Investigation into the Propagation Characteristics of Photonic Crystal Fiber

Dr.Raad H. Thaher /Electrical Engineering Department College of Engineering-Al-Mustansiryah University.
Oras A.Shareef / Technical Computer Department - College of Electrical & Electronic Techniques
Sondus D.Yousif / Electrical Engineering Department- College of Engineering-Al-Mustansiryah University.

Abstract:
Photonic crystal fiber (PCF) is a new class of optical fiber based on the properties of photonic crystals. It has the ability to confine light in hollow cores. In this paper, the propagation characteristics of PCF described, using different materials, was investigated such as effective area, effective refractive index , numerical aperture and material dispersion for three different materials . It is concluded that zero dispersion occurs at less wavelength when there is no silica in the constriction of PCF (i.e. 0.83µm for sapphire (extra ordinary wave). Also, the three dimension relation between dispersion ,bit error rate ,and fiber length for the three different materials was presented.

Keywords: BER, Dispersion, Numerical aperture, PCF

خصائص الانتشار في الليف الكرستالي الفوتوني.

أ.م.د رعد حمدان ظاهر
الجامعة المستنصرية/كلية الهندسة
قسم هندسة الكهرباء

م.م أوراس احمد شريف
كلية التقنيات الكهربائية والالكترونية
قسم هندسة الحاسبات

م.م سندس داود يوسف
الجامعة المستنصرية/كلية الهندسة
قسم هندسة الكهرباء

المستخلص :
فايبر الكرستال الفوتوني هو تصنيف جديد من الفايبرات البصرية ، يعتمد على صفات الكرستالات الضوئية حيث يمتلك القدرة على تركيز الاشعاع الضوئي في قلب الليف البصري المجوف. في هذا البحث تم ت دراسة خصائص الانتشار للموجات الضوئية في فايبر الكرستال

الضوئي باستخدام مواد مختلفة مثل المساحة الفعالة ، الفتحات العددية لمعامل الانكسار وتشتت المواد لثلاثة مواد مختلفة . استنتج من النتائج أن الطول الموجي المقابل للتشتت الصفري يحصل في طول الموجي اقصر عندما يكون عنصر السيليكا قليلاً او شبه معدوم في تركيب الليف البصري . كما تم التطرق الى العلاقة الثلاثية الابعاد بين التشتت ، نسبة نقل المعلومات وطول الليف البصري كما مبين في متن البحث.

1. Introduction

Over the past few years, photonic crystal fiber (PCF) technology has evolved from a strong research – oriented field to a commercial technology providing characteristics such as a wide single-mode wavelength range, a bend-loss edge at shorter wavelengths, a very large or small effective core area, group velocity, dispersion at visible and near field arrangement of air holes running along the length of the fiber. PCF is now finding applications in fiber-optic communications, fiber lasers, non-linear devices, high-power transmission, highly sensitive gas sensors and other areas.

The Research cover the last decades and generated a wide range of rigorous numerical algorithms for modeling PCF ,such as plane wave expansion(PWE),finite difference time domain, finite element methods. These versatile algorithms have been applied with success to study issues such as dispersion and losses for PC wave-guide.

The common term used in all these numerical methods is to calculate the effective refractive index of PCF because all linear and non-linear propagation properties of PCF can be analysed using effective refractive index.

We consider the type of PCF which consists of pure silica with a cladding and air holes of diameter (d) arranged in a triangular lattice with pitch (Λ).

The effective area is a quantity of great importance. It is originally introduced as a measure of non-linearities , a low effective area gives a high density of power needed for non-linear effect to be significant [1].The effective area can be related to the spot size and it is also important in the context of confinement loss [2], microbending loss[3], macrobending loss splicing loss[4]and numerical aperture[5].

The chromatic dispersion of the PCF s can be determined by:

$D = -\frac{\lambda}{c} \cdot \frac{d^2 n_{eff}}{d\lambda^2} + D_m \; , n_{eff} = \frac{\beta}{K_o} \; , \; k_o = \frac{2\pi}{\lambda}$

Where λ , c are wavelength and speed of light respectively in free space

n_{eef} the effective refractive index of the PCF core

D_m the material dispersion

However , the material dispersion can be calculated using sellmeier equation[6].

Their combination leads to signal degradation in optical fibers for telecommunications because of the varying delay in arrival time between different components of signal "smearont" the signal in time[7].

2. Theoretical Background [2,5,7]

Maxwell's equations predict the propagation of electromagnetic energy away from time varying source in the form of waves.They can be expressed by:

$\nabla X\vec{E} = -\frac{dB}{dt} = -jw\mu\vec{H}$ .... **(1)**

$\nabla X\vec{H} = J + \frac{d\vec{D}}{dt} = (\sigma + jw\epsilon)\vec{E}$ .... **(2)**

$\nabla . \vec{D} = \rho_v$ .... **(3)**

$\nabla . \vec{B} = 0$ .... **(4)**

By taking the curl of equation (1) and substitute in equation (2), we get

$\nabla^2 E = jw\mu(\sigma + jw\epsilon)\vec{E} = \beta^2\vec{E}$ ....

(5)

And by taking the curl of equation (2)and substitute in equation (1)

$\nabla^2 H = jw\mu(\sigma + jw\epsilon)\vec{H}$ .... **(6)**

Where β: is the propagation constant and can be expressed as

$\beta = \sqrt{jw\mu(\sigma + jw\epsilon)} = \alpha + j\gamma$ .... **(7)**

Where α the attenuation constant that defines the rate which the fields of the waves are attenuated as the wave propagates

γ is the phase constant that defines the phase rate at which the phase changes as the wave propagates

From the properties of the medium (μ, ϵ, σ)the attenuation and phase constants can be calculated

(i.e. $\beta^2 = jw\mu(\sigma + jw\epsilon) = (\alpha + j\gamma)^2 = \alpha^2 + 2j\alpha\gamma - \gamma^2$

Therefore

$$\left.\begin{aligned} &\alpha = w\ \left(\sqrt{\frac{\mu\epsilon}{2}\left(1 + \left(\frac{\sigma}{w\epsilon}\right)^2 - 1\right)}\right. \\ &\textbf{And} \\ &\gamma = w\ \left(\sqrt{\frac{w\mu}{2}\left(1 + \left(\frac{\sigma}{w\epsilon}\right)^2 + 1\right)}\right. \end{aligned}\right\} \quad \text{.....(8)}$$

W is the signal frequency in rad/sec

The propagation constant can express the effective refractive index and the wavelength dispersion as

$$\left.\begin{aligned} &D_w(\lambda) = -\frac{\lambda}{c}\cdot\frac{d^2 n_{eff}}{d\lambda^2} \\ &\textbf{And} \\ &n_{eff} = \frac{\beta(\lambda, n_m)}{K_o} \end{aligned}\right\} \quad \text{.........(9)}$$

Where n_m is the refractive index of any material, K_o is the wave number

2.1 Dispersion Calculation

PCF s are made of a periodic arrangement of fused silica and air holes running to the parallel axis of the fiber . An essential effect of the transverse periodic structure to alter the effective index for propagation along the direction of the fiber leading to intriguing new dispersive properties

We focus on the dispersion property of PCFs with triangular air silica structure where the central air hole is missing as a high index defect as shown in figure (1)

(d and Λ are air hole diameter and pitch respectively)

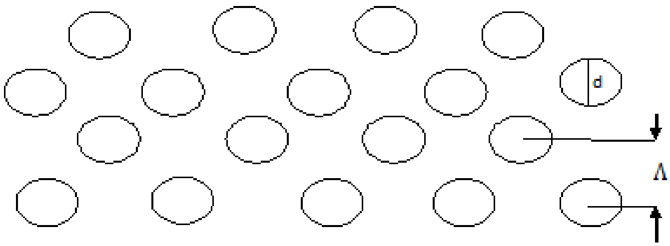


Figure (1) All Silica Photonic Crystal Fiber

In the PCF design , the air hole diameter to pitch ratio is a key parameter
The total dispersion loss of a PCF can be approximated [9] by the sum of waveguide dispersion and material dispersion as

$$D(\lambda) = D_w(\lambda) + \Gamma(\lambda) D_m(\lambda)$$

Where $\Gamma(\lambda)$ is the confinemental factor of silica (≈ 1 for most practical PCF's)
The material dispersion D_m is decided by the material that is used in the PCF. The material dispersion can be directly derived from the Sellmeier formula [10] which can be expressed by

$$n^2(\lambda) = 1 + \frac{\beta_1 \lambda^2}{\lambda^2 - c_1} + \frac{\beta_2 \lambda_2^2}{\lambda^2 - c_2} + \frac{\beta_3 \lambda_2^2}{\lambda^2 - c^2}$$

Where n is the refractive index . β_1 ,β_2 ,β_3 and c_1 , c_2 ,c_3 are experimentally determined sellmeier coefficients .Table (1) shows the coefficients values for the three different materials (borosilicate, silica, sapphire for extra ordinary wave)which will be considered in our research paper.

Table (1)
Sellmeier Coefficients for Three Different Materials

Material	Coefficient					
	β_1	β_2	β_3	C_1	C_2	C_3
Borosilicate	1.03961212	0.231792344	1.01046945	6.00069867	2.00179144	$1.03560653*10^{2}$
Fused Silica	0.69616300	0.407942600	0.897479400	$4.67914826*10^{-3}$	$1.35120631*10^{-2}$	97.9340025
Sapphire for extra ordinary wave	1.5039759	0.55069141	6.5927379	$5.48041129*10^{-3}$	$1.47994281*10^{-2}$	$4.0289514*10^{2}$

Figure (2) shows the relationship between $\eta_{eff}(\lambda)$ with wavelength for the three different materials which shows that the fused silica gives better refractive index for different wavelengths.The waveguide dispersion of PCF is related to the transversal geometrical structure which contributes all the design freedom.

2.2 Effective Area

The effective area is a quality of great importance. It was considered as a measure of non-linearities . A low effective area gives a high density of power needed for non linear effects to be significant [1].However, the effective area can be related to the spot area (w) through $A_{eff} = \pi w^2$ and thus it is also important in the context of confinement loss , microbending loss , splicing loss ,and numerical aperture .

2.3 Non Linearity Coefficient

The non-linearity coefficient is given by [1]

$$\Psi = \frac{n_2 \omega}{cA\_eff} = \frac{2\pi n_2}{\lambda A_{eff}} \qquad \text{.........(10)}$$

Where n_2 is the non-linear index coefficient in the non linear part of the refractive index (that is mean $\delta_n = n_2 \, |E|^2$). Thus, knowledge of A_{eff} is an important starting point in understanding of non-linear phenomena in PCFs.

2.4 Numerical Aperture (NA)

The numerical aperture (NA) relates to the effective area. For a Gaussian field of width z , one has the standard approximate expression

tan$\theta = \frac{\lambda}{\pi z}$ **………..(11)**

for half divergence angle θ of light radiated from the end facet of the fiber [8]. The corresponding numerical aperture can be expressed as

NA=sin$\theta \cong \left(1 + \pi A_{eff}\right)^{-\frac{1}{2}}$ **………..(12)**

2.4 Macro- Bending Loss

For the estimation of the macro-bending loss coefficient the sakai-Kimra formula [11] can be applied to PCFs. This involves the evaluation of the ratio of $\frac{A_e^2}{P}$ where A_e is the amplitude coefficient of the field in the cladding and P is the power carried by the fundamental mode.

The Gassian approximation gives:

$\frac{A_e^2}{P} = \frac{1}{A_{eff}}$ **……..…(13)**

And this was used to calculate the marco bending loss in the PCFs based on fully eigenmodes of maxwell equations.

2.5 Splicing Loss

Splicing loss can be quantified in terms of the concept of effective areas. The splicing of two aligned fibers with effective areas $A_{eff1} and\ A_{eff2}$ will have a power transmission coefficient T< 1 is given by

$T \approx \frac{4A_{eff1}A_{eff2}}{\left(A_{eff1}+A_{eff2}\right)^2}$ **………..(14)**

Due to the mismatch of effective areas.

2.6 The Bit Error Rate (BER)

The bit error rate (BER) can be expressed by[7]

$BER = \frac{1}{4D\,(\lambda)*L*\Delta\lambda}$ **……….(15)**

Where L is the fiber length, $\Delta\lambda$ is the spectral width of the light source

3- Results and Conclusions:

The results show the propagation characteristics for different materials (silica, borosilicate, and sapphire) was carried out using MATLAB software program . Figure (2) shows the relationship between the refractive index and wavelengths for the silica, borosilicate and sapphire (extraordinary wave). It can be noted that the fused silica and borosilicate graphs are near to each other because the silica enter in the construction in both materials.

Figure (3) shows the effect of (A_{eff} /Pitch) ratio and wavelength for different pitch values. The micro-bending loss and diameter was shown in figure (4).However the effective area play an important role in the behavior of PCF because it determines the numerical aperture (NA) and its relation to wavelength as shown in figure (5) which shows the numerical aperture for different effective areas.

The most important factor is the fiber dispersion for the three different materials which is evaluated from Sellimer equation for η_{eff} and equation (9) which are shown in figures (6),(7),(8) respectively .It can be seen from figure (7) that zero dispersion occur at 1.28 μm for silica ,at 1.19 μm for borosilicate, and 0.83 μm for sapphire (for extraordinary wave). It can be concluded that when there is no silica in the construction of the PCF it will lead low zero dispersion wavelength. Also when the construction contains silica gives ,approximately, characteristics near to each other. As a Suggestion to modify this work, on can study other materials such as florid or phosphate .in the construction of photonic crystal fibers. Also the bit error rate variation with dispersion for different fiber lengths (for borosilicate , fsed silica,sapphire) are shown in figures (9),(10),(11) respectively. Figure (12)show the three dimension graph between the three variables (fiber length , dispersion and bit error rate)for the different materials as shown in figures(12),(13),(14) respectively .

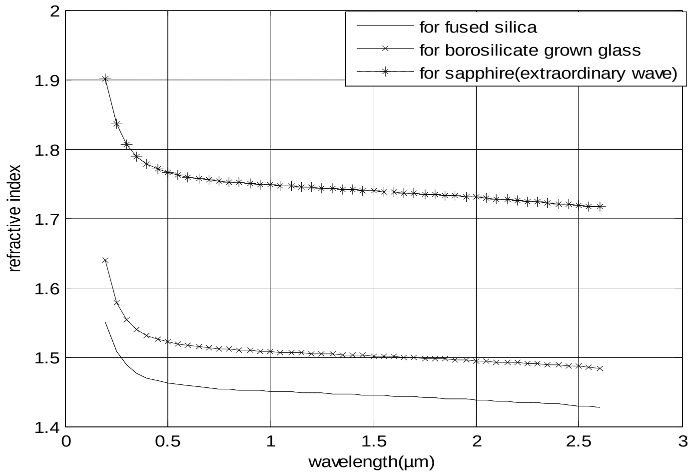
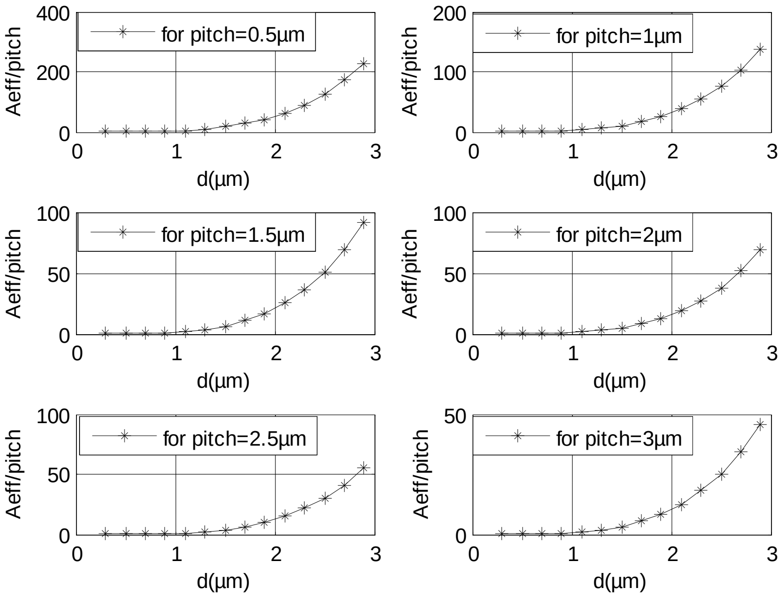


Figure (2) Refractive Index & Wavelength for Different Materials.



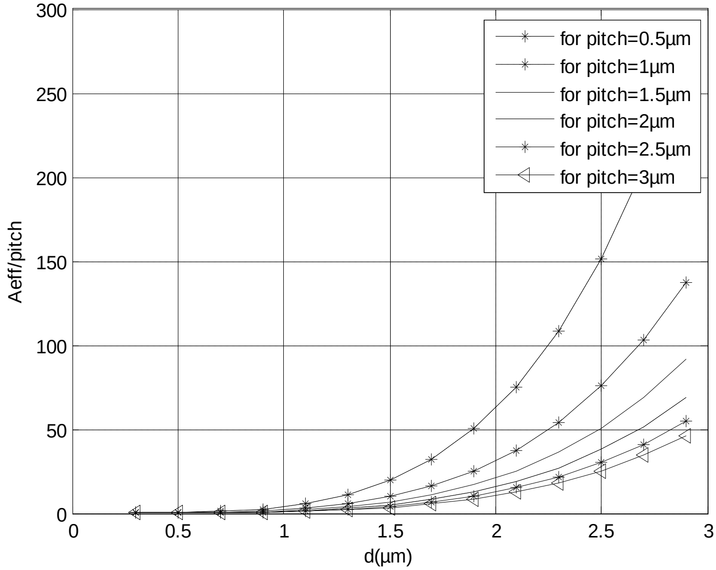


Figure (3) The Variation of Effective Area and Diameter for Different Pitches.

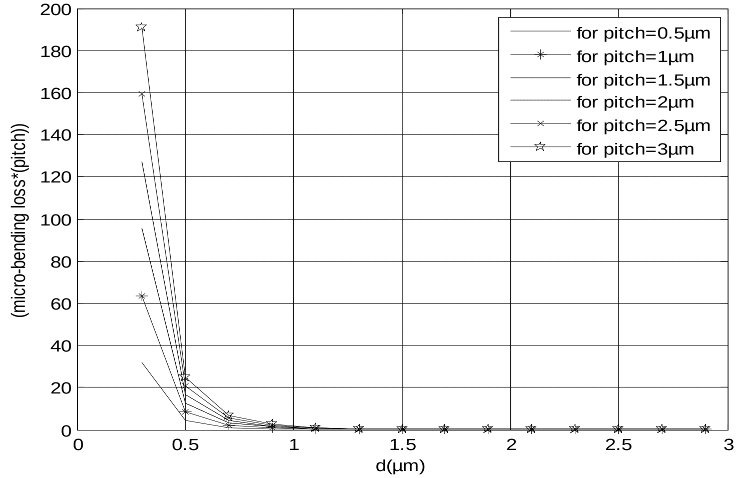


Figure (4) Microbending Loss and Diameter for Different Pitches.

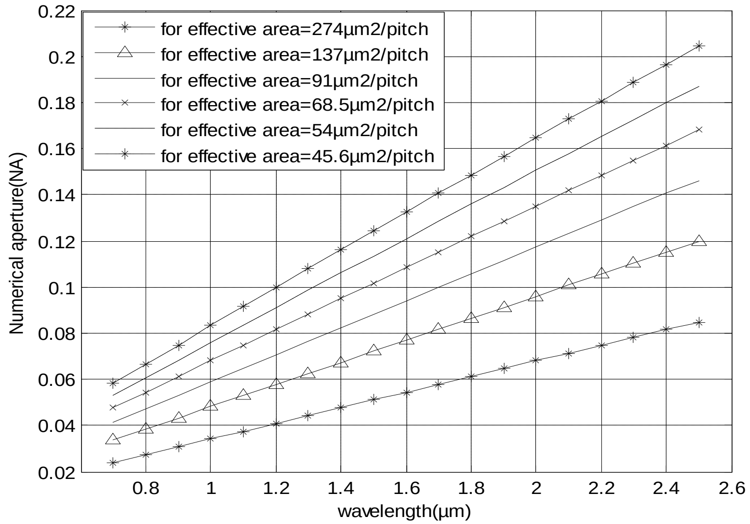


Figure (5) Numerical Aperture and Wavelength for Different Effective Areas.

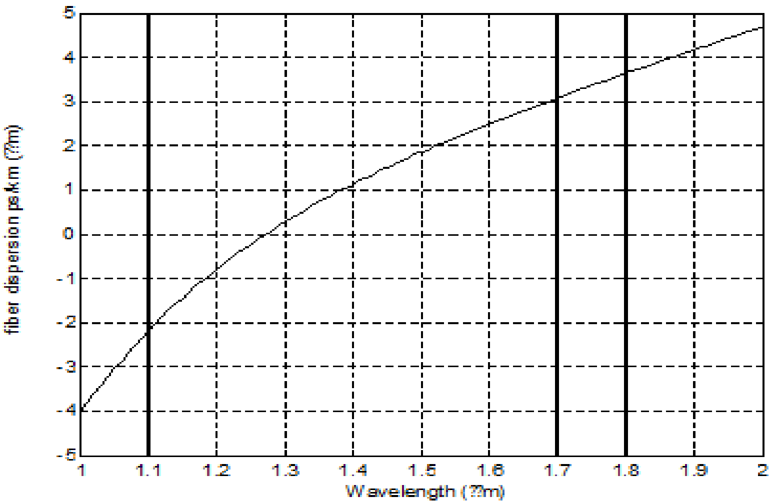


Figure (6) The Relation Between Dispersion &Wavelength for Fused Silica.

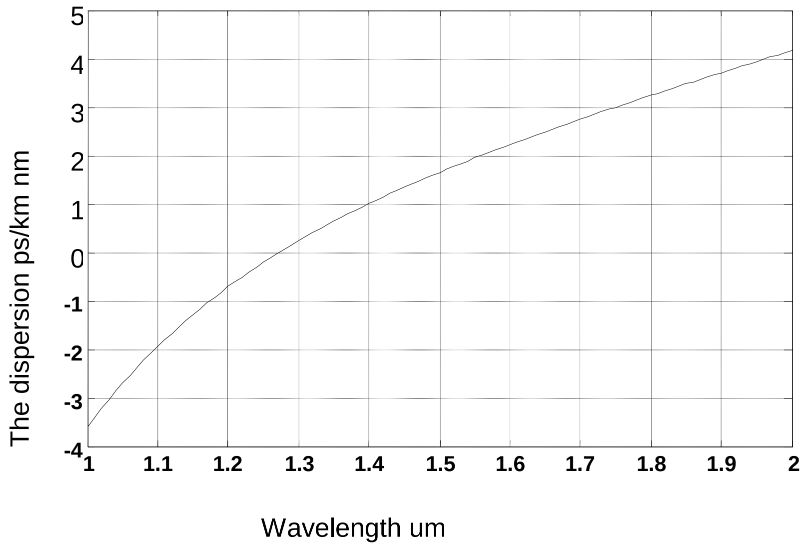


Figure (7) The Relation between Dispersion and Wavelength for Borosilicate.

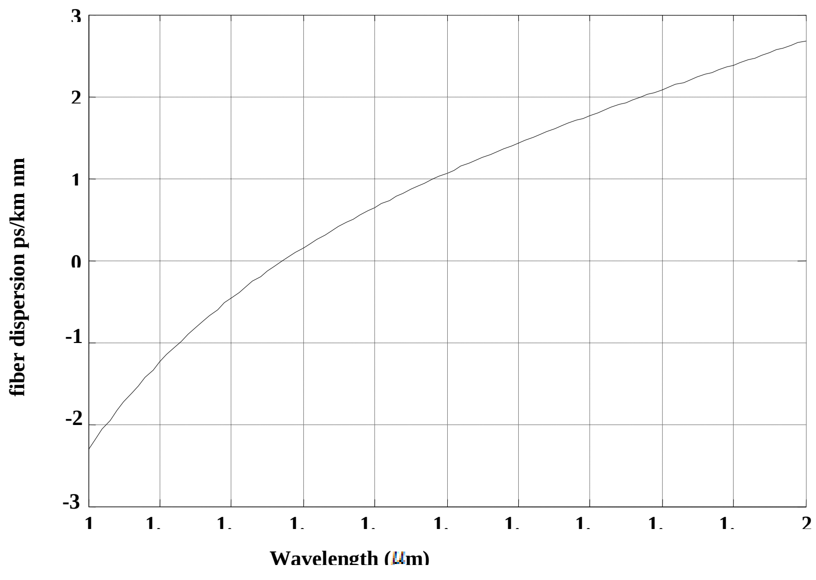


Figure (8) The Relation between Dispersion and Wavelength for Sapphire.

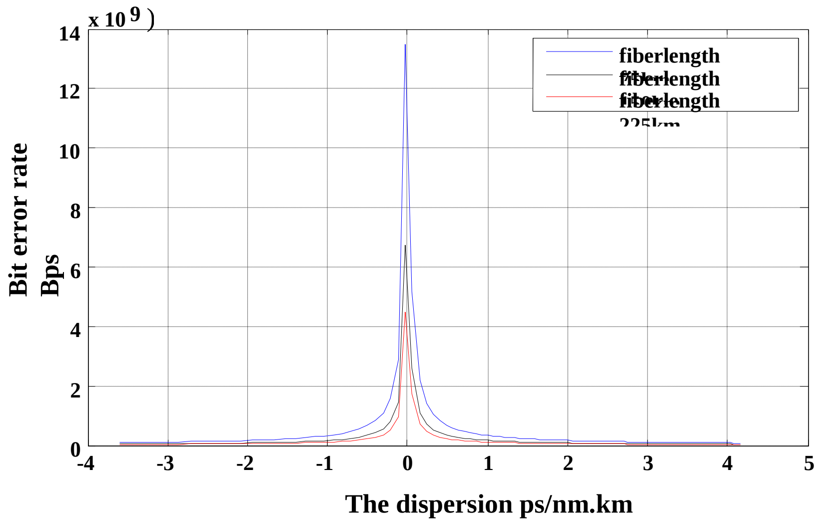


Figure (9) The Relation between Bit Error Rate & Dispersion for Borosilicate.

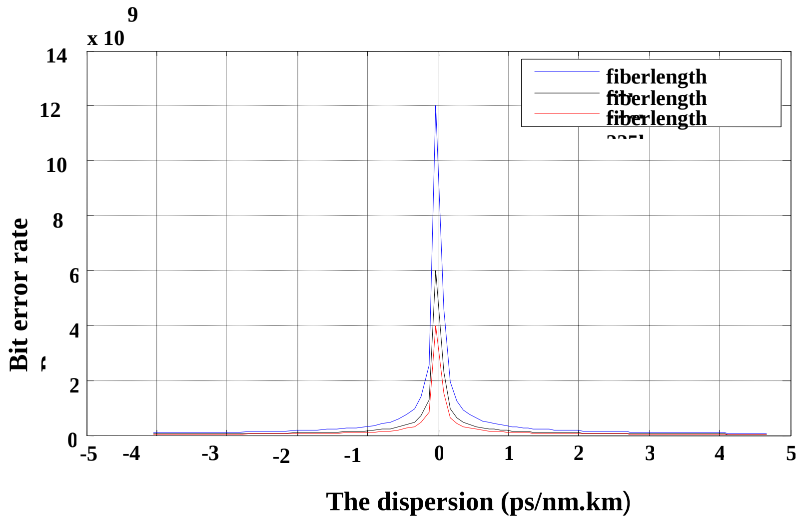


Figure (10) The Relation between Bit Error Rate & Dispersion for Fused Silica

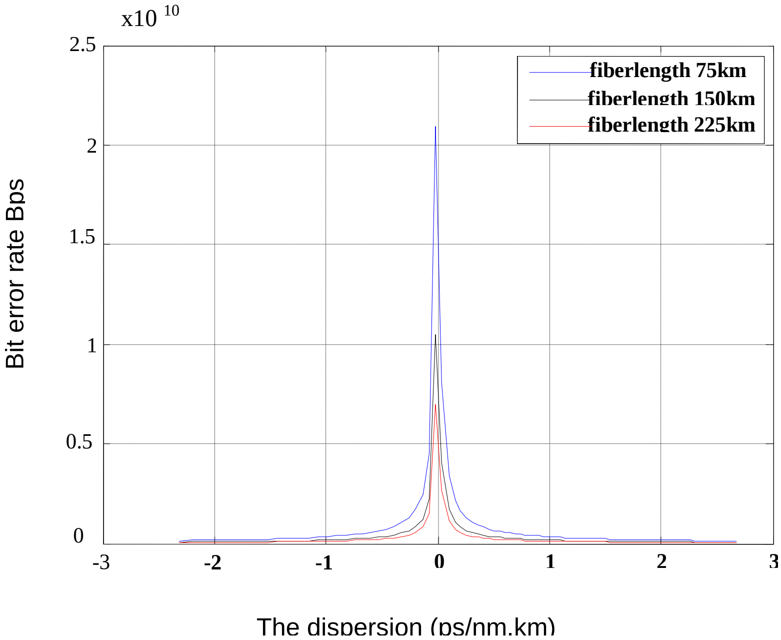


Figure (11) The Relation between Bit Error Rate & Dispersion for Sapphire.

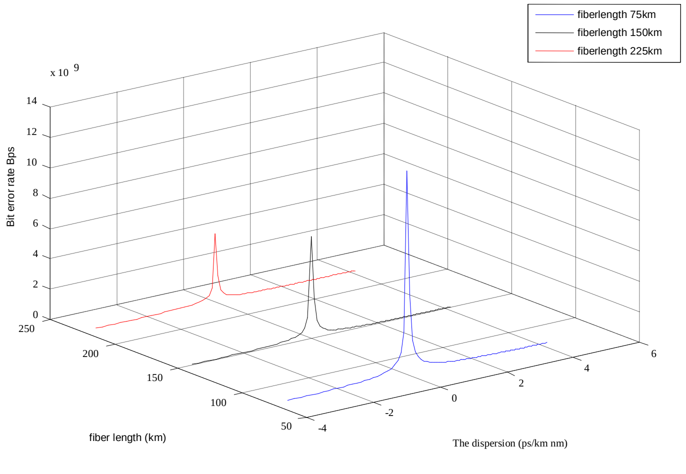


Figure (12) The Relation between Bit Error Rate & Dispersion for Borosilicate in 3-D

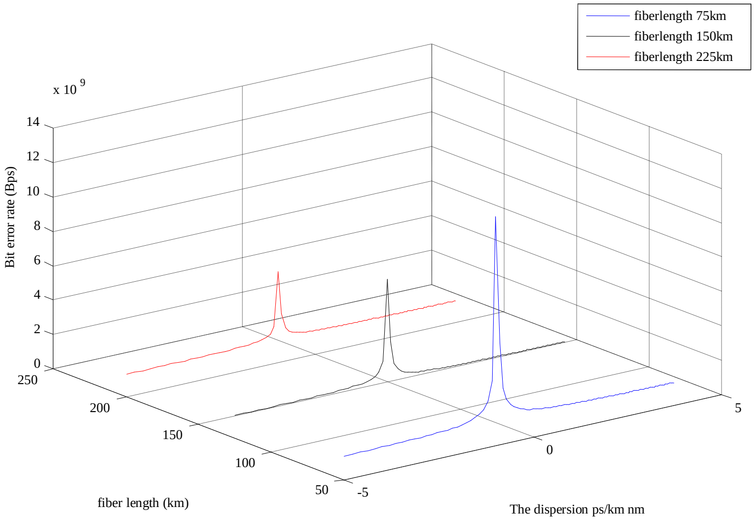


Figure (13) The Relation between Bit Error Rate & Dispersion for Fused Silica in 3-D.

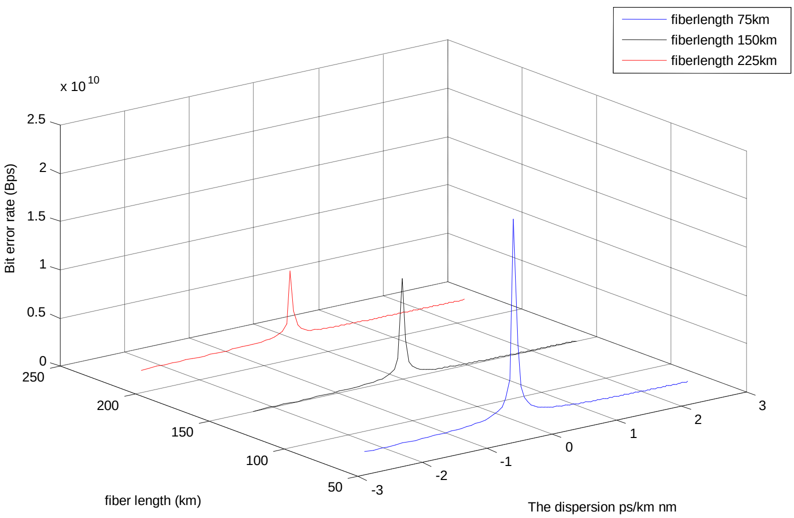


Figure (14) The Relation between Bit Error Rate & Dispersion for Sapphire in 3-D.

References

1. G.P.Agrawal , "Non-Linear Fiber Optics", Academic Press .San Diego,2001.
2. T.P.White,R.C.Mcphedran and M.J.Steel ,"Confinement Losses in Microstructured Optical Fibers,"Opt.lett.26,pp1660-1662,2001.
3. K.Peterman , "Fundamental Mode Microbending Loss in Graded Index and w fibers",Opt.Quantum Electron g,pp 167-175,1977.
4. D.Marcuse,"Loss Analysis of Single-Mode Fiber Splices" , Bell System.Tech.J.56,pp 703.1977
5. N.A. Mortenson, J. Broeng ,"Numerical Aperture of single – Mode Photonic Crystal Fibers ",http//arxiv .org/abs/physics/ 0202073
6. H.Tanzer,"Course Materials for EE167",California State University ,Sacramento,2002
7. Fayroz.A.S and Zahraa.H.M," Studying the Effect of Fiber Length on Bit Error Rate and Chromatic Dispersion for Different Materials of Fiber " Conference of University of Technology 2011
8. A.K.Ghatak and K.Thygarajan"Introduction to fiber optics" , Cambridge University Press,Cambridge,1998
9. S.S Mishra et.al ," Full-Vector Finite Element Method ",International Jornal of Engineering Science and Technology,vol.2(9),pp4520-4525,2010
10. CHI.Hao and Shenlin-Fang,"Design of Photonic Crystal Fibers with Anomalus Dispersion " , Optoelectronics Letters,Vol.2 , No.1 , Jan 2006
11. J.Sakai and T.Kimura ,"Bending Loss of Propagation Modes in Arbitrary-Index Profile Optical Fibers", Appl.optics 17,pp 1499-1506,1978.