478	0.97

Table 4.20 changes in the Refractive index of layer 3(–0.02% to +0.02%) for fiber1 from group B.

Tolerance	A_{eff} µm	MFD µm	D Ps/nm.km	DS Ps/nm2.km	λc µm
+0.02%	107.8	10.71	3.23	0.005072	1.01
+0.01%	108.6	10.73	1.738	0.00128	1
0.00%	109.6	10.77	-0.008864	-0.00397	0.99
-0.01%	110.8	10.81	-2.065	-0.001001	0.98
-0.02%	112.5	10.86	-4.55	-0.0181	0.97

Table 4.21 changes in the Refractive index of layer 4(–0.02% to +0.02%) for fiber1 from group B.

Tolerance	A_{eff} µm^2	MFD µm	D Ps/nm.km	DS Ps/nm2.km	λc µm
+0.02%	144.4	12.8	-14.75	-0.04924	0.95
+0.01%	122.2	11.28	-5.265	-0.01854	0.97
0.00%	109.6	10.77	-0.008864	-0.00397	0.99
-0.01%	101.3	10.4	3.339	0.004546	1.01
-0.02%	95.59	10.13	5.627	0.0009566	1.03

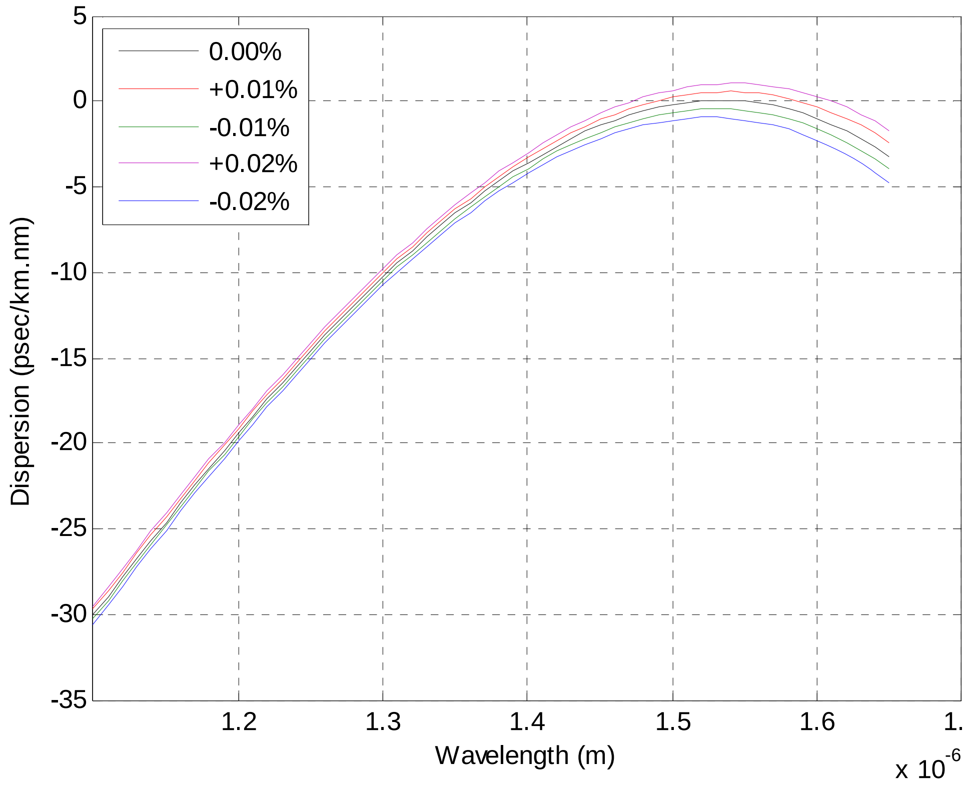


Figure 4.42: Variations of dispersion versus wavelength for fiber1 from group B. Refractive index layer1 is varied (–0.02% to +0.02%)

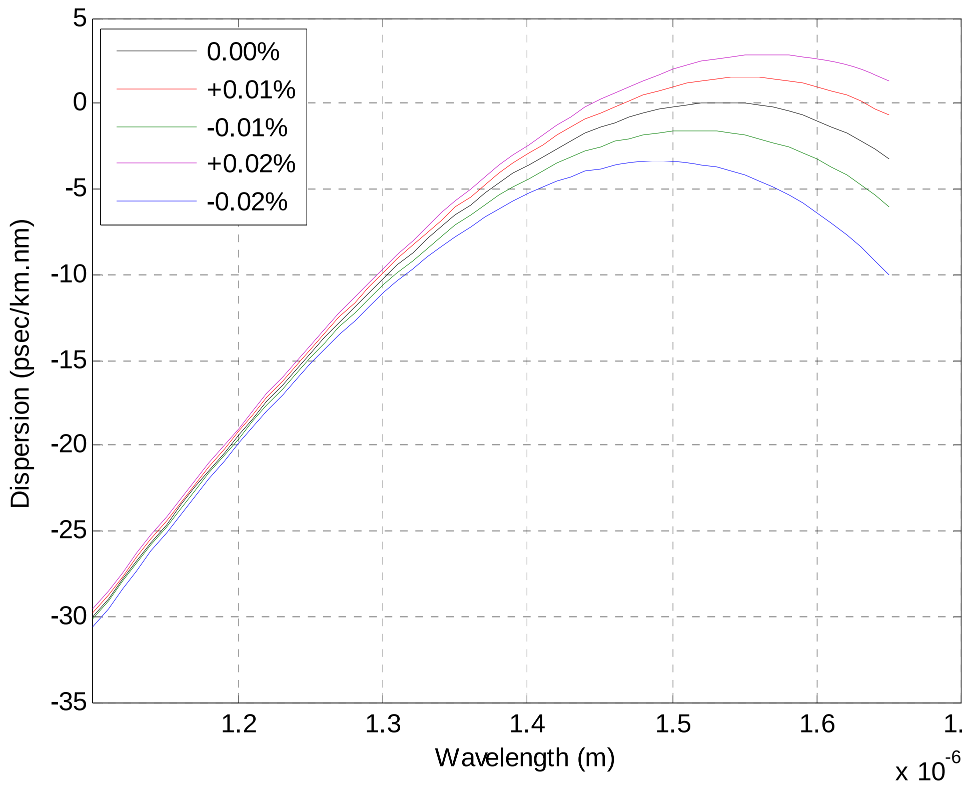


Figure 4.43: Variations of dispersion versus wavelength for fiber1 from group B. Refractive index layer2 is varied (–0.02% to +0.02%)

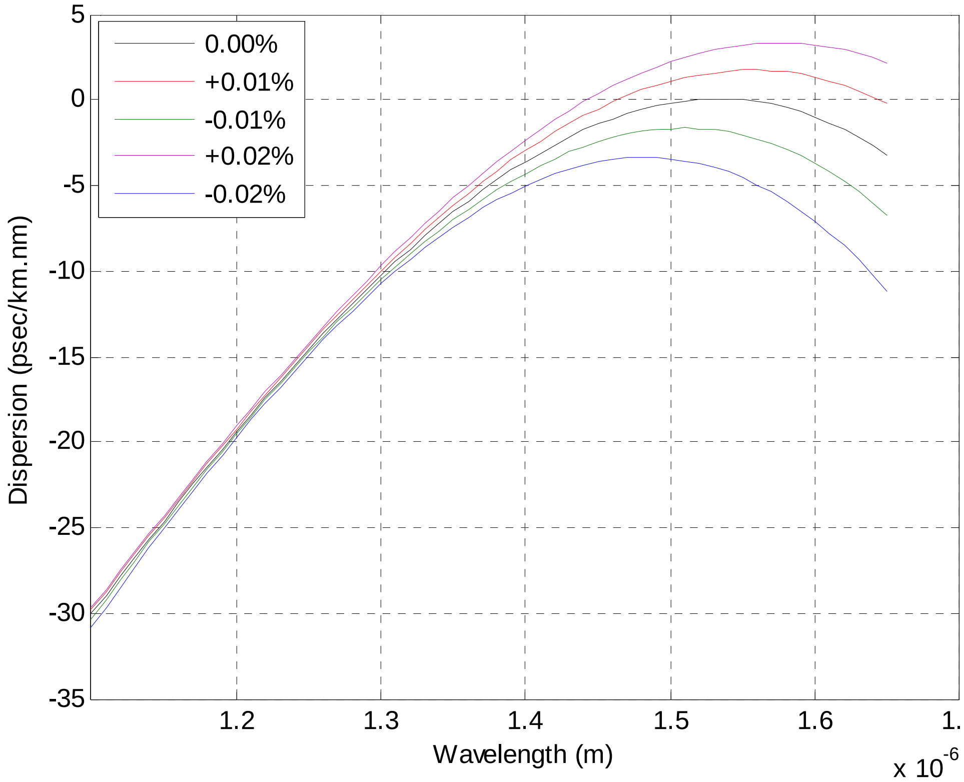


Figure 4.44: Variations of dispersion versus wavelength for fiber1 from group B. Refractive index layer3 is varied (–0.02% to +0.02%).

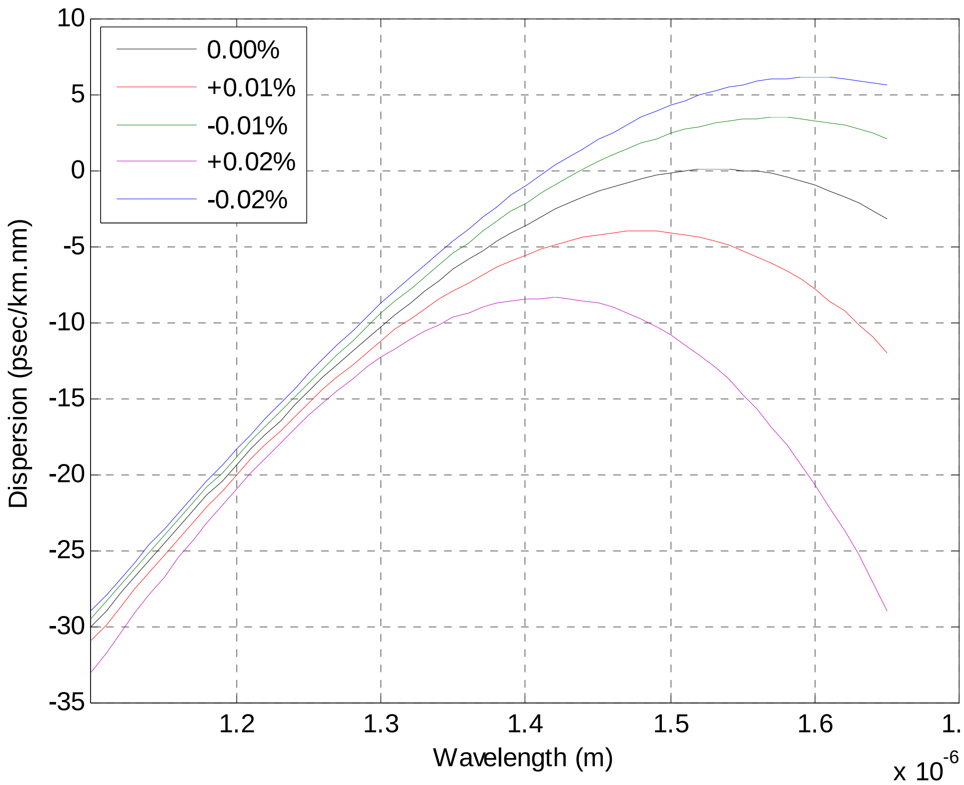


Figure 4.45: Variations of dispersion versus wavelength for fiber1 from group B. Refractive index layer4 is varied (–0.02% to +0.02%).

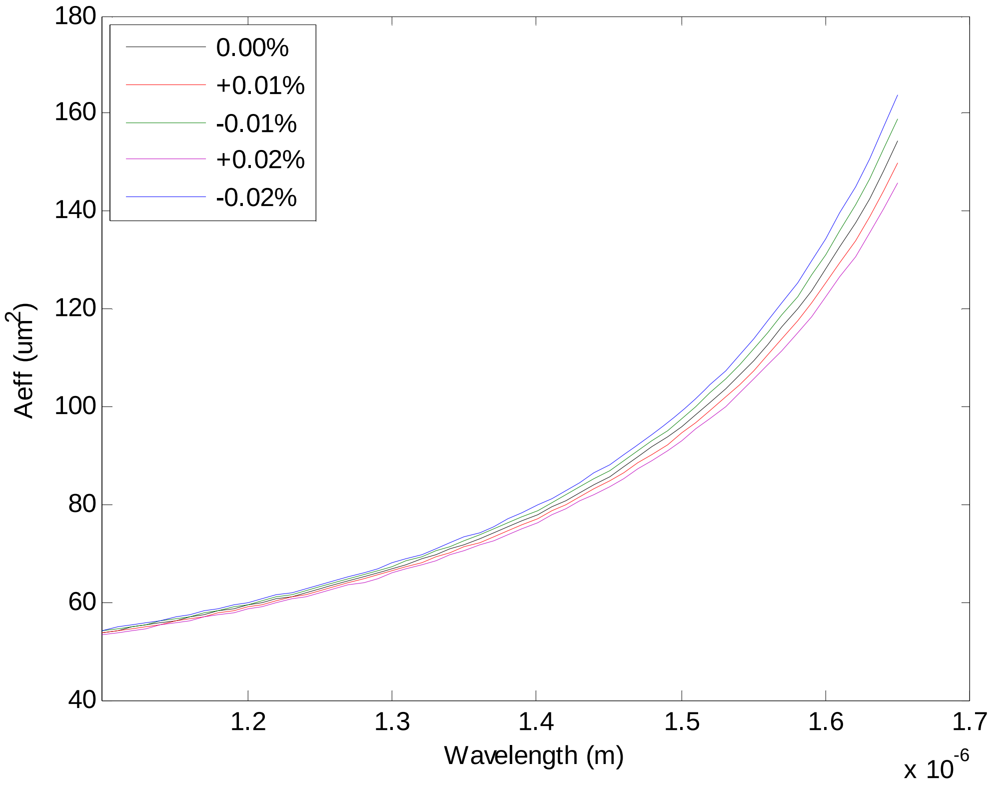


Figure 4.46: Variations of effective-area versus wavelengths for fiber1 from group B. Refractive index layer1 is varied (–0.02% to +0.02%).

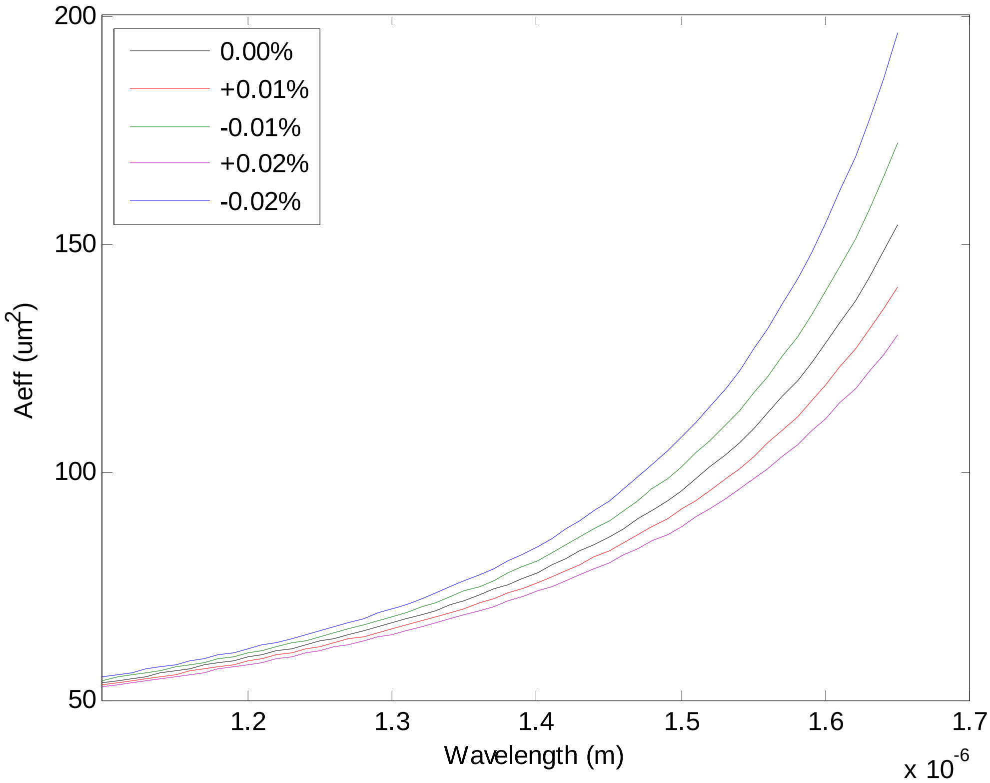


Figure 4.47: Variations of effective-area versus wavelengths for fiber1 from group B. Refractive index layer2 is varied (–0.02% to +0.02%).

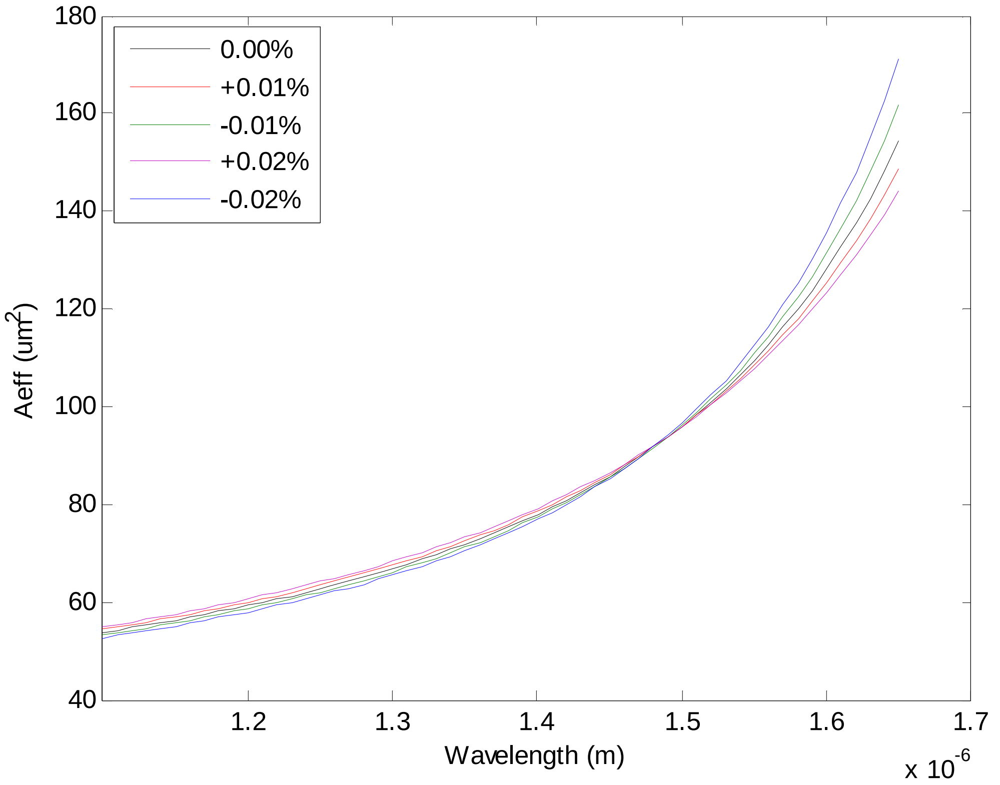


Figure 4.48: Variations of effective-area versus wavelengths for fiber1 from group B. Refractive index layer3 is varied (–0.02% to +0.02%).

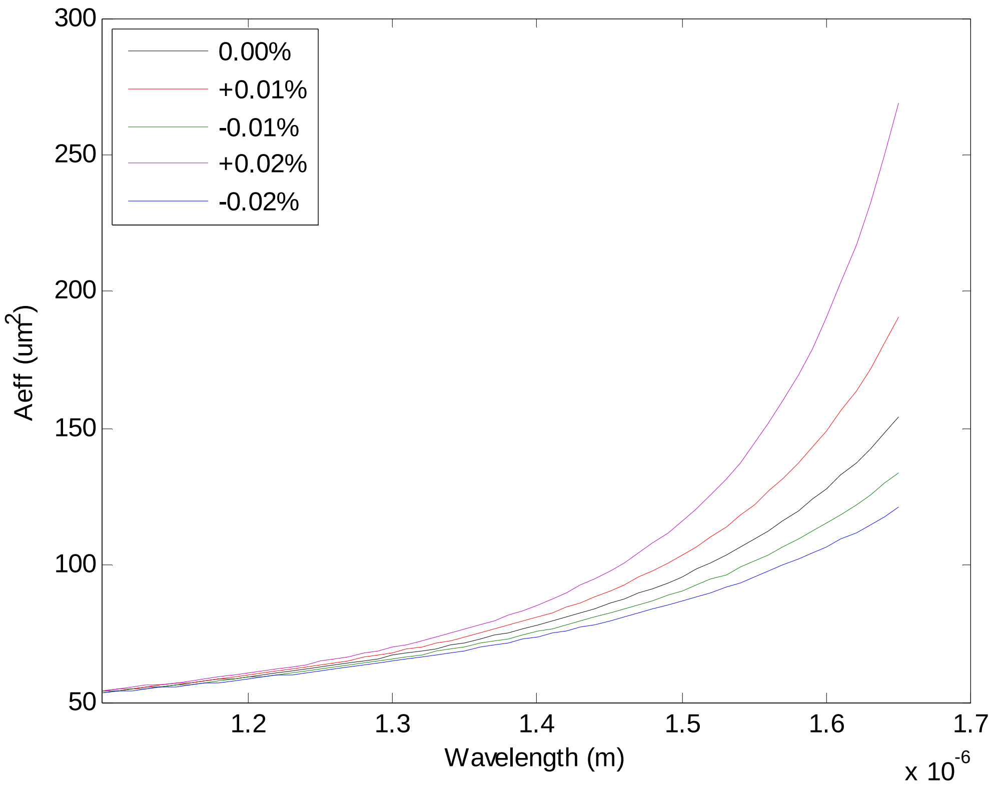


Figure 4.49: Variations of effective-area versus wavelengths for fiber1 from group B. Refractive index layer4 is varied (–0.02% to +0.02%).

4.6.3. Tolerance of wavelength

The wavelength is considering one of the most important parameter in optical communication system because transmission properties of optical fiber depended on wavelength.

Table 4.21**,** changes in the wavelength respectively at 1.55 µm (–2% to +2%) for fiber1 from group B.

Figures 4.50, 4.51, 4.52 and4.53, show variations of dispersion, dispersion slope, effective-area and mode-field-diameter respectively versus wavelength when wavelength, for fiber 1 from group B are varied by the amounts ±1% and ± 2%**.**

From this table and figures it shown, that tolerance of wavelength is accepted.

Table 4.22: changes in the wavelength at 1.55 µm (–2% to +2%) for fiber1 from.

Tolerance	A_{eff} µm^2	MFD µm	D Ps/nm.km	DS Ps/nm^2.km	λc µm
+2%	110.2	10.8	0.1946	-0.002141	0.99
+1%	109.9	10.78	0.108	-0.002809	0.99
0%	109.6	10.77	-0.008864	-0.00397	0.99
-1%	109.2	10.75	-0.2285	-0.005291	0.99
-2%	108.9	10.73	-0.5616	-0.007264	0.99

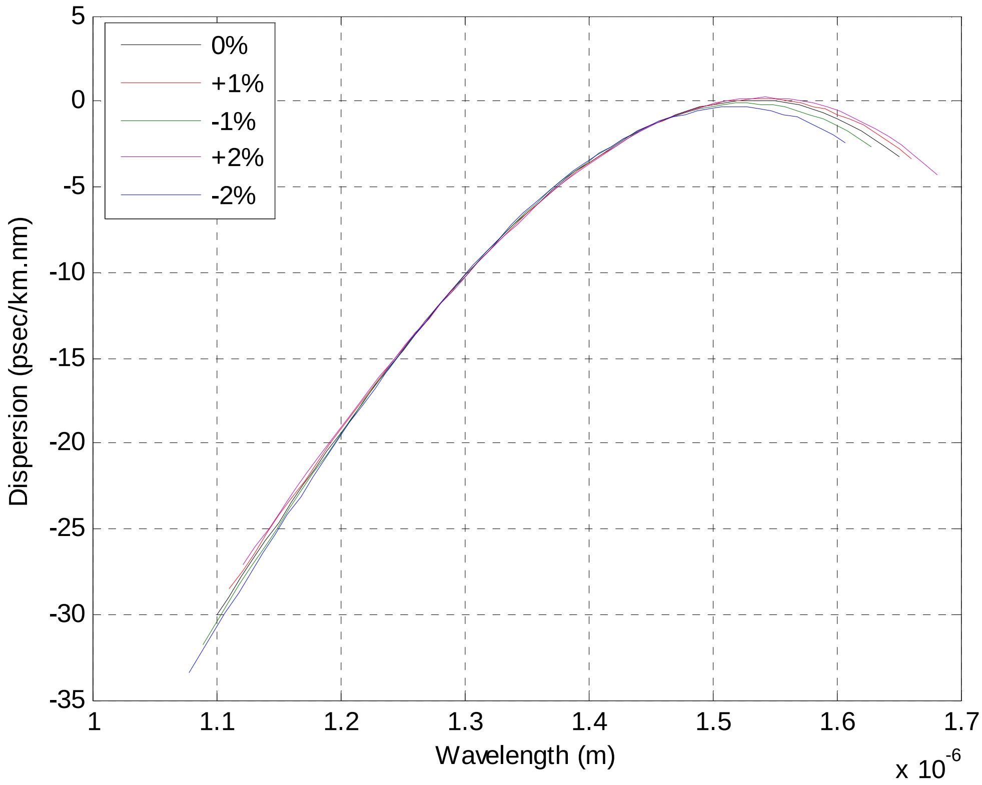


Figure 4.50: Variations of dispersion versus wavelength for fiber 1 from group B. wavelength is varied ±1% and ±2%

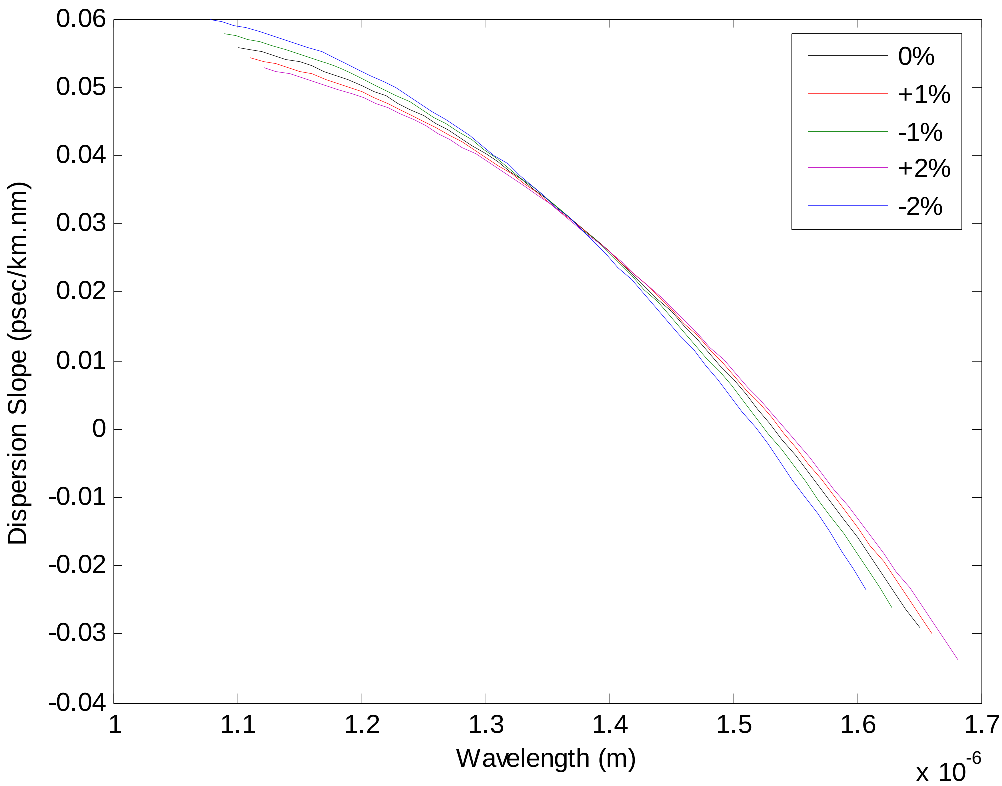


Figure 4.51: Variations of dispersion slope versus wavelength for fiber 1 from group B. wavelength is varied ±1% and ±2%

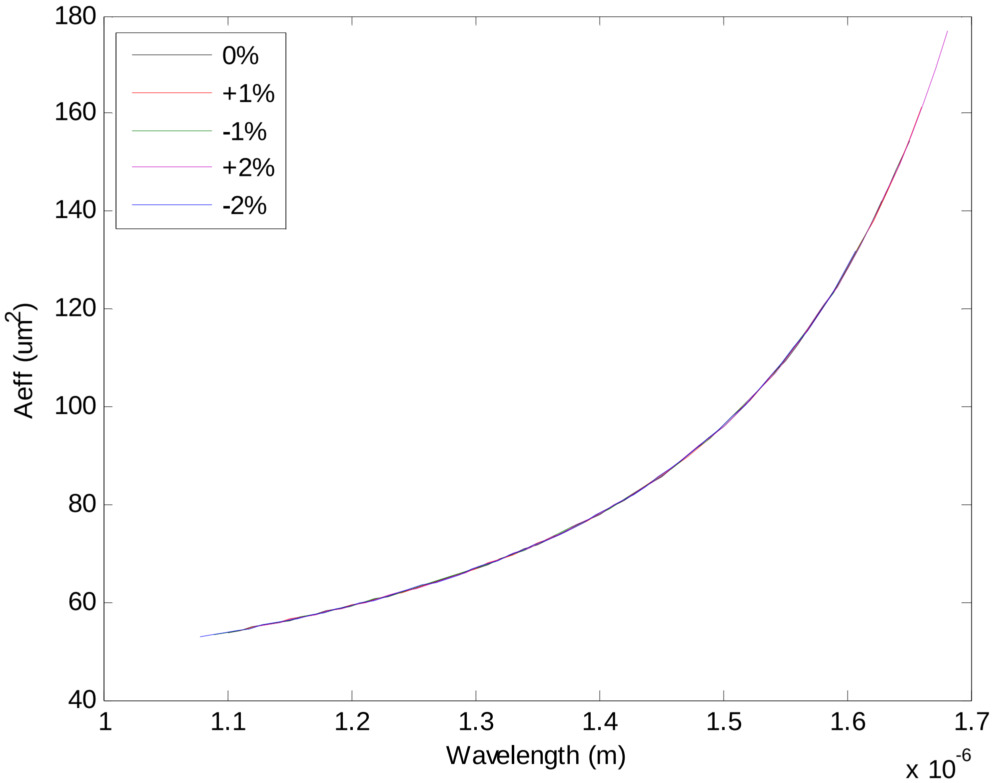


Figure 4.52: Variations of effective-area versus wavelength for fiber 1 from group B. wavelength is varied ±1% and ±2%

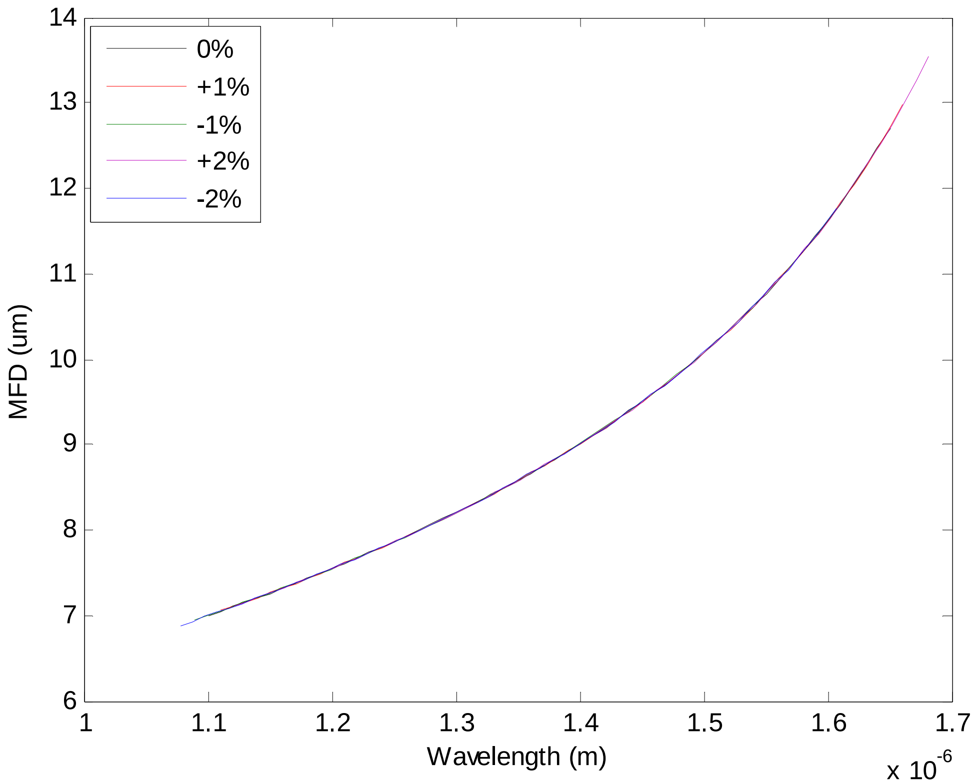


Figure 4.53: Variations of mode-field-diameter versus wavelength for fiber 1 from group B. wavelength is varied ±1% and ±2%

4.7. The Effects of Nonlinearity

After designing low nonlinearity dispersion-flattened fibers, employing large effective-area and small mode-field-diameter according the quality factor (Q). The nonlinear effects in optical fiber in chapter two shown employing elastic and inelastic nonlinear effects. In this chapter will be study the behavior of phase modulation nonlinear effects (Kerr effect) in fiber through optical communication with high power (1 watt) will be study on fiber 1 from group B because large effective-area and small mode-field-diameter according the quality factor(Q). Figure (4.54) shows variations dispersion versus wavelength of linear and nonlinear effect for fiber 1 from group B it noted that the phase modulation nonlinear effects (Kerr effect) has small effect on this design because the changing of the refractive indices is very small according the low phase modulation nonlinear effects. Fiber nonlinearity is due to weak dependence of the refractive index of glass on light intensity. This dependence may be expressed [14,15].

$$n = n_0 + n_{non}(p / A_{eff})$$

Where

n is the modulate refractive index,

n_o is the linear refractive index,

n_{non} is nonlinear coefficient which is about 3.4×10^{-8}mμ^2/W,

P is the power,

For example when n_o=1.4422 at 1.55µm.

A_{eff} =109.6 mμ^2

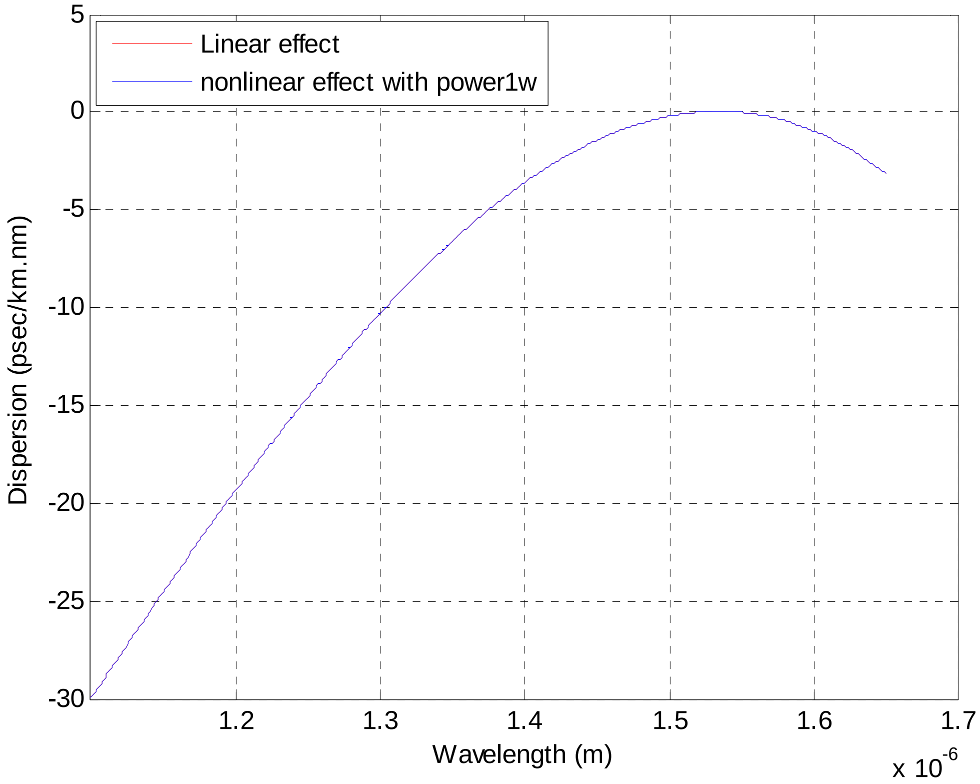
P=1 watt

n = 1.4422+3.4×10^{-8}mμ^2/w (109.6 mμ^2/1 w) ≈1.4422

From this expression, the effects of nonlinearities on the refractive index of the fiber core are very low.

Figure (4.55) shows variations dispersion versus wavelength of linear and nonlinear effect for fiber 1 from group B after the zooming of more than five times by using matlab program.

Figure 4.56 illustrates variations of effective-area versus wavelength of linear and nonlinear effect for fiber 1 from group (B). Figure 4.57 shows variations of effective-area versus wavelength of linear and nonlinear effect for fiber 1 from group B after the zooming of more than five times by using matlab program. Figure 4.58 illustrate mode-field-diameter variations versus wavelength of linear and nonlinear effect for fiber 1 from group (B). Figure 4.59 shows variations of mode-field-diameter versus wavelength of linear and nonlinear effect for fiber 1 from group (B) after the zooming of more than five times by using matlab program.



Figures 4.54: show variations dispersion versus wavelength of linear and nonlinear effect for fiber 1 from group B

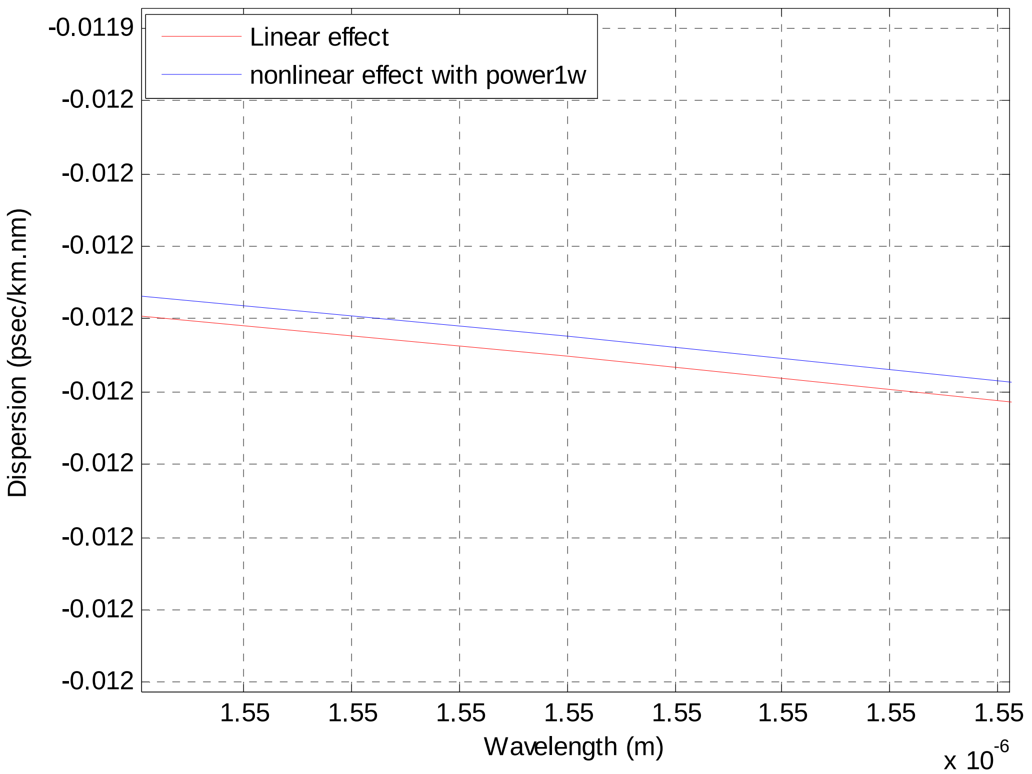


Figure 4.55: show variations dispersion versus wavelength of linear and nonlinear effect for fiber 1 from group B after the zoom more than five times by using matlab program

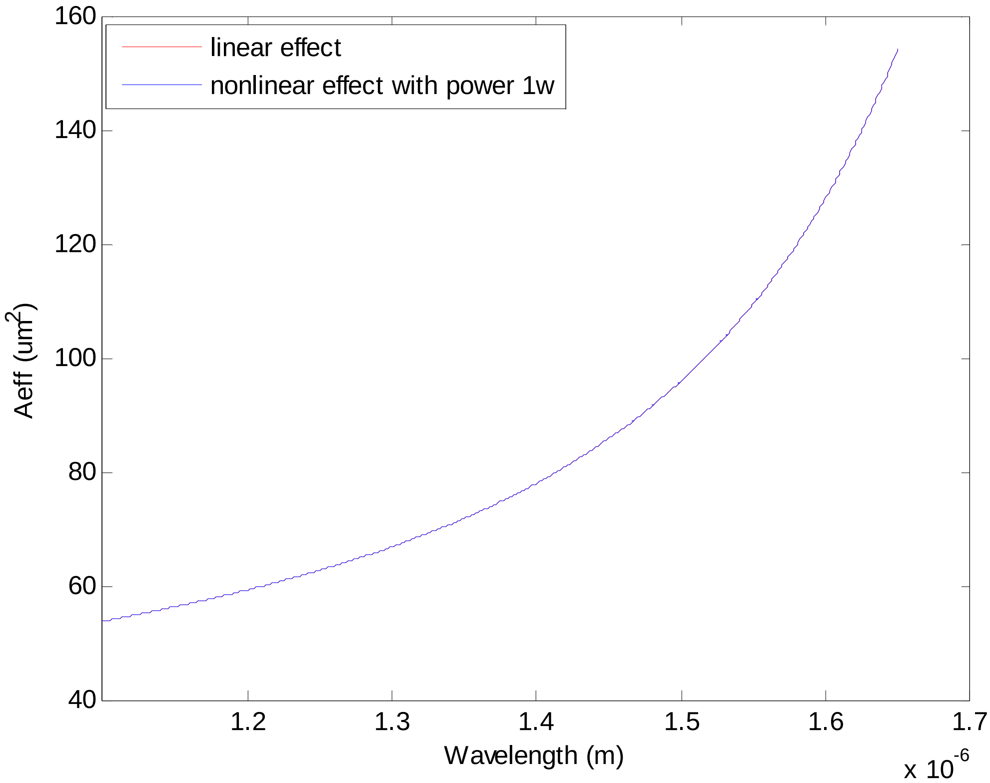


Figure 4.56: illustrate variations of effective-area versus wavelength of linear and nonlinear effect for fiber 1 from group B

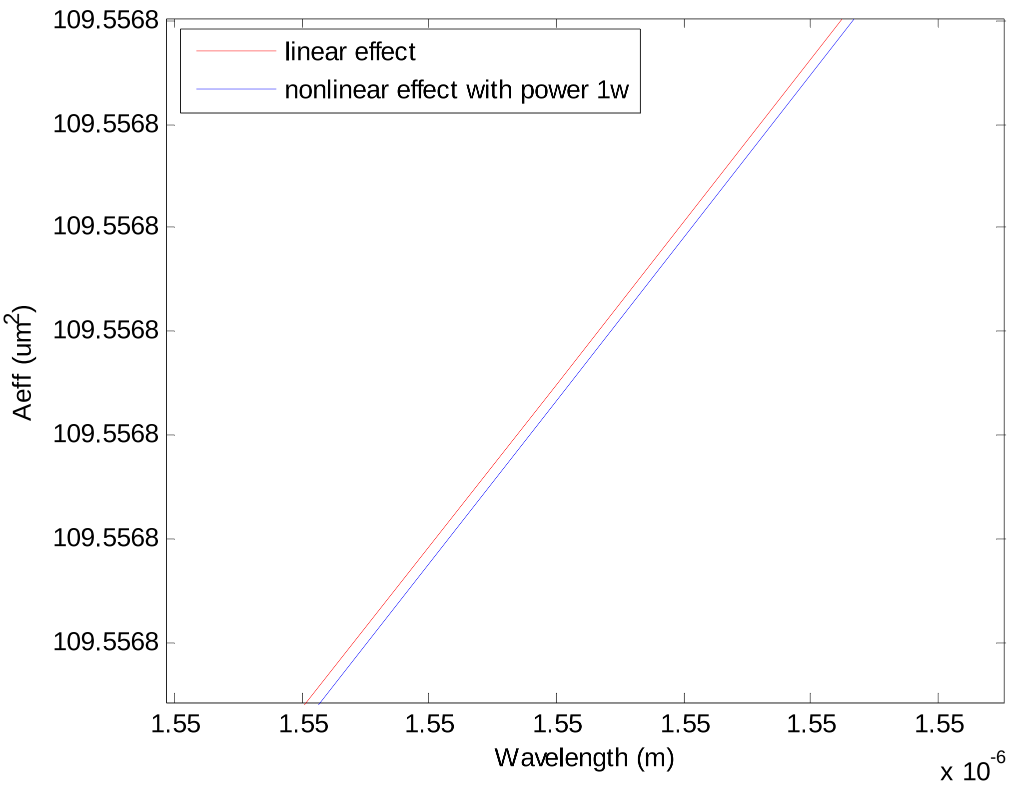


Figure 4.57: show variations of effective-area versus wavelength of linear and nonlinear effect for fiber 1 from group B after the zoom more than five times by using matlab program

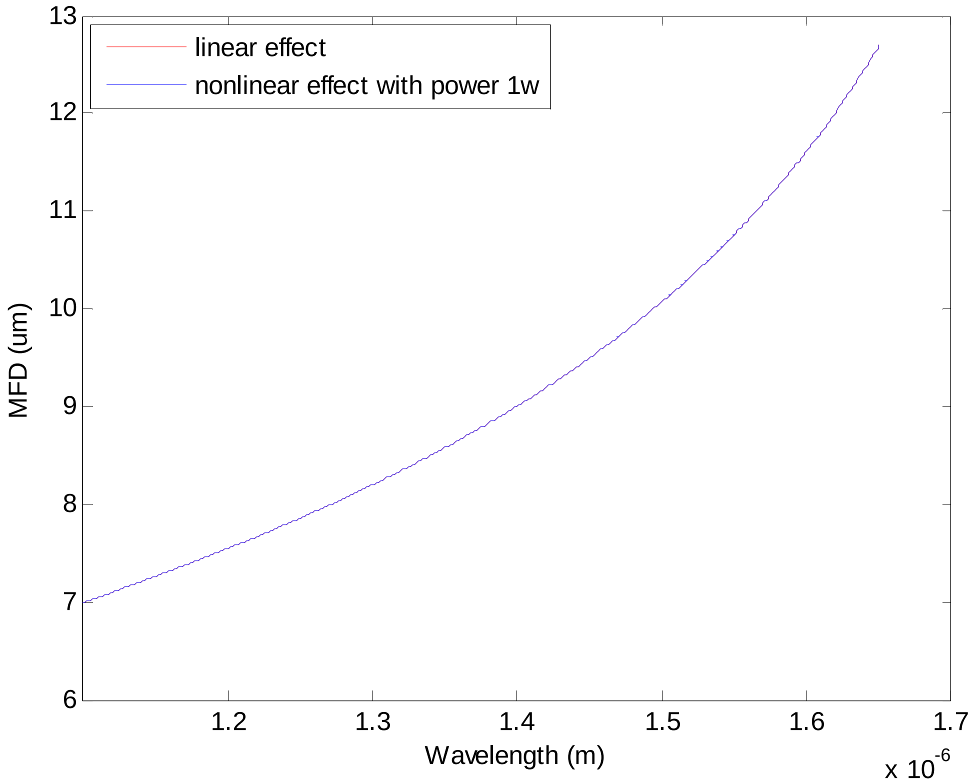


Figure 4.58: illustrate mode-field-diameter variations of versus wavelength of linear and nonlinear effect for fiber 1 from group B

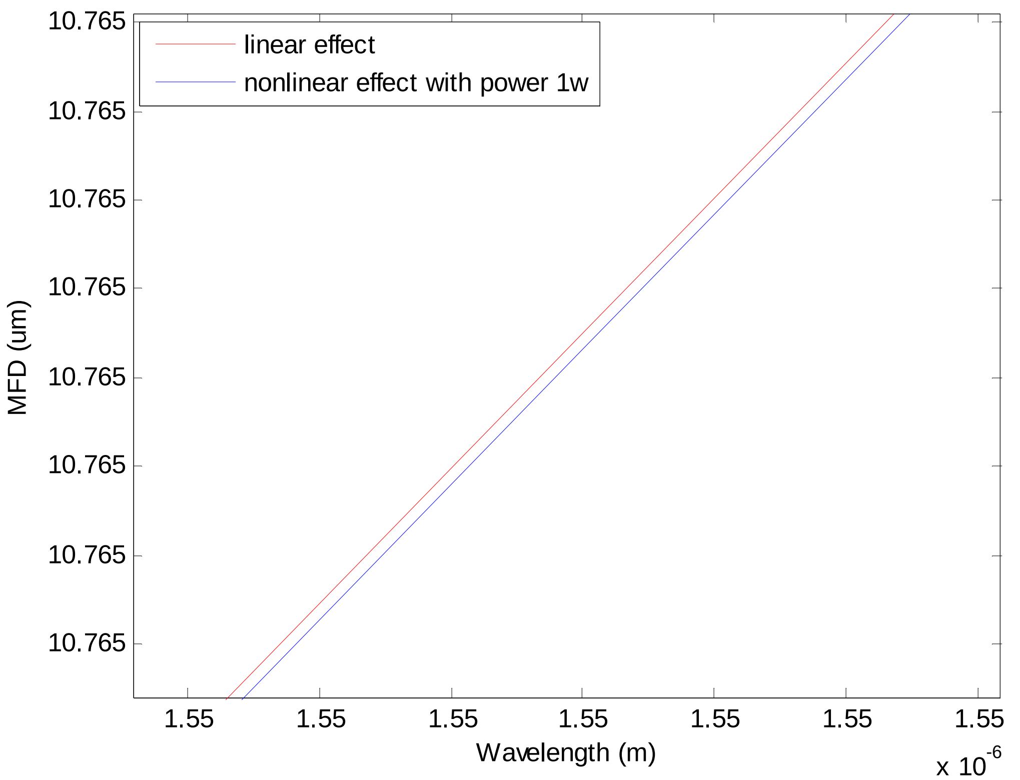


Figure 4.59: show variations of mode-field-diameter versus wavelength of linear and nonlinear effect for fiber 1 from group B after the zoom more than five times by using matlab program

Chapter Five

Conclusions and Future Work

5.1. Conclusions

The important facts derived from the numerical results and obtained according to the mathematical model can be summarized as follows:

1. A mathematical model is carried out numerical and it is applicable to any optical fiber structure.
2. The dispersion does not predominate by a direct relation. To get the minimum dispersion of any fiber structure, a careful attenuation should be paid to fiber parameters throughout the design process.
3. Large effective area associated with large mode field diameter leads to increase bending loss. Thus, a large effective-area and low bending loss are conflicting requirements. This parameter is solved by parameter Q.
4. A large effective area with the dispersion flattened fiber can be obtained (about 109.6μm^2) by employing four layer fiber structure with suitable mode field diameter (10.77 μm), dispersion (-0.008864 Ps/nm.km), dispersion slope (-0.00379 Ps/nm^2.km), and quality factor (0.94488).
5. To obtain a large effective area with suitable mode field diameter and zero or near zero, dispersion does not depend only on the profile index but also on the refractive index and core radius.
6. It can be extended to be applied to designs in the range of wavelength, (1.3-1.6) μm and (1.4-1.6) μm.
7. The tolerance of core radius and wavelength is more flexible and the tolerance of refractive index especially with ±0.01%, also flexible.

8. The nonlinearity causes a change in refractive index due to the Kerr effect which is very small according to the low phase modulation nonlinear effects.

Finally, the proposed presented a value of Q (0.76131-0.944885) has been obtained which is better than that of the conventional fiber; which is (0.741). However, large effective area associated with a large mode field diameter leads to high bending losses. There is a relation among bending radius, mode field diameter and bending loss.

5.2. Suggestions of Future Work

This thesis has significantly contributed to the design, analysis, and understanding of transmission properties of Large effective-area dispersion-flattened fibers. However, further improvements in the designs and further investigation in nonlinear effects in these fibers are needed to be pursued. Some suggestions of future work can be summarized as follows:

1. Calculation of splicing losses can be obtained by the use of the calculation of mode field diameter.
2. Evaluation of microbending losses due to the specific mode field diameter and determining the bending limit due to the mode field diameter and the radius of the bending.
3. Use of bending losses as a quality factor, instead the quality factor Q to choose the optimum design.

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WESAM

Abstract

A special design of optical fibers namely multi layer single mode is adopted in order to achieve effective-areas much larger than those in conventional optical fibers and zero or near zero dispersion for (1100nm-1650nm), (1300nm-1600nm) and (1400nm-1600nm) band region.

Mathematical representation of Multi-layer Optical Fibers was obtained by a numerical solution of scalar wave equation based on weakly guiding approximation.

Designs of dispersion flattened single mode fiber including three different profiles of four layer fiber are adopted to introduce about 18 designs of fibers. This design with effective areas about 62.45μm^2 and 121.7μm^2, mode-field-diameter between 9.05μm and 11.6μm and dispersion in the range of (-0.03539 to 0.03017) ps/nm.km. are achieved (values at 1.55 μm) and cutoff wavelength well below 1μm. Tolerance analysis is worked out on the transmission parameters due to 1% and 2% variations in the radii of the core and wavelength also due to 0.01% and 0.02% variations in the refractive index.

Finally the nonlinearity due to Kerr effect in optical fiber is investigated.

The most important result is the large effective area (109.6μm^2) and mode-field-diameter (10.77 μm) with respect to the quality factor of near zero dispersion-flattened fibers. Reviewing previous reported works, results obtained in the present work look more acceptable in modern optical communication application.

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Chapter Five:

Conclusions and Future Work

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List of Abbreviations

Symbol	Meaning
A	Amplitude
A	Area
AR	Anti-Reflection
D	Dispersion
DCF	Dispersion Compensating Fiber
DFB	Distributed Feed Back Laser
DFF	Dispersion Flattened Fiber
DM	Material Dispersion
DS	Dispersion Slope
DSF	Dispersion Shifted Fiber
DW	Waveguide dispersion
DWDM	Dense Wavelength Division Multiplexing
E	Electric field
EDFA	Erbium Doped Fiber Amplifier
E(r)	Electric amplitude at distance (r)
EH	Helical mode
EM	Electromagnetic
FWM	Four Wave Mixing
GVD	Group Velocity Dispersion
H	Magnetic field
HE	Helical mode
I(r)	Intensity at distance (r)
LP	Linearly Polarized
M	material compositions
MFD	Mode Field Diameter
NA	Numerical Aperture

OA	Optical amplifier
PMD	Polarization Mode Dispersion
Q	quality factor
R	Regenerator
SBS	Stimulated Brillouin Scattering
SLA	Semiconductor Laser Amplifier
SNR	Signal to Noise Ratio
SPM	Self Phase Modulation
SRS	Stimulated Raman Scattering
TDM	Time Division Multiplexing
TE	Transverse Electric
TEM	Transverse Electromagnetic
TM	Transverse Magnetic
TW	Traveling Wave

List of Symbols

Symbol	Meaning
a	core radius of fibers
b	Normalized Propagation Constant
C_0	Speed of light
k	Wave number
k_o	Free space wave number
LP_{01}	Linearly Polarized zero mode
LP_{11}	Linearly Polarized 1st mode
N_g	Group index
n	Refractive index
n_{clad}	Refractive index of the clad
n_{core}	Refractive index of the core
n_{eff}	Effective refractive index
n_{max}	Maximum refractive index
n_{non}	Nonlinear refractive index
n_0	Linear refractive index
R_X	Receiver
T_X	Transmitter
V	Normalized frequency
V_g	Group velocity
v_{phase}	Phase velocity
ε	Material permittivity
ε_0	Free space permittivity
ε_r	Dielectric constant of material
λ	wavelength
λ_C	Cutoff Wavelength

μ	Material permeability
μ_0	Free space permeability
μ_r	Relative permeability
τ	Group delay
Δ	Relative refractive index
β	propagation constant

References

1. G. P. Agrawal, "Fiber-Optic Communication Systems", *University of Rochester Rochester*, *New York*, 2nd Edition 1997.
2. B. Cuenot, "Contribution to engineering of WDM Nx160 Gbit/s optical transmission systems. Analysis of optical signal degradation induced by propagation impairments.", Thesis of Ph.d, *The Louis Pasteur University Of Strasbourg,* 2003.
3. H. Louchet, " Top-Down Analysis of High-Capacity Fiber-Optic Transmission", Thesis of Ph.d, *University of Berlin*, 2006.
4. S. M. Hasan, "Design and Implementation of a Optical Communication Systems Between Two Computer for Data Transmission" Thesis of M.Sc, *Laser Engineering of University of Technology*, 2004.
5. H. J. R. Dutton, “Understanding Optical Communications.” *International Technical Support Organization*, (September 1998).
6. O. K. Tonguz and B. Hwang, "A Generalized Suboptimum Unequally Spaced Channel Allocation Technique-Part II: In Coherent WDM Systems", *IEEE Transactions on Communications*, vol. 46, no. 9, September 1998.
7. M. G. Said, "Modelling, Simulation and Proposal Design for Multi-layer Fiber Optic", Ph.d, *thesis Submitted to the Council of the College of Education University of Mosul*, 2005.
8. H. T. Hattori, "Low Nonlinearity Optical Fibers for Broadband and Long-Distance Communications.", Thesis of Ph.d, *Virginia Polytechnic Institute and State University*, 1998.
9. R. Billington, "Effective Area of Optical Fibers - Definition and Measurement Techniques", *The national physical laboratory Centre for Optical and Environmental Metrology*.

10. S. Hur, J. Ko and I. Lee, "Theoretical Investigation of 8×10 GB/sWDMSignal Transmission Performance Based on Gain-Equalized SOAs Using Backward Raman Pumping at DCF", *Journal of Lightwave Technology* , vol. 21, no. 6, June 2003.
11. R. K. Varshney, A.K. Ghatak, I.C. Goyal, and S. Antony, "Design of a flat field fiber with very small dispersion slope" R.K. Varshney et al. / *Optical Fiber Technology* Let. 9 (2003) 189-198.
12. H. R Sahu and S. Kant, "Enhanced bend insensitive high effective area NZDS fiber", *proceeding of international conference on optics and optoelectronics /*12-15 December 2005 IRDE, Dehradun, India.
13. S. Kim, "Large-Mode-Area Index-Guiding Holey Fibers with Ultra-Low Ultra-Flattened Dispersion Using a Novel Hollow-Ring Defect Structure", *Journal of the Korean Physical Society*, vol. 48, no. 5, May 2006, pp. 897_901.
14. G. P. Agrawal, "Nonlinear Fiber Optics", *University of Rochester Rochester, New York*, 3rd Edition, 2003.
15. G. Keiser, "Optical Fiber Communications.", *Mc Graw Hill, New York, 2nd Edition*, (2000).
16. T. Bilici, "Microspheres Based Channel Dropping for Optical Communication", Thesis of M.Sc, Submitted to the *Institude for Graduate Studies in Science and Engineering Boðaziçi University,* 2003.
17. J. M. Sonior, "Optical Fibre Communications", *Department of Electrical and Electronic Engineering Manchester Polytechnic*, 1985.
18. J. Wilson and J. Hawkes, "Optoelectronics An introductions." *Prentice-Hall International*, (1983).
19. G. P. Agrawal, "Fiber-Optic Communication Systems" *University of Rochester Rochester*, *New York*, 2nd Edition, 2002.

20. M. R. Mokhtar, "Bragg Grating Filter For Optical Network " Thesis of Ph.d, *University of Southampton Faculty of Engineering 'Science and Mathematics*, January 2005.

21. F. E. Seraji and N. P. Afshar, "Design of Large Effective Area Fiber Using Variational Method for High-Capacity NGN's", *Iran Telecom Research Center, Tehran, Iran And Physics Group, Uromia University, Uromia.* September 10-12, 2005.

    Emails: feseraji@itrc.ac.ir, pakzadafshar@yahoo.com

22. J. I. Kim, "Analysis and Applications of Microstructure and Holey Optical Fibers." Thesis of Ph.d, *in Electrical and Computer Engineering Presented to the Virginia Polytechnic Institute and State University*, September 10, 2003.

23. M. A. Ingale, "Error Correcting Codes in Optical Communication Systems" Thesis of M Sc, Submitted to the *School of Electrical Engineering Department of Signals and Systems Chalmers University of Technology Gothenburg, Sweden*, January 2003.

24. W. H. Park, "Fluorescence lifetime sensor using optical fiber and optical signal processing" M.Sc. Thesis in Graduate Department of Aerospace Science and Engineering, in the University of Toronto Canada 1998.

25. T. Barake, "A Generalized Analysis of Multiple-Clad Optical Fibers with Arbitrary Step-Index Profiles and Applications", Thesis of M.Sc, *Virginia Polytechnic Institute and State University*, (1997).

26. T. Niemi, "Dispersion measurements of fiber-optic components and applications of a novel tunable filter for optical communications" Thesis of Ph.d, from *Helsinki University of Technology Department of Electrical and Communications Engineering*, 2002.

27. G. Keiser, "Optical Fiber Communications.", *Mc Graw Hill, New York*, 2nd Edition, (1983).

28. H. Sunnerud, M. Karlsson, C. Xie, and P. A. Andrekson, "Polarization-Mode Dispersion in High-Speed Fiber-Optic Transmission Systems", *Journal of Lightwave Technology*, vol. 20, no. 12, December 2002.
29. A. Goel and R. K. Shevgaonkar, "Wide Band and Dispersion Compensating Optical Fiber" *IEEE Photonic Technology Letters*, vol. 8, no. 12, December 1996.
30. G. Mahlke and P.Gossing, "Fibre Optic Cables", *company of simines*, third Edition, 1997.
31. A. Lamminpää, "Measurement of nonlinearity of optical fiber" Thesis of M.Sc, *University of Espoo*, on the 17th of July, 2003.
32. Y. Song, "Optical Communication Systems for Smart Dust", Thesis of M.Sc. *Department of Electrical Engineering ,Virginia Polytechnic Institute and State University*, August 2002.
33. S. Li and D. V. Kuksenkov, "A Novel Dispersion Monitoring Technique Based on Four-Wave Mixing in Optical Fiber", *IEEE Photonic Technology*, Letters vol. 16, no. 3, March 2004.
34. P. O. Hedekvist, P. A. Andrekson, and K. Bertilsson, "Impact of Spectral Inverter Fiber Length on Four-Wave Mixing Efficiency and Signal Distortion", *Journal of Lightwave Technology*, vol. 13,no. 9, September 1995.
35. K. M. Patel, "Spatially Resolved Equalization: A New Concept in Intermodal Dispersion Compensation for Multimode Fiber", A Thesis of Ph.d, *Presented to The Academic Faculty School of Electrical and Computer Engineering Georgia Institute of Technology*, July 2004.
36. G. Ghosh and M. Endo, "Temperature-Dependent Sellmeier Coefficients and Chromatic Dispersions for Some Optical Fiber

Glasses", *Journal of Lightmwave Technology*, vol. 12, NO. 8, August 1994.