Prediction of Performance Penalty due to Pump-Signal Overlap in Raman-amplified Systems

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Abstract: We present an efficient numerical model to predict the performance penalty induced by Rayleigh backscattered light arising from counter-propagating pumps in Raman-amplified ultra-wide-band transmission systems. The model is validated through comparison with experimental findings. © 2020 The Author(s)

1. Introduction

The ever-increasing need for higher data throughput, together with the requirement to find cost-effective solutions, is fostering research in the development of ultra-wide-band systems operating on the available fiber infrastructure [1]. Wavelength division multiplexed (WDM) transmission over C- and L-bands is approaching the spectral efficiency limit while bandwidth extension offers a more rewarding increase of the throughput [2]. One of the main challenges related to multi-band systems is the development of suitable amplification schemes. Recently, S+C+L band flat amplification has been demonstrated with different techniques, employing rare-earth doped fiber amplifiers, semiconductor optical amplifiers and Raman amplification [2–4]. It has been shown in particular how multi-stage backward pumped discrete Raman amplifiers (DRAs) are able to provide improved noise figure over a large bandwidth [4]. When the WDM signal bandwidth exceeds the peak Raman gain shift of $\approx$ 100 nm, wavelength regions in which both signals and pumps are present arise. Evident transmission penalties induced by Rayleigh backscattered light (RBS) have been experimentally observed in this scenario [5].

We develop an efficient numerical model to easily predict the transmission penalty induced by RBS generated by counter-propagating pumps in Raman amplification schemes. The model is validated by comparison with the experimental results obtained in [5] and provides a very good agreement while keeping low the algorithmic complexity.

2. Simulation setup and model derivation

The simulation setup is shown in Fig. 1. The input signal ranges from 1485 to 1625 nm and is propagated over 70 km of standard single mode fiber (SSMF) before entering the dual stage backward pumped DRA under analysis. In S-band we consider two 30 GBaud quadrature phase-shift keying modulated signals shaped using a raised cosine filter with 0.2 roll-off factor. Their central wavelengths are swept respectively around 1485 nm and 1508 nm in a range of ± 3.2 nm to span over the overlapping broadband pumps spectra, whose peaks are found around these same two central wavelengths. In C- and L-band the channels are represented simply as single spectral lines to take into account the Raman power transfer in an efficient way. The DRA is composed of two inverse dispersion fiber (IDF) spans of length $L = 7.5$ km. This fiber is characterized by a linear Rayleigh backscattering coefficient of $\gamma_r = 1.6 \times 10^{-7}$ m^{-1}. In order to establish a common reference performance level between the experiment in [5] and our model, we introduce additive white Gaussian noise (AWGN) at the input of the system. The noise power is set to obtain a reference Q^2 factor $\approx$ 20 dB at 1508 nm and $\approx$ 17.2 dB at 1485 nm at the output of the amplifier when RBS is not taken into account.

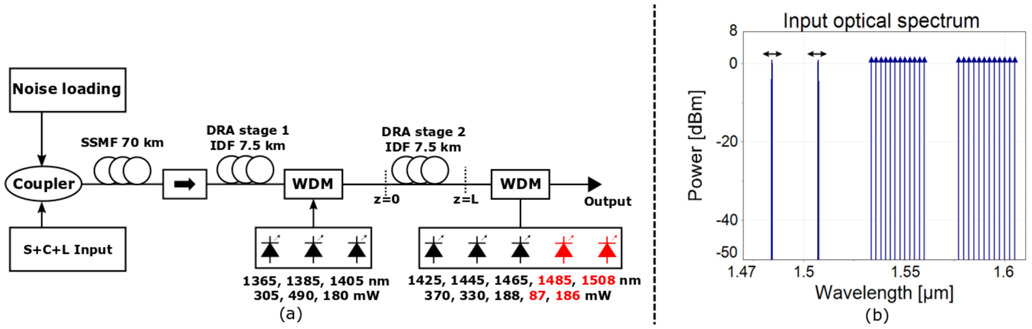

Fig. 1: (a) Simulation setup. In red the pumps that overlap with the signal. The wavelengths and respective powers of the pumps are reported. The DRA provides an average gain $\approx$ 15 dB. (b) Optical spectrum of the S+C+L input.

Recalling that the Q factor has for noise-limited systems an equivalent description in the signal to noise ratio (SNR), we can now define $\mathrm{SNR}_{ref}(\lambda_i)$ as the value that corresponds to our reference Q^2 factor for $\lambda_i = \{1485, 1508\}$ nm. To evaluate then the RBS induced penalty we calculate the total SNR as in (1).

$$\mathrm{SNR}_{tot}(\lambda) = \frac{P_s^+(z=L,\lambda)}{P_s^+(z=L,\lambda)/\mathrm{SNR}_{ref}(\lambda_i) + P_{RBS}^+(z=L,\lambda)} \tag{1}$$

Where $P_s^+(z=L,\lambda)$ and $P_{RBS}^+(z=L,\lambda)$ are respectively the signal and RBS forward propagating power at the output of the DRA. In order to estimate these two quantities, it is needed to describe the longitudinal evolution of P_s^+ and of the counter-propagating Raman pump power, which we refer to as $P_p^-(z,\lambda_i)$. Extensive literature regarding the numerical solution of this problem is available. During our work we evaluated it through the model included in VPIphotonics Design Suite 10.0. For this operation the broadband pumps are described as single spectral components located at wavelengths λ_i. This approximation proved to provide reliable results while significantly decreasing the algorithmic complexity. Once P_s^+ and P_p^- have been obtained on the domain $z \in [0, L]$ the problem reduces to the estimation of $P_{RBS}^+(z=L,\lambda)$. In our scenario, where the pump power is much higher than the overlapping signal, it is reasonable to neglect double RBS arising from the signal. Hence, we can estimate $P_{RBS}^+(z=L,\lambda)$ as the sum of all the RBS contributions from the pump generated along the DRA, appropriately scaled by the gain or attenuation they are subject to when propagating from the generation point to $z = L$. If we spatially divide our amplifier into infinitesimally small sections dz we can then write (2).

$$P_{RBS}^+(z=L,\lambda) = \int_0^L \gamma_r P_p^-(z,\lambda) \frac{P_s^+(L,\lambda)}{P_s^+(z,\lambda)} dz \tag{2}$$

Here P_p^- is the pump power that falls inside the receiver bandwidth. This term takes into account the spectral shape of the broadband pump, which proved to be a key parameter in order to obtain reliable predictions.

3. Model validation

From the derived SNR_{tot} we calculate the Q^2 factor and verify our model through comparison with the experimental penalty reported in [5]. As can be observed in Fig. 2, the model provides a very good estimation of the performance penalty versus the wavelength separation between the central wavelengths of the overlapping pump and signal. The agreement is good at 1485 nm, where a worst case Q^2 drop ≈ 2 dB is present, and at 1508 nm, where higher pump power and Raman gain cause a much larger RBS induced penalty ≈ 15 dB. The different shape of the two graphs is due to the different pumps' spectra [5], which are then taken into account in our model.

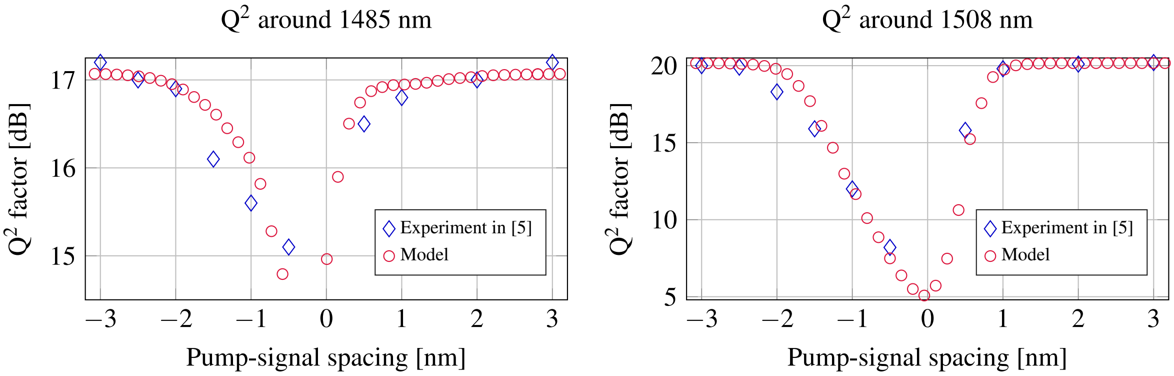

Fig. 2: Comparison between the simulation results and the experimental penalty observed in [5].

4. Conclusions

We presented an efficient method to predict the performance penalty arising from pump-signal overlap in Raman-amplified ultra-wide-band systems. We demonstrated excellent agreement of our model predictions with experimental results, both proving its reliability and corroborating the findings in [5]. In particular we confirmed that the penalty observed is entirely due to RBS and is strongly influenced by the spectral shape of the pump.

Acknowledgments

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