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Thermal Penalty and Sensitivity Effects on the Optical Bit Rate Transmission Networks

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Abstract**- *The temperature environmental in the fiber structure (silica) effects on the chromatic dispersion, fiber losses, fiber core radius, and normalized frequency in single mode and in multi-mode fibers.Highly accurate linear relationship between the zero dispersion wavelength and temperature, has been correlated for long and short distance are modeled and cast in simple linear correlations for temperature ranges 250k up to 600k ,and the thermal field affects on the system bit-rate due to the lattice vibrations of the optical transmission link.The thermal sensitivity , thermal penalty of the high data rate in lightwave system ,dispersion , losses and optical band width are modeled and analyzed parametrically according to the set of controlling parameters flattened thermal penalties are found under certain sets of these parameters.***

Index Terms**— *Optical Communication, Sensitivity effects, Temperature Effects, Power penalty, and Transmission bit rates.***

I. INTRODUCTION

The developments introduced in the optical communication systems have been focused in 3 main objectives: increase of the propagation distance, increase of the transmission capacity (bit rate) and reduction of the deployment and operation costs. In the work of [1] analyze the thermal effects occurring in optical fibers, such as the coating heating due to high power propagation in bent fibers and the fiber fuse effect. Nowadays, the most accepted explanation for the fuse effect describes it as an absorption enhanced temperature rise that propagates toward the light source by thermal conduction and driven by the optical power itself. The first numerical simulation of the fuse propagation used an explicit finite-difference method where it was assumed that the electrical conductivity and consequently the absorption of the core increase rapidly above a given temperature, T. Using this thermally induced optical absorption, T of 1100 ºC and an optical power of 1 W, the core temperature reached to 100000 ºC [1-3].

One of the basic parameters, characterizing a given glass as an optical material is the refractive index dispersion. This parameter is of a particular importance in complex optical systems, in which aberration due to dispersion is to be fully minimized (e.g., in optical telescopes), or where the precise value of dispersion is to be known in a wide spectral range (e.g., in prism spectrum analyzers). Refractive index dispersion is of major importance in fiber optic telecommunications. In particular, the information capacity of a single-mode fiber depends primarily on its chromatic dispersion [4]. The latter consists of waveguide and material dispersion. The waveguide dispersion can be adjusted by choosing an appropriate refractive index profile of the fiber, whereas, the material dispersion is an invariable characteristic of a specific material (e.g., see [1]). Therefore, reliable and accurate data on the material dispersion is indispensable in designing high-bit-rate optical communication systems. Multimode fibers are usually used in fiber-optic local area networks. In this case, inter-modal dispersion is the main factor limiting the information capacity (e.g., see [2]). A graded-index profile of the fiber core is used to minimize this dispersion. However, the optimal profile shape also depends on refractive index dispersion of the core and cladding materials. Finding a single optimal profile for a wide spectral region would make it possible to use one and the same fiber at different wavelengths without a reduction of the bit-rate due to inter-modal dispersion. It would permit application of a practically unlimited number of spectral channels and, hence, a dramatic increase of the information capacity of optical communication links. Thus, accurate determination of the material dispersion of the fiber glass is a topical problem. Germanium is currently the most important dopant when forming the core of the silica fiber [5, 6]. Apart from germanium some other dopants are used, e.g., phosphorus, fluorine, boron, and aluminum [3, 5, 6]. A comparatively new dopant is nitrogen [7]. In many ways nitrogen-doped-silica core fibers are quite competitive with germano silicate fibers. The former are superior to germano silicate fibers in a number of parameters, such as radiation resistance and thermal resistance of in-fiber Bragg gratings [8–10]. Among the advantages of nitrogen-doped silica-core fibers is their potential low cost, because nitrogen is far cheaper than germanium and its resources cannot be exhausted.

Special emphasis is focused on both thermal-dependent dispersion, thermal-dependent loss [4] and sensitivities as major environmental affecting parameters. It had experimentally reported and slightly theoretically justified that the increase of the environmental temperature leads to high spectral loss and moves the zero-dispersion wavelength to higher values or in general alters dispersion characteristics [5].

II. BASIC MODEL AND ANALYSIS

THE THERMAL DEPENDENCE BANDWIDTH:

The fiber bandwidth due to the thermal chromatic dispersion, τ_{ch} in single mode fiber is given by [7]:

$$F_t = \frac{0.44}{\tau_{ch} L} \tag{1}$$

Where L is the optical fiber cable length.

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THE THERMAL DEPENDENCE BIT-RATE:

Based on thesis [7, 8] derived a formula for the system bit rate B_r,

$$B_r^2(\lambda, L, T) = 8F_t^2(\lambda, L, T)\log\left(\frac{B_m(\lambda, L, T)}{B_r(\lambda, L, T)}\right) \qquad (2)$$

Where:

$$B_m = B_u \exp(-\sigma L + \sigma_m) \qquad (3)$$

B_u is the maximum allowable bit rate that depends on the source detector combination, σ is the fiber losses, and σ_m is the accounts to the coupling, connecting and the marginal losses. The relative change of the bit-rate with the temperature, which is defined as [8]:

$$R_{B_r} = \frac{1}{B_r}\frac{\partial B_r}{\partial T} \qquad (4)$$

Over wide ranges of variations of the controlling set of parameters namely:

a) Germania percentage, x
b) Optical wavelength , λ and
c) Medium temperature, T

THE THERMAL PENALTY :

The newly introduced term, thermal penalty, P_T is defined as [9]:

$$P_T = \frac{B_r(T) - B_r(T_o)}{B_r(T_o)} \qquad (5)$$

Where B_r (T) is the bit rate at temperature T,K, $B_r(T_o)$ is the bit rate at room temperature T_o,K

THE THERMAL SENSITIVITY:

Using Eqn.1, the fiber bandwidth, the thermal sensitivity is derived as [10]:

$$F_t\tau_{ch} = \frac{0.44}{L} \qquad (6)$$

By using the differentiation with respect to a temperature ,T,K

$$F_t\frac{\partial \tau_{ch}}{\partial T} + \tau_{ch}\frac{\partial F_t}{\partial T} = 0.0 \qquad (7)$$

Then we get:

$$\frac{\partial F_t}{\partial T} = -\frac{F_t}{\tau_{ch}}\frac{\partial \tau_{ch}}{\partial T} = -\frac{F_t}{\tau_{ch}}\tau'_{ch} \qquad (8)$$

$$\frac{F'_t}{F_t} = -\frac{\tau'_{ch}}{\tau_{ch}} \qquad (9)$$

$$\frac{\partial \tau_{ch}}{\partial T} = \left(\frac{\frac{\partial \tau_{ch}}{\partial \lambda}}{\frac{\partial n}{\partial \lambda}}\right)\frac{\partial n}{\partial T} \qquad (10)$$

From Eqn. 2, the formula of the relative temperature rate of variations of bit rate can be derived by taking the differentiation with respect to the temperature as follows [11, 12]:

$$\frac{B_r^2}{F_t^2} = 8[\log B_m - \log B_r]$$

$$= \frac{2F_t^2 B_r B'_r - 2B_r^2 F_t F'_t}{F_t^4} = 8\left[\frac{B'_m}{B_m} - \frac{B'_r}{B_r}\right] \qquad (11)$$

Therefore:

$$\frac{B_r B'_r}{F_t^2} - \frac{B_r^2 F'_t}{F_t^2} = 4\left[\frac{B'_m}{B_m} - \frac{B'_r}{B_r}\right] \qquad (12)$$

Then we get:

$$\frac{B'_r}{B_r} = \frac{B'_m}{B_m} + \frac{B_r B'_r}{4F_t^2} - \frac{B_r^2 F'_t}{4F_t^3} \qquad (13)$$

From Eqn.3 to calculate $\frac{B'_m}{B_m}$ as follows [13]:

$$\frac{B'_m}{B_m} = \frac{\partial}{\partial T}[-\sigma L]/4343 \qquad (14)$$

Where σ is the total loss, L is the optical length in K_m

$$\sigma = \sigma_{uv} + \sigma_I + \sigma_{IR} + \sigma_R \qquad (15)$$

$$\frac{B'_m}{B_m} = -L[A_m - A_n + \sigma_R]/4343 \qquad (16)$$

Where:

$$A_m = \sigma_{uv}\left(\frac{4.9}{\lambda}\right)\left[\frac{0.731(0.117)}{0.848 - 0.117(T/300)}\right] \qquad (17)$$

$$A_n = -\sigma_{IR}\left(\frac{48}{\lambda}\right)\left[\frac{1.1214(0.0258 + 0.0396(T/300))}{\left[1.167 - 0.0258(T/300) - 0.0198(T/300)^2\right]^2}\right] \qquad (18)$$

Then we get:

$$\frac{B'_m}{B_m} = \frac{L}{\lambda}\left[48\sigma_{IR}E'_{g1} - 4.9\sigma_{uv}E'_{g2} - \left(\frac{\sigma'_R}{\lambda}\right)\right]/4343 \qquad (19)$$

$$\sigma_{IR} = 7x10^5\left[\exp(-24/\lambda)E'_{g1}\right]^2 \qquad (20)$$

$$\sigma_{uv} = \frac{0.0132x}{1.0 + 0.733x}\exp\left(\left(\frac{4.9}{\lambda}\right)E_{g2}\right) \qquad (21)$$

$$\sigma_R = [0.75 + 66\Delta n(T/300)]/\lambda^4 \qquad (22)$$

$$E'_{g1} = \left[\frac{1.1214(0.0258 + 0.0396(T/300))/300}{\left[1.167 - 0.0258(T/300) - 0.0198(T/300)^2\right]^2}\right] \qquad (23)$$

$$E'_{g2} = \left[\frac{0.731(0.117)/300}{(0.848 - 0.117(T/300))^2}\right] \qquad (24)$$

Thus the normal sensitivity, $S_T^{B_r}$ is calculated by multiplying (B'_r/B_r) with T, where we have [14, 15]:

$$S_T^{B_r} = \frac{T}{B_r}B'_r \qquad (25)$$

THE CORE RADIUS THERMAL DEPENDENCE:

The temperature-dependent core radius ,R is modeled under the form [16]:

$$R = R_o\left[1 + \varepsilon\left(T - T_o\right)\right] \tag{26}$$

Where: $R_o$is the fiber radius at room temperature., ε is the linear expansion coefficient [17],

$$\varepsilon = 7.067\text{x}10^{6} + 2.11\text{x}10^{-8}\,T \tag{27}$$

THE CHROMATIC DISPERSION MODEL:

Based on the analysis of [18] the chromatic dispersion is retrieved as:

$$\tau_{ch} = \tau_m + \tau_{wg} + \tau_p \tag{28}$$

Where: τ_m, τ_{wg} and τ_p are respectively material, waveguide and profile dispersions. Then the Egn. 28 is rewritten under the form [19, 20]:

$$\tau_{ch} = D_t \Delta\lambda \tag{29}$$

Where: D_t is the total chromatic dispersion coefficient, Δλ:is the optical source spectral width

$$\tau_{ch} = \frac{\lambda}{c}\Delta\lambda\frac{d^2 n}{d\lambda^2} \tag{30}$$

Where c is velocity of light

$$\tau_{wg} = -\left(\frac{n}{c}\right)\left(\frac{\Delta n}{\lambda}\right)\left(\frac{m}{n}\right)^2 M(v)\Delta\lambda \tag{31}$$

Where: $\Delta n = \dfrac{n_1 - n_2}{n_1}$ (32)

$$m = n - \lambda\left(\frac{dn}{d\lambda}\right) \tag{33}$$

$$M(v) = 0.08 + 0.549\left(2.834 - v\right)^2 \tag{34}$$

Where: $v = 2\pi R^2 n_1\left(\dfrac{\Delta n}{\lambda}\right)$ (35)

$$\tau_p = \left[\left(-n/c\right)\left(\Delta n\right)^{\prime}\left(\frac{\lambda}{4}\frac{\left(\Delta n\right)^{\prime}}{\Delta n}\right) - \left(\frac{m}{n_1}\right)\right]M(v) \tag{36}$$

$$\left(\Delta n\right)^{\prime} = \frac{d\Delta n}{d\lambda} \tag{37}$$

In fact τ_{ch} and consequently D_t are functions of set parameters (R, x, Δn, T, λ, Δλ), Where: Δn is the core-clad refractive index difference [21, 22].

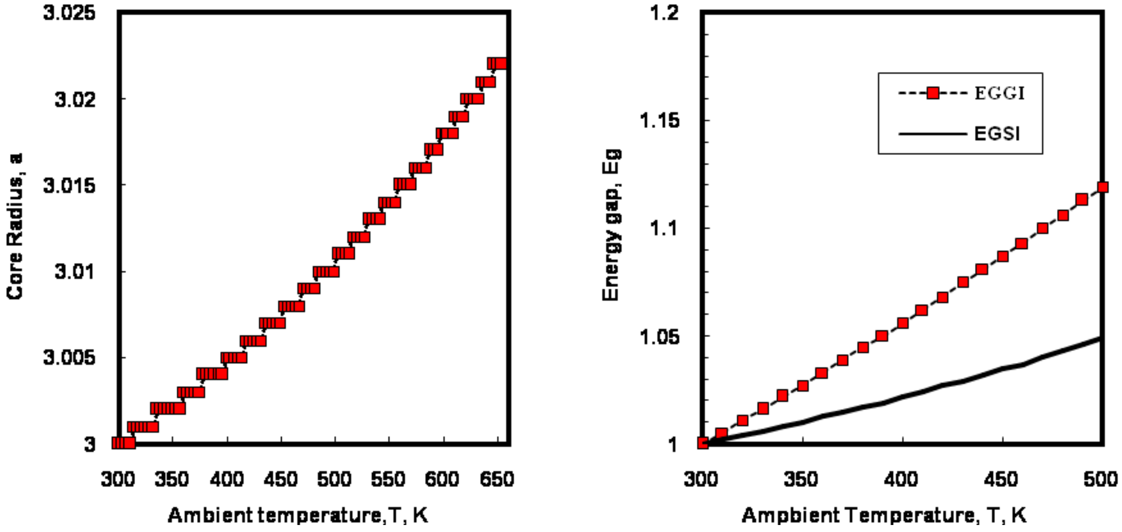
III. RESULTS AND PERFORMANCE ANALYSIS

Once an optical cable is installed, temperature changes surrounding the cable or produced by powerful optical pulses propagating through the fiber can significant impact on fiber performance, with especial emphasis on its pulse – carrying capacity. Such problem is accurately investigated through a well –cast model taking into account the thermal dependence and the spectral loss. The mentioned model is employed to investigate the variations dependent parameters (Δn, τ_{ch}, B_r, P_T, $S_T^{B_r}$) against the variations of one or more of the effecting set of independent parameters (R, T, x, λ). Suitable software programmed is designed and constructed to numerically investigate Eqns. (1 to 37) and to study the effect of different parameters. Over wide ranges of the controlling sets of parameters namely:

a) Germania percentage,
b) Optical wavelength, and
c) Medium temperature.

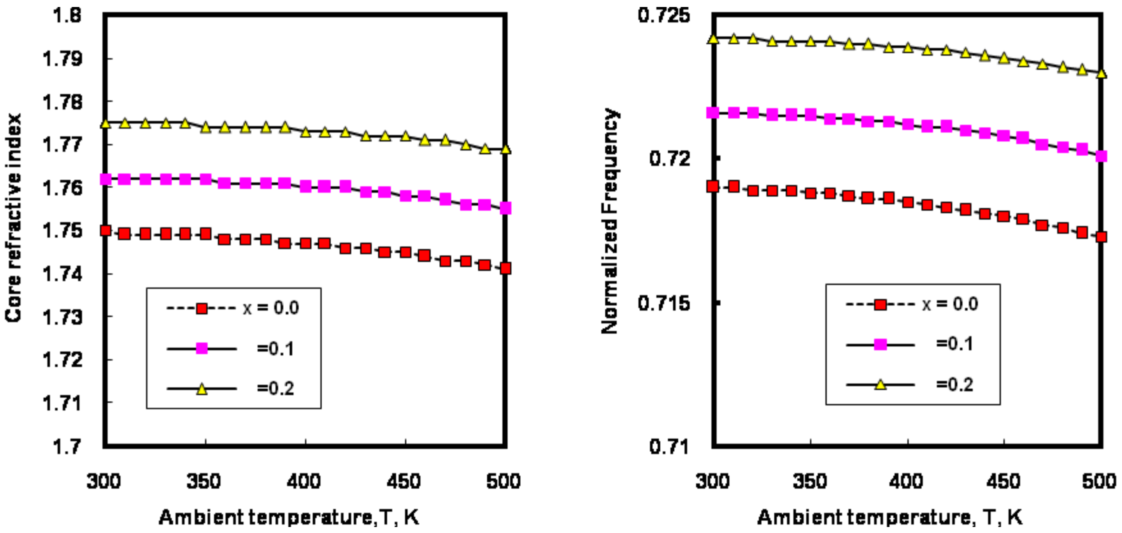
Based on the clarified figures from Figs. (1-14), the following facts are assured:

i) Figs. (1, 2) have assured that with increasing ambient temperature of fibers this results in the increased core radius and band gap energy for both step and graded index fibers.
ii) As shown in Figs. (3, 4) have demonstrated that as ambient temperature increases and germania percentage dopant decreases, this leads to increase in both normalized frequency and core refractive index of used fibers.
iii) Fig. 5 has proved that as ambient temperature increases and germania percentage dopant decreases, this results in the increased in thermal dispersion coefficient.
iv) Fig. 6 has indicated that as temperature and germania percentage dopant increase, this results in increasing the thermal losses.
v) Figs. (7, 8) have indicated that thermal dispersion sensitivity and thermal refractive index sensitivity increase with increasing germania percentage dopant and decreases ambient temperature.
vi) Fig. 9 has indicated that thermal pulse time spreading increases with increasing both spectral line width of the source and ambient temperature of the source.
vii) Fig. 10 has assured that thermal dispersion sensitivity decreases with decreasing of both ambient temperature of the fiber and spectral line width of the optical source.
viii)As shown in Figs. (11, 12) have assured that thermal bandwidth and thermal bit rates decreases with increasing both transmission distances and ambient temperature.
ix) Fig. 13 has indicated that thermal bit rate sensitivity increases with increasing ambient temperature while decreases the transmission distances.
x) Fig. 14 has indicated that thermal bit rate penalty decreases with increasing both ambient temperature and the transmission distances.



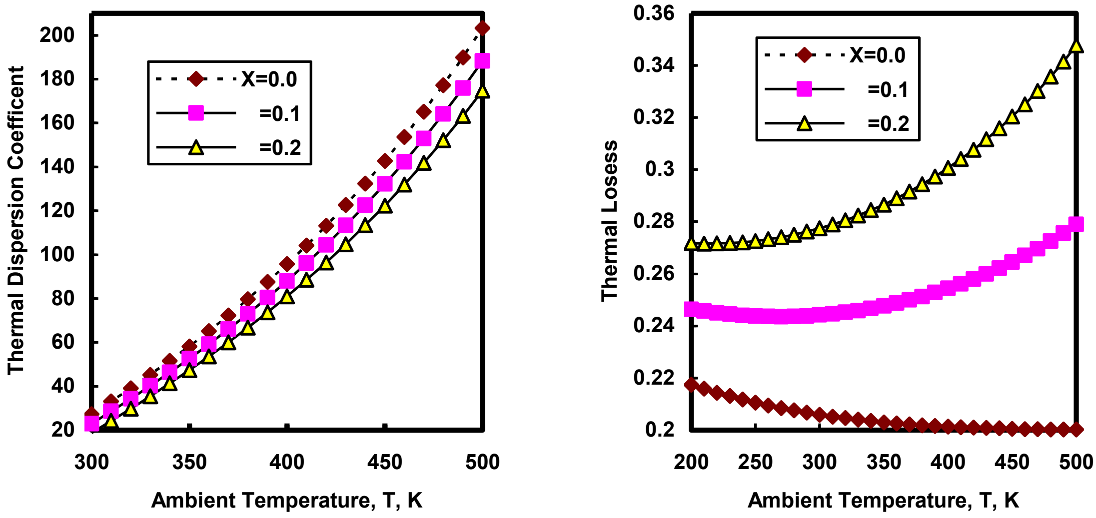
Figs.1, 2. Variations of the thermal core radius of the fiber and the energy gap of silica and Germania.

λ = 1.55 µm, ΔN=0.001	λ = 1.55 µm, ΔN=0.001



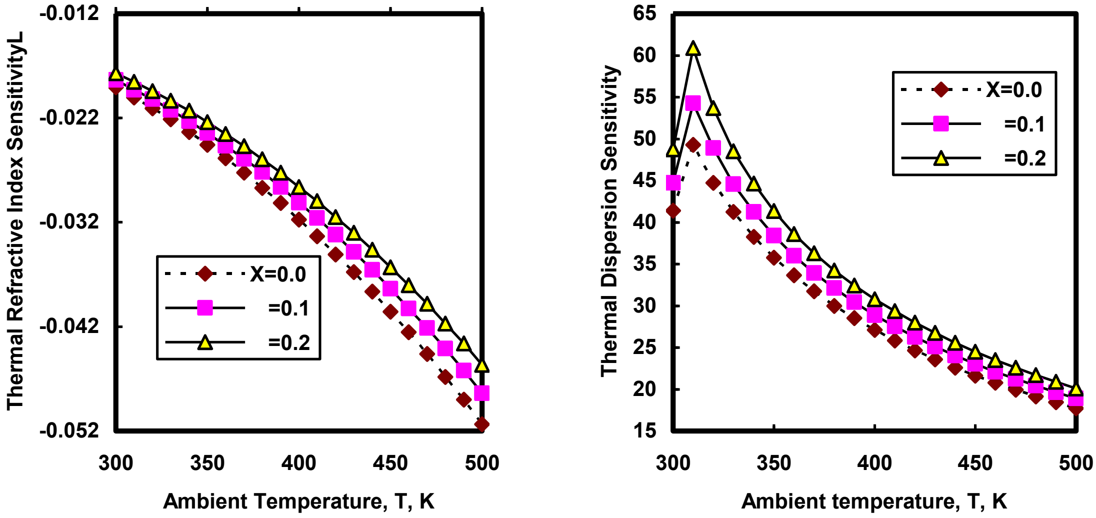
Figs.3, 4. Variations of the thermal core refractive index of the fiber and the normalized frequency.

$\lambda = 1.55\ \mu m$ ΔN=0.001	$\lambda = 1.55\ \mu m$ ΔN=0.005Δλ =0.2nm



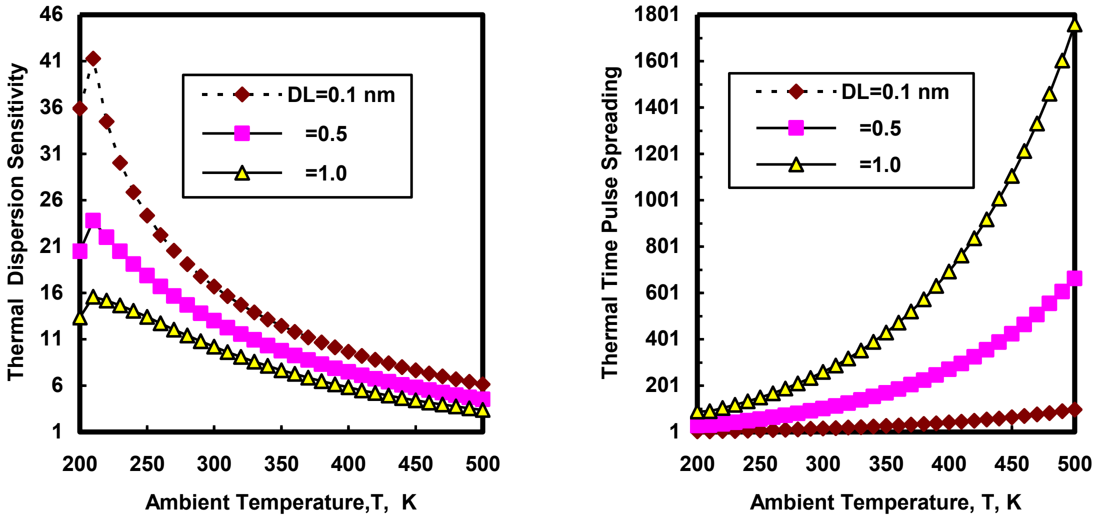
Figs.5, 6. Variations of the thermal (losses and dispersion) of the fiber.

$\lambda = 1.55\ \mu m$ ΔN=0.005Δλ =0.2nm	$\lambda = 1.55\ \mu m$ ΔN=0.005Δλ =0.2nm

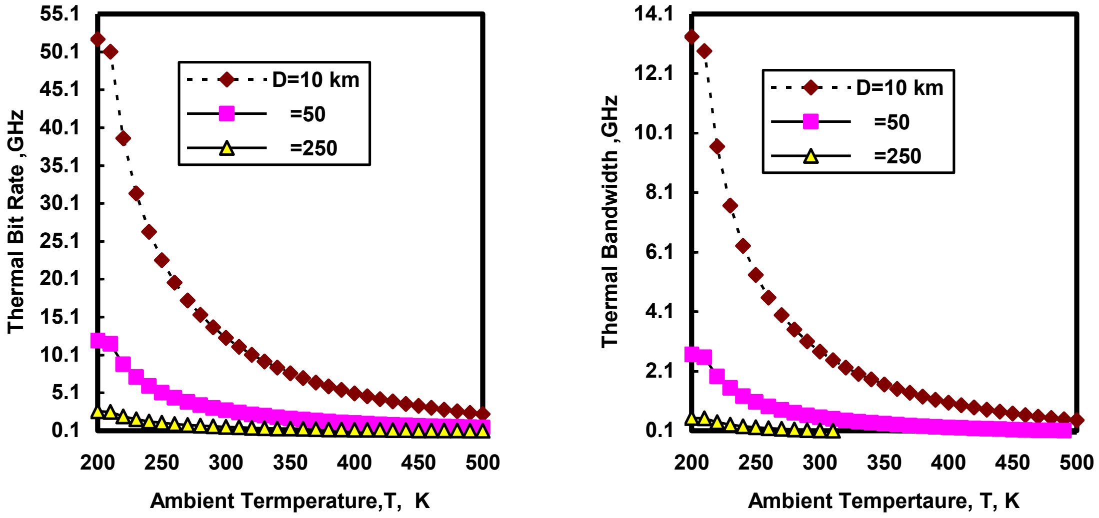


Figs.7,8. Variations of the thermal(refractive index, dispersion) sensitivities.

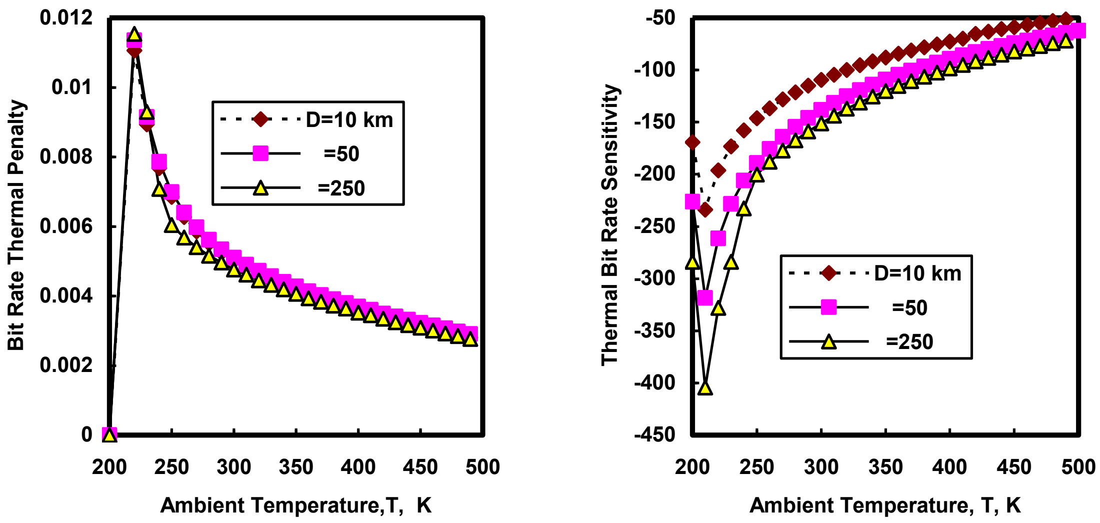
X=0.1 λ = 1.55 μm Δn=0.005	X=0.1 λ = 1.55 μm Δn=0.005



Figs. 9,10. Variations of the thermal (time pulse spreading, dispersion sensitivity)



Figs. 11, 12. Variations of the thermal (bandwidth and bit rate).



Figs.13, 14. Variations of the thermal bandwidth sensitivity and bit rate thermal penalty.

IV. CONCLUSIONS

The refractive index as a function of wavelength was directly measured to a high accuracy in a wide spectral range for standard and new silica for fiber optics. In particular, it was found that germania doped silica is a well-suited material for wide-band graded-index fibers. It was shown that the dispersion properties of such fibers can be easily optimized for any type of silica used in the cladding. It is evident that the dramatic effects of medium temperature, spectral line width of the optical source on the transmission bandwidth and transmission bit rates. Moreover it is found that the serious ambient temperature and transmission distance on bit rate thermal sensitivity and penalty.

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