

Characteristics of the Gain and Signal-To-Noise Ratio of a Distributed Erbium-Doped Fiber Amplifier

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Abstract—The effects of the stimulated Raman scattering (SRS) on the gain and signal-to-noise ratio (SNR) of the DEDFA with 100-km fiber length and with bidirectional pumps are numerically studied. It is found that the gain and SNR are significantly enhanced by the SRS with practical parameters. For 1.55- μm signal and 10- μW initial signal power, there are 8.8-dB gain enhancement and 3.3-dB SNR enhancement for 1.48- μm pump wavelength and 75-mW initial pump power. The characteristics of the gain and SNR enhancements due to SRS are studied for different signal wavelength, signal powers, pump wavelengths, pump powers, and effective fiber cross sections. The results show that the gain and SNR are decreased by SRS only for the unpractical high pump power and/or small effective fiber cross section.

I. INTRODUCTION

THE erbium-doped fiber amplifier (EDFA) is an optical amplifier in the third telecommunications window near 1.55- μm regime [1], [2]. There are extensive studies about the EDFA [3]. These works show the EDFA is effective and practical for optical communication systems. The erbium ions are doped in the fiber core and the waveguide structure provides excellent power confinement to pump the erbium ions over long interaction length. Besides, the EDFA can be used in the wavelength-division-multiplexing (WDM) communication system because of its large gain bandwidth in the 1.55- μm regime. The fiber of a few tens of meters in length and with heavily doped erbium ions is used as a lumped EDFA (LEDFA) [4]. The LEDFA amplifies the signal power within the erbium-doped fiber and provides few tens of dB gain. On the other hand, the fiber of several tens of kilometers in length and with lightly doped erbium ions is used as a distributed EDFA (DEDFA) [5], [6]. The DEDFA provides the gain and it is itself the transmission line. In theory, the DEDFA can have lower amplified spontaneous emission noise (ASE) than the LEDFA [7], [8], but, in practice, the advantage is not significant [9]. However, because the DEDFA has the advantage of lower excursion of the signal power than the lumped amplifier, the DEDFA is more suitable for both linear or nonlinear signal transmission at the ultra-high bit rate.

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The LEDFA and DEDFA are basically the same, except their fiber lengths and doping densities differs about three order of magnitudes. Recently, it is found that the SRS [10] enhances both the gain and SNR of the DEDFA at the 1.55- μm signal wavelength [11]. While, the SRS in LEDFA can be neglected because the fiber length is too short. There are several bands of wavelengths that can be used to efficiently pump the erbium-doped fiber to provide gain at 1.55- μm regime [12], [13]. Because the intrinsic loss of the fiber is important for the long distance fiber, the pump wavelength near 1.48 μm has the advantage of lower intrinsic loss than the other bands [6], [14], [15] and is used in the DEDFA. Because the Raman gain is maximum for 440- cm^{-1} frequency separation, the 1.55- μm wavelength regime is within the Raman gain spectral width for 1.48- μm pump wavelength. In the DEDFA, the effect of the SRS reduces the gain from the pumped erbium ions because part of the pump power is depleted by SRS. Although the efficiency of the SRS is less than the stimulated emission of the pumped erbium ions, the pump power simultaneously utilized by the two effects leads to the result that the gain from the SRS is larger than the reduction of the gain from the pumped erbium ions and the total gain increases.

In this paper, we consider the effects of the SRS on the DEDFA for different signal wavelengths, signal powers, pump wavelengths, pump powers, and effective fiber cross sections to numerically study the characteristics of the gain and SNR of the DEDFA with SRS. The theoretical model used in this paper is described in Section II. The evolutions of the optical powers and gain coefficients along the fiber are considered in Section III. In Section IV, the characteristics of the effects of the SRS on the gain and SNR of the DEDFA are studied. The conclusions are given in Section V.

II. THEORETICAL MODEL

The signal propagating in the erbium-doped fiber of long length experiences the gain from the pumped erbium ions and the SRS. Fig. 1 shows both the absorption cross-section lineshape ($\sigma_a(\lambda)$) and emission cross-section lineshape ($\sigma_e(\lambda)$) of the erbium ions doped in the fiber [16]. The maximum emission cross section is near 1.53 μm . Fig. 2 shows the Raman gain spectrum ($g_r(\Delta\nu_r)$) [17], where $\Delta\nu_r$ is the frequency difference between the pump wave and the stoke wave. In Fig. 2, the maximum gain coefficient is $1.97 \times 10^{-14}/\lambda_p$ m/W when $\Delta\nu_r = 440 \text{ cm}^{-1}$, where λ_p is the pump wavelength and in unit of micrometers [18]. It is noticed that the absorption and emission cross sections considered in [11] are different from that given in Fig. 1.

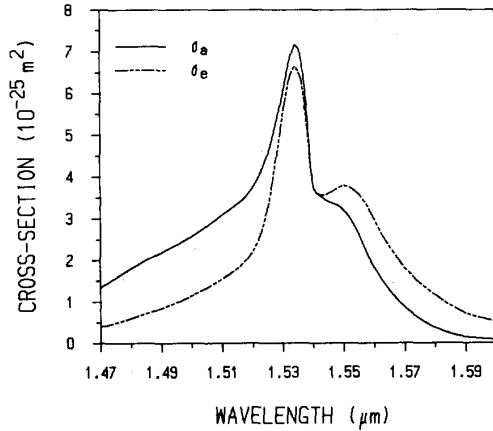


Fig. 1. Spectra of the absorption cross section $\sigma_a(\lambda)$ and emission cross section $\sigma_e(\lambda)$ of the erbium ions doped in the fiber.

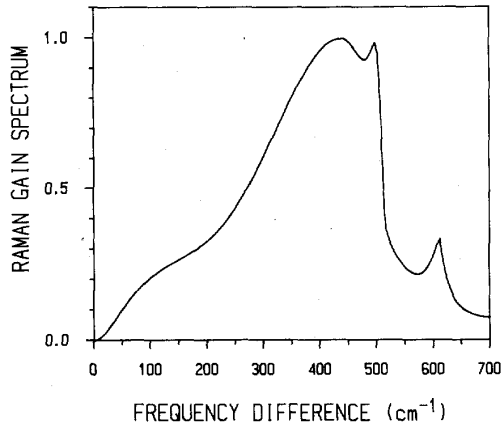


Fig. 2. Spectrum of the Raman gain $g_r(\Delta\nu_r)$ in the fiber. The maximum gain coefficient is $1.97 \times 10^{-14}/\lambda_p$ at the frequency difference $\Delta\nu_r = 440 \text{ cm}^{-1}$ where λ_p is pump wavelength and in unit of micrometers.

where the data are reported more recently. Because of the high gain of the DEDFA, the spontaneous emission noise is amplified and depletes the pump power. From Figs. 1 and 2, the gain bandwidths of both effects are large and the spectrum of the amplified spontaneous emission noise (ASEN) is broadband. We consider the ASEN as a number of optical beams with frequency bandwidth $\Delta\nu_k$ centered at the optical wavelength $\lambda_k = c/\nu_k$ to resolve the ASE spectrum [16]. For the pump wavelength $\lambda_p = 1.45\text{--}1.5 \mu\text{m}$, the pumped erbium ions can be modeled as a two level system and its rate equations describing the effects of the signal power intensity ($I_s(z, r, \phi)$), pump power intensity ($I_p(z, r, \phi)$) and ASEN power intensity ($I_k(z, r, \phi)$, $k = 1, N$) on the population densities are [16]

$$\frac{dn_2}{dt} = \left[\frac{\sigma_{as}}{h\nu_s} I_s + \frac{\sigma_{ap}}{h\nu_p} (I_p^+ + I_p^-) + \sum_{k=1}^N \frac{\sigma_{ak}}{h\nu_k} (I_k^+ + I_k^-) \right] n_1(z, r, \phi)$$

$$- \left[\frac{\sigma_{es}}{h\nu_s} I_s + \frac{\sigma_{ep}}{h\nu_p} (I_p^+ + I_p^-) + \sum_{k=1}^N \frac{\sigma_{ek}}{h\nu_k} (I_k^+ + I_k^-) + \frac{1}{\tau} \right] n_2(z, r, \phi) \quad (1)$$

and, $n_1 = n_t - n_2$, where n_t is the total erbium ions density, and n_1 and n_2 are the populations densities of the ground level and upper level, respectively. In this paper, we use the superscripts + and - to denote the variables corresponding to the optical beam propagating along +z and -z directions, respectively. We will call the wave propagating in +z direction the forward wave and the wave propagating in -z direction the backward wave. For example, in (1), I_p^+ is the forward pump power intensity and so on. The absorption and emission cross sections of the signal beam, pump beam and k th ASE beam are $\sigma_{a,e:s,p,k}$. τ is the spontaneous life time of the upper level. The rate equation given by (1) depends on the coordinates z, r, ϕ . To simplify the rate equation, we make the following assumptions. We assume a Gaussian approximation for the optical mode of wavelength λ_j and

$$I_j^\pm(z, r, \phi) = \frac{1}{\pi\omega_j^2} P_j^\pm(z) e^{-r^2/\omega_j^2} \quad (2)$$

where P_j^\pm is the power of the optical mode and ω_j is the mode spot size. The erbium ions are assumed to be uniformly doped within a radius of b in the fiber core and the radius b is small enough that the erbium ions are uniformly pumped. With these assumptions, we have the rate equation which depends only on z by integrating (1) over the transverse cross section of the fiber and it becomes

$$\begin{aligned} \frac{dn_2}{dt} = & \left[\frac{\sigma_{as}\Gamma_s}{h\nu_s A_e} P_s + \frac{\sigma_{ap}\Gamma_p}{h\nu_p A_e} (P_p^+ + P_p^-) \right. \\ & + \sum_{k=1}^N \left. \frac{\sigma_{ak}\Gamma_k}{h\nu_k A_e} (P_k^+ + P_k^-) \right] n_1(z) \\ & - \left[\frac{\sigma_{es}\Gamma_s}{h\nu_s A_e} P_s + \frac{\sigma_{ep}\Gamma_p}{h\nu_p A_e} (P_p^+ + P_p^-) \right. \\ & + \sum_{k=1}^N \left. \frac{\sigma_{ek}\Gamma_k}{h\nu_k A_e} (P_k^+ + P_k^-) + \frac{1}{\tau} \right] n_2(z) \quad (3) \end{aligned}$$

where $A_e = \pi b^2$ is the dopant area and Γ_j is the confinement factor related to the optical mode of wavelength λ_j and

$$\Gamma_j = 1 - e^{-b^2/\omega_j^2}. \quad (4)$$

The equations to describe the variations of the powers of the optical beams through the fiber are

$$\frac{dP_s}{dz} = \left[\Gamma_s (\sigma_{es} n_2 - \sigma_{as} n_1) + \frac{g_{rs}}{A_{op}} (P_p^+ + P_p^-) - \alpha_{is} \right] P_s^\pm \quad (5)$$

$$\begin{aligned} u^\pm \frac{dP_p^\pm}{dz} = & \left[\Gamma_p (\sigma_{ep} n_2 - \sigma_{ap} n_1) - \frac{\lambda_s g_{rs}}{\lambda_p A_{os}} P_s \right. \\ & \left. - \sum_{k=1}^N \frac{\lambda_k g_{rk}}{\lambda_p A_{ok}} (P_k^+ + P_k^-) - \alpha_{ip} \right] P_p^\pm \quad (6) \end{aligned}$$

$$u^\pm \frac{dP_k^\pm}{dz} = \left[\Gamma_k (\sigma_{ek} n_2 - \sigma_{ak} n_1) + \frac{g_{rk}}{A_{op}} (P_p^+ + P_p^-) - \alpha_{ik} \right] P_k^\pm + \left[\Gamma_k \sigma_{ek} n_2 + \frac{g_{rk}}{A_{op}} (P_p^+ + P_p^-) \right] m h \nu_k \Delta \nu_k \quad (7)$$

where $A_{oj} = \pi \omega_j^2$ is the mode area related to the optical mode of wavelength λ_j ; α_{ij} is the intrinsic loss at the wavelength λ_j ; in (7), $m = 2$ represents the two polarization modes of the ASE; $u^+ = +1$ and $u^- = -1$ correspond to the forward and backward waves, respectively. In (6), the terms with the Raman gain coefficient g_{rk} represent the pump depletion due to SRS. On the other hand, in (5) and (7), the terms with g_{rk} represent the Raman gain from the pump waves, and the terms with $h\nu_k \Delta\nu_k$ in (7) represent the spontaneous emission. It is noticed that, the Raman effect among the signal and the ASE beams are neglected. The neglect is valid when the power of the signal and the ASE are small. Assuming the steady-state condition for the rate equation (3), the population densities n_1 and n_2 in (5)–(7) can be derived in terms of the optical mode powers. With this assumption, (5)–(7) become

$$\frac{dP_s}{dz} = \left[(\alpha_{gs} + \alpha_{ls}) \frac{n_2}{n_t} - \alpha_{ls} + \frac{g_{rs}}{A_{op}} (P_p^+ + P_p^-) - \alpha_{is} \right] P_s \quad (8)$$

$$u^\pm \frac{dP_p^\pm}{dz} = \left[(\alpha_{gp} + \alpha_{lp}) \frac{n_2}{n_t} - \alpha_{lp} - \frac{\lambda_s g_{rs}}{\lambda_p A_{os}} P_s - \sum_{k=1}^N \frac{\lambda_k g_{rk}}{\lambda_p A_{ok}} (P_k^+ + P_k^-) - \alpha_{ip} \right] P_p^\pm \quad (9)$$

$$u^\pm \frac{dP_k^\pm}{dz} = \left[(\alpha_{gk} + \alpha_{lk}) \frac{n_2}{n_t} - \alpha_{lk} + \frac{g_{rk}}{A_{op}} (P_p^+ + P_p^-) - \alpha_{ik} \right] P_k^\pm + \left[\alpha_{gk} \frac{n_2}{n_t} + \frac{g_{rk}}{A_{op}} (P_p^+ + P_p^-) \right] m h \nu_k \Delta \nu_k \quad (10)$$

where the ratio of the population density of the upper state n_2 and the erbium ion density n_t is

$$\frac{n_2}{n_t} = \left[\frac{P_s}{P_s^{th}} + \frac{P_p^+ + P_p^-}{p_p^{th}} + \sum_{k=1}^N \frac{P_k^+ + P_k^-}{p_k^{th}} \right] \div \left[1 + \frac{P_s}{P_s^{is}} + \frac{P_p^+ + P_p^-}{p_p^{is}} + \sum_{k=1}^N \frac{P_k^+ + P_k^-}{p_k^{is}} \right] \quad (11)$$

and the coefficients in (8)–(11) are

$$\alpha_{gk} = \sigma_{ek} \Gamma_k n_t, \quad \alpha_{lk} = \sigma_{ak} \Gamma_k n_t, \quad P_k^{th} = \frac{A_e h \nu_k}{\sigma_{ak} \Gamma_k \tau}, \quad P_k^{is} = \frac{A_e h \nu_k}{(\sigma_{ek} + \sigma_{ak}) \Gamma_k \tau}, \quad (12)$$

for $k = s, p, 1, 2, \dots, N$.

In this paper, the coupled equations (8)–(10) are numerically solved with the absorption cross section σ_{ak} and emission cross section σ_{ek} given by Fig. 1, the Raman gain coefficient g_{rk} given by Fig. 2, and the following parameters: $\tau = 10$ ms, $n_t = 1 \times 10^{22}$ m $^{-3}$, $b = 1$ μ m ($A_e = 3.14$ μ m 2), fiber length $L = 100$ km, and $\alpha_{ik} = 0.26$ dB/km, $\omega_k = \omega(A_{ok} = A_o)$ for all k for simplicity. The mode spot size ω is varied in the followings.

The initial signal power $P_s(0) = P_{s0}$ is launched into the fiber at $z = 0$. For bidirectional pumping, the initial pump powers $P_p^+(0) = P_p^-(L) = P_{p0}$ are launched into the fiber at $z = 0$ and L , respectively. We use 100 points to sample the ASE spectrum from 1.5–1.6 μ m, which corresponds to the wavelength spacing of $\Delta\lambda = 1$ nm (the corresponding frequency spacing $\Delta\nu_k = 128.1$ GHz at $\lambda_k = 1.53$ μ m), and there are $1 + 2 + 2 \times 100 = 203$ differential equations necessarily to be solved simultaneously for bidirectional pumping.

Before considering the effect of SRS on the DEDFA, we estimate the power range that SRS should be considered. Inspecting the gain coefficients in (8), the effect of SRS is important when the pump power is high enough. When the pump power equals

$$P_p^c = \left(\frac{A_o}{g_{rs}} \right) \left[(\alpha_{gs} + \alpha_{ls}) \left(\frac{n_2}{n_t} \right) - \alpha_{ls} \right] \quad (13)$$

the gain coefficients from the pumped erbium ions and SRS are equal. Therefore, P_p^c is the pump power when the gains from the pumped erbium ions and SRS are comparable for the wavelength at λ_s . We call P_p^c the comparable pump power. In (13), n_2/n_t depends on z and, from (11), the maximum achievable value of n_2/n_t is

$$\text{Max} \frac{n_2}{n_t} = \frac{\sigma_{ap}}{\sigma_{ep} + \sigma_{ap}} \quad (14)$$

for the pump power $P_p \gg P_p^{is}$, where P_p^{is} is only few milli-Watts for the parameters given above. Substituting (14) into (13), we have the comparable pump power

$$P_p^c = \frac{A_o \Gamma_s n_t}{g_{rs}} \left[\frac{\sigma_{es} - \sigma_{as} (\sigma_{ep} / \sigma_{ap})}{1 + (\sigma_{ep} / \sigma_{ap})} \right]. \quad (15)$$

In (15), the ratio $\sigma_{ep} / \sigma_{ap}$ should be small for efficient pump rate. From Fig. 1, $\sigma_{ep} / \sigma_{ap} = 0.3$ for $\lambda_p = 1.48$ μ m. From (15), P_p^c increases as the emission cross section at the signal wavelength and decreases as the Raman gain coefficient increases. The comparable pump power P_p^c varies with the wavelength. For $\lambda_p = 1.48$ μ m, $A_o = 35$ μ m 2 for the dispersion shifted fiber [19], and the other numerical parameters given above, we have $P_p^c = 330$ mW for $\lambda_s = 1.53$ μ m and $P_p^c = 150$ mW for $\lambda_s = 1.55$ μ m.

III. EVOLUTIONS OF THE OPTICAL WAVES ALONG THE FIBER

In this section, we consider the variations of the optical powers and gain coefficients along the fiber to show the gains from the pumped erbium ions and SRS. Fig. 3(a) and (b) shows the evolutions of the signal power P_s , pump powers P_p^+, P_p^- , and total ASE powers P_a^+, P_a^- along the fiber for

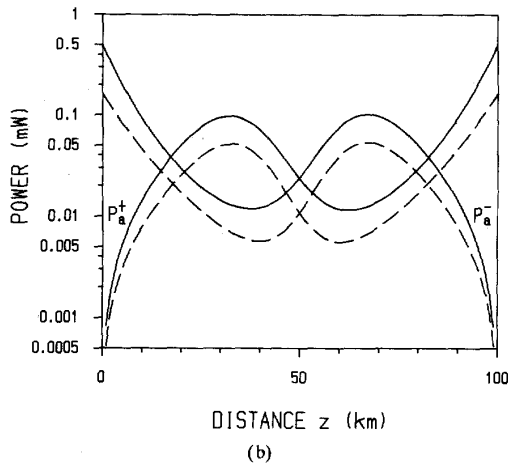
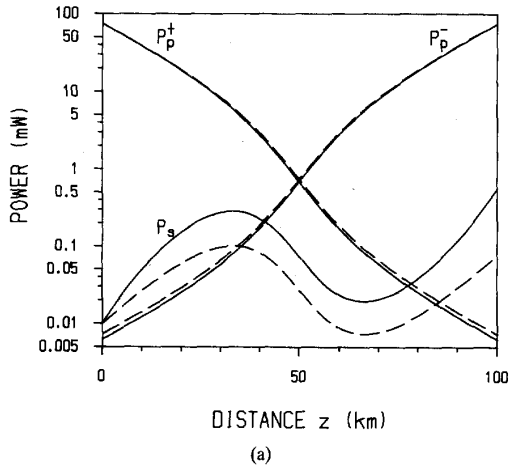


Fig. 3. Variations of the (a) signal power P_s , forward pump power P_p^+ , backward pump power P_p^- and (b) total forward ASE power P_a^+ , total backward ASE power P_a^- along the fiber of length $L = 100$ km and erbium ions density $n_t = 1 \times 10^{22} \text{ m}^{-3}$ for 1.55- μm signal and 1.48- μm pump. The initial signal power $P_{s0} = 10 \mu\text{W}$ and the initial pump power $P_{p0} = 75 \text{ mW}$. The powers with and without SRS are shown by the solid and dashed lines, respectively.

the signal with 1.55- μm wavelength and 10- μW initial power, and the pump with 1.48- μm wavelength and 75-mW initial power, and the effective fiber cross section $A_o = 35 \mu\text{m}^2$. The total ASE powers are defined as $P_a^\pm = \sum_{k=1}^N P_k^\pm$. It is noticed that the given pump power is the case half of the comparable pump power shown in the last section. In Fig. 3(a) and (b), the case without SRS is also shown for comparison. From Fig. 3(a), it is seen that the signal power with SRS at the output end of the fiber ($z = L$) is higher than the signal power without SRS and the pump powers with SRS are depleted more seriously than the pump powers without SRS. Therefore, in the case with SRS, the pump powers are more efficiently utilized and the signal obtains more gain. From Fig. 3(a), the gain with SRS is 17.6 dB and the gain without SRS is only 8.8 dB. The effect of the SRS enhances 8.8-dB gain in this case. The gain enhancement ΔG is defined as $\Delta G = G_{er} - G_e$, where G_{er} is the gain with SRS and G_e is the gain without SRS.

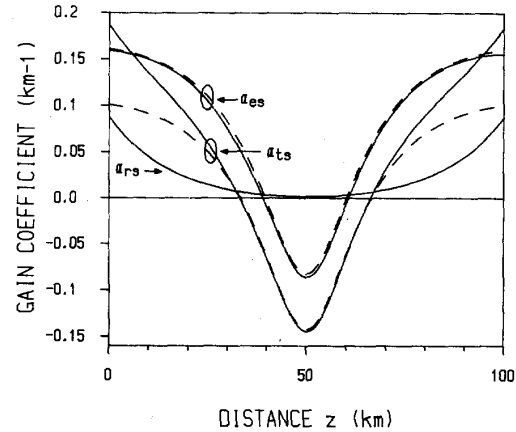


Fig. 4. Variations of the gain coefficients α_{es} , α_{rs} , and α_{ts} of the case shown in Fig. 3(a). The gain coefficients with and without SRS are shown by the solid and dashed lines, respectively.

The gains from the pumped erbium ions and SRS can be clearly seen by the evolutions of the gain coefficients from the two effects. From (8), we define the gain coefficient from the pumped erbium ions is $\alpha_{es} = (\alpha_{gs} + \alpha_{ls})n_2/n_t - \alpha_{is}$ and the gain from the SRS is $\alpha_{rs} = (g_{rs}/A_o)(P_p^+ + P_p^-)$. The gains from the two effects are the integrations of the gain coefficients over the fiber length. Because there is the intrinsic fiber loss, the total gain coefficient is $\alpha_{ts} = \alpha_{es} + \alpha_{rs} - \alpha_{is}$. It is noticed that the total gain coefficient α_{ts} defined here is different from that defined in [11], where α_{is} is not included in α_{ts} . For the case without SRS, $\alpha_{rs} = 0$ and $\alpha_{ts} = \alpha_{es} - \alpha_{is}$. Fig. 4 shows the evolutions of the gain coefficients for the cases with SRS and without SRS shown in Fig. 3. It is seen that the gain coefficient from SRS is significant at the beginning but decays quickly due to decaying pump power. The gain coefficient from the pumped erbium ions is lower than the case without SRS due to part of the pump power is depleted by SRS. The total gain coefficient of the DEDFA with SRS is larger than the gain coefficient of the DEDFA without SRS except in the middle of the transmission length. Although the gain from the pumped erbium ions is reduced due to part of the pump powers is depleted by SRS, the gain from SRS is larger than the reduction of the gain from the pumped erbium ions.

Although the signal gain is enhanced by the SRS, the gain of the ASE is enhanced also as is shown in Fig. 3(b). An important problem is whether the SNR is also enhanced by the SRS. Using the bandpass optical filter with center of wavelength at $\lambda = \lambda_s$ and bandwidth $\Delta\lambda_f = 0.2 \text{ nm}$ at the end of the fiber, we define the SNR as the ratio of the output signal power and the output ASE power and

$$\text{SNR} = 10 \times \log(\Delta\lambda P_s(L)/\Delta\lambda_f P_n^+(L)) \quad (16)$$

where $P_n^+(L)$ is the power of the forward ASE with bandwidth $\Delta\lambda$ centered at λ_s . For the case shown in Fig. 3(a) and 3(b), the SNR with SRS is 25.3 dB and the SNR without SRS is 22.0 dB. Therefore, the effect of SRS enhance 3.3-dB SNR in this case. The SNR enhancement ΔSNR is defined as $\Delta\text{SNR} = \text{SNR}_{er} - \text{SNR}_e$, where SNR_{er} is the SNR with SRS and SNR_e is the SNR without SRS.

IV. GAIN AND SNR

The DEDFA is usually designed to have zero decibel net gain, i.e., the fiber loss is just compensated. The 17.6-dB gain of the DEDFA shown in the last section is much higher than required. If the pump power is reduced for zero decibel gain, the SNR reduces to 13.5 dB. To improve the SNR, either higher initial signal power or higher pump power is required [11]. In this section, we will consider the cases of different signal power levels and pump power levels for which the corresponding gains may be higher than zero decibel. The cases of different signal wavelengths, pump wavelengths, and effective fiber cross sections are also considered. The results are useful for the design of DEDFA's.

A. Dependence of the Signal Wavelength

Fig. 5(a) and (b) shows the gain and SNR of the DEDFA versus the signal wavelength, respectively, for different initial signal powers. In Fig. 5(a) and 5(b), the case without SRS is also shown for comparison. In the figures, the pump wavelength is 1.48 μm , the initial pump power is 75 mW, and the effective fiber cross section is 35 μm^2 . It is seen that both the gain and SNR are enhanced for all the considered wavelength range. The SNR increases as the initial signal power, but the gain decreases as the initial signal power increases because of the gain saturation. There are two gain peaks near the wavelengths 1.534 and 1.557 μm . For the SNR, the two peaks are not so obvious.

The corresponding enhancements of the gain and SNR shown in Fig. 5(a) and (b) are given in Fig. 6(a) and (b), respectively. Because the Raman gain increases with the wavelength in the considered wavelength range, the enhancements of the gain and SNR, basically, follow the Raman gain profile except there are concavities of the profiles near the wavelengths 1.534 and 1.557 μm . It is noticed that there are gain peaks near the two wavelengths and the enhancements near the two wavelengths are less than the enhancements at the wavelengths of lower gains due to the gain saturations. The enhancements of the gain and SNR decreases as the initial signal power increases and this is also due to the gain saturation. The value in the concavities of the profiles near 1.534 μm for the case with 1- μW initial signal powers will become negative if the initial pump power is higher than about 250 mW, i.e., the SRS decreases the gain and SNR. For higher initial signal power, the initial pump power to make the enhancements of the gain and SNR negative is even higher.

B. Dependence of the Initial Pump Power

In [11], it is shown that both the gain and SNR increase with the initial pump power. The results are recalculated with the same parameters as in the [11] except the absorption and emission cross sections now given in Fig. 1. Fig. 7(a) and (b) shows the gain and SNR of the DEDFA versus the initial pump power, respectively, where the signal wavelength is 1.55 μm , pump wavelength is 1.48 μm , and the effective fiber cross section is 35 μm^2 . In Fig. 7(a) and (b), the case without SRS is also shown for comparison. It is seen that both the gain and SNR with SRS are larger than the gain and SNR without SRS. For both the cases with SRS and without SRS, the gain

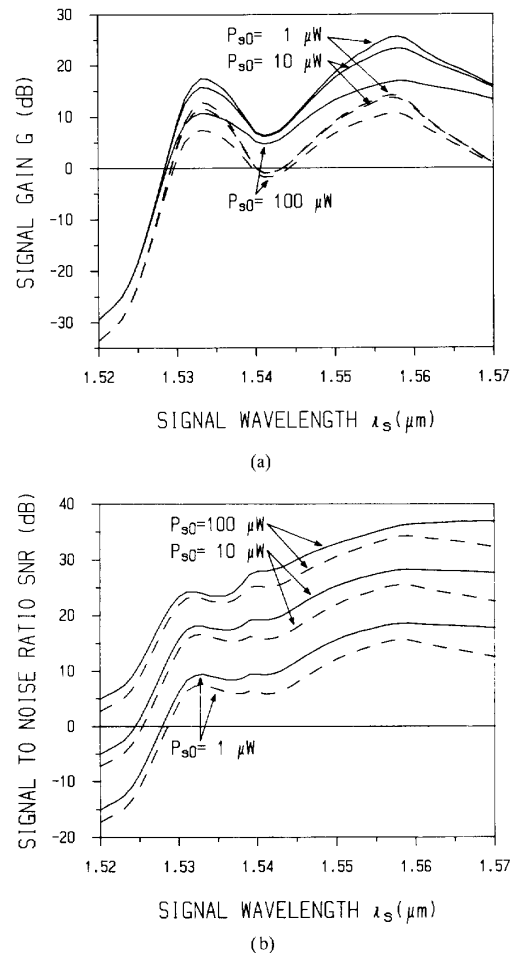
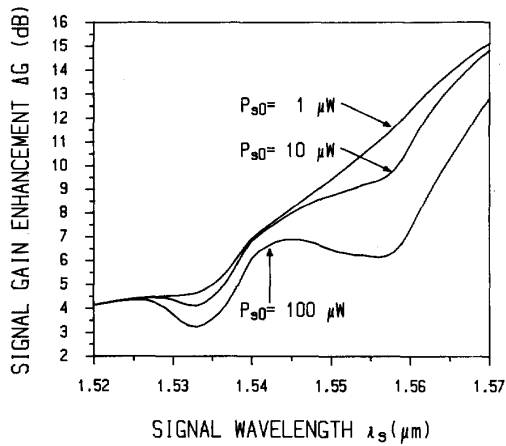
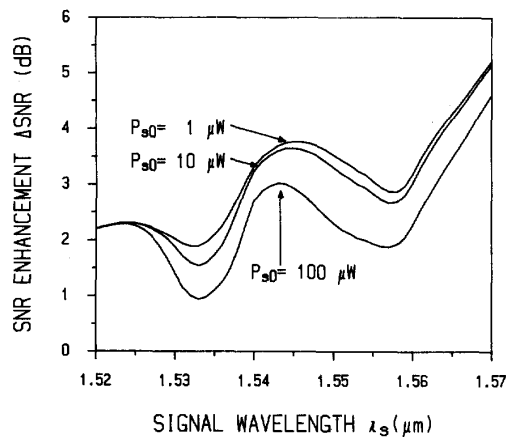


Fig. 5. (a) Signal gain G and (b) SNR versus the signal wavelength λ_s for different initial signal power P_{s0} . The pump wavelength $\lambda_p = 1.48 \mu\text{m}$, initial pump power $P_{p0} = 75 \text{ mW}$, fiber length $L = 100 \text{ km}$ and erbium ions density $n_t = 1 \times 10^{22} \text{ m}^{-3}$. The cases with and without SRS are shown by the solid and dashed lines, respectively.

and SNR increases as the initial pump power and saturate when the initial pump power is larger than about 80 mW. Because the slope of the gain curve with SRS is larger than that without SRS in saturation region, the gain enhancement due to SRS is more significant for higher pump power. As to the dependence of the initial signal power, gain decreases as the initial signal power increases but the SNR increases as the initial signal power. From the figures, the required initial pump power for the zero dB gain are around 55 mW for the case with SRS and the corresponding SNR's are 3.6, 13.4, and 23.2 dB for $P_{s0} = 1, 10, \text{ and } 100 \mu\text{W}$, respectively. For the case of low initial signal power, higher initial pump power is required to improve the SNR. However, for the initial pump power higher than about 90 mW, the SNR increases only slightly due to the saturation. The saturation SNR at 90-mW initial pump power is 18.1, 27.8, and 35.7 dB for $P_{s0} = 1, 10, \text{ and } 100 \mu\text{W}$, respectively. It is found that, for the system with the requirement of the SNR higher than 20 dB, the initial signal power should be higher than 1.6 μW .



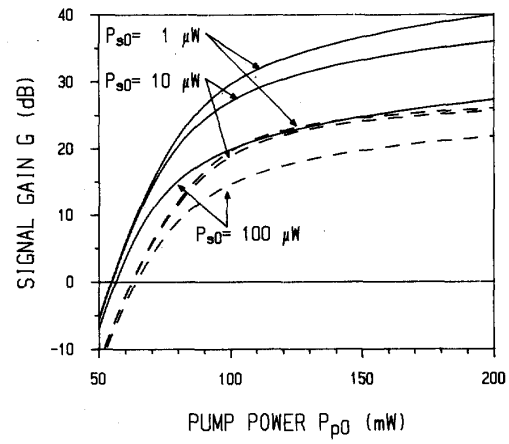
(a)



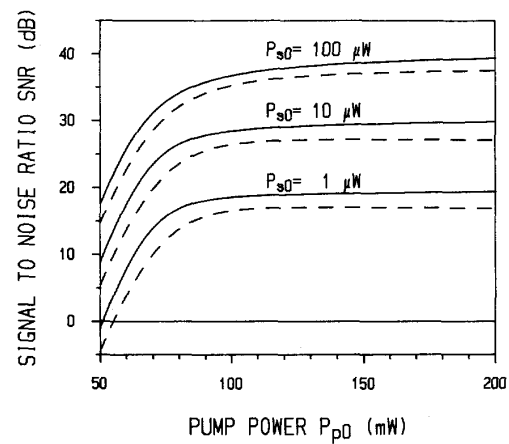
(b)

Fig. 6. (a) Signal gain enhancement ΔG and (b) SNR enhancement ΔSNR versus the signal wavelength λ_s shown in Figs. 5(a) and 6(b), respectively.

The enhancements of the gain and SNR due to SRS in Fig. 7(a) and (b) are shown in Fig. 8(a) and (b), respectively. In Fig. 8(a) and (b), the case of 1.53- μm signal is also shown as the initial pump power is increased up to 400 mW. For the 1.55- μm signal, as the initial pump power increases, the enhancements of the gain and SNR increase until the initial pump power reaches near the saturation power. For the initial pump power around the saturation power, the enhancements decrease as the initial pump power increases. As the initial pump power further increases, the enhancements increase thereafter. It is noticed that the enhancements are significant even for the 50-mW initial pump power. The 50-mW initial pump power is only one third of the comparable pump power shown in the last section. For the 1.53- μm signal, the amount of the enhancements are smaller than the case of 1.55- μm signal because the wavelength difference between the signal wavelength and pump wavelength is smaller and hence the Raman gain is smaller. Furthermore, the dependences of the enhancements on the initial pump power are different for the cases of the 1.53- and 1.55- μm signals for high initial pump power. In the case of 1.53- μm signal shown in Fig. 8(a), as



(a)



(b)

Fig. 7. (a) Signal gain G and (b) SNR versus the initial pump power P_{p0} for different initial signal power P_{s0} . The signal wavelength $\lambda_s = 1.55 \mu\text{m}$, the pump wavelength $\lambda_p = 1.48 \mu\text{m}$, fiber length $L = 100 \text{ km}$ and erbium ions density $n_t = 1 \times 10^{22} \text{ m}^{-3}$. The cases with and without SRS are shown by the solid and dashed lines, respectively.

the initial pump power increases beyond the saturation power, the gain enhancement decreases as the initial pump power increases. It is found that the gain enhancements become negative when the initial pump powers are larger than 250, 258, and 372 mW for the cases of 1, 10, and 100- μW initial signal powers, respectively. In Fig. 8(b), for the case of 1.53- μm signal, the SNR enhancements of the cases with 10 and 100 μW initial powers increase as the initial pump power in the high pump power region, but SNR enhancement for the case of 1- μW initial power becomes negative for the initial pump power larger than 337 μW . However, because of the saturation of the gain and SNR shown in Fig. 7(a) and (b), it is impractical to use such a high initial pump power.

C. Dependence of the Pump Wavelength

From the previous results, the SRS enhances both the gain and SNR when the pump wavelength is 1.48 μm . Because the Raman gain increases as the frequency difference be-

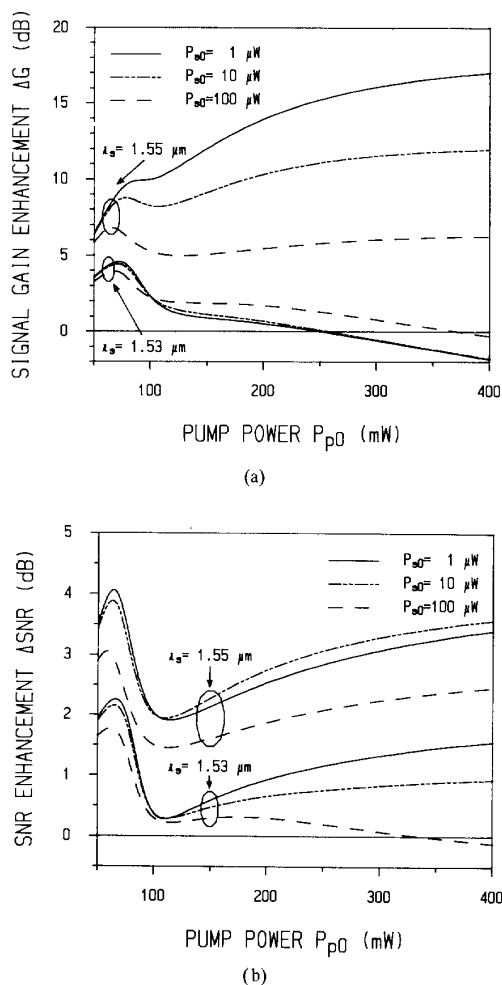


Fig. 8. (a) Signal gain enhancement ΔG and (b) SNR enhancement ΔSNR versus the initial pump power P_{p0} shown in Figs. 7(a) and 6(b), respectively.

tween the signal and pump if the difference is within the 440 cm^{-1} gain width, larger enhancements may be achieved with shorter pump wavelength. On the other hand, the gain from the pumped erbium ions depends on the emission and absorption cross sections of the pump wavelength. Shorter pump wavelength may not result in higher gain and SNR. To choose the optimal pump wavelength, both effects should be considered.

In this section, we consider the gain and SNR for three pump wavelengths of 1.47, 1.48, and 1.49 μm . Fig. 9(a) and (b) shows the gain and SNR versus the signal wavelength for the above three pump wavelengths, where the initial signal power is $10 \mu\text{W}$, the initial pump power is 75 mW and the effective fiber cross section is $35 \mu\text{m}^2$. In Fig. 9(a) and (b), the cases without SRS are shown for comparison. It is seen that, for the cases without SRS, the best pump wavelength λ_{pb} among the three considered wavelengths is 1.48 μm for the gain and is 1.49 μm for the SNR for all the considered signal wavelengths. With SRS, the dependence of the best pump wavelength on the signal wavelength is more complicated.

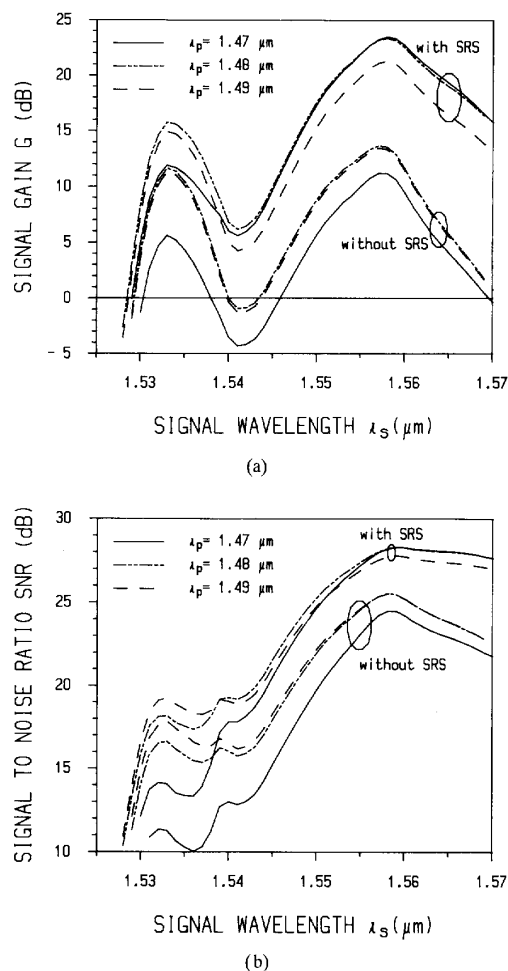


Fig. 9. (a) Signal gain enhancement G and (b) SNR versus the signal wavelength λ_s for different pump wavelength λ_p . The initial signal pump power $P_{s0} = 10 \mu\text{W}$, initial pump power $P_{p0} = 75 \text{ mW}$, fiber length $L = 100 \text{ km}$ and erbium ions density $n_t = 1 \times 10^{22} \text{ m}^{-3}$.

When the signal wavelength is shorter than $1.539 \mu\text{m}$, the best pump wavelengths are the same as the cases without SRS. When the signal wavelength is longer, the gain and SNR are more enhanced for shorter pump wavelength. For 1.47- μm pump wavelength, which is the worst pump wavelength for the cases without SRS, it becomes the best pump wavelength for both the gain and SNR when the signal wavelength is larger than about $1.555 \mu\text{m}$.

Tables I(a) and I(b) summarize the best pump wavelengths λ_{pb} for the gains and SNR's of the 1.53- and 1.55- μm signals for the cases shown in Fig. 9(a) and (b) and the cases of higher initial pump powers. In Tables I(a) and I(b) the cases without SRS are also shown for comparison. From Tables I(a) and I(b), for the cases without SRS, the best pump wavelengths for the gain are all 1.48 μm and the best pump wavelengths for the SNR are shifted to shorter wavelength as the initial pump power increases. With SRS, for the case of 1.55- μm signal, the best pump wavelengths for both the gain and SNR are shifted to shorter wavelength as the initial pump power

TABLE I (a)

THE BEST WAVELENGTH λ_{pb} AMONG THE 1.47-, 1.48-, AND 1.49- μm PUMP WAVELENGTHS FOR (a) THE GAIN AND (b) THE SNR AT THE SIGNAL WAVELENGTHS $\lambda_s = 1.53$ AND 1.55 μm FOR SEVERAL INITIAL PUMP POWERS, WHERE THE OTHER NUMERICAL PARAMETERS ARE THE SAME AS THE CASES CONSIDERED IN FIG. 9(a) AND (b). BOTH THE CASES WITH SRS AND WITHOUT SRS ARE SHOWN FOR COMPARISON.

$\lambda_{pb}(\mu\text{m})$		$P_{p0}(\text{mW})$				
		75	100	125	150	
λ_s (μm)	1.53	†	1.48	1.48	1.48	1.49
		*	1.48	1.48	1.48	1.48
1.55	†	1.48	1.47	1.47	1.47	
	*	1.48	1.48	1.48	1.48	

† : with SRS ; * : without SRS

TABLE I (b)

$\lambda_{pb}(\mu\text{m})$		$P_{p0}(\text{mW})$				
		75	100	125	150	
λ_s (μm)	1.53	†	1.49	1.49	1.48	1.48
		*	1.49	1.48	1.48	1.47
1.55	†	1.48	1.47	1.47	1.47	
	*	1.49	1.48	1.47	1.47	

† : with SRS ; * : without SRS

increases. The best pump wavelengths are also shifted to shorter wavelength to compare with the case without SRS. As to the case of 1.53- μm signal, the best pump wavelengths for both the gain and SNR are shifted to longer wavelengths to compare with the case without SRS. Although, the Raman gain is larger for shorter pump wavelength. Because the gain at 1.53 μm is small for the considered pump wavelengths, the effect of the depletion of the pump power due to the ASE of long wavelength, which are with high Raman gain, may be significant. When the effect of the depletion due to the long wavelength ASE is important, the longer pump wavelength for the short signal wavelength is preferred.

D. Dependence of the Effective Fiber Cross Section

There are two areas considered in the DEDFA with SRS. One is the dopant area A_e and the other is the effective fiber cross section A_o . The smaller dopant area provides the higher gain from the pumped erbium ions. The smaller effective fiber cross section also provides higher optical power density and higher gain from the Raman effect. Both areas can be made smaller during the fabrication of the erbium-doped fiber, but the fiber of too small effective cross section is impractical. The dispersion, coupling and splice losses are serious problems for the fiber of too small effective cross section.

So far we only consider the cases with 3.14- μm^2 dopant area and 35- μm^2 effective fiber cross section. In this section, we will consider the dependences of the enhancements of the gain and SNR on the effective fiber cross section. Fig. 10(a) and (b) shows the enhancements of the gain and SNR, respectively, for the 3.14- μm^2 dopant area and the effective fiber cross section varies from 5 to 60- μm^2 . In Fig. 10(a) and (b), we

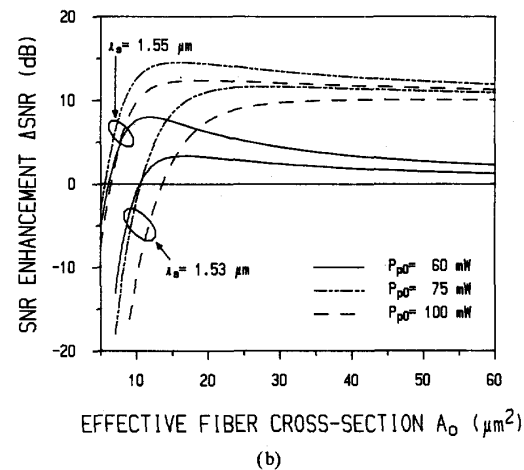
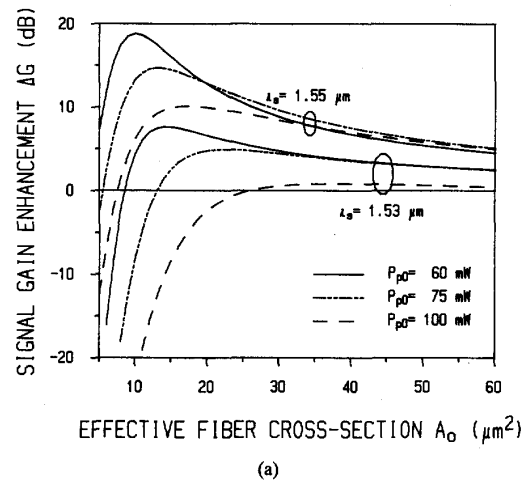


Fig. 10. (a) Signal gain enhancement ΔG and (b) SNR enhancement ΔSNR versus the effective fiber cross section A_o for different signal wavelength λ_s and initial signal power P_{s0} . The pump wavelength $\lambda_p = 1.48 \mu\text{m}$, initial pump power $P_{p0} = 75 \text{ mW}$, fiber length $L = 100 \text{ km}$ and erbium ions density $n_t = 1 \times 10^{22} \text{ m}^{-3}$.

consider two cases with 1.53- and 1.55- μm signal wavelengths. The other parameters are 10- μW initial signal power, 1.48- μm pump wavelength and three different initial pump powers which are 60, 75, and 100 mW. From the figures, it is seen that, there exist the optimal effective fiber cross sections for the maximum gain and SNR. When the effective fiber cross section is small enough, the effect of the SRS is very significant and the pump power is seriously depleted due to the SRS and the gain from the pumped erbium ions is greatly reduced. To remember that the pumping efficiency of the SRS is in fact less than the pumped erbium ions, the gain from the SRS is no longer larger than the reduction of the gain from the pumped erbium ions in such a case. This effect leads to the decrement of the enhancement for small effective fiber cross section. On the other hand, as the effective fiber cross section is large, the effect of the SRS is reduced and the enhancements of the gain and SNR due to the SRS decrease. Therefore, there exists the optimal effective fiber cross section. However, the

optimal cross sections are all less than $20 \mu\text{m}^2$ and too small in practice. The practical cross-section range is from 35 to $50 \mu\text{m}^2$. It is seen that the variations of the enhancements of the gain and SNR in this range are small, especially for the enhancement of the SNR.

V. CONCLUSIONS

The effects of the SRS on the gain and SNR of the DEDFA of 100-km fiber length and bidirectional pumps are numerically studied. The signal is amplified by both the pumped erbium ions and the SRS. Although the gain from the pumped erbium ions is reduced by the SRS because part of the pump power is depleted by the SRS, it is found that the gain from the SRS is larger than the decrement of the gain from the pumped erbium ions. The total gain is enhanced by the SRS. Furthermore, the SRS also enhances the SNR. The evolution of the signal power, ASEN power, and pump power are shown. The effect of the gain enhancement is clearly shown in the evolutions of the gain coefficients from the pumped erbium ions and the SRS along the fiber. The enhancements are significant for practical parameters. For $1.55\text{-}\mu\text{m}$ signal and $10\text{-}\mu\text{W}$ initial signal power, there are 8.8-dB gain enhancement and 3.3-dB SNR enhancement for $1.48\text{-}\mu\text{m}$ pump wavelength and 75-mW initial pump power. The gain and SNR enhancements due to SRS are studied for the signal wavelength varied from 1.52 to $1.57 \mu\text{m}$, signal power varied from 1 to $100 \mu\text{W}$, pump wavelength varied from 1.47 to $1.49 \mu\text{m}$, pump power varied from 50 to 350 mW , and effective fiber cross section varied from 5 to $60 \mu\text{m}^2$. The results are summarized as follows.

1) In the considered signal wavelength range and initial signal power range, both the gain and SNR are enhanced for $1.48\text{-}\mu\text{m}$ pump wavelength and 75-mW pump power. The enhancements increase as the signal wavelength except in the high gain regions near 1.534 and $1.557 \mu\text{m}$ where the enhancements are lowered due to gain saturation.

2) For 1.53- and $1.55\text{-}\mu\text{m}$ signal wavelengths, the gain and SNR increase with the initial pump power and saturate at about 80-mW pump power. Both the gain and SNR enhancements increase as the initial pump power when it is lower than the saturation pump power. For very high initial pump power, the gain and SNR may be decreased by the SRS for the case of $1.53\text{-}\mu\text{m}$ signal, e.g., for $1\text{-}\mu\text{W}$ initial signal power, the gain and SNR decrements occur for the initial pump power higher than 250 and 337 mW, respectively.

3) For the same initial signal power, the best pump wavelengths of the gain and SNR depend on the signal wavelength and initial pump power. For the signal near $1.55 \mu\text{m}$, the best pump wavelengths are shifted to shorter wavelength as the initial pump power increases. For the signal near $1.53 \mu\text{m}$, the best pump wavelengths may not be shifted to shorter wavelength as the initial pump power increases due to the pump depletion by the long wavelength ASEN.

4) The gain and SNR enhancements increase when the effective fiber cross section decreases until the cross section reaches an optimal value. In practice, the optimal cross section is too small. For the effective fiber cross section smaller than

the optimal value, the enhancements decrease as the effective fiber cross section and become negative for too small a cross section.

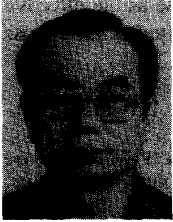
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