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Comparison of conventional and dense dispersion managed systems for 160 Gb/s transmissions

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Abstract

In this paper, we carry out, by numerical simulations and experiments on recirculating loop, a comparative analysis of the performances of two types of dispersion management techniques for 160 Gb/s transmission systems, which correspond to short-period dispersion maps (dense dispersion management) and long-period dispersion maps (conventional dispersion management), respectively. We show that the dense dispersion management system suffers performance degradation by the effects of polarization mode dispersion (PMD) and fiber splicing losses, in a more dramatic manner than in the system with long-period map. We experimentally find that, at constant PMD, dense dispersion managed system permits to achieve a transmission distance that is twice larger than that obtained with the conventional dispersion management; however, the polarization mode dispersion significantly reduces the gap between the transmission performances of the two types of systems.

1. Introduction

Dispersion management has been proved to be an efficient way to improve the performance of high speed long-distance communication systems [1,2]. Basically, dispersion management consists of the concatenation of fiber sections with alternately positive and negative dispersion, so as to reduce the average dispersion experienced by a propagating pulse. In particular, the effectiveness of dispersion management at bit rates of 10, 20, 40, and 160 Gb/s/channel has been demonstrated in several transmission experiments using various types of dispersion map [1–8] that can be broadly divided into two major categories. The first one is the conventional dispersion management technique, in which the dispersion map is made up of a standard single mode fiber (SMF) with a dispersion compensating fiber (DCF), and where the map length Z_P is longer than or equal to the amplifier spacing Z_A. Using this technique, several experiments related to single-channel transmissions [3,4] and wavelength division multiplexing (WDM) transmissions [5] at low and moderate bite rate per channel have been carried out. But those experiments indicate a significant drop in the transmission performances as one increases the bit rate per channel [6–8]. In fact, it is difficult to propagate pulses at bit rates larger than 40 Gb/s/channel in conventional dispersion managed systems on transoceanic distances because of large pulse breathing (induced by the high local dispersion of DCFs and SMFs), which leads to significant pulse overlap and intra-channel four-wave mixing interactions [9].

To overcome this issue, a second major category of technique called "dense dispersion management", based on the use of non-zero dispersion shifted fibers (NZDSF), has been developed [10–16]. In densely dispersion managed (DDM) systems the map length is much shorter than the amplifier span ($Z_P \ll Z_A$); which allows small pulse breathing and hence reduces the pulse-to-pulse interactions. Several numerical studies have suggested the possibility

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of achieving 160 Gb/s single-channel transmissions over transoceanic distances (>6000 km) through DDM systems [15,16]. Such transmission distances are one order of magnitude larger than the transmission distances that can be achieved at 160 Gb/s with CDM systems [17,18]. Thus, previous studies suggest that DDM systems lead to transmission performances that are largely superior to those of CDM systems [15–18]. But here, we like to point out that important propagation effects, namely the polarization mode dispersion (PMD) and coupling losses at the junction between fiber sections in DDM systems, have been ignored in the previous evaluation of the transmission performances of CDM and DDM systems [15–18]. Knowing that when the effects of PMD are considered they become one of the major limiting factors of the system performance at 160 Gb/s [15], it becomes difficult to clearly identify (between the CDM and DDM systems), on the basis of previous studies, what type of dispersion management technique is more robust in the practical situation. Furthermore, in previous studies, CDM and DDM systems have been always examined separately, in operating conditions that are so varied that a fair comparison between these two types of DM systems becomes very complicated.

In this study, we present numerical simulations and experiments on pulse propagation in CDM and DDM systems performed in the same operating conditions (i.e., same transmitter and receiver setup) which allow a direct and fair comparison between these two major types of DM systems. Our study reveals that in the practical situation, the gap between the transmission performances of CDM and DDM systems is much smaller than the theoretical predictions mentioned above. We find that CDM system yields a transmission performance that is only moderately lower than that of DDM system because of the combined effects of splicing losses and PMD, which tend to severely annihilate the robustness of DDM system against intra-channel pulse-to-pulse interactions. The paper is organized as follows: in the following section, we describe the transmission systems and present numerical simulations of the pulse propagation in these two systems. In Section 3, we present the experimental results that we have obtained by means of recirculating loops. In Section 4, we give some concluding remarks.

2. Map design and numerical simulations

2.1. Conventional dispersion managed system

The standard CDM system is schematically represented in Fig. 1(a). This map consists of two sections of fibers: a single mode fiber (SMF) with the following typical parameters: dispersion $D^- = 17$ ps/nm/km, dispersion slope $S^- = 0.056$ ps/nm^2/km, length $L^- = 100$ km, losses $\alpha^- = 0.2$ dB/km, effective core area $A^-_{\text{eff}} = 80\ \mu\text{m}^2$, followed by a dispersion compensating fiber (DCF) with typical parameters $D^+ = -100$ ps/nm/km, $L^+ = 17$ km, $\alpha^+ = 0.6$ dB/km and $A^+_{\text{eff}} = 20\ \mu\text{m}^2$.

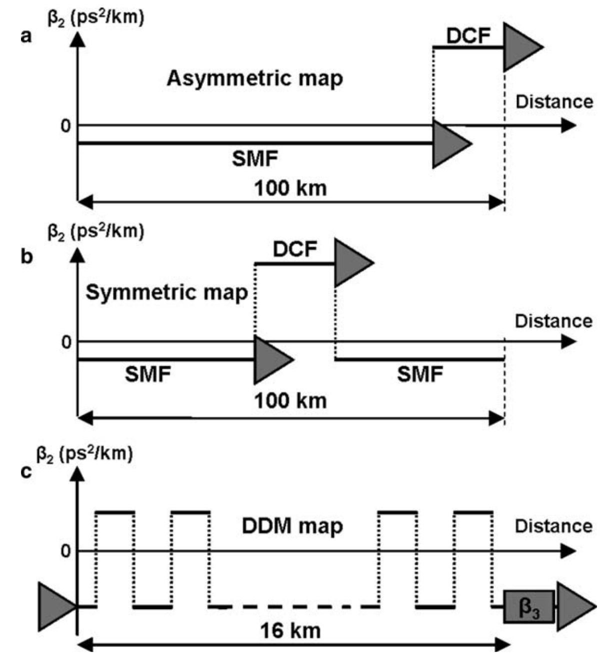

Fig. 1. Schematic diagram of: (a) CDM system with asymmetric dispersion map, (b) CDM system with symmetric dispersion map and (c) DDM system.

As can be seen in Fig. 1(a), the CDM system makes use of a double-stage amplification [17] and can be divided into two categories. The first one corresponds to an asymmetric map (AM), that is, a map in which the input point of the dispersion map is relatively far from the nearest chirp-free point. Consequently, this map corresponds to an AM. On the other hand, it has been shown that CDM with symmetric dispersion map (i.e., in which the chirp-free point is close to the input point of the dispersion map), yields a better performance than that of the CDM with AM [18]. Indeed, in the system with symmetric map (SM) the range of intra-channel interactions of each pulse with neighbouring pulses is half of the range of such interactions in the AM, which makes transmission of pulse trains in the AM more prone to pulse interactions and related effects such as generation of ghost pulses and amplitude fluctuation by intra-channel four wave mixing [18,19]. The CDM system with a symmetric map (SM) consists of three sections of fibers ($L^-/2$, L^+, $L^-/2$), as Fig. 1(b) shows, and two amplifiers with equal gains [18]. Throughout the present paper we have not considered elements of pre- and post-compensation of dispersion in any of the systems that we have considered. For the two configurations of CDM systems under consideration, the length of the period of dispersion swing is $Z_D = L^+ + L^- = 117$ km. The system design is essentially based on a careful choice of the DCF parameters (length and slope), so as to satisfy the 100% compensation of the second and third-order dispersion of the CDM map. Then, each map is repeated to build the line associated with each configuration. A major advantage of CDM system is that one can easily design the dispersion map by using the current fiber technology.

To examine the influence of PMD on the transmission performance of the CDM system in a more realistic situation than that of previous studies [17,18], we have performed numerical simulations of transmission of 1024-bit PRBS patterns of Gaussian pulses in a single channel lines operating at 160 Gb/s, with an amplifier noise figure of 5 dB, Gaussian filters with bandwidth 1.8 THz and 3 dB losses. For the simulations, we have solved the generalized NLSE including the third-order dispersion and amplifier noise, by means of a split-step Fourier simulation tool [20]. In our simulations, we have included the polarization mode dispersion (with a coefficient of 0.1 ps/km$^{1/2}$), which has been neglected in previous studies [17,18]. We have not included the stimulated Raman scattering, which plays a relatively minor role at 160 Gb/s [21]. The transmission performance is evaluated by means of the Q factor in linear units and a set of 50 simulations was averaged for each map in order to take into account the statistic feature of PMD. $Q = 6$ corresponds to a bit-error ratio of 10^{-9}. We define the *transmission distance*, $L_{\max}$, as the distance over which the Q factor remains higher than 6. Fig. 2(a) shows the results that we have obtained after optimising the input average power, say P_{opt}, for each configuration of CDM system to achieve maximum transmission distance. We then find the following transmission performances: AM: $L_{\max} = 675$ km, $P_{\text{opt}} = 5.9$ dBm; SM: $L_{\max} = 750$ km, $P_{\text{opt}} = -3.8$ dBm. For comparison, Fig. 2(b), which shows the simulations neglecting the PMD effect, gives a transmission performance of $L_{\max} = 800$ km for the AM, and $L_{\max} = 900$ km for the SM. This comparison clearly demonstrates that the performance degradation induced by PMD in the CDM system is relatively moderate (about 10%).

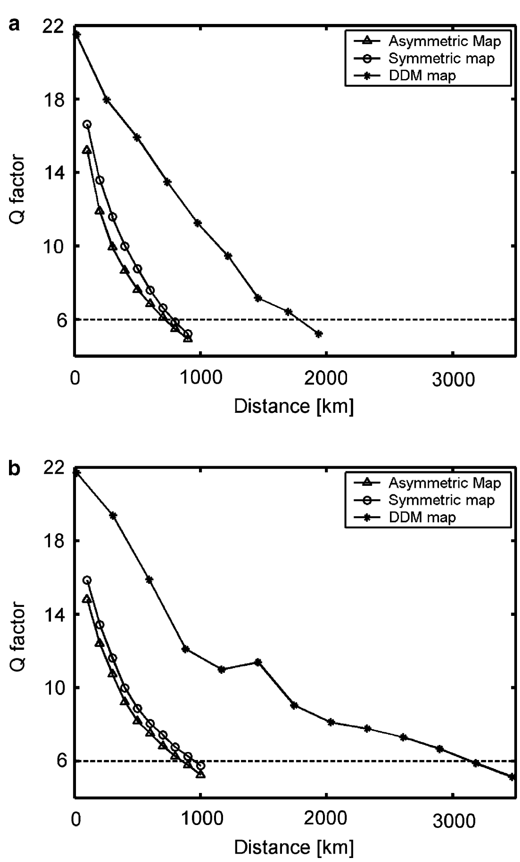

Fig. 2. (a) Numerical simulation results in presence of PMD and (b) the same without PMD.

2.2. Densely dispersion managed system

DDM systems are generally made up of non-zero dispersion-shifted fibers (NZDSF) having a much smaller local dispersion than that of CDM systems [10–16]. Basically, the amplifier span Z_a is made up of many periods of dispersion management, Z_p, such that $Z_a = nZ_p$ with $n \gg 1$, as schematically represented in Fig. 1(c). Pulse breathing and transmission performances of DDM systems are closely related to the map strength defined by $S = \lambda^2[D^+L^+ - D^-L^-]/2\pi c\Delta^2$ [10–16], where Δ is the full width of the pulse at half-maximum (FWHM) at chirp-free point, c is the light velocity, λ the transmission wavelength, and D^+, L^+, D^-, L^- are the second-order dispersions (in ps/nm/km) and lengths (in km) of the normal and anomalous fiber sections of the DM period. An important feature of DDM systems is the presence of a large number of periods within each amplifier span, which considerably increases the amount of coupling losses at junction points between the different pieces of fibers (whereas in the CDM systems, there are only two junctions points in each amplifier span).

Designing and optimizing a DDM system is a lengthy and complicated procedure (when compared with that of a CDM system), developed in [14–16,22]. A study of the transmission performance of a DDM system has been carried out in [14], based on NZDSF with local dispersions of 1.64 and −1.84 ps/nm/km, respectively, effective areas of 59 and 55 μm^2, linear fiber losses of 0.2 dB/km and splicing losses between adjacent fibers of 0.1 dB. The amplifier span was fixed to 16 km, and the map strength S could be varied through variation of the number of dispersion period n within each amplification span. An amplifier with a 5.5 dB noise figure was used to compensate for the total losses within each amplifier span and an optical bandpass filter with 1.8 THz FWHM and 3 dB losses was used to suppress noise accumulation. Nevertheless, the relatively short length of the amplifier span of the DDM system imposes the use of a considerably large number of amplifiers to cover a distance of several thousands of kilometers. This gives rise to a relatively large amount of amplifier noise in the system, which cannot be totally suppressed by the filters. Consequently, the noise effect should play a harmful role in the transmission performance of the DDM system. On the other hand, as negative slope NZDSFs are not yet commercially available, in previous works [15,16], the problem of third-order dispersion (TOD) compensation was resolved in a rather artificial way by assuming an ideal NZDSF with negative slope. In our study, the TOD compensation is achieved by means of a compensating module (HOM) which fully compensates for the total dispersion slope of the DDM line, but meanwhile, this device introduces additional 3 dB coupling losses, which increase the instability of the DDM system. The input pulses are chosen to be a 160 Gb/s train of transform-limited Gaussian pulses with 1.27 ps FWHM. Neglecting the PMD, the optimum configuration was found to be $S = 2.6$ [14] (which corresponds to $n = 8$, $L^- = 1059.3$ m and $L^+ = 940.7$ m) while an average power of 7 dBm, which leads to a maximum transmission distance of ~3000 km, as shown in Fig. 2(b). This distance is three times larger than the transmission distance achieved with the CDM systems in the absence of PMD. On the other hand, we have carried out numerical simulations in the same conditions as for Fig. 2(b), but by including not only the splicing losses but also the PMD (with a coefficient of 0.1 ps/km$^{1/2}$). Here also, in order to take into account the statistic feature of PMD, we have evaluated the Q factor from an average over 50 realizations. The system performance is displayed in Fig. 2(a), which shows a transmission distance of 1700 km. This distance is half of the transmission distance without PMD and only twice larger than the transmission distance achieved with the CDM system. Thus, these numerical simulations show that PMD dramatically degrades the transmission performance of DDM systems and consequently, strongly contribute to reduce the gap between the transmission performances of DDM and CDM systems.

3. Experiments

To verify experimentally the general features mentioned above, we have built three recirculating loop setups corresponding to the CDM system with AM, the CDM system with SM, and the DDM system, respectively. Those recirculating loops are schematically represented in Fig. 3(a)–(c).

We have injected in each loop a 1.3 ps pulse train generated at 160-GHz by means of a multiple four-wave mixing (FWM) technique [23]. This FWM-based pulse train generator is schematically represented in Fig. 3(d). We have analyzed the quality of transmission by means of an autocorrelator and recorded the autocorrelation traces as a function of propagation distance for the three kinds of configurations. As typical example, Fig. 4(a) displays the autocorrelation function in the symmetric dispersion map from 0 to 3100 km. In these experiments, the optimum average powers leading to the best performances were found to be 9 dBm for the CDM system with AM, −1 dBm for the CDM system with SM, and 11.1 dBm for the DDM system, respectively, in quite good agreement with the numerical results (note that the experimental bit sequence contains only "ones" marks). Finally, considering the difference between the PMD parameters of the fibers available for our experiments (0.1 ps/km$^{1/2}$ for the DDM system and 0.05 ps/km$^{1/2}$ for the CDM system), in an effort to obtain a fair comparison between the transmission qualities for the CDM and DDM system, we have measured the autocorrelation background as a function of the cumulated Differential Group Delay (DGD = PMD · Distance$^{1/2}$). Fig. 4(b) exhibits the following general features: one can clearly observe that during propagation, the CDM system with a SM ensures a better quality of transmission than the CDM system with AM can do, in agreement with the theoretical predictions. Secondly, for a constant autocorrelation background of 0.66 (dashed line in Fig. 4(b)), i.e., for a pulse quality corresponding to 3.125 ps Gaussian pulses, the DDM configuration leads to a total DGD that is 20% greater than that of the other configurations (3.2 ps vs. 2.63 ps for SM), which corresponds to an improvement of the transmission distance by nearly 50% at a constant PMD. This result is also in good agreement with the numerical simulation results.

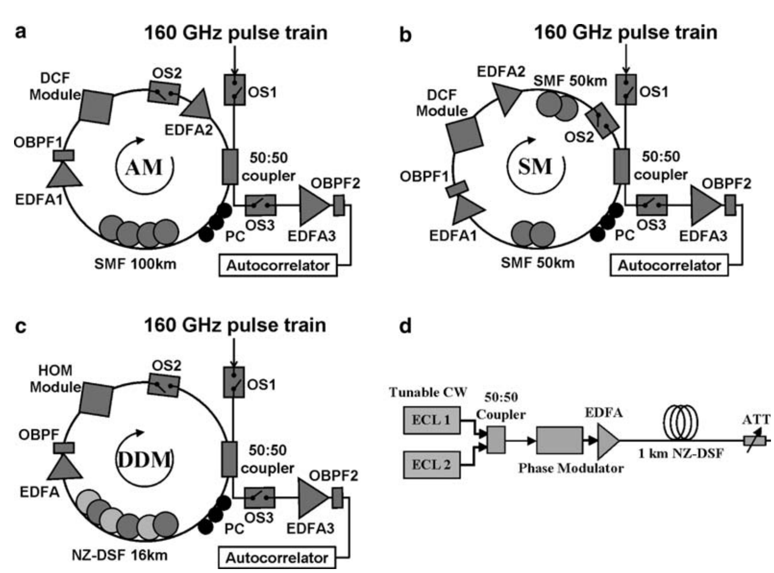

Fig. 3. Experimental setups of the three maps under test: (a) asymmetric map, (b) symmetric map, (c) DDM map (OS: optical switch, PC: polarization controller) and (d) experimental setup of the 160-GHz source.

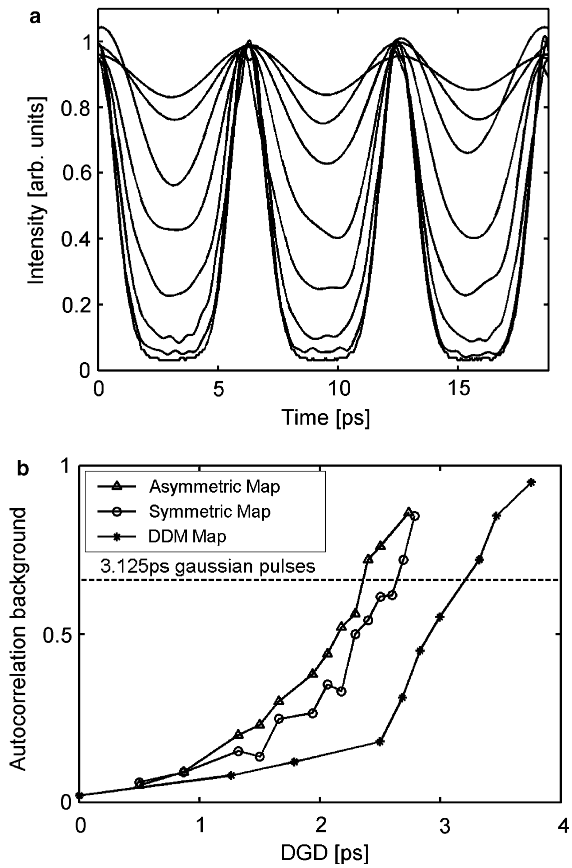

Fig. 4. (a) Evolution of the autocorrelation trace of the 160-GHz pulse train as a function of propagation distance in the symmetric dispersion map, from bottom to top at 0, 100, 900, 1500, 1900, 2100, 2700, 2900 and 3100 km, (b) autocorrelation background of the 160-GHz pulse train as a function of cumulated DGD for the three different maps.

4. Conclusion

In the present context of research and development activities in the area of optical communications, the *capacity × distance* product is no longer at the top of the list of factors of high interest. Factors such as the cost constraint, complexity of system design, and technology availability, are becoming key factors, which will prominently determine the development of optical transmission systems in the next years. Consequently, to achieve a fair comparison between current transmission technologies that are under development for increasing the bit-rate per channel in future transmission systems, it is useful to take into account several important factors. In this paper, we have numerically and experimentally compare the CDM and DDM systems that have been promoted in previous studies to the rank of potential candidate for ensuring long-distance transmissions at 160 Gb/s per channel [15]. We have shown that the performance of DDM systems, which have been proposed as one of the best ways to achieve 160 Gb/s single-channel transmissions over transoceanic distances [15], are highly sensitive to the effects of PMD and splicing losses. Another important factor lies in the presence of a relatively large amount of amplifier noise in DDM systems, which is only partially suppressed by the filters. Hence, the combined effects of PMD, excess (splicing) losses, and amplifier noise, induced by the particular configuration of the DDM system, considerably reduce the gap between the transmission performances of the DDM and CDM systems. Indeed, whereas the transmission distances for DDM systems have been found to be one order of magnitude larger than the transmission distances for CDM systems in the ideal case without losses and without PMD [15,16], we have shown that in the presence of the excess splicing losses induced by the DDM configuration, the ratio between the transmission distances of these two systems drops to $\sim$3. In the presence of splicing losses and PMD, the DDM system still exhibits the largest transmission distance, but which is only twice larger than that of the CDM system. Nevertheless, the CDM system offers several advantages over the DDM system, such as the:

(i) Availability of simple rules for designing and optimising the system, whereas an appropriate design of a DDM system corresponds to a complicated and lengthy procedure, which generally ends up with severe constraints on the input pulse parameters. Indeed, as DDM systems are ruled by several important (fiber and pulse) parameters, one should carry a multi-dimensional analysis applying simultaneous variations of all major parameters. This approach, involves massive numerical simulations, is considerably complex and time-consuming.
(ii) Technology availability, which enables fabrication of slope compensating DCF that perfectly compensates the SMF dispersion.
(iii) Presence of SMF in many existing terrestrial networks, which provides the possibility of upgrading those networks in much easier and less costly way than one could do with a DDM system.

The above-mentioned advantages make the CDM systems quite attractive at least for future terrestrial networks. Furthermore, we have established a slight improvement of the transmission performance in a CDM system using a symmetric map, which suggests that a more advanced dispersion map can make the CDM system more robust and attractive for a large variety of transmission networks. Comparatively, we believe that much effort remains to be done to make the DDM system attractive for future networks. Although current fiber technology allows to suppress the fiber splicing losses (i.e., makes possible the fabrication of a fiber with alternately positive and negative dispersion in a continuous draw without splicing [13]), other important issues such as the PMD effects, the tolerance of the system with respect to fluctuations in the input pulse parameters or fluctuations in the line parameters, remain to be resolved to make the DDM system more robust. This effort can be carried out in at least two directions: a breakthrough towards a more refined dispersion map and the use of active control elements may reinforce the pulse robustness in DDM systems.

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