Transmission of 80 x 10 Gbit/s WDM channels with 50 GHz spacing over 500 km of LEAF® fiber

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We demonstrate transmission of 80x10 Gbit/s channels over 5x100 km of LEAF® fiber. The impact of optical nonlinearities for Δν=50 GHz is evaluated by comparing the results of different interleaved channel polarization experiments.

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Introduction: In general, the upgrade paths to increase transmission capacity involve either using higher bit rates, increasing the number of WDM channels and/or closer channel spacing. For example, it has been demonstrated that with OC-192 systems it is possible to combine more than 100 WDM channels, with 50 (C-band) and 100 GHz (L-band) spacing, to achieve 1 Tb/s transmission capacity [1]. More recently, it has been demonstrated that with 40 Gbit/s systems the same capacity can be achieved with 25 channels separated by 1 nm [2]. In these systems, because of nonlinear optical channel interactions during propagation and chromatic dispersion of the optical fiber, a very careful management of both effects is necessary to attain an acceptable performance. Because of the trade-off between dispersion and optical nonlinearities, the characteristics of the transmission fiber becomes critical in determining the performance limits of the system. Non-zero dispersion-shifted fibers (NZ-DSF) are used to reduce the impact of chromatic dispersion and four-wave mixing (FWM)[1-4]. However, there are other nonlinear effects that also limit the transmission capacity and, as with FWM, worsen with closer channel spacing. A simple solution to avoid or reduce the presence of nonlinear effects is to increase the effective area of the fiber [5]. This allows the use of higher signal power and longer transmission distances, avoiding the need for dispersion management [1,4] or band-splitting for dispersion compensation.

In this paper, we demonstrate transmission of 80x10 Gbit/s WDM channels on the ITU grid with 50 GHz spacing over 5x100 km spans of Corning® LEAF® fiber. The margin required by installed systems was simulated by padding the loss of each span to 25 dB. We studied the performance of this system by launching adjacent channels with parallel and perpendicular relative polarizations. The first situation represents the worst-case scenario for optical nonlinearities, because all channels are launched with the same polarization. In the second case, we observe that the crossed polarization between adjacent channels at the input of the system reduces the impairment caused by optical nonlinearities by 0.86 dB. The impact of FWM and cross-phase modulation (XPM) contributions are identified when we compare the performance of this system with the modulation of the odd channels turned off.

Experiment: The experimental setup is shown in Fig. 1. We used two sets of 40 DFB lasers, each having a channel spacing of 100 GHz, which are combined to deliver 80 interleaved channels on the ITU grid separated by 50 GHz. Each set of lasers is multiplexed with fiber couplers and modulated with a 2^{31}-1, 10 Gbit/s pseudorandom bit stream (PRBS) by a Li:NbO3 Mach-Zehnder modulator. The wavelengths of the first set of lasers (odd channels) range from λ_1=1531.90 nm to λ_{79}=1563.05 nm, while the second set (even channels) goes from λ_2=1532.30 nm to λ_{80}=1563.50 nm. After amplification, the signals were transmitted over a 500 km transmission line consisting of 5 x 100 km spans of LEAF® fiber and four in-line optical amplifiers. The relative polarization between even and odd channels is set with a polarization controller after each modulator and an in-line polarizer at the output of the 3 dB coupler. In the parallel launch case we maximize the transmission through the in-line polarizer for both sets of lasers. To set the relative polarization between even and odd channels to be perpendicular, we maximize the transmission through the polarizer for the odd channels first and then turn them off. After that, we adjust the polarization controllers of the even channels until the transmission is minimized, remove the in-line polarizer and turn all the lasers back on. With a polarization analyzer we measure the degree of polarization for each set of lasers before the first fiber span to confirm the relative polarization between the adjacent channels.

LEAF fiber has a typical effective area of 72 μm^2, which is about 30% larger than typical NZ-DSF. The dispersion minimum is 2 ps/nm at 1530 and the maximum is 6 ps/nm at 1565 nm. A variable optical attenuator (VOA) was used to adjust the total launched power into each span to 19 dBm, corresponding to an average power of approximately 0 dBm/channel. In order to simulate the performance of real systems, the span loss was increased to 25 dB by adding optical attenuators before each amplifier. Dispersion compensating fibers (DCF) were placed at each terminal, as indicated in Fig. 1, and the same amount of pre- (–830 ps/nm) and post-compensation (–650 ps/nm) was used for all channels. At the system output the total accumulated dispersion for the first channel is –87 ps/nm and +1155 ps/nm for the last channel.

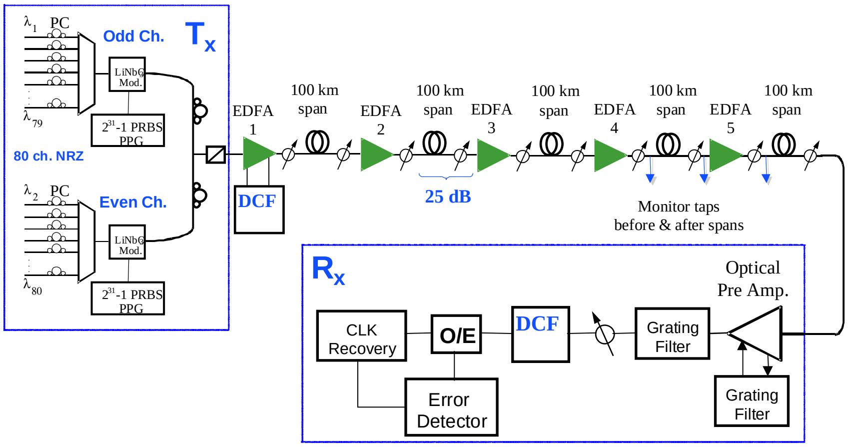

Fig. 1: Experimental setup. PC = polarization controller, PPG = pulse pattern generator, VOA = variable optical attenuator.

Results and discussion: The transmission performance was characterized by measuring the bit error rate as a function of the decision threshold for each channel. From these curves we estimate the system Q [6]. The results for both parallel and perpendicular polarization launches are presented in Fig.2a. We selected and characterized some channels across the spectrum for both cases. For parallel polarized adjacent channels, 62 channels have Q > 8.5 dB (BER < $1.0\text{x}10^{-12}$) and the worst performance is for channel 10 with a Q = 7.9 dB (BER = $2.0\text{x}10^{-10}$). In the cross-polarized adjacent channels launch, all channels have Q > 8.6 dB (BER < $1.3\text{x}10^{-13}$). The difference in performance between parallel and orthogonal launch becomes more pronounced for the long wavelength channels with a maximum of 0.86 dB for channel 70. Fig.2b shows the result for the case in which we removed the polarization controllers and the in-line polarizer, allowing the relative polarization state of the adjacent channels to evolve randomly up to the fiber span input. All 80 channels obtained a Q > 8.5 dB, which indicates that the polarization of the channels were not parallel and most likely at an intermediate state closer to the orthogonal polarization launch.

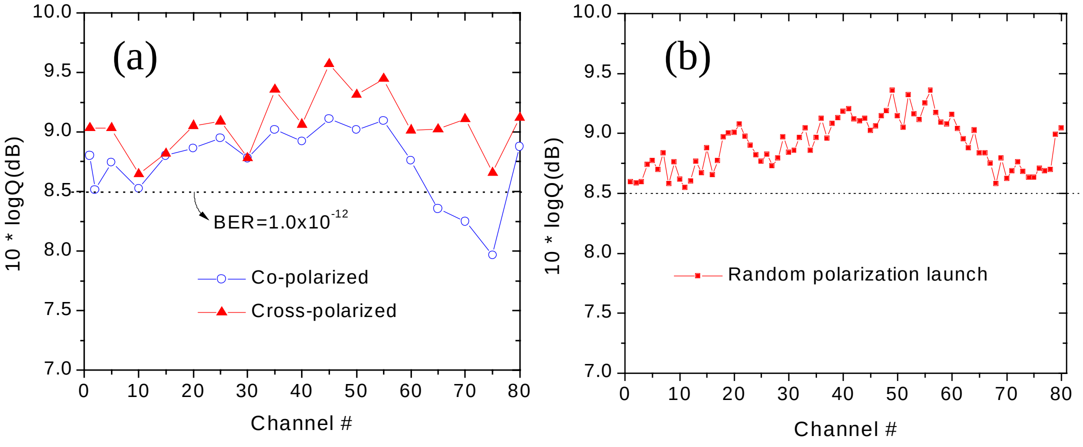

Fig. 3: (a) Comparison of Q performance for parallel and orthogonal channel polarization launches; (b) Q performance with no control on the polarization of adjacent channels launched into the first fiber span.

The difference between the results of parallel and orthogonal polarization launch has already been investigated and it is explained in terms of the polarization dependence of FWM and XPM. It has been shown that orthogonal launch of the adjacent channels significantly reduces the contribution from FWM [7,8]. Taking into consideration the reduction of the penalties caused by optical nonlinearities due to the large effective area of the fiber and the average power per channel level of

0 dBm, it is expected that the FWM contribution would be very small even for the parallel polarization launch. This is confirmed by the low FWM crosstalk level observed at the output of the system when we turn some of the channels off (Fig. 3a). With these arguments and the small difference observed between the results for parallel and orthogonal polarization launch, we can say that FWM contribution is not the major source of impairment for this system. This conclusion is reasonable for the short wavelength channels, for which the difference in performance and dependence on the polarization state of the adjacent channels is almost negligible. However, for the long wavelength channels the difference in performance is small but it is not negligible.

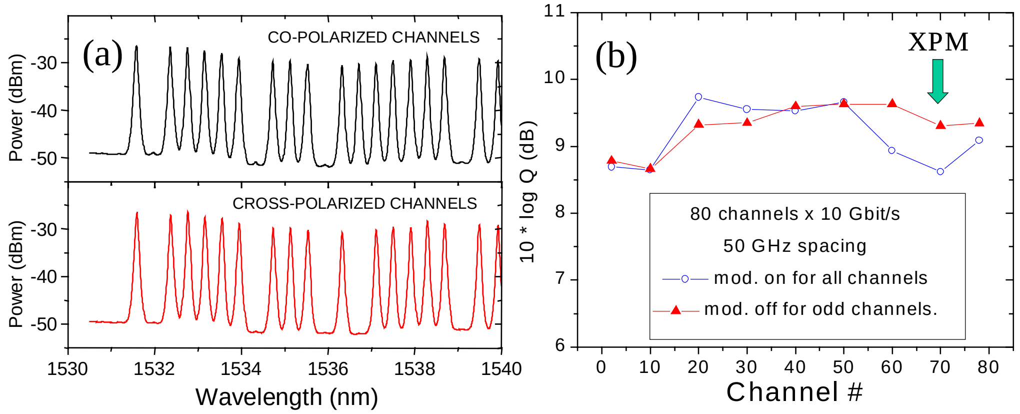

Fig. 3: (a) FWM crosstalk measured at the output of the system (0.05 nm resolution) co- and cross-polarization launch; (b) Performance comparison between all 80 channels with modulation on and odd channels with modulation off.

As mentioned before, XPM contribution is also reduced for orthogonal polarization launch. To assess the magnitude of its contribution, we turned off the modulation of the odd channels and compared the performance of selected channels to their performance obtained when the modulation was on all the channels. The result of this comparison is shown in Fig. 3b. With the modulation of odd channels off, the performance degradation caused by the contribution of XPM to the even channels disappears. The reduction of the penalty caused by XPM becomes clear when we look at the improved performance of the long wavelength channels (channels 50 to 80). This observation is in agreement with the fact that these channels have more accumulated dispersion, which enhances the XPM contribution, and with the increased performance difference of these channels that is observed for parallel and orthogonal polarization launch. This result indicates that XPM is the dominant source of performance degradation for this system and it confirms the conclusion of our previous study [9].

Conclusion: We demonstrated the feasibility of transmission of 80x10 Gbit/s WDM channels on the ITU grid with 50 GHz spacing over 5x100 km spans, with 25 dB loss budget, of Corning® LEAF® fiber with BER performance better than $1.3\text{x}10^{-13}$ for all channels. The comparison of system performance for parallel and perpendicular polarization launch of adjacent channels reveals that degradation is dominated by XPM contributions. Although FWM is present, its contribution is small and almost negligible at this power per channel level. Orthogonal channel polarization launch reduces both FWM and XPM contributions and improves the system performance by up to 0.86 dB in comparison with parallel polarization launch. Pre- and post-dispersion compensation of all 80 channels was done with only a single dispersion compensation fiber at the transmitter and receiver terminals.

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