Mitigation of Polarization-Mode Dispersion in Optical Multichannel Systems

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***Abstract*—Simulations of first-order polarization-mode dispersion (PMD) mitigation, based on the electrical power spectrum has been performed. We show that, although first-order compensation significantly improves the signal quality for PMD values of a few tenths of the bit-slot, the improvement still is deficient for telecom purposes when the PMD value neighbors a third of the bit-slot. We, therefore, propose and analyze a novel concept for PMD mitigation in optical multichannel systems, which increases the systems reliability at the expense of the total capacity for the same system. With the proposed method, which uses switching to redundant channels based on measurements of signal quality of all channels in the actual system, the PMD value can be increased to a half of the bit-slot while still keeping the probability for signal outage at acceptable low levels. In the appendixes we simulate the statistical impact of different PMD-emulator models and we show that static bit sequences may induce notches in the electrical power spectrum. These notches may obstruct the extraction of feedback signals for PMD-mitigator schemes based on electrical power spectrum.**

***Index Terms*—Compensation, electrical power spectra, optical-fiber communication systems, polarization-mode dispersion (PMD), PMD emulator, PMD mitigator, polarization, wavelength division multiplexing (WDM) systems.**

I. Introduction

A. Polarization-Mode Dispersion (PMD)

POLARIZATION mode-dispersion (PMD) arises in fibers when the cylindrical symmetry is broken due to noncircular core or noncircular symmetric stress. The loss of circular symmetry destroys the degeneracy of the two eigenpolarization modes in the fiber, which will cause different group velocities for these modes. In standard single-mode fibers PMD is random, i.e., it varies from fiber to fiber. Moreover, in the same fiber PMD will vary randomly with respect to wavelength and ambient temperature. This behavior can be explained by different geometrical stress irregularities along the fiber length combined with coherent interference between the two eigenpolarization modes. Since there are many cross-coupling points in the fiber, in which coherent interference occur, the final result can be described as a random-walk process according to a Maxwellian distribution [1]. Since PMD has a statistical nature, it is common to denote a single outcome of the statistical process as differential group delay (DGD) whereas PMD is the expected mean value of the same process.

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B. Compensation of PMD

Due to the statistical nature of PMD, it cannot be compensated or mitigated with fixed compensators and all PMD compensation techniques must, therefore, rely on feedback systems. Two common sources of feedback information is the degree of polarization (DOP) and the electrical power spectrum. The first method utilizes the depolarizing effect that PMD has on signals by measuring and maximizing the degree of polarization in order to suppress PMD induced broadening of the input pulse [2]. In a field measurement with this method in combination with first-order compensation, a receiver ran "mostly error-free," at 10 Gb/s with an average DGD of 30% of the bit-slot, for a time span of 45 days [3]. The second method is potentially more straightforward to implement in a practical system and it bases the feedback on the electrical power spectrum [4]. This method has also shown an ability to control a compensator for mostly error-free results [5], [6]. The feedback information from the two methods is often used to control a first-order compensator consisting of a polarization controller followed by a birefringent section, but multisection setups have also been used [7], [8]. Alternative compensating methods are, among others, equalizers in the electrical domain [9] or launching of the output polarization in a principal state [10]. However, a drawback with all published compensation methods is that they merely suppress first-order effects and that they do not work satisfactory in the tail of the PMD distribution.

C. This Paper

The purpose of this paper is twofold. First we investigate the limitations of first-order compensation based on simulations of feedback from the electrical power spectrum, and of first-order compensation in general. We show that the spectral feedback method has the ability to utilize compensation possibilities of a first-order compensator and we conclude that first-order compensation is beneficial for pulse-shape restoration of random bit sequences. However, to reach a signal outage level acceptable in telecommunications systems, higher order compensation is probably necessary. In Section III, we propose a novel method to improve the bit error rate (BER) of a system limited by PMD. The concept uses switching in a wavelength-division multiplexed (WDM) system, where some channels are reserved for protection. Thereby, high-quality transmission capacity can be obtained at bit rates substantially higher than in present systems. The reason is that the method enables both compensated and uncompensated systems to operate at bit rates where single channels have a relatively high probability of failure. When traffic on a channel starts to be distorted it can be redirected. Correctly designed, the increased channel bit rate will surpass the average channel capacity needed for protection. With this method, five times as much PMD can be tolerated compared to the suggested International Telecommunications Union (ITU) limit (Recommendation G.691).

II. Mitigation of PMD

A. Single-Channel Simulations

1) The PMD Emulator: The model used for single-channel simulations is explained with reference to Fig. 1. The optical modulator to the left generates a nonreturn-to-zero (NRZ) data signal at 10 Gb/s with a raised-cosine pulse-form, i.e., a single pulse has a $\cos^2$-shaped pulse-form. The next block is the PMD emulator which consists of 20 randomly concatenated segments of high-birefringence fiber. The number of segments was considered as high enough to give a continuum of time-of-flights for this purpose [11], see Appendix A. In the PMD emulator, the difference of time-of-flight for the two eigenmodes in each segment was set to $(\Delta\tau/\sqrt{20})N(1, 0.2)$, where $N(\mu, \sigma)$ is the normal distribution with expectation value μ and variance σ^2, where $\Delta\tau$ was the PMD value for the emulator.

2) The PMD Mitigator: The PMD mitigator, the dashed box in Fig. 1, consists at its input of a polarization converter directly followed by a single segment of high-birefringence fiber; the difference of flight-of-times was set to the same $\Delta\tau$ that was used for the PMD emulator. The polarization converter can be modeled in a number of different ways. Here we used a standard configuration of a lambda-quarter plate followed by a lambda-half plate and a second lambda-quarter plate. All three plates can be rotated independently relatively to each other. With a static $\Delta\tau$ for the PMD mitigator, we can look upon the mitigator as a device that adds a PMD vector of length $\Delta\tau$ to the PMD vector generated by the emulator. This means that the PMD mitigator might run into trouble for very low and very high DGD levels out from the PMD emulator, i.e., in the tails of the DGD distribution.

3) The Detector and the Bandpass Filters: The signal at the output of the birefringent fiber was detected with a standard intensity detector followed by a fourth-order Bessel–Thomson filter with a 3-dB bandwidth of 7.5 GHz.[1] The feedback signal was extracted from two bandpass (BP) filters with center frequency and 3-dB bandwidth of 2.5 GHz and 0.5 GHz for the first BP filter and 5.0 GHz and 0.5 GHz for the second BP filter. All BP filters were in this case modeled with Lorentzian transfer functions. The response from the BP filters is then fed to the control logic which controls the polarization converter. The PMD mitigated output signal is taken at the output from the fourth-order Bessel–Thompson filter.

4) Random or Static Bit Sequences: After every simulation we saved three time-domain signals after the detector: the uncompensated signal, the lowest eye-opening penalty after 216 different combinations of the wave-plate positions, and the signal for which the added power from the BP filters was maximized. The latter signal was chosen among the above mentioned 216 scanned positions. This signal will hereafter be referred to as the first-order compensated signal. In the simulations, we used optical signals with cyclic bit sequences containing 128 randomly selected bits. The reason for this choice is that a random signal describe the reality better than tested static signals, see Appendix B for a discussion concerning bit sequences.

[1]According to the ITU-T Recommendation G.957.

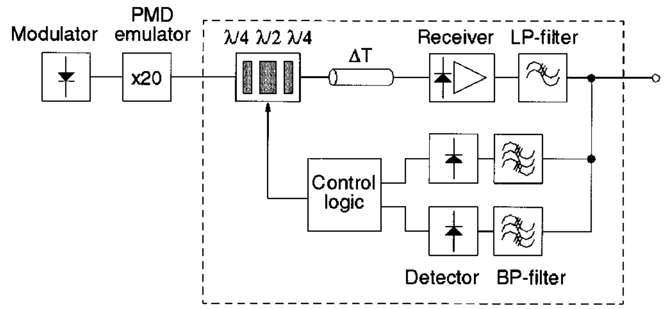

Fig. 1.

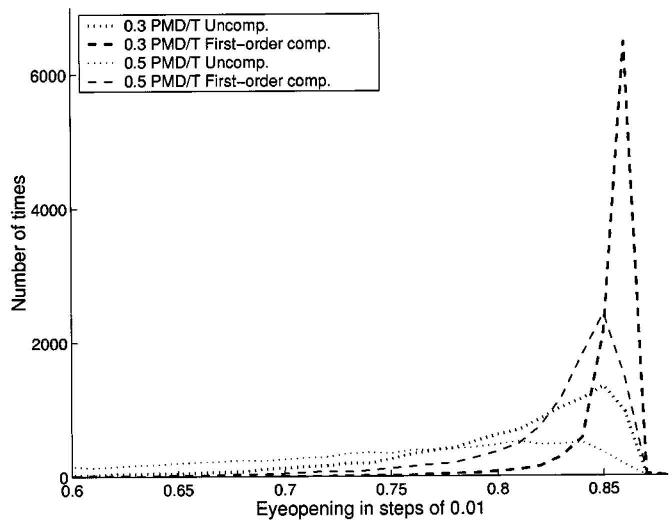

Fig. 2. PMD is stochastic. This can be visualized by plotting the eye opening in steps of 0.01 for 10^4 simulations, e.g., measurement situations, with PMD/T-ratios of 0.3, respectively 0.5.

B. Success Ratio

With published methods like the ones mentioned in Section I it might be possible to compensate for a PMD value of half of the bit slot, which equals a PMD/T ratio of 0.5, during a time span limited to some hours or some days. However, no method makes it possible to compensate for enough of all statistical outcomes of PMD-induced pulse distortion to meet normal system requirements on a year-long basis. This problem is visualized in Fig. 2, where the eye opening after 10^4 simulations before and after first-order compensation is plotted. Every simulation was followed by a random change in input polarization, bit sequence, angles between the fiber sections, phase shift in the splices, and the birefringence in order to simulate measurements separated by a time span long enough to remove all correlation with the previous one. The resulting eye openings varied from values close to zero up to an upper limit of 0.87 instead of 1.0, due to a fourth-order Bessel–Thompson LP filter in the receiver model.

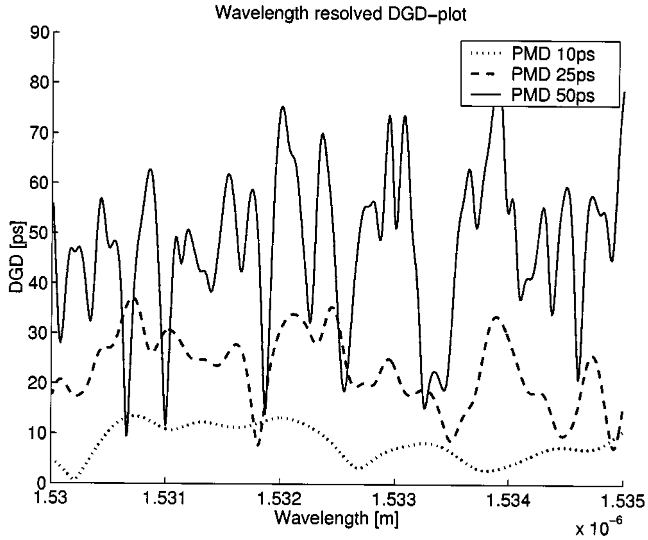

Fig. 3. DGD versus wavelength for 10/25/50 ps of PMD according to our 20-section emulator model. The wavelength span corresponds to six channels separated by 0.8 nm or 100 GHz.

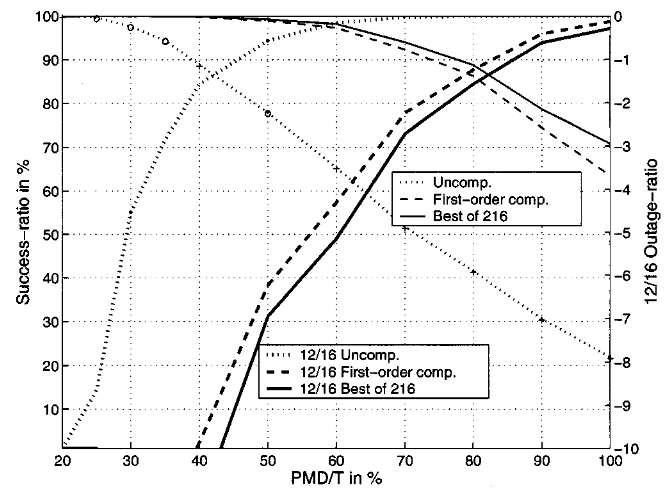

Fig. 4. Success ratio and $\log_{10}$ of the $12/16$ outage ratio; "+" denotes 10^3 simulations and "o" denotes 10^4 simulations. Note that at 0.5 PMD/T, the compensated single-channel signal has a success ratio of 99% which means that 99% of the samples in Fig. 2 should statistically have an eye opening greater than 0.63.

When the eye opening is close to the upper limit, the BER of the channel can be assumed to be limited by the system as such. To have an unambiguous definition of a successful compensation we choose to define a lower limit or a success limit as an eye opening of 0.63, corresponding to a 2-dB reduction in receiver sensitivity in a system that is limited by thermal noise. At this success limit, we assume that the BER is 10^{-6}. After a fiber with a PMD/T ratio of 0.5, our first-order compensator managed to exceed the success limit in 99% of the situations, which equals a success ratio of 99%. This meant that the first-order compensator did not work in 10^2 out of 10^4 measurement situations and, as can be seen in Fig. 2, the first-order compensated 0.5 PMD/T statistics is only slightly better or more biased to the right than the uncompensated 0.3 PMD/T statistics, compare the dashed line (0.5 PMD/T first-order compensated) with the bold dotted line (0.3 PMD/T uncompensated). The average first-order compensated eye opening after the 0.5 PMD/T fiber in Fig. 2 is 82%, but the lower tail of the distribution is wide. For some statistical outcomes our PMD first-order compensator and the best of the 216 points did not work well enough. This lead to periods of time with unacceptable high BER. With 20 000 simulations with a PMD/T-ratio of 0.3 the compensator as well as the best of the 216 scanned points failed four times. This indicates that already at this level it is difficult to benefit from first-order compensation in practice.

III. A Multichannel System

The switched mitigating method can be explained in three steps. First, we start with some observations which are presented in Fig. 3. In a WDM system over a fiber link with PMD, the DGD for different channels varies in time compared to each other. The time and wavelength variations for all channels are centered on the same DGD, i.e., all channels experience the same PMD. We also assume that the PMD value is high enough to remove all correlation between neighboring channels, for a WDM system with, e.g., a 100-GHz channel spacing this is valid when the PMD value exceeds 10 ps [12]. Second, we calculate the previously mentioned success ratio for a number of uncorrelated samples at each PMD value. In a third step, we consider a WDM system as a unit and use the success ratio for a single channel as an input to a binomial distribution. This enables us to calculate an outage ratio for a system, which is the probability that less than 12 out of 16 channels have an eye opening that exceeds the success limit. As can be seen from the right y-axis in Fig. 4, a 10^{-6} outage ratio for the WDM system as a unit is found at a PMD/T ratio slightly over 0.5 for a first-order-compensated system. For an uncompensated system, the 10^{-6} outage ratio is found at a PMD/T ratio slightly over 0.25. At these points, the success ratio for a single channel is $99 \pm 0.2\%$, with a confidence of 0.95 [13]. Note also that our algorithm in most simulations managed to find the best of the 216 scanned positions, which can be seen in the minor difference between the dashed and the solid curves in Fig. 4.

The outage ratio is 0.15 for a 16/16 system when the success ratio is 99%, [2] which means that there is a 15% probability that one channel or more should have an eye opening below the success limit in a simulation. Combined with the 12/16 outage ratio we conclude that the four channels used for protection could be used for low-priority traffic, with a BER lower than 10^{-6}, with a 0.15 probability for a channel failure, and that three fourths of the traffic could be guaranteed to carry high-priority traffic, with a BER lower than 10^{-6}, with a 10^{-6} probability of failure. In other words, if a system has several channels and switching is allowed, and if the system is considered as a unit, it is possible to construct an acceptable system at PMD/T ratios where a single channel has a 1% probability for an outage. This is illustrated in Fig. 5, where DGD is mapped as a function of time and wavelength and, as additional information, 10 WDM channels are marked as black lines, solid when the DGD is low and dotted when the DGD is too high to enable quality transmission.

[2]The 16/16 outage ratio is calculated as $1 - 0.99^{16}$.

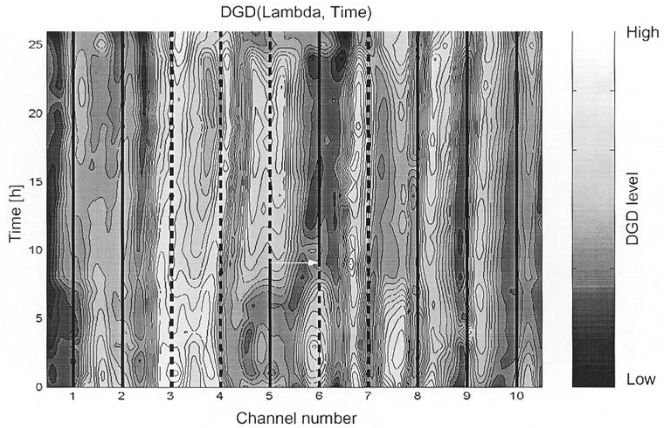

Fig. 5. Wavelength–time resolved DGD plot. The DGD value is represented as greyscale in the xy-plane. The solid black lines represent active channels and the dashed black lines represent inactive channels. The white arrow marks channel switching where a channel with high DGD is switched to another channel with low DGD. The DGD plot is based on a real measurement, but channel spacing, wavelength interval, etc., have been altered for illustrative purposes. In this example, we use six out of ten channels with one channel switching during a 26-h period.

As can be seen from the figure, five channels could be used continuously for 26 h, whereas a sixth channel could be held open by switching.

The switching will additionally make it possible to exploit the performance improvement of different modulation formats or the PMD compensators of today, even if they do not reach a satisfying statistics on a single-channel basis. In Fig. 6, which is a suggested implementation, the switching is controlled by quality monitoring in the management system.

The suggested ITU limit (Recommendation G.691) for PMD/T, a theoretical prediction [14] of first-order compensation with a BER of 10^{-6}, and our results are summarized in Table I. It should be noted that the statistical models differ between the rows of the table and they should not be straightforwardly compared with each other. We can just note that if a single uncompensated channel is operated at the suggested ITU limit of 0.1 PMD/T, the momentary DGD exceeds 0.35 with a probability of 10^{-6}. Exactly how this would affect the BER of a channel is system-dependent and the same eye-opening dependence in BER calculations is also valid for a 12/16 system.

The new fiber has PMD ratios below 0.1 ps/$\sqrt{\text{km}}$, but in many fibers installed, the PMD ratios are in the range between 0.1 and 2 ps/$\sqrt{\text{km}}$ [5]. This means that PMD values between 2.5 and 50 ps are common in 600-km links whereas the ITU standard proposes 10/2.5 ps as PMD limits for 10/40-Gb/s transmission. When the protection level of the switched method is increased, both the BER and the maximum tolerated PMD are improved, at the expense of total capacity of the system. In our first-order compensated 12/16 example, the PMD/T ratio is increased five times. If we assume that the BER at the 12 best channels out of 16 at a PMD/T ratio of 0.5 is comparable to the BER at the suggested ITU limit of 0.1 PMD/T, a four-time faster system could be installed, which is the common increase in bit rate of telecommunication systems, see Table II.

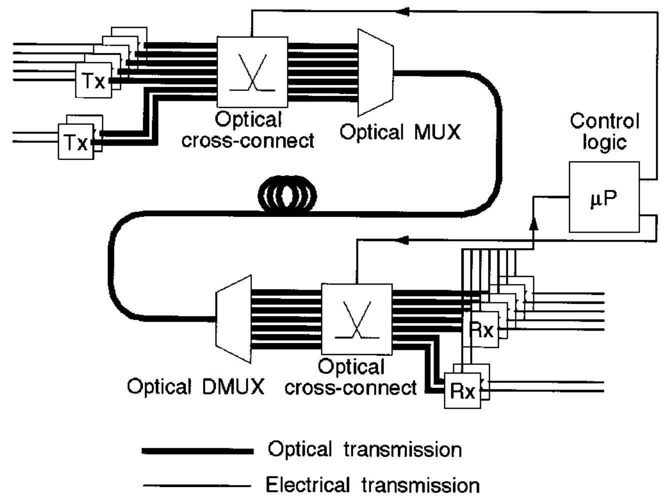

Fig. 6. The switching can be performed in the electrical or in the optical domain.

TABLE I
MAXIMUM PMD AND AVERAGE CHANNEL BIT RATE OF A 16-CHANNEL EXAMPLE SYSTEM FOR FOUR DIFFERENT SYSTEM MODELS

Method	Max PMD	Channel Cap.
ITU	0.1T	16/16B
Theoret.	0.35T	16/16B
Switched	0.25T	12/16B
Switched&Comp.	0.5T	12/16B

TABLE II
MAXIMUM PMD AND TOTAL SYSTEM BIT RATE OF A 16-CHANNEL SYSTEM FOR FOUR DIFFERENT SYSTEM MODELS

Method	10 Gbps PMD	10 Gbps Sys.Cap.	40 Gbps PMD	40 Gbps Sys.Cap.
ITU	10 ps	160 Gbps	2.5 ps	640 Gbps
Theoret	35 ps	160 Gbps	8.5 ps	640 Gbps
Switched	25 ps	120 Gbps	6 ps	480 Gbps
Sw.&Comp	50 ps	120 Gbps	12 ps	480 Gbps

IV. CONCLUSION

We have proposed an analyzed a novel concept for PMD mitigation in multichannel systems. The method is based on looking at the system as a unity and define the system as working when a certain part of the total number of channels is working. Thereby an uncompensated system can be operated at a PMD/T ratio of 0.25 and if the proposed method is combined with first-order PMD mitigators, working on single-channel basis, the PMD/T ratio can be increased to 0.5. In both cases, the number of available channels is decreased by one fourth, i.e., four channels are used for protection in a 16-channel system. In other words, with the proposed method we do not try to fight the tail of the PMD distribution, we simply switch over to another channel with a better signal quality. This makes it is possible to construct an acceptable system even if a single channel has a probability of 1% for a BER higher than 10^{-6}. The simulations also showed that a first-order PMD mitigator controlled by feedback from

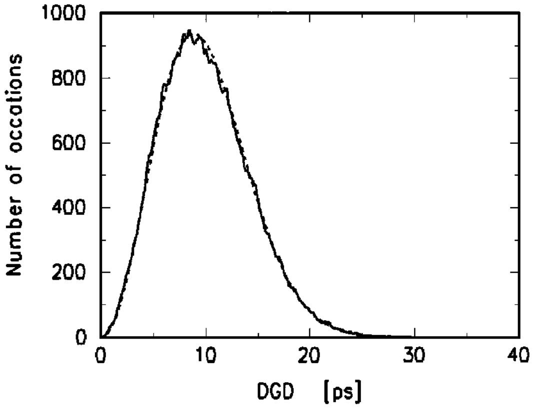

Fig. 7. Variable connections and different fiber lengths. The solid line in the figure is the calculated DGD distribution, the dashed line is the theoretical prediction.

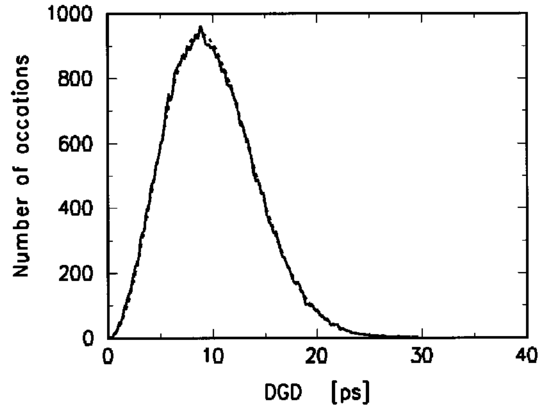

Fig. 8. Variable connections and equal fiber lengths. The solid line in the figure is the calculated DGD distribution, the dashed line is the theoretical prediction.

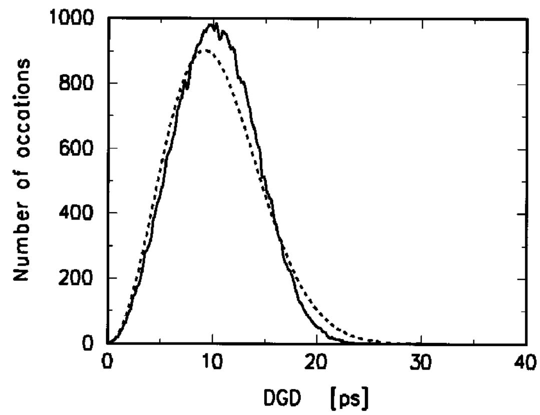

Fig. 9. Fixed connections and different fiber lengths. The solid line in the figure is the calculated DGD distribution, the dashed line is the theoretical prediction.

the detected electrical power spectrum usually managed to find the best of the 216 different mitigator settings for tested PMD/T ratios in the range between 0.2 and 1. This means that electrical feedback offers an excellent method to control a first-order PMD mitigator.

APPENDIX A

Today, it is a common method in laboratory environment to build PMD emulators by fusing short lengths of randomly connected high-birefringence (HiBi) fibers together. The number of fibers normally varies between 10 and 20 [11], [15]. In computer models, HiBi-fiber PMD emulators are often simulated with one section where the signal is coupled to both the fast and the slow axes of the HiBi fiber; thereafter, the signal arrives at the output of the fiber with different flights of time. Then the signal is coupled into the next HiBi fiber, which has a random orientation of its principal axis with respect to the previous one. This coupling is done with both amplitude and phase taken into account at the cross-coupling point. The reason that both amplitude and phase are treated at the cross-coupling points is that the total DGD of the emulator is considered to be smaller than the coherence time of the DFB laser used. This procedure is repeated for every section in the PMD emulator.

Common questions for HiBi-fiber PMD emulators are how many sections shall be used, if all fiber sections shall be of equal or of random length, and if there should be fixed or variable connections between the sections. In a practical case, variable connections can be difficult to administrate, but in a computer model they can be added with very little extra effort. In Figs. 7–9, we compare the DGD statistics produced by simulated wavelength scanning at 10^5 wavelengths with a theoretical prediction for three different 20-section HiBi-fiber PMD emulators, each designed for a PMD of 10 ps. The three cases are: a variable connections and different fiber lengths, Fig. 7; a variable connections and equal fiber lengths, Fig. 8; and a fixed connections and different fiber lengths, Fig. 9. A variable connection means that new angles were used between fibers for every simulation. A fixed connection means the same angles for all simulations. A different fiber length means that new Gaussian-distributed fiber lengths were calculated for every simulation. An equal fiber length means that the same and equal fiber lengths were used for all simulations. Comparing the curves in Figs. 7–9 we can conclude that it is the variable connections that ensures the really good Maxwellian statistics for the probability density curve of the DGD distribution, and not the different HiBi-fiber lengths. However, different fiber lengths have been advocated as important parameters for HiBi-fiber PMD emulators connected to light sources with low coherence time [11], e.g., LEDs. But that has not been investigated here. In our calculations, we used a 20-section HiBi-fiber PMD emulator with both variable connections and different HiBi-fiber lengths, i.e., a PMD emulator comparable to Fig. 7.

APPENDIX B

The transfer function for a single section of birefringent fiber gives rise to spectral notches at subharmonics of the bit frequency, if the light is launched in both the slow and the fast axis of the fiber [4]. The origin of the notches are the different times of flight in the axis and the notches can be used to control a first-order compensator consisting of e.g., a polarization controller and a birefringent fiber with the same DGD as the original link. In order to restore the input pulse, the energy at the subharmonics can be detected and maximized by turning the

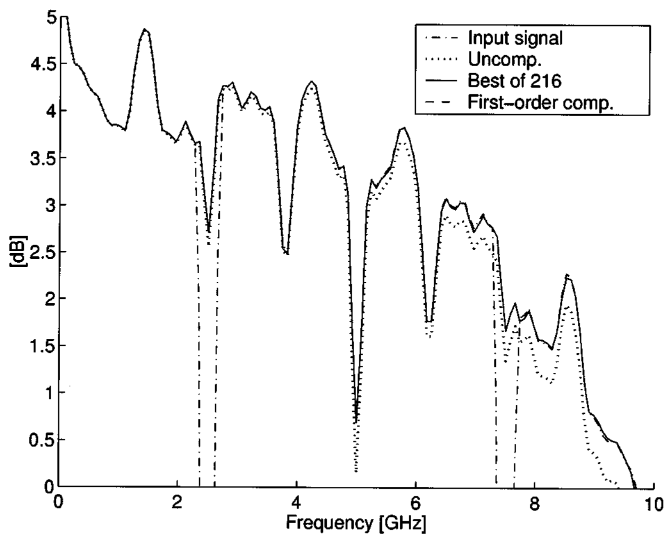

Fig. 10. Electrical power spectrum for a static seqeunce of 128 bits after a fiber with a PMD/T ratio of 0.5.

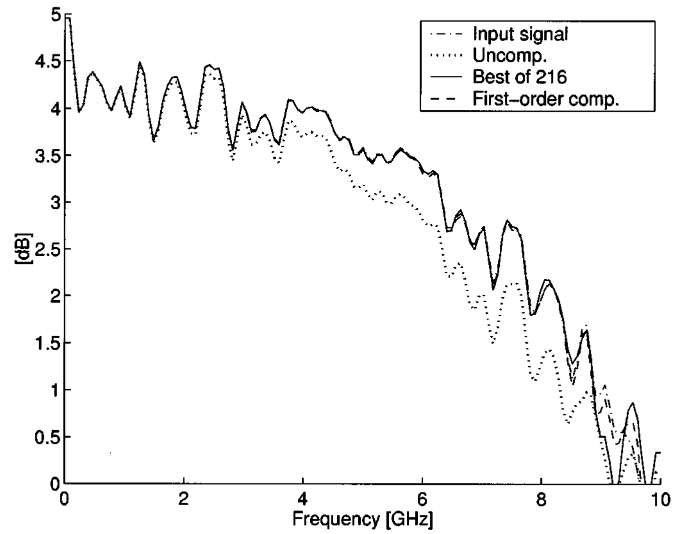

Fig. 11. Electrical power spectrum for a random seqeunce of 128 bits after a fiber with a PMD/T ratio of 0.5.

polarization controller. This procedure leads to a minimization of the total difference in time of flight for launched pulses. In the presence of PMD the same method can be applied to suppress first-order effects.

If PMD is simulated with static bit sequences it is important that its spectral properties are well known, especially when using the DGD-notch method, because a static sequence might have imperfections in the frequency spectra. This might lead to bit-sequence-dependent notches at subharmonics in the spectrum, which, in turn, might lead to unintended effects, especially when combined with a control method based on DGD-induced notches in the spectrum. In Fig. 10, notches due to the bit sequence are visualized for a fast Fourier transform (FFT) compatible 2^7-bit static sequence.[3] This sequence can be compared to a random sequence, which is not likely to have pronounced notches like the ones that can be found in the spectrum of a static signal. With a random bit sequence it was not of primary importance where exactly in the spectrum below the bit-rate frequency the filters of our first-order compensator were placed, because DGD-induced notches could not be noticed after a 20-section emulator, see Fig. 11. Instead, the important factors seemed to be the combination of filter placement, filter bandwidth, and weight factors that allowed the first-order compensator to retain the energy of the output spectrum close to the undistorted spectrum, starting from a dc level and as high in frequency as possible. In Figs. 12 and 13 the eye openings of the spectrum in Fig. 11 are presented.

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[3]Before we started the simulations we performed tests with bit sequences of 1024 bits instead of 128 bits, 1728 settings instead of 216 settings of the polarization converter, and combinations of the 2.5/5.0-GHz filters with a third BP-filter that had a central frequency of 7.5 GHz and 3-dB bandwidth of 2 GHz. No significant differences were observed with longer bit patterns, higher number of settings, or different BP-filter combinations. However, it shall be noted that the receiver was modeled with a perfect response down to direct currect (dc).

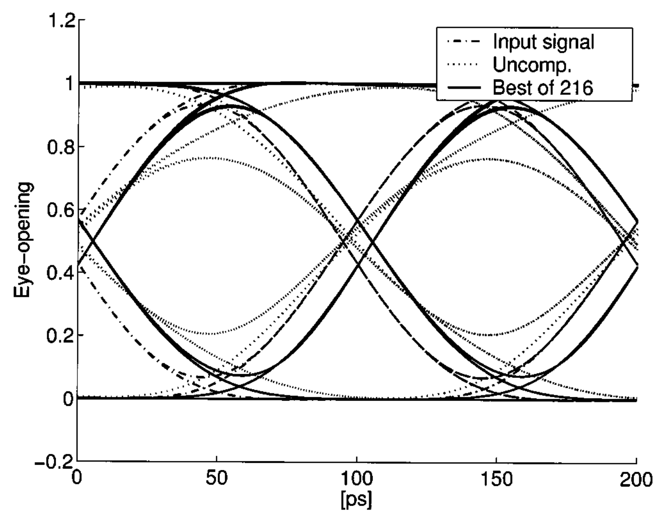

Fig. 12. Eye openings of a random signal.

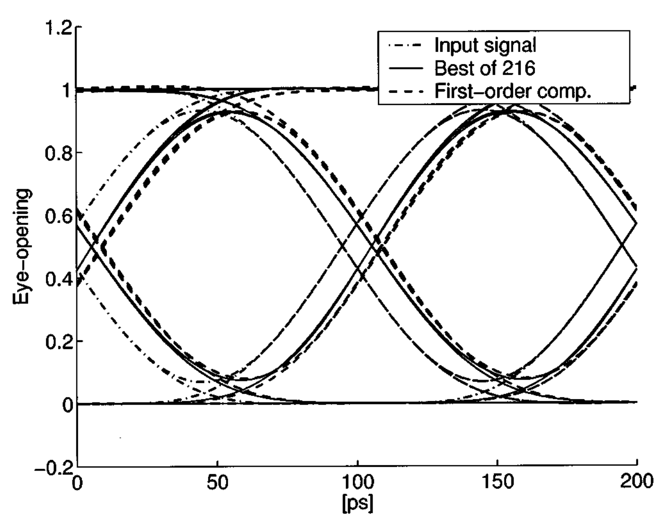

Fig. 13. Eye openings of a random signal.

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REFERENCES

[1] G. J. Foschini and C. D. Poole, “Statistical theory of polarization dispersion in single mode fibers,” *J. Lightwave Technol.*, vol. 9, pp. 1439–1456, 1991.

[2] C. Francia, F. Bruyère, J.-P. Thiéry, and D. Penninckx, “Simple dynamic polarization mode dispersion compensator,” *Electron. Lett.*, vol. 35, pp. 414–415, 1999.

[3] M. W. Chbat, J.-P. Soigné, T. Fuerst, J. T. Anthony, S. Lanne, H. Février, B. M. Desthieux, A. H. Bush, and D. Penninckx, “Long term field demonstration of optical PMD compensation on an installed OC-192 link,” presented at the OFC’99, 1999,. Postdeadline paper DP12.

[4] T. Takahashi, T. Imai, and M. Aiki, “Automatic compensation technique for timewise fluctuating polarization mode dispersion in-line amplifier systems,” *Electron. Lett.*, vol. 30, pp. 348–349, 1994.

[5] H. Ooi, Y. Akiyama, and G. Ishikawa, “Automatic polarization-mode dispersion compensation in 40-Gbit/s transmission,” in *OFC’99*, 1999, pp. 86–88. Paper WE5.

[6] D. A. Watley, K. S. Farley, B. J. Shaw, W. S. Lee, G. Bordogna, A. P. Hadjifotiou, and R. E. Epworth, “Compensation of polarization-mode dispersion exceeding one bit period using single high-birefringence fiber,” *Electron. Lett.*, vol. 35, pp. 1094–1095, 1999.

[7] R. Noé, D. Sandel, S. Hinz, M. Yoshida-Derolf, V. Mirvoda, G. Feise, H. Herrmann, R. Ricken, W. Sohler, F. Wehrmann, C. Glingener, A. Schöpflin, A. Färbert, and G. Fisher, “Integrated optical $LiNbO_3$ distributed polarization mode dispersion compensator in 20 Gbit/s transmission system,” *Electron. Lett.*, vol. 35, pp. 652–654, 1999.

[8] R. Noé, D. Sandel, M. Yoshida-Derolf, S. Hinz, V. Mirvoda, A. Schöpflin, C. Glingener, E. Gottwald, C. Scheerer, G. Fisher, T. Weyrauch, and W. Haase, “Polarization mode dispersion compensation at 10, 20 and 40 Gb/s with various optical equalizers,” *J. Lightwave Technol.*, vol. 17, pp. 1602–1615, 1999.

[9] J. H. Winters and M. A. Santoro, “Experimental equalization of polarization dispersion,” *IEEE Photon. Technol. Lett.*, vol. 8, pp. 591–593, 1990.

[10] B. W. Hakki, “Polarization mode dispersion compensation by phase diversity detection,” *IEEE Photon. Technol. Lett.*, vol. 9, pp. 121–123, 1997.

[11] C. H. Prola, J. A. Periera da Silva, A. O. Dal Forno, R. Passy, J. P. von derWeid, and N. Gisin, “PMD emulators and signal distortion in 2.48-Gb/s IM-DD lightwave systems,” *IEEE Photon. Technol. Lett.*, vol. 9, pp. 842–844, 1997.

[12] S. Betti, F. Curti, G. de Marchis, E. Iannone, and F. Matera, “Evolution of the bandwidth of the principal states of polarization in single-mode fibers,” *Opt. Lett.*, vol. 16, pp. 467–469, 1991.

[13] K. Konradsen, *An Introduction to Statistics*, 4th ed. Lyngby, Denmark: Inst. Math. Statist. Oper. Res., Tech. Univ. Denmark, 1976, vol. 1. (in Danish) .

[14] H. Bülow, “Limitation of optical first-order PMD compensation,” in *OFC/IOOC’99, Tech. Dig.*, 1999, pp. 74–76. Paper WE1.

[15] I. T. Lima, R. Khosravani, P. Ebrahimi, E. Ibragimov, A. E. Willner, and C. R. Menyuk, “Polarization mode dispersion emulator,” in *Proc. OFC-2000*, 2000, pp. 31–33. Paper ThB4.

S. Särkimukka, photograph and biography not available at the time of publication.

A. Djupsjöbacka, photograph and biography not available at the time of publication.

A. Gavler, photograph and biography not available at the time of publication.

G. Jacobsen, photograph and biography not available at the time of publication.