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Effect of Temperature and Germanium on the Performance of Germanium Doped Silica Fiber Raman Scattering Amplifier

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Abstract: The Raman gain coefficient, the attenuations at signal and pump wavelengths and the refractive indices of both core and cladding of silica doped Germanium optical fiber are functions of the Germanium ratio, temperature and wavelengths. The Raman amplifier gain increases with Germanium ratio but it decreases with temperature. Also, Raman gain either increases or decreases with signal wavelength. As the fiber core radius increases, the Raman gain decreases.

The gain distribution through the amplifier length of dual pumps with power divided ratio ($S=0.5$) is better than that for the forward pump amplifier and the backward pump amplifier. The forward pump has a maximized gain but the backward pump has a minimized gain, while the dual pumps have both the maximum and minimized gains. The final amplifier gain for the three kinds of pumps with the same pump power (P_p) is equally.

The pump wavelength ($\lambda_p=1.4553\mu\text{m}$) gives the biggest Raman gain at the center of wideband signal wavelength ($\lambda_s=1.50$ to $1.60\mu\text{m}$). With $\lambda_p=1.48\mu\text{m}$, the gain increases with λ_s until $\lambda_s=1.57\mu\text{m}$ and after that the gain decreases with λ_s and so with the above three kinds of pumps, gain fluctuations over the band wavelength of signal. The threshold pump power and gain saturation are studied.

Keyword's: Stimulated Raman Scattering (SRS), threshold pump power ($P_{p\text{thr}}$), saturation gain (G_s), Germanium doped silica fiber, effective length (L_{eff}), forward pump, backward pump.

I. Introduction

Raman amplifier is widely used with optical telecommunication systems [1]. Raman gain occurs by transfer of power from optical pump (which has power, P_p , and wavelength, λ_p) to the optical signal (which has power, P_s , and wavelength, λ_s , where $\lambda_p < \lambda_s$) [2]. Nonlinear effect requires an optical power higher than a threshold pump power ($P_{p\text{thr}}$) [1]. The telecommunications bands are around 1500nm (13.2 THz) corresponds to approximately 100 nm (40THz) [2]. GeO_2 molecules exhibit a larger Raman gain peaking near 13.1 THz [3]. The Raman scattering effect constitutes one of the basic physical mechanisms exploited in optical fiber distributed temperature sensing.[4].

The signal attenuation coefficient (α_s at signal wavelength, λ_s) and the pump attenuation coefficient (α_p , at pump wavelength, λ_p) are increasing with Germanium ratio (x_1) and temperature (T). The minimum attenuation coefficient of Germanium doped silica fiber (α_{min} occurs at $\lambda_{\alpha \text{ min}}$, around $1.55\mu\text{m}$) is crawling apart from $\lambda=1.5\mu\text{m}$ with increasing T and x_1 . The value of α_p decreasing with increasing λ_p because of λ_p usually less than $\lambda_{\alpha \text{ min}}$. The attenuation (A_n) increases with x_1 , T and L .

The Raman gain coefficient (g_{rxt}) increases with x_1 but it decreases with T . The effective Raman length (L_{eff}) decreases with x_1 and T but it increases with the amplifier length (L). Therefore, for the same net gain, as g_{rxt} increases, the required L decreases. The gain becomes more with x_1 while in the other side, the value of the allowable core radius (a) becomes little than the required value for telecommunications. Also, more x_1 gives best power launched into fiber.

The net Raman amplifier gain (G db) decreases linearly with the product $\alpha_s L$ but G increases linearly with the product of ($g_{\text{rxt}} L_{\text{eff}}$) until the gain saturation (G). Therefore, G increases with x_1 but G decreases with T . As the effective fiber core area (A_{eff}) increases, the value of g_{rxt} decreases. The value of A_{eff} increase with λ_s and λ_p while it decreases with x_1 and T .

The final Raman gain with the three kinds of bumps (forward pump, G_F , backward pump, G_B , and dual pumps, G_D) are equally. The Raman gain distribution with dual pumps, $G_D(z)$, is better than that with forward pump, $G_F(z)$ or backward pump, $G_B(z)$ (especially with divided pump power factor, $S=0.5$). With forward pump, there is a maximum gain ($G_{F\text{max}}$ which occurs at $Z_{F\text{max}}$) but with backward pump, there is a minimum gain ($G_{B\text{min}}$ which occurs at $Z_{B\text{min}}$), while with dual pumps, there are both maximum gain ($G_{D\text{max}}$ which occurs at $Z_{D\text{max}}$) and minimum gain ($G_{D\text{min}}$ which occurs at $Z_{D\text{min}}$). The power transferred between lower signal wavelengths to higher signal wavelengths due to the stimulated Raman scattering is neglected.

In this study, the Raman amplifier is analyzed with temperature range ($T=-20$ to 60°C), signal wavelength range ($\lambda_s=1.50$ to $1.60\ \mu\text{m}$), pump wavelength ($\lambda_p=1.45$ to $1.49\ \mu\text{m}$) and Germania ratio ($x_1=0.03$ to 0.05). To operate the optical fiber as a single mode during the last ranges of T , x_1 and λ_s , the allowable core radius (a) ranges between $a=3.36$ to $3.74\ \mu\text{m}$ (simulation results is calculated with $a=3.5\ \mu\text{m}$). The simulation results are done for the three kinds of pumps.

II- Mathematical Analysis

II.1 Effect of T and x_1 on the refractive indices (n_1 and n_2), effective core area (A_{eff}) and attenuations (α_s and α_p) of a single mode fiber.

The refractive indices of core (silica doped Germania, n_1) and clad (pure silica, n_2) materials are increases with both temperature ($T^{\circ}\text{K}$) and Germania ratio (x_1) while they are decreases with wavelength ($\lambda_{\mu\text{m}}$) as explained in Appendix A.

Effective fiber core area (A_{eff}) is defined as [5]

$$A_{\text{eff}} = \frac{1}{2}(A_s + A_p) = \frac{\pi}{2}(W_s^2 + W_p^2) \dots \dots \dots (1.a)$$

Where, A_s is the effective cross section area of the optical fiber at signal wavelength (λ_s), A_p is the effective cross section area of the fiber at optical pump wavelength (λ_p), W_s is the effective core radius at signal wavelength and W_p is the effective core radius at pump wavelength. $W_{s,p}$ is defined as [6];

$$W_{s,p} = 0.65 + \frac{1.619}{V_{s,p}^{1.5}} + \frac{2.879}{V_{s,p}^6} \dots \dots \dots (1.b)$$

Where V_s and V_p are the normalized frequencies of fiber at λ_s and λ_p , respectively.

As expected, the value of normalized frequency $\{V = (2\pi a / \lambda) (n_1^2 - n_2^2)^{0.5} [6]\}$ increases with x_1 but V decreases with both T and λ as indicated in Fig.1. a.

The value of A_s usually greater than the value of A_p , because of the value of λ_s must be greater than that the value of λ_p . Also, the value of A_{eff} increases with increasing both λ_p and λ_s . But A_{eff} decreases with increasing the Germania ratio (x_1) as shown in Fig.1.b (where the values of V_s and V_p are increased with x_1 as shown in Fig.1.a, so more optical confinement). Also, A_{eff} decreases with higher temperature as shown in Fig.1. b.

The attenuation of optical through Germania doped silica fiber (α_i) is a function of x_1 , λ and T as defined in [7];

$$\alpha_1 = 0.003 + \frac{0.75+66 \Delta T}{\lambda^4 T_0} + 7.81 * 10^{11} e^{-48.48/\lambda} + \frac{1.542 x_1 e^{4.63/\lambda}}{60+46.6 x_1} \quad (\text{db/km}) \dots \dots \dots (2.a)$$

Where Δ is the relative refractive index difference $\{2\Delta = 1 - n_{22} / n_{21} [6]\}$ and T_0 is the reference temperature ($T_0 = 300^{\circ}\text{K}$). Note, α (in km^{-1}) = $0.2303 \alpha_1$ (in db/km).

For Germania doped silica fiber, there is minimum value of attenuation (α_{min}) which occurs at wavelength (λ_{amin}). Both the values of α_{min} and λ_{amin} are increasing with the doping ratio (x_1) as shown in Fig.1. c. The value of λ_{amin} occurs around $1.55\ \mu\text{m}$.

So, the signal attenuation (α_{s1} db/km) decreases with $\lambda_s < \lambda_{\text{amin}}$ while, α_{s1} increases with $\lambda_s > \lambda_{\text{amin}}$ as shown in Fig.1. c. While, the pump attenuation (α_{p1} db/km) decreases with increasing λ_p (where $\lambda_p < \lambda_{\text{amin}}$). Both the values of α_{s1} and α_{p1} are increased with increasing the value of Germania (x_1) and temperature (T) as shown in Fig.1. c.

a) V_s with $a=3.5\ \mu\text{m}$ b) A_{eff} with $a=3.5\ \mu\text{m}$ c) attenuation coefficient α_{s1}

Fig.1 Effect of both temperature (T), Germania ratio (x_1) and the wavelength (λ) on V_s , A_{eff} and α_{s1} with $T_0=300^{\circ}\text{K}$, $\lambda_p=1.48\ \mu\text{m}$ and $a=3.5\ \mu\text{m}$

II.2 Effective Raman scattering length (L_{eff})

Because of the pump absorption, the effective amplification length is reduced from the amplifier length (L) to the effective length (L_{eff}). It is the distance that equates a distance during which the power is transferred from the pump to the signal. It is defined as [8]

$$L_{\text{eff}} = (1 - e^{-\alpha_p L}) / \alpha_p \quad \text{km} \quad (\text{where } \alpha_p \text{ in km}^{-1}) \dots \dots \dots (3.a)$$

From Eq.3.a, the value of L_{eff} increases with lowering α_p as shown in Fig.2.a (so, L_{eff} decreases with T and x_1 as indicated in Fig.2.b). The attenuation α_p decreases with λ_p (usually $\lambda_p < \lambda_{\text{amim}}$; λ_{amim} around $1.55\mu\text{m}$). So, the value of L_{eff} increases with the pump wavelength (λ_p).

From Eq.3.a, the ratio (L_{eff}/L) versus the product ($\alpha_p L$) is;

$$L_{\text{eff}}/L = (1 - e^{-\alpha_p L}) / (\alpha_p L) \dots \dots \dots (3.b)$$

Fig.2 Effective Raman scattering length (L_{eff}) versus both span length (L) and α_p (db/km) with ($T_0=300^\circ\text{K}$), $\lambda_p=1.48\mu\text{m}$, $a=3.5\mu\text{m}$

The value of L_{eff} becomes $0.5L$ at $\alpha_p L = 1.593$ (where α_p in km^{-1}) i.e. $\alpha_p L = 6.91$ (with α_p in db/km, as shown in Fig.2.c). Therefore, with conventional value of $\alpha_p = 0.05152 \text{ km}^{-1}$ (Note, with $x_1=0.03$, $T=300^\circ\text{K}$ and $\lambda=1.48\mu\text{m}$, the value of $\alpha_{p1} = 0.2238 \text{ db/km}$, i.e., $\alpha_p = 0.05152 \text{ km}^{-1}$), the corresponding values of $L = 30.92 \text{ km}$ and $L_{\text{eff}} = 15.46 \text{ km}$. So, the dual pumps (forward and backward pumps) are used without fear of accumulation of the two pumps effective Raman scattering lengths where the Raman amplifier length usually greater than 100 km (where signal attenuation by some 20 dB makes it necessary to restore the power level by amplification [9]).

II.3 Stimulated Raman scattering gain coefficient ($g_{\text{R}T}$)

Stimulated Raman scattering gain coefficient for pure silica, $g_{\text{R}0}$ (m/W) is defined by using the published data which stated in [10] as shown in Fig.3 and the relation between $g_{\text{R}0}$ and Δk_{ps} (the modified wave number difference) is derived in Appendix B.

Where, Δk_{ps} is defined as;

$$\Delta k_{\text{ps}} = 10000 \left(\frac{1}{\lambda_p} - \frac{1}{\lambda_s} \right) \quad \text{cm}^{-1} \quad \{ \text{with, } \lambda_p (\mu\text{m}) \text{ and } \lambda_s (\mu\text{m}) \} \dots \dots \dots (4.a)$$

So, for $\lambda_s = 1.5$ to $1.60\mu\text{m}$ and $\Delta k_{\text{ps}} = 90$ to 584 cm^{-1} (optimum values of Δk_{ps}), the corresponding value of $\lambda_p = 1.48\mu\text{m}$.

For pure silica, the maximum Raman scattering gain $g_{\text{R}0\text{max}} = 0.65 \times 10^{-13} \text{ m/W}$ [11] which it occurs at $\Delta k_{\text{ps}} = 420 \text{ cm}^{-1}$ as shown in Fig.3. Therefore, with $\lambda_p = 1.48\mu\text{m}$, the value of $g_{\text{R}0\text{max}}$ occurs at $\lambda_s = 1.5781\mu\text{m}$.

The modified wavenumber difference (Δk_{ps}) decreases with λ_p while Δk_{ps} increases with λ_s as shown in Fig.4.

Fig.3 The value of $g_{\text{R}0}$ versus Δk_{ps} from [10]

Fig.4 Effect of both λ_p and signal wavelength λ_s on (Δk_{ps})

* The dependence of g_r on the doping ratio (x_1) is [10];

$$g_{Rx} = \frac{n_2^2}{n_1^2} \{g_{R0} + 100 C_v x_1 g_{R0max} \frac{\lambda_s^3}{\lambda_{smax}^3}\} \dots \dots \dots (5.a)$$

Where, g_{R0max} is the maximum value of g_{R0} , λ_{smax} is the wavelength at which g_{R0} becomes g_{R0max} , n_1 and n_2 are the refractive indices of core and clad respectively at λ_s and the parameter C_v is defined in Appendix C.

The value of g_{R0max} as a function of x_1 is [12];

$$g_{Rxmax} = (1+8.0x_1) g_{R0max} \quad (\text{where } x_1 \text{ ratio}) \dots \dots \dots (5.b)$$

For silica, g_{R0max} occurs at $\Delta k_{ps} = 420 \text{ cm}^{-1}$, therefore from Eq.4.a,

$$\lambda_{smax} = (\lambda_p^{-1} + 0.042)^{-1} \dots \dots \dots (5.c)$$

* The temperature dependence of Raman scattering gain(g_{RxT}) is derived from the relation between zero Kelvin Raman cross section of pure silica (σ_0) and temperature (T) which stated in [13]. So g_{RxT} is derived as;

$$g_{RxT} = g_{Rx} T_{p1} \dots \dots \dots (6.a)$$

Where, $T_{p1} = T_p / T_{p(T=300)}$ and T_p is the thermal population factor [4,14];

$$T_p = 1 + \frac{1}{-1 + \exp\{h(f_p - f_s)/T K_B\}} \dots \dots \dots (6.b)$$

Where; h is the plank's constant ($h=6.625 \times 10^{-34} \text{ J.s}$), T is the temperature ($T \text{ }^\circ\text{K}$) and K_B is the Boltzmann constant ($K_B = 1.38 \times 10^{-23} \text{ J/}^\circ\text{K}$) and f_p and f_s are the pump and signal frequencies. So,

$$T_p = 1 - \exp(-1.44 \Delta k_{ps}/T) \dots \dots \dots (6.c)$$

The temperature dependence of T_{p1} becomes little at higher values of Δk_{ps} as shown in Fig.5. With $\Delta k_{ps} = 90 \text{ cm}^{-1}$ the value of T_{p1} decreases from 1.1427 (at $T=253\text{K}$) to 0.9190 (at $T=333\text{K}$), while with $\Delta k_{ps} = 507 \text{ cm}^{-1}$ the value of T_{p1} decreases from 1.0350 (at $T=253\text{K}$) to 0.9738 (at $T=333\text{K}$). From Fig.5 for $T < 300\text{K}$, the value of g_{RxT} becomes greater than that g_{RxT} ($T=300\text{K}$) and decreases with T . But for $T > 300\text{K}$, the value of g_{RxT} becomes smaller than that g_{RxT} ($T=300\text{K}$) and decreases with T . The final effective stimulated Raman scattering gain coefficient (g_{rxT}) is defined as

$$g_{rxT} = 100 g_{RxT} / A_{eff} \quad (W^{-1} \text{ km}^{-1}) \dots \dots \dots (7.a)$$

where, g_{RxT} (in 10^{-13} m/W) and A_{eff} (in μm^2)

Finally, the value of g_{RxT} increases with x_1 but it decreases with T as explained in [15]. Also, the value of g_{rxT} decreases with core radius as explained in [15].

Fig.5 Modified thermal population T_{p1}

II.4 Raman amplifier

From the propagation coupled equations [16] between the optical power of input signal (P_s) and the optical power of pump (P_p) and with assume that, the pump depletion $\{-\frac{\lambda_s}{\lambda_p} g_{rxT} P_s(z) P_p(z)\}$ [16] is very small, the signal power distribution, $P_s(z)$, of dual pumps is derived as;

$$P_{sD}(z) = P_{s0} e^{-\alpha_s z} * \text{Exp} \left\{ \left[\frac{g_{rxT} P_p (1 - e^{-\alpha_p z})}{\alpha_p} \right] [S + (1 - S)e^{-\alpha_p (L-z)}] \right\} \dots \dots \dots (8.a)$$

Where, P_{s0} is the optical input signal at $z=0$, α_s (km^{-1}) is the attenuation coefficient for optical signal at λ_s , P_p is the summation of input pumps power (forward pump, P_{pF} , at $z=0$ (in z -direction) with wavelength, λ_p , and backward pump, P_{pB} , at $z=L$ (in negative z -direction), with the same wavelength, λ_p), α_p (km^{-1}) is the attenuation coefficient for optical pump at λ_p , g_{rxT} is the Raman coefficient ($W^{-1} \text{ km}^{-1}$), S ($0 \leq S \leq 1$) is the ratio of pump power at $z=0$ to the total pump power, therefore $P_{pF} = S P_p$ and $P_{pB} = (1-S) P_p$ and L is the amplifier length.

From Eq.8.a, the final signal power at $z = L$;

$$P_{sD}(L) = P_{s0} e^{-\alpha_s L} \text{Exp}\{g_{rxT} P_p L_{eff}\} \dots \dots \dots (9.a)$$

Also from Eq.8.a, the Raman amplifier gain, $G_D(z)$ is;

$$G_D(z) = P_{sD}(z)/P_{sD}(0) = e^{-\alpha_s z} * \text{Exp} \left\{ \left[\frac{g_{rxT} P_p (1 - e^{-\alpha_p z})}{\alpha_p} \right] [S + (1 - S)e^{-\alpha_p (L-z)}] \right\} \dots\dots\dots(10.a)$$

The final gain G_D at $z=L$

$$G_D = e^{-\alpha_s L} \text{Exp} \{ g_{rxT} P_p L_{eff} \}$$

Special case 1: with $S=1$ (i.e. Forward pump only), from Eq.8.a, $P_{sD}(z)$ becomes $P_{sF}(z)$ as;

$$P_{sF}(z) = P_{s0} e^{-\alpha_s z} * \text{Exp} \left\{ \left[\frac{g_{rxT} P_p (1 - e^{-\alpha_p z})}{\alpha_p} \right] \right\} \quad \text{as indicated in [17]} \dots\dots\dots(11.a)$$

Special case 2: with $S=0$ (i.e. Backward pump only), from Eq.8.a, $P_{sD}(z)$ becomes $P_{sB}(z)$ as;

$$P_{sB}(z) = P_{s0} e^{-\alpha_s z} \text{Exp} \left\{ \left[\frac{g_{rxT} P_p (1 - e^{-\alpha_p z})}{\alpha_p} \right] [e^{-\alpha_p (L-z)}] \right\} \quad \text{as indicated in [17]} \dots\dots\dots(12.a)$$

Then the final gain (gain at $z = L$) of forward pump (G_F), backward pump (G_B) and dual pumps (G_D) are equally as ;

$$G = G_F(\text{db}) = G_B(\text{db}) = G_D(\text{db}) = -4.343 \alpha_s L + 4.343 g_{rxT} L_{eff} P_p \dots\dots\dots(13.a)$$

As explained in [18]. So, gain (G) decreases with fiber core radius (a) where g_{rxT} decreases with a (because, A_{eff} increases with a).

Maximized and minimized values of $P_s(z)$

* For dual pumps, by putting $dP_{sD}(z)/dz = 0$ of Eq.8.a, there are maximized value of P_{sD} (P_{sDmax} occurs at Z_{Dmax}) and minimized value of P_{sD} (P_{sDmin} occurs at Z_{Dmin}) where,

$$Z_{Dmax} = -\frac{1}{\alpha_p} \ln(y_1) \quad \text{and} \quad Z_{Dmin} = -\frac{1}{\alpha_p} \ln(y_2) \dots\dots\dots(14.a)$$

Where, y_1 ($0 < y_1 < 1$) and y_2 ($0 < y_2 < 1$) are the two solutions of the following equation;

$$s y^2 - \frac{\alpha_s}{P_p g_{rxT}} y + (1 - S) e^{-\alpha_p L} = 0 \quad \{ \text{where, } y = \exp(-\alpha_p z) \} \dots\dots\dots(14.b)$$

So,

$$y_{1,2} = \frac{\alpha_s}{2S P_p g_{rxT}} \pm y_y^{0.5} \quad \text{where } y_y = \left(\frac{\alpha_s}{2S P_p g_{rxT}} \right)^2 - (s^{-1} - 1) e^{-\alpha_p L} \dots\dots\dots(14.c)$$

i- With $y_y > 0$, in this case;

$$P_p^2 < \frac{1}{(S-S^2)} \frac{\alpha_s^2}{4g_{rxT}^2} e^{\alpha_p L} \dots\dots\dots(15.a)$$

$$zz = Z_{Dmax} + Z_{Dmin} = L - \frac{1}{\alpha_p} \ln\left(\frac{1-S}{S}\right) \dots\dots\dots(15.b)$$

So, $zz < L$ (with $0 < S < 0.5$), $zz = L$ (with $S = 0.5$) and $zz > L$ (with $0.5 < S < 1.0$)

ii-With $y_y = 0$, in this case ($y_1=y_2 = \frac{\alpha_s}{2S P_p g_{rxT}}$),

$$P_p^2 = \frac{1}{(S-S^2)} \frac{\alpha_s^2}{4g_{rxT}^2} e^{\alpha_p L} \dots\dots\dots(15.c)$$

Therefore,

$$Z_{Dmax} = Z_{Dmin} = -\frac{1}{\alpha_p} \ln\left(\frac{\alpha_s}{2S P_p g_{rxT}}\right) \quad , \quad Z_{Dmin} = L - Z_{Dmax} \dots\dots\dots(15.d)$$

iii-With $y_y < 0$, in this case, the two solutions (y_1 and y_2) become complex and the gain distribution hasn't peak with;

$$P_p^2 > \frac{1}{(S-S^2)} \frac{\alpha_s^2}{4g_{rxT}^2} e^{\alpha_p L} \dots\dots\dots(15.e)$$

Note, the value of $(S-S^2)$ always greater than zero and it has maximum value at $S=0.5$. Therefore, the required P_p to give maximized and minimized values of gain, the value of P_p becomes lowest at $S=0.5$

*For forward pump only, the position of maximized value is derived from Eq.13.a as;

$$Z_{Fmax} = \frac{1}{\alpha_p} \ln(P_{pF0} g_{rxT} / \alpha_s) \dots\dots\dots(16.a)$$

This expression can be also defined from Eq.14.a by putting $S=1$. Although, the value of Z_{Fmax} increases with both P_{pF0} and g_{rxT} but it decreases with both α_p and α_s (i.e., Z_{Fmax} decreases with x_1 and T). The value of Z_{Fmax} is named as the optimum Raman length, $L_{optimum}$ [16].

* For backward pump only, the position of minimized value is derived from Eq.14.a as;

$$Z_{Bmin} = L - \frac{1}{\alpha_p} \ln(P_{pBL} g_{rxT} / \alpha_s) = L - Z_{Fmax} \dots\dots\dots(16.b)$$

This expression can be also defined from Eq.14.a by putting $S=0$.

II.5 Optimum pump wavelength (λ_p), Threshold pump power (P_{pthr}) and Gain saturation (G_s)

* **The optimum pump wavelength (λ_p)** is selected to give; (i) higher bandwidth (around 100nm, with λ_s usually ranged between 1.50 to 1.60 μ m), (ii) higher value of g_{R0} (which occurs with $\Delta k_{ps} = 90$ to 580 cm^{-1} as shown in Fig.3. So, for $\lambda_s = 1.50$ to 1.60 μ m and from Eq.4.a, the corresponding value of $\lambda_p = 1.48\mu$ m), (iii) lower A_p (i.e., lower value of λ_p to give more g_{RXT}) and (iv) lower α_p (i.e., higher value of λ_p to give more value of L_{eff}). Although, the optimum value of λ_p ranges between 1.4 to 1.5 μ m (this range of λ_p is used to avoid noise and losses). For wideband Raman amplifier, each pump wavelength is best for some signal wavelengths and vice versa for the other signal wavelengths, as indicated in Table 1.

Table1: Effect of pump wavelength (λ_p) on the Raman amplifier gain (G) at several signal wavelengths (λ_s). Amplifier data is stated in section 3 below

		$\lambda_p = 1.46 \mu\text{m}$	$\lambda_p = 1.47 \mu\text{m}$	$\lambda_p = 1.48 \mu\text{m}$	$\lambda_p = 1.49 \mu\text{m}$
Gain (db)	$\lambda_s = 1.50 \mu\text{m}$	1.63	-2.30	-4.79	40.93
	$\lambda_s = 1.55 \mu\text{m}$	46.27	34.32	20.23	8.30
	$\lambda_s = 1.60 \mu\text{m}$	-9.42	9.32	35.90	14.93

* **Threshold pump power (P_{pthr})** is defined as the incident power at which half of the pump power is transferred to the Stokes field at the output end of a fiber of length L [19]. It is defined as [19-22];

$$P_{pFthr} = 16/(g_{RXT} L_{eff}) \quad (\text{Forward pump}) \dots \dots \dots (17.a)$$

$$P_{pBthr} = 20/(g_{RXT} L_{eff}) \quad (\text{Backward pump}) \dots \dots \dots (17.b)$$

Therefore, as T increases, the value of P_{pthr} increases (where both L_{eff} and g_{RXT} are lowered with higher T) and vice versa for the Germania ratio (because as x_1 increases, g_{RXT} increases but L_{eff} decreases, while the product $g_{RXT} L_{eff}$ increases with x_1). Pump power must be greater than the threshold pump power ($P_p > P_{pthr}$) [23]

* **Gain saturation (G_s):** The amplification factor (G db) increases linearly with P_{pF0} (Eq.13.a), but experimentally the relation between gain (db) and the pump power deviate from linearity after the value of gain saturation G_s (where G_s occurring because of pump depletion) [6]. The gain saturation is defined as [6];

$$G_s = \frac{1+r_o}{r_o + G_a^{-(1+r_o)}} \dots \dots \dots (18.a)$$

Where, $G_a = \exp(g_{RXT} P_{pF0} L_{eff})$ and $r_o = (\lambda_s P_{s0})/(\lambda_p P_{pF0})$

Although, as the amplifier length (L) increases (i.e., L_{eff} increases), G_s increases. But, as pump power (P_{p0}) increases, G_s decreases as shown in Fig.6

Fig.6 Effect of P_{p0} on the saturation gain (G_s)

III. Simulation Results and Discussions

In this study the main data is $a = 3.5\mu\text{m}$, $x_1 = 0.03$ to 0.05, $L = 100\text{km}$, $\lambda_p = 1.48\mu\text{m}$, $P_p = 1.0\text{W}$, $T_0 = 300^\circ\text{K}$, $T = 253$ to 333°K , $P_{s0} = 0.1\text{mW}$, and $\lambda_s = 1.50\mu\text{m}$ to $1.60\mu\text{m}$ (i.e., Δk_{ps} increases from 90cm^{-1} to 507cm^{-1}). This data is used with both forward, backward and dual pumps (with $S = 0.5$).

Simulation example 1: Effect of x_1 , T and λ_s on the performance of amplifier. The results are shown in Fig.7 and Tables 2.a and 2.b which show that;

- Gain distribution of the dual pumps (G_D) is the best (especially at $S = 0.5$) than that gain distributions of forward (G_F) and backward (G_B) pumps.
- The summation of $Z_{Fmax} + Z_{Bmin} = L$ (as explained)

-The difference ($\Delta G_{as}=G_a-G_s$) between Raman amplifier gain (G_a) and saturation gain (G_s) very little at $\lambda_s=1.5\mu m$ but it becomes large at $\lambda_s=1.6\mu m$. Also, ΔG_{as} decreases with temperature (T) but increases with Germania ratio (x_1).

- With $x_1=0.03$ and $x_1=0.05$, there aren't peaks ($y_y < 0$) at $\lambda_s=1.55\mu m$ (T= 253K), $\lambda_s=1.60\mu m$, (T= 253K) and $\lambda_s=160\mu m$ (T=300K).

- Finally; the amplifier gain ($G = -4.343 \alpha_s L + 4.343 g_{rxT} L_{eff} P_p$) decreases with T but it increases with x_1 and λ_s . Where, α_s decreases with λ_s until $\lambda_s < \lambda_{min}$ and vice versa for $\lambda_s > \lambda_{min}$. Table 2.c indicates that, the conclusion of effect of x_1 , T and λ_s on all parameters of Raman amplifier. Also Fig.8 shows the effect of x_1 and T on the amplifier gain.

Fig.7 Gain distribution through the amplifier length , for forward pump (G_F) , backward pump (G_B) and dual pumps (G_D) with $\lambda_p=1.48\mu m$, $P_p=1W$, $T_0=300K$, $L=100km$,
Upper figures $x_1=0.03$ and lower figures $x_1=0.05$

Table 2.a: Design example 1: Effect of T and λ_s on
 α_{s1} , A_{tt} , α_{p1} , L_{eff} , g_{rxT} , G, Z_{Fmax} , G_{Fmax} , Z_{Bmin} , G_{Bmin} , Z_{Dmax} , G_{Dmax} , Z_{Dmin} , G_{Dmin} , P_{thF} , P_{thB} , P_{pmaxD} .
 With $x_1=0.03$ and $Ps_0=0.1mW$

$\lambda_s \mu m$		$\lambda_s=1.50 \mu m$ ($\Delta k_{ps} = 90$)			$\lambda_s=1.55 \mu m$ ($\Delta k_{ps} = 305$)			$\lambda_s=1.60 \mu m$ ($\Delta k_{ps} = 507$)		
T	°K	253	300	333	253	300	333	253	300	333
α_{s1}	db/km	0.1853	0.2153	0.2345	0.1775	0.2038	0.2207	0.1934	0.2165	0.2315
A_{tt}	db	-18.53	-21.53	-23.45	-17.75	-20.38	-22.07	-19.34	-21.65	-23.15
α_{p1}	db/km	0.1922	0.2238	0.2441	0.1922	0.2238	0.2441	0.1922	0.2238	0.2441
L_{eff}	km	22.32	19.29	17.73	22.32	19.30	17.73	22.32	19.29	17.73
g_{rxT}	1/W. km	0.2247	0.1997	0.1870	0.5107	0.4846	0.4696	0.6982	0.6869	0.6795
G	db	3.2455	-4.79	-9.05	31.76	20.24	14.09	48.35	35.90	29.17
G_a	db	21.78	16.73	14.4	49.5	40.61	36.16	67.68	57.55	52.32
G_s	db	21.19	16.55	14.29	29.84	37.17	28.91	29.67	29.66	29.65
Z_{Fmax}	km	37.52	27.04	22.10	57.06	45.32	39.57	62.19	50.90	45.29
G_{Fmax}	db	10.90	6.83	5.10	35.97	27.66	23.63	52.11	42.67	37.90
Z_{Bmin}	km	62.48	72.96	77.90	42.94	54.69	60.43	37.81	49.10	54.71
G_{Bmin}	db	-11.58	-15.70	-18.27	-7.62	-11.14	-13.34	-7.31	-10.63	-12.66
Z_{Dmax}	km	24.02	14.06	9.97	No *	35.96	28.80	No*	No*	36.48
G_{Dmax}	db	3.01	1.36	0.78	No*	10.53	8.4584	No*	No*	15.07
Z_{Dmin}	km	75.98	85.94	90.03	No*	64.04	71.20	No*	No*	63.52
G_{Dmin}	db	0.2323	-6.156	-9.83	No*	9.70	5.63	No*	No*	14.09
P_{thF}	W	3.1906	4.1528	4.8256	1.40	1.71	1.92	1.0266	1.2073	1.3283
P_{thB}	W	3.99	5.19	6.03	1.75	2.14	2.40	1.2833	1.5091	1.6604
P_{pDmax}	W	3.47	6.53	9.59	1.46	2.55	3.60	1.1662	1.9092	2.6061

* Note; No means there isn't peaks ($y_y < 0$)

Table 2.b: design example 2: Effect of T and λ_s on
 α_{s1} , A_{tt} , α_{p1} , L_{eff} , g_{rxT} , G, Z_{Fmax} , G_{Fmax} , Z_{Bmin} , G_{Bmin} , Z_{Dmax} , G_{Dmax} , Z_{Dmin} , G_{Dmin} , P_{thF} , P_{thB} , P_{pmaxD} .
 With $x_1=0.05$ and $Ps_0=0.1mW$

λ_s		$\lambda_s=1.50 \mu m$ ($\Delta k_{ps} = 90$)			$\lambda_s=1.55 \mu m$ ($\Delta k_{ps} = 305$)			$\lambda_s=1.60 \mu m$ ($\Delta k_{ps} = 507$)		
T	°K	253	300	333	253	300	333	253	300	333
α_{s1}	db/km	0.2182	0.2525	0.2747	0.2066	0.2368	0.2563	0.2193	0.2459	0.2632
A_{tt}	db	-21.82	-25.25	-27.47	-20.66	-23.68	-25.63	-21.93	-24.59	-26.32
α_{p1}	db/km	0.2267	0.2630	0.2863	0.2267	0.2630	0.2863	0.2267	0.2630	0.2863
L_{eff}	km	19.05	16.48	15.15	19.053	16.48	15.15	926.9	16.48	15.15
g_{rxT}	1/W. km	0.3961	0.3500	0.3264	0.9060	0.8542	0.8239	1.2751	1.2456	1.2257
G	db	10.95	-0.206	-6.00	54.30	37.45	28.57	83.57	64.54	54.32
G_a	db	32.77	25.05	21.48	74.96	61.14	54.21	105.49	89.19	80.65
G_s	db	28.15	23.86	20.92	29.81	29.80	29.79	29.67	29.67	29.67
Z_{Fmax}	Km	39.55	29.65	24.89	56.44	45.44	39.99	61.85	51.05	45.61
G_{Fmax}	db	20.14	13.45	10.50	59.75	46.60	40.14	88.31	72.73	64.75
Z_{Bmin}	km	60.45	70.35	75.11	43.56	54.56	60.01	38.15	48.95	54.39
G_{Bmin}	db	-13.19	-17.77	-20.63	-9.00	-12.92	-15.38	-8.367	-12.04	-14.31
Z_{Dmax}	km	28.13	18.56	14.52	No *	37.16	30.61	No*	No*	37.90
G_{Dmax}	db	6.84	3.85	2.66	No*	19.22	15.93	No*	No*	27.70
Z_{Dmin}	km	71.87	81.44	85.48	No*	62.84	69.39	No*	No*	62.10
G_{Dmin}	db	4.11	-4.05	-8.65	No*	18.23	12.64	No*	No*	26.62
P_{thF}	W	2.1204	2.7744	3.2361	0.93	1.14	1.2821	0.6587	0.7796	0.8618
P_{thB}	W	2.65	3.47	4.05	1.16	1.42	1.6027	0.8233	0.9745	1.0772
P_{pDmax}	W	3.45	6.86	10.47	1.43	2.64	3.8700	1.0775	1.8771	2.6709

* Note; No means there isn't peaks ($y_y < 0$)

Table 2.c Conclusion of effect of x_1 , T and λ_s

	α_s	α_p	L_{eff}	g_{rxT}	Z_{Fmax}	G_{Fmax}	Z_{Bmin}	G_{Bmin}	Z_{Dmax}	G_{Dmax}	Z_{Dmin}	G_{Dmin}	P_{thr}	P_{Dmax}	G_s	G
x_1	H	H	L	H	H	L	L	H	L	H	L	H	L			H
T	H	H	L	L	L	L	H	H	L	L	H	H	H	T		L
λ_s	L	-	-	H	H	H	L	L	H	H	L	H	L	L		H

a) effect of x_1 with $T=300^\circ\text{K}$

b) effect of T with $x_1=0.03$

Fig.8 Effect of Germania ratio (x_1) and temperature (T) on the performance of Raman amplifier

$\lambda_p=1.4553\mu\text{m}$, $\lambda_s=1.55\mu\text{m}$, $\Delta k_{ps}=420\text{cm}^{-1}$, $T_o=300^\circ\text{K}$, $a=3.5\mu\text{m}$, $L=120\text{km}$

Simulation example 2; Effect of ratio S (forward pump power / total input pump power) on the gain distribution:

With, $\lambda_s=1.55\mu\text{m}$, $T=300\text{K}$, $x_1=0.05$, the values of $\alpha_s=0.2563\text{ db/km}$, $\alpha_p=0.2861\text{ db/km}$, $\Delta k_{ps}=305\text{cm}^{-1}$, $L_{\text{eff}}=15.15\text{ km}$, $g_{\text{rxt}}=0.8239\text{ W}^{-1}\text{km}^{-1}$ and gain $G=28.57\text{db}$. For dual pumps, the values of $Z_{D\text{max}}$, $G_{D\text{max}}$ and $Z_{D\text{min}}$, $G_{D\text{min}}$ are increased with the parameter S as indicated in Table 3.

The best value of parameter at $S=0.5$ (dual pump) which makes the maximum and minimum values of the amplifier gain are little as shown in Fig.9. The summation of $Z_{D\text{max}} + Z_{D\text{min}} < L$ (where $S < 0.5$) but $Z_{D\text{max}} + Z_{D\text{min}} > L$ (with $S > 0.5$) while $Z_{D\text{max}} + Z_{D\text{min}} = L$ (with $S = 0.5$) as explained above and as indicated in Table 3.

Table 3: Effect of S on the values of $Z_{D\text{max}}$, $G_{D\text{max}}$, $Z_{D\text{min}}$, $G_{D\text{min}}$, $P_{F\text{th}}$, $P_{B\text{th}}$ and $P_{D\text{max}}$

Kind of pump		Backward	Dual				Forward
parameter	unit	$S=0.00$	$S=0.25$	$S=0.50$	$S=0.75$	$S=1.00$	
$Z_{D\text{max}}$	km	-	19.78	30.61	36.45	39.99	
$Z_{D\text{min}}$	km	60.01	63.55	69.39	80.22	-	
$Z_{D\text{max}}+Z_{D\text{min}}$	km	-	83.33	100	116.67	-	
$G_{D\text{max}}$	db	-	4.97	15.93	27.87	40.14	
$G_{D\text{min}}$	db	-15.38	0.70	12.64	23.60	-	
$P_{D\text{max}}$	W	-	2.234	1.935	2.234	-	
$P_{F\text{th}}$	W	-	-	-	-	1.282	
$P_{B\text{th}}$	W	1.603	-	-	-	-

a) Gain with peaks ($y_y > 0$)

b) Gain without peaks ($y_y \leq 0$)

Fig.9 Gain of Raman amplifier with different values of S

Simulation example 3: Effect of signal wavelength (λ_s) on Raman amplifier gain

With $x_1=0.05$, $a=3.5\mu\text{m}$, $\lambda_p=1.48\mu\text{m}$, $L=100\text{km}$, $T=300\text{K}$ and $P_p=0.5\text{W}$;

- The values of $\alpha_p=0.2630\text{db/km}$ and $L_{\text{eff}}=16.48\text{km}$

- The attenuation ($\alpha_s L$) decreases from 25.25db (at $\lambda_s=1.50\mu\text{m}$) to 23.61db (at $\lambda_s=1.563\mu\text{m}$) and increases again to 24.59db (at $\lambda_s=1.60\mu\text{m}$), then the variation of attenuation around one db as shown in Fig.9. a.

- The effective cross section area (A_{eff}) increases linearly from $53.7951\mu\text{m}^2$ (at $\lambda_s=1.50\mu\text{m}$) to $56.8074\mu\text{m}^2$ (at $\lambda_s=1.60\mu\text{m}$).

- The value of Δk_{ps} increases from 90.09cm^{-1} (at $\lambda_s=1.50\mu\text{m}$) to 583.92cm^{-1} (at $\lambda_s=1.60\mu\text{m}$).
- The Raman gain coefficient (g_{rxt}) increases from $0.3500\text{ W}^{-1}\text{ km}^{-1}$ (at $\lambda_s=1.50\mu\text{m}$) to $1.5756\text{ W}^{-1}\text{ km}^{-1}$ (at $\lambda_s=1.5781\mu\text{m}$) and it decreases to $0.3360\text{ W}^{-1}\text{ km}^{-1}$ (at $\lambda_s=1.60\mu\text{m}$) as shown in Fig.9. b.
- From Eq.12.a,

$$G = 35.78 g_{\text{rxt}} - 100 \alpha_{s1} \text{db} \quad (\text{where } \alpha_{s1} \text{ in db/km}) \dots \dots \dots (13.a)$$

So, the profile of final Raman gain (Gdb) approximately similar with the profile of Raman gain coefficient (g_{rxt} $\text{W}^{-1}\text{ km}^{-1}$) as shown in Figs.9.b and 9.c

a) signal loss ($\alpha_s L$) b) Raman gain coefficient (g_{rxt}) c) Raman gain (G)

Fig.10 The output gain as a function of signal wavelength (λ_s).

With $x_1=0.05$, $a=3.5\mu\text{m}$, $\lambda_p=1.48\mu\text{m}$, $T=300\text{K}$ and $P_p=0.5\text{W}$

Simulation example 4: Effect of pump wavelength (λ_p) on Raman amplifier gain

The gain becomes peaks at $\lambda_p=1.4553\mu\text{m}$ with $\lambda_s=1.55\mu\text{m}$ as indicated in Table 4

Table 4: Effect of pump wavelength (λ_p) on the performance of Raman amplifier
With $\lambda_s=1.55\mu\text{m}$, $x_1=0.03$, $T=300^\circ\text{K}$, $T_0=300^\circ\text{K}$, $a=3.5\mu\text{m}$, $L=100\text{km}$, $P_p=0.5\text{W}$

λ_p	α_p	L_{eff}	α_s	att	Δk_{ps}	g_{rxt}	G	$g_{\text{rxt}} L_{\text{eff}}$
1.44	0.2456	17.62	0.1886	-18.86	493	0.7726	38.76	13.613
1.4553	0.2172	19.86	0.1886	-18.86	420	0.8837	57.37	17.550
1.48	0.2238	19.29	0.1886	-18.86	305	0.4846	20.23	9.348
λ_p	ZFmax	GFmax	ZBmin	GBmin	ZDmax	GDmax	ZDmin	GDmin
1.44	49.54	45.64	50.46	-10.28	45.96	28.76	54.04	19.36
1.4553	60.26	61.62	39.74	-7.50	-	-	-	-
1.48	45.31	27.66	54.69	-11.14	35.96	10.53	64.04	9.70

Conclusion:

The performance of Germania doped silica Raman amplifier fiber is affected by the optical fiber structure (core radius, a , ratio of Germania, x_1 , and pump type) and the operating parameters (signal wavelength, λ_s , pump wavelength, λ_p , and temperature, T).

The general formula for the Raman gain coefficient (g_{rxt}) as a function of core radius (a), Germania ratio (x_1), signal wavelength (λ_s), pump wavelength (λ_p) and operating temperature (T) is derived. The effect of x_1 , T and λ_s (λ_p) on the attenuation coefficient α_s (α_p) is done. The final optical signal gain (G) independent on the position of pump. The gain value decreases with temperature but it increases with x_1 ,

The gain distribution through the longitudinal coupler length of dual pumps becomes the best than distributions of forward and back pumps. Additionally, the gain distribution becomes very best with the power of the two pumps of dual pump are equals. The effect of λ_s on the amplifier gain becomes very evident.

Magnitude of gain variation depends upon the product of Raman gain coefficient, effective amplifier length and the pump power. With $L=100$, $P_p=1.0\text{W}$, $\lambda_p=1.48\mu\text{m}$, $x_1=0.03$, when the Germania ratio increases from 0.03 to 0.05, the gain G increases from 171% ($T=253\text{K}$) to 202% ($T=333\text{K}$) with $\lambda_s=1.55\mu\text{m}$ while with $\lambda_s=1.60\mu\text{m}$, the percentage becomes 173% ($T=253$) to 186% ($T=333\text{K}$).

Raman gain of an optimized bi-directionally pumped fiber Raman amplifier is studied. The gain decreases with increasing the fiber core radius (a).

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Appendix A: Refractive index of silica doped Germania

The refractive indices of core (silica doped Germania, n_1) and clad material (silica, n_2) are functions of temperature (T °K) and the ratio of Germania (x_1) as defined in [7].

$$n_1^2 = 1 + \frac{a_{1xt}\lambda^2}{(\lambda^2 - b_{1xt}^2)} + \frac{a_{2xt}\lambda^2}{(\lambda^2 - b_{2xt}^2)} + \frac{a_{3xt}\lambda^2}{(\lambda^2 - b_{3xt}^2)} \dots\dots\dots (A.1)$$

$$n_2^2 = 1 + \frac{a_{1t}\lambda^2}{(\lambda^2 - b_{1t}^2)} + \frac{a_{2t}\lambda^2}{(\lambda^2 - b_{2t}^2)} + \frac{a_{3t}\lambda^2}{(\lambda^2 - b_{3t}^2)} \dots\dots\dots (A.2)$$

where;

$a_{1xt} = (a_{10} + u_1 x_1) f_{1t}$, $a_{2xt} = (a_{20} + u_2 x_1) f_{1t}$, $a_{3xt} = (a_{30} + u_3 x_1) f_{1t}$,
 $b_{1xt} = (b_{10} + v_1 x_1) f_{1t}$, $b_{2xt} = (b_{20} + v_2 x_1) f_{1t}$, $b_{3xt} = (b_{30} + v_3 x_1) f_{1t}$
 $a_{10} = 0.6961663$, $a_{20} = 0.4079426$, $a_{30} = 0.8974794$, $b_{10} = 0.0684043$, $b_{20} = 0.1162414$, $b_{30} = 9.8961610$
 $f_{1t} = e_1 + e_2 T$, $f_{2t} = T_0 / T$, $e_1 = 0.93721$, $e_2 = 0.0002143$, $T_0 = 293$ °K,
 $u_1 = 0.1107001$, $u_2 = 0.31021588$, $u_3 = -0.04331091$, $v_1 = 0.000568306$, $v_2 = 0.03772465$, $v_3 = 1.94577$
 a_{1t} , a_{2t} , a_{3t} , b_{1t} , b_{2t} and b_{3t} are defined by putting the value of $x_1 = 0$ through the parameters a_{1xt} , a_{2xt} , a_{3xt} , b_{1xt} , b_{2xt} and b_{3xt} respectively.

Appendix B Stimulated Raman scattering gain coefficient of pure silica (g_{R0})

By using the published data [10] and by using the fitting curve technique, g_{R0} versus Δk_{ps} is defined from Fig.B.1 as;

For $\Delta k_{ps} = 50$ to 200 cm^{-1} ; $10^{13} g_{R0} = 0.0237 + 0.0034 \Delta k_{ps} - 2.385 \times 10^{-5} \Delta k_{ps}^2 + 6.235 \times 10^{-8} \Delta k_{ps}^3$
For $\Delta k_{ps} = 201$ to 300 cm^{-1} ; $10^{13} g_{R0} = -2.4733 + 0.03532 \Delta k_{ps} - 0.0001537 \Delta k_{ps}^2 + 2.25925 \times 10^{-7} \Delta k_{ps}^3$
For $\Delta k_{ps} = 301$ to 417 cm^{-1} ; $10^{13} g_{R0} = -1.88 + 0.01145 \Delta k_{ps} - 1.29 \times 10^{-5} \Delta k_{ps}^2$
For $\Delta k_{ps} = 418$ to 440 cm^{-1} ; $10^{13} g_{R0} = 1.5565 - 0.002174 \Delta k_{ps}$
For $\Delta k_{ps} = 441$ to 460 cm^{-1} ; $10^{13} g_{R0} = -0.39 + 0.00223 \Delta k_{ps}$
For $\Delta k_{ps} = 461$ to 535 cm^{-1} ; $10^{13} g_{R0} = 0.4787 + 0.001635 \Delta k_{ps} - 2.745 \times 10^{-6} \Delta k_{ps}^2$
For $\Delta k_{ps} = 536$ to 567 cm^{-1} ; $10^{13} g_{R0} = 7.7912 - 0.01353 \Delta k_{ps}$
For $\Delta k_{ps} = 568$ to 600 cm^{-1} ; $10^{13} g_{R0} = 0.0341 + 0.0001515 \Delta k_{ps} \dots\dots\dots (B.1)$

Where, $\Delta k_{ps} = 10000 \left(\frac{1}{\lambda_p} - \frac{1}{\lambda_s} \right) \text{ cm}^{-1}$ {where, λ_p (μm) and λ_s (μm)} $\dots\dots\dots (B.2)$

Appendix C : Values of parameter C_v

The values of parameter C_v is defined by using the published data [24] which is shown in Fig.C.1 and by using the fitting curve technique, C_v versus Δk_{ps} is defined as;

For $\Delta k_{ps} = 70$ to 220 cm^{-1} : $c_v = 0.011$
For $\Delta k_{ps} = 220$ to 350 cm^{-1} : $c_v = 0.08963 - 0.000688 \Delta k_{ps} + 1.51786 \times 10^{-6} \Delta k_{ps}^2$
For $\Delta k_{ps} = 350$ to 430 cm^{-1} : $c_v = -0.55117 + 0.002559 \Delta k_{ps} - 2.53247 \times 10^{-6} \Delta k_{ps}^2$
For $\Delta k_{ps} = 430$ to 500 cm^{-1} : $c_v = -0.635875 + 0.003689 \Delta k_{ps} - 4.70238 \times 10^{-6} \Delta k_{ps}^2$
For $\Delta k_{ps} = 500$ to 620 cm^{-1} : $c_v = 1.5979 - 0.008927 \Delta k_{ps} + 1.718 \times 10^{-5} \Delta k_{ps}^2 - 1.1162 \times 10^{-8} \Delta k_{ps}^3$

Fig.A.1 Refractive index (n_{xt})

Fig.B.1: g_{R0} [10]

Fig.C.1: Values of C_v [24]