Hybrid gain-flattened and reduced power excursion scheme for distributed Raman amplification

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Abstract: We propose and evaluate through extensive numerical modelling a novel distributed hybrid amplification scheme combining first and second-order Raman pumping which gives reduced signal power excursion over a wide spatial-spectral range of 60 km × 80 nm in C + L-bands.

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

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1. Introduction

Using distributed amplification to reduce the signal power level variations along the transmission spans in optical fibre communications systems provides a method of optimizing the trade-off between the requirements for high OSNR and low nonlinear phase shift [1]. To achieve this, quasi-lossless amplification schemes have been proposed which allow very low signal power variations along the transmission spans [2–6]. Here we further develop this technique by combining, in an optimized manner, one 2nd-order pump at 136X nm and two 1st-order pumps at 14XX nm to achieve simultaneous spectral gain flatness and minimal signal power excursion during transmission. We demonstrate the advantage of the proposed scheme in comparison with only backward pumping and conventional first-order distributed Raman amplification schemes.

2. The proposed amplification system

The schematic of the proposed transmission span shown in Fig. 1 includes two equal power primary pumps around 1366 nm (2nd-order pumping), launched from both ends of a transmission span comprised of single-mode fiber SMF-28e + . Two fiber Bragg grating-reflectors positioned at the ends of the span creates a cavity for radiation in the vicinity of the primary pumps' Stokes peak. The reflectivities of the fiber Bragg gratings (FBGs) are close to 99%. The additional pumping sources (1st-order pumping) around 1420 and 1480 nm are launched from both ends of the cavity in order to extend the low and high wavelength ends of the amplification band around the C band. The particular choice of 1420 and 1480 nm additional pumps here is not a restriction, and is simply due to available results of 3-lambda pumping scheme optimisation presented in [3]. These pumping sources in combination with fiber Bragg gratings creates a 3-wavelength bi-directional distributed Raman amplifier over a wide spectral band from 1520 to 1600 nm. The key idea behind this scheme is to take advantage of the second-order pumping that distributes the gain more uniformly along the transmission span [1–5] and extend it with minimal efforts to a broader spectral interval.

The use of multi-wavelength pumping sources makes it possible to provide a broad gain bandwidth with a good spectral uniformity in addition to low power excursion.

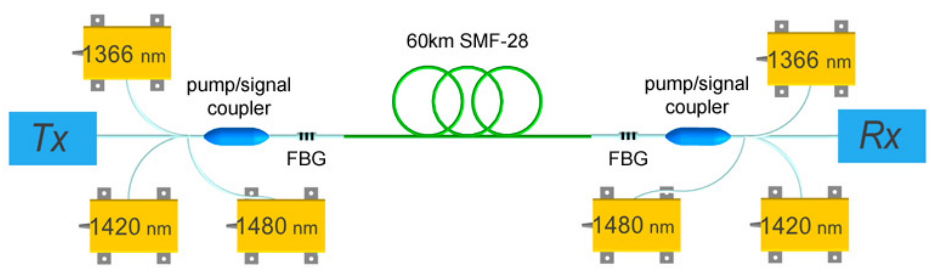

Fig. 1. Schematic of the proposed transmission fiber span set-up.

The central wavelength of the FBGs and pumping powers have all been optimized numerically aiming at minimization of signal power variations over the spatial-spectral window. The optimization algorithm was previously reported to be efficient approach to the design of 3-wavelength discrete (point) Raman backward–pumped Raman amplifiers with increased gain flatness [2]. We extend the method proposed in [3] to the case of distributed amplification.

We demonstrate the feasibility of such configuration and perform numerical analysis clarifying laser operation using average power equations, which take into account all important physical effects, including pump depletion, ASE noise and Rayleigh scattering. Our

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quantitative comparison results are based on a transmission span of 60km, but the proposed technique is applicable to different span lengths.

2. Results and discussion

In this section we present and discuss results of numerical optimization of the proposed amplification scheme in the multi-parametric space of possible pumping powers and wavelengths. We introduce an efficient approach to minimize gain variation over both the amplification bandwidth and distance. In order to find an optimal configuration of the proposed Raman amplification scheme and compare it to other distributed Raman amplification schemes, we introduce first the global (in wavelength and space simultaneously) power excursion parameter $\delta G = | P_s^{\max}(\lambda, z) - P_s^{\min}(\lambda, z) |$ defined as the maximum signal power variation in the whole spatial-spectral window.

As an ultimate goal we aim to approach a transmission media with simultaneous spectral and spatial transparency [1]. By "spectral and spatial transparency" we mean here zero or very small local attenuation across the space-frequency domain. Total pumping power required to overcome signal attenuation must satisfy the condition $1/\Lambda \int P_s(0,\lambda)\, d\lambda = 1/\Lambda \int P_s(L,\lambda)\, d\lambda = 0\, dBm$, where Λ is the signal amplification bandwidth.

The signal distribution in the cross-domain plane depends on the pump wavelengths and total pump powers at each wavelength. We consider system optimization based on the following three dimensionless optimization parameters [2, 3]:

1. The power split between pumping at 1420 nm and 1480 nm is the first optimization parameter. The corresponding non-dimensional parameter $k_1 = (P_{1420} - P_{1480})/(P_{1420} + P_{1480})$.
2. Central wavelength of FBGs is subject to optimization. The pump wavelength around 1366 nm changes with the central wavelength of the FBGs in order to achieve maximum Raman gain and vice-versa. The corresponding non-dimensional parameter $k_2 = (\lambda_{1480} - \lambda_{1420})/(\lambda_{14XX} - \lambda_{1420})$.
3. The third optimization parameter is first order pumping power around 1366 nm. The corresponding dimensionless parameter is $k_3 = P_{13XX}/P_{total}$, where P_{total} denotes the total power of all pumping sources.

In order to find an optimal value of the parameters (k_1, k_2, k_3) in terms of gain flatness and signal power variation along the length of the 60 km transmission span, three-dimensional optimization was implemented using the Nelder-Mead simplex algorithm in Matlab [7,8] where δG serves as an objective function. The results have been obtained for input WDM channels equally spaced over 80 nm amplification bandwidth with 0 dBm average input power per channel. The spectral bandwidth for single channel and its associated noise is equal to 125 GHz. An input OSNR of 50 dB was assumed.

The clear minimum for the objective function δG, which defines an amplitude of the gain ripples, is found using the optimization algorithm. The function δG = 1.8 dB at $k_1 = 0.1$, $k_2 = 0.63$, $k_3 = 0.7$ corresponding to $\lambda_1 = 1369$ nm, $\lambda_2 = 1420.0$ nm, λ_3(FBG) = 1458 nm, $\lambda_4 = 1480.0$ nm, $P_{1370} = 0.35$ W, $P_{1420} = 0.08$ W and $P_{1480} = 0.066$ W. The dependence of δG on the optimization parameters k_1 and k_3 for a fixed $k_2 = 0.64$, and on the parameters k_1 and k_2 for a fixed $k_3 = 0.7$ is shown in Fig. 2. Note that these plots are interesting from a practical implementation point of view, because they show how much impact on δG have pumps power decreases (or increases) or wavelength shifts. The results, shown in Fig. 2, help to estimate how tightly do control the pump powers and pump wavelengths.

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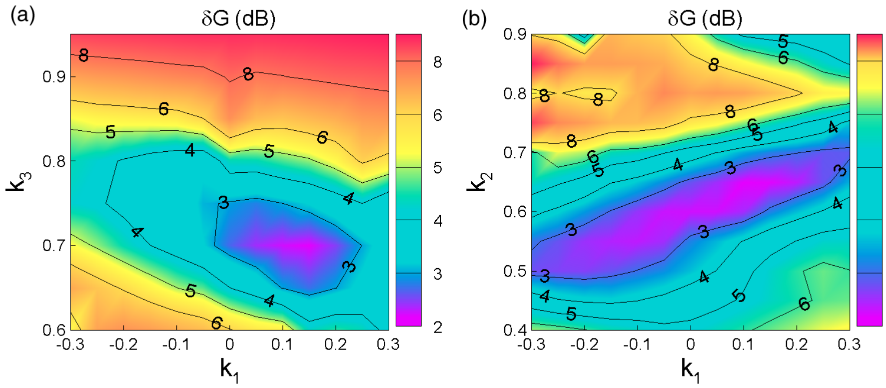

Fig. 2. (a) Contour plot of δG in the plane of optimization parameters (k_1, k_3) for a fixed k_2 = 0.64; (b) Contour plot of δG in the plane of optimization parameters (k_1, k_2) for a fixed k_3 = 0.7.

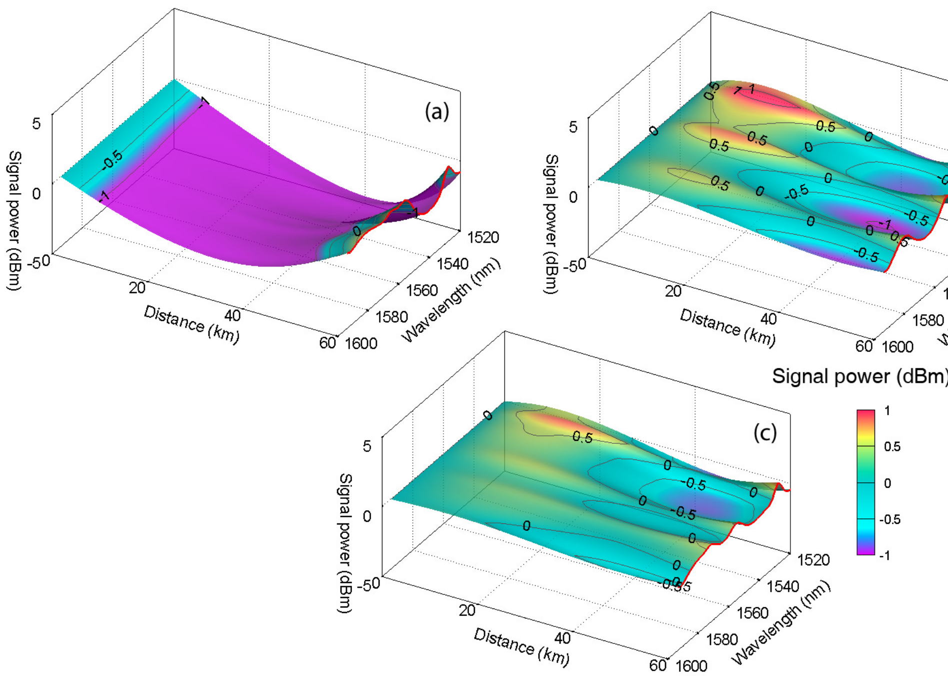

Fig. 3. Numerical signal power excursion in the spectral-spatial plane for 60 km link. The wavelength range is 76 nm (1st-order backward pumping (a), optimized 1st-order bi-directional pumping (b) and hybrid bi-directional pumping (c))

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Table 1. Amplification Schemes and Associated Pparameters

	Scheme	Total power (W)	**Wavelength/power (nm/W)**	**Gain flatness Δ G(dB)**	**OSNR (dB)**	δG **(dB)**
1	1st-order backward pumping (k1 = 0.2817, k2 = 0.5275, k3 = 0.1170	0.55	**1420.0 1457.1 1480.0** 0.31 0.064 0.175	2.29	37.8	5.2
2	1st-order bi-directional pumping (k1 = 0, k2 = 0.34, k3 = 0.24)	0.56	**1420.0 1440.0 1480.0** 0.1 0.068 0.1	1.9	39.87	2.16
3	Hybrid bi-directional pumping (k1 = 0.1, k2 = 0.63, k3 = 0.7)	0.1	**1369.0 1420.0 1480.0 (FBG at 1458 nm)** 0.35 0.08 0.066	1.45	39.9	1.80

The signal evolution in the spectral range from 1520 nm to 1594 nm is shown in Fig. 3 for the three configurations described in Table 1. Note that we also improved performance of the both 1st-order schemes using the described numerical algorithm to determine a location of pump wavelengths and pump powers, that is an important result itself. All the systems under consideration have 125 GHz channel spacing.

It is seen from the Table 1 that a hybrid bi-directional pumping scheme (lower figure in the centre in Fig. 3) shows the smallest signal power excursion along the propagation distance in comparison with conventional 1st-order backward pumping (Fig. 3 left upper corner) and (also optimized) 1st-order bi-directional pumping(right upper figure) schemes. We believe that further optimization and application of various methods in distributed Raman amplification [9–19], [1–5] will make it realistic to approach within a reasonable accuracy a cross-domain transparency in optical fiber spans.

3. Conclusions

In conclusion, a novel design of hybrid (combining 1st and 2nd-order pumping) bi-directional Raman amplification scheme is proposed for simultaneous reduction of the power excursion over propagation distance and improving gain flatness. The proposed scheme was compared to other distributed Raman amplification schemes and has shown the best signal power variation and gain flatness.

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