

## Temperature Dependence of Zero Dispersion Wavelength in Single-Mode optical Fibers for Different Materials

W. El Shirbeeny<sup>1</sup>, Moustafa H. Aly<sup>2</sup>, Ahmed E. El-Samahy<sup>1</sup>, Khaled M. Emad<sup>1</sup>

<sup>1</sup> Faculty of Science, Alexandria University, Alexandria, Egypt

<sup>2</sup> Faculty of Engineering, Arab Academy for Science & Technology, Alexandria, Egypt

\* Member of the Optical Society of America (OSA), e-mail: [mosaly@aast.edu](mailto:mosaly@aast.edu)

E-mail: [waleed\\_shirbeeny@hotmail.com](mailto:waleed_shirbeeny@hotmail.com)

E-mail: [a\\_samahy@hotmail.com](mailto:a_samahy@hotmail.com)

E-mail: [Khemad73@gmail.com](mailto:Khemad73@gmail.com)

### Abstract

The zero dispersion wavelength,  $\lambda_0$ , for single mode fibers is modelled and investigated for silica, aluminosilicate and vycor glasses. Both step index and graded index fibers are considered. The used model depends mainly on the temperature dependent Sellmeier coefficients of the core refractive index. Temperature effects on  $\lambda_0$  are investigated for a wide range (-100 °C to +100 °C) as well as the fiber parameters including the core radius and the relative refractive index difference.

### Introduction

Single-mode optical fibers are optimized for low loss (< 0.2 dB/km) and near zero dispersion (< 3.5 ps/nm.km) at 1300 nm [1-3]. On the other hand, fibers which are made of silica exhibit lowest attenuation (mainly due to low inherent scattering) at 1550 nm. If the 1300 nm optimized fiber is operated at 1550 nm, it will exhibit a nominal dispersion of about 18-20 ps/nm.km. In order to achieve both low loss and low dispersion at 1550 nm, one can choose the advanced single-mode fiber design which is the dispersion shifted fiber (DSF). In the dispersion shifted single-mode (DS-SM) designs, the magnitude of the waveguide dispersion is enhanced by tailoring the shape of the refractive index profile such that the sum of material and waveguide dispersions is made to be near zero at 1550 nm while maintaining the inherent scattering loss to a minimum in the fiber [1, 2, 4].

In 1982, most trunk applications started converting from multimode to step index single-mode fibers operating at 1300 nm. Today, a few trunk applications are being planned for use with multimode fibers and the systems operating wavelength has to move to 1550 nm. Initial single-mode systems were 140 Mb/s and today, most systems are 40 Gb/s. In the future up to 150 Gb/s systems are anticipated [5].

The dispersive properties of single-mode fibers owe their origin to the wavelength dependence of the refractive indices of the core and the cladding glasses of the fiber structure, as well as explicit dependence of modal propagation constant which depends on the fiber structural characteristics and the source wavelength [2]. Since every source exhibits some wavelength spread in its emission pattern, the above mentioned wavelength dependent effects lead to temporal broadening of the launched pulse. Accurate estimation of this broadening in a repeater section and its compatibility with the system information carrying capacity are necessary for control of bit error rate of actual systems [6]. 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, using the weakly guiding approximation, Gambling et al. succeeded in partially separating these terms [1, 7]. In practice, this separation is widely used and the total dispersion parameter,  $D_T$ , is expressed as;

$$D_T = M_D + W_D, \quad (1)$$

where  $M_D$  and  $W_D$  are the material and waveguide dispersion parameters, respectively.

### Theoretical Model

In the following, the equations for finding Sellmeier coefficients of the core refractive index are described for three kinds of fiber glasses: SiO<sub>2</sub>, aluminosilicate, and vycor glasses. The temperature dependence of these coefficients is determined. Material and waveguide dispersion parameters are studied leading to the zero dispersion wavelength,  $\lambda_0$ , of the total dispersion parameter. The temperature effect on  $\lambda_0$  is investigated and the obtained results are compared with the published experimental ones.

### Sellmeier Coefficients

The core refractive index,  $n$ , as a function of the operating wavelength,  $\lambda$ , is defined through the Sellmeier equation which has the form [8, 9]:

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

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.

Using the data in [8], the temperature dependent Sellmeier coefficients A, B, C, D and E at any temperature, T (°C), in the (-100 °C to 100 °C) can be obtained for the SiO<sub>2</sub>, aluminosilicate, and vycor glasses. The core refractive index, n<sub>T</sub>, can then be calculated from its value, n<sub>R</sub>, at room temperature, R (°C), and the smoothed dn/dT values using the relation [8]:

$$n_T = n_R + (T - R) \left( \frac{dn}{dT} \right)_{smoothed} \quad (3)$$

### Material Dispersion

Material dispersion manifests through the wavelength dependence of the refractive index, n(λ), Eq. (2), by the following relation [3, 8, 9, 10]:

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

where c is the free space speed of light.

So,

$$M_D(\lambda) = -1/(cn) [-4/\lambda^5 \{BC^2/(1-C/\lambda^2)^3 + DE^2/(1-E/\lambda^2)^3\} + \lambda(dn/d\lambda)^2 + 3n(dn/d\lambda)] \quad (5)$$

### Waveguide Dispersion

The waveguide dispersion in optical fibers is given by [3, 11]:

$$W_D = -\frac{V^2}{2\pi c} \cdot \frac{d^2 \beta}{dV^2} \quad (6)$$

where V is the normalized frequency and β is the propagation constant.

For step-index fibers, the propagation constant, β, is given by [2, 12, 13]:

$$\beta = \left( \frac{V^2}{2\Delta a^2} - \frac{\pi^2}{a^2} \right)^{1/2} \quad (7)$$

where a is the core radius, Δ is the relative refractive index difference between core and cladding

While, for graded-index fibers, β is given by [2, 12, 13]:

$$\beta = \left( \frac{V^2}{2a^2 \Delta} - \frac{6V}{a^2} \right)^{1/2} \quad (8)$$

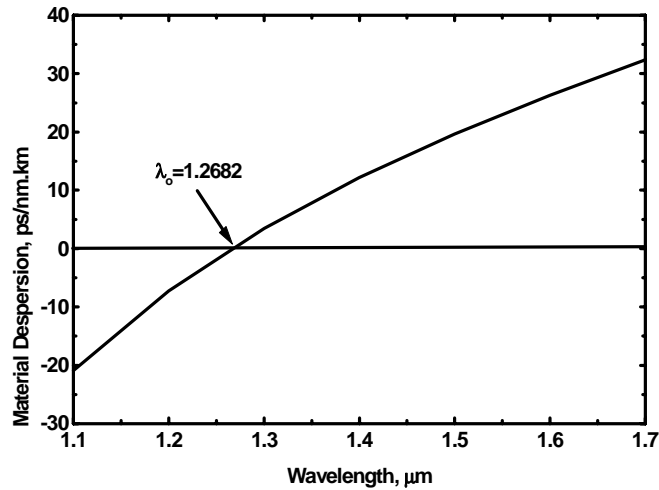
## Results and Discussion

### Sellmeier Coefficients

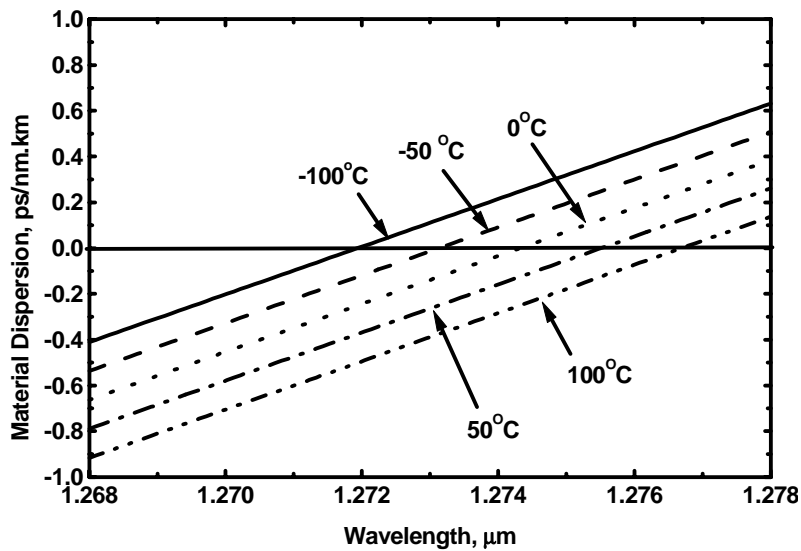
The temperature-dependent Sellmeier coefficients, Eq. (2) are calculated for the three optical fiber glasses from which the refractive indices are calculated at any wavelength and at any operating temperature. All are found to fit nicely into straight lines.

**Material Dispersion**

Material dispersion is calculated for the three mentioned glass types at 26°C using the temperature dependence Sellmeier coefficients, Eq. (2). The zero material dispersion wavelengths are 1.2734, 1.3929 and 1.2682 μm for SiO<sub>2</sub>, aluminosilicate and vycor glass, respectively, and the dispersion characteristics are not linear for the whole spectral region. A sample of the results is shown in Fig.(1) for vycor glass.



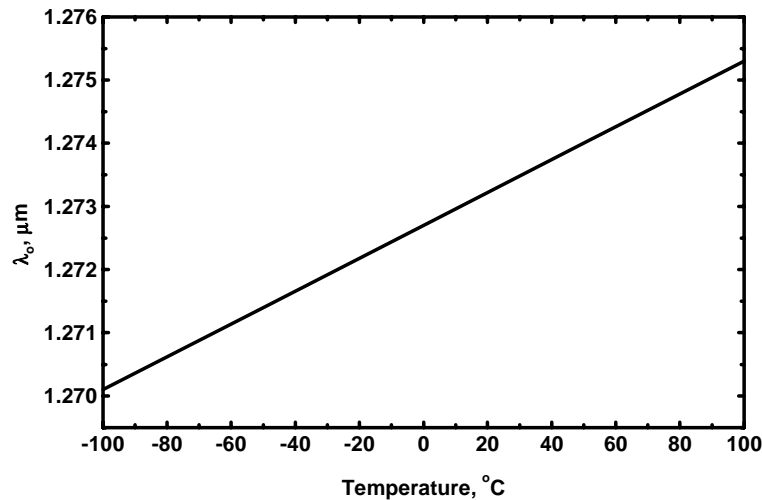
**Figure 1:** Material dispersion for vycor glass at 26°C



**Figure 2:** Material dispersion of SiO<sub>2</sub> glass at different temperatures.

For a wide range of temperature (-100°C to 100 °C), we have calculated the material dispersion and the zero material dispersion wavelength, λ<sub>0</sub>, for the three glass types. Again, a sample of the obtained results is shown in Fig.(2) for the SiO<sub>2</sub> glass.

The zero material dispersion wavelength as a function of temperature  $T$  is displayed in Fig.(3) for  $\text{SiO}_2$ . Interestingly, the temperature dependence is linear and  $d\lambda_0/dT=0.025 \text{ nm}/^\circ\text{C}$  for  $\text{SiO}_2$ . This value has a fair agreement with the published experimental values  $0.029\pm 0.004 \text{ nm}/^\circ\text{C}$  and  $0.031\pm 0.004 \text{ nm}/^\circ\text{C}$  for two dispersion shifted fibers within the experimental accuracy [4]. The corresponding values of  $d\lambda_0/dT$  is found to be  $0.03 \text{ nm}/^\circ\text{C}$  for both aluminosilicate and vycor glasses.



**Figure 3:** Variation of zero material dispersion wavelengths with temperature for  $\text{SiO}_2$  glass.

## Waveguide Dispersion and Total Dispersion

### Single mode step index fiber

Through the temperature dependent Sellmeier coefficients and the corresponding values of the  $V$ - number, the waveguide dispersion is calculated at a core radius,  $a = 2 \mu\text{m}$  and  $\Delta = 0.005$  for the three glass types. Following Eq.(1), the material dispersion parameter is added to the waveguide dispersion parameter to get the total dispersion parameter,  $D_T$ . Figure 4 shows a sample of the obtained results for the aluminosilicate glass.

From Fig.(4), at  $26^\circ\text{C}$ , the zero total dispersion wavelength,  $\lambda_0$ , is  $1.4259 \mu\text{m}$ . The corresponding values for are found to be  $1.2954$  and  $1.2894 \mu\text{m}$  for  $\text{SiO}_2$  and vycor glasses, respectively. In the same manner as done with the material dispersion, and in the temperature range  $-100^\circ\text{C}$  to  $100^\circ\text{C}$ ,  $\lambda_0$  is calculated showing a linear dependence, with  $d\lambda_0/dT= 0.027$ ,  $0.0325$  and  $0.032$  for  $\text{SiO}_2$ , aluminosilicate, and vycor glasses, respectively.

The variation of  $\lambda_0$  with the core radius,  $a$ , at constant values of  $\Delta$  at  $26^\circ\text{C}$ , is displayed in **Fig.5** for  $\text{SiO}_2$  glass showing that  $\lambda_0$  decreases with  $a$ . The obtained results depict that whatever the value of  $\Delta$ , all the curves coincide with each other (i.e.,  $\Delta$  has a negligible effect on  $\lambda_0$ ).

From the above discussion of our results one can conclude that as  $T$  increases,  $\lambda_0$  increases at constant  $\Delta$  and  $a$ . Also, as  $a$  increases,  $\lambda_0$  decreases at constant  $\Delta$  and  $T$ , whereas as  $\Delta$  has a negligible effect on  $\lambda_0$  at constant values of  $a$  and  $T$ .

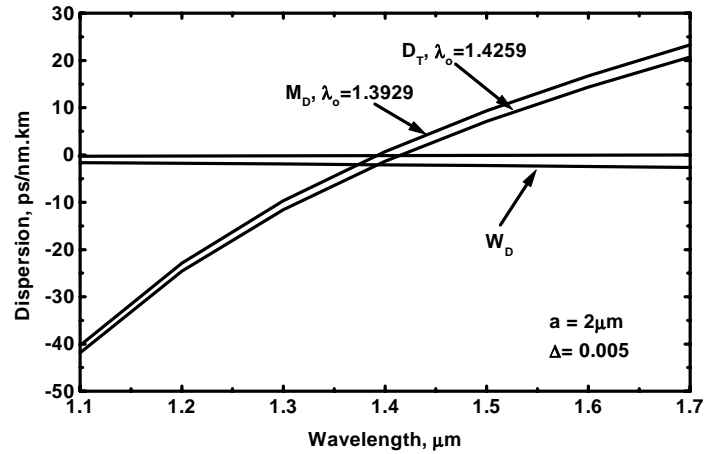


Figure 4: Total dispersion parameter for aluminosilicate glass at 26°C (Step Index)

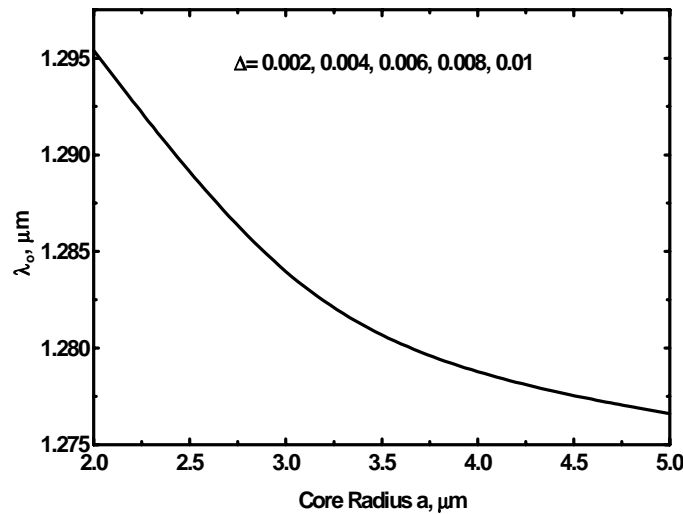


Figure 5: Variation of zero dispersion wavelength with,  $a$ , at 26°C for  $\text{SiO}_2$  glass (Step Index)

**Single mode graded index fiber**

The whole procedure is repeated for graded index single-mode fibers. The only difference between graded and step index fibers is the waveguide dispersion. Again, using temperature dependent Sellmeier coefficients, and the corresponding values of the V-number, waveguide dispersion is calculated at a core radius  $a = 2 \mu\text{m}$  and  $\Delta = 0.0085$  for the three kinds of glasses. The obtained results for aluminosilicate (as an example) are shown in Fig.(6) This particular value of  $\Delta$  is chosen because above it, the V-number exceeds the cutoff value for single-mode operation (3.401) and also it causes a considerable shift in  $\lambda_0$  when we calculate the total dispersion.

From Fig.6, at 26 °C, the zero total dispersion wavelength  $\lambda_0$  is found to be 1.4398  $\mu\text{m}$ . The corresponding values are found to be 1.3086 and 1.3023  $\mu\text{m}$  for  $\text{SiO}_2$  and vycor glasses, respectively. It is also found that the temperature dependence is also linear and  $d\lambda_0/dT = 0.027, 0.033$  and  $0.0325 \text{ nm}/^\circ\text{C}$  for  $\text{SiO}_2$ , aluminosilicate, and vycor glasses, respectively. These variations of  $\lambda_0$  versus T are shown for aluminosilicate (as a sample) in Fig.(7).

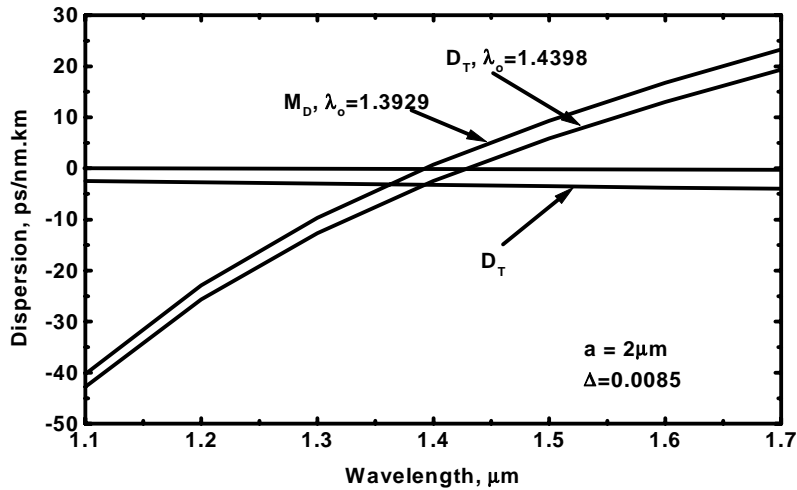


Figure 6: Dispersion behavior for aluminosilicate glass at 26°C (Graded Index)

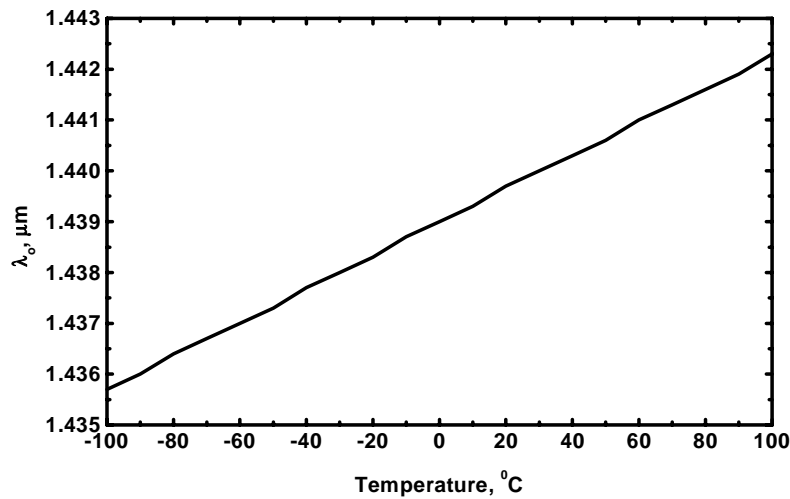
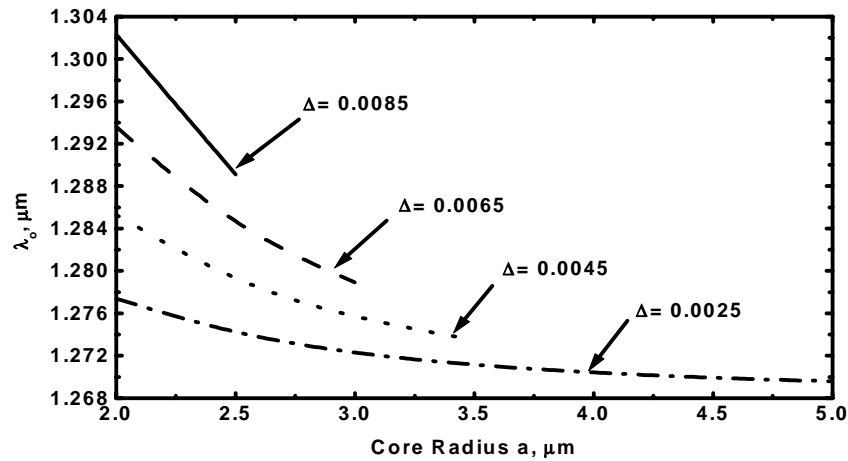


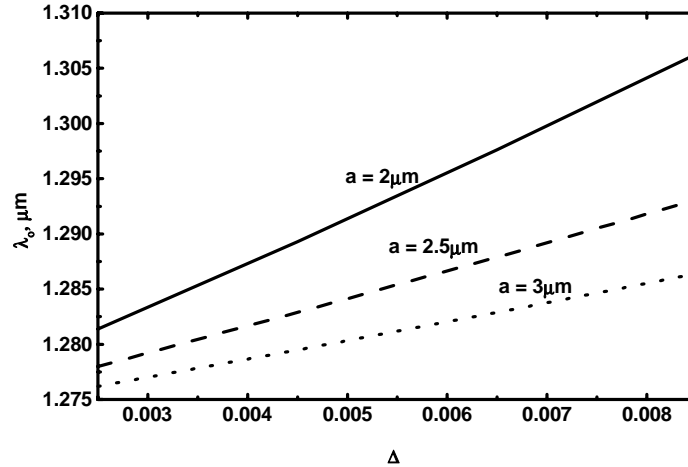
Figure 7: Variation of zero dispersion wavelengths with temperature for aluminosilicate (Graded Index)

The variation of the zero dispersion wavelength,  $\lambda_0$ , with the core radius,  $a$ , at different values of  $\Delta$  at 26°C is shown in Fig.(8) for vycor glass. It is clear that,  $\lambda_0$  decreases with  $a$  and the flatness of the curves increases as  $\Delta$  decreases.

The variation of the zero dispersion wavelength,  $\lambda_0$ , with  $\Delta$  at different core radii is shown in Fig.(9) for SiO<sub>2</sub> glass, where as  $\Delta$  increases the zero dispersion wavelength  $\lambda_0$  increases. The whole behavior is nearly linear and the gradient increases as the core radius decreases.



**Figure 8:** Variation of zero dispersion wavelength with,  $a$ , for vycor glass (Graded Index)



**Figure 9:** Variation of zero dispersion wavelength with  $\Delta$  at 26°C for SiO<sub>2</sub> (Graded Index).

It is useful to note that for SiO<sub>2</sub> and for a value of  $\Delta = 0.0025$  all the values of the V- number are less than 3.401 for,  $a = 2 \mu\text{m}$  till  $5\mu\text{m}$  (i.e. single mode). Whereas for  $\Delta = 0.0045$ , we have a single mode behavior till,  $a = 3.5 \mu\text{m}$  and above this value we turn into multimode, where  $V > 3.401$ . Also, for  $\Delta = 0.0065$  and  $0.0085$ , the fiber behaves as single mode till  $a = 3 \mu\text{m}$  and above this value, it turns into multimode. While for aluminosilicate glass and for a value of  $\Delta = 0.0025$ , we have a single mode for  $a = 2 \mu\text{m}$  till  $a = 4.5 \mu\text{m}$ . For  $\Delta=0.0045$ ,  $0.0065$  and  $0.0085$ , single mode operation



occurs till  $a = 3.5, 3$  and  $2.5 \mu\text{m}$ , respectively. Finally, for vycor glass and for a value of  $\Delta = 0.0025$ , all the values of the V- number are less than 3.401 for  $a = 2 \mu\text{m}$  till  $5 \mu\text{m}$  (i.e. single mode). But for  $\Delta = 0.0045, 0.0065$  and  $0.0085$  we have a single mode behavior till  $a = 3.5, 3.0$  and  $2.5 \mu\text{m}$ , respectively. These values are taken into consideration when the relation between  $\lambda_o$ ,  $\Delta$  is studied for the three mentioned types of glass.

As a summary of the obtained results, we found that, the value of  $\lambda_o$  increases with T at constant values of  $\Delta$  and  $a$  and decreases with  $a$  at constant  $\Delta$  and T. Finally,  $\lambda_o$  increases with  $\Delta$  at constant  $a$  and T. So, the variation of  $\lambda_o$  due to the temperature increase can be compensated by increasing the value of the core radius,  $a$ , with the same rate the temperature increase. This is can be done in a fiber optic cable consisting of two parts or more connected to each other and passing through different environments.

## Conclusions

The wavelength,  $\lambda_o$ , corresponding to zero total dispersion is calculated at a wide range of temperature ( $-100 \text{ }^\circ\text{C}$  to  $100 \text{ }^\circ\text{C}$ ) through the temperature dependent Sellmeier coefficients of the refractive index for silica, aluminosilicate and vycor glasses. The effect of fiber parameters such as: core radius,  $a$ , and the relative refractive index difference,  $\Delta$ , is also investigated. It is found that,  $\lambda_o$  has a linear temperature dependence in the chosen range of temperature. The the value of  $\lambda_o$  is appreciably affected by the change in both  $a$  and  $\Delta$  for graded index fibers. While for step index fibers,  $\Delta$  has nearly no effect on  $\lambda_o$  and the only effect which is due to the change in core radius,  $a$ . Among of the three studied types of optical fiber glasses,  $\text{SiO}_2$  appears the best one because, for a wide range temperatures,  $d\lambda_o/dT$  is less than those obtained for aluminosilicate or vycor glass and it has a single mode behavior for enormous values of  $a$  and  $\Delta$  compared with the other two kinds of optical glasses.

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