Analysis of Double Rayleigh Scattering Noise in Higher-order Pumped Distributed Raman Amplifiers

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Abstract

A theoretical analysis of double Rayleigh scattering (DRS) noise in higher-order Raman pumping schemes is presented. Simulations confirm an unexpected DRS noise decrease for pumping schemes above 3rd-order.

Introduction

Higher-order Raman pumping (HOP) schemes are an effective solution for improving the performance of Raman-amplified links, especially for submarine, long-haul and unrepeated transmission systems [1,2]. In higher-order schemes, shorter-wavelength pumps provide Raman amplification for longer wavelength pumps, thus amplifying the WDM channels deep inside the transmission fiber. In this way HOP is able to provide significant benefits in distributed Raman amplifiers in terms of optical signal-to-noise ratio (OSNR) at receiver [2,3], as well as an increase of the 1480nm light power delivered to remotely-pumped EDFAs [4].

Higher-order pumping can be deployed both in co-propagating and counter-propagating configuration; the former configuration is strongly affected by pump-to-signal relative intensity noise (RIN) transfer and requires low-noise pumps, while counter-pumping scheme is less affected by intensity noise and is most commonly employed. In both schemes, the major impairment source is given by double Rayleigh scattering (DRS) noise, which presently limits the benefits provided by HOP. Actually, while the amplifier noise figure (NF) is known to improve for increasing pumping orders, the induced DRS noise under same conditions is shown to worsen for orders up to 3rd order [5], thus potentially cancelling out the NF benefits, especially at high gain values.

In this paper, we present the results of a numerical analysis (carried out with both a full numerical method and a semi-analytical approach) on higher-order counter-propagating pumping schemes up to fifth order, showing a possible reduction in DRS for HOP higher than 3rd order. Actually simulations point out a significant dependence of DRS noise on signal power profile within the optical fiber, leading to a possible unexpected decrease of DRS noise with increasing pumping order at the same gain. Hence, smart pumping configurations can be devised which are capable to fully exploit the OSNR benefit provided by higher-order pumping without significant DRS-induced penalties.

Theory

Two different approaches have been followed in order to analyse the behaviour of double Rayleigh scattering noise. In the first approach, the propagation equations have been fully numerically integrated in a WDM scenario, as detailed in [5], taking into account fiber absorption, signal Rayleigh scattering and Raman effect among pumps and signals. A numerical integration of the set of differential equations allows one to obtain the power evolution along the fiber distance z for the m counter-propagating pumps $P_{P\_m}(z)$, the n WDM channels $P_{S\_n}(z)$ and n-th signal double Rayleigh scattering light $P_{DRS\_n}(z)$.

In the second approach, a fast-computing, semi-analytical evaluation of DRS has been obtained through the integration of the scattering contributions along the fiber, following the derivation in [6]. If the signal gain profile along the fiber is known (e.g. from numerical simulation or OTDR measurements), then the amount of signal DRS noise P_{DRS} at the fiber-end can be determined from:

$$\frac{P_{DRS}}{P_S} = \gamma^2 \int_0^L \int_0^z \left[\frac{G(z)}{G(\varsigma)} \right]^2 d\varsigma dz \qquad (1)$$

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.

Results

The analysis of DRS has been carried out with both approaches for a WDM system with counter-propagating distributed Raman amplification.

Fig. 1 shows the modelled configuration schemes. Eight WDM channels (100 GHz spacing from 1546.9 to 1552.5. nm) with 0 dBm input power per channel are transmitted through 140 km of standard single mode fiber (SMF). Raman amplification is achieved in the counter-propagating direction starting from 1st up to 5th order (pumping orders higher than 5th order have not been considered due to multi-mode propagation in SMF for pump wavelengths below ~1150 nm not considered in simulations). The Rayleigh scattering coefficient was $4 \cdot 10^{-8}$ m^{-1}. All values of fiber absorption and input pump power (P_{IN}) for highest-order pump wavelength in different pumping orders are summarized in Table 1. The Raman gain coefficient

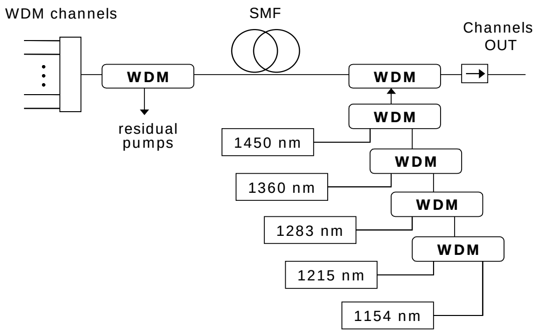

Fig. 1. Scheme of simulated counter-propagating Raman amplification with increasing pumping orders

	Fiber loss	Highest-order pump P_{IN}
1^{st} order (1450 nm)	0.28 dB/km	800 mW
2^{nd} order (1360 nm)	0.32 dB/km	1300 mW
3^{rd} order (1283 nm)	0.35 dB/km	1900 mW
4^{th} order (1215 nm)	0.52 dB/km	2400 mW
5^{th} order (1154 nm)	0.58 dB/km	3000 mW

Tab. 1. Fiber parameters and pump power conditions employed for different pumping orders

used in the simulations has been measured for a SMF fiber; its peak value is $3.8 \cdot 10^{-4}$ [1/m·W] at 13.2 THz frequency shift. Note that the input power values for lower-order seeds are varied depending on pumping to ensure an optimal signal power evolution along the fiber and to keep a constant gain for all pumping schemes (G_{ON-OFF}=26.7 dB at 1550.1 nm, $G_{RIPPLE} \leq 1$ dB), thus providing a fair HOP comparison. The evolution of pump power for different pumping orders is shown in Fig. 2, where the effect of indirect pumping in HOP schemes is evident. In particular, the 1450 nm light is amplified at about 20 km distance from fiber end in a 5^{th} order pumping scheme, resulting in an improved OSNR.

This reflects into a different signal evolution along fiber length for increasing pumping orders, as shown in Fig. 3 reporting the power distribution of the channel at 1550.1 nm (highest gain and worst case channel). These power profiles, obtained by full numerical analysis, are then used to calculate the DRS noise through Eq. (1) for different pumping orders. Fig. 4 hence reports the signal-to-DRS noise ratio (OSXR) at the fiber end for increasing different pumping order (from 1^{st} t 5^{th}) obtained by the aforementioned semi-analytical approach (open symbols) and directly by the full numerical

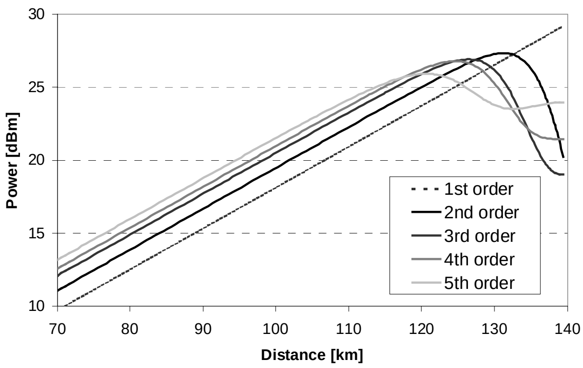

Fig. 2. Power evolution for the 1450 nm pump under different pumping orders

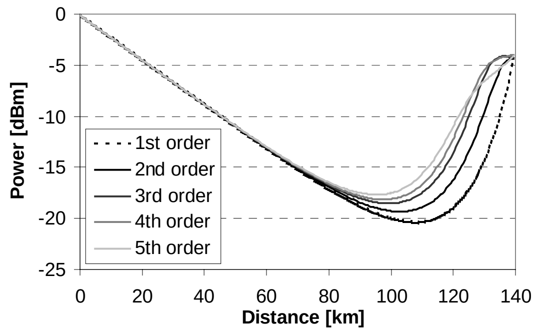

Fig. 3. Scheme of power evolution of the signal at 1550.1 nm under different higher-order schemes

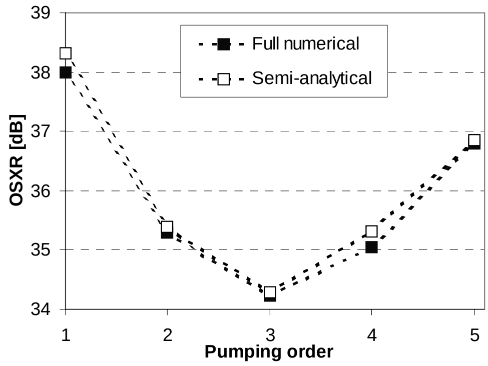

Fig. 4. OSXR vs pumping order calculated with full numerical and semi-analytical methods.

integration (solid symbols). The agreement between the two methods is good, confirming the accuracy of the semi-analytical approach in calculating DRS for HOP. One notable feature observed in Fig. 4 is the behaviour of OSXR, which, for our pump conditions, is degraded for HOP below 3^{rd} order, and then appears improving for HOP values above 3^{rd} order.

Note that this result is in agreement with [5] up to 3^{rd} order, but may appear different from what emerged in [3]. However, note that in [3] 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 in strong RIN-induced penalties in 6^{th}-order (due to co-propagating pump power fraction in FBG-assisted light generation), leading to a smaller optimal gain for 6^{th} order pumping than for lower-order schemes

In conclusion, we have performed an analysis on behaviour of DRS noise in higher-order Raman pumping schemes. Results point out a significant dependence of DRS noise on signal power distribution along the fiber, making possible to attain a DRS noise decrease (and an overall Q-factor increase) for HOP schemes above 3^{rd} order.

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