Experimental demonstration of 160-GHz densely dispersion-managed soliton transmission in a single channel over 896 km of commercial fibers

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Abstract: We experimentally demonstrate the first 160-GHz densely dispersion-managed soliton transmission in a single channel at 1550 nm over nearly 900 km using commercially available non-zero dispersion-shifted fibers. This performance has been achieved by using a 16 km-long recirculating loop configuration and an appropriate design of the dispersion map.

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1. Introduction

Dispersion management (DM) has been proved to be the best way for upgrading pre-installed WDM optical communication systems at 10 and 40-Gb/s [1]. However, for future high-speed transmissions and in the present context of bit-cost reduction, there is a growing demand to increase the bit rate per channel and 160-Gb/s transmission seems to be the next step in upgrading the channel rate. However, in conventional dispersion-managed (CDM) systems, where the length of the dispersion map is larger than or equal to the amplifier span, it is difficult to propagate pulses with bit rates larger than 40-Gb/s per channel, because of large breathing and large power enhancement factor of these CDM solitons. Consequently, for such systems, the best transmission performances reported so far in the literature do not exceed a few hundreds of kilometers (i.e., less than 500 km) [2,3]. In this context, an important but challenging question arises as to whether or not such high-speed transmission technologies can be promoted up to the stage of ultra-long (or transoceanic) distances. To overcome this issue, Liang et al [4] proposed a Densely Dispersion-Managed (DDM) fiber system whose map length is shorter than the amplifier span and in which the pulse propagates with a strongly reduced breathing compared with the case of conventional DM solitons or quasi-linear pulses. The DDM technique was then considered in several numerical and experimental investigations [4-10]. For example, in 1999, a 100-Gb/s DDM single-channel transmission has been achieved over 1000 km by means of a continuous Dispersion-Managed Fiber (DMF) [8] and more recently, in 2000, a 87-GHz pulse train was successfully transmitted over 336 km in a DDM map configuration based on commercially available fibers [9]. On the other hand, in Ref. 10, an average-dispersion decreasing densely dispersion-managed (A4DM) system was proposed as an efficient way for improving the performance of high-speed optical transmission systems. In A4DM systems a high stability of pulses is obtained by decreasing the average dispersion from one dispersion map to another within each amplification period, in such a way to follow the decrease of energy due to fiber losses. The major advantages of the A4DM soliton over conventional DDM soliton are that it does not require any initial chirp, it requires a reduced energy, and the transmission line can be designed analytically. But the major drawback of the A4DM is that the dispersion maps of the amplification span are all different, which implies a larger number of pieces of fiber with all different lengths to build up each amplification span [10].

In this paper, we consider a much simpler line (than the A4DM line), in which each amplification span is made up of a repetition of a single type of map, with the same span average dispersion as that of an equivalent A4DM system [10]. We investigate the transmission of a 1.27-ps pulse train, at 1550 nm and 160-GHz repetition rate, and demonstrate the reliability of the DDM soliton by means of a 16 km-long recirculating loop composed of standard non-zero dispersion-shifted fibers (NZ-DSF). The measured autocorrelation traces show that a highly stable propagation is achieved over 896 km, which corresponds, to the best of our knowledge, to the maximum transmission distance of a DDM soliton in a single channel at 160-GHz repetition rate, reported to date.

2. Map design and simulation results

The technique of dense dispersion management is schematically described in Fig. 1(a). Basically, the amplifier span Za is made up of many periods Zp of dispersion management such that Za=n.Zp with n>1. DDM systems may be characterized by several fundamental parameters, such as the map strength parameter, S, defined by $S = \lambda^2[D_1L_1-D_2L_2]/2\pi c\Delta^2$ [11], where Δ is the full width at half-maximum (FWHM) at chirp-free point, c is the light velocity, λ the wavelength of the field, and D_1, L_1, D_2, L_2 are the dispersions (in ps/nm/km) and lengths (in km) of the first and second fiber sections of the DM period.

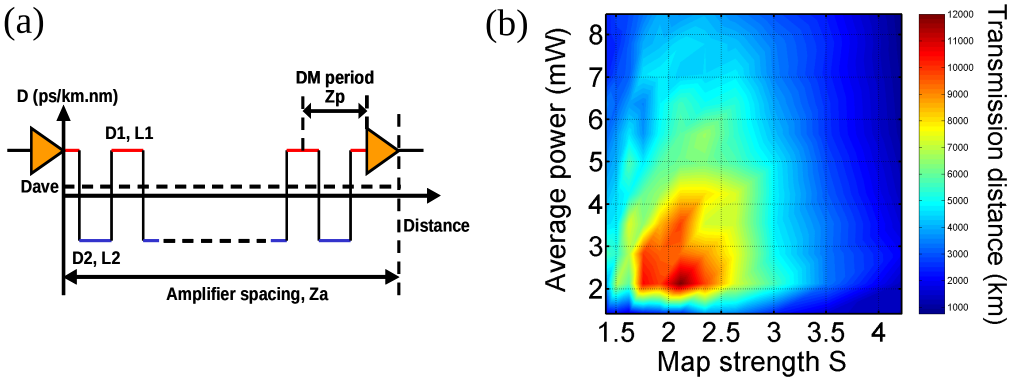

Fig. 1. (a) Schematic diagram of a densely dispersion-managed map. (b) Maximum propagation distance versus map-strength and average power for a deployed transmission line.

In this work, we consider a DM period composed of two kinds of NZ-DSF with local dispersions at 1550 nm of 1.64 ps/nm/km and -1.84 ps/nm/km respectively, effective areas of 59 and 55 μm^2 and an average fiber loss of 0.2 dB/km. The amplifier span is fixed to 16 km, so that S depends directly on n. For simplicity, polarization mode dispersion (PMD) was neglected in our simulations. We have also neglected the influence of the third-order dispersion (TOD) because of the availability of a TOD compensator module, described below in our experimental set-up. An amplifier with a 5.5-dB noise figure is used to compensate for the total loss within each amplifier span and a 1.8-THz FWHM optical bandpass filter is used to suppress noise accumulation. The input pulses correspond to a 160-GHz train of transform-limited Gaussian pulses with 1.27-ps FWHM. The system performance is evaluated by means of the Q factor. We define the transmission distance “Zmax” as the distance over which the Q factor remains higher than 6. For a given map strength and input average pulse power, the optimum lengths of the fiber sections of the dispersion map and the corresponding average dispersion, are obtained through an analytical design procedure similar to that reported in Ref. 10. In particular, the dispersion map is designed in such a way that the input pulses do not require any pre-chirp to execute stationary propagation. The different maps obtained for different map strengths and input average powers are then successively tested and compared through a large set of simulations leading to the transmission distance Zmax.

Figure 1(b) shows the evolution of Zmax as a function of the map-strength and average power for a deployed transmission line. The optimum configuration is achieved for S=2.1 (n=10), which corresponds to L_1=846.44 m and L_2=753.56 m, and an average dispersion of 0.001 ps/nm/km. The optimum average power is 2.1 mW (3.2 dBm), and the maximum transmission distance Zmax is equal to 12000 km. However, it is worth noting that the recirculating loop used in our experiments described below, contains additional devices not present in the deployed line, namely, a fiber fused 50:50 coupler and an optical switch (OS), which lead to significant coupling losses (6 dB). To appropriately design the experimental set-up, we have carried out a series of simulations including these 6 dB coupling losses. The results are given in Fig. 2(a), in which one can clearly observe that the optimum S parameter moves to S=2.6 (n=8) which corresponds to L_1=1059.3 m, L_2=940.7 m and an average dispersion of 0.0032 ps/nm/km. Note that this optimum value of S differs clearly from the corresponding value for the ideal case of a lossless DM line, for which S=1.6, and which was found to be the transmission point where the DM solitons have minimal pulse-pulse interactions [12]. In our system, for values of S that are larger than 2.6 (n < 8 maps), the pulses execute a relatively large breathing favouring pulse-pulse interactions, which therefore

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represent a major limiting factor of the transmission performances. On the other hand, for small values of S (large n), the pulse breathing gets reduced, but meanwhile, the coupling losses significantly increase, thus degrading the signal to noise ratio (OSNR). The transmission point S=2.6 (n=8 maps) corresponds to an optimum point which minimizes both the pulse-pulse interactions and the effects of the SNR. On the other hand, an outstanding point in Fig. 2(a) is that the optimum average power moves up to 4.95 mW (6.95 dBm) while Zmax falls to 2800 km. This drop in the transmission performance (due to the 6 dB coupling losses) is one of the major differences between the loop and the deployed line. On the basis of these numerical results, we have designed the parameters of our recirculating loop, but during the stage of practical implementation of the experimental set-up, we found that our TOD compensator module induces non negligible coupling losses, that we found from measurement to be 4 dB. The effects of these extra losses on the transmission performance of the optimum S=2.6 DDM configuration are represented in Fig. 2(b), which we obtained by taking into account the dispersion slope of the NZ-DSF±, the action of the TOD compensator module and the associated coupling losses of the loop configuration. We have found that the optimum DDM configuration undergoes a significant increase of the optimum average power up to 14.15 mW (11.5 dBm) and a drop of Zmax to 1040 km. On the other hand, we have numerically investigated the effect of a weak variation of the average-dispersion around this optimum S=2.6 DDM system on the transmission performance. The evolution of Zmax as a function of the map average-dispersion, given in Fig. 2(b), confirms that this optimum DDM configuration leads to the best performance.

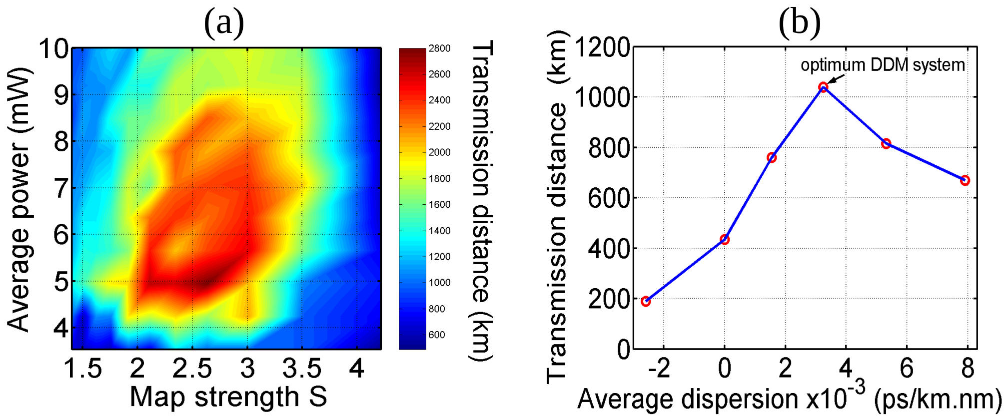

Fig. 2. (a) Maximum propagation distance versus map-strength and average power for a recirculating loop configuration: idem as Fig. 1(a) + 50:50 coupler and OS. (b) Maximum propagation distance as a function of the average dispersion for the experimental configuration with TOD, HOM-DCM, coupling losses and for an input average power of 14.15 mW.

3. Experimental set-up and results

An overview of the experimental set-up is shown in Fig. 3. The 160-GHz picosecond pulse train is generated at 1550 nm using multiple four-wave mixing temporal compression of an initial dual frequency beat-signal propagating in a 1-km long NZ-DSF with an anomalous dispersion of 1 ps/nm/km [13]. The beat-signal is synthesized from two cw external cavity lasers (ECL) and subsequently amplified by an erbium-doped fiber amplifier (EDFA 1) at an average power of 27.2 dBm. A phase modulator permits to suppress the stimulated Brillouin scattering effect. After nonlinear reshaping in the NZ-DSF, 1.27-ps transform-limited pedestal-free Gaussian pulses are generated with an extinction ratio between peak power and interpulse background better than 20 dB. Pulse propagation is then studied by means of a recirculating loop, which consists of eight spans of NZ-DSF± with a total length of 16 km, corresponding to the optimum DDM configuration described in Fig. 2(a). The average PMD of the loop was measured and found to be around 0.1 ps/km$^{1/2}$, while the average dispersion slope of the transmission fibers was measured and found to be 0.08 ps/nm^2/km. We have observed from numerical simulations that, in the absence of TOD compensation, the performance of our system gets dramatically reduced to only 100 km. In fact, at 160-GHz repetition rate with pulse width around 1 ps, the TOD becomes the major limiting effect, and consequently, TOD compensation becomes absolutely necessary. To overcome this drawback a high-order mode dispersion compensator module (HOM-DCM) is inserted at the end of the amplifier span. The HOM-DCM is based on the conversion of the LP_{01} mode into the LP_{02} mode, which can reach larger dispersion and dispersion-slope values [14]. The HOM-DCM, with a total dispersion-slope of -1.326 ps/nm^2, is consequently capable to compensate for 96.4% of the total TOD of the loop. The 5.5-dB noise-figure EDFA 2 was inserted into the loop for compensation of the total losses (21 dB) and a 1.8-THz filter prevents amplified spontaneous emission (ASE) noise accumulation in the loop. The signal power at the loop input is controlled by a variable attenuator at optimum level to achieve maximum transmission distance while a set of three optical switches: OS1, OS2 and OS3 ensures the loop synchronization. The ultrashort pulse EDFA 3 finally boosts the signal before detection by a second-harmonic-generation autocorrelator or an optical spectrum analyzer (OSA).

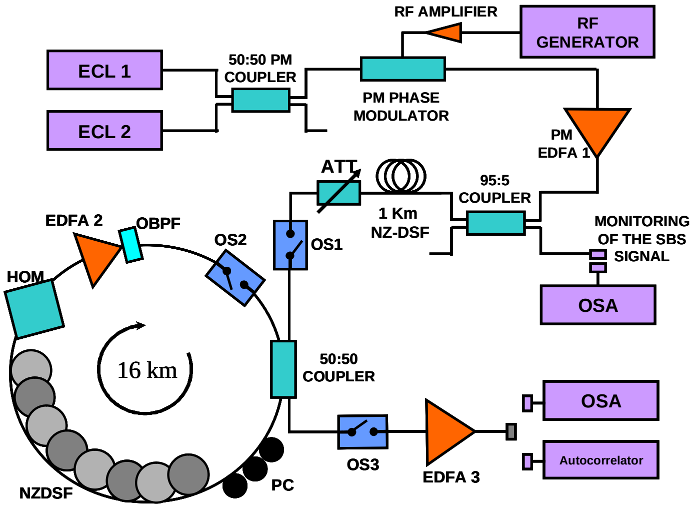

Fig. 3. Experimental set-up showing the 160-GHz pulse train generation and the recirculating loop.

The loop was carefully optimized by inserting about 5 m of SMF for fine-tuning of dispersion compensation. A manual adjustment of the state of polarization within the loop was also required in order to minimize degradation due to PMD. Figure 4(a) shows the evolution of the autocorrelation trace of the 160-GHz pulse train as a function of the propagation distance. Pulse degradations appear as the propagation distance increases, but the signal can be clearly observed until 896 km (56 round trips). We have checked from numerical simulations that the experimental autocorrelation trace obtained at 896 km corresponds to a pulse broadening over less than half of the bit slot, limit in blue dash line on Fig. 4(a). The slight discrepancy between experimental (896 km) and numerical results (1040 km), optimum DDM system on Fig. 2(b), stems from imperfect slope compensation and PMD effect. Indeed, with a PMD of 0.1 ps/km$^{1/2}$, numerical simulations of the coupled nonlinear Schrödinger equations [15] show that Zmax is reduced from 1040 km to 590 km (i.e., below the experimental value) demonstrating the effective role of the polarization controller placed inside the loop.

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After 480 km of propagation the measured autocorrelation traces for different average input powers are shown in Fig. 4(b). It clearly appears from Fig. 4(b) that there exists an optimum average input power of about 13 mW, close to the optimum theoretical value (14.15 mW), for which the output pulse shape gets slightly distorted, while the pulse shape spreads significantly for smaller and higher powers, thus demonstrating the soliton feature of the transmission.

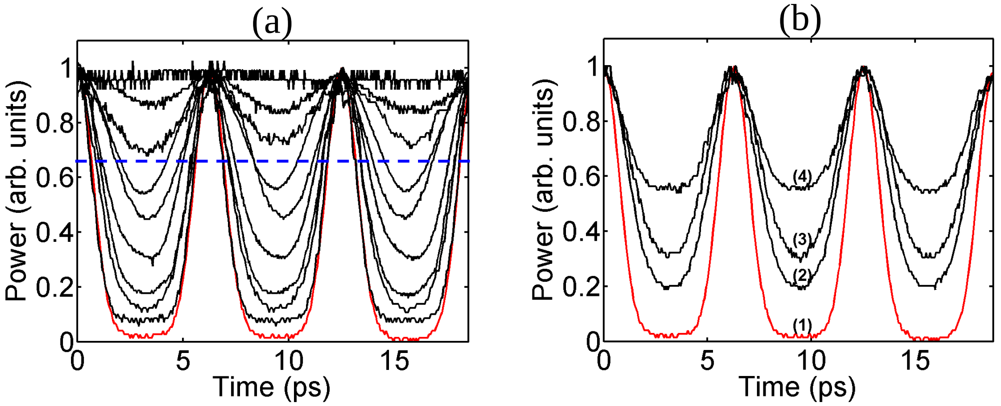

Fig. 4. (a) Evolution of the autocorrelation traces during the propagation. From bottom to top: at 0 km in red solid line, 160, 320, 624, 720, 800, 896, 1104, 1200 and 1408 km. The blue dash-line corresponds to a pulse width of half bit-slot. (b) Autocorrelation traces after 480-km of propagation versus average input power. (1) Initial (red solid line), (2) 13 mW, (3) 10 mW, (4) 17 mW.

From a practical point of view, an amplifier spacing of only 16 km could appear as a bit short for a practical system implementation of a real deployed transmission line, but the total amount of losses in our 16 km-long recirculating loop, corresponds to the same as in a deployed transmission line with an amplifier spacing of 40 km; which implies the same amplifier gain and same noise figure. Consequently, although one can not straight forwardly compare a recirculating loop with a deployed transmission line, our recirculating loop permits to examine the pulse stability in some fundamental conditions which are close to that of a real deployed transmission line. Finally, regarding a pseudo random bit sequence (PRBS); we have noted from numerical simulations that the PRBS case leads to an average penalty of 1dB on the Q factor, thus leading to a transmission distance of 900 km instead of 1040 km in the periodic 160-GHz pulse train case.

4. Conclusion

We have successfully demonstrated the effectiveness of DDM solitons for the practical design of a single-channel 160-GHz transmission system composed of short lengths of standard NZ-DSF±. Through a careful design of the dispersion map and a careful control of the average dispersion, we have constructed a 16 km long recirculating loop enabling a DDM soliton transmission over up to 896 km, without any pre or post-compensation of dispersion. This performance, which was found to be limited by the PMD effect, can be substantially improved through a careful control of the main limiting effects, such as PMD, TOD and coupling losses, by using Raman amplification, alternating polarization of adjacent bits or active inline control elements. Therefore, the present work represents an important step towards 160 Gb/s single channel transmissions over transoceanic distance using short-period dispersion management.

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