Signal power asymmetry optimisation for optical phase conjugation using Raman amplification

Signal power asymmetry optimisation for optical phase conjugation using Raman amplification

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Abstract: We numerically optimise in-span signal power asymmetry in different advanced Raman amplification schemes, achieving a 3% asymmetry over 62 km SMF using random DFB Raman laser amplifier. We then evaluate the impact of such asymmetry on the performance of systems using mid-link OPC by simulating transmission of 7×15 Gbaud 16QAM Nyquist-spaced WDM-PDM signals.

OCIS codes: (060.1660) Coherent communications; (060.2320) Fiber optics amplifiers and oscillators; (060.4370) Nonlinear optics, fibers.

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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 (signal×signal) nonlinear impairments. However, the degree of nonlinear compensation using mid-link OPC is related to the asymmetry 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 asymmetry 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 letter, 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 [5–7]. 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 length of 62 km SMF, which constitutes the lowest asymmetry level achieved up to date on such a long span [8]. 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 simulated transmission with mid-link OPC using random DFB Raman laser amplifier, 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 lowest level of asymmetry with low non-deterministic impairments.

2. Distributed Raman amplification schemes

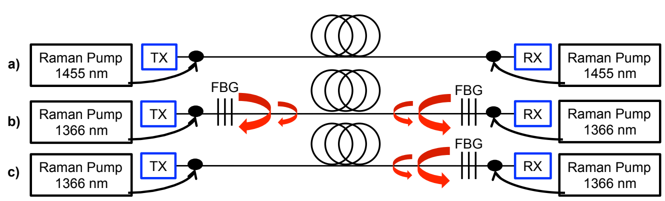

Fig. 1. Schematic design of 1st order Raman (a), 2nd order URFL (b) and 2nd order random DFB Raman laser amplifiers (c).

In our search for an optimal setup for OPC we consider three different bi-directional distributed Raman amplification schemes. In each configuration, signal power excursion for different pump power ratios and span lengths was simulated using the experimentally verified [5] model with an appropriate boundary conditions that is fully described in [7, 9]. Simulations are performed at room temperature with the assumption that Raman pumps at 1366 nm are fully

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depolarised. The noise was calculated in a bandwidth of 0.1 nm. The Raman gain and attenuation coefficients at the laser wavelength were obtained from measured gain and attenuation curves for standard SMF silica fibre [7], respectively. The values of the Rayleigh backscattering coefficients at pump wavelength at 1366 nm, lasing at 1455 nm and the frequency of the signal are assumed to be 1.0×10^{-4}, 6.5×10^{-5} and 4.5×10^{-5} km^{-1}, respectively.

2.1. 1^{st} -order Raman amplifier

The conventional 1^{st} order Raman amplifier [Fig. 1(a)] is bi- directionally pumped from both ends of the transmission span at 1455 nm, with the signal being amplified via the first Stokes shift.

2.2. 2^{nd} -order ultra-long Raman fibre laser amplifier

The configuration of an ultra-long Raman fibre laser (URFL) amplifier [Fig. 1(b)] allows achieving 2^{nd} order pumping with a single wavelength pump [9]. To form a distributed 2^{nd} order URFL amplifier, Raman fibre laser pumps are downshifted in wavelength by two Stokes with respect to the frequency of the signal. High reflectivity (99%) FBGs centered at 1455 nm with a 200 GHz bandwidth were deployed at the beginning and the end of the transmission line to reflect Stokes-shifted light from the pumps at 1366 nm and, once the threshold of about 0.8 W is reached, form a stable ultra-long lasing acting as a 1^{st} order pump that amplifies the signal. The advantage of this model is that the gain bandwidth and profile can be modified by selecting appropriate FBGs rather than deploying an active seed at different wavelength. In this case the reflectivity of the FBGs was chosen high to provide better pump-to-signal power conversion efficiency.

2.3. 2^{nd} -order random DFB Raman laser amplifier

The schematic design of the random DFB Raman laser amplifier [Fig. 1(c)] is similar to that of an URFL with the difference that instead of using a closed cavity with a pair of FGBs, a single high reflectivity FBG at 1455 nm (we also simulated FBGs reflectivities of 50% and 70% but found no significant improvement to the signals symmetry) is deployed at the end of the transmission span to reflect backscattered Rayleigh Stokes-shifted light from the backward pump at 1366 nm and form a random DFB laser [10] at the frequency specified by the wavelength of the FBG. The lack of an FBG on the side of the forward pump reduces the RIN transfer [11] from the forward pump to the Stokes-shifted light at 1455 nm at the cost of a reduction in the power efficiency conversion in comparison to the 1^{st} order Raman and URFL amplification schemes. This is particularly important, as forward-pumping RIN transfer from inherently noisy high-power pumps can seriously hinder data transmission [12, 13].

3. Signal power asymmetry in distributed Raman amplifiers

To compare signal power asymmetry in the proposed configurations, we simulated a single-channel in the middle of the C-band at 1545 nm with the fixed launch power (0 dBm) into the transmission span. 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 [14]

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

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

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random DFB Raman laser amplification. Note that optimal asymmetry in 1st-order Raman 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. Figure 2(b) shows accumulated residual phase shift (a product of an optimal asymmetry at a given distance and corresponding nonlinear phase shift).

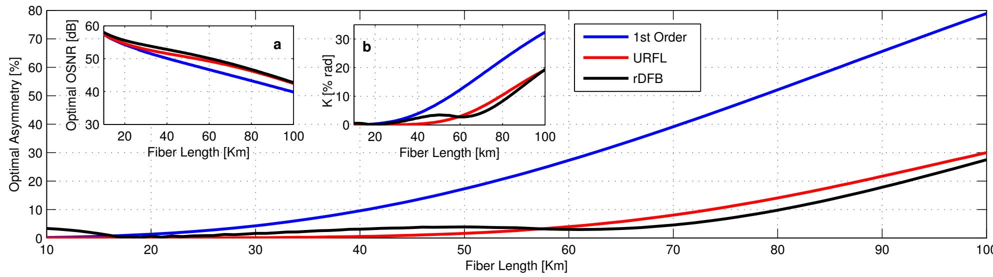

Fig. 2. Lowest signal power asymmetry for a given length and amplification setup. Insets show the corresponding best OSNR (a) and the accumulated residual phase shift (b).

The asymmetry (Fig. 2), an OSNR [Fig. 2(a)], residual phase shift [Fig. 2(b)] results and its better resiliency to forward- pumping RIN in coherent transmission applications [5], shows that 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. Considering these results, random DFB Raman laser amplifier was chosen for the further characterisation study.

4. Characterisation of random DFB Raman laser amplifier for a transmission with OPC

The asymmetry of the signal power evolution in the transmission fibre using random DFB Raman laser amplifier with span lengths up to 120 km as a function of FPP with the optimal backward pumping is shown in Fig. 3(a). The ”sweet spot” is found to be at 62 km with the signal power asymmetry just below 3%, for a symmetrical forward/backward pump power split. In this scheme, the same asymmetry level can be achieved using two different values of the FPP, which allows us to further study the design principle considering both ASE noise and nonlinearity compensation. The optimal forward/total pump power (FPP/TPP) ratio in each case as a function of forward pump power values is shown in Fig. 3(b). To visualise the signal power distribution at different lengths, example power evolution profiles for 62 km and 100 km spans are shown in Fig. 4.

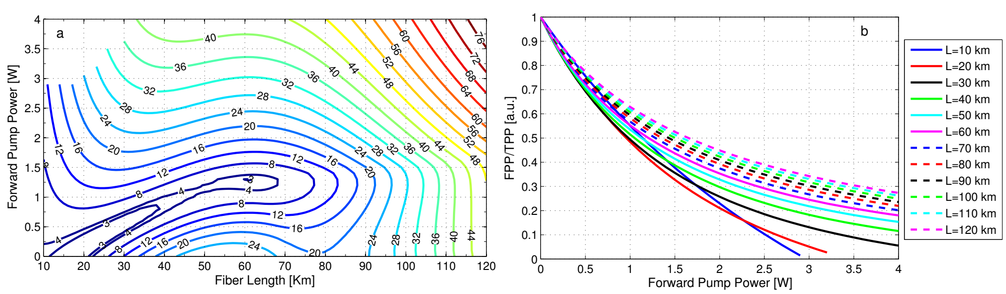

Fig. 3. Signal power asymmetry as a function for different span lengths and FPP (a) and the optimal forward/total pump power (FPP/TPP) ratio as a function of FPP (b).

Signal power asymmetry as a function of a single channel launch power is shown in Fig. 5 (left). The asymmetry is pretty constant with the launch powers up to 5 dBm and increases

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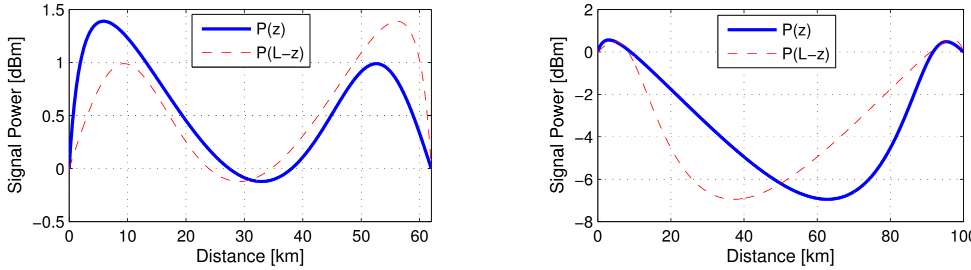

Fig. 4. Power evolution profiles for configurations with minimal power asymmetry corresponding to 62 km (left) and 100 km (right) periodic spans.

steadily after that. To simulate the impact of the pump depletion on the signals asymmetry in dense WDM (DWDM) transmission, the pump powers were optimised for a central channel at 1545 nm to give 0 dB net gain and the number of 25 GHz spaced WDM channels (0 dBm per channel) was incremented. The DWDM channel provisioning started in the centre of the C-band at 1545 nm, with subsequent channels being added in either side in the band centre building out towards both ends of the band. The results for the asymmetry in DWDM transmission up to 42 channels assisted with the random DFB fibre laser amplifier are shown in Fig. 5 (right). The results in Fig. 5 shows great asymmetry tolerance to increased launch power and pump depletion using random DFB Raman laser amplifier in OPC assisted DWDM transmission.

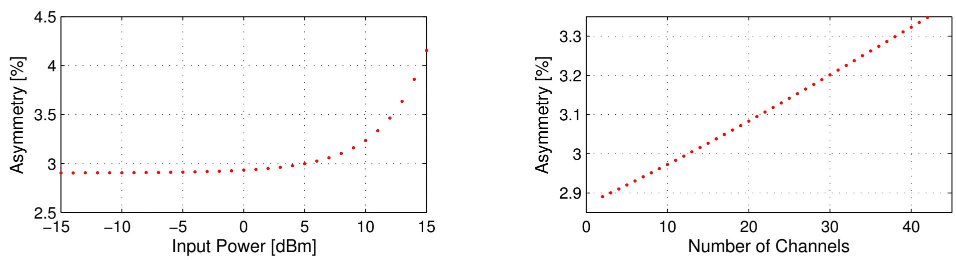

Fig. 5. Signal power asymmetry as a function of a single channel launch power (left) and the number of the WDM channels in 62 km (right).

5. Modeling the 7×15 Gbaud 16 QAM transmission with an OPC

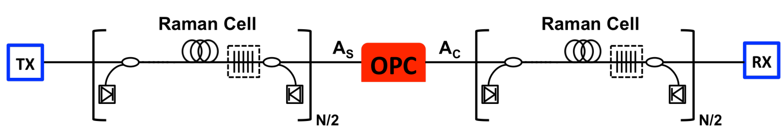

Fig. 6. Schematic design of a OPC system.

To investigate the impact of signal power asymmetry on the performance of system employing mid-link OPC (Fig. 6), we simulated the transmission of 7×15 Gbaud 16 QAM 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 16 QAM, oversampled 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 15 Gbaud. 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 well- known 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.

6. Simulation results and discussion

We simulated the performance of an OPC-assisted system (Fig. 6) 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. 7(a)) as well as the actual noise power in each configuration [Fig. 7(b)]. There is a perfect match of the pump powers ratio requirement for the optimum signal power asymmetry in 62 km link (Fig. 3) 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 simulated to give 0 dB net gain) is shown in Fig. 8. We can notice that when the noise is fixed, the optimum Q-factor varies by 5 dB, showing clearly that the asymmetry of the signal power evaluation has a significant impact on the performance of an OPC- assisted system. In the case of actual noise power, the optimum asymmetry level offers an additional 3 dB performance gain in comparison with the backward pumping only case, indicating the importance of the optimisation task performed in this work.

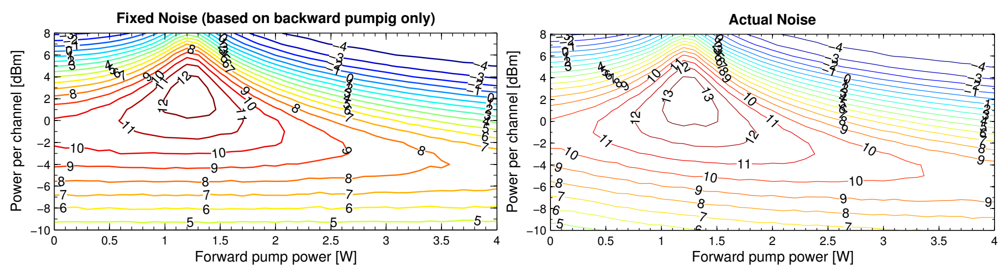

Fig. 7. Q-Factor vs. launch power with the fixed noise based on backward pumping only configuration (left) and the actual noise (right). The backward pump power was simulated to give 0 dB net gain.

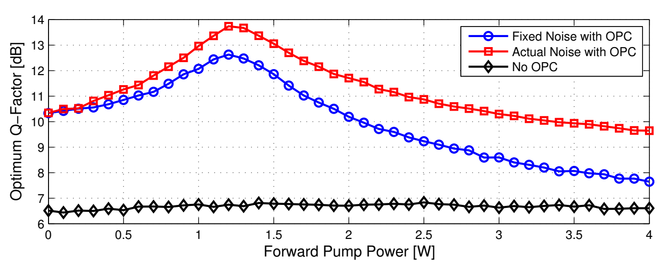

Fig. 8. Optimum Q-factor at different forward pump powers in 62 km link.

7. Conclusion

We have evaluated the impact of signal power asymmetry on transmission performance in Raman-amplified systems with mid-link OPC. We have shown that random DFB Raman laser amplifier is the most suitable solution for OPC-assisted WDM systems using span lengths between 60 and 100 km. Through simulations, we have verified, using 7×15 16QAM Nyquist-spaced WDM PDM signals, that the minimisation of asymmetry up to a 3% over a 62 km span leads to greatly improved transmission performance, improving Q-factor by 5 dB.

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