THERMAL AND POWER DISPERSION PENALTIES FLUORIDE FIBERS VERSUS SILICA FIBERS

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ABSTRACT

Thermal and power dispersion penalties of fluoride fibers (ZBGA) versus silica fibers are parametrically investigated over wide range of variation of the controlling parameters. The thermal effect as well as the chemical composition are taken into consideration when dealing with material, waveguide and profile dispersions. Sellmeier equation for ZBGA fiber is recast with correct coefficients. Both the dispersion-free wavelength and the power dispersion penalty are linearly related to the temperature. The correlations of ZBGA fibers are of negative, while these of Ge-doped fibers are positive. A good agreement is found between the published experimental data and our obtained theoretical results.

I.INTRODUCTION

The transmission capacity of optical fiber communication systems has attracted the attention through the past two decades. There has been continuing interest in the development to achieve longer repeater spaning in order to maximize the product(bit rate-repeater span)[1,2]. This demand has led to increasing interest and has put special emphasis on the need for high speed and wide-band electronics in lightwave transmitters and receivers as well as the transmission characteristics (spectral losses and chromatic dispersion) which reduce the above product [3,4].

To maximize the product (a larger capacity or a longer repeater spacing or both), recently, the following items have been stressed in the design:-

i- a distributed feedback laser diode (DFB-LD) with high speed direct modulation and high-power output,

ii- a cooled photoreceiver with low noise, high-gain and improved sensitivity,

iii- an optical guide with a window of minimum losses and a window of zero dispersion.

Through the past decade, optical fibers made of either germania doped glasses or fluoride-doped glasses have attracted the attentions of investigators both experimentally and theoretically as promise guides for long-haul optical transmission line working in the multigiga bit per second systems. The first type (germania glasses: GeO_2-SiO_2) is employed for the spectral range of 1.3 up to 1.55 μm, while the second type (fluoride glass) is employed for the spectrane range 2.0 up to 4.0 μm, where over these ranges, the guides possess the windows of dispersion-free and minimum spectral losses.

Chromatic dispersion, analysis, computation and limitations in lightwave transmission systems are still handled to reduce it and enlarge the guide bandwidth [5-15]. Such as great and continuous deal of attention has been focused recently on telecommunication systems for future deployment in local networks and subscriber loops, where these systems combine the advantages of low loss (10^3 dB/Km for fluoride doped fiber and 0.2 dB/Km for germania doped fiber), large bandwidth and upgrade potential of single mode fiber with high reliability and temperature stability as well as the low cost.

The last few years have seen considerable progress in the understanding, design and fabrication of single mode fibers [5] with dispersion characteristics which have been tuned to approach the ultimate in performance. From the dispersion shifted fibers, the art has progressed to the stage where zero dispersion together with the attenuation close to the theoretical limits have been achieved. However, the more complex dispersion-flattened fibers, have proved to be of the best reported results over a wide range of wavelengths.

The different dispersion penalties, analysis and methods of reduction, have still attracted the attension. The dominant dispersion penalties that occur in multigiga bit systems are source wavelength chirp [12,16], line broadening due to optical back reflections and mode partition noise [12]. Power dispersion penalties for single mode fibers transmission using LED,s are estimated to be up to 1 dB [16]. The thermal penalty of chromatic dispersion in single mode fiber of fluoride glasses [17] and germania doped glasses [18] are measured where the measurements demonstrated a linear relationship between the zero dispersion wavelength and the temperature. The root mean square width of pulse due to dispersion penalty [15] is derived under an approximate analytical expression for pulsing propagating in nonlinear dispersive fibers. The obtained results are useful for predicting how far a pulse can travel before it suffers significant distortion.

Thus in the present paper, two dispersion penalties, namely the thermal and the power dispersion will be theoretically and parametrically handled for fluoride doped and germania doped fibers.

II. Basic Model and Analysis

It is well known that the total chromatic dispersion D in single mode fibers can be written as [8,19].

$$D = M + P + W \tag{1}$$

where M is the material dispersion, P is the profile dispersion and W is the waveguide dispersion. It is now widely known that the total dispersion in the single mode regime consists of two components only: M and W [20], P accounts for the dispersion due to irrgularities in the refractive index profile which are produced during the drawing process of the optical fibers. The material contribution results from the wavelength dependence of the refractive index where the first and second-order dispersion effects are considered as:

$$M = -\left\{\frac{\lambda}{c}\cdot\frac{d^2 n_1}{d\lambda^2} + \frac{\Delta\lambda}{2C}\left(\lambda\frac{d^3 n_1}{d\lambda^3} + \frac{d^2 n_1}{d\lambda^2}\right)\right\} \text{sec/m.m} \tag{2}$$

where C is the velocity of light and n_1 is the refractive index of the fiber core at wavelength λ. This depends on composition of the material. The waveguide dispersion arises from the variation in group velocity with the wavelength where:

$$W = -\frac{(n_1 - n_2)}{C\lambda} V \frac{d^2(V\beta)}{dV^2} \quad \text{sec/m.m} \tag{3}$$

where β is the normalized propagation constant, V is the normalized frequency, and n_2 is the refractive index of the clad. Both B and V possess the well-known expressions:

$$B = \frac{\beta^2 - n_2^2}{n_1^2 - n_2^2} \tag{4}$$

and

$$V = \frac{2\pi R}{\lambda}\sqrt{n_1^2 - n_2^2} \cong \frac{2\pi R}{\lambda}\sqrt{2n_1^2\Delta} \tag{5}$$

where β and R are, respectively, the normalized propagation constant and the fiber radius ($\beta = \frac{\beta}{k}$ with $k = \frac{2\pi}{\lambda}$ β is the longitudinal propagation constant.)

Refractive index dispersion chromatics for BaF_2-GdF_3-ZrF_4-AlF_3 flouried glasses (BGZA glass) were measured [21,22] and the measured values were substituted into the conventional dispersion equation

$$\lambda^4 n(\lambda, T) = A + B\lambda^2 + C\lambda^4 + D\lambda^6 + E\lambda^8 \tag{6}$$

The coefficients A-E are determined by the least squares method based on the data of Table I for BGZA of 4mole % AlF_3 doped $33BaF_2$-$4GdF_3$-$63ZrF_4$ [21]. These measured values clarify the complicated thermal dependence of these coefficients. Thus the computations will be carried out step by step for the lack of thermal correlations.

Table I. Refractive Index of BGZA of 4 mole % AlF_3 doped $33BaF_2$-$4GdF_3$ - $63ZrF_4$ at various temperature [21]

λ (μm) \ T °C	25	50	100	150	200	250
0.404656	1.52756	1.52716	1.52705	1.52597	1.52556	1.52529
0.435835	1.52459	1.52416	1.52404	1.52298	1.52264	1.52222
0.447100	1.52357	1.62327	1.52252	1.52205	1.52164	1.52114
0.501500	1.51994	1.51968	1.51887	1.51843	1.51802	1.51754
0.546074	1.51787	1.51742	1.51723	1.51622	1.51580	1.51548
0.576959	1.51663	1.51618	1.51599	1.51495	1.51458	1.51416
0.587561	1.51622	1.51586	1.51519	1.51470	1.51427	1.51388
0.667815	1.51391	1.51357	1.51281	1.51233	1.51185	1.51146
0.706519	1.51308	1.51281	1.51198	1.51148	1.51092	1.51062
1.016980	1.50904	1.50860	1.50836	1.50740	1.50695	1.50645
1.08297	1.50844	1.50808	1.50763	1.50683	1.50639	1.50599
1.12866	1.50809	1.50775	1.50751	1.50646	1.50604	1.50567
1.36220	1.50651	1.50611	1.50583	1.50641	1.50441	1.50406
1.52952	1.50555	1.50528	1.50474	1.50395	1.50345	1.50306
1.66060	1.50486	1.50462	1.50415	1.50350	1.50283	1.50262
1.69320	1.50456	1.50423	1.50402	1.50401	1.50256	1.50220
1.81307	1.50282	1.50300*	1.50250*	1.50245*	1.50100*	1.50600*
2.05810	1.50247	1.50218	1.50135	1.50089	1.50041	1.49987
2.15260	1.50187	1.50160	1.50106	1.50042	1.49980	1.49940
2.32542	1.50079	1.50060*	1.50060*	1.49600*	1.49844*	1.49800*
2.43740	1.50022	1.49986	1.49926	1.49877	1.49814	1.49761
3.23890	1.49384	1.49367	1.49302	1.49251	1.49175	1.49141
3.30360	1.49347	1.49311	1.49259	1.49207	1.49143	1.48090
3.41150	1.49240	1.49212	1.49150	1.49105	1.49040	1.48994
3.41990	1.49211	1.49181	1.49111	1.49080	1.49010	1.48973
3.55240	1.49081	1.48895	1.48999	1.48949	1.48886	1.48839
3.70770	1.48927	1.48895	1.48836	1.48792	1.48716	1.48680
3.76010	1.48883	1.48866	1.48787	1.48745	1.48672	1.48595
3.84800	1.48813	1.48802	1.48735	1.48679	1.48611	1.48537
3.97880	1.48632	1.48612	1.48555	1.48483	1.48440	1.48391
4.2580	1.48488	1.48301	1.48246	1.48208	1.48136	1.48073
4.3769	1.48174	1.48156	1.48097	1.48046	1.47985	1.47950
4.5960	1.47902	1.47890	1.47829	1.47781	1.47720	1.47679
4.6885	1.47783	1.47765	1.47709	1.47656	1.47583	1.47548
4.8598	1.47518	1.47521	1.47447	1.47461	1.47351	1.47315
5.1088	1.47218	1.47101	1.47057	1.47048	1.47013	1.46949
5.3036	1.47068	1.46863	1.46806	1.46749	1.46748	1.46645

* Extrapolated values.

Based on Eq.(3), the waveguide dispersion coefficient of fluoride glass is calculated with the aid of [23]

$$B = (\omega/V)^2 \tag{7}$$

and

$$\omega = 1.1428V - 0.9966 \tag{8}$$

in the range of $0.4\ (V=1.2) \leq \omega \leq 1.75\ (V=2.4)$ with $\pm$ 1.5% error.

Based on the analysis of Adams [19], the profile dispersion coefficient is given as:

$$P = \frac{n_1 \Delta'}{C}\left(\frac{\lambda \Delta'}{4\Delta} - 1\right) V \frac{d^2(Vb)}{dV^2} \tag{9}$$

where $$\Delta' = \frac{d\Delta}{d\lambda}$$

with the aid of Eqs.(7) and (8) the quantity $V \frac{d^2(Vb)}{dV^2}$ is expressed as

$$V \frac{d^2(Vb)}{dV^2} = 1.9864231\, V^{-2} \tag{10}$$

Based on the work of fleming [24], the dispersion characteristics of germania doped fiber may be evaluated following the three terms sellmeier equation:

$$n^2 = 1 + \sum_{i=1}^{3} \frac{A_i \lambda^2}{\lambda^2 - \lambda_i^2} \tag{11}$$

where $A_{i,s}$, $\lambda_{i,s}$ are the oscillator strengths and are related to the number of particles in material that can oscillate at wavelengths $\lambda_{i,s}$ where

$$A_1 = 0.6961663 + 0.1107001x \tag{12}$$

$$A_2 = 0.4079426 + 0.31021588x \tag{13}$$

$$A_3 = 0.8974794 - 0.04331091x \tag{14}$$

$$\lambda_1 = 0.0684043 + 0.000568306x \tag{15}$$

$$\lambda_2 = 0.1162414 + 0.03772465x \tag{16}$$

$$\lambda_3 = 9.896161 + 1.94577x \tag{17}$$

To account the temperature effect, the oscillator wavelengths $\lambda_{i,s}$ are inversely proportional to the temperature, thus we multiply the right hand-side of Eqs. (15-17) by (300/T) to obtain $\lambda_i\ (x,T)$, i = 1,2,3 respectively

The quantity $V \frac{d^2(Vb)}{dV^2}$ for germania fiber is given as [25]:

$$V \frac{d^2(Vb)}{dV^2} = 0.08 + 0.549(2.834 - V)^2 \tag{18}$$

The power dispersion penalty for single mode fiber is given by

$$P_d = 22 B^2 \sigma^2 L^4 \left(\frac{d^2 n}{d\lambda^2}\right)/C^2 \ \text{dB} \tag{19}$$

where B is the transmission rate, σ is the initial pulse width, and L is the fiber length. P_d represents the power loss due to the dispersion effects [6]. It is considered through the power budget in optical communication systems via the marginal loss.

III. RESULTS AND DISCUSSION

Based on the above model, a new software program is designed and employed to parametrically study the mentioned penalties. The experimental data that are reported and analyzed in References [21,22] are handled again. On the same fashion as Eq.(6), the data of Table I are correlated and the A,B,C,D, and E coefficients are as listed in Table II.

Table II. Coefficients refactive index (eq. (6)).

T_1° c	A.10^5	B.10^3	C	D.10^3	E.10^6
25	9.37701	2.4426	1.49239	-1.26055	-4.01125
50	9.37443	2.4344	1.49188	-1.26020	-4.01015
100	9.36927	2.4182	1.49116	1.25951	-4.00794
150	9.36412	2.4020	1.49034	-1.25882	-4.00573
200	9.35896	2.3858	1.48895	-1.25812	-4.00353
250	9.35380	2.3696	1.48869	-1.25742	-4.00132

Thus we feel that the data [21,22] which are reported in Table III is-incorrect as it does not give the average value of n (λ) which is localized around the value of 1.5 approximately.

Table III. Coefficients of refactive index dispersion curve.

T_1° c	A.10^6	B.10^3	C.10^3	D.10^3	E.10^6
25	2.98316	3.3974	6.81447	-1.20276	-5.48085
50	25.8587	3.22151	6.72199	-1.18996	-6.48090
100	61.2582	3.0117	6.51185	-1.27783	-3.45226
150	27.3317	3.21624	5.51406	-1.22231	-4.74014
200	33.2719	4.18401	5.13625	-1.27398	-2.68308
250	46.2903	3.12261	4.78751	-1.28172	-2.84427

The obtained results are employed throughout the present paper.

Mitachi [22], based on the work of Shibata and Edahiro [25], reported that zero material dispersion λ_o of SiO_2, 15 % germania doped SiO_2 , and ZBGA (fluoride glass) is given respectively as:

$$\lambda_o (SiO_2) = 1.272 + 6.02 (T-T_o) 10^{-5} \quad (20)$$

$$\lambda_o (15\% GeO_2) = 1.358 + 7.81 (T-T_o) 10^{-5} \quad (21)$$

$$\lambda_o (ZBGA) = 1.675 - 1.778 (T-T_o) 10^{-4} \quad (22)$$

where $T_o = 300$ °K

The suggested model in the present paper yields the following correlations

$$\lambda_o (ZBGA) = a_o + a_1 (T-T_o) \quad (23)$$

$$\lambda_o (SiO_2 - GeO_2) = b_o + b_1 (T-T_o) \quad (24)$$

where a_o is a function of the set of controlling parameters {R, Δn} while a_1 is approximately constant, = 1.855×10^{-4} μm/ °K, also b_o is a function of the set {R, x, Δn} while b_1 is a function only of x. The obtained results are, respectively, listed in Tables IV and V and depicted in Figures(1) - (8). Based on these Tables and Figures. A very good agreement between the theoretical results and the experimental data is found.

Table IV. Coefficient a_o of ZBGA fiber, m.

R_1 μm / n_1-n_2	4.5	5.0	5.5	6.0
0.003	1.8185	1.7955	1.7215	1.6875
0.004	1.8050	1.7360	1.6875	1.6575
0.005	1.7720	1.9685	1.6595	1.6465
0.006	1.7305	1.6690	1.6505	1.6580

Table IV. Coefficient b_o of germania doped fiber, μm

	R_1 μm / n_1-n_2	4.0	5.0	6.0
x = 0.0	0.003	1.3275	1.2915	1.2775
	0.004	1.3145	1.2815	1.2850
	0.005	1.2995	1.2815	1.3090
	0.006	1.2885	1.2940	1.3460
X = 0.05	0.003	1.3530	1.3155	1.3000
	0.004	1.3395	1.3045	1.3055
	0.005	1.3245	1.3030	1.3280
	0.006	1.31125	1.3235	1.3630

with

$$b_1 = 6.15 \times 10^{-5} + 3.6 \times 10^{-4} x \quad (25)$$

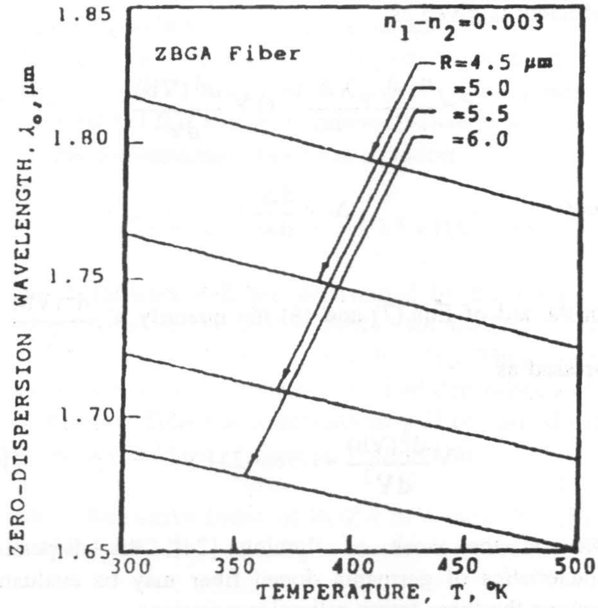

Figure 1. Variation of λ_o with T for n_1-n_2= 0.003 and different values of R for ZBGA fiber.

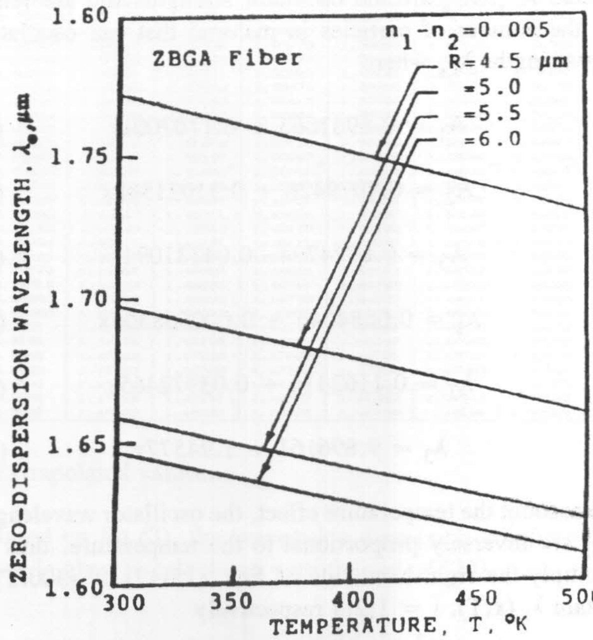

Figure 2. Variation of λ_o with T for n_1-n_2 = 0.005 and different values of R for ZBGA fiber.

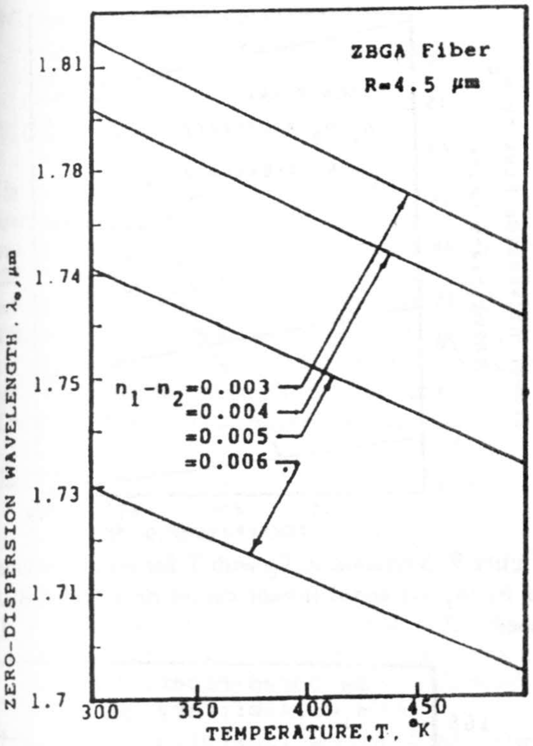

Figure 3. Variation of λ_o with T for R = 4.5 μm and different values of (n_1-n_2) for ZBGA fiber.

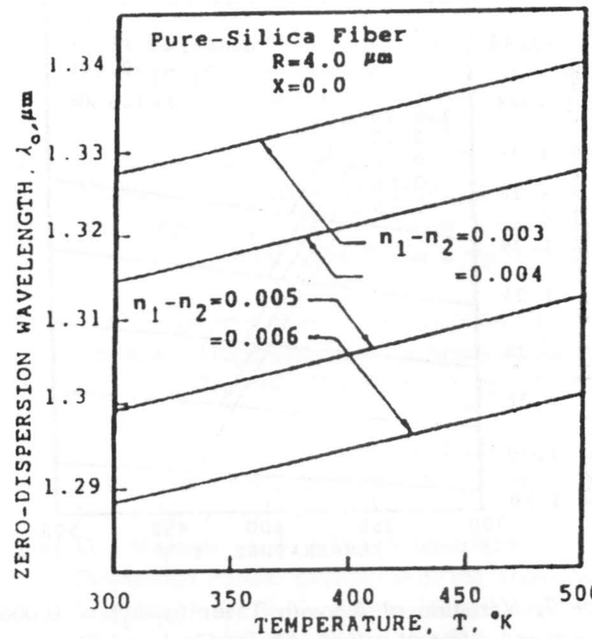

Figure 5. Variation of λ_o with T for R = 4. μm, x=0 and different values of (n_1-n_2) for pure-silica fiber.

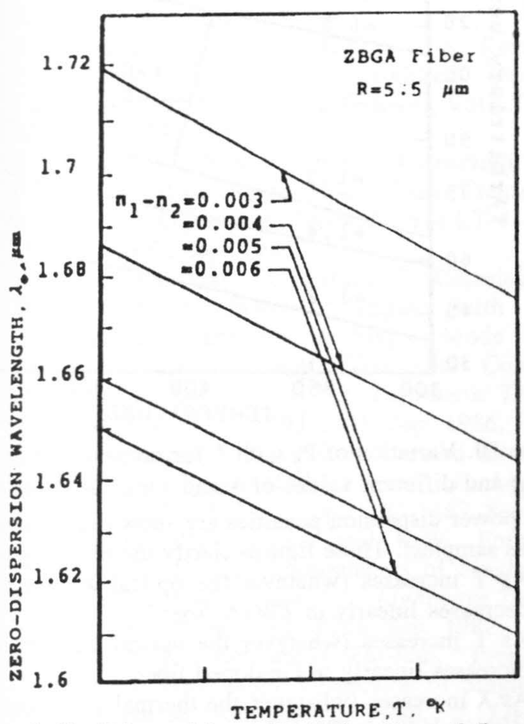

Figure 4. Variation of λ_o with T for R = 5.5 μm and different values of (n_1-n_2) for ZBGA fiber.

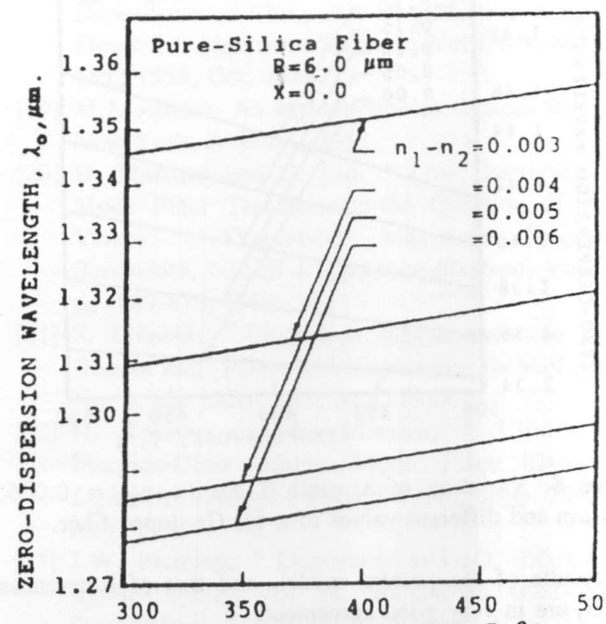

Figure 6 .Variation of λ_o with T for R = 6. μm, x=0 and different values of (n_1-n_2) for pure-silica fiber.

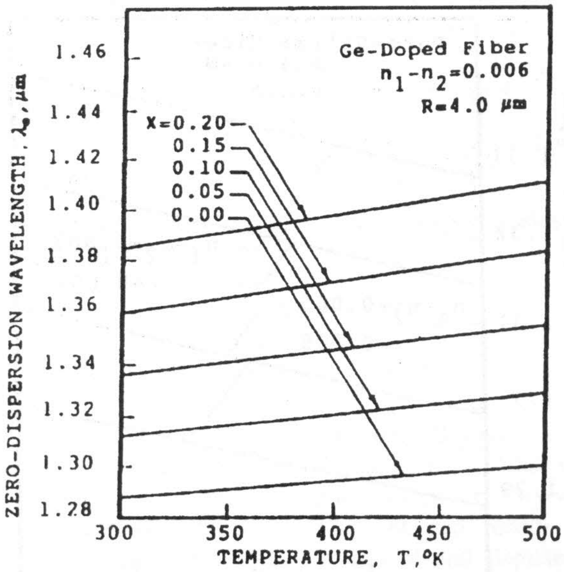

Figure 7. Variation of λ_o with T for $(n_1\text{-}n_2)$ = 0.006, R=4.μm and different values of x for Ge-doped fiber.

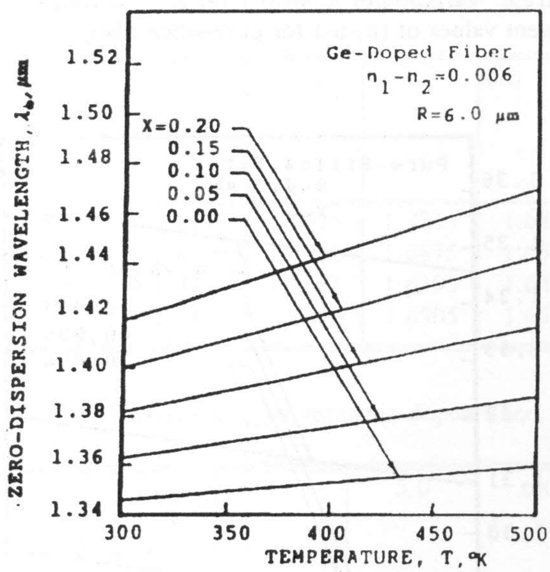

Figure 8. Variation of λ_o with T for $(n_1\text{-}n_2)$ = 0.006, R=4.μm and different values of x for Ge-doped fiber.

The results of the present model, and that of References [22,25] are in very good agreement.

While the thermal penalty of germania doped fibers increases the zero dispersion optical wavelength, the thermal penalty of ZBGA fibers decreases it. Thus, this reality assures the idea of employing successive segments of ZBGA and germania-doped fiber to cancel the thermal dispersion effect.

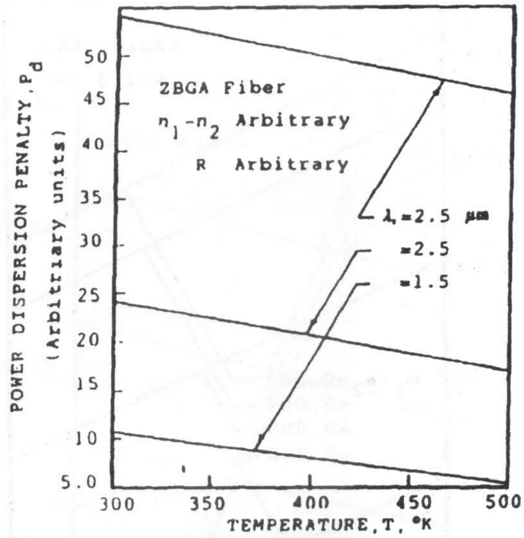

Figure 9. Variation of P_d with T for arbitrary values of R, $(n_1\text{-}n_2)$ and different values of λ for GZBGA fiber.

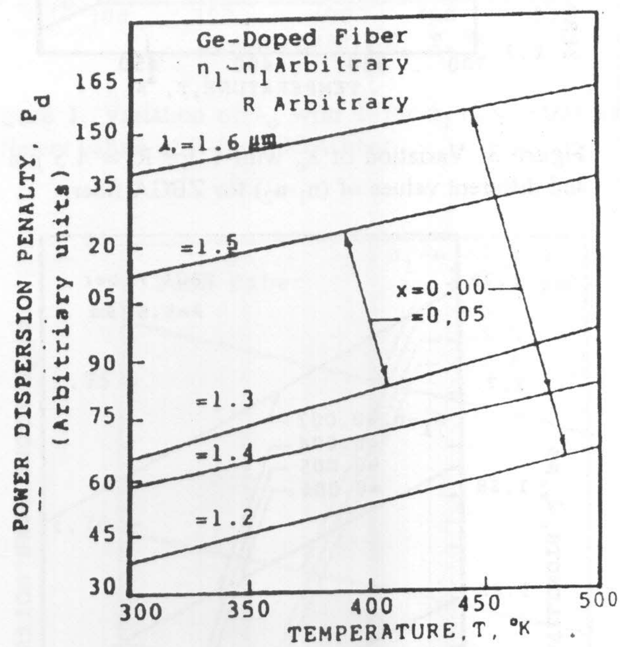

Figure 10. Variation of P_d with T for arbitrary values of R, $(n_1\text{-}n_2)$ and different values of λ and x for Ge-doped fiber.

The power dispersion penalties are shown in Figures (9) - (10) (as samples). These figures clarify the following points:

i- As T increases (whatever the optical wavelength) P_d decreases linearly in ZBGA fiber.

ii- As T increases (whatever the optical wavelength) P_d increases linearly in Ge-doped fiber.

iii- As λ increases (whatever the thermal conditions) the relation between P_d and λ possesses a minimum value at the optical wavelength which yields $d^2n/d\lambda^2$ of minimum value.

iv- Two successive segments of ZBGA in Ge-doped fibers make stable link from the sensitivty piont of view of the power dispersion penalty.

IV. CONCLUSION

In the present paper, both the dispersion-free optical wavelength and the power dispersion penalty are theoretically processed for two optical waveguides, namely, ZBGA fiber and Ge-doped fiber. All the processed correlations are, in general, of linear tone. Good agreement of the experimental data and our present theoretical results is obtained ZBGA fibers yield negative correlations. The results assure the fact of employing two successive segments of these two fibers to compensate the thermal effects.

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