DISPERSION IN DIFFERENT SINGLE MODE OPTICAL FIBER MATERIALS AT DIFFERENT TEMPERATURES

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ABSTRACT

Optical fiber is a physical medium for optical communication system. It is offer high capacity, very wide band and high data rate. There are two main problems in this physical medium that are dispersion and power loss. The significant restriction in optical fiber system is the dispersion. The dispersion affects the performance of the system and bit error rate. There are two types of dispersion Intermodal and Intramodal. Intermodal occurs in multimode fiber only. Intramodal occur in all type of fiber. The total dispersion in single mode fiber is the sum of material and waveguide dispersion.

In this paper the effect of temperature variations on fiber dispersion is investigated. The temperature variant is a vital factor which plays an effective role on activity of the communication system especially in environmental of Iraq and other Middle East country.

The Sellemeier Coefficients equation is derived for fixed and discrete temperature values. A derivation for this equation to fit continues variation of temperature is done in this paper for optical fiber. Depend on formula of dispersion, Sellemeier Coefficients equation and relation of refractive index at any temperature derivation of propagation constant with normalized frequency for waveguide dispersion is done.

The Temperature effect on total dispersion is modeled for most popular material used in fabrication optical fiber, silica (SiO_2), aluminosilicate (Al_2SiO_5) and vycor glass (96.4%SiO_2 ,3% B_2O_3, 0.5%Al_2O_3, 0.1% Miscellaneous Traces). Both single mode step index and graded index fibers are considered. The results investigated by using MATLAB and Maple programs.

The refractive index temperature dependence for all three fiber types are fitted in to straight line. The material dispersion and zero material dispersion "λ_o" wavelengths have approximately linear temperature dependence for all three fiber types. For wide range of increasing temperature [-100°C to 100°C] SiO_2 and vycor glass fiber has less effect than for Aluminosilicate. The temperature variation shows the step index fiber batter than graded index fiber. The SiO_2 is the best one of three fiber types.

التشتت في مختلف مواد الالياف البصرية ذات النمط الواحد عند درجت حرارة مختلفة

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الكلية التقنية / النجف

الخلاصة:

الألياف الضوئية هي واحدة من الاوساط المادية المستخدمة للاتصالات، و التي مع زيادة معدل نقل البيانات نتيجة لمتطلبات التطور الحاصل في مجال الاتصالات، تعاني من تدهور الاشارة بسبب التشتت، و الذي اخذ بعين الاعتبار في هذا العمل . ولقد تم أختيار

دراسة تأثير تغيرات درجة الحرارة على الألياف الضوئية ، وما ينجم عن ذلك من تشتت وتباين للاشارة الضوئية المنقولة عبر الليف الضوئي ، حيث ان حساباتنا اعتمدت على أساس الصيغة الرئيسية للتشتت واشتقاق علاقة التشتت المادي مع الطول الموجي واشتقاق علاقة ثابت الانكسار مع تردد التطبيع لتشتت الدليل الموجي .

ان القيم الاساسية لمتغيرات معامل الانكسار وعلاقة ايجاد هذه المتغيرات عند درجات حرارة مختلفة مع معطيات الليف الضوئي المعتمد في الدراسة موجودة في الملحق. التشتت الكلي هو حاصل جمع التشتت المادي وتشتت الدليل الموجي . تم اختار درجة الحرارة كعامل مؤثر على انتقال الاشارة خلال الليف الضوئي وذلك لئن بلدنا والكثير من بلدان الشرق الأوسط تعاني من درجات الحرارة عالية لفترة طويلة من السنة ، مما يعطي عاملا هاما في الاتصالات باستخدام الألياف الضوئية كوسيلة المادية وعلى غرار تأثير درجة الحرارة على تشتت (المادي والدليل الموجي) والتحقيق فيه بشأن المواد الأكثر استخدما في تصنيع الألياف الضوئية ،مثل السليكا (SiO2) ، ألومينوسيليكات (Al2SiO5) والزجاج vycor. النتائج التي تم الحصول عليها من البرمجة باستخدام برنامج الماتلاب والبرامج المايل . حيث ظهر ان اعتماد معامل الانكسار على درجة الحرارة لجميع أنواع مواد الألياف الثلاثة انطبق على شكل خط مستقيم، التشتت المادي والطول الموجي الصفري "λo"ظهر تقريبا ذو علاقة خطية مع درجة الحرارة لجميع أنواع الألياف الثلاثة . حيث لمدى واسع من تغير درجة الحرارة [-١٠٠ الى ١٠٠ مئوية] ظهر أن الألياف الضوئية الوصنوعة من (SiO_2 و Vycor) تأثرت بشكل أقل من الالياف المصنعة من الألومينوسيليكات (Al2SiO5). و كما ظهر أن التباين الكبير في درجة الحرارة الليف ذو مؤشر الخطوة أفضل من الليف ذو مؤشر المتدرج، .وأن الليف المصنوع من [SiO2]هو أفضل واحد من أنواع الألياف الثلاثة.

KEYWORDS

Temperature effect on dispersion, total dispersion, zero dispersion wavelengths, chromatic dispersion, optical fiber, Sellmeier coefficients, intermodal dispersion, interamodal dispersion, Sellemeier Coefficients, refractive index.

INTRODUCION

Optical fiber is more preferred medium for high capacity communication systems.[Michael 2002] Due to the fast grow up of communication system. Due to low insertion loss, high flexibility in spectral design and high data rate transmission many intensive studies done for applications in optical communications.

Dispersion is the phenomenon in which the phase velocity of a wave depends on its frequency, or when the group velocity depends on the frequency. Dispersion of the transmitted optical signal causes distortion (broadening) of transmitted signal (pulses) along optical fibers.

There are two types of dispersion intermodal and interamodal. The intermodal dispersion results from the propagation delay differences between modes within a multimode optical fiber. Intramodal or chromatic dispersion occur in all fiber types and results from the finite spectral line width of the optical source. Chromatic dispersion it is wavelength-dependent nature. Single mode fiber has only intramodal mechanisms. The propagation delay differences between the different spectral components of the transmitted signal may be caused by:

- The dispersive properties of the fiber material (material dispersion; $\mathbf{D_m}$)
- The guidance effects within the fiber structure (waveguide dispersion $\mathbf{D_w}$). .[Rostami 2007][Jeong2009][Michael2002]

Generally two sources of Intramodal (or chromatic) dispersion: **material dispersion** and **waveguide dispersion**.

- Material dispersion comes from a frequency dependent on waveguide material. Waveguide dispersion comes from a frequency dependent on waveguide geometric. It is independent on materials from which it is constructed. .[**Rostami 2007**][**Jeong2009**][**Tzong1995**]

In 1982, most applications started converting from multimode to step index single-mode fibers operating at 1300 nm. Today, a few applications are being planned for use with multimode fibers and the systems operating wavelength has to move to 1550 nm. [**DeBell1989**]

Much research deal with dispersion, experimentally measured the refractive index and dependent on temperature for calcium telluride by using liquid helium as a coolant. [**DeBell1989**] modeled the chromatic dispersion in single mode fiber by using material dielectric function for material dispersion and dependence of both propagation constant and normalized frequency on wavelength. [**Moustafa1991**] proposed a novel numerical approach for calculation of dispersion coefficients of dual mode elliptical core fiber with arbitrary refractive index profile**.** [**Kato2000**] measured refractive indices of several fused silica and calcium fluoride. [**Gupta1998**] experimentally study the change of chromatic dispersion of optical fiber with temperature by demonstrated the empirical model of last reaches. [**Hamp2002**]. investigates imperially the impact of dispersion and dispersion slop on transmission performance including the effect of temperature variation of fiber optic.[**Vorbeck 2003**] determine numerically the dispersion in optical fiber modeled investigated by Vorbeck.[**Chich-Chenge Chou 2003**] derive chromatic dispersion slop variation with temperature as a function of zero dispersion wavelength and chromatic dispersion slop at zero dispersion wavelength.[**Andre 2004**] experimentally demonstrated a novel chromatic dispersion monitoring techniques using frequency modulated and amplitude modulated pilot tones.[**Pual2006**] use analytical method to compensated the chromatic dispersion in optical fiber by management of optimum group velocity dispersion.[**Rostami 2007**] presents a modification of interferometric method for measurement of optical fiber chromatic dispersion using Michelson interferometer.[**Peterka 2008**] modeled a new method to control free spectral range of long period fiber grating.[**Jeong2009**] experimentally measure the temperature and pressure verses wavelength in different elliptical core fiber.[**Urbanczyk 2010**]

Mathematical Model

In the following, the equations of Sellmeier coefficients for the core refractive index are described for three kinds of fiber glasses: SiO_2, aluminosilicate (Al_2SiO_5), and vycor glasses. The temperature dependence of these coefficients is determined. Material and waveguide dispersion parameters are studied leading to the zero dispersion wavelengths, λ_o, of the total dispersion parameter. The temperature effect on λ_o is investigated. The result obtained for λ_o under different temperature environments.

• Sellemeier Coefficients

The core refractive index, n, as a function of the operating wavelength, λ, is defined through the Sellmeier equation which has the form: [.Li1989], [Paul 2006][**Gupta1989**]

$$n^2 = A + \frac{B\lambda^2}{\lambda^2 - C} + \frac{D\lambda^2}{\lambda^2 - E} \tag{1}$$

Where:

A, B, C, D and E: are Sellmeier coefficients
λ : is the wavelength of optical signal (nm)
n: is the refractive index of optical fiber core

The first and second terms represent, respectively, the contribution to refractive index due to higher energy and lower energy gaps of electronic absorption, while the last term accounts for the decrease in refractive index due to lattice absorption. The values of the Sellmeier coefficients are listed (table (1)) in appendix and the relation of finding these coefficients at any temperature are given by: **.[** Matsuoka1989]

$$n_T = n_R + (T - R)(\frac{dn}{dT}) \tag{2}$$

Where:

T: is the temperature in degree centigrade,
R: is the room temperature,
n_T and n_R are the refractive indexes at T and room temperature, respectively

- **Material Dispersion**

Total dispersion of a fiber is conventionally expressed as temporal broadening per unit length of the fiber, per unit width of the light source used. This total dispersion caused by material and structural properties of the fiber is in fact totally coupled. However, the total dispersion parameter, DT, is expressed As[Chou2003][Jeong2009][. Bass 2002]

$$D_T = M_D + W_D \tag{3}$$

Where:
M_D: material dispersion (ps / nm.km)
W_D: waveguide dispersion (ps / nm.km)

Material dispersion manifests through the wavelength dependence of the refractive index, n(λ), by the following relation: [Chou2003][Jeong2009][Hamp 2002][Paul and Park2006]

$$M_D(\lambda) = -\frac{\lambda}{c} * \frac{d^2 n}{d\lambda^2} \tag{4}$$

Where:
M_D: is the material dispersion (ps / nm.km)
λ : is the wavelength of optical signal (nm)
c: is the free space speed of light.

- **Waveguide Dispersion**

The waveguide dispersion in optical fibers is given by: [**Jeong2009**][**Hamp 2002**][**Paul and Park2006**]

$$W_D = -\frac{V^2}{2\pi c} \frac{d^2 \beta}{dV^2} \tag{5}$$

Where:
W_D: Waveguide dispersion (ps / nm.km)
V: is the normalized frequency
β: is the propagation constant.
c: is the free space speed of light.

Now the normalized frequency “V “given by: [12]

$$V = \frac{2\pi}{\lambda}.a.(n_n^2 - n_b^2)^{\frac{1}{2}} \tag{6}$$

Where:
n_n: core refractive index,
n_b: cladding refractive index,

a: is the core radius (µm)
λ : is the wavelength of optical signal (nm)

For step-index fibers, the propagation constant, β, is given by: [.Rostami2007][Paul and Park2006]

$$\beta = \left[\frac{V^2}{2\Delta a^2} - \frac{\pi^2}{a^2} \right]^{0.5} \tag{7}$$

Where:

β:is the propagation constant
a: is the core radius (µm),
Δ: is the relative refractive index difference between core and cladding
$\Delta = n_n - n_b$
V: is the normalized frequency

While, for graded-index fibers, β is given by: [**Rostami2007**][**Paul and Park2006**]

$$\beta = \left[\frac{V^2}{2\Delta a^2} - \frac{6V}{a^2} \right]^{0.5} \tag{8}$$

Results and Discussion

The temperature dependent of refractive index (using equation (1)) simulated for the SiO_2, aluminosilicate (Al_2SiO_5), and vycor glasses which are used in fabrication of optical fiber, the results shown in **Figure (1)**. The refractive indices are calculated at 850nm wavelength and at temperature ranged from 20°C to 100°C , the Sellmeier coefficients that used in simulation listed in appendix and relation of founding Sellmeier coefficients at any temperature written in appendix. The refractive index results are found to fit nicely into straight lines for the three material simulated. Material dispersion is calculated for the three optical fiber glass types (SiO_2, aluminosilicate (Al_2SiO_5), and vycor glasses) at 26°C using the temperature dependence of Sellmeier coefficients, as shown in **Figure (2)**. The zero material dispersion wavelengths are 1.2734, 1.3929 and 1.2682 µm for SiO_2, aluminosilicate (Al_2SiO_5) and vycor glass, respectively, and the dispersion characteristics are approximately linear for the whole spectral region.

For a wide range of temperature (-100°C to 100°C), the material dispersion and the zero material dispersion wavelength, λ_o, has been calculated for the three optical fiber glass types. The obtained results are shown in **Figure (3)**, **Figure (5)** and **Figure (6)** for the SiO_2, aluminosilicate and vycor glass, respectively. The material dispersion linearly related to temperature, and increases with increase the wavelength for all three tested optical fiber material.

The zero material dispersion wavelength (λ_o) as a function of temperature (T °C) is displayed in **Figure (4)** for SiO2. Interestingly, the temperature dependence is linear and $d\lambda_o/dT=0.0242$ nm/°C for SiO2. This value has a fair agreement with the published experimental values 0.029±0.004 nm/°C and 0.031± 0.004nm/°C for two dispersion shifted fibers within the experimental accuracy. The values of $d\lambda_o/dT$ are found to be 0.0223 nm/°C for vycor glasses. While the corresponding values of $d\lambda_o/dT$ are found to be 0.03 nm/°C for aluminosilicate (Al_2SiO_5).

Using the temperature dependent Sellmeier coefficients and the corresponding values of the V-number, Waveguide Dispersion and Total Dispersion for Single mode step index fiber calculated at a core radius, a = 2 µm , relative refractive index difference between core and cladding $\Delta = 0.005$, and temperature 26 ^{o}C.

The waveguide dispersion results of optical fiber (SiO_2 material) are shown in **Figure (7)** and material, waveguide and total dispersion shown in **Figure (8)**. The waveguide dispersion results of optical fiber (aluminosilicate (Al_2SiO_5)) are shown in **Figure (9)** and material, waveguide and total dispersion shown in **Figure (10)**. The waveguide dispersion results of optical fiber (vycor glass) are shown in **Figure (11)** and material, waveguide and total dispersion shown in **Figure (12)**. The waveguide dispersion results have line curved and shift of total dispersion from material dispersion.

For SiO_2 fiber material dispersion has (λ_o = 1.2723 µm) and total dispersion has (λ_o = 1.28 µm), aluminosilicate fiber, material dispersion has (λ_o = 1.3925 µm) and total dispersion (λ_o = 1.397 µm), vycor glass fiber, material dispersion has (λ_o =1.2675 µm) and total dispersion has (λ_o = 1.275 µm).

The waveguide dispersion results has line curved and slight shift of total dispersion from material dispersion, since the value of waveguide dispersion be smaller than the material dispersion the aluminosilicate (Al_2SiO_5) fiber give little different results from that given by SiO_2 fiber and vycor glass fiber.

Waveguide Dispersion and Total Dispersion for Single mode graded index fiber calculated at a core radius, a = 2 µm, relative refractive index difference between core and cladding $\Delta = 0.0085$, and temperature 26 ^{o}C.

The waveguide dispersion results of optical fiber (SiO_2 material) are shown in **Figure (13)** and material, waveguide and total dispersion shown in **Figure (14)**. The waveguide dispersion results of optical fiber (aluminosilicate (Al_2SiO_5)) are shown in **Figure (15)** and material, waveguide and total dispersion shown in **Figure (16)**. The waveguide dispersion results of optical fiber (vycor glass) are shown in **Figure (17)** and material, waveguide and total dispersion shown in **Figure (18)**. The waveguide dispersion results have line curved and shift of total dispersion from material dispersion.

For SiO_2 fiber material dispersion has (λ_o = 1.2723 µm) and total dispersion has (λ_o = 1.285 µm), aluminosilicate fiber, material dispersion has (λ_o = 1.3925 µm) and total dispersion (λ_o = 1.405 µm), vycor glass fiber, material dispersion has (λ_o =1.2675 µm) and total dispersion has (λ_o = 1.28 µm)

The first and second derivative of refractive index is as follow:

$$\frac{dn}{d\lambda}=\frac{0.5\left[-\frac{2B\lambda^3}{(\lambda^2-C)^2}-\frac{2D\lambda^3}{(\lambda^2-E)}\right]}{\left[A+\frac{B\lambda^2}{\lambda^2-C}+\frac{D\lambda^2}{\lambda^2-E}\right]^{0.5}}$$

$$\frac{d^2n}{d\lambda^2}=-\frac{0.25\left[-\frac{2B\lambda^3}{(\lambda^2-C)^2}-\frac{2D\lambda^3}{(\lambda^2-E)}\right]^2}{\left[A+\frac{B\lambda^2}{\lambda^2-C}+\frac{D\lambda^2}{\lambda^2-E}\right]^{1.5}}+\frac{0.5\left[-\frac{8B\lambda^4}{(\lambda^2-C)^3}-\frac{2B\lambda^2}{(\lambda^2-C)^2}+\frac{8D\lambda^4}{(\lambda^2-E)^3}-\frac{8D\lambda^2}{(\lambda^2-E)^2}\right]}{\left[A+\frac{B\lambda^2}{\lambda^2-C}+\frac{D\lambda^2}{\lambda^2-E}\right]^{0.5}}$$

The first and second derivative of step index propagation constant equation done is as follow:

$$\frac{d\beta}{dV}=\frac{0.5V}{\Delta a^{2}\left(\frac{0.5V^{2}}{M a^{2}}-\frac{\pi^{2}}{a^{2}}\right)^{0.5}}$$

$$\frac{d^{2}\beta}{dV^{2}}=-\frac{0.25V^{2}}{\Delta^{2}a^{2}\left(\frac{0.5V^{2}}{M a^{2}}-\frac{\pi^{2}}{a^{2}}\right)^{1.5}}+\frac{0.5}{\Delta a^{2}\left(\frac{0.5V^{2}}{M a^{2}}-\frac{\pi^{2}}{a^{2}}\right)^{0.5}}$$

The first and second derivative of graded index propagation constant equation is as follow:

$$\frac{d\beta}{aV}=\frac{0.5\left(\frac{V}{\Delta a^{2}}-\frac{6}{a^{2}}\right)}{\left(\frac{0.5V^{2}}{\Delta a^{2}}-\frac{6V}{a^{2}}\right)^{0.5}}$$

$$\frac{d^{2}\beta}{aV^{2}}=-\frac{0.25\left(\frac{V}{\Delta a^{2}}-\frac{6}{a^{2}}\right)^{2}}{\left(\frac{0.5V^{2}}{\Delta a^{2}}-\frac{6V}{a^{2}}\right)^{1.5}}+\frac{0.5}{\Delta a^{2}\left(\frac{0.5V^{2}}{\Delta a^{2}}-\frac{6V}{a^{2}}\right)^{0.5}}$$

Conclusion:

The refractive index temperature dependence for all three fiber types are fitted in to straight line. The material dispersion and zero material dispersion " λ_o" wavelengths has approximately linear temperature dependence for all three fiber types, SiO_2 and vycor fibers give nearly similar results while Aluminosilicate give little difference one. For wide range of increasing temperature [-100°C to 100°C] SiO_2 and vycor glass fiber has less effect than for Aluminosilicate, since the zero material dispersion shifted by 0.01 for SiO_2 and vycor fiber while 0.025 for Aluminosilicate fiber.

The linearly shift the total dispersion zero wavelength. For large variation of temperature range step index fiber batter than graded index fiber since for step index "λ_o" affected by fiber core radius and little affected by the relative refractive index difference between core and cladding " Δ" while for graded index fiber "λ_o" affected by fiber core radius and relative refractive index difference between core and cladding " Δ". The SiO_2 is the best one of three fiber types. The aluminosilicate (Al_2SiO_5) fiber give different results from that given by SiO_2 fiber and vycor glass fiber.

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Table (1)

Material	Temp. (˚C)	Sellmeier coefficients				
		A	B	C	D	E
SiO_2	20	1.310723	0.7935797	$1.0959659*10^{-2}$	0.9237144	100
	26	1.3121622	0.7925205	$1.0996732*10^{-2}$	0.9116877	100
	45.2	1.3066410	0.7994875	$1.091946*10^{-2}$	0.9598566	100
	471	1.3148367	0.8034391	$1.1248041*10^{-2}$	0.9119589	100
Alumino-silicate	28	1.4136733	0.8503994	$1.3249011*10^{-2}$	0.9044591	100
	526	1.5205253	0.8556256	$1.520523*10^{-2}$	0.9092824	100
Vycor glass	28	1.2754213	0.8271916	$1.0653107*10^{-2}$	0.9384236	100
	526	1.3488048	0.7695233	$1.1884981*10^{-2}$	0.946169	100

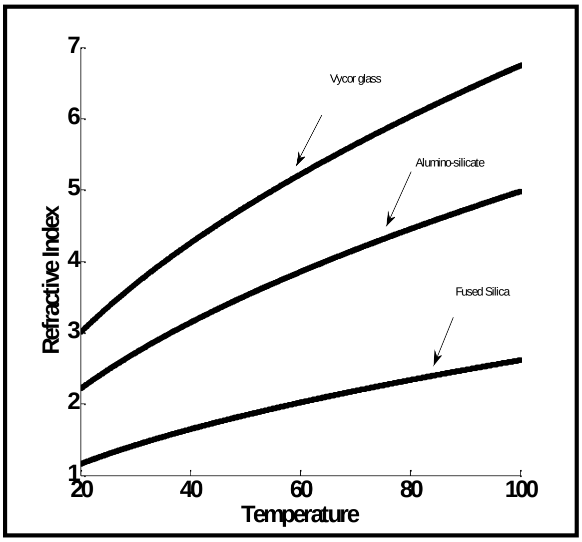

Figure (1) Refractive index for three types of fiber material

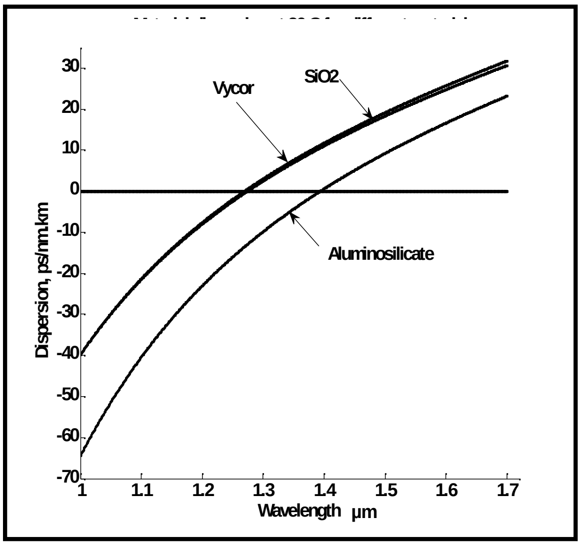

Figure (2) Material dispersion at 26°C for different

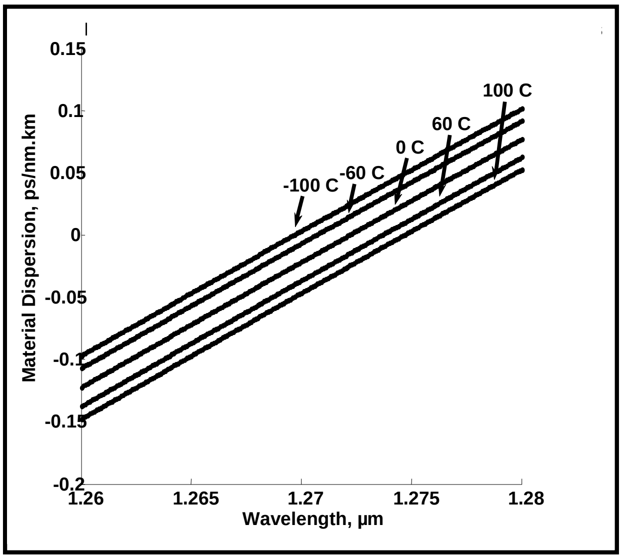

Figure (3) Material dispersion of SiO_2glasss at different temperature

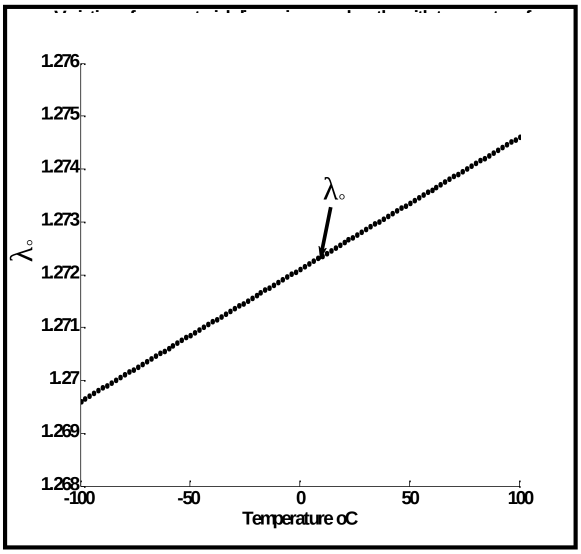

Figure (4) Variation of zero material dispersion wavelengths with temperature for SiO glass

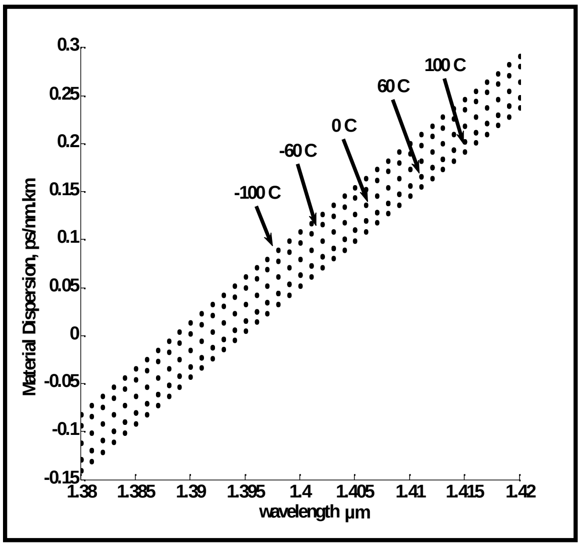

Figure (5) Material dispersion of aluminosilicate glass at different temperature

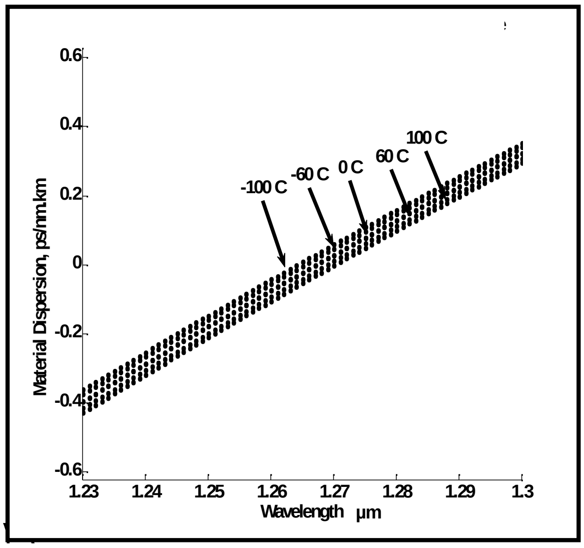

Figure (6) Material dispersion for vycor glass at different temperature

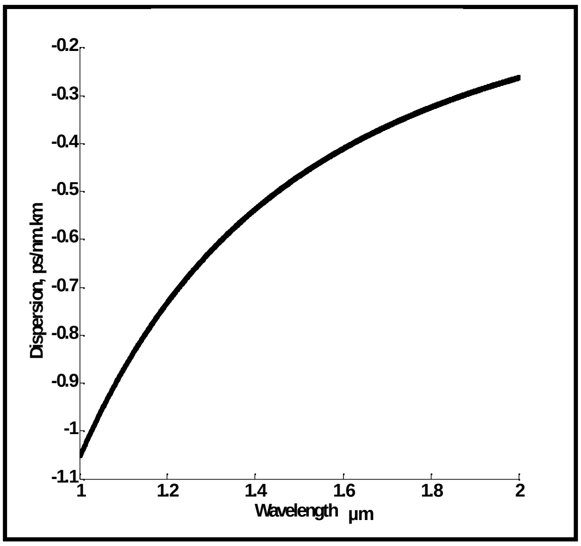

Figure (7) Waveguide dispersion for SiO_2 at T= 26°C

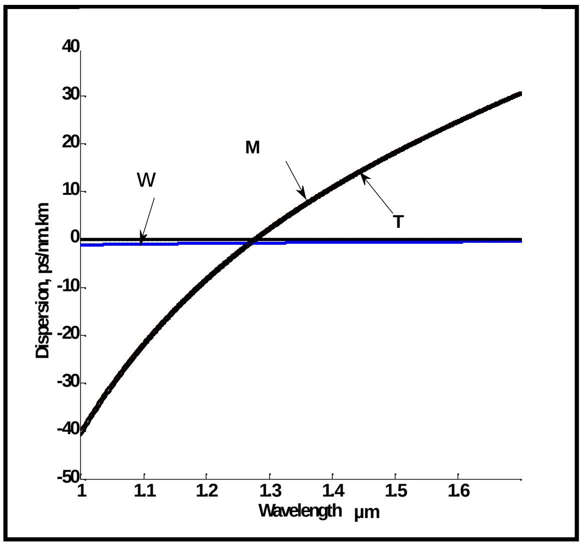

Figure (8) Total dispersion parameter for SiO_2 at T=26°C

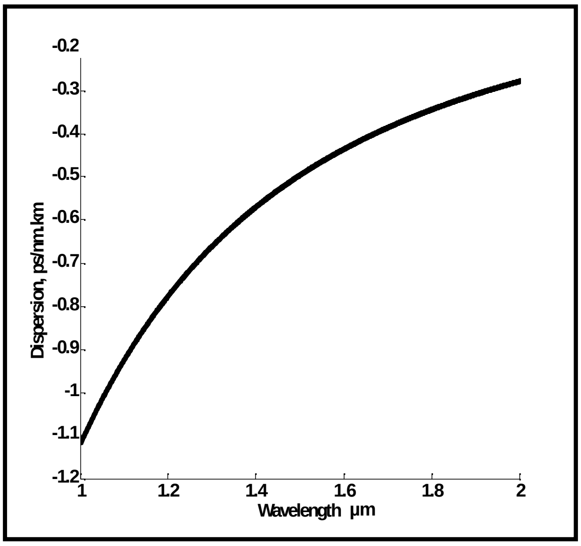

Figure (9) Waveguide dispersion for Aluminosilicate at T=26°C

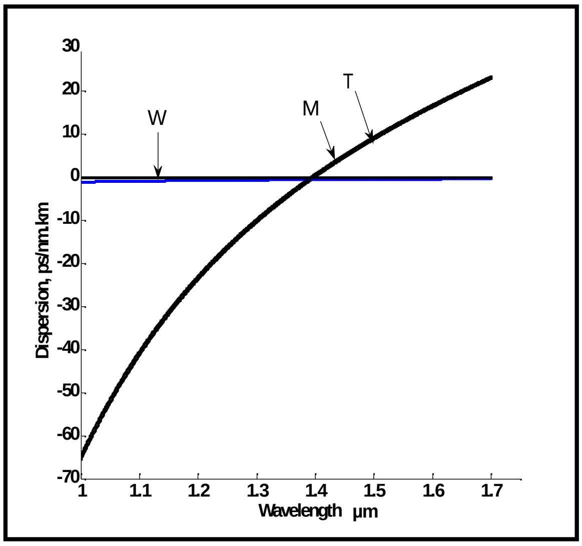

Figure (10) Total dispersion parameter for Aluminosilicate glass at T=26°C

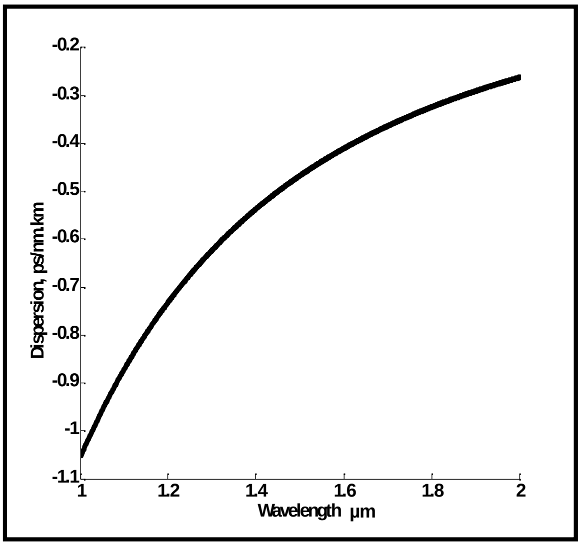

Figure (11) Waveguide dispersion for Vycor glass at T=26°C

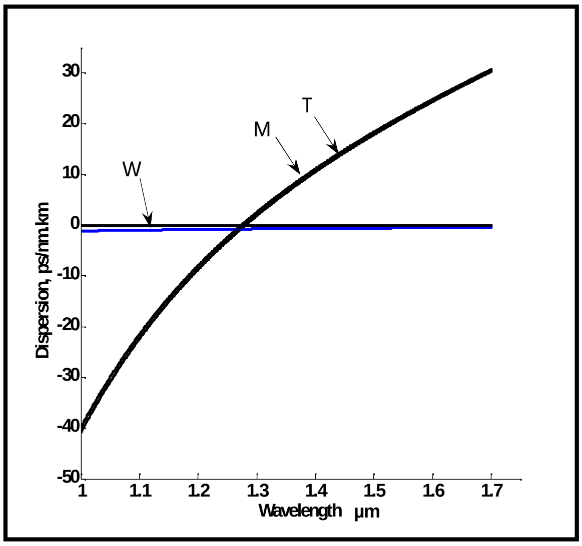

Figure (12) Total dispersion parameter for Vycor glass at T=26°C

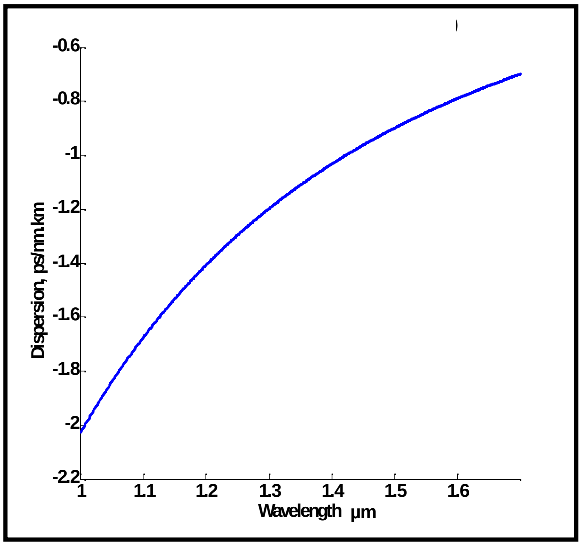

Figure (13) Waveguide dispersion for SiO_2 (graded index)

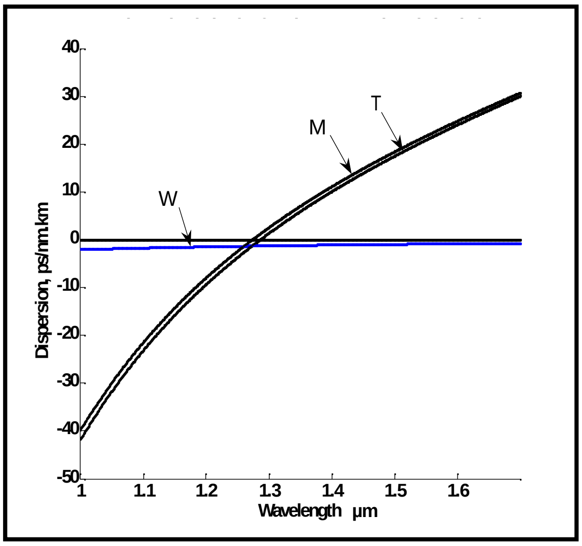

Figure (14) Dispersion behavior for SiO_2 (graded index)

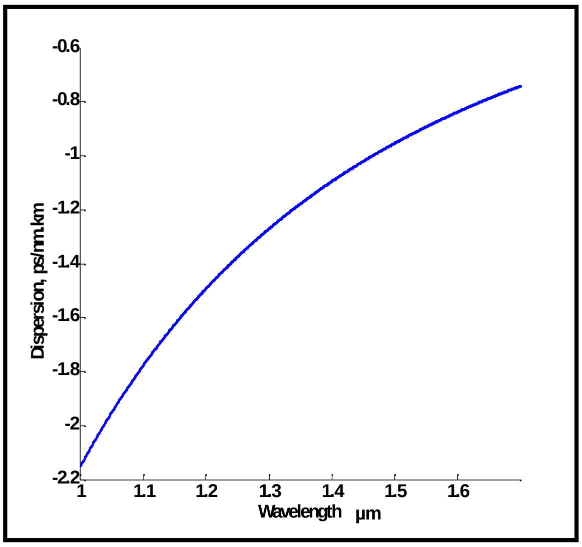

Figure (15) Waveguide dispersion for aluminosilicate at T=26°C (graded index)

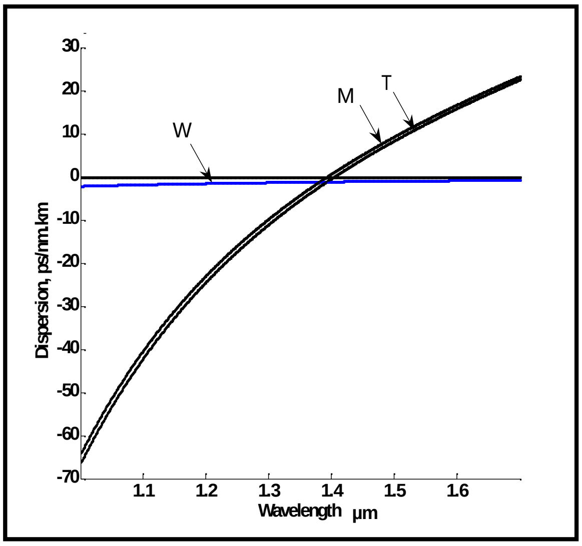

Figure (16) Dispersion behavior for aluminosilicate at T=26°C (graded index)

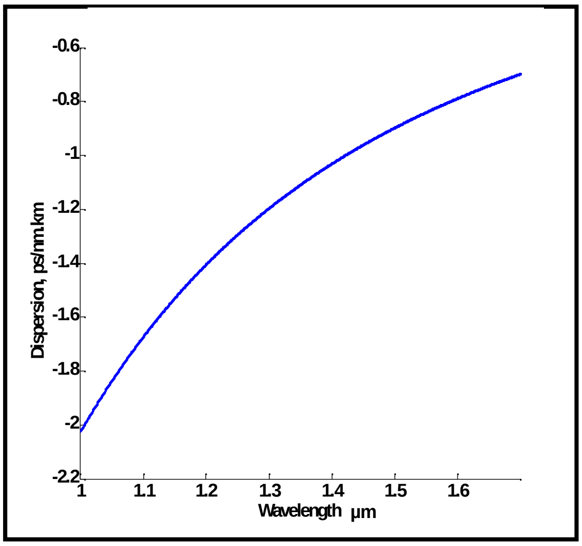

Figure (17) Waveguide dispersion for Vycor at T=26°C (graded index)

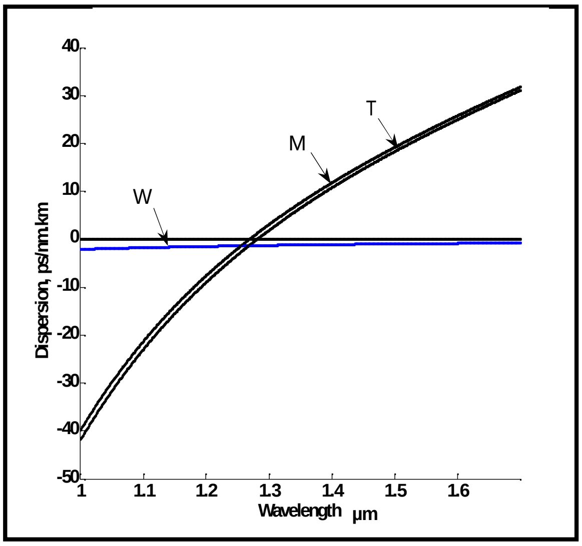

Figure (18) Dispersion behavior for vycor glass at T=26°C (graded index)