Quasi-lossless transmission using second-order Raman amplification and fibre Bragg gratings

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Abstract: A novel distributed amplification scheme for quasi-lossless transmission is presented. The system is studied numerically and shown to be able to strongly reduce signal power variations in comparison with currently employed schemes of similar complexity. As an example, variations of less than 3.1 dB for 100 km distance between pumps and below 0.42 dB for 60 km are obtained when using standard single-mode fibre as the transmission medium with an input signal average power of 0 dBm, and a total pump power of about 1.7 W.

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

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1. Introduction

Recent years have seen an increase of the use of distributed Raman amplification in optical fiber transmission links, thanks to the availability of strong Raman pumps. At present, the key trend in the study of distributed amplifiers is the search for the ideal signal power evolution

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within the transmission span [1]. The use of bi-directional pumping schemes [2] with modern, stable pump sources, and the possibility of performing effective core area management (employing dispersion-managed fiber) [3-5], have been studied with the goal of distributing the gain more evenly along the transmission line. Higher-order pumping structures [6,7] can also be used to reduce the variation of the effective gain-loss coefficient along the propagation. A perfectly even distribution of the gain along the propagation distance would lead to ideally lossless transmission. Lossless transmission is not necessarily the optimal solution for every situation, since it can lead to strong nonlinear impairments from relatively low signal powers, but it has been nevertheless a long-term goal of optical communications, as it would bring with it a minimization of the amplified spontaneous emission (ASE) noise build-up. Indeed, if ASE is considered the only contribution to the noise, the fundamental limit for the ratio between optical signal-to-noise ratio (OSNR) and path-averaged signal power is approached as signal power variations along the transmission line are minimized [8]. A quasi-lossless transmission system would be ideal both for systems with very low signal powers (with noise as the main limiting factor) and for systems in which high nonlinearities play a positive role, such as those based on conventional solitons [9].

In this manuscript we propose a novel amplifier scheme that combines second order bi-directional pumping and fiber Bragg grating reflectors to achieve quasi-lossless transmission over long spans. The scheme is shown to significantly reduce the signal power variation over the span as compared to commonly used schemes with the same number of pump sources.

2. Theory and proposed system

In the proposed design, schematically depicted in Fig. 1, two equal power primary pumps around 1366 nm are launched from both extremes of a periodic transmission cell comprised of standard single-mode fiber (SMF). This bi-directional pumping structure is combined with two fiber Bragg grating-reflectors positioned at both ends of the cell. The central wavelength of the gratings is chosen to be 1455 nm, in the vicinity of the primary pumps' Stokes peak, so that the pair of gratings creates a cavity for the radiation at this wavelength. If the primary pumps power is above the threshold necessary to overcome the attenuation of the first Stokes, a stable secondary pump at 1455 nm is generated in the cavity from the ASE noise at this wavelength. This secondary pump, that is used to amplify the signal centred at 1550 nm, presents a nearly constant combined forward and backward-propagating power, and can therefore provide a nearly constant gain that can be adjusted to closely match the signal attenuation at every step of the propagation. The choice of wavelengths in the proposed example has been dictated by the adoption of the typical transmission wavelength of about 1550 nm for our signal. Although a wavelength slightly higher than 1366 nm for the primary pumps would have been desirable in order to maximize the Raman conversion to the 1455 nm component, the proximity of the water peak in the fiber attenuation profile (in the vicinities of 1370 nm) imposes a limitation to our choices.

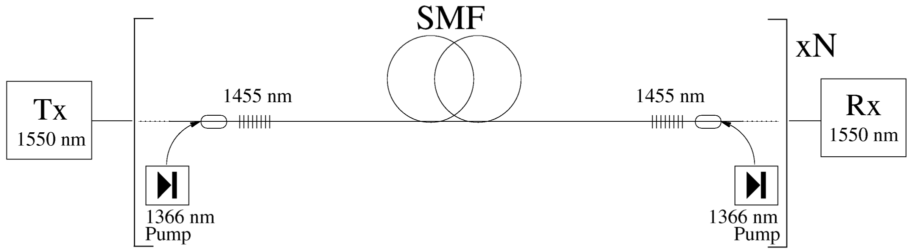

Fig. 1. Schematic depiction of the system.

We note that the proposed scheme is able to accommodate a limited number of wavelength-division multiplexed (WDM) signal channels over the typical nearly flat Raman gain band of about 8 nm, although the effective bandwidth for amplification can be increased to some extent by adequately adjusting the spectral response of the grating reflectors in order

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to control the bandwidth of the 1455 nm pump [10]. The system can be described in terms of average power evolution by the following set of equations [2], which take into account all important effects, including pump depletion, ASE and double Rayleigh scattering (DRS) noise:

$$\frac{dP_{P1}^{\pm}}{dz} = \mp\alpha_1 P_{P1}^{\pm} \mp g_1 \frac{\nu_1}{\nu_2} P_{P1}^{\pm}\left(P_{P2}^{+} + P_{P2}^{-} + 4h\nu_2\Delta\nu_2 (1+\frac{1}{e^{h(\nu_1-\nu_2)/K_BT}-1})\right) \pm \varepsilon_1 P_{P1}^{\mp} \tag{1}$$

$$\frac{dP_{P2}^{\pm}}{dz} = \mp\alpha_2 P_{P2}^{\pm} \pm g_1\left(P_{P2}^{\pm} + 2h\nu_2\Delta\nu_2 (1+\frac{1}{e^{h(\nu_1-\nu_2)/K_BT}-1})\right)(P_{P1}^{+} + P_{P1}^{-})$$

$$\mp g_2 \frac{\nu_2}{\nu_S} P_{P2}^{\pm}\left(P_S + N_S^{+} + N_S^{-} + 4h\nu_S\Delta\nu_S (1+\frac{1}{e^{h(\nu_2-\nu_S)/K_BT}-1})\right) \pm \varepsilon_2 P_{P2}^{\mp} \tag{2}$$

$$\frac{dP_S}{dz} = -\alpha_S P_S + g_2 P_S (P_{P2}^{+} + P_{P2}^{-}) \tag{3}$$

$$\frac{dN_S^{+}}{dz} = -\alpha_S N_S^{+} + g_2\left(N_S^{+} + 2h\nu_S\Delta\nu_S (1+\frac{1}{e^{h(\nu_2-\nu_S)/K_BT}-1})\right)(P_{P2}^{+} + P_{P2}^{-}) + \varepsilon_S N_S^{-} \tag{4}$$

$$\frac{dN_S^{-}}{dz} = \alpha_S N_S^{-} - g_2\left(N_S^{-} + 2h\nu_S\Delta\nu_S (1+\frac{1}{e^{h(\nu_2-\nu_S)/K_BT}-1})\right)(P_{P2}^{+} + P_{P2}^{-}) - \varepsilon_S (P_S + N_S^{+}) \tag{5}$$

Here, the (+) and (-) superscripts represent forward and backward propagation respectively, the 1, 2, and S subscripts identify the first-order pump, second-order pump and signal respectively, P_{Pi} are the pump powers, P_S are the signal powers and N_S are the noise powers at the frequency of the signal, the v_i are the corresponding frequencies of the pumps and signal, the Δv_i represent the effective bandwidths of the secondary pump and the signal (limited, in the case of the secondary pump, by the bandwidth of the fiber Bragg gratings), the g_i are the corresponding Raman gain coefficients (divided by the effective area) for each of the Raman transitions, the α_i are the fiber attenuations at each respective frequency, h is Plank's constant, K_B is Boltzmann's constant, T is the absolute temperature of the fiber and the ε_i are the double Rayleigh scattering coefficients of the fiber at each particular frequency.

The boundary conditions for the problem defined in Eqs. (1) – (5) are:

$$P_{P1}^{+}(0) = P_{P1}^{-}(L) = P_0;\, P_{P2}^{+}(0) = R_1 P_{P2}^{-}(0);\, P_{P2}^{-}(L) = R_2 P_{P2}^{+}(L);\, N_S^{+}(0) = N_0;\, N_S^{-}(L) = 0;\, P_S(0) = P_{IN} \tag{6}$$

where R_1 and R_2 are the reflectivities of the fiber Bragg gratings at the beginning and end of the periodic cell respectively (typically close to 99%), and L is the length of the transmission span. The model safely assumes that the effect of frequencies far from the first and second Stokes of the primary pump can be considered negligible, and that the contribution from ASE and DRS is purely noisy.

In the particular examples considered here, the transmission span consists of SMF. In order to use the quasi-lossless SMF cell in a dispersion-managed system, group velocity dispersion could be periodically compensated with chirped low-loss Bragg gratings or dispersion-compensating fiber (DCF) sections placed between transmission cells. Amplification inside each DCF might be performed using a similar quasi-lossless scheme, to maintain a minimal signal variation. Alternatively, the SMF transmission cell alone can be repeated periodically for use in conventional soliton-based transmission systems.

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Table 1. Characteristics of the SMF

λ (nm)	g ($W^{-1}km^{-1}$)	α (dB km^{-1})	ε (km^{-1})
1366	0.53	0.38	1.0×10^{-4}
1455	0.43	0.27	6.0×10^{-5}
1550	-	0.19	4.3×10^{-5}

3. Results and discussion

The evolution of the signal, pumps and noise powers along the cell is obtained by solving numerically Eqs. (1)-(5) with boundary conditions (6), at room temperature (25 °C) and typical values for the various SMF parameters, which are detailed in table 1. The pumps are assumed to be depolarized, so the gain coefficients that appear on the table correspond to this case (i.e., have been multiplied by a factor ½). The bandwidth of the fiber gratings is assumed to be 125 GHz. It is worth noting that the resolution of the equations shows that the threshold condition for the generation of the secondary pumps is satisfied in all the cases considered in the manuscript. As an example of the performance that can be expected from the proposed system, Figs. 2(a) and 2(b) show the evolution of the pumps, signal and noise powers for two different lengths of the periodic cell, for the case of a single-channel input signal with 0 dBm average power at 1550 nm. The variation of the signal power over 100 km (2(b)) is very small (3.08 dB), even smaller for 80 km (1.4 dB) and it becomes nearly negligible (0.418 dB) for 60 km propagation distance between pumps (2(a)). The noise term in Fig. 2 corresponds to the integrated power of the forward-propagating noise over a 1 nm bandwidth centered at 1550 nm.

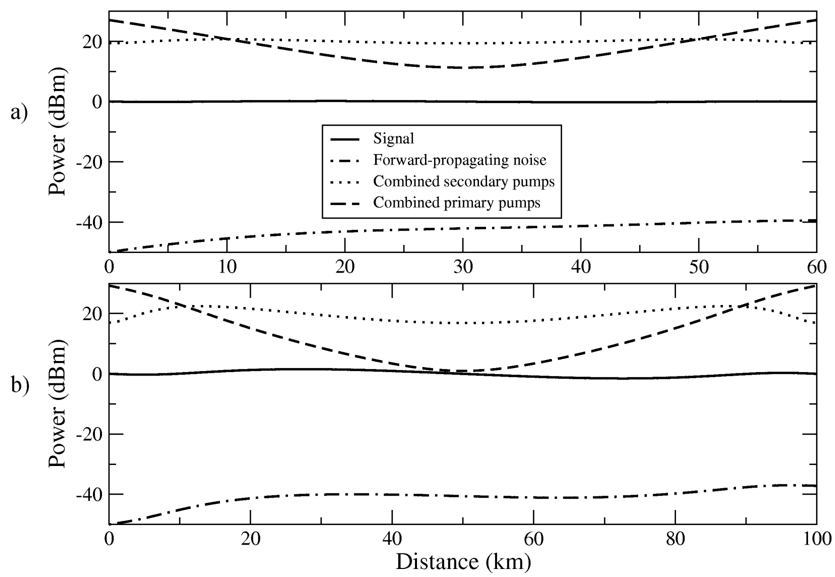

Fig. 2. (a) Pumps, signal and noise evolution inside the cell for a 60 km cell length. (b) Pumps, signal and noise evolution inside the cell for a 100 km cell length.

The improved performance of the proposed scheme with respect to other typical configurations can be seen in Fig. 3, which shows the signal evolution in an 80 km transmission cell for the cases of single backward pumping, bi-directional first order pumping and the proposed scheme. The total power variation during the propagation vs. the length of the periodic cell (i.e., distance between two laser pumps) for the proposed scheme, both for a single channel and for 8 WDM channels equally spaced over 8 nm (equally spaced at both

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sides of 1550 nm) with 0 dBm average input power per channel, is shown in Fig. 4, together with the variation for the case of a first-order bi-pumped single-channel scheme. The fiber characteristics are assumed to be the same for all the channels. As a result of the second order pumping structure, the conversion efficiency between the primary pump and the signal is lower than in the case of direct pumping, but the pump power required is still well within the reach of typical commercial pump lasers. Indeed, 100 km signal transmission requires a power of 849 mW per pump, in the case of a single channel, and of 893 mW in the case of 8 channels.

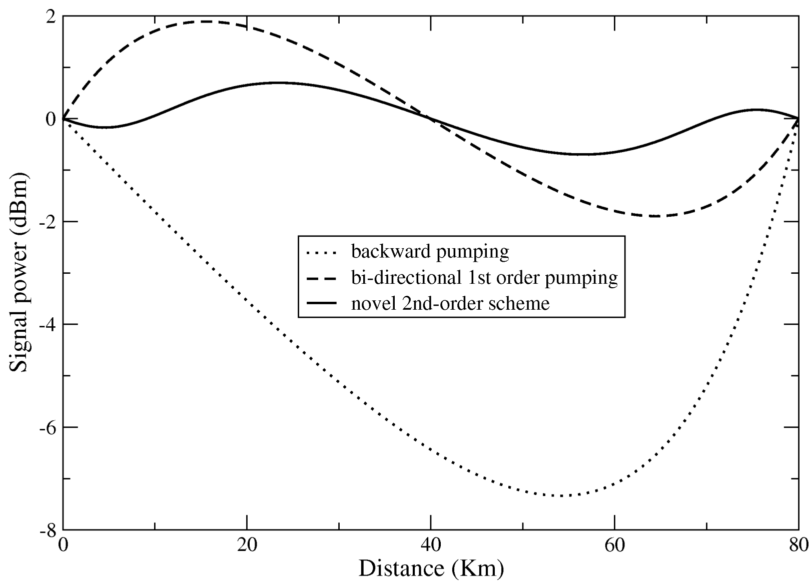

Fig. 3. Signal power evolution in the transmission cell for different amplifying solutions, for a cell length of 80 km.

Thanks to the increased gain flatness obtained during the propagation, the noise performance is excellent, being slightly better than in the case of bi-directional first order pumping. For an input OSNR of 50 dB, the OSNR (assuming a 125 GHz spectral bandwidth for each signal channel and its associated noise, and 0 dBm per channel for the input signal) at the end of the first cell for the 100 km case is found to be 37.19 dB, whereas an optimised first-order bi-directional pumping scheme provides an output OSNR of 36.85 dB. The difference in performance between the single-channel and the multi-channel case, which is already very small in terms of power variation, is actually negligible in terms of output OSNR. System performance is also polarization independent, thanks to the use of depolarized pumps. The system is robust against temporal cell length variations in the cavity length, too. Extreme variations of up to 100 m in 100 km cause output power variations smaller than 0.05 dB, that can be corrected by varying the pump power in 1 mW. The presence of a large number of longitudinal modes (of the order of 100 million) for the secondary pump within the gain bandwidth of 1 nm delimited by the fibre Bragg gratings, means also that the system does not suffer power fluctuations due to mode sweeping caused by cavity length variations of the order of the secondary pump wavelength.

We note that, in the considered examples, an equal split of the initial pump powers is the best choice, since the natural symmetry of the problem is not broken by a strong depletion of the secondary pump. This increases the easiness of operation because, if the power of the primary pumps is adjusted so that we totally compensate for the signal attenuation in the periodic cell, a nearly constant secondary pump and thus quasi-lossless transmission of the signal are guaranteed by construction. If the input signal power is increased, pump depletion

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eventually becomes noticeable and the power split between the primary pumps may therefore have to be made asymmetric, or alternatively the reflectivities of the fiber gratings adjusted, in order to keep the power of the secondary pump as stable as possible along the periodic cell. However, the effect that an increase of the signal power has on the optimal configuration is small, and the performance for input signal powers as high as 15 dBm can still be considered optimized with a symmetric pump power split, although of course the performance of the amplifier in terms of the gain variation over a distance and of total required pump power degrades as the input signal power increases.

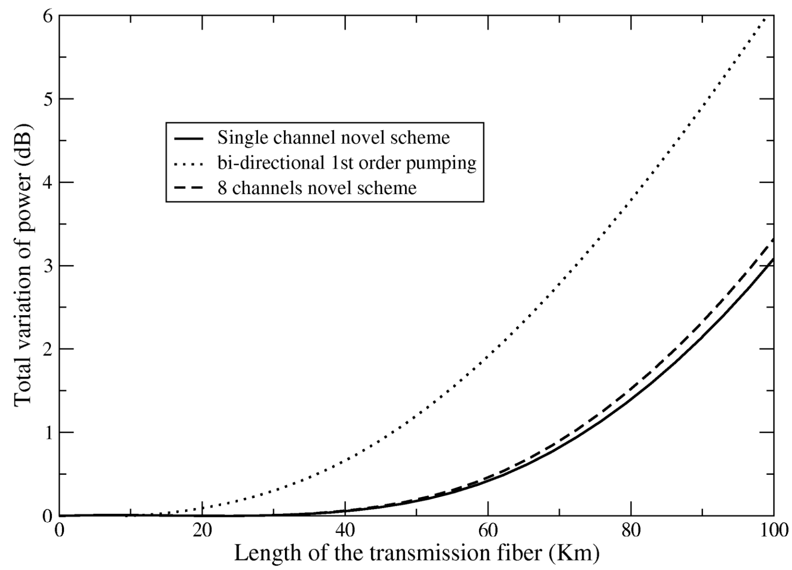

Fig. 4. Signal power variation vs. cell length for single and multiple channels. The dotted line corresponds to direct first order bi-directional amplification.

The results obtained with this scheme can be reproduced by a more-complex four pump configuration, similar to the one in [6], in which the grating cavity would be replaced by two additional Raman pumps at 1455 nm. Nevertheless, the solution presented in this manuscript offers a simpler design, which translates into reduced costs and eliminates the necessity for careful adjustment of the secondary pumps powers. Not only that, but it also allows for the generation of a spectrally broader secondary pump, which may be useful for application in WDM transmission. Its reliance on conventional transmission fibre also sets this system apart from options based on distributed EDFA [11,12], that would undoubtedly provide excellent performances, but at a cost that rules out their application to long-haul transmission.

4. Conclusion

In conclusion, a novel design that promises to deliver quasi-lossless transmission over conventional fibre has been presented. Its performance has been compared to that of other typical currently used schemes and shown to be superior in terms of gain variation over the transmission distance. More complex schemes, making use of multiple primary pumps and able to amplify in a broad band are possible, and will be the subject of further study.

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