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Bidirectional optical fiber transmission scheme through Raman amplification: Effect of pump depletion

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Abstract

In this paper, we have presented the comparative study of bidirectional optical fiber transmission scheme for various cases using Raman amplification process with and without pump depletion. Signal power amplification, pump depletion effect and equivalent fiber loss are discussed for various cases. The results are compared.

Keywords: Raman amplification system, pump depletion effect

1. Introduction

In this paper, we have analyzed signal propagation in forward and backward directions by using Raman amplification process. We assume that the initial signal power is much larger than the spontaneous emission power. With this assumption, spontaneous Raman scattering effect can be neglected. Gain spectrum is assumed to be standard broadband spread over 14 THz frequency band, as in literature [1–19]. Here we deal with single mode transmission systems with propagation distance L. Pump power $P_1(0)$ and signal power $S_1(0)$ are injected at $z = 0$ and travel in $+z$ direction. On the other hand, pump power $P_2(L)$ and signal power $S_2(L)$ are injected at $z = L$ and travel in $-z$ direction. We consider the following coupled equations [17],

$$\frac{dN_{pf}(z)}{dz} = -\alpha.N_{pf}(z) - r_0 N_{pf}(z)(N_{s1}(z)+1), \tag{1}$$

$$\frac{dN_{pb}(z)}{dz} = +\alpha.N_{pb}(z) + r_0 N_{pb}(z)(N_{s1}(z)+1), \tag{2}$$

$$\frac{dN_{sj}(z)}{dz} = -\alpha_{sj}.N_{sj}(z) + r_0[N_{pf}(z)+N_{pb}(z)](N_{sj}(z)+1) - r_j N_{sj}(z)(N_{s2}+1), \tag{3}$$

where z is the distance from the fiber input, N_{pf}, the forward pump photon number, N_{pb}, the backward pump photon number, N_{sj}, the *jth* order stokes photon number, α, the fiber loss

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coefficient and r_0, the Raman gain coefficient. For ease of simplicity, we have substituted, $r_0 \to g_0$, $N_{pf} \to \frac{P_{pf}(z)}{h\nu \times A}$, $N_{pb}(z) \to \frac{P_{pb}(z)}{h\nu \times A}$ and $N_{sj}(z) \to \frac{N_{sj}(z)}{h\nu \times A}$, where A and $h\nu$ are effective core area and energy of each photon, respectively. Here we have neglected the higher-order Stokes generation and spontaneous terms. Forward Raman amplification systems, pump and signal power are denoted respectively by $P_1(z)$ and $S_1(z)$, while backward cases are denoted by $P_2(z)$ and $S_2(z)$. Equations (1–3) are valid if pump frequency is almost equal to signal frequency [14].

2. Bidirectional Raman amplification schemes without pump depletion

When pump is continuous wave with high transmitted power, one can ignore pump depletion. This is practical and is often used. If pump depletion is neglected in eqns (1–3), it would become a forward (+z direction) case as,

$$\frac{dN_{pf}(z)}{dz} = -\alpha . N_{pf}(z), \tag{4}$$

$$\frac{dN_{s1}(z)}{dz} = -\alpha_{s1} N_{sj}(z) + r_0 N_{pf}(z) N_{s1}(z), \tag{5}$$

which can be written by using our notations as

$$\frac{dP_1(z)}{dz} = [-\alpha] P_1(z), \tag{6}$$

$$\frac{dS_1(z)}{dz} = \left[-\alpha + \frac{g}{A} P_1(z) \right] S_1(z). \tag{7}$$

The various situations are given in Table I, where ♣ are governing equations for pump and signal power, ◊ are solutions for signal and pump power, ♠ are directions of transmitted signal, F is forward transmission scheme, B is backward transmission scheme and Δ are types of transmission system, respectively. Fiber loss (α) is $0.0461 \frac{1}{km}$, effective core area of the fiber (A_{eff}) is $5*10^{-11}$ m^2, fiber length (L) is 200 km and Raman gain constant (g) is $7.5*10^{-14} \frac{h\nu \times m}{W}$. In addition, $\frac{\lambda_p}{\lambda_s} \approx 1$ has been used for all calculations.

3. Bidirectional Raman amplification schemes with pump depletion

Next we analyze total situation with similar notations considering the effect of pump depletion. The pump power $P_1(z)$ and signal power $S_1(z)$ propagating in $+z$ direction are given by [8]:

$$\frac{dS_1(z)}{dz} = \left[\frac{g}{A} P_1(z) - \alpha \right] S_1(z), \tag{8}$$

Table I

Bidirectional Raman amplification schemes without pump depletion $\left[L_{eff} = \dfrac{1-\exp(-\alpha z)}{\alpha} \right]$**: various situations**

♣ Pump power[eq. 1] ♣ Signal Power [eq. 2]	Signal ◊ Pump ◊	Dir. of trans. ♠ ($\pm z$)	Types T.S.[Δ]
$\frac{dP_1(z)}{dz} = -\alpha P_1(z)$ $\frac{dS_1(z)}{dz} = \left(-\alpha + \frac{g}{A} P_1(z)\right) S_1(z)$	$S_1(z) = S_1(0)\exp\left(\frac{g}{A} P_1(0) L_{eff} - \alpha z\right)$ $(0 \le z \le \infty)$ $P_1(z) = P_1(0)\exp(-\alpha z)$ $(0 \le z \le \infty)$	$S_1(z)^{+z}$, $P_1(z)^{+z}$	F[Fig. 1a]
$\frac{dP_2(z)}{dz} = \alpha P_2(z)$ $\frac{dS_2(z)}{dz} = \left(\alpha - \frac{g}{A} P_2(z)\right) S_2(z)$	$S_2(z) = S_2(L)\exp$ $\left(\alpha(z-L) - \frac{g}{A}\frac{P_2(L)}{\alpha}(\exp(\alpha(z-L))-1)\right)$ $(L \le z \le -\infty)$ $P_2(z) = P_2(L)\exp(\alpha(z-L))$ $(L \le z \le -\infty)$	$S_2(z)^{-z}$, $P_2(z)^{-z}$	F[Fig. 1a]
$\frac{dP_2(z)}{dz} = \alpha P_2(z)$ $\frac{dS_1(z)}{dz} = \left(-\alpha + \frac{g}{A} P_2(z)\right) S_1(z)$	$S_1(z) = S_1(0)\exp$ $\left(-\alpha . z + \frac{g}{A}\frac{P_2(L)}{\alpha}\exp(-\alpha L)(\exp(\alpha z)-1)\right)$ $(0 \le z \le \infty)$ $P_2(z) = P_2(L)\exp(\alpha(z-L))$ $(L \le z \le -\infty)$	$S_1(z)^{+z}$, $P_2(z)^{-z}$	B[Fig. 1b]
$\frac{dP_1(z)}{dz} = -\alpha P_1(z)$ $\frac{dS_2(z)}{dz} = \left(\alpha - \frac{g}{A} P_1(z)\right) S_2(z)$	$S_2(z) = S_2(L)\exp$ $\left(\alpha(z-L) + \frac{g}{A}\frac{P_1(0)}{\alpha}(\exp(-\alpha z) - \exp(-\alpha L)\right)$ $(L \le z \le -\infty)$ $P_1(z) = P_1(0)\exp\left(-\alpha z\right)$ $(0 \le z \le \infty)$	$S_2(z)^{-z}$, $P_1(z)^{+z}$	B[Fig. 1b]
$\frac{dP_1(z)}{dz} = -\alpha P_1(z)$	$S_1(z) = S_1(0)\exp$ $\left(\begin{array}{l} -\alpha z + \\ \frac{g}{A}\left(L_{eff} P_1(0) + P_2\left(L\right).\left(\frac{e^{\alpha z}-1}{\alpha}\right)\exp\left(-\alpha L\right)\right)\end{array}\right)$ $(0 \le z \le \infty)$	$S_1(z)^{+z}$, $P_1(z)^{+z}$, $P_2(z)^{-z}$	F[Fig. 1d] + B[Fig. 1d]

Contd

Table I (*Contd*)

♣ Pump power[eq. 1] ♣ Signal Power [eq. 2]	Signal ◊ Pump ◊	Dir. of trans. ♠ ($\pm z$)	Types T.S.$^{\Delta}$
$\frac{dP_2(z)}{dz} = \alpha P_2(z)$	$P_1(z) = P_1(0)\exp(-\alpha z)$		
$\frac{dS_1(z)}{dz} = \left(-\alpha + \frac{g}{A}(P_1(z) + P_2(z))\right)S_1(z)$	$(0 \le z \le \infty)$		
	$P_2(z) = P_2(L)\exp(\alpha(z-L))$		
	$(L \le z \le -\infty)$		
$\frac{dP_1(z)}{dz} = -\alpha P_1(z)$	$S_2(z) = S_2(L)$	$S_2(z)^{-z}$,	F[Fig. 1e]
$\frac{dP_2(z)}{dz} = \alpha P_2(z)$	$\exp\left(\begin{array}{l}\alpha(z-L) - \\ \frac{g}{A}.\frac{1}{\alpha}\left(\begin{array}{l}P_2(L)(\exp(\alpha(z-L))-1) - \\ P_1(0)(\exp(-\alpha z) - \exp(-\alpha L))\end{array}\right)\end{array}\right)$	$P_1(z)^{+z}$,	+
	$(L \le z \le -\infty)$	$P_2(z)^{-z}$	B[Fig. 1e]
$\frac{dS_2(z)}{dz} = \left(\alpha - \frac{g}{A}(P_1(z) + P_2(z))\right)S_2(z)$	$P_1(z) = P_1(0)\exp(-\alpha z)$		
	$(0 \le z \le \infty)$		
	$P_2(z) = P_2(L)\exp(\alpha(z-L))$		
	$(L \le z \le -\infty)$		
$\frac{dP_1(z)}{dz} = -\alpha P_1(z)$	$S_1(z) = S_1(0)\exp$	$S_1(z)^{+z}$,	'Full'
$\frac{dP_2(z)}{dz} = \alpha P_2(z)$	$\left(\begin{array}{l}-\alpha z + \\ \frac{g}{A}\left(L_{eff}P_1(0) + P_2(L)\left(\frac{e^{\alpha.z}-1}{\alpha}\right)\exp(-\alpha L)\right)\end{array}\right)$	$S_2(z)^{-z}$	F[Fig. 1f]
	$(0 \le z \le \infty)$	$P_1(z)^{+z}$,	+
$\frac{dS_1(z)}{dz} = \left(-\alpha + \frac{g}{A}(P_1(z) + P_2(z))\right)S_1(z)$	$S_2(z) = S_2(L)\exp$	$P_2(z)^{-z}$	B[Fig. 1f]
	$\left(\begin{array}{l}\alpha(z-L) - \\ \frac{g}{A}\frac{1}{\alpha}\left(\begin{array}{l}P_2(L)(\exp(\alpha(z-L))-1) - \\ P_1(0)(\exp(-\alpha z) - \exp(-\alpha L))\end{array}\right)\end{array}\right)$		
$\frac{dS_2(z)}{dz} = \left(\alpha - \frac{g}{A}(P_1(z) + P_2(z))\right)S_2(z)$	$(L \le z \le -\infty)$		
	$P_1(z) = P_1(0)\exp(-\alpha z)$		
	$(0 \le z \le \infty)$		
	$P_2(z) = P_2(L)\exp(\alpha(z-L))$		
	$(L \le z \le -\infty)$		

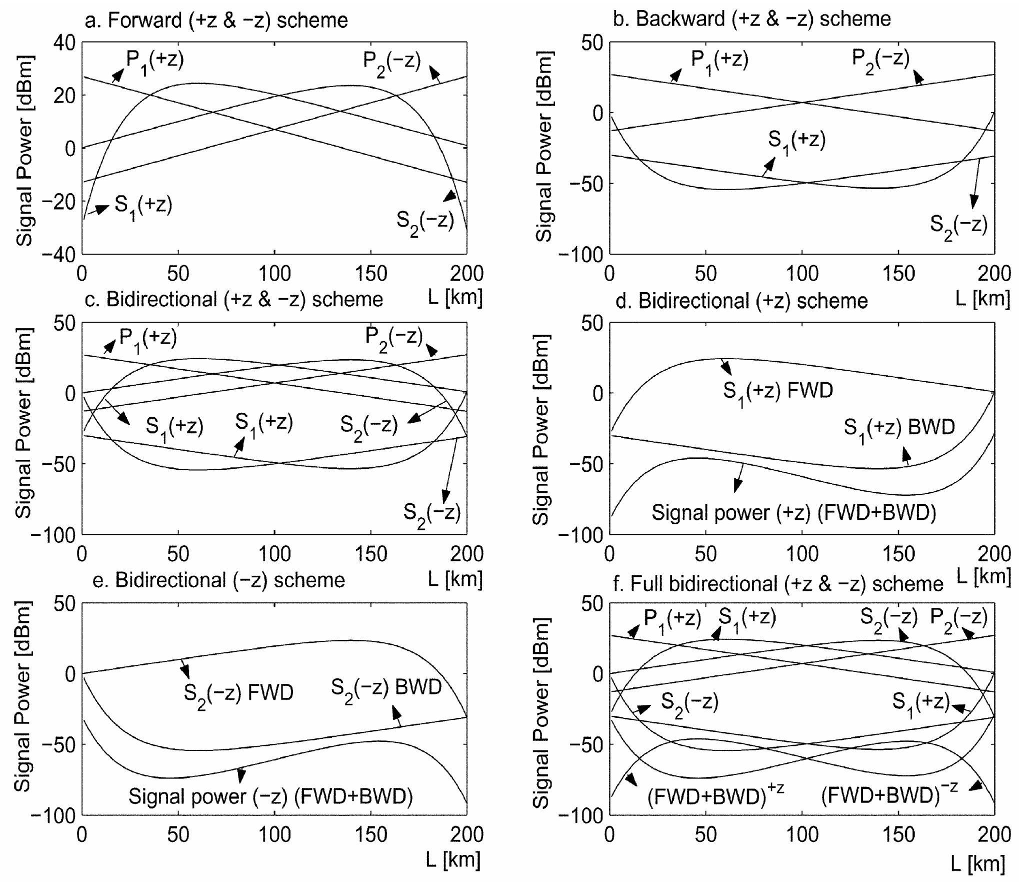

FIG. 1. Signal power amplification schemes without pump depletion: $S_1(0) \rightarrow 0.001$ mW, $S_2(L) \rightarrow 0.001$ mW, $P_1(0) \rightarrow 500$ mW, $P_2(L) \rightarrow 500$ mW.

$$\frac{dP_1(z)}{dz} = -\left[\frac{g}{A}\frac{v_p}{v_s}S_1(z) + \alpha\right]P_1(z). \tag{9}$$

Similarly, the equations for the pump $P_2(z)$ and the signal $S_2(z)$ propagating in -z direction are given by [8]:

$$\frac{dS_2(z)}{dz} = -\left[\frac{g}{A}P_2(z) - \alpha\right]S_2(z), \tag{10}$$

$$\frac{dP_2(z)}{dz} = \left[\frac{g}{A}\frac{v_p}{v_s}S_2(z) + \alpha\right]P_2(z). \tag{11}$$

The analytical solution of eqns (8–11) are given by [8]:

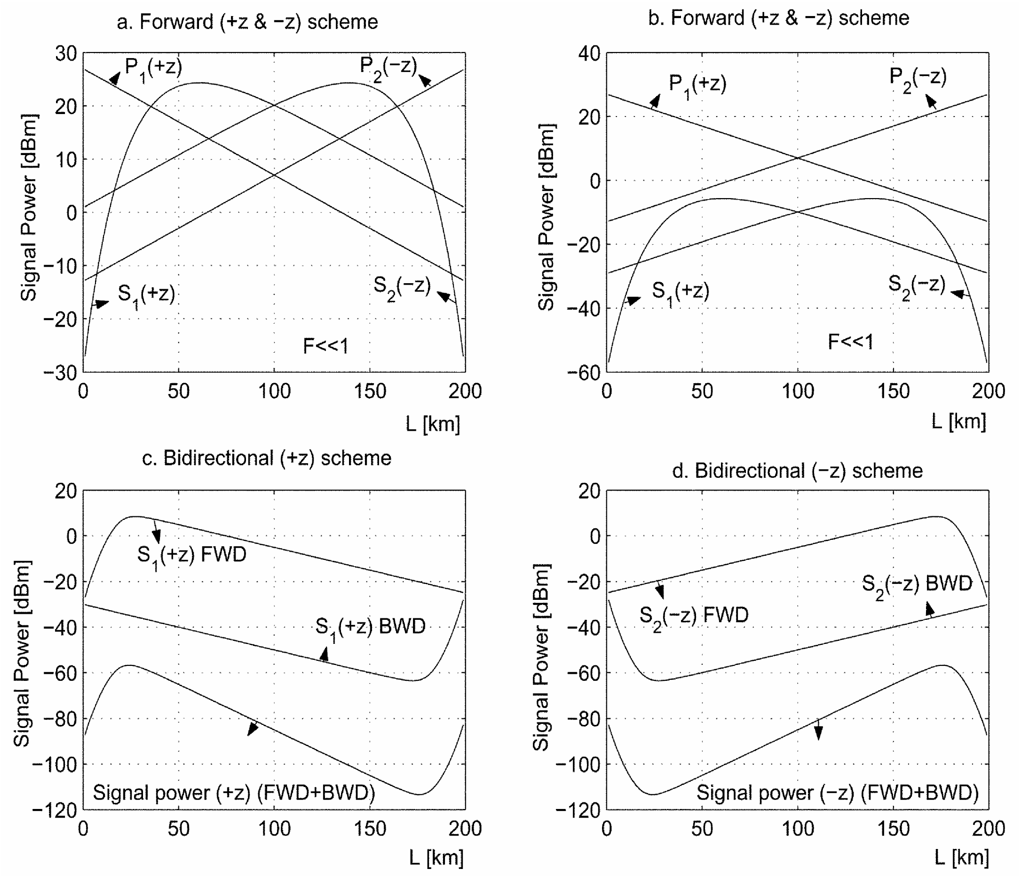

FIG. 2. (a) and (b). Signal power amplification schemes with pump depletion ($F << 1$) using the same simulation parameters as in Fig. 1, except in (b), where $S_1(0)$ is 0.000001 mW and $S_2(L)$ is 0.000001 mW with the same pump power in both ways, (c) and (d) Same cases as in Figs 1(d) and (e), considering the $1 + F$ term.

$$S_1(z) = \frac{S_1(0)\exp[K'(1-e^{-\alpha.z}) - \alpha.z]}{1 + B'\exp[K'(1-e^{-\alpha.z})]}, \tag{12}$$

$$P_1(z) = \frac{P_1(0)e^{-\alpha.z}}{1 + B'\exp[K'(1-e^{-\alpha.z})]}, \tag{13}$$

$$S_2(z) = \frac{S_2(L)\exp[K(1-e^{-\alpha.(L-z)}) - \alpha.(L-z)]}{1 + B\exp[K(1-e^{-\alpha.(L-z)})]}, \tag{14}$$

$$P_2(z) = \frac{P_2(L)e^{-\alpha(L-z)}}{1 + B\exp[K(1-e^{-\alpha(L-z)})]}, \tag{15}$$

where $B = \dfrac{v_p S_2(L)}{v_s P_2(L)}$, $B' = \dfrac{v_p S_1(0)}{v_s P_1(0)}$, $K = \dfrac{g.P_2(L)}{\alpha.A}$ and $K' = \dfrac{g.P_1(0)}{\alpha.A}$. We define the constant F as $F' = F = B'\exp[K'(1 - e^{-\alpha z})] = B.\exp[K(1 - e^{-\alpha(L - z)})]$. For low loss region of the fiber, if we assume $F << 1$, as described in [5], then eqns (12–15) would become

$$S_1(z) = S_1(0)\exp[K'(1 - e^{-\alpha.z}) - \alpha.z], \tag{16}$$

$$P_1(z) = P_1(0)e^{-\alpha.z}, \tag{17}$$

$$S_2(z) = S_2(L)\exp\{K[1 - e^{-\alpha.(L-z)}] - \alpha.(L - z)\}, \tag{18}$$

$$P_2(z) = P_2(L)e^{-\alpha(L-z)}. \tag{19}$$

While considering backward Raman amplification, the expression for $S_1(z)$ is given by [8]:

$$\frac{dS_1(z)}{dz} = \left[\frac{g}{A}P_2(z) - \alpha\right]S_1(z), \tag{20}$$

where $P_2(z)$ is given by eqn (15). The expression for $S_2(z)$ is given by [8]:

$$\frac{dS_2(z)}{dz} = -\left[\frac{g}{A}P_1(z) - \alpha\right]S_2(z), \tag{21}$$

where $P_1(z)$ is given by eqn (13). Equation (20) can be solved analytically and $S_1(z)$ is given by [8]:

$$S_1(z) = S_1(0)\frac{\exp[Ke^{\alpha(z-L)}] + Be^K}{\exp[Ke^{-\alpha L}] + Be^K}e^{-\alpha z}. \tag{22}$$

Similarly, $S_2(z)$ is given by

$$S_2(z) = S_2(L)\frac{\exp[K'e^{-\alpha z}] + B'e^{K'}}{\exp[K'e^{-\alpha.L}] + B'e^{K'}}e^{-\alpha(L-z)}. \tag{23}$$

The treatment described in Table I is repeated here considering the effect of pump depletion. More detailed data is available with the authors. The whole process is shown in Figs 2 and 3.

Now, we define the equivalent fiber loss by the following expression [17]:

$$\alpha_{eq}(z) = -\frac{d\log(S_{signal\_power}(z))}{dz} \tag{24}$$

$$\alpha_{eq}(dB/km) =$$

$$\begin{cases}
\alpha - \frac{g}{A}P_1(0)\exp(-\alpha.z) & \text{‘Forward (Fig. 4a)’, signal}^{+z}, {}^{1}\text{effect} \\
\alpha - \frac{g}{A}P_2(L)\exp[-\alpha(L-z)] & \text{‘Backward (Fig. 4a)’, signal}^{+z}, {}^{1}\text{effect} \\
\alpha - \frac{g}{A}\{P_1(0)\exp(-\alpha z) + P_2(L)\exp[-\alpha(L-z)]\} & \text{‘Bidirection (Fig. 4a)’, signal}^{+z}, {}^{1}\text{effect} \\
\alpha - \alpha K'\exp(-\alpha z) & \text{‘Forward (Fig. 4c)’, signal}^{+z}, {}^{2}\text{effect} \\
\alpha - \alpha K\exp(\alpha z)\exp(-\alpha L) & \text{‘Backward (Fig. 4c)’, signal}^{+z}, {}^{2}\text{effect} \\
\alpha - \alpha[K'\exp(-\alpha z) + K\exp(-\alpha L)\exp(\alpha z)] & \text{‘Bidirection (Fig. 4c)’, signal}^{+z}, {}^{2}\text{effect} \\
-\alpha + \frac{g}{A}P_2(L)\exp[-\alpha(L-z)] & \text{‘Forward (Fig. 4b)’, signal}^{-z}, {}^{1}\text{effect} \\
-\alpha + \frac{g}{A}P_1(0)\exp(-\alpha z) & \text{‘Backward (Fig. 4b)’, signal}^{-z}, {}^{1}\text{effect} \\
-\alpha + \frac{g}{A}\{P_1(0)\exp(-\alpha z) + P_2(L)\exp[-\alpha(L-z)]\} & \text{‘Bidirection (Fig. 4b)’, signal}^{-z}, {}^{1}\text{effect} \\
-\alpha + \alpha K\exp[-\alpha(L-z)] & \text{‘Forward (Fig. 4d)’, signal}^{-z}, {}^{2}\text{effect} \\
-\alpha + \alpha K'\exp(-\alpha z) & \text{‘Backward (Fig. 4d)’, signal}^{-z}, {}^{2}\text{effect} \\
-\alpha + \alpha[K\exp[\alpha(z-L)] + K'\exp(-\alpha z)] & \text{‘Bidirection (Fig. 4d)’, signal}^{-z}, {}^{2}\text{effect.}
\end{cases}$$

Here ^{1}effect is without pump depletion and ^{2}effect is with pump depletion, F and $F' << 1$ (Fig. 4).

4. Results and discussion

The following conclusions can be drawn from the work

$$^{\dagger} = \begin{cases}
S_1(+z),\ P_1(+z) & \text{‘Forward’} \\
S_2(-z),\ P_2(-z) & \text{‘Forward’} \\
S_1(+z),\ P_2(-z) & \text{‘Backward’} \\
S_2(-z),\ P_1(+z) & \text{‘Backward’}
\end{cases}$$

$$^{\ddagger} = \begin{cases}
S_1(+z),\ P_1(+z),\ P_2(-z) & \text{‘Bidirectional’} \\
S_2(-z),\ P_1(+z),\ P_2(-z) & \text{‘Bidirectional’} \\
S_1(+z),\ S_2(-z),\ P_1(+z),\ P_2(-z) & \text{‘Full bidirectional’}
\end{cases}$$

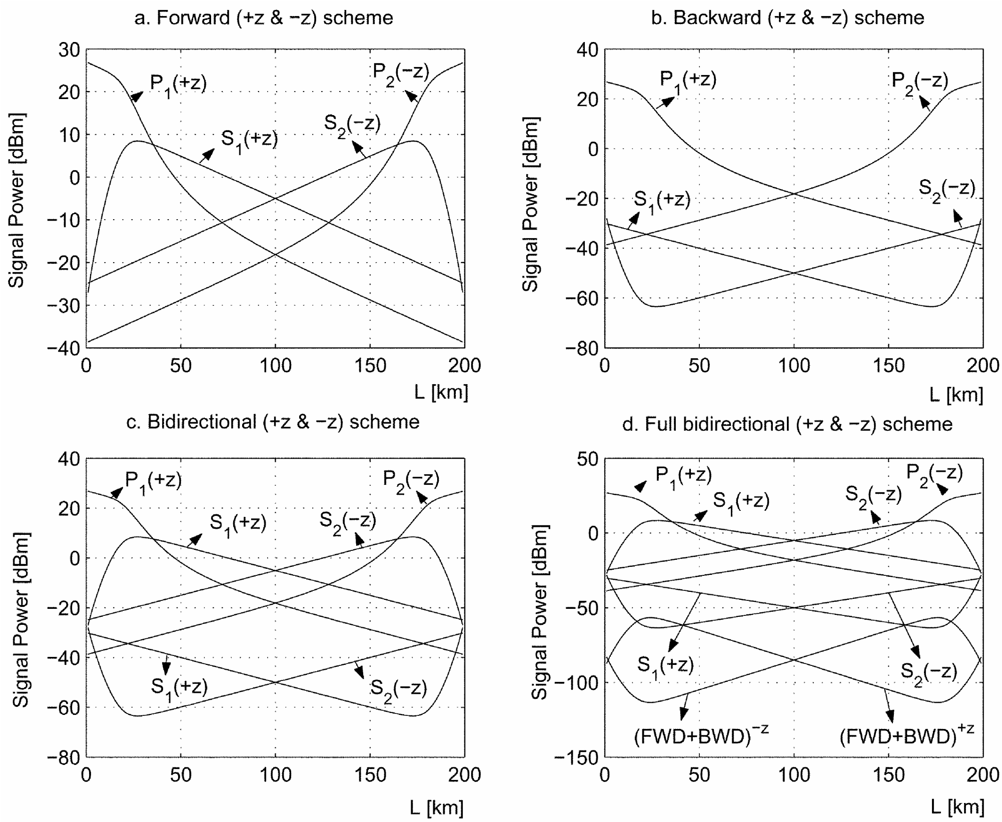

FIG. 3. The same cases as in Figs 1(a), (b), (c) and (f), respectively, considering 1 + F term.

Here, † refers to schemes that have already been discussed in the existing literature [5]–[9] and ‡ deals with the new schemes which we have developed in this paper. Since all the equations are coupled to each other, getting the analytical solution is not a trivial task. The work addresses the transient effect in Raman amplification process. We can easily find the effect of pump channel addition and dropping on signal power amplification. Pump depletion plays a critical role in the signal power amplification process. Pump depletion effect has not been discussed in the literature because of the complexity of the analysis (analytical solutions are possible for coupled gain equations only for a few cases). The purpose of the pump is to amplify the signal power by transferring power through stokes generation process. Whenever pump and signal channel interaction takes place there will be power transfer among channels as the input signal power level is only –30 dBm irrespective of the pump power level. At low signal power (–60 dBm), pump depletion does not play any significant role in signal power amplification process (Fig. 2(b)), but at high power (–30 dBm, Fig. 2(a)), the signal gets amplified drastically when pump interacts significantly with the signal channel. Hence, pump depletion is defined as the amount of loss of power to the signal. Signal channel gets amplified significantly as long as the pump keeps on interacting with the signal (or giving power to the signal) or until the pump starts depleting. At the point

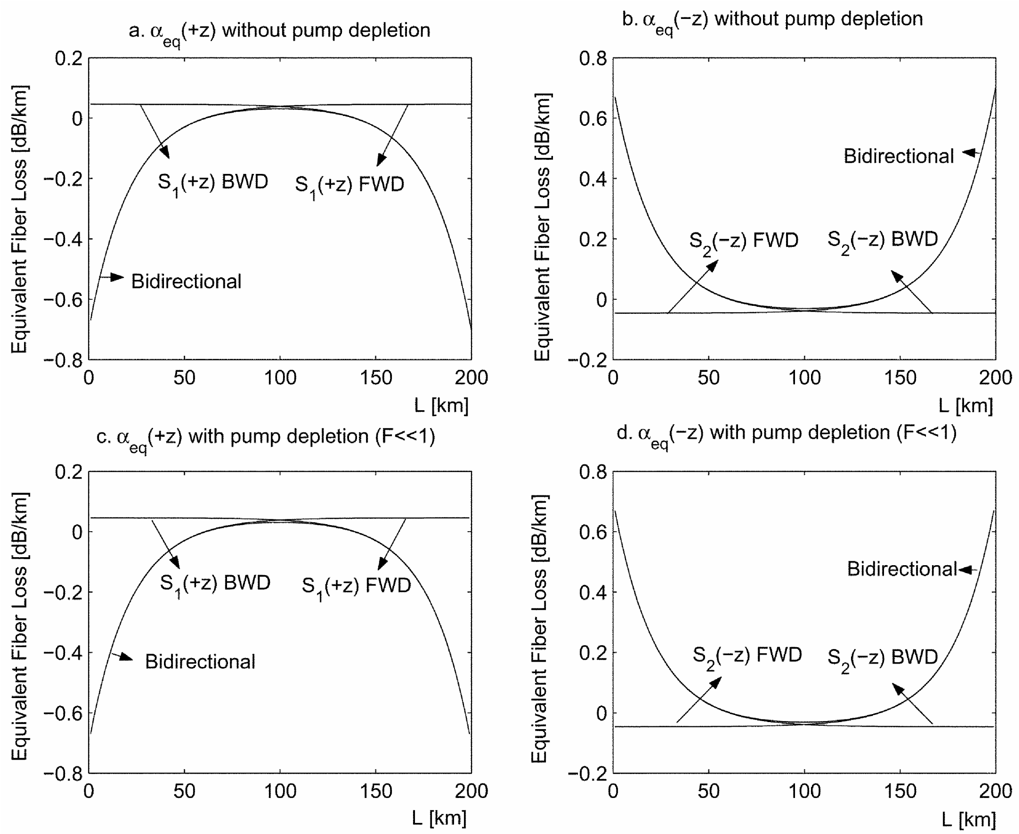

FIG. 4. Fiber equivalent loss for transmitted optical signals (a) and (b) without and (c) and (d) with pump depletion ($F \ll 1$) using the same simulation parameters as in Fig. 1. Comparison suggests that α_{eq} is the same in both the cases.

where the pump loses company with the signal, pump power starts depleting quickly and signal power too starts reducing. The point where the maximum signal gain achieved is called the 'Gain saturation point' of the signal (optimal pump power for the maximum unrepeated transmission length). In this paper, pump depletion does not mean performance degradation of the systems but its capability to amplify the signal power by depletion effect. If we do not consider pump depletion effect, it means that pump power remains constant throughout the length of the fiber (if the input pump power is 500 mW, the output power will still remain at 500 mW), except for fiber loss. It is worth mentioning here that our analysis is valid for conditions when pump and signal are not continuous wave but are of pulse-type shape. It also does not mean that pump depletion is harmful in amplification process, but it is essential to consider, as it means performance degradation due to pump depletion. The physical interpretation of this work is that one can predict the signal power amplification with constraints while locating pump and signal channel at different locations. One can see in the plots the interaction length between the pump and the signal channels.

With this study one can predict the optimal length of signal amplification with constraints and also the maximum unrepeated length of transmission with constraints.

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