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Impulsive pump depletion in saturated Raman amplifiers

A. Bononi, M. Papararo and A. Vannucci

The analytical results available for counter-propagating pump distributed Raman amplifiers in the undepleted pump approximation are shown to be easily extended to the signal-saturated case by using effective values of both input pump and signals.

Introduction: The quantities of most interest in counter-propagating pump distributed Raman amplifiers are easily obtained in closed form in the unsaturated regime, in which the pump is not appreciably depleted by the signals [1 – 3]. In this Letter we show that such results are valid in signal-saturated amplifiers, provided a smaller, effective input pump value, and pre-emphasised effective input signal values are used. A single transcendental equation must be solved to find the pump reduction factor. Consider the case of N channels of average power S_{j0}, $j = 1, ..., N$, injected in a fibre L kilometres long, pumped from the output by a single pump of power P_0, with signal attenuation α_s and pump attenuation α_p. Neglecting noise, Rayleigh scattered signal power, and signal-signal Raman crosstalk, the implicit solution of the propagation equations in the $+z$ direction for pump and signals is:

$$P(z) = P_0 e^{-\Gamma(z)} e^{\alpha_p(z-L)} \tag{1}$$

$$S_j(z) = S_{j0} e^{\left(-\alpha_s z + \gamma_{pj} \int_0^z P(z')dz'\right)} \tag{2}$$

for $j = 1, ..., N$, where $\gamma_{pj} > 0$ is the modal Raman gain factor [$W^{-1}km^{-1}$] from the pump at λ_p to a signal at λ_j, $\hat{\gamma}_{pj} \triangleq \gamma_{pj}(\lambda_j/\lambda_p)$, and where

$$\Gamma(z) \triangleq \sum_{j=1}^{N} \hat{\gamma}_{pj} K_j(z) S_j(L) \tag{3}$$

is the pump depletion factor, and

$$K_j(z) \triangleq \int_z^L \frac{S_j(z')}{S_j(L)} dz' \tag{4}$$

for $j = 1, ..., N$. To obtain an explicit form of eqns. 1 and 2, some approximations are necessary.

Impulsive pump depletion: The impulsive pump depletion approximation relies on the signals mostly depleting the pump within a very short distance from the link output, where the pump is injected. Hence $P(z)$ at those z values where the pump power is significant for amplification can be accurately predicted by concentrating the depletion at the very end of the link. This amounts to approximating $S_j(z')$ in eqn. 4 as a Dirac impulse placed at $z' = L$, so that K_j is z-independent, and so is Γ. Hence we can define the effective injected pump power as

$$P_0^{eff}(\Gamma) = P_0 e^{-\Gamma} \tag{5}$$

so that the explicit form of eqns. 1 and 2 is:

$$P(z) = P_0^{eff}(\Gamma) e^{\alpha_p(z-L)} \tag{6}$$

$$S_j(z) = S_{j0} e^{\left[-\alpha_s z + Q_j(\Gamma) e^{-\alpha_p L}(e^{\alpha_p z} - 1)\right]} \tag{7}$$

where $Q_j(\Gamma) \triangleq \gamma_{pj} P_0^{eff}(\Gamma)/\alpha_p$; i.e. the same equations as in the undepleted pump approximation are obtained [3], provided that we use the effective pump power P_0^{eff} instead of P_0. An approximate expression for the unknowns K_j can now be obtained considering that, to get an accurate expression for the signal power in eqn. 2, a good approximation of the pump $P(z)$ in eqn. 1 is needed only for z, being not too far from the output, where the pump is large and thus Raman amplification of the signals is significant. Hence using eqn. 7 in eqn. 4 we obtain

$$\begin{aligned} K_j &= \int_z^L e^{\left[-\alpha_s(z'-L) + Q_j\left(e^{\alpha_p(z'-L)} - 1\right)\right]} dz' \\ &\simeq \int_0^L e^{\left[(\alpha_p Q_j - \alpha_s)(z'-L)\right]} dz' \\ &= \frac{1 - e^{-(\alpha_p Q_j - \alpha_s)L}}{\alpha_p Q_j - \alpha_s} \end{aligned} \tag{8}$$

where in the second line we linearised the exponential term $e^{\alpha_p(z'-L)}$ of the first line. Using such $K_j(\Gamma)$ and eqn. 7 in eqn. 3 gives a transcendental equation from which the pump depletion factor Γ can be obtained:

$$\Gamma = \sum_{j=1}^{N} \hat{\gamma}_{pj} K_j(\Gamma) S_{j0} e^{\left[-\alpha_s L + Q_j(\Gamma)(1 - e^{-\alpha_p L})\right]} \tag{9}$$

This procedure gives accurate results for the output signal powers if the injected signals have low power, so that signal-signal Raman crosstalk is negligible. Otherwise there is a simple trick to account for such crosstalk. It is sufficient to (i) evaluate the power tilt that would be induced by signal-signal Raman crosstalk in the unpumped fibre [4]:

$$T_j \triangleq \frac{S_T}{\sum_{k=1}^{N} S_{k0} \exp\left\{-\gamma_{kj} S_T \frac{1 - e^{-\alpha_s L}}{\alpha_s}\right\}} \tag{10}$$

where $S_T = \Sigma_{j=1}^{N} S_{j0}$ is the total launched signal power, and the modal Raman gain γ_{kj} is positive for $\lambda_k > \lambda_j$, and negative otherwise; (ii) then use the effective input signal power $S_{j0}^{eff} = T_j S_{j0}$ instead of S_{j0} in eqns. 7 and 9.

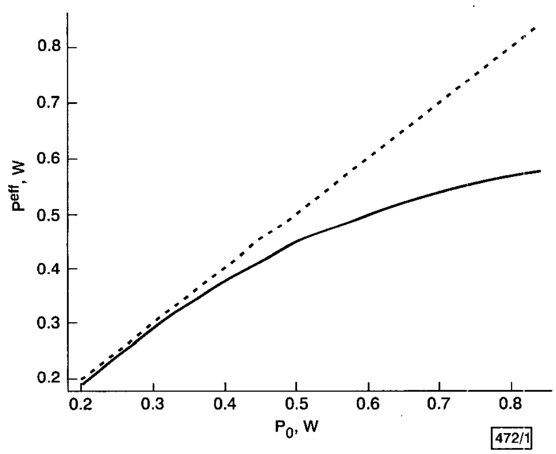

Fig. 1 *Effective pump power against input pump power*

Numerical results: To illustrate the procedure, consider a link of L = 150 km of NZDSF+ fibre, with α_s = 0.205 dB/km, α_p = 0.265 dB/km, with peak Raman gain 0.740 $W^{-1}km^{-1}$. N = 50 channels with spacing 0.8 nm, from 1513.8 to 1553 nm, all with power S_{j0} = 6.3 mW (8 dBm), are launched at the input, with a counter-propagating pump at λ_p = 1438 nm. Fig. 1 shows the effective pump power eqn. 5 against input pump power P_0. It is seen that at small pump values $P_0^{eff} \cong P_0$, while at large pump values the effective pump tends to saturate. Fig. 2 shows the power evolution along the line of both pump and three selected signals, those at channels 20, 30 and 40. Solid lines represent the exact powers, evaluated by solving the complete propagation equation. Dotted lines refer to the values obtained in the simple undepleted pump approximation, i.e. assuming $P(z) = P_0 e^{\alpha_p(z-L)}$. Clearly, such approximation is unrealistic at such signal values. Dashed line values represent our impulsive pump approximation, which makes use of the effective pump and signal powers. It can be seen that using the effective input signal powers S_{j0}^{eff}, as per eqn. 10, has the effect of treating

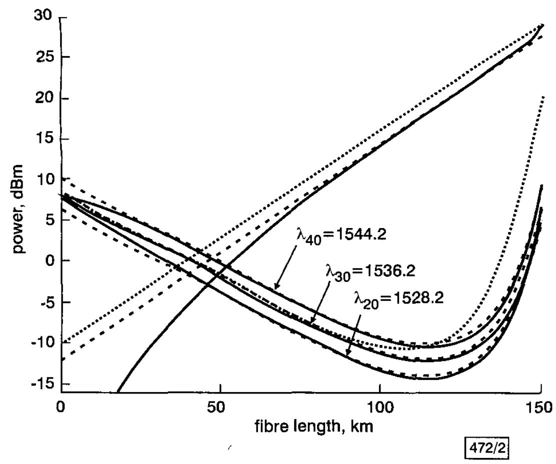

Fig. 2 *Power evolution along line of both pump and three selected signals (channels 20, 30, 40)*

Injected pump: 840 mW, injected signal power: 6.3 mW/channel
——— numeric solution (exact)
– – – – impulsive pump depletion
·········· undepleted pump

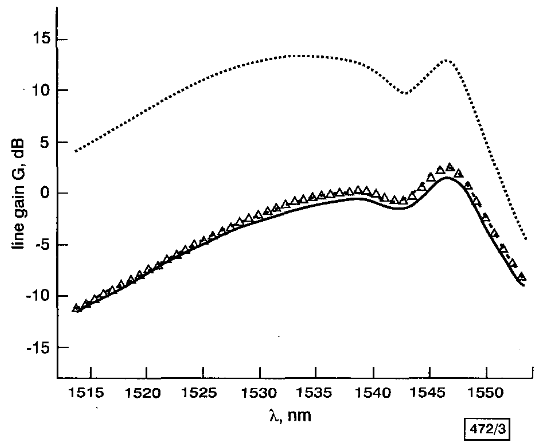

Fig. 3 *Line gain against wavelength*

△ numeric solution (exact)
——— impulsive pump depletion
– – – – undepleted pump

the signals as uncoupled in the unamplified span, but starting from fictitious pre-emphasised values that give the correct values $S_j(z)$ when Raman amplification starts to pick up. As for the pump, the impulsive pump depletion approximation is seen to closely follow the pump profile in the range where pump amplification is significant, except only in the last few kilometres. Signal induced pump depletion observed for the exact solution in the vicinity of the input is not influential regarding the correct output signal power evaluation. Finally, Fig. 3 shows the output gain $G_j = S_j(L)/S_{j0}$ for all 50 channels, both in the undepleted pump (dashed line) and in the impulsive pump approximation (solid line). In the latter case the match with the exact value (triangles) is within 1 dB over the whole signals range.

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Radiation-induced attenuation in Co^{2+}-doped fibre attenuators

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Long-term resistance of Co^{2+}-doped fibre attenuators exposed to gamma-ray irradiation was investigated. The attenuation increase during 25 years is predicted to be 0.004 dB for a 20 dB attenuator, which consists of a 1.5 dB/m attenuation fibre, in the worst case encountered in undersea conditions.

Introduction: In dense-wavelength division multiplexing (DWDM) networks, optical power control using optical attenuators is one of the most important operations, because DWDM networks require power equalisation of multi-channel signals [1]. Co^{2+}-doped silica fibre attenuators have been installed in the DWDM network to control the power of multi-channel signals, pump power of Er^{3+}-doped fibre amplifiers and optical line-test light power [2 – 4].

For Co^{2+}-doped silica fibres (CoDF) applied to undersea cable systems, it is important to study γ-ray irradiation effects. The fibres may be continuously exposed to low γ-ray doses (< 10 R) during a working life of 25 years [5]. For silica glass fibres, it is well known that an increase in loss under γ-ray irradiation is caused by the creation of colour centres [6]. It is also known that, for Er^{3+}-doped fibre amplifiers, dopants (Er, Al) in the fibre induce gain degradations under γ-ray irradiation [5]. However, little is known about γ-ray irradiation effects on transition-metal-doped fibres [4].

In this Letter, the radiation-induced degradation of attenuation in CoDFs under γ-ray irradiation was investigated. Simulated experiments using ^{60}Co γ-rays indicate long-term durability of CoDFs in practical applications.

Experiment: CoDFs were fabricated through conventional procedures [3]. First, a Co^{2+}-doped Ge-SiO_2 glass rod for a doped region in a core was fabricated using a vapour-phase axial deposition and a solution-doping method. Second, a Ge-P-SiO_2 glass rod for a Co^{2+}-undoped region of a core was prepared by a rod-in-tube method. P_2O_5 with 0.5 mol% concentrations was added here, since it made the fabrication of the glass rod easier. The diameter of the Co^{2+}-doped region was adjusted to one third of the undoped core. This selective doping was demonstrated to be effective in obtaining flat-attenuation spectra in the wavelength range of 1530–1610 nm [3]. Third, a cladding glass was fabricated by a jacketing-tube method. Finally, three kinds of singlemode CoDFs, which had 1.5, 3.9, and 9.5 dB/m of the attenuation levels at 1550 nm, were prepared. The concentrations of Co^{2+} ions were estimated at 0.1–1 ppm by comparing the absorption with a previous result [7]. The mode field diameters at 1550 nm and the cut-off wavelengths were about 9.5 μm and 1250 nm.

The CoDFs were exposed to ^{60}Co γ-ray irradiation, which has characteristic energies of 1–2 MeV, and the optical attenuation was monitored *in situ* using a Fabry–Perot laser diode operating at 1550 nm and a power meter. Dose rates of the γ-ray irradiation were 10, 100 and 1000 R/hour. In addition, attenuation spectra of the 1.5 dB/m CoDF were measured *ex situ* before and after an exposure of 1000 R/hour for 20 hours.

Results and discussion: Fig. 1 shows the attenuation spectra of the 1.5 dB/m CoDF before and after irradiation. The absorption peak at 1400 nm is caused by OH^-, which can be neglected for the present application in the 1550 nm communication band. The dif-