Optimal Placement of Isolators in Raman Amplified Optical Links

A. Bononi, M. Papararo, and A. Vannucci

Dip. Ing. dell'Informazione, Universita' di Parma, Parma, Italy

email: bononi@tlc.unipr.it

Abstract: Explicit formulae for the optimal placement of isolators inside distributed Raman amplifiers for the minimization of signal Double Rayleigh Backscattering are provided, and the achievable improvement in optical signal to noise ratio is assessed.

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Signal double Rayleigh backscattering (SDRB) is a serious impairment in both distributed and lumped Raman amplifiers, which may pose stringent limits on the maximum signal output power [1]. In this paper, we provide explicit formulae for the optical signal to SDRB power ratio (OSXR), and more generally of the signal to noise ratio (OSNR) including both SDRB and amplified spontaneous Raman scattering (ASRS), at the line output in the presence of distributed Raman amplification with counter-propagating pump. We also give explicit formulae for the OSXR and OSNR when an optical isolator with pump bypass is inserted along the line. Such solution provides a quite effective way of reducing SDRB [2]. We provide guidelines for the optimal placement of the isolator, and a quantitative estimation of the OSNR improvement obtained by use of the isolator, both with and without pump bypass.

Consider a single fiber span of length L, with a single signal propagating downstream. The fiber has loss, and may also have distributed gain. Let $\varepsilon_{dir}(t, L)$ be the transmitted signal emerging at the span output if no reflections were present, referred to as the direct signal. Then the SDRB at the output is [3]

$$\varepsilon_{SDRB}(t,\,L) = \int_0^L \int_0^{z_2} \varepsilon_{dir}\left(t - 2\beta_1(z_2 - z_1),\,L\right) \mathrm{e}^{-j2\beta_0(z_2 - z_1)} G\left(z_2,\,z_1\right) \rho\left(z_2\right) \rho\left(z_1\right) dz_2 dz_1 \qquad (1)$$

where β_0 is the propagation constant and β_1 is the inverse group delay; $\rho(z)$ is the Rayleigh backscattering density, which is assumed to be a random delta-correlated process: $< \rho(z_1)\rho^*(z_2) >= \mathcal{R}\delta(z_2 - z_1)$, with $\mathcal{R} = \alpha_{rs} S$, being α_{rs} and S the Rayleigh scattering coefficient and recapture factor, respectively; and finally $G(z_2, z_1) = P_{dir}(z_2)/P_{dir}(z_1)$ is the gain/loss experienced by the direct signal from point z_1 to point $z_2 > z_1$. In (1) distortion of the direct signal is neglected. Such formula clearly shows that the dominant contributions to the SDRB come from double reflections at points z_1, z_2 sandwiching fiber segments of largest gain. From (1), one can evaluate the SDRB power $P_{SDRB}(L)$ by averaging with respect to the backscattering process. One finds that the ratio of average SDRB power to direct signal power at L is [3],[4]:

$$OSXR^{-1} \triangleq P_{SDRB}(L)/P_{dir}(L) = \mathcal{R}^2 \int_0^L \int_0^{z_2} \frac{G^2(z_2)}{G^2(z_1)}\, dz_1\, dz_2 \qquad (2)$$

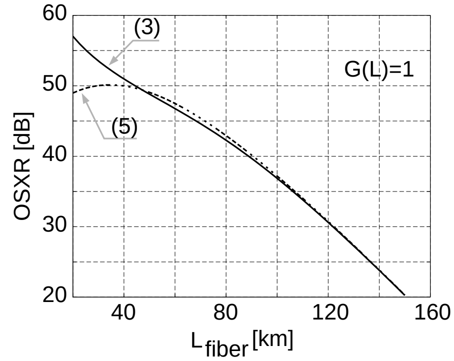

Fig. 1. OSXR versus line length L for a transparent line ($G(L) = 1$) of standard SMF. Counter-propagating pump at 1480 nm. Solid: eq. (3); dashed: eq. (5).

where $G(z) = P_{dir}(z)/P_{dir}(0)$. It can be shown that such formula holds even when the randomly modified state of polarization of the signal backscattered light is accounted for.

In the case of distributed Raman amplification with counter-propagating pump, the gain is expressed, in the undepleted pump approximation, as [5],[6]: $G(z) \cong \mathrm{e}^{\left\{-\alpha_s z + Q\mathrm{e}^{-\alpha_p L}(\mathrm{e}^{\alpha_p z}-1)\right\}}$, where α_s, α_p are the attenuations on signal and pump, respectively, and $Q \triangleq \beta_R P_0/\alpha_p$, being P_0 the launched pump power at L, and β_R the Raman gain coefficient. It is easily seen [6] that Q is approximately equal to the on-off logarithmic gain: $Q = (\ln G_{on-off})/(1-\exp(-\alpha_p L))$. With a suitable reduction of Q, the gain formula can be made fairly accurate even in the presence of pump depletion [7]. Inserting the Raman gain expression in (2) we get:

$$OSXR^{-1} = \left(\frac{\mathcal{R}}{\alpha_p}\right)^2 \mathrm{F}\left(2\mathrm{Q}, \alpha_p L, \frac{\alpha_s}{\alpha_p}\right) \tag{3}$$

where we defined the following function:

$$\mathrm{F}\left(A,B,C\right) \triangleq \int_0^B \mathrm{e}^{-2Cx}\left\{Ei\left[A\left(1-\mathrm{e}^{-x}\right)\right] - Ei\left[A\left(\mathrm{e}^{x}-1\right)\mathrm{e}^{-B}\right]\right\}dx \tag{4}$$

being $Ei(x)$ the exponential integral, which is easily evaluated by its series expansion [5]. We find that, for $\alpha_p L \gg 1$ and $Q > 5$ (i.e. $G_{on-off} > 20$ dB), the OSXR in (3) can be well approximated as:

$$OSXR^{-1} \cong \left(\frac{\mathcal{R}}{\alpha_p}\right)^2 \frac{\mathrm{e}^{2\mathrm{Q}}}{(2\mathrm{Q})^{\theta+2}}\, p_\theta\left(\frac{1}{2\mathrm{Q}}\right) \tag{5}$$

where $\theta \triangleq 2\frac{\alpha_s}{\alpha_p} - 1$, and $p_\theta(x) = \sum_{i=0}^{3} b_i x^i$ is a polynomial in x, with $b_i = i\, b_{i-1} + \Gamma(\theta + i + 1)$, being $\Gamma()$ the Gamma function. Consider the case of a single span of standard single-mode silica fiber of length L, with a signal in the C band, $\alpha_s = 0.22$ dB/km, a pump at wavelength 1480 nm, with $\alpha_p = 0.287$ dB/km, and a Rayleigh backscattering coefficient $\mathcal{R} = 10^{-7}$ m^{-1}. We assume the line is transparent, i.e. $G(L) = 1$. Fig. 1 shows the OSXR versus link length L. The solid line shows the exact expression (3), the dashed line its approximation (5). We note that for span lengths above 100 km the OSXR degrades to unacceptable levels. We also note the excellent fit of formula (5) in the long length range.

A more complete analysis of the OSNR should include the ASRS. Let $P_{ASRS}(L)$ be the forward propagating ASRS power at the line output. The optical signal to ASRS power ratio is $OSAR \triangleq P_{dir}(L)/P_{ASRS}(L)$, and taking both SDRB and ASRS noise into account, the output OSNR is

$$OSNR = \left(OSXR^{-1} + OSAR^{-1}\right)^{-1} . \tag{6}$$

In the undepleted pump approximation, an explicit expression for the in-band ASRS power is known in the further simplifying assumption $\alpha_s = \alpha_p = \alpha$ [8], [6]:

$$P_{ASRS}(L) = E_0 \left[\left(\frac{1}{Q} + e^{-\alpha L}\right) e^{Q[1-e^{-\alpha L}]} - \left(\frac{1}{Q} + 1\right)\right] \tag{7}$$

where

$$E_0 \triangleq 2\, h\nu\Delta\nu = 2\frac{hc^2\Delta\lambda}{\lambda^3} . \tag{8}$$

We find that a general closed-form expression of the in-band forward ASRS power can be found even when $\alpha_s \neq \alpha_p$:

$$P_{ASRS}(L) = E_0\, H\left(Q, \alpha_p L, \frac{\alpha_s}{\alpha_p}\right) \tag{9}$$

where

$$H(a,b,c) \triangleq \frac{e^a}{a^c}\left[\gamma(a, c+1) - \gamma(ae^{-b}, c+1)\right] \tag{10}$$

and $\gamma(x,a) \triangleq \int_0^x t^{a-1} \mathrm{e}^{-t}$ $(a > 0)$ is the incomplete gamma function. Equation (9) reduces to (7) when $\alpha_s = \alpha_p$. We also find that for $\alpha_p L \gg 1$ and $Q > 5$ equation (9) reduces to

$$P_{ASRS}(L) \cong E_0 e^Q Q^{-(\alpha_s/\alpha_p)} \Gamma\left(\frac{\alpha_s}{\alpha_p} + 1\right) . \tag{11}$$

Suppose now an isolator is placed at distance L_I from the output. The back-propagating pump can bypass the isolator by means of two WDM couplers and a fiber bridge [2]. In the ideal case of negligible signal and pump loss induced by such device, its effect is to suppress all SDRB infinitesimal terms in (1) in which z_1 is on the left of the isolator ($z_1 < L - L_I$), and z_2 on the right ($z_2 > L - L_I$). This amounts to removing the white rectangle A_I from the integration domain in (1) and (2), as shown in Fig. 2. The OSXR can still be calculated as in (2), but now the integration domain consists only of the shaded triangles: the domain A_1 gives the SDRB contribution of the section from 0 to $L - L_I$, while A_2 gives the contribution of the section following the isolator. Our objective is to position the isolator so as to suppress the dominant SDRB terms. Hence we select L_I so that most of the significant portion of the integrand $G^2(z_2)/G^2(z_1)$ falls in A_I. Clearly, the optimal value of L_I depends on the shape of the gain/loss profile $G(z)$. For exponential gain $G(z) = e^{gz}$, typical of discrete Raman amplifiers (DRA), the optimal value is $L_I = L/2$, which makes the two shaded triangles equal. For distributed Raman amplifiers, consider the point of minimum signal power along the line, which occurs at distance $L_m \cong \ln(\mathrm{Q})/\alpha_p$ from the output, in the undepleted pump approximation. Then, roughly speaking, we can think of the line as a lossy portion from 0 to $L - L_m$, followed by a DRA of length L_m. Hence the optimal position of the isolator should not be far from

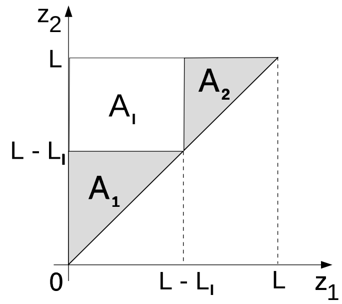

Fig. 2. Integration domain when an ideal isolator with bypass is placed L_I meters from the output.

$L_I = L_m/2$. Numerical optimization gives indeed values only slightly smaller than $L_m/2$, as we will see next.

The zero loss assumption of the isolating device is unrealistic. Assume that the power of the counter-propagating pump is attenuated by a factor $0 \leq \eta_p \leq 1$ when crossing the device, and that the direct signal is attenuated by a factor $0 \leq \eta_s \leq 1$. For comparison with the line without isolator, we impose that the signal gain $G(L) = P_{dir}(L)/P_{dir}(0)$ be the same both with and without the isolator. This implies that the pump must be increased in the presence of the isolating device. We find that the required extra pump power is:

$$\frac{P_{0_I}}{P_0} = \frac{\mathrm{Q}_I}{\mathrm{Q}} = \left(1 + \frac{-\left.\eta_s\right|_{dB}}{\left.G(L)\right|_{dB} + \left.(\alpha_s L)\right|_{dB}}\right)\left(1 - (1-\eta_p)\frac{e^{-\alpha_p L_I} - e^{-\alpha_p L}}{1 - e^{-\alpha_p L}}\right)^{-1} \tag{12}$$

where subscript I denotes quantities in the presence of the isolator, and $\left.(x)\right|_{dB} \triangleq 10\log_{10}(x)$. Note the very weak dependence on η_s for large link loss. Since the isolator effectively breaks the distributed Raman amplifier into two independent Raman amplifiers, we easily find that the OSXR_I with the isolator is

$$\mathrm{OSXR}_I^{-1} = \left(\frac{\mathcal{R}}{\alpha_p}\right)^2 \left\{\mathrm{F}\left(2\eta_p \mathrm{Q}_I e^{-\alpha_p L_I}, \alpha_p(L-L_I), \frac{\alpha_s}{\alpha_p}\right) + \mathrm{F}\left(2\mathrm{Q}_I, \alpha_p L_I, \frac{\alpha_s}{\alpha_p}\right)\right\} \tag{13}$$

The first F() term gives the SDRB contribution of the section from 0 to $L - L_I$, while the second F() term gives the contribution of the section following the isolator. Setting $\eta_p = 0$ (infinite pump loss) models a device where the pump is stopped by the isolator, i.e. there is no pump bypass and we have a DRA. By the same reasoning, we find that the received forward ASRS power is:

$$P_{ASRS,I} = E_0 \left\{\eta_s \mathrm{e}^{\left[-\alpha_s L_I + Q_I\left(1-\mathrm{e}^{-\alpha_p L_I}\right)\right]} H\left(\eta_p Q_I \mathrm{e}^{-\alpha_p L_I}, \alpha_p(L-L_I), \frac{\alpha_s}{\alpha_p}\right) + H\left(Q_I, \alpha_p L_I, \frac{\alpha_s}{\alpha_p}\right)\right\}. \tag{14}$$

Consider the following numerical example. We have a line of $L = 150$ km of standard single-mode silica fiber with signal and pump as before. Again we assume the line is transparent, i.e. $G(L) = 1$. The signal loss at the isolating device is $-\left.\eta_s\right|_{dB} = 3$ dB. Fig 3(a) shows the required pump increase with respect to the case of no isolation, eq. (12), for pump loss increasing from zero to 20 dB, i.e. for various amounts of pump bypass, versus isolator distance from the output, L_I. Clearly the maximum required pump increase is obtained when the isolator is closest to the output, and essentially equals

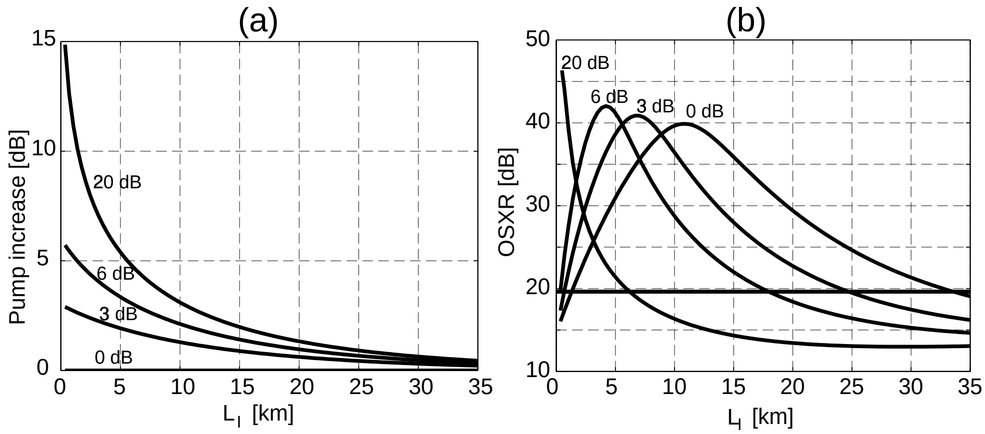

Fig. 3. (a) Pump increase P_{0I}/P_0, and (b) OSXR_I vs. isolator location L_I. Signal loss at the isolating device: 3 dB.

the pump loss. Fig. 3(b) shows the corresponding OSXR. The horizontal line is the case without isolation. In the ideal case of 0 dB pump loss, the maximum OSXR is reached at $L_I = 11$ km, not far from the predicted $L_m/2 = 15$ km, and there is an improvement of 20 dBs in OSXR with respect to the case without isolation, without any appreciable pump increase. With a realistic 3 dB pump loss the optimal point shifts to 8 km, and the gain in OSXR is 21 dBs, at the expense of only 1.5 dB of pump increase, as seen in Fig. 3(a).

The trend is towards larger OSXR improvements at the optimum point, which shifts to a shorter distance from the output as the pump loss increases. The 20 dB loss in Fig. 3(b) is well representative of the complete blocking of the pump, i.e. of a discrete Raman amplifier. Clearly, the shorter the DRA, the smaller the SDRB, as confirmed by Fig. 3(b). However, this comes at the expense of an unrealistic increase in pump power, as shown in Fig. 3(a), and also of a complete performance degradation due to the amplified spontaneous Raman scattering, as we show next.

To correctly evaluate system performance one should consider the received OSNR (6) which includes both ASRS and SDRB, which are both well modeled by gaussian independent random processes, independent of the signal. For SDRB this is so, since the scattering process decorrelates the back-scattered field form the signal, and the total SDRB is the superposition of echoes from a huge number of preceding signal bits, at bit rates above 1 Gb/s. In Fig. 4 we plot the OSNR curves corresponding to the OSXR curves in Fig. 3(b) for the two cases $-\eta_p|_{dB} = 3$ dB (right), and $-\eta_p|_{dB} = 20$ dB (left). The OSNR is provided for several values of the transmitted signal P_{dir}, and we used an ASRS noise bandwidth $\Delta\lambda = 0.1$ nm. Let's first look at the 3 dB pump loss case. We see that the OSNR increases with launched signal power in a region around 8 km. The OSNR increases up to the limiting case in which OSXR dominates (infinite signal power). We see that for lower signal levels, the peak shifts towards shorter L_I values, but becomes broader, indicating a larger tolerance to the placement of the isolator. The OSNR away from the "good" region around 8 km is essentially independent of the launched signal power, which indicates that SDRB is dominant over ASRS. Now take a look at the plots on the left, corresponding to a DRA. We see that by shrinking the DRA length, we increase the OSXR, but the OSNR is dominated by ASRS, since the signal enters the DRA at an extremely small power level.

In conclusion, we have given closed form expressions for the OSXR and OSNR in counter-propagating

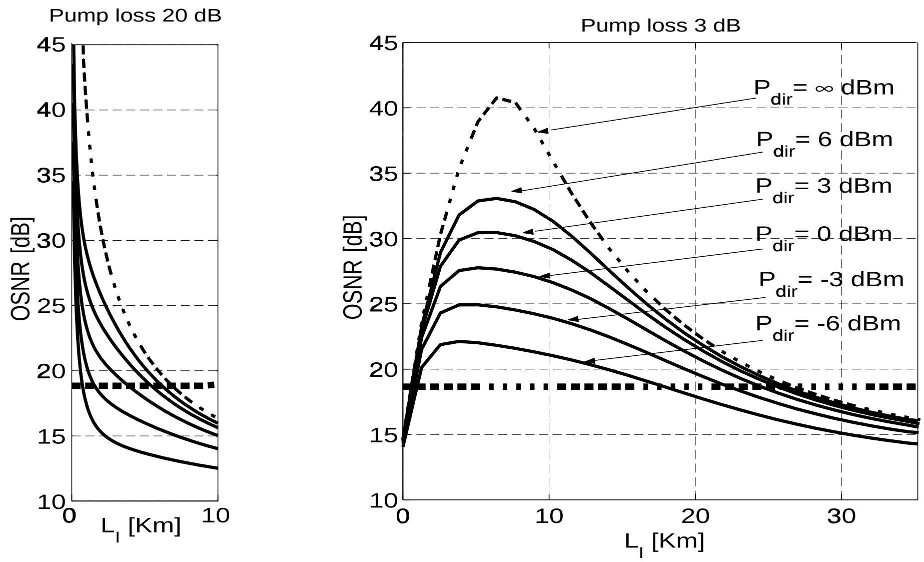

Fig. 4. OSNR in 150 km transparent link versus isolator location L_I, for varying launched power P_{dir} . Pump loss: (Right) 3 dB; (Left) 20 dB. Horizontal line: OSNR without isolator for $P_{dir} = -6$ dBm. Signal loss at the isolating device is 3 dB. ASRS noise bandwidth $\Delta\lambda = 0.1$ nm.

pump Raman amplified optical links, which allow a quick evaluation of the optimal position of an isolating device that reduces SDRB. The value of such closed form expressions is that they avoid the long run-times associated with the numerical solution of the partial differential equations with boundary conditions that describe CW signal and ASRS propagation along the line. Such formulas, along with the use of the effective pump approximation [7], allow us to quickly obtain the OSNR for all channels in a WDM system, and are thus an invaluable tool for system optimization. In the presented case study of a 150 km transparent line, we found that the isolating device should be placed at a distance from the output not far from Lm/2=15 km, and closer to the output for smaller signal power and larger pump loss, with maximum OSNR gain around 20 dB.

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