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# Optimal Placement of Isolators in Raman Amplified Optical Links

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**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) at the line output in the presence of distributed Raman amplification with counter-propagating pump. We also give explicit formulae for the OSXR when an optical isolator with pump bypass is inserted along the line. Such solution provides a quite effective way of improving the OSXR [2]. We provide guidelines for the optimal placement of the isolator, and a quantitative estimation of the OSXR 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]

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

where: $\beta$ is the propagation constant; $v_g$ the 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 $\alpha_{rs}$ and $S$ the Rayleigh scattering coefficient and recapture factor, respectively; and finally $G\left(z_2,\, z_1\right) = P_{dir}(z_2)/P_{dir}(z_1)$ is the gain/loss experienced by the direct signal from point $z_1$ to point $z_2 > z_1$. From (1), one finds that the ratio of average SDRB power to direct signal power at $L$ is

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

where $G(z) = P_{dir}(z)/P_{dir}(0)$. SDRB is here assumed to be co-polarized with the signal. Polarization effects affect (2) through a constant factor [3], which is not relevant for the following development.

In the case of distributed Raman amplification with counter-propagating pump, the gain is expressed, in the undepleted pump approximation, as [4],[5]: $G(z) \cong \exp\left\{-\alpha_s z + Q e^{-\alpha_p L}\left(e^{\alpha_p z} - 1\right)\right\}$, where $\alpha_s, \alpha_p$ are the attenuations on signal and pump, respectively, and $Q \stackrel{\triangle}{=} \beta_R P_0/\alpha_p$, being $P_0$ the launched pump power at $L$, and $\beta_R$ the Raman gain coefficient. It is easily seen [5] 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. 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:

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

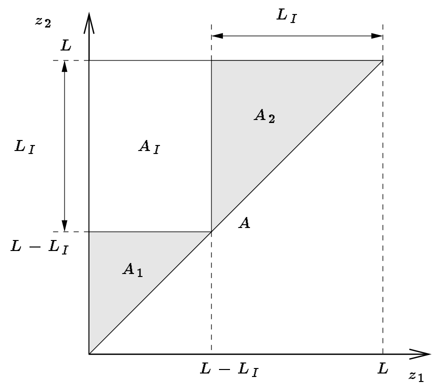


Fig. 1. Integration domain when an ideal isolator with bypass is placed $L_I$ meters from the output..

being $E_i(x)$ the exponential integral, which is easily evaluated by its series expansion [4]. 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:

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

where $\gamma \stackrel{\triangle}{=} 2\frac{\alpha_s}{\alpha_p} - 1$, and $p_\gamma(x) = \sum_{i=0}^{3} b_i x^i$ is a polynomial in $x$, with $b_i = i\, b_{i-1} + \Gamma(\gamma + i + 1)$, being $\Gamma()$ the Gamma function.

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, the OSXR can still be calculated as in (2), but now the integration domain consists only of the shaded triangles shown in Fig. 1. 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. The reduction with respect to the case without isolator is due to the removal of the white domain $A_I$, where typically most of the significant portion of the integrand $G^2(z_2)/G^2(z_1)$ is concentrated. 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, 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 $L_m = \ln(\mathrm{Q})/\alpha_s$ from the output, in the undepleted pump approximation. Then, roughly speaking, we can think of the line as a lossy portion from from 0 to $L - L_m$, followed by a discrete Raman amplifier of length $L_m$. Hence the optimal position of the isolator should not be far from $L_I = L_m/2$. Numerical optimization gives indeed values only slightly larger than $L_m/2$, as we will see next.

The zero loss assumption of the isolating device is unrealistic. Assume thus that the power of the back-propagating pump is attenuated by a factor $0 \leq \gamma_p \leq 1$ when crossing the device, and that the signal is attenuated by a factor $0 \leq \gamma_s \leq 1$. 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:

$$\frac{P_{0_I}}{P_0} = \frac{\mathrm{Q}_I}{\mathrm{Q}} = \left(1 + \frac{-\left.\gamma_s\right|_{dB}}{\left.G(L)\right|_{dB} + \left.(\alpha_s L)\right|_{dB}}\right)\left(1 - (1-\gamma_p)\frac{e^{-\alpha_p L_I} - e^{-\alpha_p L}}{1 - e^{-\alpha_p L}}\right)^{-1} \tag{6}$$

where the subscript $I$ denotes quantities in the presence of the isolator, and $\left.(x)\right|_{dB} \stackrel{\triangle}{=} 10\log_{10}(x)$. Note the very weak dependence on $\gamma_s$ for large link loss. We also find that the $\mathrm{OSXR}_I$ with the isolator is

$$\mathrm{OSXR}_I^{-1} = \left(\frac{\mathcal{R}}{\alpha_p}\right)^2 \left\{\mathrm{F}\left(2\gamma_p \mathrm{Q}_I e^{-\alpha_p L_I}, \alpha_p(L - L_I), \frac{\alpha_s}{\alpha_p}\right) + \mathrm{F}\left(2\mathrm{Q}_I, \alpha_p L_I, \frac{\alpha_s}{\alpha_p}\right)\right\} \tag{7}$$

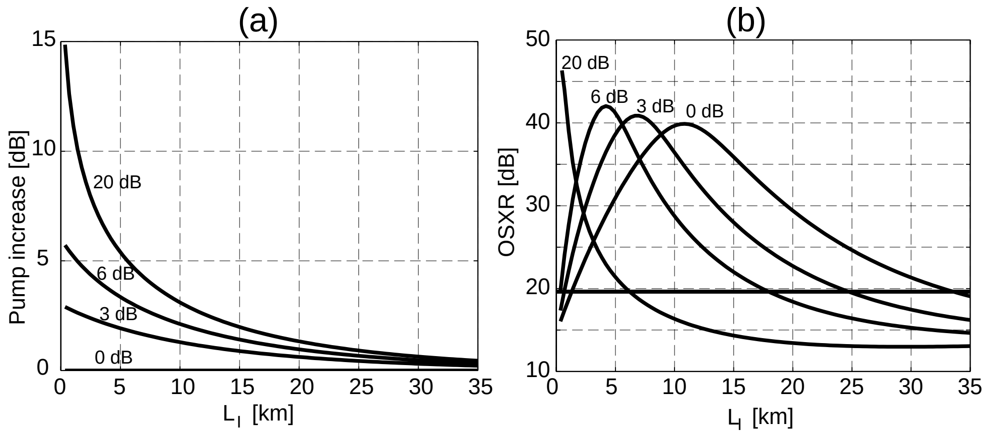


Fig. 2. (a) Pump increase $P_{0I}/P_0$, and (b) OSXR$_I$ vs. isolator location $L_I$.

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 $\gamma_p = 0$ (infinite pump loss) models a device where the pump is stopped by the isolator, i.e. there is no pump bypass.

Consider the following numerical example. We have a line of $L = 150$ km of standard single-mode silica fiber ( although there is a very weak dependence on $L$ provided that $\alpha_p L \gg 1$ ) 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 Rayleigh backscattering coefficient $\mathcal{R} = 10^{-7}$ m$^{-1}$. We assume the line is transparent, i.e. $G(L) = 1$. The signal loss at the isolating device is $-\left.\gamma_s\right|_{dB} = 3$ dB. Fig 2(a) shows the required pump increase with respect to the case of no isolation, eq (6), 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 the pump loss. Fig. 2(b) shows the corresponding OSXR. The horizontal line is the case without isolation. In the ideal case of no pump loss, the maximum OSXR is reached at $L_I = 11$ km, not far from the predicted $L_m/2 = 8$ km, and there is an improvement of 20 dBs in OSXR with respect to the case without isolation, without any required pump increase. With a realistic 3 dB pump loss the optimal point practically coincides with $L_m/2$, and the gain in OSXR is 21 dBs, at the expense of only 1.5 dB of pump increase, as seen in Fig. 2(a). When blocking the pump at the isolator (infinite pump loss, well approximated by the 20 dB curve in Fig. 2(b)), one can suppress the SDRB by shortening to zero the resulting discrete Raman amplifier, at the expense of an infinite pump increase. From Fig. 2(b) we see that the same OSXR increase of 21 dBs obtained at the peak of the curve for 3 dB pump loss can be obtained also by pump blocking using $L_I \cong 1$ km and more than 11 dBs of pump increase. The added cost of the WDM couplers in the first case must be traded off against the cost of the pump increase in the second case.

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