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

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Abstract

The zero dispersion wavelength, λ_o, 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 λ_o are investigated for a wide range (-100 ^oC to +100 ^oC) 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;

$$D_T = M_D + W_D, \tag{1}$$

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_2, 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, λ_o, of the total dispersion parameter. The temperature effect on λ_o 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, λ, is defined through the Sellmeier equation which has the form [8, 9]:

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

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 (^oC), in the (-100 ^oC to 100 ^oC) can be obtained for the SiO_2, aluminosilicate, and vycor glasses. The core refractive index, n_T, can then be calculated from its value, n_R, at room temperature, R (^oC), and the smoothed dn/dT values using the relation [8]:

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

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 desipersion in optical fibers is given by [3, 11]:

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

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^{o}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_2, 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.

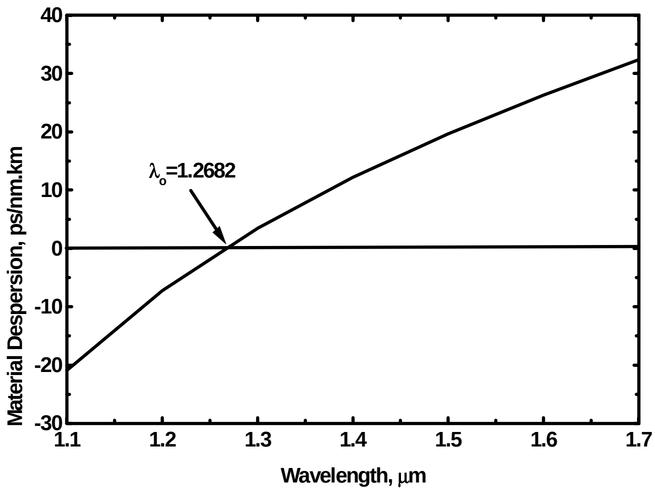

Figure 1: Material dispersion for vycor glass at 26^{o}C

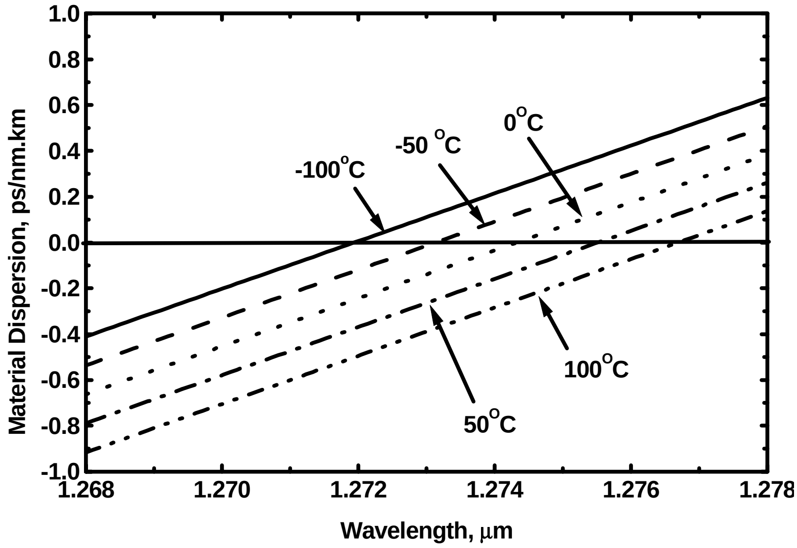

Figure 2: Material dispersion of SiO_2 glass at different temperatures.

For a wide range of temperature (-100^{o}C to 100 ^{o}C), we have calculated the material dispersion and the zero material dispersion wavelength, λ_o, for the three glass types. Again, a sample of the obtained results is shown in Fig.(2) for the SiO_2 glass.

The zero material dispersion wavelength as a function of temperature T is displayed in Fig.(3) for SiO_2. Interestingly, the temperature dependence is linear and $d\lambda_o/dT$=0.025 nm/^oC for SiO_2. This value has a fair agreement with the published experimental values 0.029±0.004 nm/^oC and 0.031± 0.004nm/^oC for two dispersion shifted fibers within the experimental accuracy [4]. The corresponding values of $d\lambda_o/dT$ is found to be 0.03 nm/^oC for both aluminosilicate and vycor glasses.

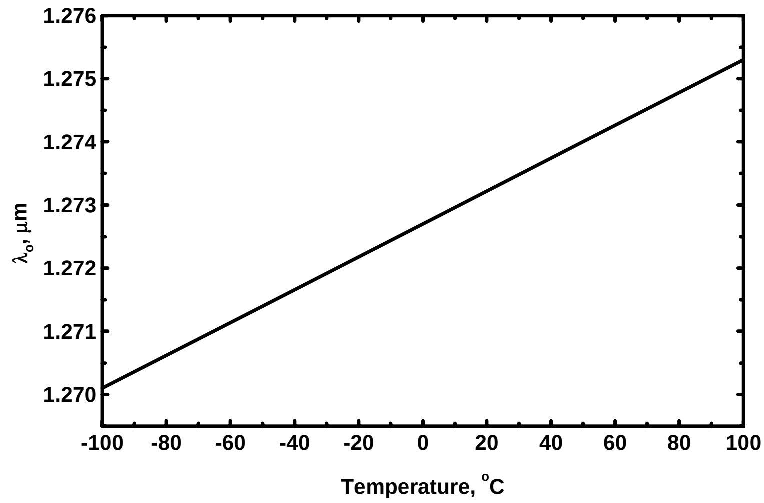

Figure 3: Variation of zero material dispersion wavelengths with temperature for SiO_2 glass.

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 μm and Δ = 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 ^oC, the zero total dispersion wavelength, λ_o, is 1.4259 μm. The corresponding values for are found to be 1.2954 and 1.2894 μm for SiO_2 and vycor glasses, respectively. In the same manner as done with the material dispersion, and in the temperature range -100 ^oC to 100 ^oC, λ_o is calculated showing a linear dependence, with $d\lambda_o/dT$= 0.027, 0.0325 and 0.032 for SiO_2 , aluminosilicate, and vycor glasses, respectively.

The variation of λ_o with the core radius, a, at constant values of Δ at 26 ^oC, is displayed in **Fig.5** for SiO_2 glass showing that λ_o decreases with a. The obtained results depict that whatever the value of Δ, all the curves coincide with each other (i.e., Δ has a negligible effect on λ_o).

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

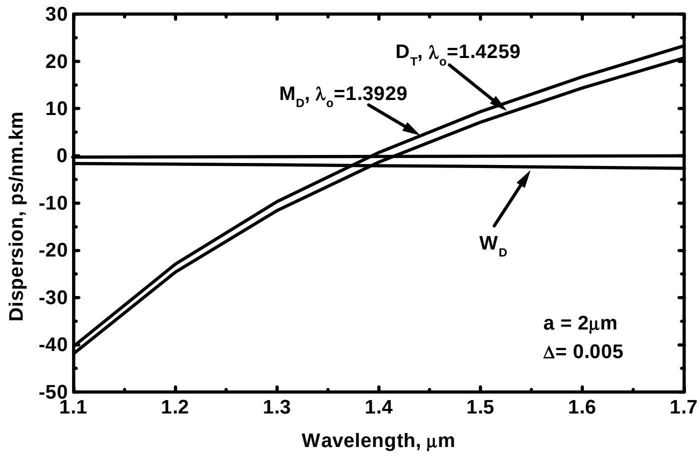

Figure 4: Total dispersion parameter for aluminosilicate glass at 26°C (Step Index)

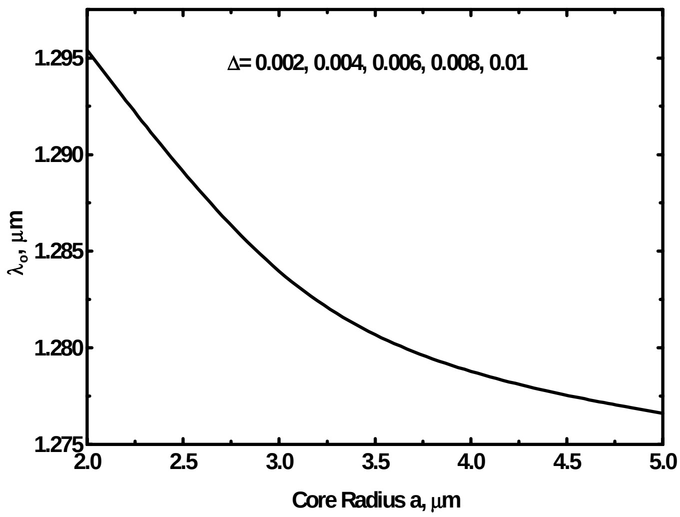

Figure 5: Variation of zero dispersion wavelength with, a, at 26°C for SiO_2 glass (Step Index)

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 μm and Δ = 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 Δ 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 λ_o when we calculate the total dispersion.

From Fig.6, at 26 ^oC, the zero total dispersion wavelength λ_o is found to be 1.4398 μm. The corresponding values are found to be 1.3086 and 1.3023 μm for $SiO_2$and vycor glasses, respectively. It is also found that the temperature dependence is also linear and $d\lambda_o/dT$ = 0.027, 0.033 and 0.0325 nm/^oC for SiO_2, aluminosilicate, and vycor glasses, respectively. These variations of λ_o versus T are shown for aluminosilicate (as a sample) in Fig.(7).

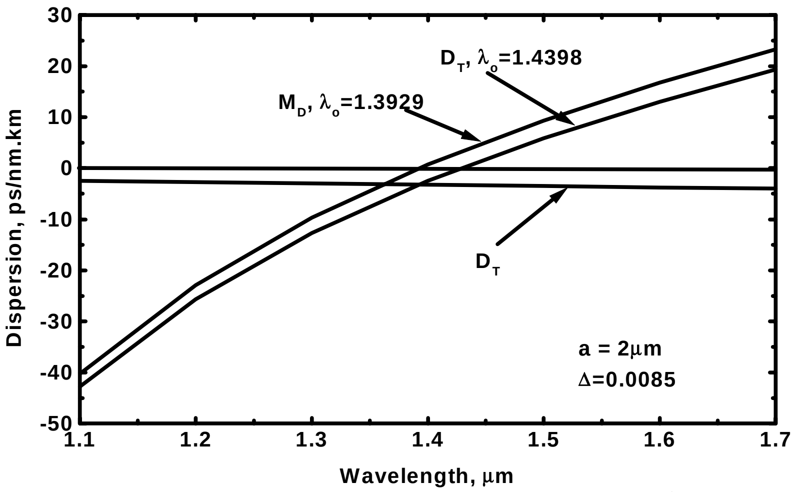

Figure 6: Dispersion behavior for aluminosilicate glass at 26^oC (Graded Index)

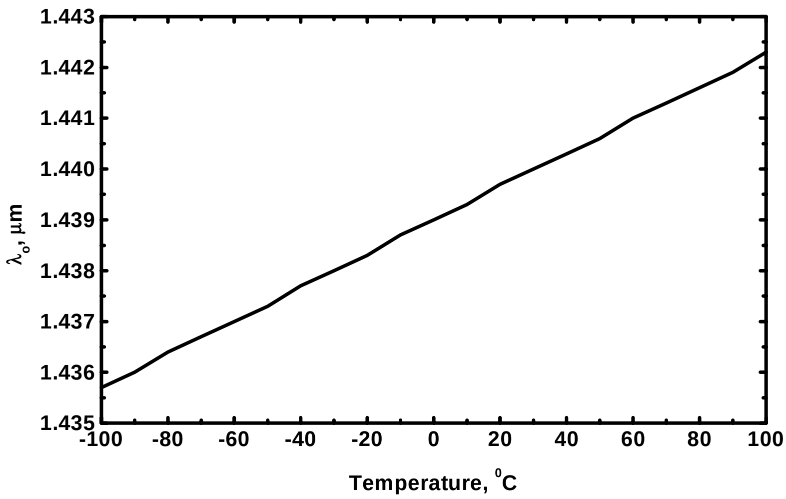

Figure 7: Variation of zero dispersion wavelengths with temperature for aluminosilicate (Graded Index)

The variation of the zero dispersion wavelength, λ_o, with the core radius, a, at different values of Δ at 26^oC is shown in Fig.(8) for vycor glass. It is clear that, λ_o decreases with a and the flatness of the curves increases as Δ decreases.

The variation of the zero dispersion wavelength, λ_o, with Δ at different core radii is shown in Fig.(9) for SiO_2 glass, where as Δ increases the zero dispersion wavelength λ_o increases. The whole behavior is nearly linear and the gradient increases as the core radius decreases.

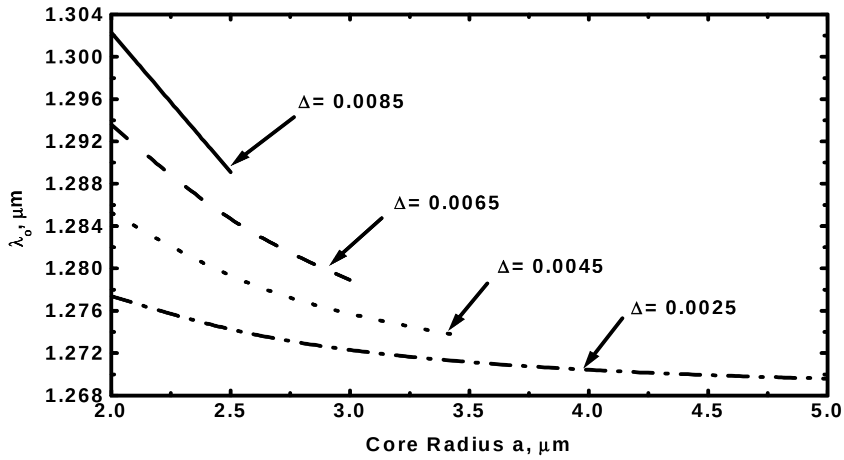

Figure 8: Variation of zero dispersion wavelength with, a, for vycor glass (Graded Index)

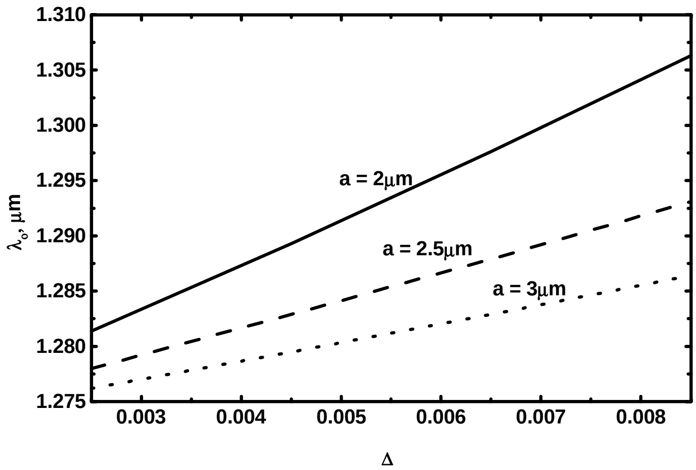

Figure 9: Variation of zero dispersion wavelength with Δ at 26^{o}C for SiO_2 (Graded Index).

It is useful to note that for SiO_2 and for a value of Δ = 0.0025 all the values of the V- number are less than 3.401 for, a = 2 µm till 5µm (i.e. single mode). Whereas for Δ = 0.0045, we have a single mode behavior till, a = 3.5 µm and above this value we turn into multimode, where V > 3.401. Also, for Δ = 0.0065 and 0.0085, the fiber behaves as single mode till a = 3 µm and above this value, it turns into multimode. While for aluminosilicate glass and for a value of Δ = 0.0025, we have a single mode for a = 2 µm till a = 4.5 µm. For Δ=0.0045, 0.0065 and 0.0085, single mode operation occurs till a = 3.5, 3 and 2.5 μm, respectively. Finally, for vycor glass and for a value of Δ =0.0025, all the values of the V- number are less than 3.401 for a = 2 μm till 5 μm (i.e. single mode). But for Δ = 0.0045, 0.0065 and 0.0085 we have a single mode behavior till a = 3.5, 3.0 and 2.5 μm, respectively. These values are taken into consideration when the relation between λ_o, Δ is studied for the three mentioned types of glass.

As a summary of the obtained results, we found that, the value of λ_o increases with T at constant values of Δ and a and decreases with a at constant Δ and T. Finally, λ_o increases with Δ at constant a and T. So, the variation of λ_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, λ_o, corresponding to zero total dispersion is calculated at a wide range of temperature (–100 ^{o}C to 100 ^{o}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, Δ, is also investigated. It is found that, λ_o has a linear temperature dependence in the chosen range of temperature. The the value of λ_o is appreciably affected by the change in both a and Δ for graded index fibers. While for step index fibers, Δ has nearly no effect on λ_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, 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 Δ compared with the other two kinds of optical glasses.

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