FBG Reflectivity Impact on RIN in Ultralong Laser Amplifiers

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Abstract *We analyse, both numerically and experimentally, the Relative Intensity Noise transfer in ultra-long Raman laser amplifiers isolating the combined effect of front-FBG reflectivity and pump power split and quantitatively showing their impact on a 100 km, 2nd-order, bidirectionally pumped configuration.*

Introduction

Limiting amplified spontaneous emission noise build-up is of primary importance in high capacity/long distance optical communication systems. High-order distributed amplification schemes based on ultra-long Raman fibre laser[1] (URFL) architectures have proven suitable for this purpose, thanks to a flatter signal power excursion, allowing for improved optical signal-to-noise ratios (OSNRs). This amplification solution has proven its potential in long-haul transmission, even allowing for capacities above the nonlinear Shannon limit in combination with optical phase conjugation[2]. However, the benefits from OSNR improvement in URFLs can be easily offset by the impairments caused by relative intensity noise (RIN) transfer from the forward pump to the signal. This problem worsens when high power forward pumping is combined with a high reflectivity fibre Bragg grating (FBG) at the front-end of the ultralong cavity[3,4]. We have recently shown[5] how reflectivity levels as low as 10% at the input end of a URFL amplifier result in a Q penalty of about 1 dB in a 30 GBaud PM-QPSK transmission system. This penalty is associated with the transition from a random lasing regime to well structured cavity lasing. Here we extend our study of the impact of reflectivity on RIN transfer through a detailed analysis of the signal RIN based on experimental measurements and numerical simulations. Our analysis takes into account the contribution of relevant effects not previously considered, such as effective reflectivity variation due to Stokes broadening and temperature-induced FBG shift or pump RIN variability.

Experimental setup

Fig. 1. shows a schematic diagram of our 2nd order URFL. 100 km of ITU G.652 fibre are bi-directionally pumped by two fully depolarized fibre lasers emitting at 1366 nm. Two wavelength division multiplexers (WDM) couple/split signals at three different wavelengths: the pump, a -10 dBm signal at 1550 nm and a Stokes wave at the 1455nm central wavelength of the high reflectivity FBG. The front-end reflections from a variable reflectivity module (VRM) were fed back into the cavity through the WDM. The VRM was built from a high reflectivity (>95%) FBG and a variable optical attenuator (VOA) placed at the 1455 nm output of the input side WDM. Lastly, two 99/1 splitters inserted inside the span allow for the direct measurement of the back reflection levels for each pumping configuration. VOAs are used at both pump lasers outputs to adjust forward (FW) and backward (BW) pump power individually and concurrently keep the output power and, thus, the output RIN of the pump lasers fixed. By doing so we ensure that any observable change in the signal RIN is to be ascribed exclusively to the combined effect of the reflectivity and pump power ratio and not to a change on the RIN levels of the pumps themselves. Both pumps are virtually identical.

Reflectivity characterization

The spectral broadening[4] of the generated 1455 nm Stokes wave due to the increase in the total pump power incident on the FBG and the consequent shift of the FBG central wavelength caused by thermal expansion directly affects the grating reflectivity. Fig. 2 shows the reflectivity provided by the input FBG as a function of the

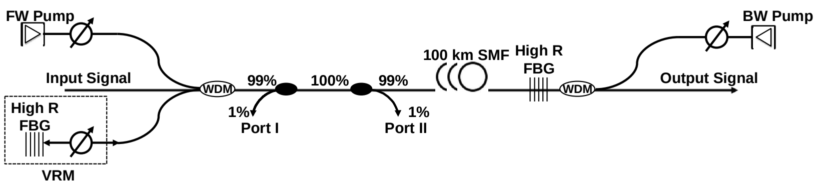

Fig. 1: Experimental setup

forward-to-total pump power ratio required to obtain zero net gain for the signal at the

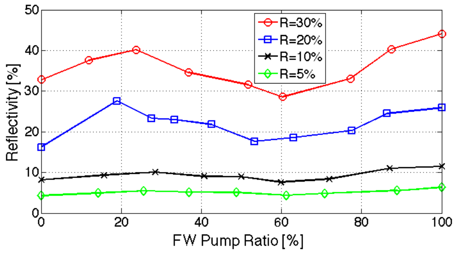

Fig. 2: Front-FBG reflectivity vs. FW pump ratio.

amplifier output. 0% denotes a BW only pumping scheme and 100% a purely FW pumped one. Effective reflectivity was measured as the ratio of the reflected power at port II to the incident power at port I for four different attenuations of the VRM VOA, corresponding to

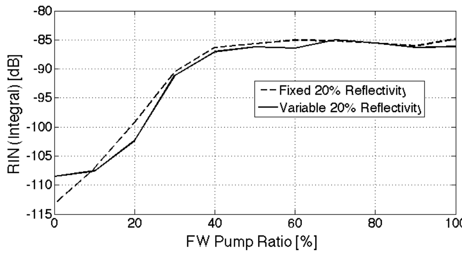

Fig. 3: Signal RIN integrated over 1MHz for variable (solid) and 20% fixed (dash) front FBG reflectivity.

reflectivities of 5%, 10%, 20% and 30%.

The effective FBG reflectivity changes as the FW pump ratio increases with a remarkable 10% peak-to-peak reflectivity variation when the VRM VOA attenuation returns a 30% reflectivity (red curve in Figure 2). As the attenuation is increased, the deviation from the average reflectivity value is reduced accordingly, but the tendency remains the same, with a first relative maximum at about 20% FW pump power ratio, a minimum around 60% where the first Stokes power is strongest, and an absolute maximum for a 100% when the total pump power injected into the cavity is lowest.

Relative intensity noise transfer

Signal RIN was measured by means of a low-noise photodetector with a 125 MHz bandwidth and then post-processed to show the overall contribution to RIN calculated as the integral of RIN over the first 1 MHz. Fig. 3 presents the typical S-shaped trend of the signal RIN as a function of the FW pump power ratio: it takes a certain amount of FW pump power for the RIN to rise above the initial baseline to the RIN level characteristic of a symmetric cavity design. Moreover, RIN transfer to the signal saturates after a certain point, so a further increase of the FW pump power has little to no impact on the RIN transfer. No difference is observed between a cavity formed by a stable 20% front-reflectivity obtained by accurately adjusting the VOA attenuation in the VRM to compensate for the effective reflectivity drift shown in Fig. 2, and the one where back reflections are initially set at 20% and allowed to vary with pump power ratio. In both cases signal RIN begins to grow at a ratio of about 20% and reaches an upper limit at ~50% proving that, although quite large, a 10% reflectivity variation doesn’t have any major

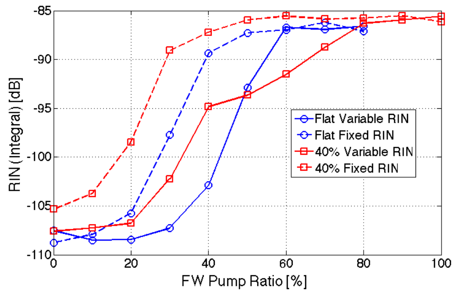

Fig. 4: Signal RIN integrated over 1MHz for variable (solid) and fixed (dashed) pump lasers RIN in the low (blue curves) and high (red curves) reflectivity regime.

impact on RIN transfer at this reflectivity level.

In order to study the influence of front-reflectivity and pump split, additional care was taken to ensure no other effects interfered with the analysis. Pump RIN is heavily dependent on pump power, so in order to keep input RIN fixed, pump power ratios were adjusted through attenuation of fixed pump output powers. Fig. 4 compares integrated RIN over 1 MHz for two fixed back reflection levels, in the cases in which pump lasers’ output RIN is kept fixed or allowed to vary with pump power. Here, the “Flat” label denotes a cavity where no VRM was present and a fixed 2% reflectivity is supplied by a straight flat-end PC connector at the 1455 nm port of the front-end WDM. As expected, low reflectivities allow for a higher contribution of forward pump power without increasing on the signal RIN level.

Although initial signal RIN level is similar in all four configurations shown in Fig. 4, the use of fixed-RIN pump sources isolates measurements from the power-related distortions noticeable in the variable RIN case as FW pump ratio is increased, leading to a better asessment of its impact on RIN transfer..

A more extensive examination of the influence of reflectivity on RIN growth is presented in Fig. 5a, showing the experimentally measured 1 MHz-integrated contribution to signal RIN as a function of the FW pump power ratio for different front-end reflectivities, ranging from 0% to 40%. It is clear that, even for a random Distributed Feedback Laser (rDFB)

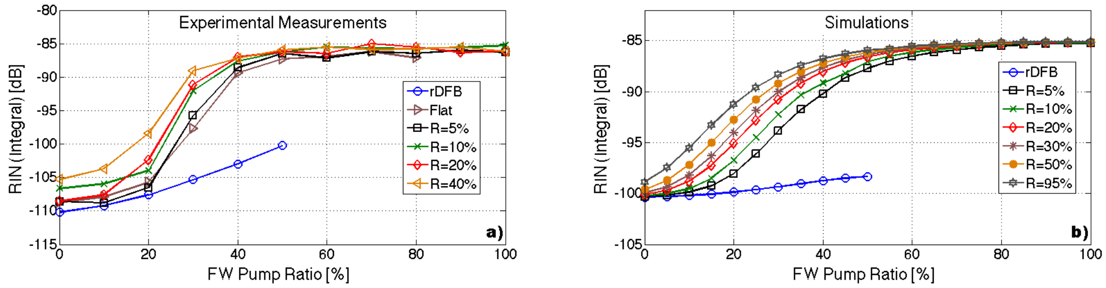

Fig. 5: a) Experimental and b) simulated signal RIN integrated over 1MHz as a function of the pump power split and front-end reflectivity for a 100 km 2nd-order ultra-long Raman laser amplifier.

amplifier based on a half-open cavity with no front-end FBG, RIN builds up with increasing FW pump power. However, in the case of such rDFB amplifier, RIN increase does not show the same steep threshold that is seen in cavity configurations for front-end reflectivities as low as 2%. The reduced efficiency of the rDFB limited our measurements to a 50% power split, corresponding to the maximum power deliverable from our pumps (33.5 dBm).

In the experiment, due to the losses in the VRM, the maximum effective reflectivity that could be measured was 40%. To investigate the behaviour at higher reflectivities numerical simulations were used, by solving a model[5] defined by two coupled sets of ordinary differential equations that describe the evolution of the average powers and the intensity noise of the different components. This model included the effects of depletion, attenuation, Rayleigh backscattering, ASE and the actual measured RIN of the pump lasers. Comparison between simulations in Fig 5(b) and experimental results in Fig 5(a) shows good agreement in the reproduction of the experimental RIN trends. Minor discrepancies between simulation and experiment absolute values are attributable to small deviations from the stock fibre characteristics used in the simulation, but don't affect the general conclusion. As reflectivity is increased, the impact on RIN of the forward pump power becomes more pronounced, and when a Fabry-Perot type cavity with very high reflectivity is used, the RIN increase is pronounced for virtually any amount of forward pumping. This leaves little room for choice, from a system design point,when pumping efficiency is the issue. Signal power excursion (and thus noise) minimisation is possible only within a limited range of FW pump powers, dictated by front-FBG reflectivity, without risking a highly detrimental RIN penalty. Increasing reflectivity results in a reduced range of acceptable FW power ratios, with a 40% reflectivity resulting in a 10% ratio cutback compared to 2% reflectivity for a -100 dB integrated RIN level. Signal RIN growth with FW power ratio saturates for ratios above 50%, so further increases in FW pump do not impose additional penalties..

Conclusions

We have characterised the impact of front-end reflectivity on RIN transfer from the forward pump to the signal in 2nd-order URFLs. Using a 100 km experimental setup with variable reflectivities, we have demonstrated that effective reflectivity variations due to first Stokes broadening and FBG shift do not have a noticeable effect on RIN transfer. To ensure the highest possible accuracy, direct control over the amount of back reflections and input RIN to the cavity has been implemented. Simulations and experiments show that the maximum tolerable forward pump power ratio for a -100 dB RIN level integrated over 1 MHz is halved when reflectivity is increased from 0% to merely 2%. High FW pump power ratios above 50% lead to RIN transfer saturation for all reflectivities..

Acknowledgements

This work was funded by FP7 ITN programme ICONE (608099), Spanish grants ANOMALOS (TEC2015-71127-C2) and SINFOTON (S2013/MIT-2790-SINFOTON-CM).

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