

Reduction of double Rayleigh scattering noise in distributed Raman amplifiers employing higher-order pumping

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Abstract: We present a theoretical study of the performance of distributed Raman amplifiers with higher order pumping schemes, focusing in particular on double Rayleigh scattering (DRS) noise. Results show an unexpected significant DRS noise reduction for pumping order higher than third, allowing for an overall performance improvement of carefully designed distributed amplifiers, ensuring a large optical signal-to-noise ratio improvement together with reduced DRS-induced penalties.

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OCIS codes: (060.4510) Optical communications; (060.2320) Fiber optics amplifiers and oscillators; (190.5650) Raman effect.

References and links

1. M. Scheiders, S. Vorbeck, R. Leppla, E. Lach, M. Schmidt, S. B. Papernyi, and K. Sanapi, "Field transmission of 8x170 Gb/s over high-loss SSMF link using third-order distributed Raman amplification," *J. Lightwave Technol.* **24**, 175-182 (2006).
2. V. Karpov, S. B. Papernyi, V. Ivanov, W. Clements, T. Araki, and Y. Koyano, "Cascaded pump delivery for remotely pumped erbium doped fiber amplifiers," in *Proceedings of Suboptic Conference*, 2004, p. We 8.8.
3. S. Faralli and F. Di Pasquale, "Impact of double Rayleigh scattering noise in distributed higher order Raman pumping schemes," *IEEE Photon. Technol. Lett.* **15**, 804-806 (2003).
4. M. Nissov, K. Rottwitt, H. D. Kidorf, and M. X. Ma, "Rayleigh crosstalk in long cascades of distributed unsaturated Raman amplifiers," *Electron. Lett.* **35**, 997-998 (1999).
5. S. Papernyi, V. Ivanov, Y. Koyano, and H. Yamamoto, "Sixth-order cascaded Raman amplification," in *Optical Fiber Communication Conference*, 2008 OSA Technical Digest, (Optical Society of America, 2008), paper OthF4.
6. G. Bolognini, S. Sugliani, and F. Di Pasquale, "Double Rayleigh scattering noise in Raman amplifiers using pump time-division multiplexing schemes," *IEEE Photon. Technol. Lett.*, IEEE Press, **16**, 1286-1288 (2004).
7. P. Kim, J. Park, H. Yoon, J. Park, and N. Park, "In situ design method for multichannel gain of a distributed Raman amplifier with multiwave OTDR," *IEEE Photon. Technol. Lett.* **14**, 1683-1685 (2002).

1. Introduction

In recent years, the performance of distributed Raman amplification for wavelength division multiplexing (WDM) transmission systems has been routinely enhanced by higher-order Raman pumping (HOP). In HOP, many pump wavelengths with spectral separation of several tens of nm are coupled into the transmission fiber together with the WDM channels. Shorter-wavelength pumps do not amplify the WDM channels directly, but provide distributed Raman amplification for longer wavelength pumps, which in turn amplify the channels deep inside the transmission fiber. This may provide a significant enhancement (up to several dB) in optical signal-to-noise ratio (OSNR) at the receiver compared to standard distributed Raman-amplified systems [1], and also results in an increased pump power at 1480 nm which can be delivered to remotely-pumped EDFAs [2]. The HOP technique has proved to be particularly

effective in long-haul, unrepeated systems for applications in undersea transmissions or in point-to-point links across large rural areas without intermediate nodes [1], where the provided OSNR improvement can avoid the introduction of active elements along the link, thus bringing significant capital and operational savings.

The main practical limitation to the use of HOP at high gains or for pumping order higher than third is given by the large required pump power (> 1 W). However, detrimental effects on optical transmission fibers due to large power can be avoided, even on a ten-year time-scale, with suitable checks of optical fiber loss, carried out for example through optical time domain reflectometry-based inspection, ensuring the absence of hot points generated by concentrated high-absorption regions, e.g. given by a bad fusion splice.

On the other hand, the principal limitations to the use of pumping orders higher than third are stemming from noise-related issues, mainly given by the transfer of relative intensity noise (RIN) from higher-order pumps to the WDM channels, and to the increase of the signal double Rayleigh scattering (DRS) multi-path interference noise. While pump RIN effects (which are critical especially in co-propagating configurations) can be avoided by employing low-RIN pump sources, the increase in DRS noise is currently the main limitation for the use of HOP with high gain or pumping order. Actually, while the amplifier noise figure (NF) is known to improve with increasing pumping orders (accounting for the above-mentioned OSNR improvement), the induced DRS noise is shown to worsen for increasing orders up to 3rd [3], thus affecting the overall system Q-factor and canceling out the provided NF benefits, especially at high gain values. Therefore, presently the pumping order in Raman HOP is limited to 3rd order due to the expected insurgence of DRS noise-related impairments. In this paper, we show the results of a theoretical study on higher-order pumping schemes, carried out with both full numerical and semi-analytical methods, showing in particular an unexpected reduction of DRS noise which can be achieved for HOP higher than 3rd order. A qualitative analytical approach is also developed in order to provide clear insight on the fundamental physical mechanisms underlying this unexpected behavior.

Actually, both theory and simulations indicate an achievable decrease of DRS noise for pumping orders higher than third, a behavior which was unknown until now, and which could lead to the implementation of optimized HOP schemes at high gain values without significant DRS-induced penalties, thus overcoming the present performance limitations in higher-order Raman pumping techniques.

2. Theory

In this work, three different approaches were used to characterize the DRS noise in HOP schemes. In the first approach, a simplified qualitative model assuming undepleted pump and transparency conditions helped pointing out the fundamentals of the physical mechanism underlying the predicted reduction of DRS for suitable signal profile conditions. In the second approach, a fast-computing, semi-analytical evaluation of DRS was obtained through the integration of the scattering contributions along the fiber, following the derivation in [4], which allowed us to provide a quantitative analysis of the behavior of DRS in HOP schemes. Finally, quantitative results were also obtained with a third full-numerical approach, which was used to cross-validate the results of the semi-analytical method. In the third approach, the complete propagation equations were numerically integrated in a WDM scenario, as detailed in [3], taking into account fiber absorption, signal Rayleigh scattering and Raman effect among pumps and signals.

2.1 Full numerical model

The employed full numerical method allows the description of both co- and counter-propagating Raman pumps. It takes into account the effects of wavelength-dependent fiber absorption, pump and signal multiple-order Raman interactions as well as Rayleigh scattering. Amplified spontaneous emission (ASE) light is neglected in order to reduce computational

effort, especially when higher-order pumps are spanning a wavelength range of several hundreds of nm, as, e.g., in 6th order pumping [5].

The complete set of differential equations describing the power evolution for the i -th forward- or backward-propagating Raman pump $P_{P_i}^\pm(z)$, the i -th forward-propagating WDM signal $P_{S_i}^+(z)$ and the corresponding backward-propagating single-Rayleigh-scattering $P_{S_i}^-(z)$, as well as the corresponding double Rayleigh scattering $P_{DRS_i}^\pm(z)$, allows to obtain the power evolution along the fiber coordinate z . The equations describing the i -th signal ($i=1\dots N$) or pump ($i=1\dots M$) evolution can be written as:

$$\frac{dP_{S_i,P_i}^\pm(z)}{dz} = \mp\alpha_{S_i,P_i} P_{S_i,P_i}^\pm(z) \pm \gamma_i P_{S_i,P_i}^\pm \pm \sum_{j \neq i} C_{ij} P_{S_i,P_i}^\pm \cdot [P_{P_j}^+ + P_{P_j}^- + P_{S_j}^+ + P_{S_j}^-] \quad (1)$$

$$\frac{dP_{DRS_i}^\pm(z)}{dz} = -\alpha_{S_i} P_{DRS_i}^\pm + \sum_j C_j \bar{P}_{P_j} \cdot P_{DRS_j}^\pm + \gamma_i \bar{P}_{SRS_i}^\pm \quad (2)$$

where $P_{S,P}$ indicate the signal/pump power values, the superscripts +/- represent the co- and counter-propagating directions and α_{S_i,P_i} the absorption coefficients at the i -th signal/pump wavelength, γ_i is the Rayleigh backscattering coefficient and C_{ij} indicates the normalized Raman gain coefficient:

$$C_{ij} = \frac{g_{ij}}{A_{\text{eff}}} \quad \text{for } \lambda_i > \lambda_j, \quad C_{ij} = -\frac{\lambda_j}{\lambda_i} \frac{g_{ij}}{A_{\text{eff}}} \quad \text{for } \lambda_i < \lambda_j$$

where g_{ij} is the Raman gain coefficient, and A_{eff} is the fiber effective area. Integration of the differential equation set is achieved using 4th-order Runge-Kutta techniques in a recursive algorithm in order to provide an accurate estimate of the power evolution in a counter-propagating signal frame, similarly to what done for both space-time variables in [6].

2.2 Semi-analytical model

The signal double Rayleigh scattering noise can also be quantitatively evaluated more simply once the signal gain profile along the fiber length is known. Such a profile can be obtained either theoretically by solving a set of simplified differential equations similar to Eq.(1) for pump and signal power evolution without ASE, as commonly implemented in many commercially-available simulators, or experimentally through optical time-domain reflectometry (OTDR) [7].

Once the signal gain profile $G(z)$ along z is known, the DRS noise power (P_{DRS}) at the fiber end can be calculated as [4]:

$$P_{DRS} = P_S \cdot \gamma^2 \int_0^L \int_0^z \left[\frac{G(z)}{G(\zeta)} \right]^2 d\zeta dz \quad (3)$$

where P_S is the signal power at fiber-end, γ is the Rayleigh backscattering coefficient, $G(z)$ is the signal gain profile, and L the fiber length. The integrand represents the double-pass gain experienced between the two Rayleigh-scattering points of the signal at coordinates ζ and z , with $\zeta < z$. From the expression of the integrand in Eq. (3), the major relative contributions to DRS are expected from those portions of the fiber in which ζ is located in a low-power lossy section, while z is in a high-power gain-section, so that the gain ratio within the integrand is large: $G(z)/G(\zeta) \gg 1$.

2.3 Simplified analytical model

A first qualitative intuition about the potential DRS decrease with HOP can be obtained by considering a transparent line, defined as a fiber transmission link with length L where the ON-OFF Raman gain equals the fiber loss, resulting in a unity net gain G at fiber output for a WDM signal (i.e. $G(L)=1$).

In order to provide a clear insight in the physical mechanism underlying the DRS noise decrease, we may consider a simplified gain $G(z)$ with a first lossy section, reproducing the input fiber section where no significant Raman gain from counter-propagating Raman pumps is experienced by the signal, followed by a constant-gain amplified section, starting at the coordinate L_1 where the penetrating high pump power levels result in non-negligible Raman gain. Therefore the simplified gain profile along the fiber becomes:

$$G(z) = \begin{cases} \exp[-\alpha z] & z \in [0, L_1] \\ \exp[g(z-L)] & z \in [L_1, L] \end{cases}, \quad (4)$$

with a constant gain coefficient g related to the absorption according to $g_1 = \alpha L_1 / (L - L_1)$ to ensure the transparency condition. The distance $d = L - L_1$ intuitively reproduces the ‘penetration depth’ of the back-propagating pumps: higher pumping orders are reproduced by larger d values. The variable $x = L_1 / L$ represents the normalized coordinate of the transition point between the two sections.

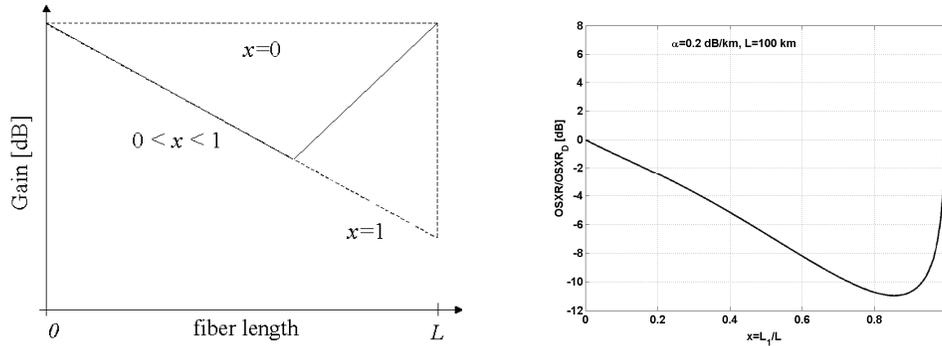


Fig. 1. (Left) Examples of simplified gain profiles versus fiber length. (Right) Signal to DRS ratio, normalized to fully distributed value, versus normalized coordinate of breakpoint between initial lossy section and final gain section.

Figure 1(left) reports an example of three possible profiles of the simplified gain in dB versus fiber length, for $x=1$ (dotted line, representing an ideal lossless fiber), for $x=0$ (dotted line, representing an ideal case with lumped amplification at fiber end), and for an arbitrary $x \in (0,1)$ (solid line). Letting $G_1 = e^{g_1 d} = e^{\alpha L x}$ the signal net gain within the amplified section, from Eqs. (3)-(4) we can find:

$$\frac{P_{DRS}}{P_s} = \frac{\gamma^2 L^2}{2} \left[\frac{(G_1^2 + 2 \ln G_1 - 1)x^2 + G_1^2 (1 - G_1^2)^2 x(1-x) + (G_1^2 - 2 \ln G_1 - 1)(1-x)^2}{2(\ln G_1)^2} \right] \quad (5)$$

where the first term in the summation within the square brackets gives the contribution of both scatter points ζ and z located in the lossy section, the second term gives the contribution for the case where the scatter point ζ is located in the lossy section and the scatter point z in the gain section, and, finally, the third term gives the contribution for the case where both scatter points are located in the gain section. The term $\gamma^2 L^2 / 2$ is the relative DRS power in Eq. (4) for the case of ideal fully distributed amplification, i.e., $G(z)=1$ for every z .

The effect of increasing pumping order on DRS noise can be qualitatively understood from Eq. (5) by decreasing x (i.e. by increasing ‘penetration depth’), representing the increasing distributed gain effect provided by higher-order pumping. The limiting value $x=1$ corresponds to the case where no gain is present throughout the fiber, and all gain is provided in a lumped amplifier stage at the fiber end; conversely, the limiting value $x=0$ corresponds to the ideal case (possibly approached by very high pumping orders) where the gain is fully distributed along the fiber, exactly compensating the fiber loss at every point, thus creating a transparent optical fiber condition at every fiber length.

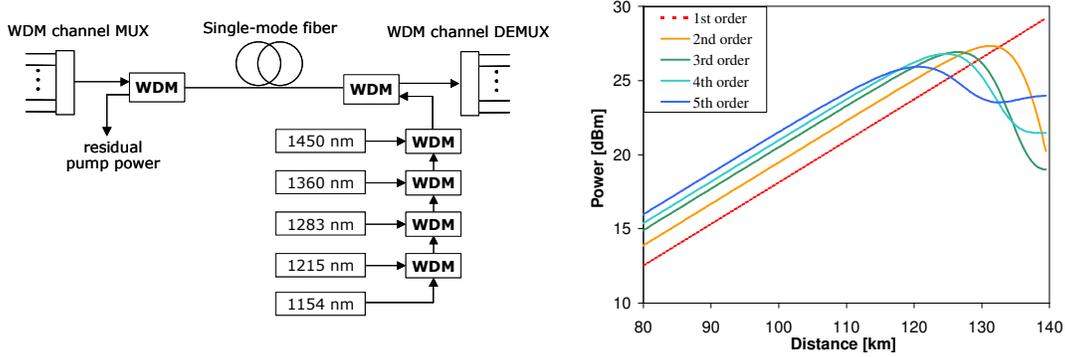


Fig. 2. (Left) Scheme of simulated counter-propagating Raman amplification with increasing pumping orders. (Right) Power evolution for the 1450 nm pump under different pumping orders.

Figure 1(right) shows the normalized optical signal to DRS crosstalk ratio ($OSXR \equiv P_s/P_{DRS}$), in a dB scale, versus normalized breakpoint location x . The OSXR parameter is normalized to its value $OSXR_D = (\gamma^2 L^2/2)^{-1}$ achieved in the case of fully distributed amplification. We can note from Fig. 1(right) that, starting from a “flat” gain profile ($x=0$), as we increase x the OSXR exhibits a degradation. This can be explained, referring to Fig. 1(left), since the signal gain profile G along z becomes more and more deeply “V” shaped, and extended sections start to appear where the gain ratio in the integrand of Eq. (1) is large, i.e. $G(z)/G(\zeta) \gg 1$; this, as noted earlier, gives rise to the well-known increase in DRS noise (thus worsening the OSXR), an effect which is commonly observed in present-day higher-order pumping schemes [3]. At the opposite extreme, $x=1$, we have the case of a lumped amplification at the fiber end, which is obtained when the breakpoint L_1 coincides with the fiber end L . In such a case, i.e. $G_1 = e^{\alpha L}$, the integrand $G(z)/G(\zeta)$ in Eq. (3) is always less than unity, and only the first term in Eq. (5) is present, so that we have:

$$\frac{OSXR}{OSXR_D} = \frac{2(\ln G_1)^2}{G_1^{-2} + 2\ln G_1 - 1} = \frac{2(\alpha L)^2}{e^{-2\alpha L} + 2\alpha L - 1} \cong \alpha L \quad (6)$$

where the approximation assumes $\alpha L \gg 1$. This is the largest achievable OSXR, clearly larger than that in case of flat gain ($x=0$). Intuitively, since a physical quantity like the OSXR should be continuous over x , a value of $x \neq 0$ must exist where the OSXR is minimum, as shown in Fig. 1(right). This simple model predicts the location of such a minimum at a penetration depth around $d \sim 0.5/\alpha$. Thus, from this simple formulation we can intuitively understand how, as we use Raman pumping of increasing order to provide a flatter gain, after exceeding the value of penetration depth where OSXR is minimum, the OSXR starts improving, i.e., the DRS noise starts decreasing for higher pumping orders.

3. Results for HOP Raman amplifiers

In order to quantify the realistic behavior of DRS in actual distributed Raman amplifiers based on HOP, we have employed both a fully numerical approach and a semi-analytical method

Table 1. Fiber parameters and pump conditions for the highest-order pump employed under different pumping order schemes

| Fiber parameters | Highest-order pump parameters | | |
|--|-------------------------------|------------|--------------------------|
| $g_R = 3.8 \cdot 10^{-4} \text{ 1/m}\cdot\text{W}^*$ | | Fiber loss | Input power |
| $\gamma = 4 \cdot 10^{-8} \text{ m}^{-1}$ | 1 st order | 0.28 dB/km | $P_{IN} = 0.8 \text{ W}$ |
| $A_{EFF} = 80 \text{ }\mu\text{m}^2$ | 2 nd order | 0.32 dB/km | $P_{IN} = 1.3 \text{ W}$ |
| $\alpha_{1550} = 0.18 \text{ dB/km}$ | 3 rd order | 0.35 dB/km | $P_{IN} = 1.9 \text{ W}$ |
| | 4 th order | 0.52 dB/km | $P_{IN} = 2.4 \text{ W}$ |
| * peak gain at 13.2 THz shift | 5 th order | 0.58 dB/km | $P_{IN} = 3.0 \text{ W}$ |

using Eq. (3) with the actual gain profile $G(z)$, as detailed in the previous Section. The scheme which has been analyzed is reported in Fig. 2(left). Eight WDM channels (range 1546.9-1552.5 nm with 100 GHz spacing, $P_{IN}/\text{ch} = 0 \text{ dBm}$) are transmitted through 140 km of standard single mode fiber (SMF). Note that results are also valid when longer transmission spans are considered, since the DRS noise behaviour is essentially dictated by the signal profile towards the fiber-end side. Raman amplification is achieved in the counter-propagating direction starting from 1st up to 5th order. Since multi-modal propagation is occurring for wavelengths smaller than $\sim 1150 \text{ nm}$, correspondingly to 5th order pumping, we did not consider higher pumping orders (or equivalently shorter pump wavelengths) in our analysis. Table 1 reports some of the used fiber parameters, such as the peak Raman gain coefficient g_R (the gain spectrum profile was actually used in simulations), the Rayleigh backscattering coefficient γ , the fiber effective area A_{EFF} , and the absorption at peak signal wavelengths α_{1550} , along with the pump conditions such as fiber absorption and input pump power (P_{IN})

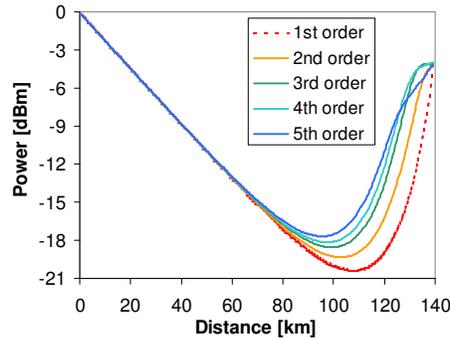


Fig. 3. Scheme of signal power evolution at 1550.1 nm under different higher-order schemes.

considered for the highest-order pump wavelength in different pumping orders.

To provide a sensible comparison, the analysis has been carried out with common gain for the schemes from 1st to 5th order. The ON-OFF peak gain value (for the channel at 1550.1 nm) was $G_{ON-OFF} = 26.7 \text{ dB}$, with a gain ripple smaller than 1 dB. This was achieved for different pumping orders by suitably varying the absolute input power of the lower-order seeds, also ensuring an optimal pump and signal power evolution. The resulting power evolution for the 1450 nm pump, which is directly pumping the WDM channels, is shown in Fig. 2(right) in case of different HOP schemes. From the figure we notice that in a 5th order scheme the 1450 nm pump exhibits the maximum power value at about 20 km from the fiber end, thus resulting in a signal amplification well inside the transmission fiber, with a consequent OSNR improvement, as it can be seen in Fig. 3, where the power profile for the 1550.1 nm channel (the one with highest gain and therefore the worst case for DRS noise assessment) is reported.

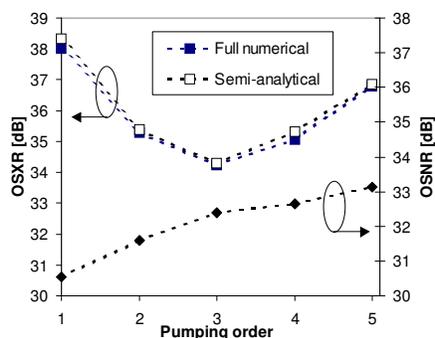


Fig. 4. OSXR vs pumping order calculated with full numerical and semi-analytical method.

Such power profiles are then employed in Eq. (1) in order to calculate the signal DRS noise at the fiber end for increasing pump order (see Sec. 2.2).

The accuracy of this semi-analytical approach is also compared with the full numerical integration providing the DRS noise directly from resolution of the set of propagation equations (as explained in Sec. 2.1). The results are shown in Fig. 4 (left y-scale), reporting the signal-to-DRS noise ratio (OSXR) at the fiber end versus pumping order (from 1st- to 5th-order), obtained with both the semi-analytical approach (open symbols) and a full numerical integration (solid symbols). Both approaches are in good agreement, thus validating the accuracy of the semi-analytical approach in estimating DRS noise in HOP schemes. The behavior of OSXR in Fig. 4 is notable: for the used pump and signal input power conditions, we can observe a monotonic decrease in OSXR up to 3rd order pumping scheme (which is well known), and an apparently surprising improvement in OSXR for pumping orders higher than 3rd one, leading to a 3 dB improvement in OSXR from 3rd to 5th order (going from ~34 dB to ~37 dB). Such an improvement is adding up to the well-known OSNR improvement which is found for increasing order, as also reported in Fig. 4 (right y-scale), and can lead to an overall Q-factor improvement for increasing pumping orders. This behavior is in agreement with [3], who observe a DRS noise increase up to 3rd order, but may appear different from what emerged in [5] for pumping orders higher than 3rd one. However, note that in that case a very different HOP scheme based on cascaded fiber-Bragg grating (FBG) light generation was used, resulting in different pump distributions from our case and, most importantly, in strong RIN-induced penalties in 6th-order (due to the fraction of pump power co-propagating with the signal in the FBG-assisted light generation scheme of [5]), leading to worse performance observed for 6th order pumping than for lower-order schemes.

To our knowledge, this is the first theoretical report of DRS-noise decrease for HOP, as opposed to the commonly reported DRS increase with increasing pumping order [2,5]. If experimentally confirmed, the existence of such a DRS decrease could be of great utility in designing future-generation distributed Raman amplification schemes with enhanced system Q-factor, since, until now, the use of Raman pumping orders higher than third was hindered - apart from power-related concerns - by the expectation of a worse DRS.

7. Conclusion

In conclusion, we carried out a theoretical analysis on the DRS noise behavior in higher-order Raman pumping schemes. Our analysis, performed through a simplified analytical treatment, as well as with semi-analytical and full numerical methods, allowed us to observe a notable phenomenon involving the decrease of DRS noise for HOP schemes above 3rd order. The occurrence of such a DRS-noise decrease was found to be dependent on the signal power profile along the fiber. Such a novel phenomenon, emerging from our simulations in Fig. 5 and also logically understandable from our simplified analytical treatment of Sec. 2.3, can thus in perspective lead to the implementation, within WDM communication systems, of HOP

Raman amplifier schemes exhibiting improved OSNR and DRS noise features, and thus finally allowing an enhanced system Q-factor.