

## Design of Zero Dispersion Optical Fiber at Wavelength 1.3 $\mu\text{m}$

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### الخلاصة

تم في هذا البحث تصميم ليف ضوئي بتقزح صفري عند الطول الموجي (1.3, 3) مايكرو (متر) بالاعتماد على عدة عوامل وهي (المقطع العرضي, تركيب مادة الليف, معامل الانكسار), هذه العوامل يجب اختيارها بدقة عند تصميم أي ليف ضوئي لأنها تؤثر بشكل كبير في أنظمة الاتصالات الضوئية وبينت المحاكاة بعض المميزات الهامة والرئيسية المتعلقة بهذا العامل. تم الحصول على ليف ضوئي مطعم بـ ( $\text{GeO}_2$ ) للقلب بنسبة (1.3%) نظرياً باستخدام البرنامج (OptiFiber2.0) والقيم المثلى لمعامل الانكسار لكل من قلب الليف وغلافه لأجل الحصول على تقزح صفري عند الطول الموجي (1.3, 3) مايكرومتر) والذي يستعمل في الاتصالات الضوئية. وقد كانت على التوالي (1, 48 و 1, 45) أي معدل الفرق بين المعاملين (0.02%) بأنصاف أقطار (6, 728 و 8, 46) مايكرومتر) على التوالي.

### Abstract:

In this article, an optical fiber was designed with zero- dispersion at wavelength of (1.3  $\mu\text{m}$ ). The design took into consideration many factors of the fiber, such as; fiber cross- section, fiber material, refractive index. These factor can affect the operation of a fiber in optical communication system.

A zero- dispersion fiber was obtained when the core was doped by (1.3%) of  $\text{GeO}_2$ . Implementing the package of computer aided design (OptiFiber 2.0). We were able to attain the optimum values for refractive index core and clad as (1.48 and 1.45) respectively, i.e, a percentage difference of (0.02) for radius (6.728 and 8.46) respectively, for zero- dispersion at wavelength of (1.3  $\mu\text{m}$ ) that is use in the optical communication.

### **1. Introduction**

Telecommunications using fibers as the transmission media is now a major industry[1]. Optical fiber technology was considered to be a major driver behind the information technology revolution and the huge progress on global telecommunications that has been witnessed in recent years. Fiber optic telecommunication is now taken for granted in view of its wide-ranging application as the most suitable singular transmission medium for voice, video, and data signals[ 2]. Indeed, optical fibers have now penetrated virtually all segments of telecommunication networks; trans-oceanic, transcontinental, inter-city, metro, access, campus, or on-premise [2].

The role of a communication channel is to transport the optical signal from transmitter to receiver without distorting it. Most light wave systems use optical fibers as the communication channel because silica fibers can transmit light with losses as small as (0.2 dB/km). Even then, optical power reduces to only (1%) after (100 km)[3]. For this reason, fiber losses remain an important design issue and determines the repeater or amplifier spacing of a long-haul light wave system [3]. Another important design issue is fiber dispersion, which leads to broadening of individual optical pulses with propagation. If optical pulses spread significantly outside their allocated bit slot, the transmitted signal is severely degraded. Eventually, it becomes impossible to recover the original signal with high accuracy[3]. The problem is most severe in the case of multimode fibers, since pulses spread rapidly (typically at a rate of  $\sim 10$  ns/km) because of different speeds associated with different fiber modes[3]. It is for this reason that most optical communication systems use single-mode fibers. Material dispersion (related to the frequency dependence of the refractive index) still leads to pulse broadening (typically  $< 0.1$  ns/km), but it is small enough to be acceptable for most applications and can be reduced further by controlling the spectral width of the optical source[3]. material dispersion sets the ultimate limit on the bit rate and the transmission distance of fiber-optic communication systems[3].

Dispersion is sometimes called chromatic dispersion to emphasize its wavelength-dependent nature, or Group Velocity Dispersion (GVD) to emphasize the role of the group velocity[4].

The group velocity associated with the fundamental mode is frequency dependent because of chromatic dispersion. As a result, different spectral components of the pulse travel at slightly different group velocities, a phenomenon referred to as group-velocity dispersion (GVD), intramodal dispersion, or simply fiber dispersion. Intramodal dispersion has two

contributions, material dispersion and waveguide dispersion. We consider both of them and discuss how GVD limits the performance of light wave systems employing single-mode fibers[3].

Dispersion represents a broad class of phenomena related to the fact that the velocity of the electromagnetic wave depends on the wavelength. In telecommunication the term of dispersion is used to describe the processes which cause that the signal carried by the electromagnetic wave and propagating in an optical fiber is degraded as a result of the dispersion phenomena. This degradation occurs because the different components of radiation having different frequencies propagate with different velocities[6].

The different velocities of the two orthogonal components generate the phase difference changing in time of propagation along a fiber and change of polarization. Beside the change of polarization with time of propagation, the different velocities of ordinary ray and extraordinary cause that the rays reach the end of a fiber in different time[7].

(OptiFiber) is the leading commercial product in that category. It is a powerful tool that blends numerical mode solvers for fiber modes with calculation models for group delay, group-velocity dispersion, effective mode area, losses, polarization mode dispersion, effective nonlinearity, etc[1].

In this article, a fiber design was intended in order to obtain a Zero\_ dispersion fiber operating in the wavelength of (1.3 μm). The design was implemented by using (OptiFiber 2.0) and solving filed equation by (MATLAB). Comparison will be stated in the article .

## **2. Fiber geometry and numerical method**

The optical properties of the fabricated fibers are assessed both experimentally and through accurate numerical simulations. The second key, optical property of a fiber, is its dispersion profile, which characterizes the wavelength dependence of the group velocity( $v_g$ ) of the guided mode[8].

Consider a single-mode fiber of wavelength ( $\lambda$ ). The fiber group index ( $n_g$ ) is related to the first order derivative of the mode propagation constant ( $\beta$ ) with respect to ( $\lambda$ ) according to the following expression[8], we have:

$$n_g = \frac{\lambda^2}{2\pi} \frac{d\beta}{\left(\frac{\lambda^2}{2\pi c} d\omega\right)} \dots\dots\dots(1)$$

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By Taylor expression around resonance frequency( $\omega_0$ ), ( $\beta$ ) can be written[5]:

$$\beta = \beta_0 + \beta_1 (\omega - \omega_0) + \frac{1}{2} \beta_2 (\omega - \omega_0)^2 + \dots \dots \dots (2)$$

With:  $\beta_1 = \left(\frac{d\beta}{d\omega}\right)_{\omega = \omega_0}$ ,  $\beta_2 = \left(\frac{d^2\beta}{d\omega^2}\right)_{\omega = \omega_0}$

using  $k = 2\pi/\lambda$ , equation (1) can be written as[8]:

$$n_g = c \left(\frac{d\beta}{d\lambda}\right) \dots \dots \dots (3)$$

By using equation (3), ( $v_g$ ) is[7]:

$$v_g = \frac{c}{n_g} \dots \dots \dots (4)$$

Dispersion is also related to ( $n_{eff}$ ) which given as[9]:

$$D = -\frac{\lambda}{c} \frac{d^2 n_{eff}}{d\lambda^2} \dots \dots \dots (5)$$

( $n_{eff}$ ) is an effective index of the fundamental mode in a single-mode fiber, and (c) is speed of light in the vacuum.

In a fiber, the materials of core and cladding are of different refractive indices. If there are (I) layers in the fiber cross-section, each layer has different refractive index. If the refractive index of the fiber material varies with wavelength, thus causing the group velocity to vary, it is classified as material dispersion[9].

The total material dispersion of a fiber in term of variation of with respect to wave length, we have[3]:

$$D_M = \frac{1}{c} \frac{dn_g}{d\lambda} \dots \dots \dots (6)$$

And waveguide dispersion is the result of the wavelength-dependence of the effective refractive index ( $n_{eff}$ ) of the fiber mode. First, the mode solver calculates the relation between ( $n_{eff}$ )and wavelength ( $\lambda$ ), then the waveguide dispersion is calculated by[1]:

$$D_w = -\frac{\beta}{c} \lambda \frac{d^2 n_{eff}}{d\lambda^2} \dots \dots \dots (7)$$

The total dispersion is the total effect of material and waveguide dispersion. It is calculated in a similar way as for calculating waveguide dispersion. In this case, the fiber refractive index profile depends on the wavelength. The material dispersion effect should be calculated first. Then the mode solver calculates the mode effective index ( $n_{eff}$ )[1].

It can be shown that the total dispersion coefficient of a fiber ( $D_T$ ) is given to a very good accuracy by the algebraic sum of two components which is[9] :

$$D_T = D_M + D_w \dots\dots\dots(8)$$

For a double-layered optical fiber structure composed of  $GeO_2$  - doped silica core and pure silica cladding, the acoustic modes have been theoretically analyzed solving the electric field equation which is given By[10]:

$$E = \begin{cases} A J_m(p\rho) \exp(im\phi) \exp(i\beta z) & ; \quad \rho < a \\ C k_m(q\rho) \exp(im\phi) \exp(i\beta z) & ; \quad \rho \leq a \end{cases} \dots\dots\dots(9)$$

Where (m) is the number of mode, ( $\phi$ ) the phase of mode, (a) core radius, ( $J_m$ ) and ( $k_m$ ) are different kinds of Bessel functions and ( $\rho$ ) is parameter taken as function of (a) [11]. The parameters (p) and (q) are defined by[3]:

$$p = n_i k - \beta \dots\dots\dots(10)$$

$$q = n_i k - \rho \dots\dots\dots(11)$$

It was clear during the 1970s that the repeater spacing could be increased considerably by operating the lightwave system in the wavelength region near  $1.3 \mu m$ , where fiber loss is below (1 dB/km). Furthermore, optical fibers exhibit minimum dispersion in this wavelength region. This realization led to a worldwide effort for the development of (InGaAsP) semiconductor lasers and detectors operating near  $1.3 \mu m$  [3].

There is currently a great deal of interest in the development of efficient  $1.3 \mu m$  optical amplifiers, because most terrestrial optical fiber communication systems work at this wavelength[12].

For the last two decades, varieties of optical fibers have been developed for optical communications in order to cope with ever increasing bandwidth, data rate, and transmission distance[13]. Conventional optical fibers consist of a solid glass core with higher refractive index encircled by cladding with a relatively lower refractive index. There are three major transmission optical fibers; single-mode fibers (SMFs), nonzero dispersion shifted fibers (NZDSF), and dispersion

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compensating fiber (DCF). With recent worldwide demand in the end of the 20th century, these silica based conventional fibers have been massively developed and deployed to obtain larger communication capacity by optimization of the chromatic dispersion at the S, C, and L-bands for the wavelength (1.55 μm) [13]. Along side with these transmission fibers, specialty fibers such as rare earth-doped fibers, photosensitive fibers, attenuation fibers, and polarization maintaining fibers have been also developed for optical devices[13]. These fibers, however, do have the common platform as transmission fibers in a sense that they do share the solid glass core/cladding structures [13]. Optical communication working at (1.3 μm) is in the O band region .

To design a fiber with zero dispersion, it is necessary to optimize both: material properties, as well as the shape of the waveguide. There exists, therefore, a wavelength, at which total dispersion is equal to zero. Beyond this, the fiber exhibits a region of anomalous dispersion, which can be used for the compression of pulses in optical fibers [14] .

The design of fiber-optic communication systems requires a clear understanding of the limitations imposed by the loss, dispersion, and nonlinearity of the fiber. Since fiber properties are wavelength dependent, the choice of operating wavelength is a major design issue [5].

Step index fiber modeling process is carried out through numerically solving of eigen value equation to calculate propagation constant for fundamental mod. Input data in the process is only index of refraction calculated from Sellmeier dispersive formula for appropriate mol percentage doping of germanium dioxide in silica glass fiber. Output data in the modeling process is optimal value of the normalized frequency, which guarantees that single mode operation region is equal to bright soliton propagation region. Final verification of the process is soliton generation up to six-order inside such modeled fiber. In this end nonlinear Schrodinger equation is solved numerically for initial condition of hyperbolic secant form of laser pulse. Maximization of single mode operation and bright soliton propagation region is essential in wavelength division multiplexing technique [15]

The refractive - index relationship with the wavelength and the concentration is given by Sellmeier equation as [16]:

$$n^2 = 1 + \sum_{i=1}^k \frac{a_i \lambda^2}{\lambda^2 - b_i^2} \dots\dots\dots(12)$$

where (k) equal to (3), represents that this is a three term Sellmeier's, equation, (λ) is in a unit of micron, (i) is the oscillator

resonance wavelength. In this equation, a certain set of parameters ( $a_i$ ) and ( $b_i$ ) are corresponding to a specific type of material such as pure silica or  $\text{GeO}_2$ -doped silica glass with a certain  $\text{GeO}_2$  concentration level. A series of ( $a_i$ ) and ( $b_i$ ) have been computed from the measured data taken from reference, as shown in Table (1). All the parameters of optical fibers were kept same except for the core radius. The inner cladding radius was ( $6.728 \mu\text{m}$ ), and the relative refractive index difference between the core and the cladding was of (2%) similar to that of conventional SMFs.

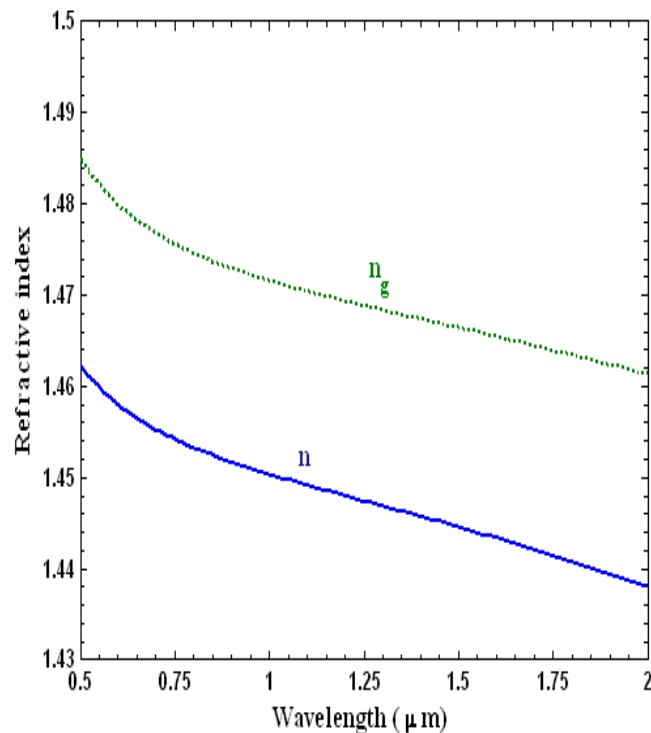
**Table (1) Sellmeier coefficients values [ 17] :**

parameter	96.9 % $\text{SiO}_2$	3.1 % $\text{GeO}_2$
$a_1$	0.6961663	0.7028554
$a_2$	0.4079426	0.4146307
$a_3$	0.89749794	0.8974540
$b_{1(\mu\text{m})}$	0.068043	0.0727723
$b_{2(\mu\text{m})}$	0.1162414	0.1143085
$b_{3(\mu\text{m})}$	9.896161	9.896161

Opti-Fibers code used to simulate the micro-fiber. The commercial single mode optical fiber parameters with dimensions squeezed were chosen for simulation. As at a very narrow core size, silica is the dominating factor rather than  $\text{GeO}_2$  to determine the propagation characteristics, the core itself was approximated to be of silica glass.

### **3. Results and discussion**

Figure (1) displays how the refractive index ( $n$ ) and the group index ( $n_g$ ) varies with wavelength for fused silica. The group velocity can be found using equation (4) by (MATLAB). Physically speaking, the envelope of an optical pulse moves at the group velocity[6].



**Figure (1): Variation of ( $n$ ) and ( $n_g$ ) with wavelength**

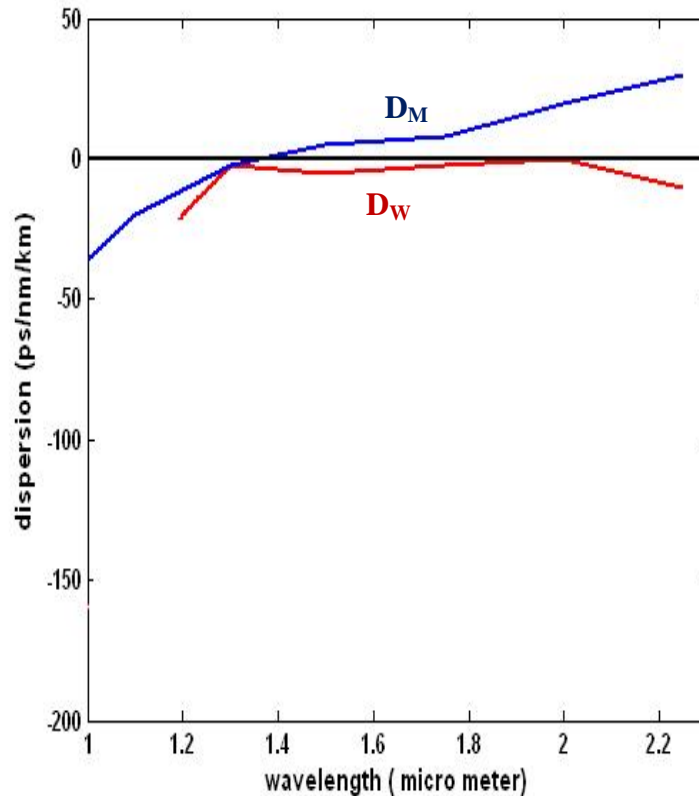
The wavelength dependence of ( $n$ ) and ( $n_g$ ) in the range (0.5–2  $\mu\text{m}$ ) for fused silica. Material dispersion ( $D_M$ ) is related to the slope of ( $n_g$ ) by the relation [Eq. (6)]. It turns out that ( $dn_g/d\lambda = 0$ ) at ( $\lambda = 1.3 \mu\text{m}$ ). This wavelength is referred to as the zero-dispersion wavelength ( $\lambda_{ZD}$ ), since ( $D_M = 0$ ) at ( $\lambda = \lambda_{ZD}$ ). The dispersion parameter ( $D_M$ ) is negative below ( $\lambda_{ZD}$ ) and becomes positive above that. It should be stressed that ( $\lambda_{ZD} = 1.3 \mu\text{m}$ ) only for pure silica. The zero-dispersion wavelength of optical fibers also depends on the core radius  $a$  and the index step  $\Delta n$  through the waveguide contribution to the total dispersion [3].

Figure (2) shows the results obtained after solving Sellmeier equation for above stated values of the coefficient in (3.1%)  $\text{GeO}_2$  doped silica fiber.

The numerical solution of Sellmeier equation was performed with Matlab after getting the appropriate values for the defined value of refractive indices for the fiber under test.

For a conventional single-mode fiber, the zero-dispersion wavelength shifts to Waveguide dispersion can be used to produce dispersion- decreasing fibers in which GVD decreases along the fiber length because of axial variations in the core radius. In another kind of fibers, known as the dispersion compensating fibers, GVD is made normal and has a relatively large magnitude [3].





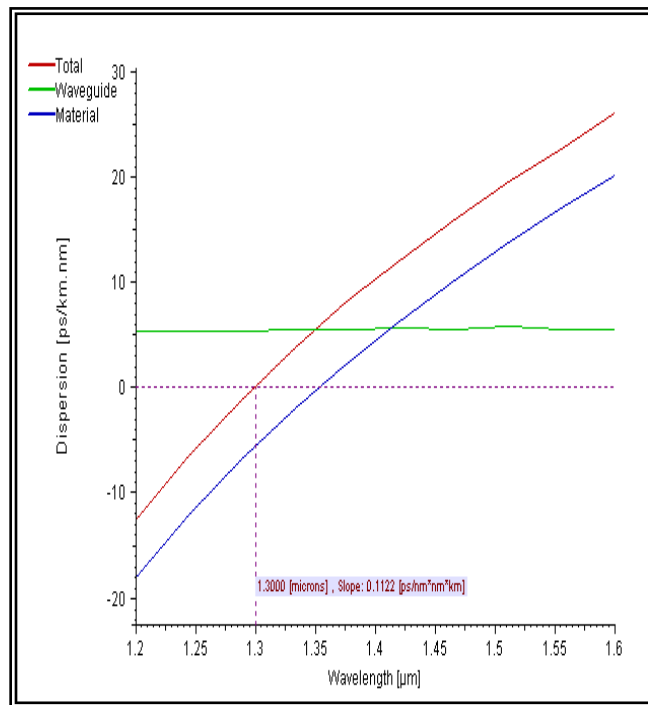
**Figure (2): Dispersion variation with wavelength**

The most notable feature is that ( $D_M$ ) vanish at a wavelength of about ( $1.3 \mu\text{m}$ ) and change sign for longer wavelengths, this is shown in figure (2). This wavelength is referred to as the zero-dispersion wavelength and is denoted as ( $\lambda_D$ ). However, the dispersive effects do not disappear completely at ( $\lambda = \lambda_D$ ). When the input wavelength ( $\lambda$ ) approaches ( $\lambda_D$ ) to within a few nanometers. The main effect of the waveguide contribution is to shift ( $\lambda_D$ ) slightly toward longer wavelengths; ( $\lambda_D \approx 1.3 \mu\text{m}$ ) for standard fibers[5].

Sellmeier equation was first showed numerically in order to estimate the refractive index of both the fiber silica and the group index for the proposed fiber, as shown in Figure (1). As we can see from the figure, the refractive index decreased with wavelength, and the required values at ( $1.3 \mu\text{m}$ ) were obtained.

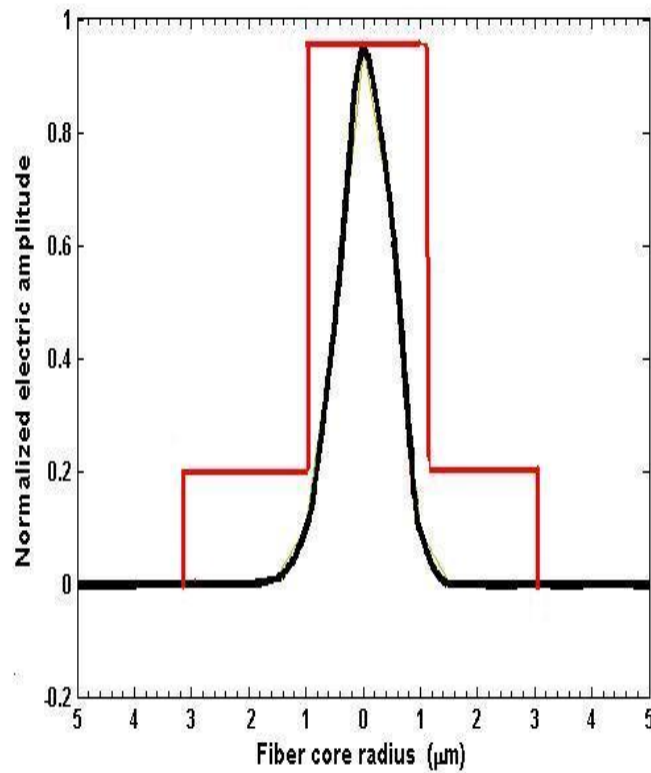
Figure (3) shows the variation of dispersion, waveguide, material, and total as function of wavelength using the OptiFiber package simulation. In comparison, we can conclude a zero – dispersion fiber at wavelength  $1.3\mu\text{m}$ .

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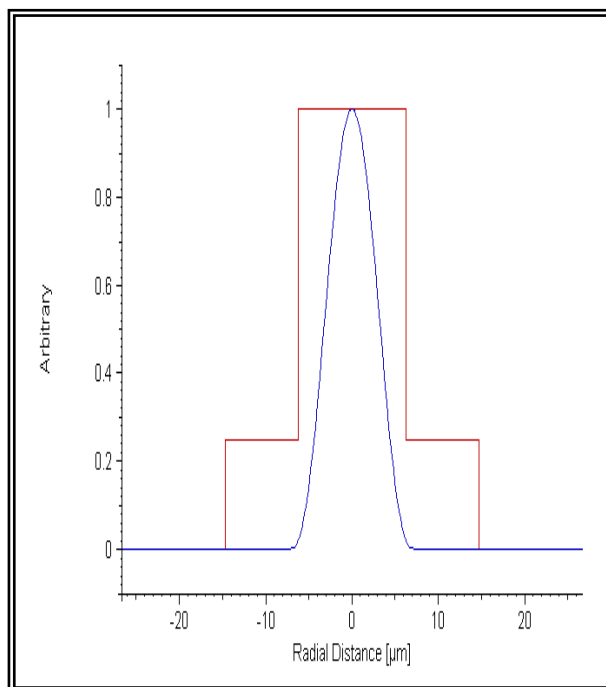


**Figure (3): Total Dispersion losses in the fiber**

One can see from Figure (3) that the increase of the negative slope of material dispersion shifts the zero of dispersion towards longer wavelengths. Thus, the obvious way of dispersion minimum shifting of transmission is enlarging the influence of the waveguide dispersion. It can be done by enlargement of difference between the core and the cladding refraction indices[6].



**Figure(4): Optical confinement within the fiber by Matlab**



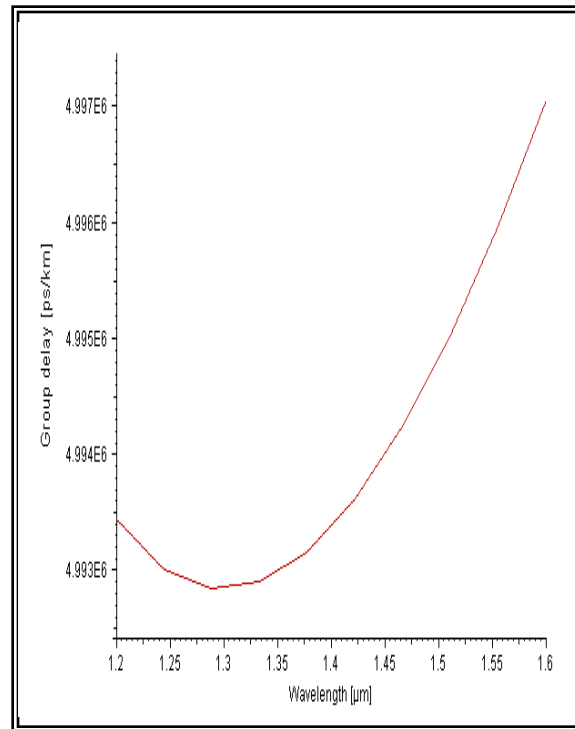
**Figure (5): Optical confinement within the fiber by "OptiFiber2.0"**

Fiber design must fulfill the requirement that the light for the has must be confined in the core of the fiber. The fulfillment was satisfied in an proposed fiber by simulation using Matlab for equation (9) and

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OptiFiber, as shown in figures (4 and 5). As can be noticed from both figure, the laser light was confined in the core and shows a Gaussian profile in both diagram.

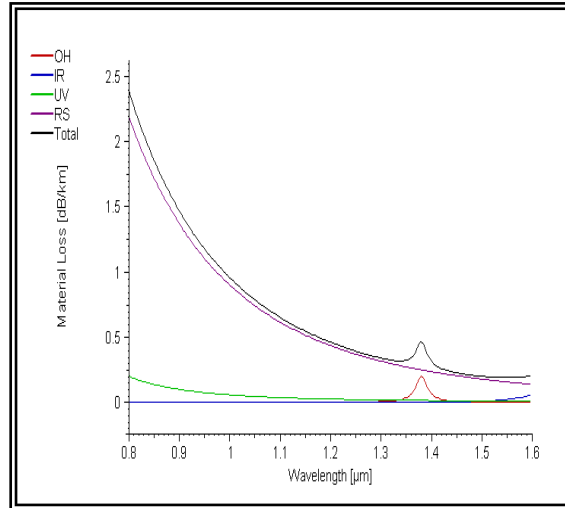
The modal intensity distribution and the direction of electric fields is for the fundamental mode as in Figure (4). The fundamental mode is linearly polarized as indicated by the electric field vectors in Figures.



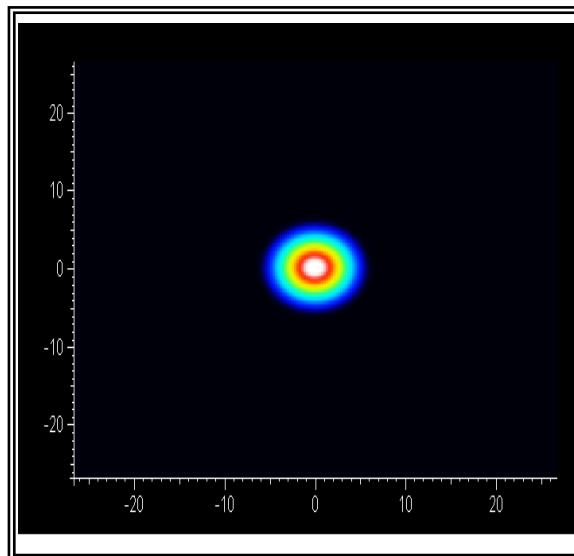
**Figure (6): Variation of group delay with wavelength for its proposed fiber**

The other most important feature of the fiber, is the group delay(ps/km). This parameter was calculated by using "OptiFiber2.0"for our proposed fiber. The minimum value of the delay, as can be noticed from the group, is at (1.3 $\mu\text{m}$ ) wavelength. the minimum value of this group delay encourage our suggestion for proposed fiber.

Now, the next step, is to calculated the losses in the proposed fiber, figure (7), all the losses (hydroxide, infrared, ultraviolet, Rayleigh scattering ), were the minimum values at (1.3 $\mu\text{m}$ ) wavelength.



**Figure (7): Calculation of the losses dependence on wavelength for the proposed fiber**



**Figure (8): Image of electric field distribution of the proposed fiber**

Figure (8) shows the confinement of fundamental mode and higher- order modes in the fiber under test. The fundamental mode was totally confined in the core of diameter (6.728 μm).

#### 4. Conclusion

The concluding remarks that can be outline from the article we as follows. The proposed fiber working at (1.3μm) with zero – dispersion and minimum optical material losses were verified. The simulation were conducted by two numerically parallel methods by solving the equation Matlab and OptiFiber2.0. Both simulation satisfied our hypothesis for such a fiber.

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