Signal Power Asymmetry Optimisation for Optical Phase Conjugation Using Random DFB Laser Raman Amplification

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Abstract: We numerically optimise in-span signal power asymmetry in advanced Raman amplification schemes, reaching 3% over 62 km SMF, and evaluate its impact on the performance of systems using mid-link OPC using 7×15 16QAM Nyquist-spaced WDM-PDM.

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1. Introduction

The nonlinear-Shannon limit sets a cap to maximum capacity in single mode optical fibres [1]. To combat fibre nonlinear effects, using mid-link [2] or transmitter-based [3] optical phase conjugation (OPC) enables real time compensation of all deterministic (signalsignal) nonlinear impairments. However, the degree of nonlinear compensation using mid-link OPC is related to the symmetry match of the conjugated and transmitted signal power evolution in the fibre. Meaningful performance improvement has only been demonstrated in Raman-based amplification optical links [4], thanks to the better control over signal symmetry provided by distributed amplification, as well as its improved noise performance. The key to maximise performance in OPC-assisted systems, lies in reducing signal power asymmetry within the periodic spans while ensuring a low impact of noise and non-deterministic nonlinear impairments in the overall transmission link.

In this paper, we demonstrate, using proven numerical models, that almost ideally symmetrical signal power evolution can be achieved in advanced distributed amplification schemes, with the best results obtained for half- open-cavity random distributed feedback (DFB) Raman laser amplifier with bidirectional 2nd order pumping [5]. This setup allows to potentially reduce signal power evolution asymmetry inside the span with respect to its middle point to a mere 3% over a realistic span of length- 62 km SMF, which constitutes the highest level of symmetry achieved up to date on such a long span. Furthermore, in order to investigate the best practical Raman-based link design and the potential impact of the reduced signal power asymmetry, we consider 7×15 Gbaud-16QAM Nyquist WDM transmission with mid-link OPC using random DFB Raman laser amplification, and numerically investigate system performance dependence on power asymmetry levels. The optimal transmission performance with forward and backward pump power ratio close to 1 is obtained for the setup that combines the highest level of symmetry with low non-deterministic impairments.

2. Raman amplification schemes

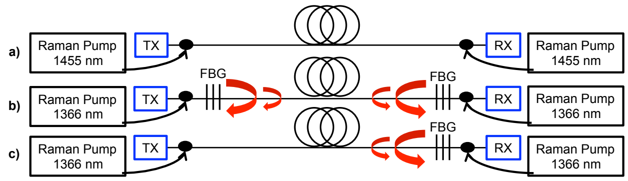

Fig. 1. Schematic design of 1st order Raman amplifier (a), 2nd order URFL amplifier (b) and random DFB Raman laser amplifier (c).

In our search for an optimal setup for OPC we consider three different amplification schemes with highly depolarised pumps, namely: - a conventional 1st order Raman amplifier bi- directionally pumped from both ends of the transmission span at 1455 nm, with the signal being amplified via the first Stokes shift (Fig.1a), - a cavity ultra-long Raman fibre laser (URFL) amplifier [6], depicted in Fig. 1b, that provides 2nd order amplification from single wavelength bidirectional pumps at 1366 nm. These pumps provide gain to the signal at 1550 nm via the cascade of two Raman Stokes in a cavity delimited by high reflectivity (99%) FBGs centered at 1455 nm with a 200 GHz bandwidth.

The advantage of this model is that the gain bandwidth and profile can be modified by selecting appropriate FBGs rather than deploying a seed at different wavelength. In this case the reflectivity of the FBGs was chosen high to provide better pump-to-signal power conversion efficiency. - a random DFB laser Raman amplification scheme (Fig. 1c), which is similar to the closed- cavity URFL, but uses an half-open cavity with a single FBG deployed at the end of the transmission span, relying on Rayleigh backscattering to provide feedback to the first Stokes in the forward direction. The lack of an FBG on the side of the forward pump significantly reduces RIN transfer from the forward pump to the Stokes-shifted light at 1455 nm at the cost of a reduction in the power efficiency conversion compared with the 1st order and URFL schemes.

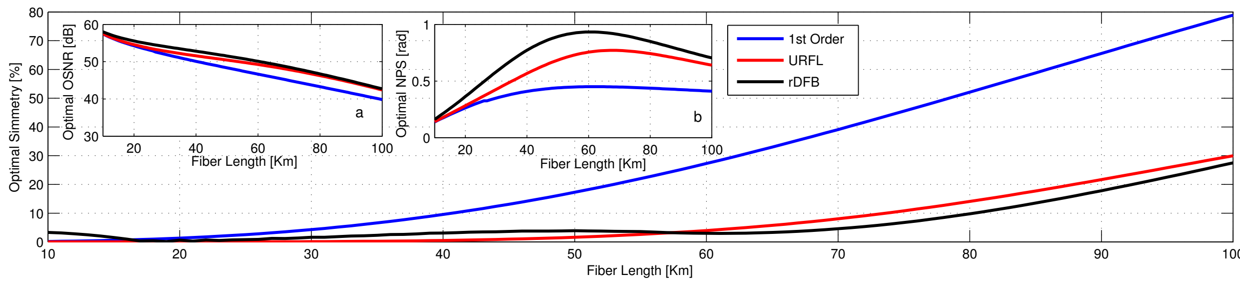

Fig. 2. Lowest signal power asymmetry for a given length and amplification setup. Insets show the corresponding best OSNR (a) and accumulated signal Nonlinear Phase Shift (b).

3. Signal Power Symmetry

Signal power excursion for different pump power ratios and span lengths in Raman amplifiers was simulated using the experimentally verified [5] model [6] with an appropriate boundary conditions that shows a high degree match with the OTDR traces. In all cases considered the Raman pumps are fully depolarised. Standard SMF-28 fibre was considered in the simulations. To compare signal power symmetry in the proposed configurations, single-channel launch power into the transmission span was fixed to 0 dBm (we simulated launched powers of -10, 0 and 4 dBm as well as FBGs reflectivities of 50% and 70% but found no significant improvement to the signals symmetry). For each forward pump power (FPP) (100 mW step), the backward pump was simulated to give 0 dB net gain for the span lengths from 10 to 100 km. Signal power asymmetry within the span was determined as in [7]

$$Assymetry = \frac{\int_0^{L/2} |P(z) - P(L-z)| dz}{\int_0^{L/2} P(z) dz} \times 100 \tag{1}$$

where L is the span length and P represents average signal power evolution.

Figure 2 summarises some of the most relevant span optimisation results. The lowest asymmetry values and highest signal OSNRs for all span lengths above 58 km were achieved with random DFB laser based amplification. Note that optimal symmetry in 1^{st}-order amplification is found for backward pumping only. For URFL, optimal forward/backward power ratios are very close to 1 for spans of up to 50 km, but the optimal contribution of backward pumping grows for longer span lengths (forward/backward ratio of 0.27 at 100 km), whereas the random DFB configuration favours backward pumping at short lengths up to 30 km, but ratios close to 1 for longer spans. Considering the symmetry results and its better resiliency to forward- pumping RIN in coherent transmission applications [5], the bi- directionally pumped random DFB laser with a single grating seems to be the best option, performance-wise, for amplification in long spans with OPC, even if it shows more accumulation of NPS prior to compensation (Fig. 2b) and higher pump power requirements (2.5 W for 62 km, as opposed to 1.2 W for the URFL and 0.44 W for 1^{st} order). Signal power asymmetry in the random DFB laser Raman amplifier vs. span length and FPP for the optimal backward pumping is shown in Fig. 3. The "sweet spot" is found to be at 62 km with the signal power asymmetry of only 3%, for a symmetrical forward/backward pump power split of 1.2 W, respectively. Considering these results, random DFB laser Raman amplification over 62 km SMF-28 was chosen for the transmission simulations. In this scheme, the same asymmetry level can be achieved using two different values of the FW pump power, which allows us to further study the design principle considering both ASE noise and nonlinearity compensation.

4. Numerical Model

To investigate the impact of signal power symmetry on the performance of systems employing mid-link OPC, we simulated the transmission of 7 × 15 Gbaud 16QAM Nyquist- spaced WDM PDM signals. For each channel and polarisation, a random binary sequence of length 218 was first mapped into the complex plane using 16QAM, over-sampled by a factor of 20 and then passed through a Nyquist filter to generate a Nyquist-shaped signal. The filter length was 128 and the baudrate was 15Gbaud. After polarisation combining, the WDM channels were multiplexed with a channel spacing equal to the baudrate. The transmission link consisted of 40 Raman loops and an OPC placed in the middle, after the 20^{th} loop. The propagation of signal in the fibre was simulated using a split-step Fourier method, with a step size of $\sim$1 km considering the simulated gain and noise profiles. At the receiver, the channel under test (central) was coherently detected, the received signal was resampled and then the Q^2 factor was estimated though EVM.

5. Transmission results and discussion

We simulated the performance of OPC-assisted system with random DFB amplifier for all pump power split ratios at 62 km. To show the true impact of the asymmetry on the OPC system we considered the case with fixed noise power (the worst OSNR case, that is backward pumping only, Fig. 3b(blue)) as well as the actual noise power in each configuration (Fig. 3b(red)). There is a perfect match of the pump powers ratio requirement for the optimum signal power symmetry in 62 km link (Fig. 2) and the Q-factor performance of the investigated OPC-assisted system that is 1.2 W for the forward and the backward pump. The optimum Q-factor as a function of FPP (BPP was fixed to give 0 dB net gain) is shown in Fig. 3b. We can notice that when the noise is fixed, the optimum Q-factor varies by 5 dB, showing clearly that the symmetry of the signal power evaluation has a significant impact on the performance of OPC- assisted system. In the case of actual noise power, the optimum symmetry level offers an additional of 3 dB performance gain in comparison with the backward pumping only case, indicating the importance of the optimisation task performed in this work.

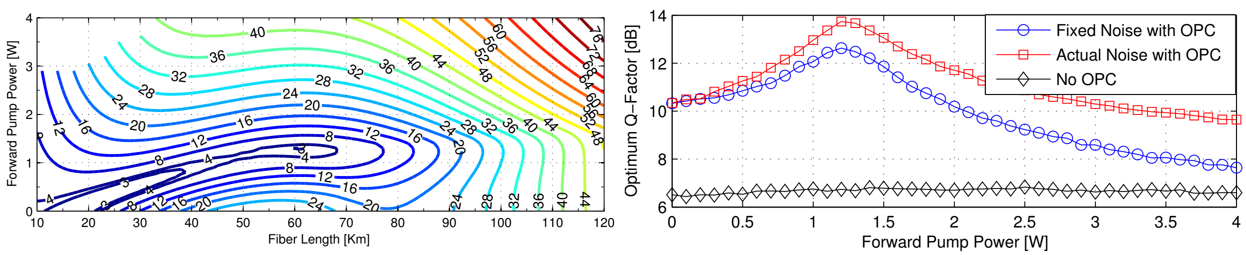

Fig. 3. Signal power asymmetry in the random DFB Raman amplifier as a function of span length and forward pump power (a) and optimum Q-factor in 62 km link (b).

6. Conclusion

We have evaluated the impact of signal power symmetry on transmission performance in Raman-amplified systems with mid-link OPC. We verify, using 7×15 16QAM Nyquist-spaced WDM PDM signals, that the minimisation of asymmetry up to a 3% using a random DFB Raman amplifier over a 62 km span, leads to optimal transmission performance.

7. Acknowledgement

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