Effect of Temperature on the Single Mode Fibers Chromatic Dispersion

P. S. André, A. N. Pinto, J. L. Pinto

Abstract— **We investigate the effect of temperature on the optical fibers chromatic dispersion and chromatic dispersion slope, once these parameters will affect dispersion compensation at high bit rates. We derive an expression for the chromatic dispersion slope variation with temperature as function of the zero dispersion wavelength and chromatic dispersion slope at the zero dispersion wavelength. We also verify that this last term has a high contribution for the total chromatic dispersion variation, and cannot be ignored. We show that the model of *Ghosh et al* for the Silica refractive index temperature dependence can be used to describe the variation of the dispersion slope within the temperature interval between -40 °C and 60 ° C. Through numerical simulation we verify that the effect of temperature cannot be ignored in the design of dispersion compensation devices for high debit systems (40 Gbit/s).**

Index Terms— **Chromatic Dispersion, Optical Fibers, Performance Degradation, Refractive Index,.**

I. INTRODUCTION

THE INCRASING transmission rates and links lengths of nowadays WDM systems, realized over standard single mode fibers (SSMF), imply a better knowledge of the temperature impact on the systems. In order to cope with the restrictions imposed by the chromatic dispersion of the SSMF fibers it is necessary to use dispersion compensation devices, especially for high bit rates signals where the chromatic dispersion tolerances are tight (≥ 40 Gbit/s). These devices should accurately manage the chromatic dispersion, compensating the residual chromatic dispersion and equalizing the chromatic dispersion slope. Since the chromatic dispersion of the deployed optical fibers depend on temperature, it is important to know the relation between chromatic dispersion and chromatic dispersion slope with temperature, in order to enable the full dispersion compensation for a width temperature range.

The previous studies of optical fibers chromatic dispersion temperature dependence, have been focused on the variations of chromatic dispersion slope at zero dispersion wavelength [1-3]. *Hamp et* al [4] have shown that the dispersion variation with temperature is related with the zero dispersion wavelength and with the dispersion slope at the zero dispersion wavelength, and that this second term cannot be ignored in general as suggested by *Kato et al* [2]. For the studied fibers *Hamp* showed that this second term contribute with around 2.5% - 16.7% to the variations of the dispersion with temperature.

We derive an expression for the variation of the chromatic dispersion slope, at the 3rd transmission window wavelengths, with temperature. By this expression, we verified that the contribution of the slope variation with temperature at the zero dispersion wavelength contributed with around 54 % for the total slope variation.

II. CHROMATIC DISPERSION IN SMF

The refractive index of any optical material can be interpolated by the *Sellmeier* formula, which has a physical basis based in the Lorentz oscillator model:

$$n = sqrt\left(A + \frac{B \cdot \lambda^2}{\lambda^2 - C} + \frac{D \cdot \lambda^2}{\lambda^2 - E} \right) \qquad (1)$$

where λ is the wavelength in μm, the first and second terms represent the contributions to the refractive index due to the higher and lower energy gaps of electronic absorption band, respectively, and the last term accounts for the lattice vibrational absorption. The constant E is not critical since the material stop transmitting long before the onset of the lattice absorption frequency. Usually, it is used the value 100. The average energy gap is given by $\sqrt{C}$.

The material chromatic dispersion is manifested through the wavelength dependence of the core refractive index, n_n, by the following relation [5]:

Manuscript received March 25, 2003. This work was supported in part by the Portuguese scientific program FCT through the DOPNET (POSI/CPS/42073/2001) project.

P. S. André is with the Instituto de Telecomunicações and the Departamento de Física da Universidade de Aveiro, 3810-193 Aveiro, Portugal, Phone: +351-234377900, Fax: +351-234377901, E-mail: pandre@av.it.pt.

A. N. Pinto, is with Instituto de Telecomunicações and the Departamento de Electrónica e Telecomunicações da Universidade de Aveiro, 3810-193 Aveiro, Portugal, E-mail: anp@det.ua.pt.

J. L. Pinto is with the Instituto de Telecomunicações and the Departamento de Física da Universidade de Aveiro, 3810-193 Aveiro, Portugal, E-mail: jlp@fis.ua.pt.

$$D_m(\lambda) = -\frac{\lambda}{c} \cdot \frac{\partial^2 n_n(\lambda)}{\partial \lambda} \quad (2)$$

where c is the speed of light in the vacuum.
The waveguide dispersion for a step index single mode optical fiber is given by:

$$D_w \approx -\frac{n_n - n_b}{c \cdot \lambda} \cdot \left[V \cdot \frac{\partial^2 (b \cdot V)}{\partial V^2} \right] \quad (3)$$

where n_b is the cladding refractive index. The term between square brackets can be computed, through an asymptotic expansion, by:

$$V \cdot \frac{\partial^2 (b \cdot V)}{\partial V^2} \approx 0.080 + 0.5439 \cdot (2.834 - V)^2 \quad (4)$$

the normalized waveguide parameter, V, is given by:

$$V = \frac{2 \cdot \pi}{\lambda} \cdot a \cdot (n_n^2 - n_b^2)^{\frac{1}{2}} \quad (5)$$

where a is the core mode field diameter.
The typical computed values for the material and waveguide dispersion can be founded in figure 1, along with the total chromatic dispersion and experimental values [6].

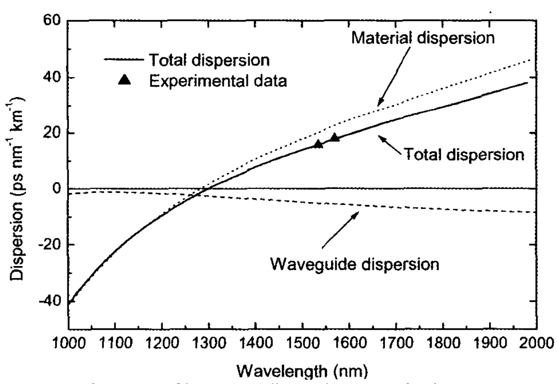


Figure 1 – Chromatic dispersion contributions

The material chromatic dispersion changes with temperature due to an increase in lattice vibrations with increasing temperature. The thermo-optic coefficient, $\partial n/\partial T$, describes the refractive index variation with respect to temperature. This coefficient contains the electronic and optical phonons contribution. The electronic effects in particular the temperature variations of the electronic absorption peak energy gap have the dominant contribution. Therefore it can be described in terms of the linear expansion coefficient α and of the temperature variation of the energy gap $(\partial E_g/\partial T)$ [7].

$$2 \cdot n \cdot \left(\frac{\partial n}{\partial T}\right) = \left(-3 \cdot \alpha \cdot \left(n_1^2 - 1\right)\right) \cdot \left(\frac{\lambda^2}{\lambda^2 - \lambda_g^2}\right) + \left(-\frac{2}{E_g} \cdot \frac{\partial E_g}{\partial T} \cdot \left(n_1^2 - 1\right)\right) \cdot \left(\frac{\lambda^2}{\lambda^2 - \lambda_g^2}\right)^2 \quad (6)$$

where E_g is the band gap energy, λ_g the wavelength correspondent to the energy gap and n_1 is the less dispersive refractive index.
Another approach to the thermo-optic coefficient is based on the Clausius-Mosotti expression:

$$\frac{\partial n}{\partial T} = \frac{\left(n^2 - 1\right) \cdot \left(n^2 + 2\right)}{6 \cdot n} \cdot (\phi - \beta_V) \quad (7)$$

where β_V is the volumetric thermic expansion coefficient and ϕ is the electric polarizability thermic coefficient.
The total chromatic dispersion, given by the sum of the material and waveguide contributions, is usually modeled by the following expression [4]:

$$D(\lambda) = \frac{S_0}{4}\left(\lambda - \frac{\lambda_0^4}{\lambda^3}\right) \quad (8)$$

where λ_0 is the zero dispersion wavelength and S_0 is the chromatic dispersion slope at λ_0. Assuming that both parameters depend on temperature, then the dispersion derivative with respect to the temperature is:

$$\frac{\partial D}{\partial T} = \frac{1}{4} \cdot \left(\lambda - \frac{\lambda_0^4}{\lambda^3}\right) \cdot \frac{\partial S_0}{\partial T} - \frac{S_0 \cdot \lambda_0^3}{\lambda^3} \cdot \frac{\partial \lambda_0}{\partial T} \quad (9)$$

For dispersion compensated spans, more important than S_0 is the dispersion slope at the transmission wavelength, $\partial D/\partial \lambda$.

$$\frac{\partial D}{\partial \lambda} = \frac{S_0}{4} \cdot \left(1 + 3 \cdot \frac{\lambda_0^4}{\lambda^4}\right) \quad (10)$$

which have a temperature dependence given by:

$$\frac{\partial}{\partial T}\frac{\partial D}{\partial \lambda} = \frac{1}{4} \cdot \left(1 + 3 \cdot \frac{\lambda_0^4}{\lambda^4}\right) \cdot \frac{\partial S_0}{\partial T} + 3 \cdot S_0 \cdot \frac{\lambda_0^4}{\lambda^4} \cdot \frac{\partial \lambda_0}{\partial T} \quad (11)$$

While S_0 varies negatively with temperature the dispersion at the C band wavelength have a positive variation with temperature.

Considering that the mean values presented in [4] for $\partial S_0/\partial T$ and $\partial \lambda_0/\partial T$ are -2.46×10^{-6} ps/nm/km/°C and 0.026 nm/°C, respectively, and assuming S_0 = 9.352 × 10^{-2} ps/nm/km, λ_0 = 1319.30 nm, we observe that the first term of expression (11) will contribute with 54.3 % for the chromatic dispersion slope variation with temperature, which have a value of 1.323 × 10^{-6} ps/nm^2/km/°C at 1550 nm.

From the values of λ_0 and S_0 reported by *Hamp et al* for a SSMF, we have calculated the chromatic dispersion and chromatic dispersion slope at 1550 nm as functions of temperature through expression (9) and (11), respectively. These values are shown in the figure 2 with the respective errors bars and linear fit, along with the results obtained from a numerical model. The numerical model calculates the total dispersion from the material and the waveguide dispersion (expression (2) and (3)). The material dispersion was computed from the refractive index (1) which have a temperature dependence given by (6). The values used in the simulations were the following: A=1.3107237, B=0.7935797, C =1.0959659 × 10^{-2}, D=0.9237144, E=100, Eg=11.38 eV, $\partial E_g/\partial T$=-1.7e-4 eV/°C, λ_g =109 nm, a =4.361 µm, n_b/n_n = 0.9979 and α = 0.55 × 10^{-6} °C^{-1}.

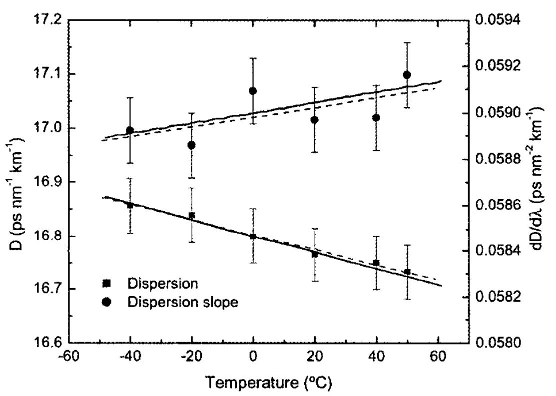


Figure 2 – Theoretical (solid) and experimental (dashed) values of chromatic dispersion and chromatic dispersion slope versus temperature at 1550 nm. The experimental values were obtained from [4] and calculated through expressions (9) and (11).

It can been seen that the model of *Ghosh* can be used to calculate the variation of dispersion slope with temperature and the obtained values matches the values of dispersion and dispersion slope for a 100 °C interval calculated from the values of *Hamp* [4] with our expressions.

III. IMPLICATIONS FOR HIGH SPEED SYSTEMS

A critical factor that will affect the performance of systems at 40 Gbit/s is the temperature fluctuations on the fibers, that induces dispersion variations. We implement a 40 Gbit/s - 500 km transmission scheme with all-at-the-end dispersion compensation, as describe in [8]. The used input impulses have a Gaussian shape with a full width- half maximum (FWHM) of 5 ps and an average power of 0 dBm. The system performance is evaluated in terms of bit error rate (BER), obtained by solving numerically the generalized *Schrodinger* equation with a split-step method [8]. We consider an exact loss compensation and a full compensation of the G.652 fiber, β_2 and β_3 coefficients, obtained from the values of figure 1 for a temperature of 20° C. Then the β_2 and β_3 coefficients were changed to reflect the effect of temperature, between – 40 ° C and 60 °C.

Figure 3 displays the signal BER for several temperatures.

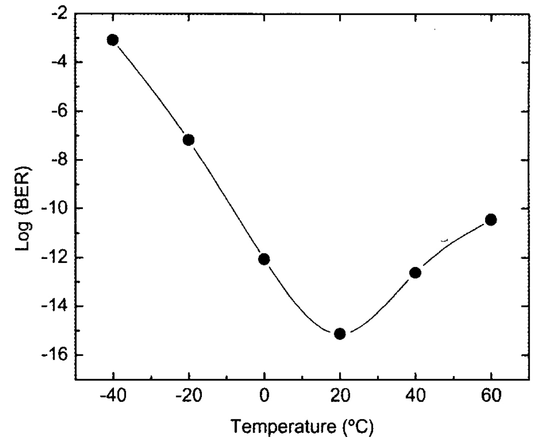
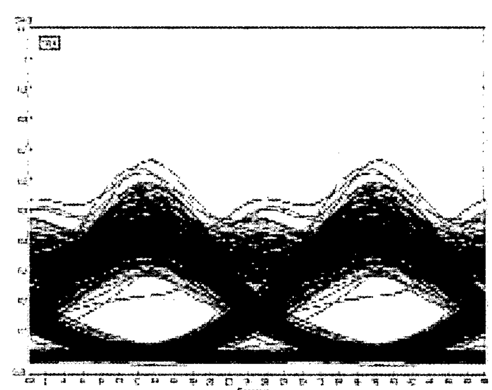
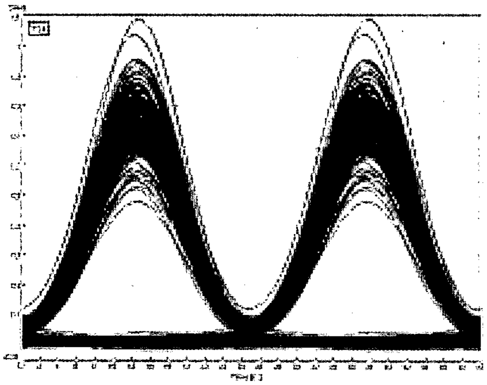


Figure 3 – BER versus temperature of the transmission fiber for 40 Gbit/s. The system have a full compensation for the 20° C temperature. The line is a guide to the eyes.

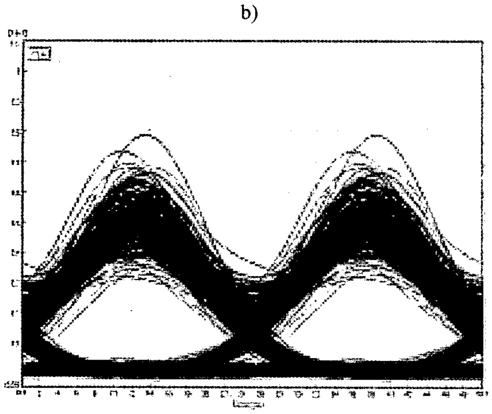
The system was initially optimized for 20 ° C. Figure 4 reports the eye diagrams corresponding to the 40 Gbit/s - 500 km system for a pseudo random bit sequence (PRBS) of 512 bits. The eye diagram on the top and bottom side are ascribed to the temperatures of – 20 °C and 60 ° C, respectively, while the center eye diagram is for a temperature of 20 ° C.



a)



b)



(c)

Figure 4 – Eye diagram after 500 km of propagation: (a) – 20 °C, (b) 20 °C and (c) 60 °C.

IV. IV. CONCLUSIONS

The temperature dependence of chromatic dispersion and chromatic dispersion slope for single mode fibers was investigate. The presented results indicate that change of dispersion and dispersion slope is dominated by the material dispersion variation and this is related with the temperature induced refractive index variations.

The simulation results show that the temperature of the fiber has a high contribution in the performance of 40 Gbit/s systems.

This effect can be mitigated using the suggestion of *Mitachi et al* for the combination of a hybrid ZBGA and SiO_2 fiber to eliminate the refractive index variation with temperature [10].

REFERENCES

[1] William Hatton, Masayuki Nishimura, "Temperature Dependence of Chromatic Dispersion in Single Mode Fibers", J. Lightwave Technol, vol. 4, pp. 1552-1555, Oct. 1986.

[2] T. Kato, Y. Koyano, N. Nishimura, "Temperature dependence of chromatic dispersion in various types of optical fiber", Opt. Lett., vol. 25, pp. 1156-1158, 2000.

[3] Gorachand Ghosh, Michiyuki Endo, Takashi Iwasaki, "Temperature-Dependent Sellmeier Coefficient and Chromatic Dispersions for some Optical Fiber Glasses", J. Lightwave Technol, vol. 12, pp. 1338- 1342, Aug. 1994.

[4] Michael J. Hamp, John Wrigtht, Michael Hubbard, Bob Brimacombe, "Investigation into the temperature Dependence of Chromatic Dispersion in Optical Fiber", IEEE Photon. Technol. Lett, vol. 14, pp. 1524-1526, Nov. 2002.

[5] Emmanuel Jaunart, Pascale Crahay, Patrice Mégret Jean-Christophe Froidure, Michael Lamquin, Michel Blondel, " Chromatic Dispersion Modeling of Single mode Optical Fibers: A detailed Analysis", J. Lightwave Technol, vol. 12, n. 11, 1910-1915, 1994.

[6] P. S. André, "Componentes Optoelectónicos para Redes Fotónicas de Alto Débito", Tese de doutoramento, Universidade de Aveiro, Aveiro, 2002.

[7] Gorachand Ghosh, "Temperature Dispersion of Refractive Indexes in Some Silicate Fiber Glasses", IEEE Photon. Technol. Lett., vol. 6, pp. 431-433, March 1994.

[8] Anna Pizzinat, Alessandro Schiffini, Francesco Alberti, Francesco Matera, Armando N. Pinto, Paulo Almeida, "40-Gb/s Systems on G.652 fibers: Comparison between periodic and all-at-the-end dispersion compensation", J. Lightwave Technol., vol. 20, pp. 1673-1679, Sept. 2002.

[9] G. P. Agrawal, Nonlinear Fiber Optics, 3rd ed. New York: Academic, 2001.

[10] Seiko Mitachi, "Dispersion Measurement on Fluoride Glasses and Fibers", J. Lightwave Technol., vol. 7, pp. 1256-1263, Aug. 1989.