Impact of Raman Amplification on a 2 Tbit/s Coherent WDM System

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***Abstract*— The impact of hybrid EDFA/Raman amplification on a spectrally efficient coherent-wavelength-division-multiplexed (CoWDM) optical communication system is experimentally studied and modeled. Simulations suggested that 23dB Raman gain over an unrepeatered span of 124km single-mode fiber would allow a decrease of the mean input power of ~6dB for a fixed bit error rate (BER). Experimentally we demonstrated 1.2dB Q factor improvement for a 2Tbit/s seven-band CoWDM with backward Raman amplification. The system delivered an optical signal-to-noise ratio of 35dB at the output of the receiver preamplifier providing a worst case BER of 2×10^{-6} over 49 subcarriers at 42.8Gbaud, leaving a system margin (in terms of Q-factor) of ~4dB from the forward error correction threshold.**

***Index Terms*— Coherent WDM, Raman amplification**

I. INTRODUCTION

RECENT high capacity and high information spectral density (ISD) systems have used a combination of techniques, such as polarization multiplexing, frequency orthogonality and phase selectivity [1], [2]. In particular, Coherent WDM (CoWDM), which employs phase control to enhance the orthogonality between adjacent frequencies when matched filters are not available, is a promising candidate to achieve high ISD. CoWDM has been demonstrated to be compatible with existing dispersion maps, tolerant to dispersion and nonlinearities using direct and real-time detection, and is well-suited for Ethernet transport [2], [3].

Accompanying this change to higher ISD formats, there is renewed interest in Raman amplification to enable increased reach and capacity of WDM systems [4]. The major advantage of distributed Raman amplification (DRA) is the reduced equivalent noise figure compared to lumped amplification [5]-[7] for the same nonlinear impact. Whilst Raman amplification has been already used to transmit high-ISD WDM [8], the enhancement in Q-factor has not been quantified yet for systems with orthogonal and closely-spaced multi-carriers.

In this letter, we demonstrate for the first time the impact of Raman amplification on a CoWDM system over 124km of unrepeatered field-installed single-mode fiber (SMF) operated by BT Ireland. We analyze the counter-play of DRA in enhancing and/or decreasing the penalty due to noise and signal distortion from fiber transmission for a 2Tbit/s CoWDM, spread over seven independent bands and a total of 49 subcarriers at 42.8Gbaud. An analytical model is introduced in order to identify high Q-factor operating areas. For such long unrepeatered transmission reaches using legacy installed SMF, the DRA is beneficial, with 1.2dB Q-factor enhancement compared to lumped amplification [3].

II. EXPERIMENTAL SETUP AND EQUIVALENT NOISE FIGURE

Fig.1 shows the system configuration. The transmitter and receiver were explained in [3]; seven seed lasers spaced at 385.52GHz passed through two cascaded Mach-Zehnder modulators (MZM), generating seven CoWDM bands each containing seven orthogonal subcarriers spaced at 42.84GHz. After impressing non-return-to-zero on-off keying (NRZ-OOK) encoding with 2^{31}-1 PRBS data electrically decorrelated between adjacent subcarriers, the transmitted spectrum had a total power of 8.7dBm (P_{TX}) over a 2.8THz bandwidth and transported a total of 2.1Tbit/s (Fig.2). The transmitted power enabled the inclusion of the dispersion compensating module (DCM)- 9dB loss, –1977ps/nm/km dispersion and 7.6$(\mathrm{W\cdot km})^{-1}$ nonlinear coefficient- before the first erbium doped fiber amplifier (EDFA #1 in Fig.1). The unrepeatered 124km of installed SMF, looped back from Cork to Clonakilty with a total loss of 26dB, could be pumped in both forward (FW) and backward (BW) directions with a commercial Raman amplifier including in band and out of band supervisory channels. Compared to post-compensation where the DCM and an additional amplifier are included in the receiver, the optical signal-to-noise ratio (OSNR) benefits of pre-compensation outweighed the potential penalties associated with the peak-to-average power ratio increase, and so pre-compensation was used throughout this work. After the transmission fiber, a variable optical attenuator, a power monitor and a 25dB small signal gain receiver preamplifier (EDFA #2) were used, and the OSNR was monitored at the output of the preamplifier with an optical spectrum analyzer. The OSNR measured was defined as the ratio of the signal power in a band (2.5nm) over the noise power in 0.1nm. The

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receiver also comprised two optical filters for subcarrier selection, additional dispersion compensating fiber, and a photodiode for direct detection [3].

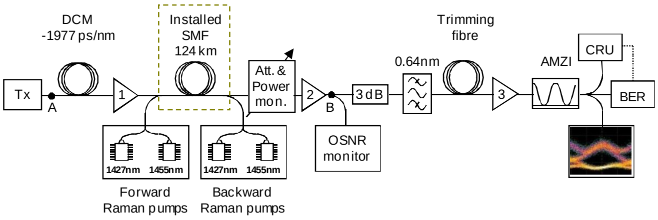

Fig. 1. Experimental setup for hybrid Raman/EDFA transmission over 124km installed-SMF of 2Tbit/s OOK CoWDM.

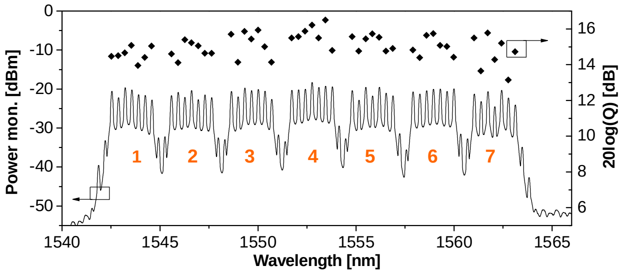

Fig. 2. Spectrum at the transmitter output, with band numeration shown (left-y axis). Calculated Q-factor from BER measurements of all 49 subcarriers with hybrid Raman/EDFA amplification (right y-axis).

We could define an equivalent noise figure NF_{AB} between the points A and B in Fig.1 as:

$$NF_{AB}=\frac{NF_1}{e^{-\alpha_{DCM}L_{DCM}}}+\frac{NF_{DRA}-1}{e^{-\alpha_{DCM}L_{DCM}}G_{E1}}+\frac{NF_2-1}{e^{-\alpha_{DCM}L_{DCM}}G_{E1}G_{net}10^{-\alpha_{ATT}/10}} \quad (1)$$

where NF_1 and G_{E1} are noise figure and gain of the first EDFA, NF_2 is the second EDFA's noise figure, α_{DCM} and L_{DCM} are loss coefficient and length of the DCM, G_{net} is the net gain over the SMF, and α_{ATT} is the insertion loss in dB of the variable attenuator and power monitor. NF_{DRA} is the equivalent noise figure of the Raman amplifier which could be expressed as in [5], [9] since BW pumping was the main source of gain in this bidirectional pumping arrangement and [10] in order to take into account of double Rayleigh backscattering (DRB).

Although Raman amplification adds noise (amplified spontaneous emission (ASE) and DRB) [10]) by transforming an optical fiber into a DRA, at a fixed BER it allows lower fiber launch powers and increases the minimum signal power in the fiber. The EDFA following the DRA has also a higher input power, and thus causes a smaller OSNR degradation when compared to the EDFA-only system [3]. Optimization of a DRA system is complex because the distribution of the gain along the transmission fiber reduces the total ASE and improves the OSNR but simultaneously increases the signal distortions that result from Kerr and other nonlinearities. The total nonlinear phase shift is equal to (2):

$$\phi_{NL}=\gamma_{DCM}\,aP_{ch}L_{effDCM}+\gamma aP_{ch}e^{-\alpha_{DCM}L_{DCM}}G_{E1}\int_0^L G_{net}(z)dz \quad (2)$$

where L is the SMF length, γ and γ_{DCM} are the nonlinear coefficients for the SMF and DCM respectively, $P_{ch}= P_{TX}/49$ is the power per channel or subcarrier, a is an experimentally fitted coefficient that accounts for self-phase (SPM) and cross-phase modulation (XPM) between phase matched channels, $L_{effDCM}=\left(1-e^{-\alpha_{DCM}L_{DCM}}\right)/\alpha_{DCM}$ represents the effective length for the DCM. $G_{net}(z)$ is the net gain and $G_{RA}(z)$ the Raman gain, along the SMF, which are given by (3) and (4) respectively:

$$G_{net}(z)=a_{Att}\exp\left[-\alpha_s z\right]G_{RA}(z) \quad (3)$$

$$G_{RA}(z)=a_x\exp\left\{g_R\left[\eta_1 I_{BW}(L)e^{-\alpha_p L}\left(e^{\alpha_p z}-1\right)+\right.\right.$$
$$\left.\left.+\eta_2 I_{FW}(0)\left(1-e^{-\alpha_p z}\right)\right]/\alpha_p\right\} \quad (4)$$

where a_{Att} is the insertion loss of the variable attenuator, α_s and α_p are the SMF loss at the signal and pump wavelengths respectively, a_x takes into account additional insertion losses due to the pump couplers, g_R is the Raman gain coefficient (~0.68×10^{-13} m/W in SMF), and η_1, η_2 are efficiencies which scale the pump intensities $I_{BW,FW}$ (= $P_{FW,BW}/A_{eff}$) to take account of the double wavelength system.

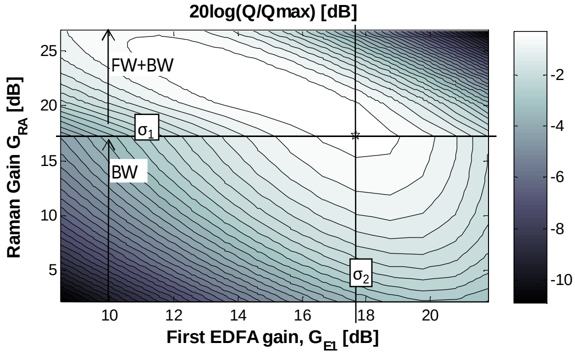

Fig. 3. Normalized Q-factor from simulations as a function of both Raman gain G_{RA} and the first EDFA gain G_{E1}. The spacing of the contour lines is 0.3.

A Q factor was calculated from the effective signal-to-noise ratio (SNR_{eff}), which sums the linear signal to noise ratio (SNR_{lin}) and nonlinear phase noise (NLPN) [11] as:

$$\frac{1}{SNR_{eff}}=\frac{1}{SNR_{lin}}+\frac{2}{3}\frac{7}{OSNR}\phi_{NL}^2 \quad (5)$$

The first term accounts for accumulated ASE and the second is the NLPN variance which depends on the OSNR per channel. In Fig.3 the Q-factor is shown as a function of both the gain in the first EDFA G_{E1} and the on-off Raman gain G_{RA}; an optimum operating area is identified. The Raman gain reached 17.2dB when maximum BW pumps only were on.

III. EXPERIMENTAL RESULTS

Experimentally two cross-sections (σ_1 and σ_2) of Fig.3 were studied. For a fixed Raman gain of ~17.2dB (BW only), the gain of the first EDFA was varied in order to evaluate the nonlinear power threshold (Fig.4). The OSNR measurements per band at the transmitter (point A in Fig. 1) were between 38 and 39dB, and corresponded to the spectrum shown in Fig.2. The flatness over the 49 subcarriers prior to launch into the link was ~5dB. Fig.4 shows the Q-factor in dB, calculated directly from the BER measurements for the worst-performing optical subcarrier #48 (left-axis, squares) at the receiver, against the first EDFA gain G_{E1} and hence the mean power per subcarrier at the input of the 124km transmission fiber (calculated as 1/49 of the total launch power). Similar nonlinear performance was observed for a number of randomly selected channels. Fig.4 also shows the OSNR for the 7th band measured at the output of the first EDFA (#1 in Fig.1). At low power levels, the Q-factor is degraded by a low OSNR (right-axis, circles); at high powers, the OSNR increases but the Q-factor starts degrading due to nonlinearities. The optimal operating condition was about –1dBm per subcarrier.

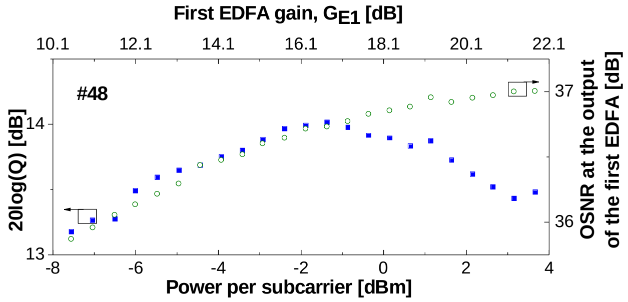

Fig. 4. Calculated Q-factor (left-y axis) from BER measurements for optical subcarrier #48, and measured OSNR (for the associated band) at the output of the first EDFA (right-y axis) against power per subcarrier at the input of 124km installed-SMF (bottom-x axis) and the first EDFA gain (top-x axis).

In order to study the impact of Raman amplification, the Raman gain was varied by changing FW or BW pump powers (reproduction of cross-section σ_2 in Fig.3). In each case, a dual wavelength pump module was used (1427nm and 1455nm, +27dBm max) and the launch powers of the two pumps were set to be nominally identical, optimizing the gain flatness across the C-band. The Q-factor (calculated from measured BER for optical subcarrier #48 (left-axis)) against the on-off Raman gain is plotted in Fig.5 as triangles. The measured OSNR is also shown on the right-axis in Fig.5; BW Raman amplification induced a 3dB OSNR improvement when compared to an EDFA only amplification system [3], but at maximum BW Raman gain only a 1.2dB improvement in the Q-factor is observed. We believe that the saturation in the Q-factor enhancement shown in Fig.3 is due to inter-subcarrier crosstalk. Typically further performance enhancement may be achieved using bi-directional pumping; however in this particular case, the supervisory channel constrained the total loss between the power amplifier and the backward Raman pump, and a degradation of the OSNR was observed if the launch power was reduced by other means. Consequently whilst FW Raman amplification further enhances the gain, Q-factor degradations were observed due to increased nonlinearities at the higher launch power.

The launched power into the installed SMF was fixed at –1dBm/ch, corresponding to G_{RA} and G_{E1} of 17.2dB (BW Raman only) and 17.7dB respectively, indicated by a star in Fig.3. At this operating point, all 49 subcarriers were characterized in terms of BER performance, and the correspondent Q-factors are shown in Fig.2 (right-y axis). An average Q-factor of 15dB across the 49 subcarriers was observed after transmission; we believe that the variation of the mean Q-factor of each band is due to the net amplification gain tilt, whilst the large fluctuations observed in bands #3 and 7 correspond to the flatness deviation of the signal at the transmitter, attributed to the WDM operation of the comb generator. The system (0.7bit/s/Hz transmitted in a single polarization) had an overall margin in terms of Q-factor of ~4dB when related to a threshold BER of 2×10^{-3}.

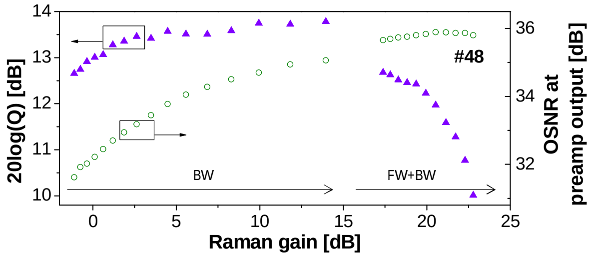

Fig. 5. Calculated Q-factor (left-y axis) from BER measurements for optical subcarrier #48, and measured OSNR (for the associated band) at the output of the receiver preamplifier (right-y axis) against Raman gain.

IV. CONCLUSION

We have experimentally demonstrated a 3dB improvement in the delivered OSNR for a 2Tbit/s CoWDM system at 42.84Gbaud over 124 km of field-installed SMF using DRA. The Q-factor improvement was 1.2dB compared with EDFA amplification alone.

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