# SEPARATE EVALUATION OF NONLINEARITY-DUE Q PENALTIES IN LONG-HAUL VERY DENSE WDM OPTICAL SYSTEMS

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Abstract: Nonlinearity-due Q penalties are experimentally evaluated on a 2000-km, 33-GHz spaced DWDM system, dependently on system length and channel spacing. SPM, FWM and XPM, which is found to be the major constrain, are separately addressed.

## 1. INTRODUCTION

In long-haul DWDM systems inter-channel nonlinear effects represent a limit in system capacity increase. While NZDS fibers are designed to prevent Four Wave Mixing (FWM), Cross-Phase Modulation (XPM) still represents the major obstacle in increasing transmission systems capacity [1].

XPM was studied both theoretically [1,2,3,4] and experimentally with pump-probe [5,6,7,8] and multichannel [9] techniques. Pump-probe scheme allows evaluating separately Self-Phase Modulation (SPM) and XPM impairments. In a WDM system, multichannel measurements account for the global effect of the interfering channels, but it is difficult to quantitatively isolate penalties due to XPM only from those due to other 3rd-order nonlinearities.

In this paper nonlinearity-due Q penalties in a DWDM system are experimentally investigated using a 39 spans optical fiber line 2000-km long. For the first time, to the best of our knowledge, SPM, FWM and XPM penalties are separately addressed in a system with 33-GHz channel spacing. Results are described and discussed as a function of optical path length and per-channel input power. XPM-due impairment appears to overweight both SPM and FWM.

## 2. EXPERIMENTAL SETUP

The employed DWDM system is 2000 km long, with 64 power-equalized, 33-GHz spaced, polarization scrambled channels, in the 1543-1560 nm window. All channels are 10 Gbit/NRZ-IMDD. The total launch power is 12.8 dBm. The system employs 55-km fiber spans with D= -2.82 ps/(nm km) at 1550 nm and a 55-km Step index fiber for in-line dispersion compensation every 6 spans. Residual dispersion is fully compensated at the receiver end. This periodical dispersion map allows evaluating penalties at different system lengths. Nonlinear effects are excited at different levels by progressively increasing the per-channel power, by turning off some of the propagating channels (channel count ranges from 64 to 18).

SPM is analyzed first: a probe channel operating at 1551.25 nm propagates without the 32 neighbouring channels, which are turned off (see the optical spectrum in the inset of Figure 1). In this situation only SPM takes place: we experimentally verified that a given channel is not impaired by other channels farer than 133 GHz. By progressively turning off the remaining channels, per-channel power and probe Optical Signal to Noise Ratio (OSNR) is increased and the received Q factor is measured.

Pump and probe measurements are then performed by introducing a pump channel 100, 66 or 33 GHz away from the probe, thus inducing on it XPM additional penalties. Again, received Q factor is measured, while per-channel power is varied by changing the total channel number. EDFA gain can be considered flat over the band relevant for nonlinear effects, thus minimizing errors in evaluating neighbouring channels power. FWM penalties are not observed owing to the fact that only two channels interact with each other. When all neighbouring channels are turned on, FWM adds to SPM and XPM. Again Q measurements are performed as a function of per-channel power and received OSNR: the channels at the far end of the spectrum are turned on/off, leaving the neighbours on. By combining experimental results, it is possible to separately account for nonlinear effects. FWM penalty is found by subtracting SPM and XPM contributions from the total nonlinearity-due impairments.

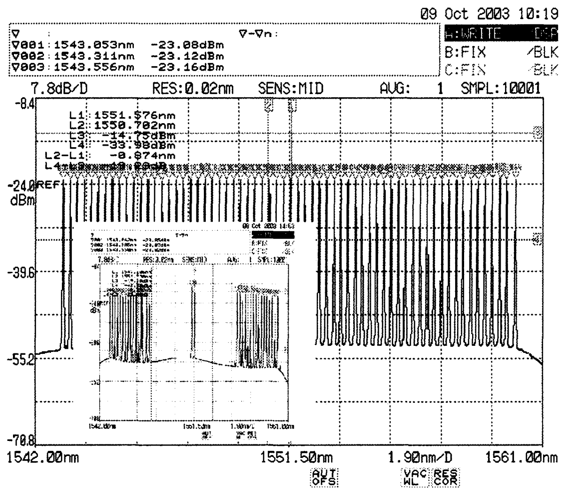


*Figure 1.* Power-equalized DWDM 64 CH-33 GHZ spaced spectrum and pump-probe measurement example (in the inset).

## 3. MEASUTEMENTS DISCUSSION

Figure 2 shows the total nonlinearity-due Q penalties for different system lengths and 33 GHz channel spacing. OSNR is chosen as reference parameter. A 1.5 dB Q penalty is found for 22.5 dB OSNR between 1257 and 2000 km propagation. For higher OSNR (higher per-channel powers) it is possible to compare all the three considered system lengths: total nonlinearity-due Q penalties grow more than linearly with total system length. When residual link dispersion is not compensated, performances worsen and a further Q penalty is added. Differently from FWM, XPM is influenced both by the dispersion compensation scheme [4,8] and by the residual dispersion value, because residual dispersion allows cumulated nonlinear phase to be further converted into intensity noise. Experiments carried out with a residual dispersion value of 557 ps/(nmkm) lead to an added Q penalty of 1 dB.

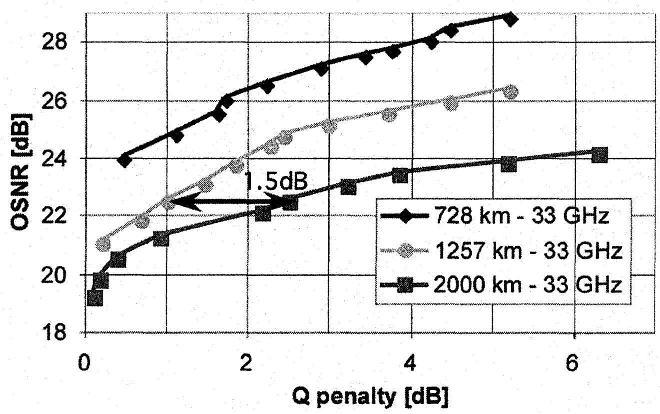


*Figure 2.* OSNR vs. total nonlinearity-due Q-penalties for different total system length.

The nonlinearity-due Q penalty is shown in figure 3 as a function of input per-channel power: XPM, FWM and SPM contributions are separately addressed. With 33 GHz channel spacing XPM-due impairment overweighs both SPM and FWM. When channel spacing increases, the amount of XPM, FWM and SPM becomes similar: in particular with 100 GHz channel spacing SPM represents the most important impairment in the 2000 km system, while XPM always produces a Q penalty higher than FWM.

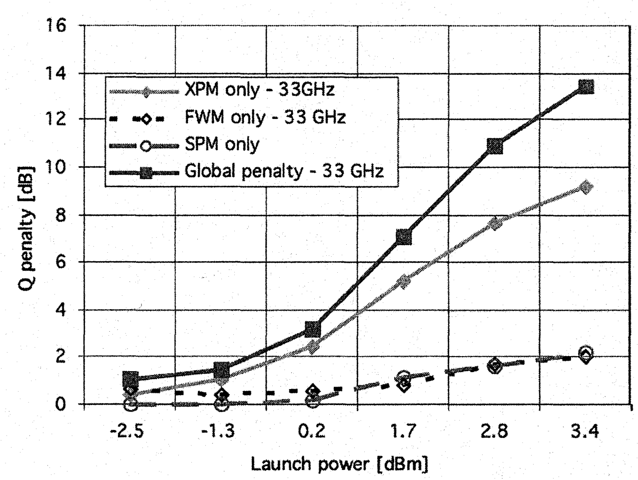


*Figure3.* Contribution of XPM, FWM and SPM to Q-penalties, for 2000 km system length.

The system under test is NZDS-fiber based and the dispersion map, typical of submarine systems, is designed to limit FWM penalties. Channels experience a significant walk-off before compensation, which is done every 6 spans, thus representing a good trade-off also for XPM penalties reduction [4,8]. At 33 GHz channel spacing, because of the relatively low fiber dispersion (D= –2.8 ps/(nmkm)), FWM still produces over 1 dB Q penalty, as high as SPM, for per-channel launch power over 1.7 dBm. XPM proves to be the main nonlinear system impairment when increasing the channel density (see Figure 3).

## 4. CONCLUSIONS

Nonlinearity-due system Q penalties in DWDM multispan systems are experimentally analysed as a function of system length and channel spacing. For the first time to our knowledge 33 GHz spacing is addressed for DWDM systems. SPM, FWM and XPM impairments are separately measured. At 33 GHz spacing XPM proves to be the most severe impairment, whereas at 66 and 100 GHz both XPM and FWM present inter-channel penalties <1 dB for relatively high powers, and the most limiting factor in increasing per-channel power and then span length is SPM, as reported in previous works [5].

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