OPTICAL TRANSMISSION IN SINGLE-MODE GERMANIA-DOPED FIBER UTILIZING RAMAN AMPLIFICATION

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ABSTRACT

Some propagation characteristics (spectral losses and signal gain) as well as the bit-rate repeater-spacing product are investigated for optical transmission in single mode germania doped fiber of imperfection loss utilizing Raman amplification. Two approaches for variable Raman gain are taken into account. Two types of transmission line configurations are considered i.e., utiliziation of forward Raman amplification configuration only or backward Raman amplification only. The problem is parametrically investigated at fractional distances of the maximum theoretical limit of repeater spacing. The maximum repeater spacing is found at the maximum Raman gain, not at the minimum fiber loss. The ultimate repeater span and the ultimate bit rate-repeater span product are estimated if the maximum Raman gain and the minimum fiber loss are at the same wavelength.

I. INTRODUCTION

Active features of single-mode germania-doped fiber, due to nonlinear optical effects, are significant in three respects namely transmission limitations, optical frequency conversion, and special optical devices functions for signal processing and transmission [1,2]. The dominant nonlinear processes in single mode optical fibers are:

i) four-photon mixing (FPM);
ii) stimulated Brillouin scattering (SBS);
iii) stimulated Raman scattering (SRS), and
iv) carrier induced phase noise [3,4].

Stimulated Raman scattering is an interaction between light and vibrations of silica molecules. Stimulated Brillouin scattering is an interaction between light and sound waves in the fibers. Cross-phase modulation is an interaction, via the nonlinear refractive index, between the intensity of one light wave and the optical phase of other light waves. Four-photon mixing is analogous to third order intermodulation distortion whereby two or more optical waves at different wavelengths mix to produce new optical waves at other wavelengths. Although Raman amplification in optical fibers was demonstrated for the first time two decades ago [5], only very recently applications in lightwave communications have been demonstrated [6]. Raman amplification is attractive for optical communication systems for several reasons. Firstly, the Raman process amplifies the optical signal, thereby opening the possibility of replacing conventional repeaters by straight optical amplification. Secondly the fiber is considered as a gain medium and hence reduces the extra components used in other optical amplifiers [7]. Thirdly the extension of repeater spacing is easily done. Numerous papers have been published on the subject of beneficial uses of nonlinear scattering interactions with special emphasis on the subject of SRS [8,9,10], and the theoretical expectation of the repeater spacing have been reported [11-13]. Over the last several years, much attention has been paid on the study of the properties of fiber Raman amplifiers and their applicability to digital optical communication systems with special emphasis toward the wave-division-multiplixing (WDM) systems [14-17], because the spectral width of a Raman amplifier can be large enough to handle two or more WDM channels. This would eliminate the need for channel seperation and recombination at each repeater. Also, Raman amplification has the advantages of self- phase matching between the pump and the signal, broad gain bandwidth or high speed response and the elimination of the need of optical/ electrical/optical conversion and complicated electronics in conventional optical repeaters. Nowadays, a great deal of progress has been made in the area of optical amplifiers and many experiments using them have been conducted aiming at practical applications to various transmission systems [18,19].

Although numerous advances have been attained towards expanding the repeater spacing of optical transmission system, such that the development of low loss optical fibers, high power lasers, heterodyne detection methods, and optical amplifiers. With the best of our knowledges, no attempt is made either theoretically or experimentally to investigate the effect of Raman amplification on the handling capacity of the fiber. In the present paper an attempt is made to parametrically investigate the bit-rate repeater-spacing product in an optical transmission line utilizing Raman amplification taking into account a suitable system marginal loss.

II. BASCI MODEL AND ANALYSIS

II.1.The Raman Gain

In the process of Raman amplification the power, the wavelength, and the gain are parameters of major interest besides the fiber raduis, and relative refractive index difference. The Raman-gain constant g was considered in [8,11,12,15,16]:

$$g = g_o\,(1 + 80\,\Delta)\,(\lambda_o/\lambda_p) \qquad (1)$$

where g_o is the gain at $\Delta=0$ and pumping wavelength $\lambda_p=\lambda_o$ (for $\lambda_o=$ 1.34 μm, $g_o = 7.4\times10^{-14}$ m/watt) and Δ is the relative refractive index of the fiber. Thus the optical signal wavelength λ_s has no effect on the amplification gain in such analysis. However, the gain is a signal frequency-dependent parameter [13,20,21] of the form:

$$g = g_o\left(\frac{\delta}{440}\right), \quad \delta \le 440 \qquad (2)$$

and

$$g = g_o\, e^{-0.005(\delta - 440)}, \quad \delta \ge 440 \qquad (3)$$

with

$$\delta = \frac{\lambda_s - \lambda_p}{\lambda_s \lambda_p}\ \ \mathrm{cm}^{-1}, \qquad (4)$$

where g_o is the peak value at $d=440$ cm^{-1}. The analysis of References [14,17,22] is based on the assumption that the Raman gain has a Lorentzian line shape and is given as:

$$g = g_o\left(\frac{\omega^2}{(\delta-\delta_o)^2+\omega^2}\right) \qquad (5)$$

where δ_o = 460 cm^{-1} and ω = 240 cm^{-1}.

II.2 *The Optical Powerds and The Maximum Repeater Span*

II.2.1.Forward signal light amplification

The differential equations governing the forward Raman amplification for signal light amplification and describing the optical powers (pump p_p, signal P_s, and Stockes wavelength) are casted as [11,12,16].

$$\frac{dp_p}{dz} + \sigma\, p_p + \frac{1}{v_p}\frac{dp_p}{dt} = -\frac{g}{A}\frac{\lambda_s}{\lambda_p} p_s p_p \qquad (6)$$

$$\frac{dp_s}{dz} + \sigma_s p_s + \frac{1}{v_s}\frac{dp_s}{dt} = \frac{g}{A}\left(p_p - \frac{\lambda_2}{\lambda_s} p_2\right) p_s \qquad (7)$$

and

$$\frac{dp_2}{dz} + \sigma_2 p_2 + \frac{1}{v_2}\frac{dp_2}{dt} = \frac{g}{A} p_s p_2 \,. \qquad (8)$$

where σ is the spectral loss, v is the propagation velocity. A is the effective core area and λ is the optical wavelength. The subscripts p, s, and 2 refers to the pump, signal, and the second Stockes [11].

At steady state and without optical interaction the set of Eqns.(6-8) yields the solutions:

$$P_{p1}(z) = P_{po}\, e^{-\sigma_p z} \qquad (9)$$

$$P_{s1}(z) = P_{so}\, e^{-\sigma_s z} \qquad (10)$$

and

$$P_{21}(z) = P_{20}\, e^{-\sigma_2 z}. \qquad (11)$$

where P_{po}, P_{so}, and P_{20} are the powers at the feeding

point. P_{20} is calculated on the same bases as [11,12]
The use of Eqns. (9) and (11) into Eqn.(6) yields:

$$P_s(z)=P_{so}\exp[-\delta_s z+A_1(1-e^{-\delta_p z})-A_2(1-e^{-\delta_2 z})] \quad (12)$$

where

$$A_1 = gP_{po}/\sigma_p A \quad (13)$$

and

$$A_2 = gP_{20}\,\lambda_2\,/A\sigma_2\,\lambda_s. \quad (14)$$

Eqn.(12) indicates that to amplify the signal at the feeding point, we must have $A_1(1-e^{-\sigma_p z})>\sigma_s z$ with $\sigma_p z < 1$ i.e. approximately the condition for Raman amplification is,

$$P_{po} > \sigma_s A/g \quad (15)$$

Thus, the threshold pump power which the pump power losses the capability for amplification, is given by

$$P_{th} = \sigma_s A/g \quad \text{Watts} \quad (16)$$

The spectral loss along a propagation distance z is given by

$$\sigma_{ef} = 10\,\text{Log}\,(P_s/P_{so}) \quad \text{dB} \quad (17)$$

where σ_{ef} is a function of z.
Without amplification the total spectral loss is given by

$$\sigma_t = \sigma_s z \quad \text{dB} \quad (18)$$

Thus, the optical signal is amplified and possesses excess power $[P_s(z)-P_{s1}(z)]$. Therefore, the signal due to forward Raman amplification, can be written as

$$G_f = 10\,\text{Log}\{\frac{P_s(z)-P_{s1}(z)}{P_{s1}(z)}\} \quad (19)$$

The span between repeaters in such a system is controlled via the equation [11],

$$10\,\text{Log}\frac{P_s(z_f)}{P_{so}} = 4.343\,[-\sigma_s z_f+A_1\,(1-e^{-\delta_p z_f})$$

$$-A_2\,(1-e^{-\sigma_2 z_f})])] \quad (20)$$

where Z_f is the maximum feeding distance for forward Raman amplification.
$P_s(z_f)$ depends on the detector and in the present analysis we will consider the left hand side of Eqn.(20) equals -30 dB on the same basis of Reference [11].

II.2.2. Backward signal light amplification

The differential equations governing the backward Raman amplification and describing the optical powers (the pump P_p, the signal P_s, and the first Stockes P_1) are casted as [11,12,16]:

$$\frac{dP_p}{dz}+\sigma_p P_p+\frac{1}{v_p}\frac{dP_p}{dt}=-\frac{\lambda_s}{\lambda_p}\cdot\frac{g}{A}(P_s+P_1)P_p \quad (21)$$

$$\frac{dP_s}{dz}+\sigma_s P_s+\frac{1}{v_p}\frac{dP_s}{dt}=\frac{g}{A}P_p P_s \quad (22)$$

and

$$\frac{dp_1}{dz}-\sigma_1 p_1-\frac{1}{v_1}\frac{dP_1}{dt}=\frac{g}{A}P_p P_1\,. \quad (23)$$

At steady state and without optical interaction, Eqns. (21-23) yield:

$$P_{p2}(z) = P_{po}\,e^{\sigma_p(Z_b-z)} \quad (24)$$

$$P_{s2}(z) = P_{so}\,e^{-\sigma_s z} \quad (25)$$

and

$$P_{21}(z) = P_{10}\,e^{-\sigma_1 z} \quad (26)$$

where Z_b is the maximum feeding distance for backward Raman amplification.
The use of Eqn. (24) into Eqn. (2) yields:

$$P_s(z) = P_{so}\,e^{-\sigma_s z}A_1 e^{-\sigma_p Z_b}(1-e^{\sigma_p z}). \quad (27)$$

The signal must be amplified before its level becomes less than that of the amplified spontaneous emission (ASP). Thus Eqn.(27) yields a minimum value P_{min} at $Z_m < Z_b$ i.e.

$$P_s(Z)=P_{so}\exp\,[-\sigma_s z-A_1\,e^{-\sigma_p Z_b}(1-e^{\sigma_p z})] \quad (28)$$

The use of Eqn. (28) into Eqn. (27) yields,

$$P_m = P_{so} \exp [-\sigma_s z_m - A_1 (e^{-\sigma_p Z_b} - \frac{\sigma_s}{\sigma_p A_1}] \quad (29)$$

with P_m = ASP. The solution of Eqns. (28) and (29) yields both Z_b and Z_m where $Z_b > Z_m$ as,

$$Z_b - Z_m = - \frac{1}{\sigma_b} \ln(\frac{\sigma_s}{A_1 \sigma_p}). \quad (30)$$

The solution of Eqn. (30) gives Z_b, while the solution of Eqn. (29) (with P_m ASP) gives Z_m which must be less than Z_b.

As given by Eqns.(17) and (19), we have:

$$\sigma_{eb} = 10 \text{ Log } (P_s/P_{so}) \text{ dB} \quad (31)$$

and

$$G_b = 10 \text{ Log } \{\frac{P_2(z) - P_{s2}(z)}{P_{s2}(z)}\} \quad (32)$$

II.2.3. The bit rate

Based on the model of CSELT [23] El-Halafawy et.al [24] have derived a transcendental equation for both dispersion and loss limited bit rate B_R under the form,

$$1.25(\frac{B_r}{F_t})^2 = 10 \text{ Log } (\frac{B_u e^{(\sigma_s z + \sigma_m)}}{B_R}) \quad (33)$$

where B_u, F_t, and σ_m are the ultimate bit rate under no limitations, the fiber bandwidth, and the system marginal loss respectively. To compute B_r taking into consideration either forward or backward Raman amplifications, $\sigma_s z$ is replaced by either σ_{ef} or σ_{eb} respectively i.e.

$$1.25(\frac{B_f}{F_t})^2 = 10 \text{ Log } (\frac{B_u e^{(\sigma_{ef} + \sigma_m)}}{B_f}) \quad (34)$$

and

$$1.25(\frac{B_b}{F_t})^2 = 10 \text{ Log } (\frac{B_u e^{-(\sigma_{eb} + \sigma_m)}}{B_b}) \quad (35)$$

where B_f and B_b are respectively the bit rates of cases of forward and backward Raman amplification. In the above analysis F_t is calculated as in [23, 25], while the spectral loss σ is calculated as in [12, 26].

III. RESULTS AND DISCUSSION

In the present paper,two approaches [Eqns.(2-3) and Eqn.(5)] are processed when dealing with Raman gain. The main features of the present analysis are:

i) variable Raman gain,
ii) real fiber,
iii) system marginal loss,and
iv) limitations due to both the spectral loss and the dispersion.

The following topics are investigated parametrically over wide ranges of variations of the affecting parameters:

a- the effective spectral loss,
b- the signal gain due to Raman amplification, and
c- the bit-rate at the maximum repeater spacing.

III-1 The numerical data

The ranges of the controlling parameters:

- Percentage doping of germania in germania-doped fiber $0.0\% \leq x \leq 20\%$
- Raman pumping power $0.25 \leq P_{po} \leq 2.0$ watt;
- Relative refractive index $0.5\% \leq \Delta \leq 1.0\%$;
- Optical signal wavelength $1.35 \leq \lambda_s \leq 1.6$ μm are handled through the computation stage.

The following variables are kept constants as:

R = fiber radius = 5 μm;
λ_p = pumping wavelength = 1.34 μm;
λ_1 = first Stocke wavelength = 1.4 μm;
λ_2 = second Stocke wavelength = 1.46 μm;
$\Delta\lambda$ = spectral width of the optical source = 5 μm;
σ_m = marginal loss of the system = 4 dB; and
g_o = peak of the Raman gain for pure silica at λ = 1.34 μm = 7.4×10^{-14} m/Watt.

The present analysis employs a laser diode-avalanche photodiode as source-detector combination of ultimate bit rate under no limitation B_u = 6.3 Tbit/sec. Throughout the following discussion, the results of the Lorentzian-Raman gain are displayed and analyzed. Such case gives higher data if compared with the straight line-exponential curve of Raman gain.

III.2. The effective spectral loss

The effective spectral losses σ_{ef} and σ_{eb} given by

Eqns.(17) and (30) are investigated parametrically. Comparisons of either σ_{ef} or σ_{eb} and σ_t (spectral loss without amplification) are made and displayed in Figures (1a-5a). The criterion at which Z_f is derived is not on the same basis as the criterion at which Z_b is derived. At $Z=Z_b$, σ_{ef} is frozen at -30 dB, while at $Z=Z_b$, σ_{eb} possesses different values that depend on the Raman pumped power. These figures clarify that s_{eb} increases as λ increases to a maximum value corresponding to the maximum Raman gain wavelength, then σ_{eb} decreases as λ increases as the fiber possesses minimum loss at λ = 1.55 μm. This situation is found at different values of either x or P_{po}.

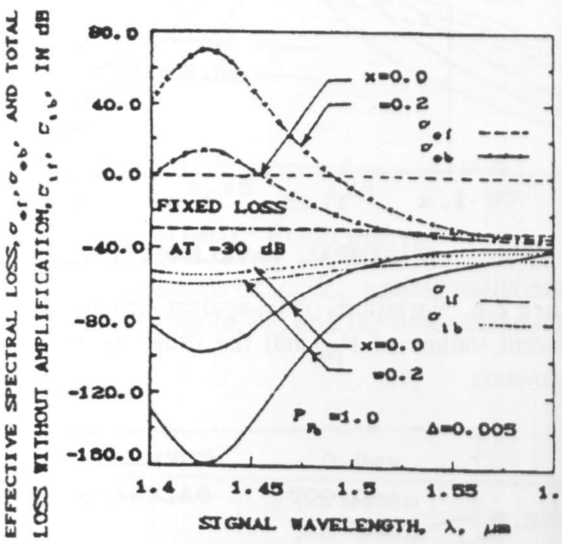

Figure 1-a. Variations of σ_{ef}, σ_{eb}, σ_{tf}, and σ_{tb} against variations of λ for different values of x and the other assumed set of parameters.

At different values of x or λ_s, σ_{eb} increases as P_{po} increases. As Δ increases, Raman gain increases also and consequently σ_{eb} increases. The increase of Raman gain yields longer repeater spans which in turns yields decreased spectral losses σ_f or σ_b.

III. 3 The signal gain due to Raman amplification

Signal gain due to either forward or backward Raman amplification is defined by Eqns.(19) and (31) respectively as a mathematical criterion to calculate the gain. The signal gain is displayed in Figures (1b-5b). At the wavelength of maximum Raman gain, the signal gain possesses a maximum value, which increases as either x or P_{po} or Δ increases due to the increase of Raman gain. Very slight differences in the value of the signal gain are found when dealing with the two schemes of Raman amplification.

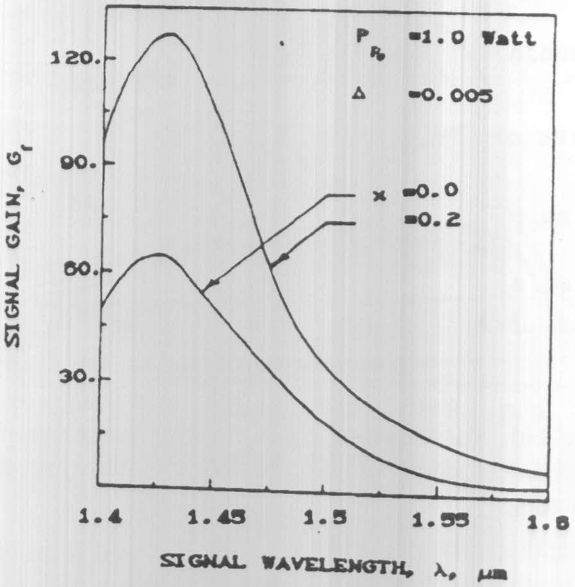

Figure 1-b. Variations of G_f against variations of λ for different values of x and the other assumed set of parameters.

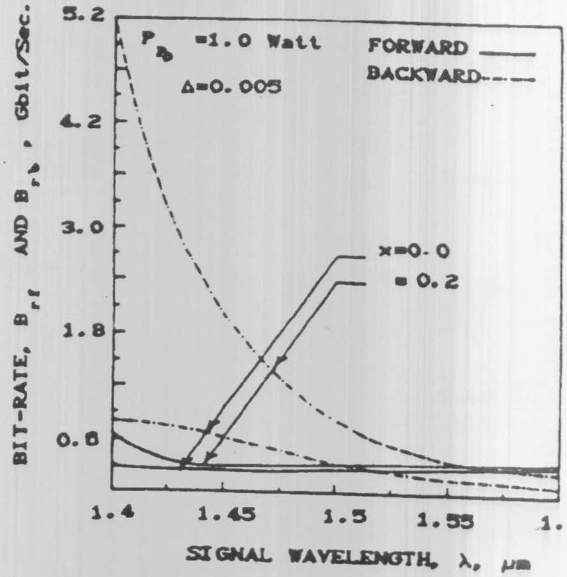

Figure 1-c. Variations of B_f, B_b against variations of λ for different values of x and the other assumed set of parameters.

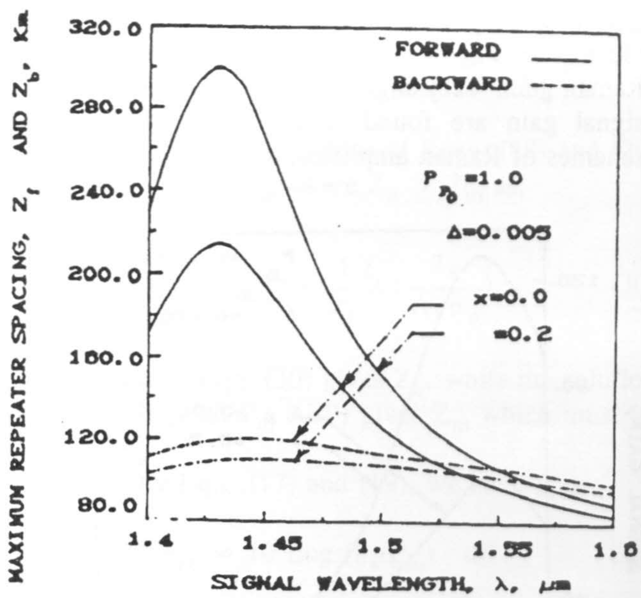

Figure 1-d. Variations of Z_f, Z_b against variations of λ for different values of x and the other assumed set of parameters.

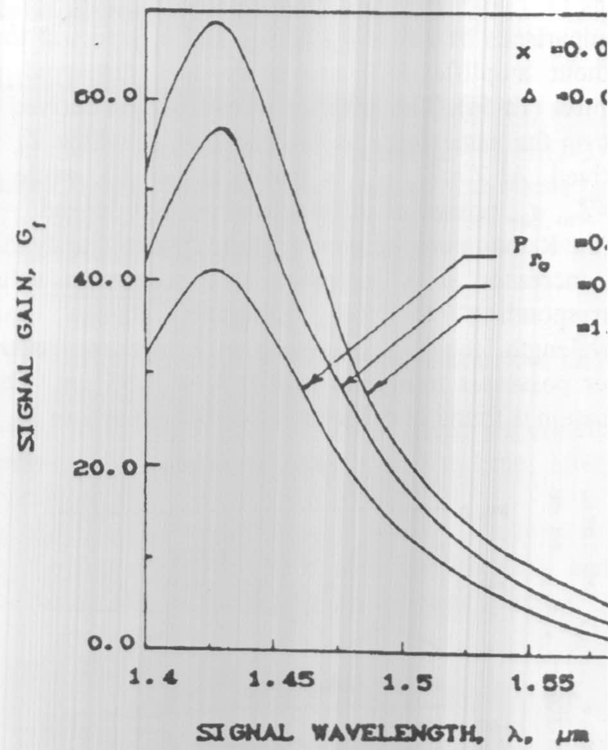

Figure 2-b. Variations of G_f against variations of λ different values of P_{po} and the other assumed set parameters.

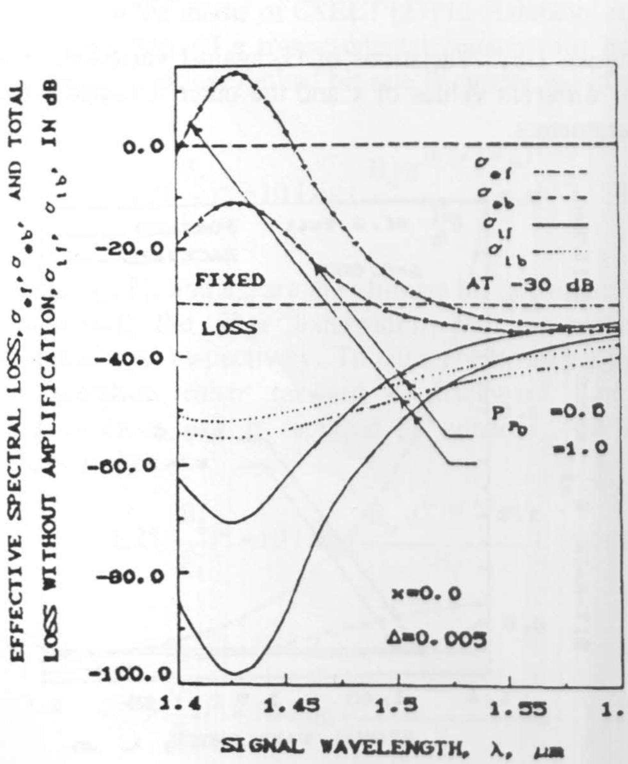

Figure 2-a. Variations of σ_{ef}, σ_{eb}, σ_{tf}, and σ_{tb} against variations of λ for different values of P_{po} and the other assumed set of parameters.

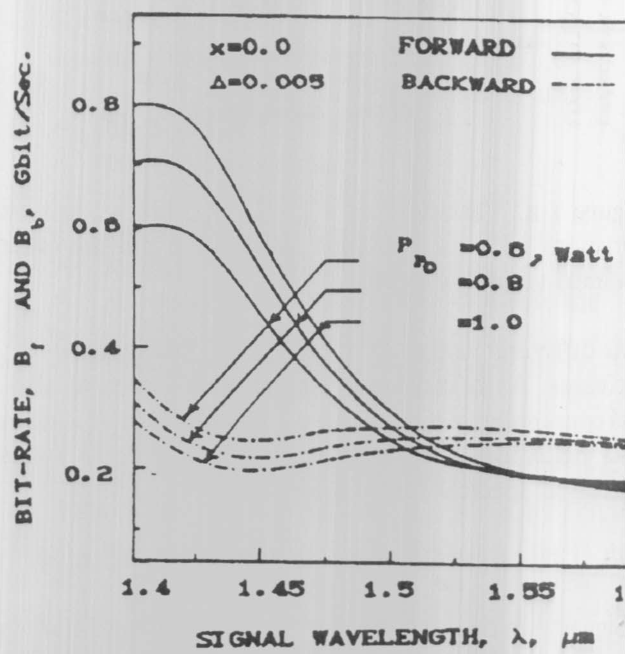

Figure 2-c. Variations of B_f, B_b against variations λ for different values of P_{po} and the other assumed of parameters.

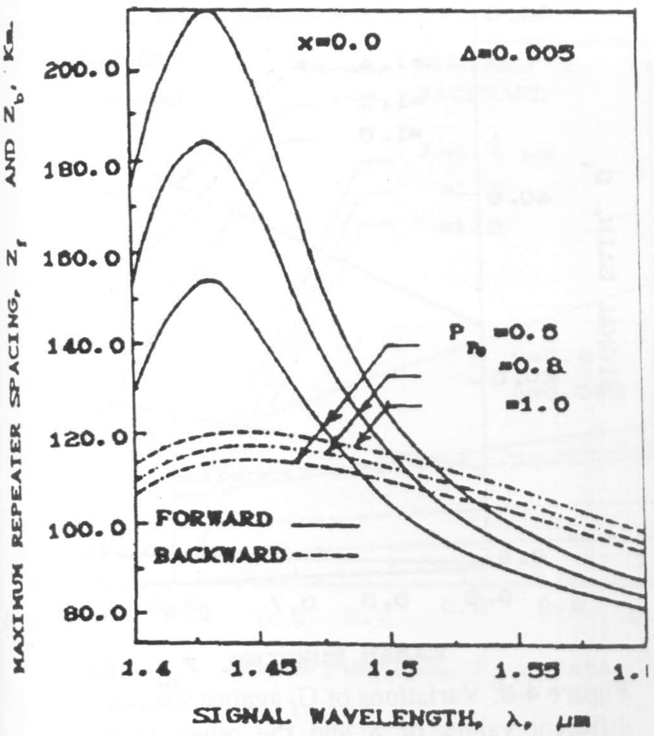

Figure 2-d. Variations of Z_f, Z_b against variations of λ for different values of P_{po} and the other assumed set of parameters.

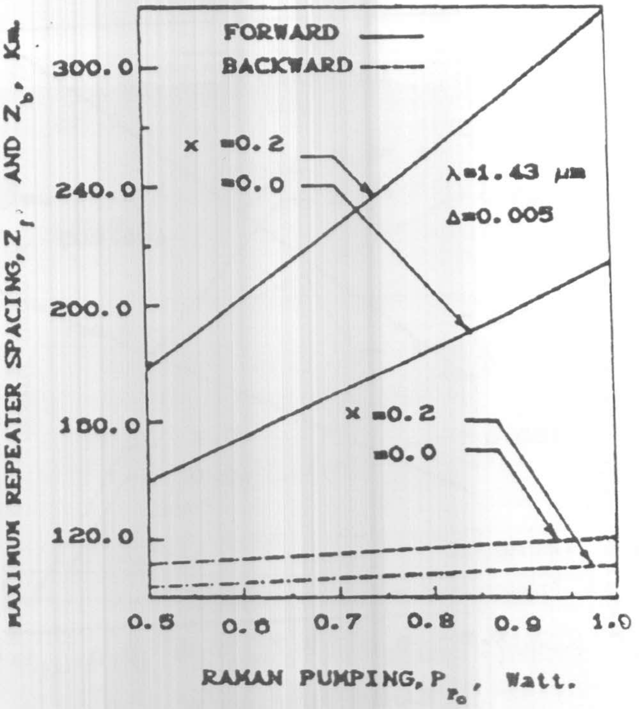

Figure 3-b. Variations of G_f against variations of P_{po} for different values of x and the other assumed set of parameters.

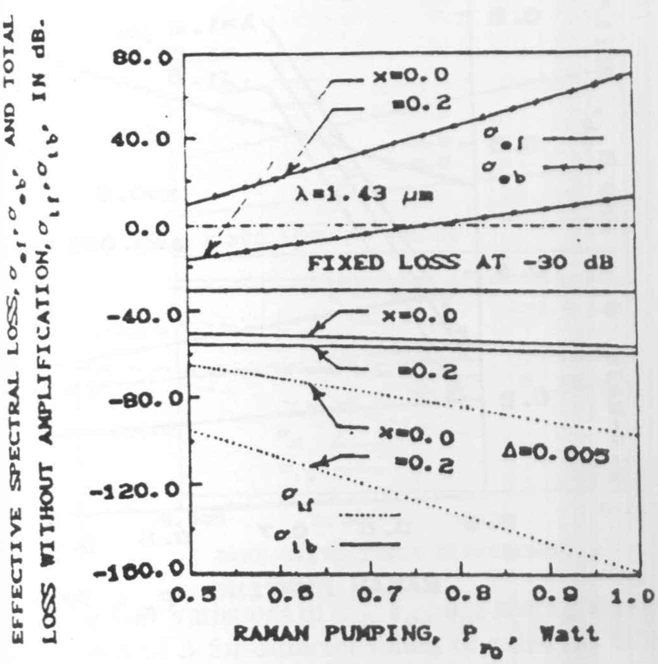

Figure 3-a. Variations of σ_{ef}, σ_{eb}, σ_{tf}, and σ_{tb} against variations of P_{po} for different values of x and the other assumed set of parameters.

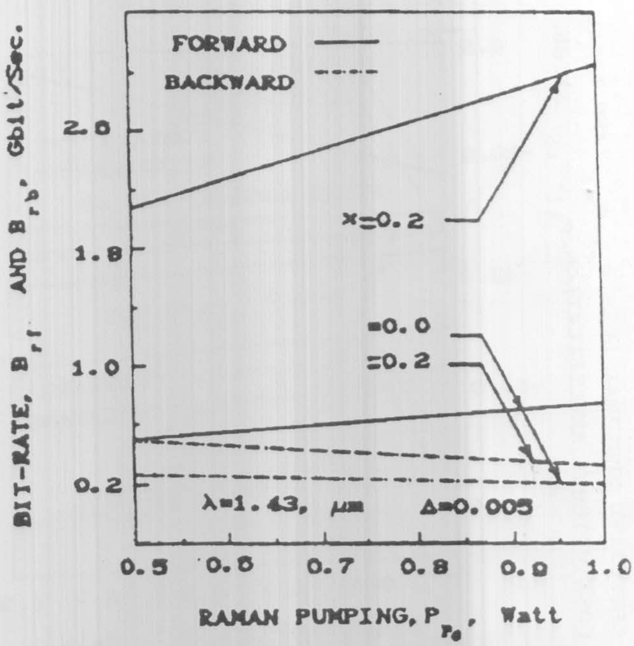

Figure 3-c. Variations of B_f, B_b, against variations of P_{po}, for different values of x and the other assumed set of parameters.

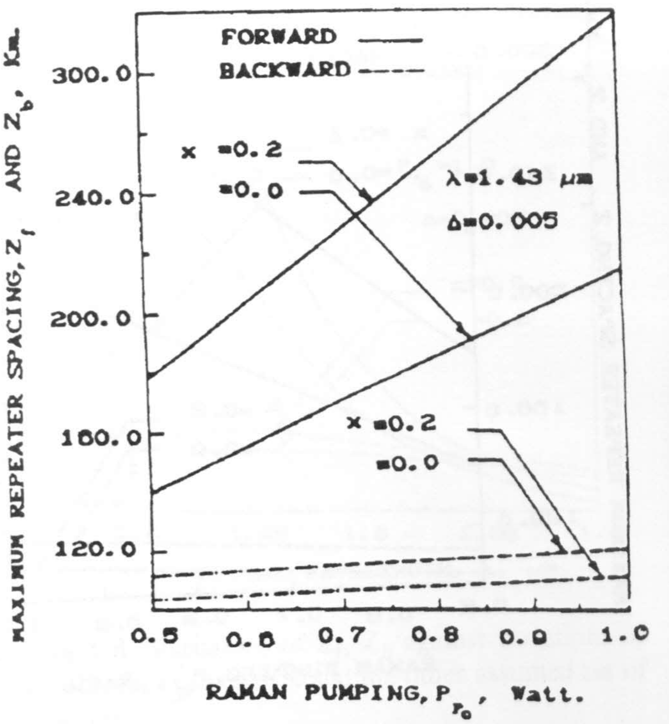

Figure 3-d. Variations of Z_f, Z_b, against variations of P_{po} for different values of x and the other assumed set of parameters.

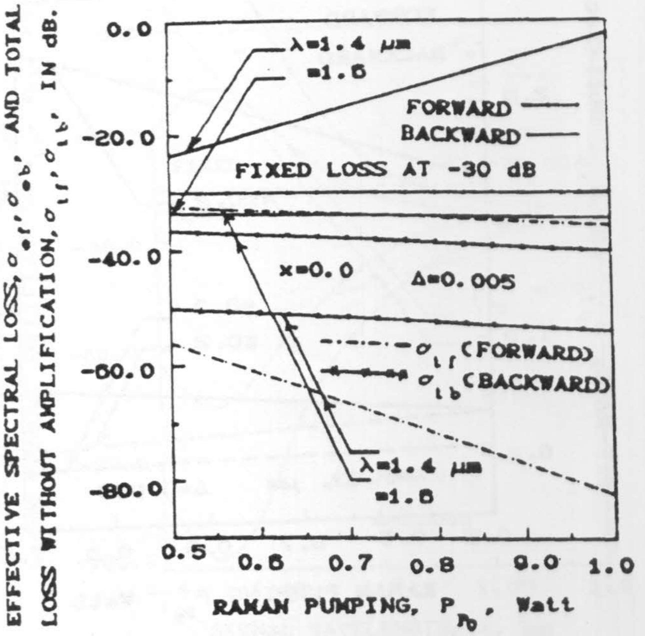

Figure 4-a. Variations of σ_{ef}, σ_{eb}, σ_{tf}, and σ_{tb} against variations of P_{po} for different values of λ and the other assumed set of parameters.

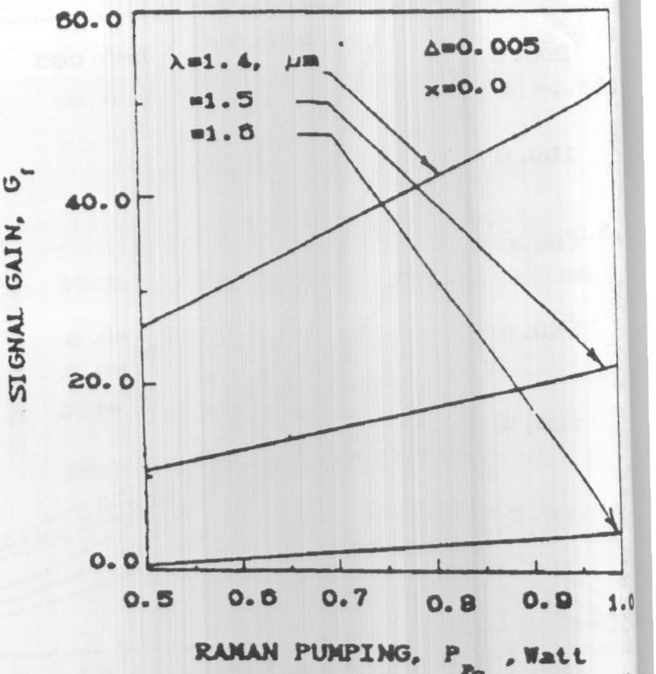

Figure 4-b. Variations of G_f against variations P_{po}, for different values of λ and the other assumed set of parameters.

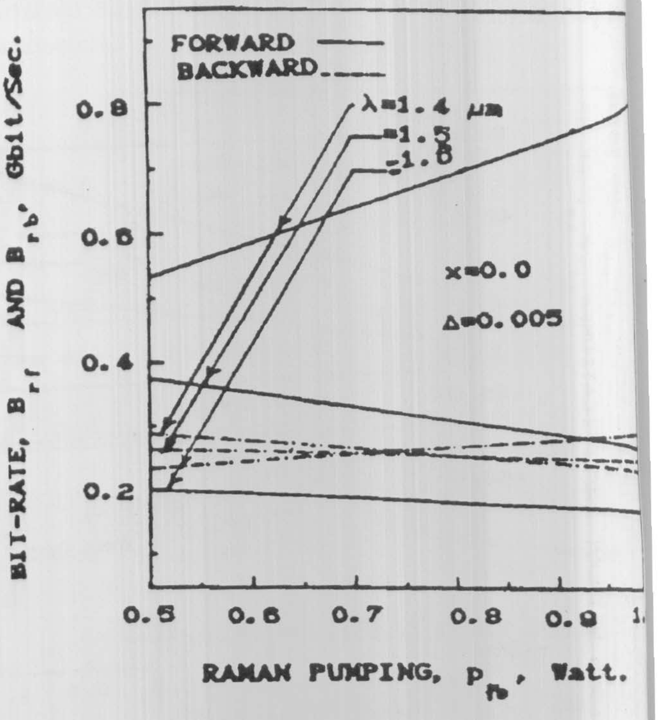

Figure 4-c. Variations of B_f, B_b, against variations of P_{po} for different values of λ and the other assumed set of parameters.

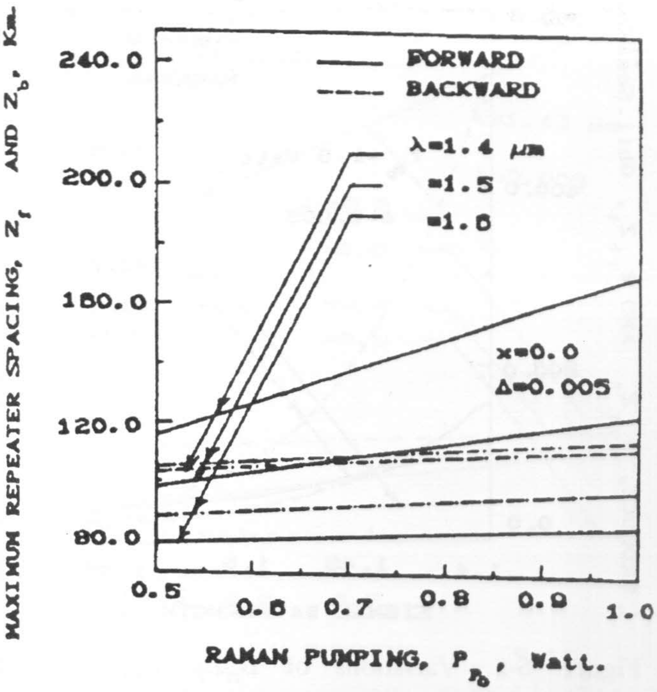

Figure 4-d. Variations of Z_f, Z_b against variations of P_{po}, for different values of λ and the other assumed set of parameters.

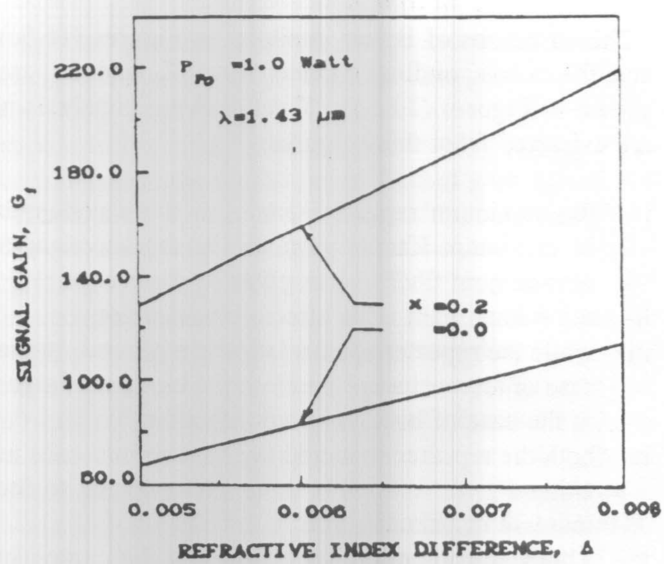

Figure 5-b. Variations of G_f against variations of Δ, for different values of x and the other assumed set of parameters.

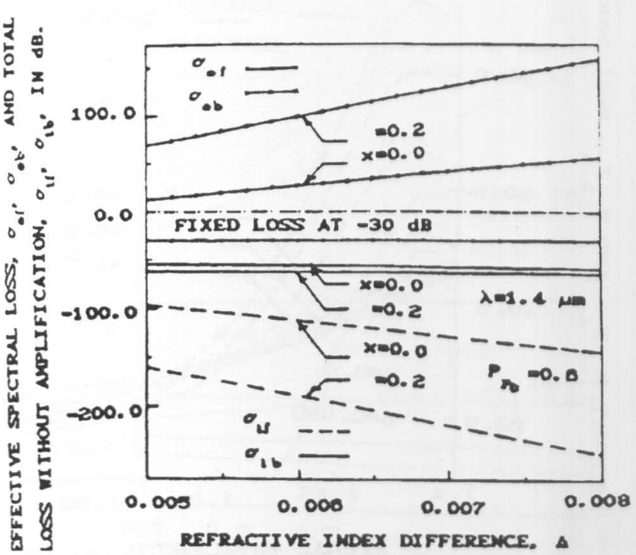

Figure 5-a. Variations of σ_{ef}, σ_{eb}, σ_{tf}, and σ_{tb} against variations of Δ for different values of x and the other assumed set of parameters.

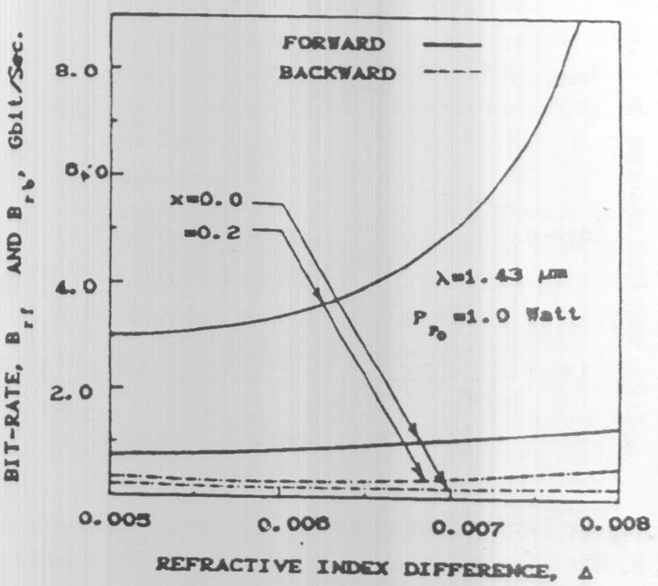

Figure 5-c. Variations of B_f, B_b against variations of Δ for different values of x and the other assumed set of parameters.

III. 4 The bit rate and the maximum repeater spacing

The variations of B_r are depicted in Figures (1c-5c) and the corresponding repeater span Z_f and Z_b are shown in Figures (1d-5d). The following conclusions are extracted from these figures:

i- the maximum repeater span is at the wavelength of maximum Raman gain, not at the wavelength of minimum fiber loss as given by Reference [12];
ii- the Raman gain is an effective parameter;
iii- while the repeater span is larger, in general, in the case of forward amplification, the bit-rate is larger in the case of backward amplification;
iv- both the repeater span and the bit-rate increases as either P_{po} or x or Δ or both increase due to the increase of Raman gain.
v- both the repeater span and the bit- rate (in general) decreases with the increase of λ due to the decrease of Raman gain.

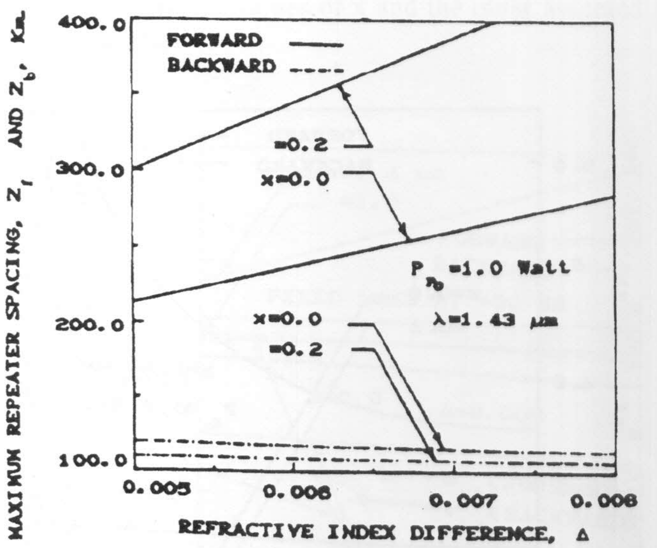

Figure 5-d. Variations of Z_f, Z_b against variations of λ, for different values of x and the other assumed set of parameters.

The bit-rate repeater span product is displayed in Figures (6a-6d). The studding of these curves shows that the same feathers of Z_f and Z_b are obtained.

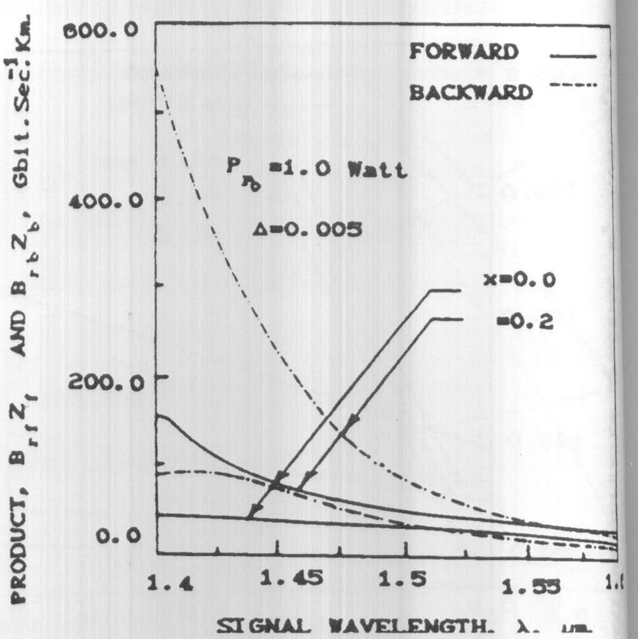

Figure 6-a. Variations of $B_{rf}Z_f$, $B_{rb}Z_b$ against variations of λ for different values of x and the other assumed set of parameters.

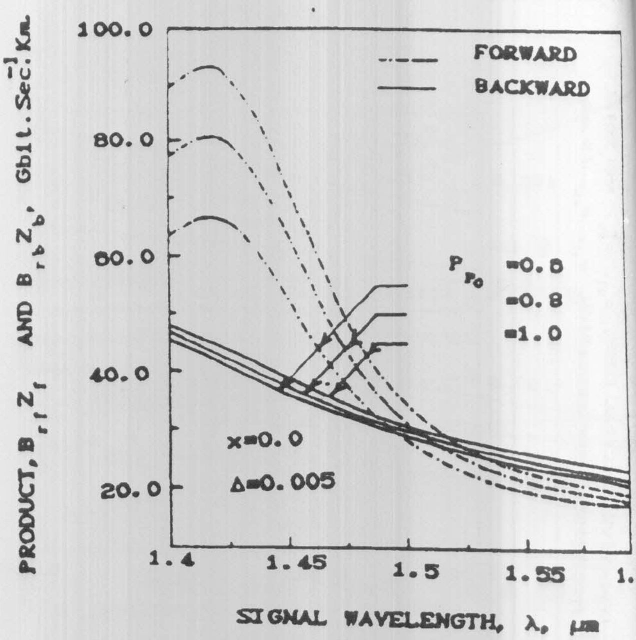

Figure 6-b. Variations of $B_{rf}Z_f$, $B_{rb}Z_b$ against variations of λ for different values of P_{po} for different values of λ and the other assumed set of parameters.

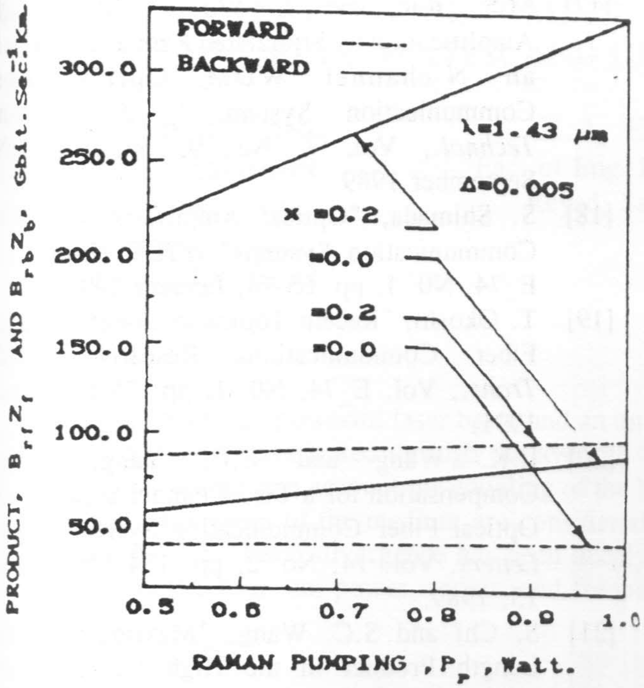

Figure 6-c. Variations of $B_{rf}Z_f$, $B_{rb}Z_b$ against variations of P_{po}, for different values of x and the other assumed set of parameters.

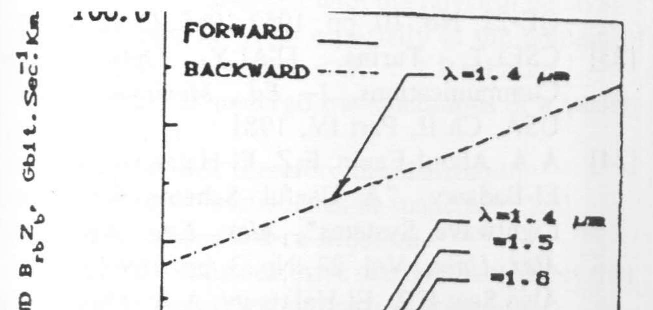

Figure 6-d. Variations of $B_{rf}Z_f$, $B_{rb}Z_b$ against variations of λ, for different values of P_{po} and the other assumed set of parameters.

IV. CONCLUSIONS

In the present analysis with either forward or backward Raman amplification, three relevant topics for long haul optical communication systems are successfully and easily processed, taking into consideration the variations of Raman gain against the variations of the signal frequency,the pumping power, the percentage of doping in the fiber,and the relative refractive index difference. Two approaches are investigated when dealing with the signal frequency namely straight line-exponential curve line shape and Lorentzian line shape. The maximum repeater-span and bit-rate repeater-span product are at the wavelength, of maximum Raman gain, not at the wavelength of minimum fiber loss. The ultimate values are obtained when both the maximum Raman gain and the minimum fiber loss are at the same wavelength namely 1.55 μm with the maximum available Raman pumping through fibers and with maximum available x and Δ, namely x =0.2 and Δ =1 %.

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