EXACT COMPENSATION FOR BOTH CHROMATIC DISPERSION AND SPECTRAL LOSSES USING CASCADED AMPLIFIERS IN GERMANIA-DOPED SILICA TRANSMISSION FIBERS

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ABSTRACT

A new method to compensate exactly and periodically both chromatic dispersion and transmission losses in germania-doped silica fibers is proposed. This method utilizes N cascaded sections of optical fibers of alternating dispersions with different values of the percentage of doping, to cancel the dispersion each two successive sections. It utilizes N Erbium doped fiber amplifiers to compensate the transmission losses at the end of each section. Both the chromatic dispersion and the transmission losses are considered temperature-dependent quantities. A 1000 km transmission fiber with 40 km length each section. Length is processed (25 cascaded sections) with 25 optical amplifiers each of a 30 dB gain. This is to overcome the spectral, splices, intrinsic, connection, and marginal losses. Useful design correlations are cast to express the two values of germania concentrations that lead to dispersion cancellation.

Keywords: Chromatic dispersion compensation, Cascaded optical Amplifiers, Germania Doped fibers

INTRODUCTION

Upgrading needs of wide-band communication systems cause the demand of large capacity optical communication systems. To improve the transmission performance, the increase of the bit rate-repeater spacing product is one answer. There are two affecting parameters which limit the mentioned product, namely; the chromatic dispersion and the spectral losses. The cancellation, or at least the minimization, of the chromatic dispersion has attracted attention of researchers two decades ago [1-2].With the increasing need for high bit rate systems, the prediction [3] and the measurment [4] of the chromatic dispersion has been handled. Deployment of single-mode optical fibers in communication networks requires an accurate determination of the fibers zero-dispersion wavelength (ZDW) for optimal performance and upgrade capability [5]. Operation of telecommunication networks in the 1.55 μm region is gaining favor as means of adding capacity, providing longer links and enhancing system economy. The use of a dispersion-shifted fiber (DSF) optimized for 1.55 μm performance allowed designers to capitalize fully on new developments in components on an ongoing basis [6]. This DSF offered a greater capacity and distance for band-based and underwater long-haul links. An efficient chromatic dispersion equalizer and novel modulational instability compensation method were proposed [7], for a highly dispersive coherent optical repeater transmission system. A novel design for the chromatic dispersion equalizer provided 44 times higher efficiency in the dispersion compensation characteristics. That novel design increases the substrate thickness for the microstrip delay equalizer. Simultaneous compensation of laser the chirp, Kerr effect, and dispersion in 10-Gb/s long-haul transmission systems were investigated by simulation, where a simple and flexible technique for compensating these effects was discussed [8]. A new design arrangement of transmission fiber dispersion for suppressing nonlinear degradation in long-distance optical transmission systems with optical repeater amplifiers was carried out [9]. Recent progress in erbium-doped optical fiber amplifiers makes it possible to carry multigigabit per second signals over thousands of kilometers of 1.55 μm zero-dispersion wavelength shifted fibers without the need for Retiming, Reshaping, and Regenerating repeaters, (no accumulated dispersion), using a 1000 km fiber loop.

The experimental study of the effect of fiber chromatic dispersion upon ultra-long distance optical communication systems with erbium-doped fiber amplifier has been evaluated [10], where 31 fiber amplifiers where used. The system ZDW was changed by changing the length of the normal single-mode fiber at the end of the fiber loop. Performance evaluation of the different types of fiber-chromatic dispersion equalization for ultralong-distance optical communication systems with erbium-doped fiber amplifiers was carried out [11]. The experiment used a 1000 km fiber loop consisting of 30-DSFs spans and 31 Er-doped fiber amplifiers. The obtained results indicated that the best type of the dispersion equalization for ultralong distance communication systems is to install DSFs with short sections of normal single mode fibers to compensate the accumulated dispersion. Using a 1000 km fiber loop, the experimental study of the effect of fiber chromatic dispersion at 10 Gb/s in standard fiber systems and the use of dispersion compensation were assessed [12], where a propagation for up to 200 km was possible using 36-km amplifier spacing and 30-ps solitons by introducing a section of dispersion compensating fiber just before each amplifier, the average dispersion is reduced. Reduction of dispersion in that manner to 6.0 ps/nm/km increased the total transmission distance to in excess of 360 km. Calculation of dispersion and nonlinear effect limited maximum time-division-multiplexing (TDM) and frequency-division-multiplexing (FDM) bit rates of transform-limited pulses in single-mode optical fibers have been calculated [13]. The maximum transmission capacities of optical fibers obtainable with combinations of TDM and WDM or FDM for Gaussian-shaped transform-limited optical pulses in low loss regions of the silicate fibers at 1.5 and 1.3 μm bands were 7.0 and 6.9 Tb/s, respectively, and those of the doped-fiber amplifiers were about 2.3 and 2.4 Tb/s. A new method to compensate exactly for both chromatic dispersion and self-phase modulation in a transmission fiber was proposed [14], where the light intensity changes due to fiber loss and amplifier gain. This method utilized optical phase conjugation (OPC). Dispersion compensation based on dual-mode optical fiber with inhomogeneous profile core was processed [15] as it was well known that the first higher order mode of optical fibers exhibits large negative waveguide dispersion by operating close to its cutoff wavelength. Using this method, the positive dispersion can be compensated. The first linear optical dispersion-compensating technique capable of more effectively compensating for dispersively chirped signal than dispersively chirp-free signal was proposed [16]. Optical dispersion eigen compensators for high-speed long-haul intensity-modulation direct detection (IM/DD) lightwave systems were processed via a computer simulation. Dispersion compensation techniques using a special dispersion-compensating fiber (DCF) for a fs pulse transmission has been demonstrated [17]. They reported the transmission of 60 fs and 245 fs pulses, respectively, over 42 m and 2.5 km fiber links which consist of standard single-mode fibers (SMF) concatenated with DCF's. The demonstration clarified the ability to achieve simultaneous dispersion and dispersion slope compensation. Soliton transmission using periodic dispersion compensation was examined [18], where the dispersion is alternated between the normal and anomalous regimes. The periodic nature of the system strongly modifies the shape of the stable soliton pulses and increases their energy when compared with solitons in equivalent uniform fibers. Automatic dispersion equalization for installing high-speed optical transmission systems was proposed [19] for cost-effective installation. They have demonstrated a simplified system; the dispersion of a 10 Gb/s-100 km, transmission line was successfully equalized in a fully automatic manner with a penalty-free or better performance. Compensation for composite second-order (CSO) distortion due to the interplay of fiber chromatic dispersion and self-phase modulation was investigated [20].

The transmission performance of a 10 Gb/s repeatered transmission system using dispersion compensating fibers (DCF's) has been investigated theoretically and experimentally [21]. The consideded system configuration was a 360 km standard 1300 nm ZDW fiber transmission system with an optical repeater including DCF's located every 120 km, or every 2100 ps/nm dispersion. The transmitter was a DFB laser externally modulated by a zero-chirp $LiNbO_3$ modulator with NRZ, 2^{23}-1 PRBS data. The system performance is evaluated in terms of electrical eye margin in the receiver/regenerator. They presented a complete description of the system performance including the nonlinear self-phase modulation (SPM) effect in both standard fiber and DCF's. The results of this investigation clearly demonstrate that the use of DCF's is an extremely effective method to overcome the chromatic dispersion in high-speed transmission systems.

The main results of this study are:

1) The new "eye position method" which presents the eye margin degradation from both "1" and "0" levels as a function of dispersion values describes the system performance more effectively than the conventional "eye opening penalty (EOP) method"
2) A rule of thumb is that the total dispersion must be slightly under compensated to include the SPM effect,
3) A very wide range of dispersion compensation values offers acceptable system performance, and ,
4) The "equal modulator compensation which is desirable from a practical point of view provides sufficiently large eye margin 33.3 % for 10^{-15} BER after 360 km. In the "customized modular compensation", the dispersion compensation is tailored to achieve the maximum eye margin without considering the performance at the intermediate repeater locations provides the largest eye margin 5% for 10^{-15} BER.

In the present paper, the periodical cancellation of dispersion in single mode fibers is analyzed taking into account the thermal effects. Germania doped silica segments of length L are connected in such a manner to periodically filter the chromatic dispersion at 2L as a periodic distance. A system of a 1000 km length with L=40 km and 25 erbium-doped fiber amplifiers to compensate the spectral losses is suggested to be employed at the third optical communication window ($\lambda \cong 1.55$ μm).

BASIC MODEL AND ANALYSIS

Cascaded erbium doped fiber amplifiers EDFA's are employed to compensate the transmission losses. The maximum gain at $\lambda \cong 1.55$ μm varies from ≅2 dB up to 50 dB at pump powers from 1mW up to 10 mW, respectively. In this situation, the length of EDFA's varies from 7 m up to 50 m [22]. Along the path of transmission with cascaded amplifiers the optical signal power undergoes zigzag variation [23]. It decreases on the transmission fiber and increases at the location of the optical amplifier. All the path amplifiers exhibit the same gain and this gain is assumed to compensate exactly for the loss of the transmission fibers between the path amplifiers.

Based on the work of Fleming [24] material dispersion (the first and the second-order dispersion effects simultaneously of binary glass) may be evaluated following the three terms Sellmeier equation:

$$n^2(\lambda, T) = 1 + \sum_{i=1}^{3} \frac{A_i(T)\lambda^2}{\lambda^2 - \lambda_i^2(T)}, \qquad (1)$$

where :

$n(\lambda,T)$: refractive index
λ : optical wavelength
T : ambient temperature
A_i : oscillator strength
λ_I : oscillator wavelength

For GeO_2-SiO_2 fibers of x% GeO_2, , the two sets of A_i and λ_i are given as follows:

$$A_1 = (0.6981663+0.1107x)\propto(T) \qquad (2\text{-a})$$

$$A_2 = (0.4079426+0.310215x)\propto(T) \qquad (2\text{-b})$$

$$A_3 = (0.897479+0.0433109x)\propto(T) \qquad (2\text{-c})$$

$$\lambda_1 = (0.0684043+0.00056306x)\,\beta(T) \qquad (2\text{-d})$$

$$\lambda_2 = (0.1162414+0.03772465x)\beta(T) \qquad (2\text{-e})$$

$$\lambda_3 = (9.8616+1.94577x)\beta(T), \qquad (2\text{-f})$$

where $\propto(T)$ is added after the report of [25] as the average thermal refractive index was:

$$\left\langle \frac{dn}{dT} \right\rangle = 1.5x10^{-5} \quad {}^{\circ}C^{-1}. \qquad (3)$$

Therefore, $\propto(T)$ is cast as :

$$\propto(T) = 0.93721+2.0857\ x10^{-4}T. \qquad (4)$$

The term $\beta(T)$ is designed on the basis that the oscillator frequency varies linearly with the temperature and consequently the oscillator wavelength is inversely proportional to the temperature, thus:

$$\beta = T_o/T, \qquad (5)$$

where T_o is the initial ambient temperature. Following the same spirit of References 26, 27, in separating the various contributions to the total chromatic dispersion in single mode fibers of core radius R, the following is processed:

$$\Delta\tau = D_t\Delta\lambda = -(M_{md}+M_{wd}+M_{pd})\,\Delta\lambda, \qquad (6)$$

where D_t, M_{md},M_{wd},M_{pd},and $\Delta\lambda$ are respectively total chromatic dispersion coefficient, material dispersion coefficient, waveguide dispersion coefficient, profile dispersion coefficient, and optical source spectral width.

Based on the work CSELT [26] and Senior [27], the system bit rate is related to transmitter, receiver, and guide characteristics through the following transcedental equation,

$$\left[\frac{B_r}{F_t}\right]^2 = 8\log\frac{B_u e^{-(\sigma L-\sigma_m)}}{B_r}, \qquad (7)$$

B_u is the limitations-free bit rate, σ is the spectral loss [28]. L is the section length, σ_m is the marginal loss, F_t is the guide 3-dB cutoff frequency given as [26]:

$$F_t = \frac{0.44}{\tau_{ch}(2L)}, \qquad (8)$$

where τ_{ch} is the chromatic dispersion of the guide. The spectral loss, σ, is designed to account for the doping percentage, x, and the thermal dependence as well as the optical wavelength.

In Equations 7 and 8, the section length L is related to the total length L_t and the number of amplifiers N via the relation:

$$L = \frac{L_t}{N}. \qquad (9)$$

The factor 2 in Equation 8 is cast to account for the 3-dB cutoff bandwidth at a distance 2L, where the positive dispersion and the negative one are cancelled. The optical amplifier cancels the losses periodically including the splice loss at the end of each section thus the dispersion is cancelled at the end of each two sections.

The use of Equation 8 and 9 into Equation 7 yields:

$$(B_r\tau L)^2 = 0.3872\ \log\frac{B_u e^{-(\sigma L-\sigma_m)}}{B_r}, \qquad (10)$$

or

$$\left(\frac{B_r \tau L_t}{N}\right)^2 = 0.3872 \log \frac{B_u e^{-(\sigma L_t / N + \sigma_m)}}{B_r}. \qquad (11)$$

For an LD source and an APD detector, the ultimate bit rate B_u =6.3 Tb/sec, while for an LED source and an APD detector, B_u =0.396 Tb/sec.[26].

RESULTS AND DISCUSSION

For a system of a 1000 km of single mode fiber of core radius R=3 μm, both the dispersion and the losses are periodically cancelled at 2L and L respectively . A special software is designed to evaluate both x_1% which yields either positive dispersion or negative dispersion and x_2% which yields either negative dispersion or positive dispersion. Both x_1 and x_2 are parametrically investigated . The causes of variations are the optical wavelength, the ambient temperature, and the numbers of the optical amplifiers. The designed model is tested for both LED's and LDs sources. The cascaded EDFA's has unfortunately two drawbacks, namely; the reduction of the flat gain width from 20 nm one stage to less than 10 nm as well as the reduction of the signal to noise ratio from approximately 25 dB one stage to less than 20 dB [29].

A real system of intrinsic loss of 0.2dB/km and marginal loss 3dB to account for the splices, connection, and other losses is investigated.

The variations of x_1 against the variations of x_2 at different values of the optical wavelength λ and the ambient temperature T are displayed in Figures 1-4. where the spectral width of the optical source is a parameter. These figures clarify the following points:

From the Point of View of λ

As the optical wavelength increases, higher values of x_1 and x_2 are required to compensate for the dispersion. The relation of x_1 and x_2 is cast under the form:

$$x_2 = a + b x_1 \qquad (12)$$

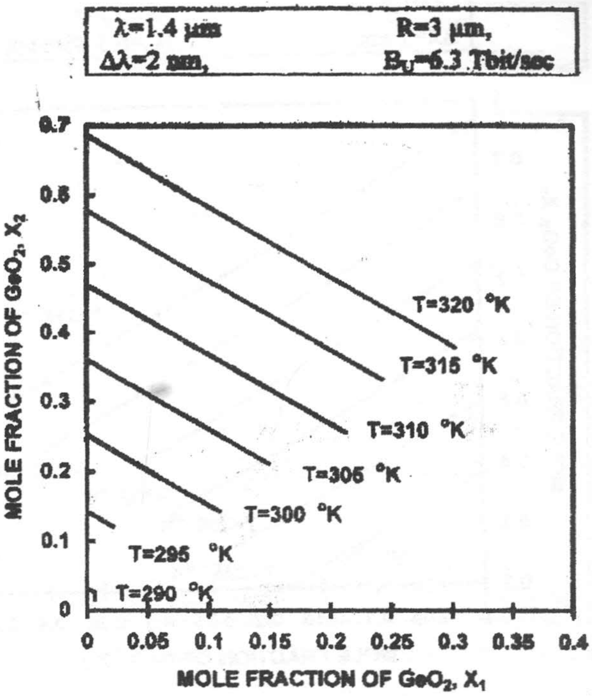

Figure 1 Variations of x2 against variations of x1 at the assumed set of parameters

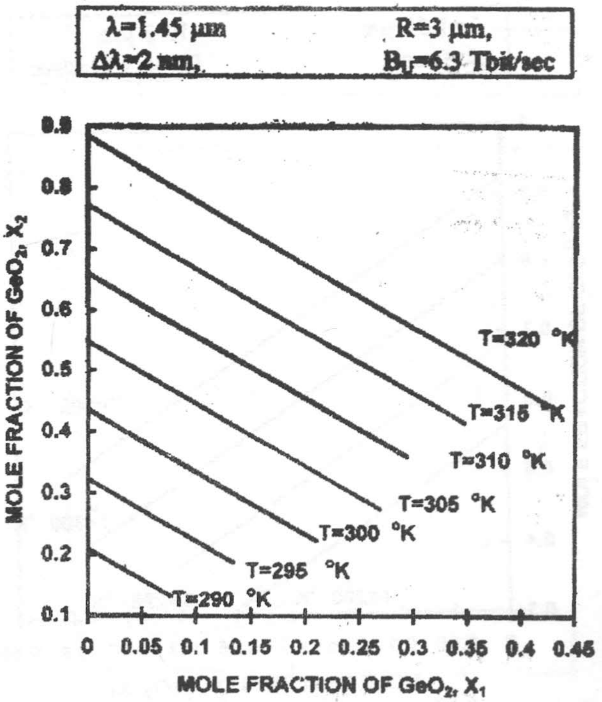

Figure 2 Variations of x_2 against variations of x_1 at the assumed set of parameters

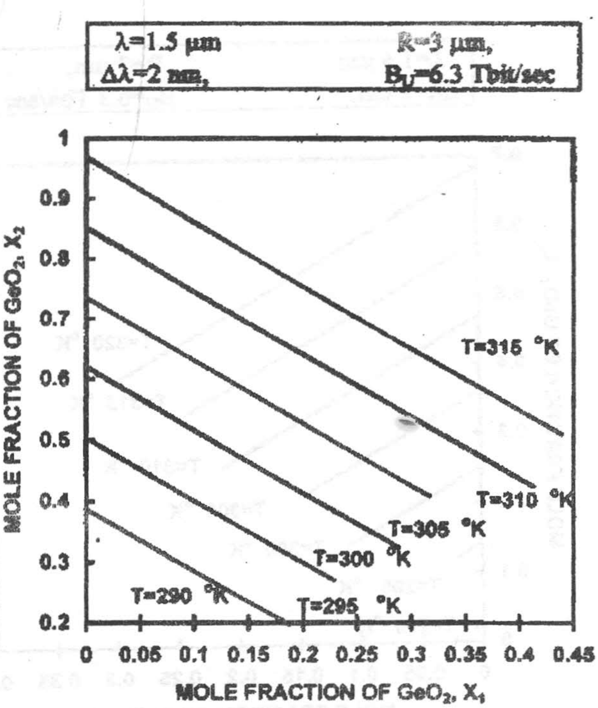

Figure 3 Variations of x2 against variations of x1 at the assumed set of parameters

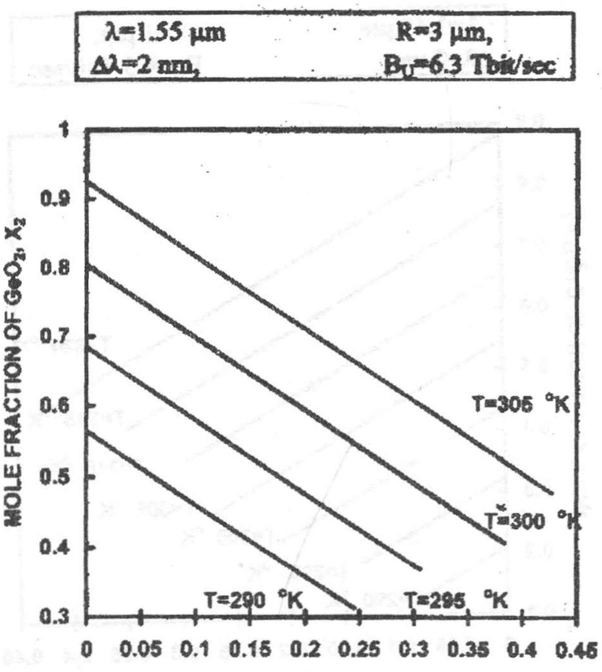

Figure 4 Variations of x2 against variations of x1 at the assumed set of parameters

with $X_1 \leq X_2$ where a is function of λ,T the forms:

i- At λ=1.4 μm

$a=-6.28711+0.021795T$ (13)

$b=-1.0$ (14)

ii- At λ=1.45 μm

$a=-6.31309+0.022495T$ (15)

$b=-1.0$ (16)

iii- At λ=1.5 μm

$a=-6.35509+0.023453T$ (17)

$b=-1.0$ (18)

iv- At λ=1.55 μm

$a=-6.40383+0.0240302T$ (19)

$b=-1.0$ (20)

The coefficient a, in general, is cast as:
$a=a_o+a_1T$
where both a_o and a_1 are functions of λ of the forms:

$a_o=-5.18289-0.784327\lambda$ (21)

$a_1=8.84633\text{x}10^{-4}+1.49207\text{x}10^{-2}\lambda$ (22)

From the Point of View of T

As the ambient temperature increases, the ranges of the relation $x_2=f(x_1)$, Equation 12, increases, and in general, subsection of x_1 requires another of a higher value of x_2 to eliminate the dispersion. As x_1 increases, x_2 decreases and the minimum bit rate B_{rm} also decreases.

The variations of B_{rm} against the variations of x_1 at different values of λ and T are displayed in Figures 5-8, where it is clear that as λ increases the spectral losses decrease and the dispersion increases yielding less bit rates.

The variations of B_{rm} against the variations of the number of the cascaded amplifiers, N, are expected by induction to be of a positive correlation as the increase of N decreases the amplifier spacing, and consequently B_{rm} increases.

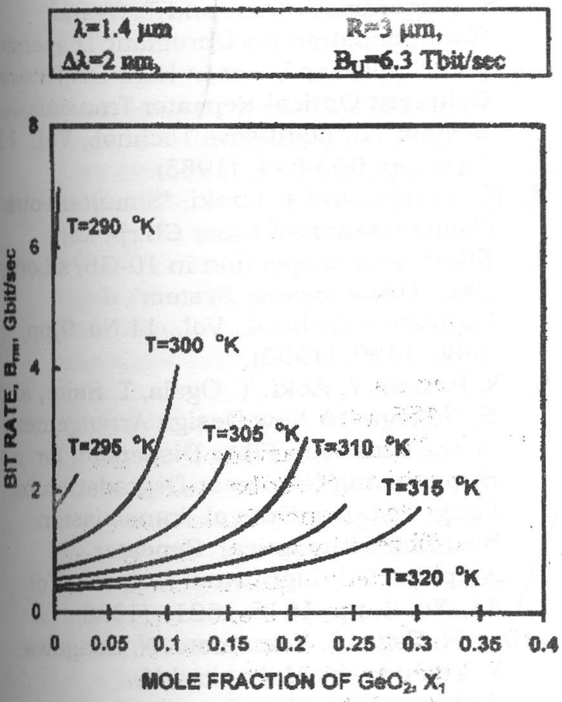

Figure 5 Variations of B_{rm} against variations of x_1 at the assumed set of parameters

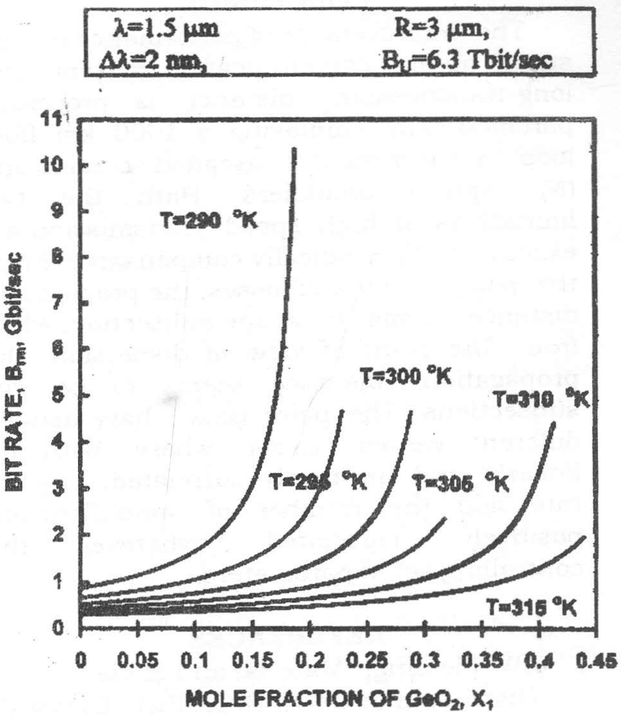

Figure 7 Variations of B_{rm} against variations of x_1 at the assumed set of parameters

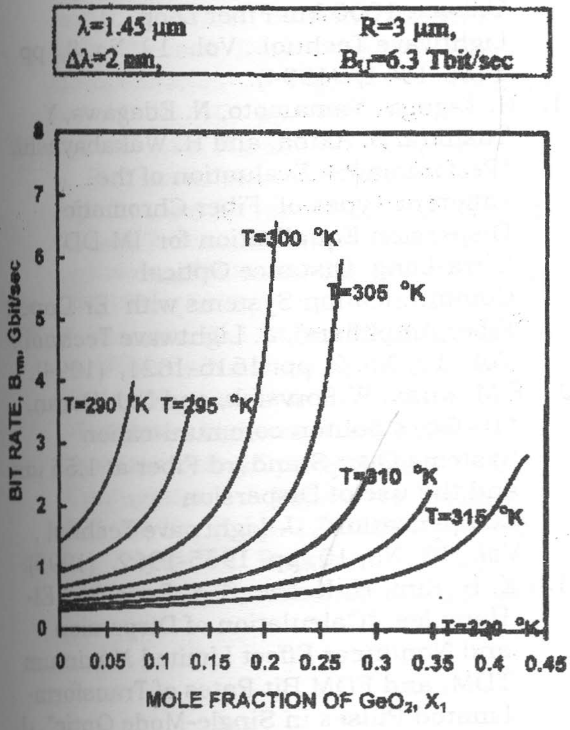

Figure 6 Variations of B_{rm} against variations of x_1 at the assumed set of parameters

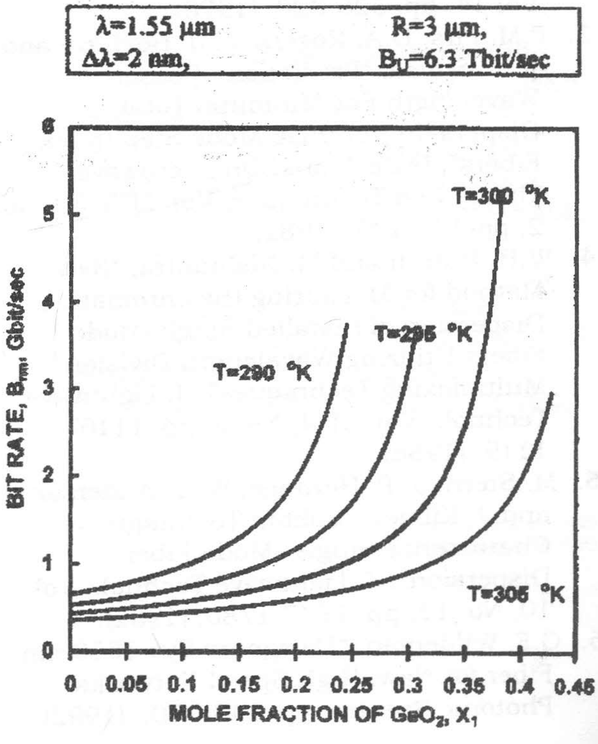

Figure 8 Variations of B_{rm} against variations of x_1 at the assumed set of parameters

CONCLUSION

The improvement of performance of high speed optical communication system after long-transmission distance is processed parametrically employing a 1000 km fiber loop in the form of N cascaded sections and (N) optical amplifiers. Both the two limitations of high speed transmission are exactly and periodically compensated. From the point of view of losses, the propagation distance seems to be one subsection, while from the point of view of dispersion, the propagation distance seems to be two subsections. The pairs (x_1,x_2) have usually different values $(x_1<x_2)$, where both are linearly and negatively correlated. The bit rate and the number of amplifiers are positively correlated whatever the controlling set of parameters.

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التعادل التام لكل من التشتت اللونى والفقد الطيفي بإستخدام المكبرات الضوئية على التعاقب فى ألياف النقل المصنعة من السليكا المطعمة بالجيرمانيا

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ملخص البحث

فى هذا البحث اقترحت طريقة جديدة لإلغاء (بدقة وبدورية) كل من التشتت اللونى وفقد النقل فى أليـاف السليكا المطعمة بالجيرمانيا. تعتمد هذة الطريقة على توظيف N جزء من أجزاء الليف البصرى على التعاقب ذى تشتت موجب وآخر ذى تشتت سالب (نتيجة أختلاف نسبة التشويب فى كل جزء) وذلك لحذف التشتت فى كل جزءين متعاقبين مع استخدام N من المكبرات الضوئية المصنوعة من الليف المطعم بمادة الإربيوم وذلك لتعويض فقد النقل عند نهاية كل جزء. هذا وقد اعتبر التشتت اللونى والفقد كميات تعتمد على درجة الحراره.

تم فى هذا البحث معالجة ليف بصرى طوله ١٠٠٠ كيلومترا (٢٥ جزءا متعاقبا طول الجزء ٤٠ كيلومترا) مع ٢٥ مكبر ضوئى ذى كسب ٣٠ ديسيبل (لتعويض كل الفقد الطيفى والفقد الناتج عن اللحامات والربط وغيرها عن كل جزء) حيث تم أستنتاج ارتباطات هامة تساعد فى التصميم عند درجات الحرارة المختلفة تربط بين درجات التشويب المختلفة التى تؤدى الى تشتت موجب يعادل تشتتا سالبا حيث وجد أن درجتى التشويب ترتبطان ارتباطا خطيا سالبا مهما كانت درجة الوسط آو الطول الموجى المستخدم.

هذا وقد درس أيضا معدل نقل البضات الثنائية مع فئة البارامترات الحاكمة حيث وجد أنها ترتبط ارتباطا موجبا مع عدد المكبرات الضوئية، حيث يؤدى ازدياد على المكبرات الى تقليل المسافات البينية وبالتالى ازدياد المعدل.