The University of Kansas

Information and Telecommunication Technology Center

Final Technical Report

PMD Characterization on an Active Fiber Link: Final Report

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Final Report

PMD Characterization on an Active Fiber Link

Project start date May 1999

KUCR project number IND18834

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Introduction

This is the final report for the PMD Characterization on an Active Fiber Link which began in May 1999. The related KUCR project number is IND18834. The Sprint award number is P.O. 21-B000016923.

For reference, text excerpts from the original proposal are included below.

Overview

We propose development of dedicated hardware for implementation of our first-order PMD adaptive compensation system. We further propose long-term operation of this system on the KU-TIOC WDM link to collect data on DGD and PSP variations over time. Through this effort we hope to learn more about the dynamics of adaptive PMD compensation and to validate the principles and effectiveness of this approach. Data collected on this project will also provide critical information on the variability of DGD and PSP (data that are not currently available). This data is essential not only for gaining a better understanding of PMD (what factors influence it, how fast does it fluctuate, when does it change the fastest, etc.), but also for enhancing the design of efficient adaptive compensation systems.

The relevance of this research to Sprint is that an understanding of the dynamics of PMD will be gained. This knowledge will be use critical for the development of specifications for future active PMD compensation systems.

Goals

Gain an understanding of how DGD and PSPs vary over time in a terrestrial link.

Tasks

1. Revise design of adaptive PMD compensation system for efficient implementation and concept validation.
2. Collection and analysis of PMD data from the KU-TIOC link.

Milestones

- Efficient implementation of the first-order PMD adaptive compensation system using dedicated signal processing hardware.
- Report describing the variation over time of the DGD and PSP on the KU-TIOC link.

All project objectives have been accomplished with minor deviations from the proposal.

Key findings:

- Importance of polarization scrambling in improving performance of PMD compensation.
- Improvements on basic PMD compensation architecture (DOP feedback signal, application to SCM).
- Relatively slow temporal variation of differential group delay on buried Sprint fiber.
- Techniques developed for predicting mean PMD-induced outage rates and outage duration based on measured PMD.

During the course of this project, numerous publications were produced. A list of these follows. Copies of most of these publications are provided in Appendix A.

In addition, a literature review was preformed regarding polarization control, polarization-mode dispersion, PMD compensation, and related topics. The resulting bibliography is provided in Appendix B.

PMD-related accomplishments under this and related previous Sprint funded projects

Below are some highlights from the previous Sprint-funded PMD-related research along with significant patents, patent applications, journal papers, conference papers, and presentations:

Developed novel PMD measurement technique.

Song, S., C. Allen, K. R. Demarest, and R. Hui, "A novel method for measuring polarization-mode dispersion using four-wave mixing," *Journal of Lightwave Technology*, 17(12), pp. 2530-2533, 1999.

Song, S., K. Demarest, C. Allen, "A Poincare sphere method for measuring polarization-mode dispersion using four-wave mixing (FWM) in single-mode optical fiber," *Symposium on Optical Fiber Measurements*, Boulder, CO, pp. 79-82, Sept. 2000.

Using laboratory test equipment, we developed of a 1st-order PMD compensation system that incorporates polarization scrambling to improve compensation effectiveness.

Pua, H. Y., K. Peddanarappagari, B. Zhu, C. Allen, K. Demarest, R. Hui, "An adaptive first-order polarization-mode dispersion compensation system: theory and demonstration," *Journal of Lightwave Technology*, 18(6), pp. 832-841, 2000.

Pua, H.Y., C. Allen, K. Demarest, R. Hui, K.V. Peddanarappagari, "Method and apparatus to compensate for polarization-mode dispersion," U. S. Patent Number 6,459,830 issued October 1, 2002.

Developed a custom 1st-order PMD compensation system with a faster response time.

Chimata, A.-P. and C. Allen, "Development of an adaptive polarization-mode dispersion compensation system," *ITTC Technical Report* **ITTC-FY2003-TR-18834-02**, January 2003.

Demonstrated concept of PMD compensation for subcarrier-multiplexed signals.

Hui, R., C. Allen, and K. Demarest, "Combating PMD-induced signal fading in SCM optical systems with diversity detection," patent application submitted to the U.S. Patent Office December 20, 2001.

Hui, R., C. Allen, and K. Demarest, "PMD-insensitive SCM optical receiver using polarization diversity," *IEEE Photonics Technology Letters*, 14(11), pp 1632-1634, 2002.

Hui, R., C. Allen, and K. Demarest, "Combating PMD-induced signal fading in SCM optical systems using polarization diversity optical receiver," *OFC '02*, Anaheim, CA, WQ4, pp. 302-304, 2002.

Analysis of long-term PMD measurements on single-spans of buried fiber

Richards, D.L., C.T. Allen, D.C. Hague, "Identifying polarization-mode dispersion," patent application submitted to the U.S. Patent Office November 19, 2002.

Richards, D.L., C.T. Allen, D.C. Hague, "Identification of polarization-mode dispersion on a communication network," patent application submitted to the U.S. Patent Office May 2003.

Allen, C.T., P.K. Kondamuri, D.L. Richards, and D.C. Hague, "Measured temporal and spectral PMD characteristics and their implications for network-level mitigation approaches," *Journal of Lightwave Technology*, 21(1), pp. 79-86, 2003.

Allen, C., P.K. Kondamuri, D.L. Richards, and D.C. Hague, "Analysis and comparison of measured DGD data on buried single-mode fibers," *Symposium on Optical Fiber Measurements*, Boulder, CO, pp. 195-198, Sept. 24-26, 2002.

Allen, C., P. K. Kondamuri, D. Richards, and D. Hague, "Measured temporal and spectral PMD characteristics and their implications for network-level mitigation approaches," *Proceedings of the IASTED International Conference on Wireless and Optical Communications*, Banff, Alberta, Canada, pp. 713-720, 2002.

Invited presentation: "Analysis and comparison of measured DGD data on buried single-mode fibers," presented to the International Electrotechnical Commission, Technical Committee No. 86 (Fibre Modules), Working Group 8 (Dynamic Modules), Atlanta, GA, March 23, 2003.

Kondamuri, P.K. and C. Allen, "Characterization of polarization-mode dispersion on buried standard single-mode fibers," *ITTC Technical Report* **ITTC-FY2003-TR-18834-01**, November 2002.

Appendix A – Publications Produced

Copies of PMD-related publications produced under this and previous Sprint-funded PMD-related research projects. Note that the two ITTC Technical reports (ITTC-FY2003-TR-18834-01, ITTC-FY2003-TR-18834-02) were previously delivered and are not duplicated here.

Copies of the following publications follow:

Allen, C.T., P.K. Kondamuri, D.L. Richards, and D.C. Hague, "Measured temporal and spectral PMD characteristics and their implications for network-level mitigation approaches," *Journal of Lightwave Technology*, 21(1), pp. 79-86, 2003.

Allen, C., P.K. Kondamuri, D.L. Richards, and D.C. Hague, "Analysis and comparison of measured DGD data on buried single-mode fibers," *Symposium on Optical Fiber Measurements*, Boulder, CO, pp. 195-198, Sept. 24-26, 2002.

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Hui, R., C. Allen, and K. Demarest, "PMD-insensitive SCM optical receiver using polarization diversity," *IEEE Photonics Technology Letters*, 14(11), pp 1632-1634, 2002.

Hui, R., C. Allen, and K. Demarest, "Combating PMD-induced signal fading in SCM optical systems using polarization diversity optical receiver," *OFC '02*, Anaheim, CA, WQ4, pp. 302-304, 2002.

Pua, H.Y., C. Allen, K. Demarest, R. Hui, K.V. Peddanarappagari, "Method and apparatus to compensate for polarization-mode dispersion," U. S. Patent Number 6,459,830 issued October 1, 2002.

Pua, H. Y., K. Peddanarappagari, B. Zhu, C. Allen, K. Demarest, R. Hui, "An adaptive first-order polarization-mode dispersion compensation system: theory and demonstration," *Journal of Lightwave Technology*, 18(6), pp. 832-841, 2000.

Song, S., K. Demarest, C. Allen, "A Poincare sphere method for measuring polarization-mode dispersion using four-wave mixing (FWM) in single-mode optical fiber," *Symposium on Optical Fiber Measurements*, Boulder, CO, pp. 79-82, Sept. 2000.

Song, S., C. Allen, K. R. Demarest, and R. Hui, “A novel method for measuring polarization-mode dispersion using four-wave mixing,” *Journal of Lightwave Technology*, 17(12), pp. 2530-2533, 1999.

Measured Temporal and Spectral PMD Characteristics and Their Implications for Network-Level Mitigation Approaches

Christopher T. Allen, *Senior Member, IEEE*, Pradeep Kumar Kondamuri, Douglas L. Richards, and Douglas C. Hague

***Abstract*—Signal degradation due to polarization-mode dispersion (PMD) effects may become significant for signaling rates of 10 Gb/s, 40 Gb/s, and beyond. To assess the utility of various PMD mitigation schemes, temporal and spectral measurements of differential group delay (DGD) were made on 95 km of buried standard single-mode fiber over an 86-d period to determine the distribution and rate of change of high-DGD events. As expected, statistical analysis of variations in DGD indicate that excursions from the mean DGD by factors of 3.7 or higher have very low probability. For this link, the DGD varied slowly with time (having a drift time of about 3.4 d) and rapidly with wavelength. The DGD data agree well with results of similar experiments reported in the literature. Statistical analysis of the measured DGD data shows that high-DGD episodes will be exceedingly rare and short-lived. The impact of PMD on network operations is explored and approaches to ensure network reliability are reviewed for network operators given the task of transporting high-bit-rate channels over fiber links with known PMD characteristics.**

***Index Terms*—Optical fiber characterization, optical fiber communication systems, polarization drift, polarization-mode dispersion (PMD), polarization-mode dispersion outage.**

I. INTRODUCTION

IN THE PHENOMENON called polarization-mode dispersion (PMD), birefringence in the optical fiber provides two polarization-dependent group velocities for optical signals. In the high-coherence model of PMD (which assumes that the coherence time of the light source is greater than the PMD-induced delays and no polarization-dependent loss), an input pulse will result in two orthogonally polarized pulses that preserve the shape of the original input pulse. The relative amplitudes of these two pulses is determined by the state of polarization (SOP) of the input pulse relative to the fiber's input principal states of polarization (PSPs). Thus, for each pulse input, two pulses arrive at the receiver with different arrival times, called the differential group delay (DGD) $\Delta\tau$. This first-order model is frequency-independent and is only valid over limited bandwidths. For wider bandwidths, higher order effects must be considered, resulting in frequency-dependent polarization-mode dispersion [1], [2]. The bandwidth over which the PSPs can be assumed constant depends on the properties of the fiber and has been shown to vary inversely with the mean DGD, $\langle\Delta\tau\rangle$ [3]. While the minimum bandwidth of the PSPs in single-mode fibers (SMFs) was found to be always over 50 GHz [3], this bandwidth for standard SMF is of the order of 100 GHz [1].

PMD may become a major impediment for network operators seeking to increase the per-channel data rate on long-haul fiber-optic links. While the DGD in buried fiber had negligible impact at 2.5-Gb/s signaling rates, upgrades to 10 Gb/s, 40 Gb/s, and beyond will require increasingly more attention. While there are PMD challenges facing carriers at 10 Gb/s, these challenges are not as severe as originally feared. Major carriers are successfully deploying 10-Gb/s dense-wavelength-division-multiplexed (DWDM) links across the core of their networks. A marked improvement in the DGD tolerance of 10-Gb/s long-reach receivers (to about 40 ps) will likely satisfy most length demands, obviating the need for PMD compensation (PMDC). Signaling rates of 40 Gb/s and beyond will most likely require some form of mitigation in long-haul applications, such as robust modulation schemes or PMDC.

To ensure signal quality on their fiber at higher bit rates, network engineers must anticipate the impact of PMD on the various fiber routes. Design of a reliable network requires a good model of the PMD characteristics on each link. An understanding of the variability of both the DGD and the PSPs is required to specify appropriate transmission parameters as well as PMDC specifications. Factors such as the mean DGD, PMD correlation time, and bandwidth, as well as second-order effects, together with performance prediction models, can provide this understanding. While the probabilistic properties of PMD variations are known, the characteristics of a particular link depend on how it was cabled and installed. Therefore, PMD measurements on installed fiber links are required.

While PMD is a vector quantity, with a magnitude (DGD) and a direction (PSP), we are deliberately focusing exclusively on DGD since this is a readily measured parameter on installed optical networks. The statistical distribution and behavior of PSPs has been extensively studied and reported elsewhere.

II. PMD STATISTICS

A. Mean DGD

For long optical fibers, the PMD figure of merit typically specified is its mean DGD $\langle\Delta\tau\rangle$ (having units of ps) or its PMD coefficient $\langle\Delta\tau\rangle/\sqrt{L}$ (having units of ps/$\sqrt{\text{km}}$), where L is the fiber length. The PMD for an installed (buried) fiber-optic cable

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is dominated by the inherent PMD of the bare fiber; however, the level of relaxation provided by the cabling and installation techniques also affects PMD. While the PMD in bare fiber is determined largely by the core-cladding concentricity achieved during manufacture, we have found that loose-tube cabling results in a lower PMD than other cabling methods, such as slotted core cabling. In addition, mechanical stresses introduced during cable installation (burial) also contribute to the PMD and will be affected by the installation practices used and whether the cable is in a protective conduit.

The mean DGD for a given fiber is a constant that represents both the average of DGD values at one time across a broad spectral bandwidth

$$\langle \Delta\tau \rangle_\lambda = \frac{1}{N_\lambda} \sum_{i=1}^{N_\lambda} \Delta\tau(\lambda_i, t) \quad (1)$$

and the average of DGD values for a single wavelength over a long time period

$$\langle \Delta\tau \rangle_t = \frac{1}{N_t} \sum_{i=1}^{N_t} \Delta\tau(\lambda, t_i) \quad (2)$$

where $\Delta\tau(\lambda, t)$ is the DGD value at wavelength λ and time t. Although the mean DGD for an installed fiber is constant, changing environmental factors (e.g., temperature) cause the instantaneous DGD at a given wavelength $\Delta\tau(\lambda, t)$ to vary randomly about that mean.

B. Maxwellian Distribution

The DGD for a given wavelength at any moment in time $\Delta\tau(\lambda, t)$ is a random variable with a Maxwellian probability density function (pdf) [4], [5]

$$p(\Delta\tau) = \sqrt{\frac{2}{\pi}} \frac{\Delta\tau^2}{\sigma^3} e^{(-\Delta\tau^2/2\sigma^2)}, \text{ where } \sigma = \langle \Delta\tau \rangle \sqrt{\frac{\pi}{8}} \quad (3)$$

for $0 < \Delta\tau < +\infty$. Therefore, the single parameter $\langle \Delta\tau \rangle$ fully specifies the distribution.

Using this distribution, the probability of $\Delta\tau$ exceeding a particular value can be found using

$$P(\Delta\tau \geq X) = 1 - \int_0^X p(\Delta\tau) d\Delta\tau. \quad (4)$$

For example, the probability of $\Delta\tau/\langle \Delta\tau \rangle$ exceeding 3.7 is 1.3×10^{-7}. Expressed another way, if the mean DGD of a fiber link is 10 ps, then 99.999 99% of the time, the DGD will be less than 37 ps.

III. Network Design Considerations

In the design of a robust, long-haul fiber-optic network, the relationship between the maximum achievable link length and bit rate must be considered. For link designs where the maximum tolerable DGD is exceeded, techniques for coping with the effects of PMD must be explored.

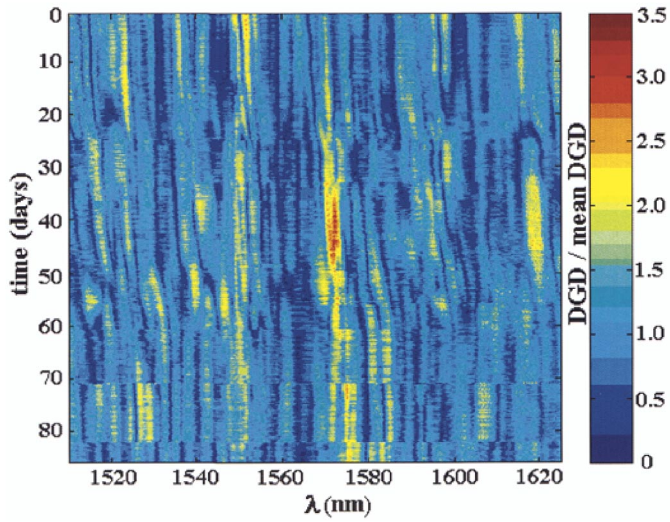

Fig. 1. Map of normalized DGD versus wavelength and time.

A. Receiver DGD Tolerance

The maximum-link DGD that a receiver can tolerate before the signal degradation becomes unacceptable depends on a variety of factors, including line bit rate, modulation format, optical signal-to-noise ratio (SNR) and receiver design. For intensity-modulated, direct-detected (IM-DD) systems, Iannone *et al.* [6] found that when the transmitted signal excites both PSPs equally (a worst-case condition), a 1-dB receiver sensitivity penalty results when the instantaneous DGD is about 23% of the signaling time period T_{bit}. For a 2.5-Gb/s nonreturn-to-zero (NRZ) signal (T_{bit} is 400 ps), this corresponds to a tolerable DGD value of about 92 ps; at 10 Gb/s, about 23 ps is tolerable; and for a 40-Gb/s NRZ signal, this corresponds to about 5.7 ps. This maximum-tolerable DGD level is representative of the NRZ IM-DD case; receiver DGD tolerance can be improved through careful receiver design, the use of PMD-tolerant signaling formats, and the use of forward-correction codes (FECs). Khosravani and Willner [7] showed that return-to-zero (RZ), chirped RZ, and dispersion-managed soliton signaling formats are much more tolerant of PMD effects, compared with NRZ formats. Shieh *et al.* [8] and Xie *et al.* [9] have demonstrated a substantial increase in receiver tolerance of DGD when the FEC is used. Modern long-haul, 10-Gb/s receivers using FEC or RZ modulation can tolerate about 40 ps of DGD with a 1-dB power penalty.

B. Probability of Signal Outage

For occurrences of high instantaneous DGD, signal quality may be intolerable, resulting in a PMD-induced outage. Such outages may significantly affect network availability for higher bit rates (10 Gb/s, 40 Gb/s, and higher). For a network to operate with an overall availability of "five nines" (i.e., 99.999% of availability), the desired PMD-related availability factor may be "seven nines" (i.e., 99.999 99%), which corresponds to a maximum-tolerable DGD 3.7 times the mean DGD. For a 2.5-Gb/s IM-DD NRZ system with a DGD tolerance of 92 ps, this results in an acceptable mean DGD value of 25 ps; for a 10-Gb/s system with a DGD tolerance of 23 ps, the acceptable mean DGD is 6.2

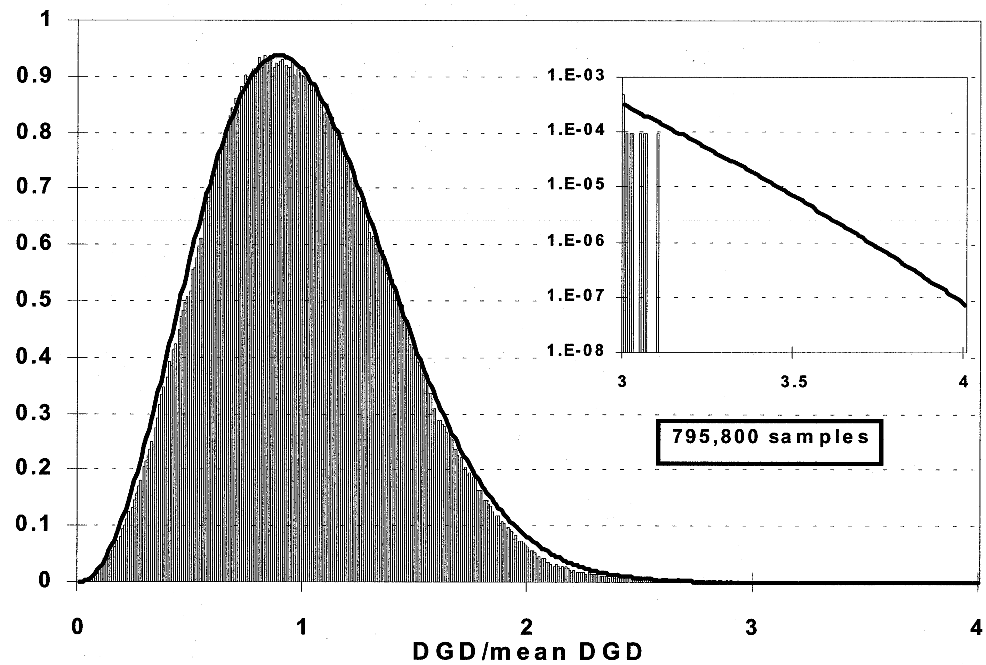

Fig. 2. Histogram of measured DGD/ mean DGD data, along with Maxwellian pdf for comparison.

ps; and for 40-Gb/s with a tolerable DGD of 5.7 ps, the acceptable mean DGD level is 1.5 ps. For DGD-tolerant receivers (40 ps at 10 Gb/s), this results in an acceptable-mean DGD of 10.8 ps.

C. Coping With PMD

For network operators faced with the challenge of upgrading the channel data rate on a high-PMD link in the network, a handful of solutions exist that will preserve the signal quality at increased data rates.

One alternative cost solution is to selectively replace those fiber segments in the link known to be the dominant contributors to the overall link DGD, if they can be identified. Another alternative cost solution is to regenerate the optical signal by placing back-to-back terminals at the point in the link where the DGD effects approach an intolerable level, thus effectively reducing the optical link length.

Still another approach is to introduce error-correction codes, such as FEC. In this approach, the optical data payload is reduced incrementally in exchange for a marginal gain in PMD tolerance.Yet another solution is to incorporate an adaptive PMDC system [8]–[12], typically located at the receiver. Typical PMD compensation systems are effective at minimizing the effects of first-order PMD and, in some cases, second-order PMD. However, both first- and second-order PMDC systems suffer the drawback that they reduce the effects of signal degradation over a very narrow optical bandwidth. This is a significant drawback for DWDM systems. For a long-haul fiber-optic link carrying hundreds of wavelengths, a separate PMDC system may be required for each wavelength to provide the desired seven-nines availability.

For DWDM systems, another potential solution exists. Särkimukka *et al.* [13] proposed a method for mitigating PMD effects in a multichannel system by moving traffic off of PMD-impaired channels onto spare channels that are not experiencing PMD degradation.

One may also rely upon more traditional protection techniques, e.g., SONET ring or Internet protocol (IP) routing at layers 1 and 3, respectively. This protection can easily provide a guard against occasional PMD-induced outages of limited duration. However, for this approach to be viable, the episodes of abnormally high-DGD events must be infrequent and spectrally localized. To evaluate the feasibility and limits of this solution, an understanding of the temporal and spectral nature of PMD is required.

Finally, there are also efficient optical networking solutions offering varying degrees of protection by using an optical cross connect with a DWDM system. Operators may then construct a mesh-protected network and provide managed wavelength services that are protected against possible PMD-induced outages. Similar to the traditional protection methods, these more recent techniques will only be viable with infrequent and spectrally localized outages.

IV. Temporal Behavior of DGD

Given the dynamic nature of PMD and the low probability of excursions to intolerable levels, measurements of $\Delta\tau(\lambda, t)$ on buried fiber spans were made over long periods to enable prediction of the potential impact of PMD on network availability. Of particular interest are the frequency and duration of these rare events. The Jones matrix eigenanalysis (JME) technique was used to measure the DGD data on a 95-km span of slotted-core, direct buried, standard single-mode (ITU G.652) fiber-optic cable made available by Sprint.

DGD was measured roughly every 3 h at wavelengths ranging from 1510 nm to 1625 nm with a spectral resolution of 0.1 nm (about 12.5 GHz). Over 86 d (from November 9, 2001, through February 2, 2002) 692 measurements were made on the 1150

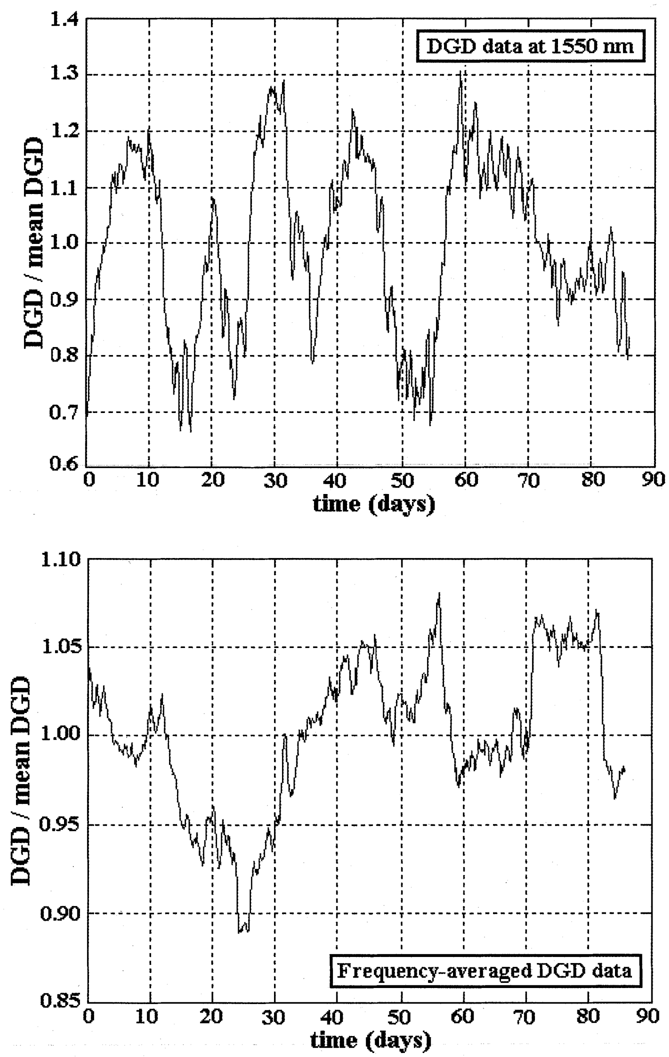

Fig. 3. Measured temporal variations in normalized DGD over 86 d at 1550 nm (top) and averaged overall 1150 frequency measurements (bottom).

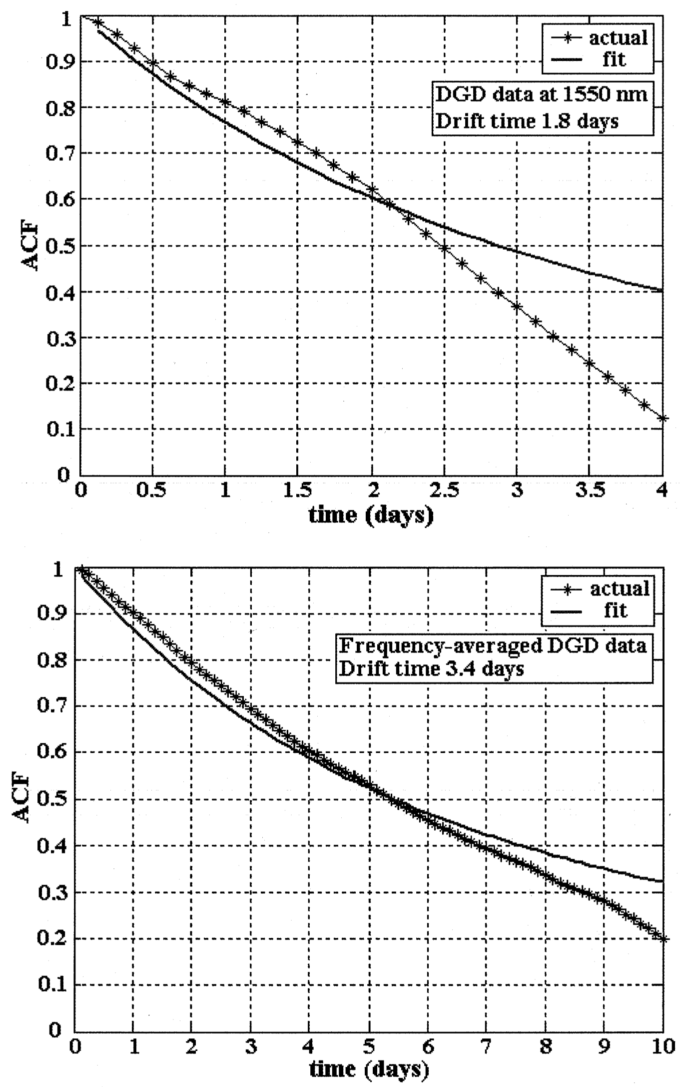

Fig. 4. Normalized temporal ACFs of normalized DGD data measured at 1550 nm (top) and across 1150 frequencies (bottom). Theoretical ACF curves are fitted to the measured temporal ACFs.

discrete wavelengths. Fig. 1 shows in a color-coded format this normalized DGD data (i.e., $\Delta\tau/\langle\Delta\tau\rangle$) representing 795 800 measured values.

A histogram of this normalized DGD data is shown in Fig. 2 and is seen to have a shape consistent with a Maxwellian distribution, as expected. A curve representing a Maxwellian distribution for a 1-ps mean DGD is superimposed for comparison. Note that no occurances of DGD/mean DGD greater than 3.1 were observed during this 86-d period.

From Fig. 1, it is apparent that for buried fiber, DGD values do not change rapidly (i.e., no abrupt changes are seen). Fig. 3 shows time histories of measured DGD data over the 86-d period. The top plot is DGD data at 1550 nm, and the bottom plot is frequency-averaged data. While the mean value of the bottom plot is one (by definition), the mean value of the top plot is 1.088. This should not be interpreted to mean that the mean DGD is changing; rather, since fewer data were used to estimate the mean, there is more uncertainty in that estimate, compared with the estimate using all of the data.

To determine the DGD rate of change, an autocorrelation analysis was performed on the DGD time histories. Fig. 4 (top) shows the normalized temporal autocorrelation function (ACF) of the DGD data measured at 1550 nm. Fig. 4 (bottom) shows the ACF for the DGD time history for frequency-averaged DGD data. Also shown in Fig. 4 are curves representing the theoretical temporal ACF for DGD [14], which has the form

$$\mathrm{AFC}\ (\Delta t) = \frac{1 - \exp\left(\frac{-|\Delta t|}{t_d}\right)}{\frac{|\Delta t|}{t_d}} \tag{5}$$

where t_d is the average drift time of DGD. The drift time indicates the time scale over which the DGD changes. Furthermore, when outages occur, the outage duration will be related to the drift time [14], [15]. Based on data collected over 86 d, the drift time for this fiber is estimated to be around 3.4 d. Expressed another way, samples should be collected about once every 3 d to obtain statistically independent DGD values on a specific wavelength; measurements collected more often are correlated.

For comparison, others have reported a range of DGD correlation times under various fiber conditions. For spools of fiber

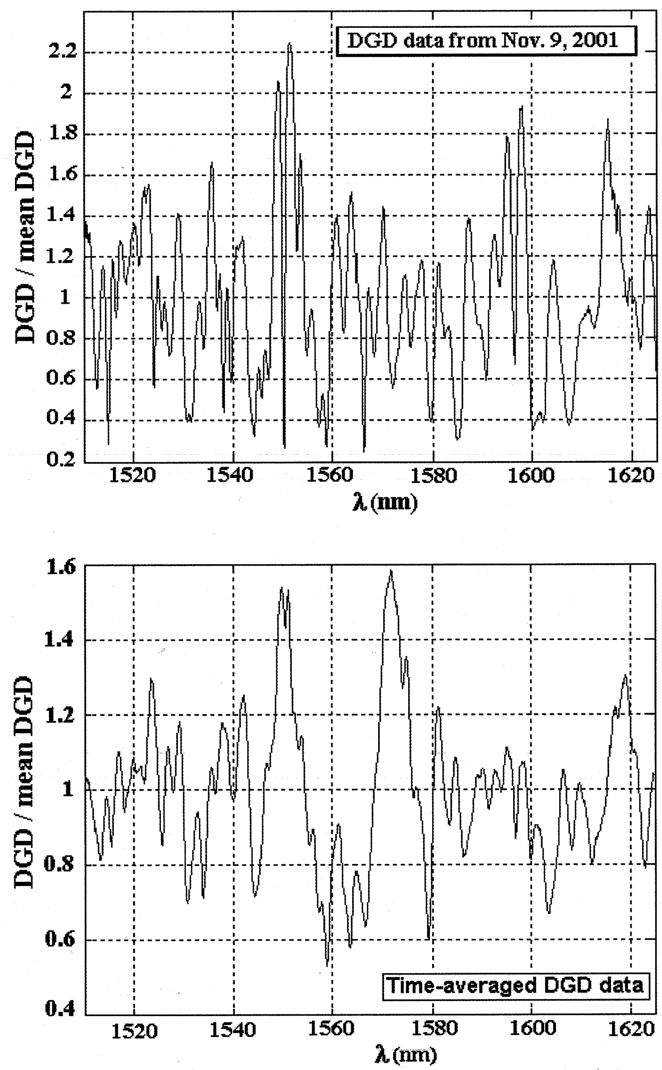

Fig. 5. Spectral variations in normalized DGD over 1150 wavelengths measured on November 9, 2001 (top), and time-averaged overall 692 time measurements (bottom).

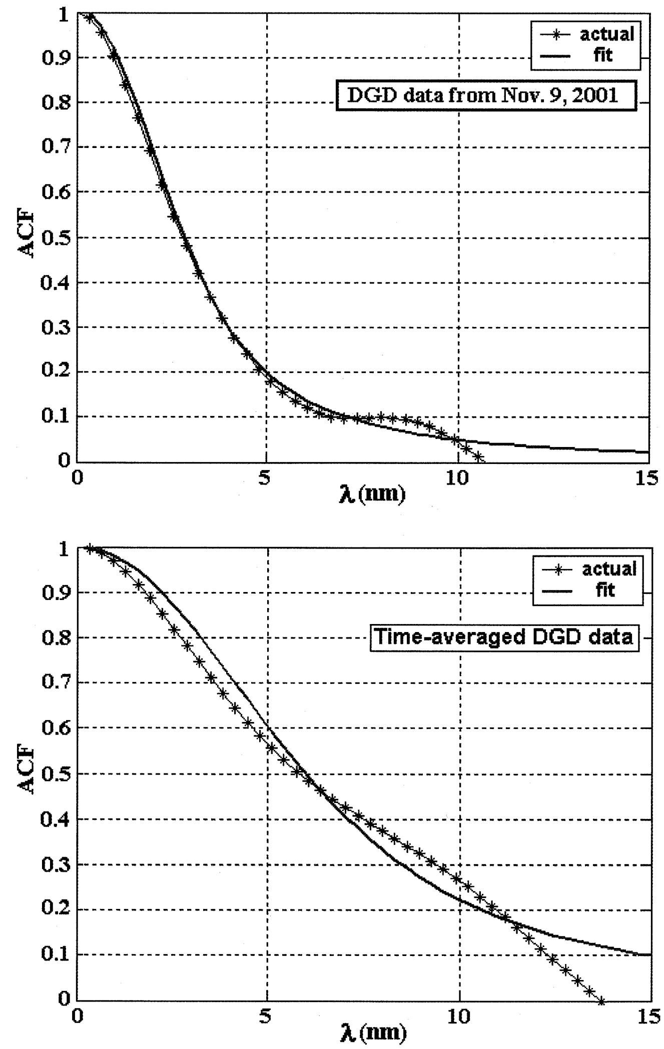

Fig. 6. Normalized spectral autocorrelation functions (ACFs) of normalized DGD data measured on November 9, 2001 (top) and time-averaged overall 692 measurements (bottom). Theoretical ACF curves are fitted to the measured spectral ACFs.

in a laboratory environment, correlation times of about 30 min on 31.6 km of fiber [16] and 3 h on a 10-km fiber [17] have been reported. DGD variations on a 48-km aerial cable exhibited time scales ranging from 5 to 90 min, depending the air temperature rate of change [18]. For submarine cables, a DGD correlation time of about 1 h was observed on a 119-km cable [19], and [20] observed PMD changes with a period of about 2 mo on a 62-km fiber-optic cable. On buried fibers, correlation times of at least 20 min (17 km) [21], 1–2 h (48.8 km) [18], 3 and 5.7 d (127 km) [14], and 19 h (114 km) [22] have been reported. The significant variation of correlation times demonstrates how the installation scheme impacts the temporal behavior of DGD. Since temperature variations are known to cause PMD variations, cables in a thermally stable environment (e.g., submarine cable) will have long correlation times, whereas cables that experience diurnal temperature variations (e.g., aerial cables and buried cables with above-ground segments) will have correlation times less than 24 h. And cables in an unstable thermal and mechanical environment (e.g., aerial cables) will have correlation times dependent on both temperature and wind conditions. Thus, our observation of 3.4 d is consistent for the buried cable having no above-ground segments.

With knowledge gained from the temporal ACF analysis, we can now interpret realistically our DGD data set. Over the 86 d of observation, about 25 independent temporal samples per wavelength were collected.

V. Spectral Behavior of DGD

From Fig. 1, we note that the DGD varies significantly with wavelength. In Fig. 5, the top plot shows the normalized spectral variation of the first DGD data (measured on November 9, 2001), and the bottom plot shows the spectral variation of the time-averaged, normalized DGD data, i.e., the normalized DGD data processed using (2).

To determine the DGD bandwidth, spectral autocorrelation analysis was performed on the normalized DGD spectral data. In Fig. 6, the top graph shows the resulting normalized spectral ACF for one spectral measurement (data collected on November 9, 2001) and the bottom shows the normalized spectral ACF for the time-averaged data. Also shown in Fig. 6 are curves representing theoretical spectral ACFs for DGD, with the form [23]

$$\text{ACF}\,(\Delta\omega) = 3\frac{1-\exp\left(\frac{-\langle\Delta\tau^2\rangle\Delta\omega^2}{3}\right)}{\Delta\omega^2} \tag{6}$$

where $\Delta\omega$ is the radian frequency and $\langle\Delta\tau^2\rangle$ represents the variance of the DGD.

From the measured data, the bandwidth for the normalized DGD is estimated to be about 7.5 nm, or 936 GHz. Therefore, if the mean DGD is 1 ps and an optical channel is affected by significant DGD, nearby channels (within about 7.5 nm) may also experience this effect.

Theory and experiments [23] have demonstrated that the DGD bandwidth is inversely proportional to the mean DGD, as follows:

$$\omega_c = \frac{4\sqrt{2}}{\langle\Delta\tau\rangle}. \tag{7}$$

Thus, fibers with a high mean DGD have a narrower DGD bandwidth than fibers with a low mean DGD. Thus, for a fiber with a mean DGD of 1 ps, the predicted DGD bandwidth is 900 GHz, which agrees well with the bandwidth found using the spectral ACF fit in Fig. 6 (bottom). Note that the normalized DGD bandwidth in Fig. 6 (top) is about 4 nm, which is significantly less than the approximately 7.5-nm bandwidth seen in Fig. 6 (bottom). This should not be interpreted to mean that the DGD bandwidth is varying; rather, the bandwidth estimate obtained using all of the data will be more accurate, since it is based on significantly more data points.

VI. Implications for Network Availability

A. Mean Time Between PMD-Related Outages

In the past, the outage probability P_{out} due to PMD effects has been expressed in terms of minutes per year [2]. In cases where the drift time is measured in days and the probability of an outage is quite small, P_{out} represents the annualized outage probability based on long time records. Accurately estimating the impact of the PMD on network availability requires statistical analysis of the DGD variability. Caponi *et al.* [24] showed how the mean time between PMD-related outages can be estimated from the temporal characteristics of DGD variations and the Maxwellian pdf. The mean outage rate R_{out} (defined as the mean number of outage events per unit time with units of events per year) is found using [24]

$$R_{\text{out}} = \frac{1}{2} f_\tau(\text{threshold}) \int_{-\infty}^{\infty} f_{\tau'}\,(\Delta\tau')\,|\Delta\tau'|\,d\Delta\tau' \tag{8}$$

where $f_\tau(\cdot)$ is the DGD pdf, $\Delta\tau'$ is the time derivative of the DGD, and $f_{\tau'}(\cdot)$ is the pdf of $\Delta\tau'$. In this analysis, it is assumed that an outage results when the DGD value exceeds the threshold value. Caponi *et al.* [24] observed $\Delta\tau$ and $\Delta\tau'$ to be statistically independent and also found that R_{out} is cable- and installation-dependent.

Fig. 7 shows the calculated outage probability P_{out} and the mean outage rate R_{out} for a given system threshold relative to the mean DGD. While P_{out} is based only on the Maxwellian distribution, R_{out} is based on measured DGD data. From our measured DGD data, we calculated an R_{out} of 0.157 outage events per year (one outage event every 6.39 y) for the case where the threshold is three times the mean. When the threshold is increased to 3.7 times the mean DGD, R_{out} becomes 0.0034 outage events per year, or one outage event in 1648 years.

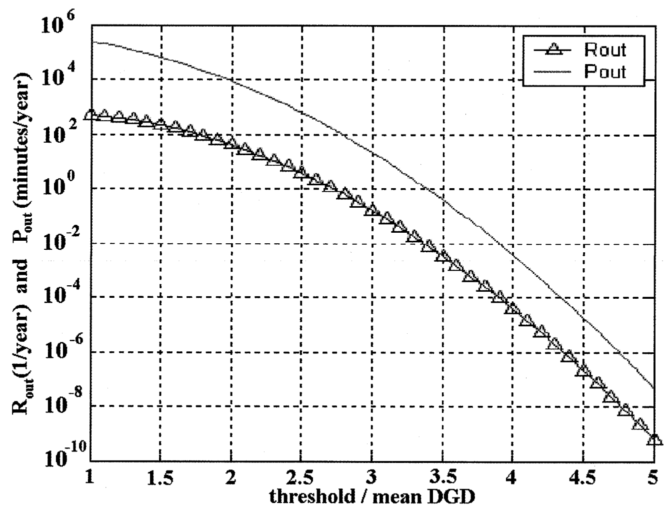

Fig. 7. Calculated outage probability P_{out} and mean outage rate R_{out} versus threshold/mean DGD.

For comparison, Nagel *et al.* [22] observed a DGD correlation time of 19 h and predicted that the DGD will exceed three times its mean value once every 3.5 y. From data measured on 37 km of buried cable (with above-ground segments) having a mean DGD of 9.44 ps, Caponi *et al.* [24] predicted that the DGD will exceed three times the mean DGD once every 2.5 y.

B. Duration of High-DGD Events

The mean duration of DGD-induced outages can be determined using statistical analysis, as well. Caponi *et al.* [24] showed that the mean outage duration T_{out} is

$$T_{\text{out}} = \frac{P_{\text{out}}}{R_{\text{out}}} \tag{9}$$

which has units of minutes.

Fig. 8 shows the calculated mean outage duration T_{out} as a function of system threshold relative to the mean DGD. Since T_{out} is found using R_{out}, which is cable- and installation-dependent, T_{out} will also be cable- and installation-dependent. For the case where the threshold is three times the mean DGD on this link, the mean duration of PMD-induced outages is about 136 min. For the case where the threshold is increased to 3.7 times the mean DGD, T_{out} reduces to about 108 min.

Again for comparison, Nagel *et al.* [22] estimated a mean outage duration (outage means DGD greater than three times mean DGD) between 10 and 20 min for their link. Similarly, Caponi *et al.* [24] predicted a mean outage duration of 56 min on their cable. Furthermore, Bülow and Veith [15] found that while unusually long duration outages occur, the probability of occurrence decreases almost exponentially with outage duration.

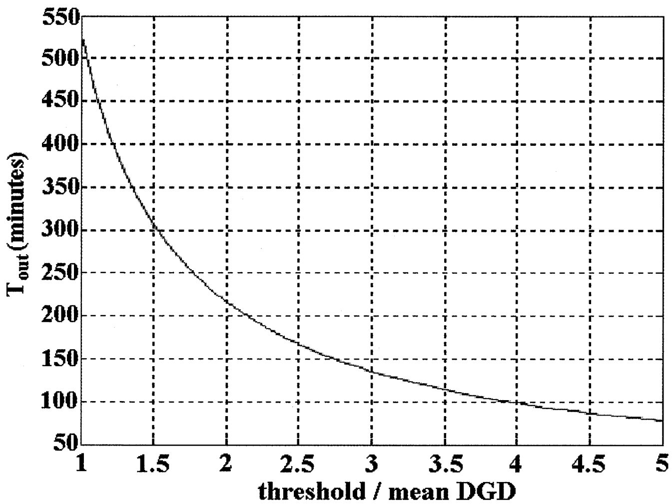

Fig. 8. Calculated mean outage duration $T_{\rm out}$ as a function of threshold/mean DGD.

C. Impact of High-DGD Events on Adjacent Channels

When a high-DGD episode occurs, how many DWDM channels will be affected? For a link with a mean DGD of 5 ps, the DGD bandwidth will be about 180 GHz, or 1.44 nm. Therefore, for a DWDM system with 50-GHz channel spacing, during a 3.7 $\times\langle\Delta\tau\rangle$ event, the DGD in adjacent channels may also experience PMD-induced signal degradation (i.e., only two or three channels will likely be affected by a single high-DGD episode).

D. Design Rules

Based on these observations and analyses, certain rules may be developed. An important parameter in making decisions regarding PMD in a network is the ratio between the receiver's DGD tolerance $\Delta\tau_{\rm RX}$ and the link's mean DGD, as follows:

$$M_\tau = \frac{\Delta\tau_{\rm RX}}{\langle\Delta\tau\rangle}. \tag{10}$$

For cases where $M_\tau > 3$, the frequency of PMD-induced outages will be low, and their duration may be brief. In these cases, the approach proposed by Särkimukka *et al.* [13] (or one utilizing new protection techniques) may be viable. The occurrences that may require the switching of this traffic will likely be infrequent (spanning years) and may only be necessary for several minutes or a couple of hours.

For cases where $2 < M_\tau < 3$, PMD-induced outages may occur with a maximum frequency of one event every few days and a mean outage duration of 2–4 h. For cases where $M_\tau < 2$, chronic PMD-induced outages will result with durations of several hours. In these instances, the option of applying PMD compensation, interrupting the link with a back-to-back terminal regenerator, or even replacing particular fiber segments, may be appropriate.

E. Example Scenarios

1) 10-Gb/s, $\langle\Delta\tau\rangle$ = 10 ps, Receiver's DGD Tolerance 40 ps: In this scenario, the DGD margin M_τ is 4. The probability of the DGD exceeding the receiver's DGD tolerance level is about 7.4×10^{-9}, or, effectively, 0. In this case, it is quite unlikely that a PMD-induced outage will ever be observed, and if one does occur, its mean duration will be 100 min. The DGD bandwidth will be about 90 GHz, or about 0.72 nm.

2) 10-Gb/s, $\langle\Delta\tau\rangle$ = 10 ps, Receiver's DGD Tolerance 23 ps: In this case, the margin M_τ will be 2.3, meaning that the probability of the DGD exceeding the receiver's limit is about 0.37%. For our buried cable, PMD-induced outages typically will occur about once a month and with a mean duration of about 3 h. The DGD bandwidth will again be about 90 GHz.

3) 40-Gb/s, $\langle\Delta\tau\rangle$ = 3.2 ps, Receiver's DGD Tolerance 5.7 ps: The DGD margin M_τ, in this case, is 1.8; therefore, the probability of the DGD exceeding the receiver's limit is 4.4%. In this scenario, PMD-induced outages typically will occur about every 6 d. The mean duration will be about 4 h; however, outages persisting for a day may occur. The DGD bandwidth is about 2.2 nm, or 280 GHz, so in a DWDM application with 100-GHz channel spacing, two or three channels may be affected during each outage.

VII. Conclusion

By examining the statistical behavior of DGD in an optical fiber and using measured DGD data on a buried optical cable, predictions regarding the probability, frequency of occurrence, and spectral extent of high-DGD episodes can be made. Our observations indicate that DGD varies slowly in time and excursions of three or more times the mean DGD are infrequent and relatively short-lived. The measured DGD data indicate that for a PMDC system to be effective on this link, the PMDC system could have a time constant of a few hours and still keep pace with the DGD variations. Furthermore, since high-DGD events are isolated spectrally, a PMDC that is tunable in wavelength may be appropriate.

Viable mitigation approaches depend greatly on the DGD margin (i.e., the ratio of the receiver's maximum-tolerable DGD to the link's mean DGD). For cases where the link's mean DGD is comparable to the receiver's maximum-tolerable DGD, approaches for ensuring network availability include incorporation of PMDC systems, shortening the link length by strategically introducing back-to-back terminal regenerators or by replacing fiber segments found to have excessively high-DGD levels. For cases where the link's mean DGD is less than a third of the receiver's tolerable DGD, network reliability may be enhanced by providing a few spare channels in a DWDM environment. This finding is significant for network operators who may consider an optical networking solution whereby traffic may efficiently share protection bandwidth rather than extensive use of PMDC systems.

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Analysis and comparison of measured DGD data on buried single-mode fibers

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Abstract

Temporal and spectral measurements were made on three different 95-km fibers within a slotted-core, direct buried, standard single-mode fiber-optic cable over many days to characterize DGD variability. From this data we observed that DGD varies slowly over time but rapidly over wavelength. This data showed good agreement with a Maxwellian distribution. The frequency-averaged mean DGD varied by about 10% or less during the periods that included significant temperature swings. Outage analysis showed that for system tolerances of three times the mean DGD, outages will occur typically every 3 to 8 years with mean outage durations ranging from about one to two hours. From this analysis we conclude that high-DGD episodes are spectrally localized and will be exceedingly rare and short lived.

Introduction

Polarization-mode dispersion (PMD) may be a major impediment for network operators seeking to increase the per channel data rate on long-haul fiber-optic links. While the differential group delay (DGD, or $\Delta\tau$) in buried fiber had negligible impact at 2.5-Gb/s signaling rates, upgrades to 10 Gb/s, 40 Gb/s and beyond will require increasingly more attention. While there are PMD challenges facing carriers operating at 10 Gb/s, these challenges are not as severe as originally feared. Major carriers are successfully deploying 10-Gb/s dense-wavelength division multiplexed (DWDM) links across the core of their networks. A marked improvement in the DGD tolerance of 10 Gb/s long-reach receivers (to about 40 ps) will likely satisfy most length demands, obviating the need for PMD compensation (PMDC). Signaling rates of 40 Gb/s and beyond will most likely require some form of mitigation in long-haul applications, such as robust modulation schemes or PMDC.

To ensure signal quality on their fiber at higher bit rates, network engineers must anticipate the impact of PMD on the various fiber routes. An understanding of the variability of both the DGD and the principal states of polarization (PSPs) is required to specify appropriate transmission parameters. Factors such as the mean DGD, PMD correlation time and bandwidth, as well as second-order effects together with performance prediction models can provide this understanding.

The availability of measured PMD data on installed, buried fibers is limited. In this paper we present measured DGD data for buried, standard single-mode fiber to improve our understanding of the variability of PMD. While PMD is a vector quantity, with a magnitude (DGD) and a direction (PSP), we are only focusing on the DGD. The statistical distribution and behavior of PSPs has been extensively studied and is shown to be correlated to DGD behavior [1,2].

Experimental setup

Experiments were conducted to measure the instantaneous DGD on three different 95-km fibers (1, 2, and 3) within a slotted-core, direct buried, standard single-mode fiber-optic cable made available by Sprint. A polarization analyzer employing the Jones-Matrix-Eigenanalysis (JME) method was used for measurements at wavelengths from 1510 nm to 1625 nm with a spectral resolution of 0.1 nm (about 12.5 GHz). Measurements on fiber span 1 were repeated approximately every 3 hrs and they were carried on for about 86 days whereas on fiber spans 2 and 3 they were repeated approximately every 1½ hours and carried out for about 14 and 9 days, respectively. Over the 86 days (from Nov. 9, 2001 through Feb. 2, 2002) 692 measurements were made on fiber span 1 across the 1150 discrete wavelengths representing 795,800 measured values. For fiber spans 2 and 3 the corresponding number of DGD measurements is about 271,600 and 181,700.

Plots of DGD vs. wavelength and time

Figures 1, 2, and 3 show in a color-coded format normalized DGD data (i.e., DGD/mean DGD) measured on the three fiber spans, respectively. From the plots it is clear that for buried fibers DGD changes with time but not at a rapid rate. This variation is random and differs from fiber to fiber. It is also evident that the DGD varies significantly with wavelength and relatively high-DGD events are spectrally localized.

A histogram of the normalized DGD data on fiber span 1, shown in Figure 4, is seen to have shape consistent with a Maxwellian distribution, as expected. A curve representing a Maxwellian distribution for a 1-ps mean DGD is also plotted for comparison.

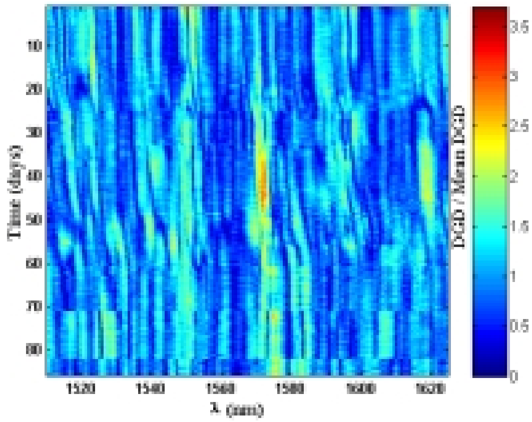


Figure 1. Measured, normalized DGD vs. wavelength and time for fiber span 1 (86 days of data).

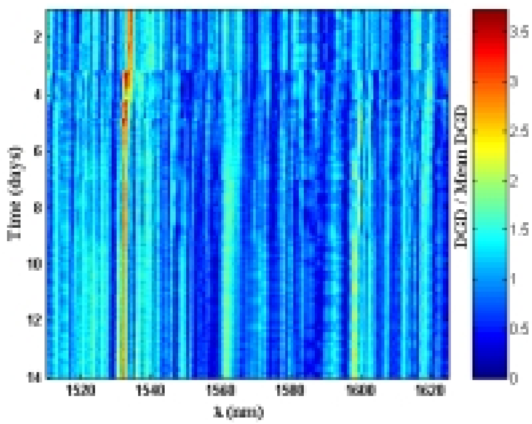
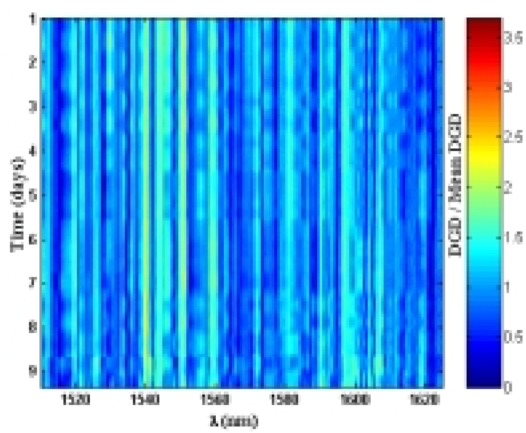


Figure 2. Measured, normalized DGD vs. wavelength and time for fiber span 2 (14 days of data).



(c)

Figure 3. Measured, normalized DGD vs. wavelength and time for fiber span 3 (9 days of data).

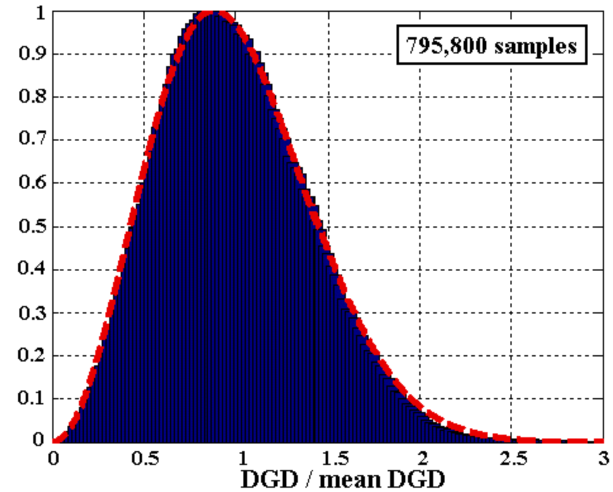


Figure 4. Histogram of measured, normalized DGD data on fiber span 1.

Similar histograms were obtained for the data on the other two fiber spans (plots not shown here) and they also showed good agreement with a Maxwellian distribution.

Mean DGD variation with time

To observe the time-dependent nature of DGD more closely, 1150 DGD measurements over all wavelengths were averaged together to obtain frequency-averaged DGD data, denoted as $\langle DGD \rangle_\lambda$ normalized by the overall mean DGD (averaged over both time and frequency), denoted as $\langle\langle DGD \rangle_\lambda\rangle_t$. Since temperature is a known driver in changing DGD changes, hourly air temperature data for the region were collected as well. The variation of frequency-averaged DGD and temperature with time on the three fiber spans is shown in Figures 5, 6 and 7. From Figure 5 it can be observed that frequency-averaged DGD varies by only about ±10% over 86 days of observations that included significant temperature swings. Since the entire length of the fiber is buried, the diurnal temperature variations do not represent the fiber temperature. Statistical analyses reveal no significant correlation between long-term temperature variations and the frequency-averaged mean DGD.

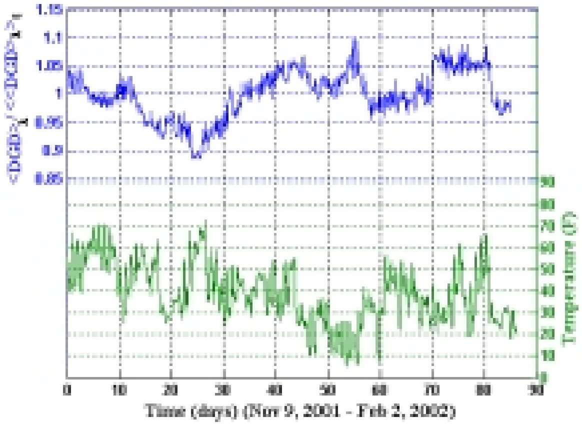


Figure 5. Frequency-averaged DGD and temperature vs. time for fiber span 1.

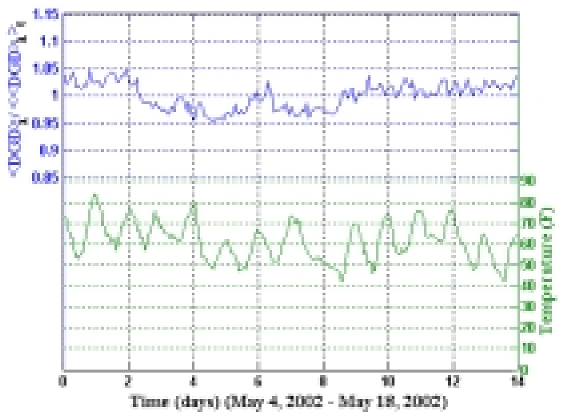


Figure 6. Frequency-averaged DGD and temperature vs. time for fiber span 2.

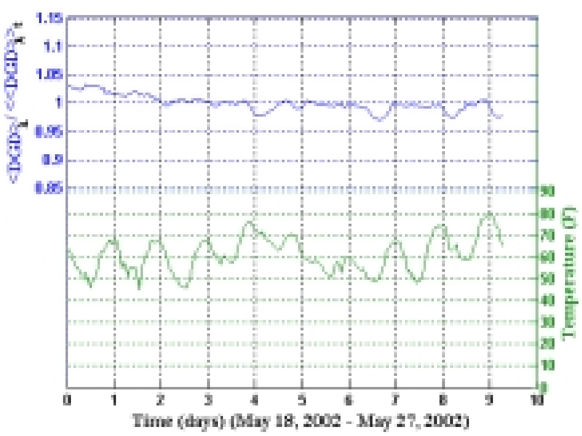


Figure 7. Frequency-averaged DGD and temperature vs. time for fiber span 3.

System outage analysis

An outage event is one which exceeds the given threshold value of DGD, $\Delta\tau_{th}$. The outage probability P_{out}, expressed in minutes/year, can be calculated from the Maxwellian probability distribution function (pdf), $f_\tau(\cdot)$ as

$$P(\Delta\tau \geq \Delta\tau_{th}) = 1 - \int_0^{\Delta\tau_{th}} f_\tau(\Delta\tau)\, d\,\Delta\tau \qquad (2)$$

and then multiplying the number of minutes in a year. As P_{out} is based on the Maxwellian pdf, it may be expressed as a function of one independent variable $M = \Delta\tau_{th}/(\text{mean DGD})$ as $P_{out}(M)$ and is clearly fiber independent and will be the same for all installations.

In cases where the probability of an outage is quite small, P_{out} represents the annualized outage probability based on long time records, however no insight is provided regarding the outage rates and their durations. Accurate estimation of the impact of PMD on network availability requires statistical analysis of the DGD variability. Caponi et al. [3] showed how the mean time between PMD-related outages could be estimated from the temporal characteristics of DGD variations and the Maxwellian probability density function. The mean outage rate, R_{out} (defined as the mean number of outage events per unit time with units of events/year), is found using [3]

$$R_{out} = \frac{1}{2} f_\tau(\text{threshold}) \int_{-\infty}^{\infty} f_{\tau'}(\Delta\tau') |\Delta\tau'|\, d\Delta\tau' \qquad (3)$$

where $\Delta\tau'$ is the time derivative of the DGD, and $f_{\tau'}(\cdot)$ is the pdf of $\Delta\tau'$. Caponi et al. observed $\Delta\tau$ and $\Delta\tau'$ to be statistically independent and also found that R_{out} is cable and installation dependent.

Figure 8 shows the calculated outage probability, P_{out}, and the mean outage rate, R_{out}, for a given system threshold relative to the mean DGD on the three fiber spans.

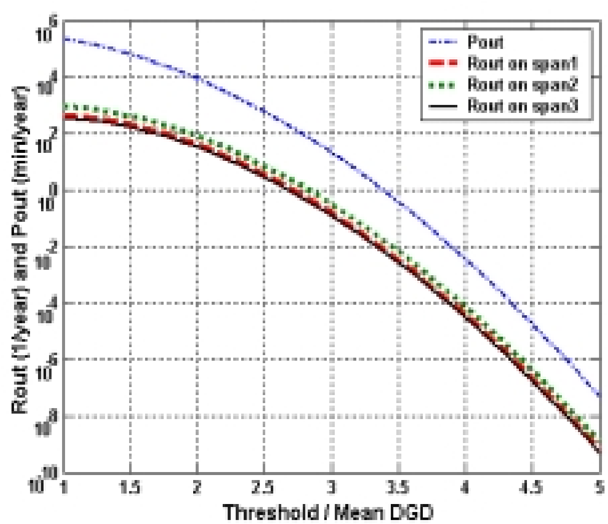


Figure 8. Calculated outage probability, P_{out}, and mean outage rate, R_{out}, versus Threshold/Mean DGD.

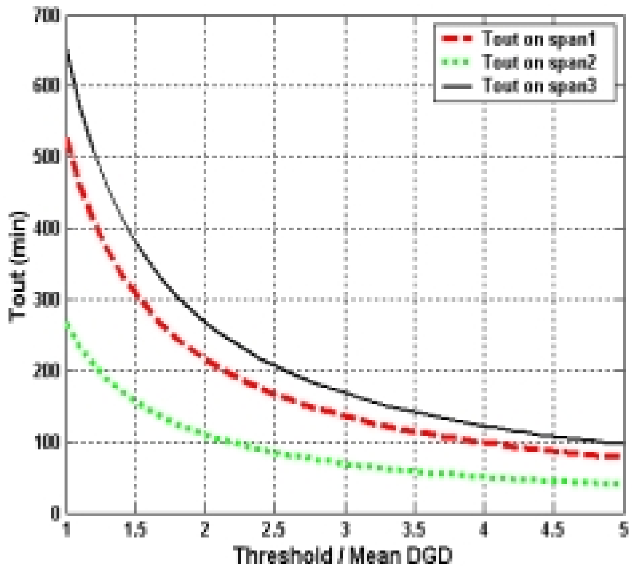


Figure 9. Calculated mean outage duration, T_{out}, as a function of Threshold/mean DGD.

Table 1. Predicted mean time between outages (MTBOs) and mean outage durations for different DGD tolerances

	3*<DGD>	3.7*<DGD>
Span 1 MTBO Outage duration	 6.39 years 136 min	 1648 years 108 min
Span 2 MTBO Outage duration	 3.25 years 69 min	 833 years 55 min
Span 3 MTBO Outage duration	 7.91 years 138 min	 2000 years 133 min

The mean duration of DGD-induced outages can be determined using statistical analysis as well. Caponi et al. [3] showed that the mean outage duration, T_{out}, is

$$T_{out} = P_{out} / R_{out} \quad (4)$$

which has units of minutes.

Figure 9 shows the calculated mean outage duration, T_{out}, as a function of system threshold relative to the mean DGD. Since T_{out} is found using R_{out}, which is cable and installation dependent, T_{out} will also be cable and installation dependent.

From the above analysis, we can estimate the mean outage time between outages (MTBOs) and mean outage durations for various DGD tolerances for these fiber spans. Table 1 lists these values for system thresholds of three and 3.7 times the mean DGD.

For comparison, Nagel et al. [4] predicted that for the 114-km buried link they studied, the DGD will exceed three times its mean value once every 3.5 years and estimated a mean outage duration of between 10 and 20 minutes for their link. From data measured on 37-km of buried cable, Caponi [3] predicted the DGD will exceed three times the mean DGD once every 2.5 years with a mean outage duration of 56 minutes.

Conclusions

We have measured DGD data on three different 95-km fibers within a slotted-core, direct buried, standard single-mode fiber-optic. From these measurements we observed that DGD varies slowly over time but rapidly over wavelength or frequency. Episodes of higher-that-average DGD were observed and seen to be spectrally localized and of limited duration.

To investigate the role of changing temperature on mean DGD variations, frequency-averaged DGD data were compared to temperature histories. The frequency-averaged DGD varied by only about ±10% over 86 days of observations that included significant temperature swings.

From this data predictions were made regarding the probability, and frequency of outage occurrence. While the statistics of Maxwellian processes adequately describe the annualized outage probability, further analysis of the DGD data revealed the mean time between outages and mean outage durations. For outages characterized by high DGD episodes (DGD more than three times the mean DGD), we found that the mean outage rates and durations for these three fibers to be similar. Our findings agree with reports by others that DGD excursions of three or more times the mean DGD are infrequent and relatively short lived. This finding is significant for network operators who must assess the impact of PMD on network reliability.

Acknowledgment

This work was funded by Sprint Corporations Company, L. P. A special tribute is paid to Francis Yarkosky, for his leadership and support.

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Measured temporal and spectral PMD characteristics and their implications for network-level mitigation approaches

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Abstract– **Signal degradation due to polarization-mode dispersion (PMD) effects may become significant for signaling rates of 10 Gb/s, 40 Gb/s, and beyond. As expected, statistical analysis of variations in differential group delay (DGD) indicate that excursions from the mean DGD by factors of 3.7 or higher have very low probability. Temporal and spectral measurements of DGD were made on 95 km of buried standard SMF over an 86 day period to determine the distribution and rate of change of high DGD events. A drift time of about 3.4 days was found. The DGD data agree well with results of similar experiments reported in the literature. Coupling the drift time characteristic with the statistical behavior of DGD, we conclude that high-DGD episodes will be exceedingly rare and short lived. The impact of PMD on network operators is explored. Approaches are reviewed for network operators tasked with transporting high bit-rate channels over fiber links with known PMD characteristics.**

INTRODUCTION

In the phenomenon called polarization-mode dispersion (PMD), birefringence in the optical fiber provides two polarization-dependent group velocities for optical signals. In the high-coherence model of PMD (which assumes the coherence time of the light source is greater than the PMD-induced delays and no polarization-dependent loss) an input pulse will result in two orthogonally polarized pulses that preserve the shape of the original input pulse. The relative amplitudes of these two pulses is determined by the state of polarization (SOP) of the input pulse relative to the fiber's input principal states of polarization (PSPs). Thus for each pulse input, two pulses arrive at the receiver with different arrival times, called the differential group delay (DGD), $\Delta\tau$. This first-order model is frequency independent and is only valid over limited bandwidths. For wider bandwidths higher order effects must be considered resulting in frequency dependent polarization and dispersion [1], [2]. The bandwidth over which the PSPs can be assumed constant depend on the properties of the fiber and has been shown to vary inversely with the mean DGD, $\langle\Delta\tau\rangle$ [3]. While the minimum bandwidth of the PSPs in single-mode fibers was found to be always over 50 GHz [3], this bandwidth for standard single-mode fiber is of the order of 100 GHz [1].

PMD may become a major impediment for network operators seeking to increase the per channel data rate on long-haul fiber-optic links. While the DGD in buried fiber had negligible impact at 2.5-Gb/s signaling rates, upgrades to 10 Gb/s, 40 Gb/s and beyond will require increasingly more attention. While there are PMD challenges facing carriers at 10 Gb/s, these challenges are not as severe as originally feared. Major carriers are successfully deploying 10 Gb/s dense-wavelength division multiplexed (DWDM) links across the core of their networks. A marked improvement in the DGD tolerance of 10 Gb/s long-reach receivers (to about 40 ps) will likely satisfy most length demands, obviating the need for PMD compensation (PMDC). Signaling rates of 40 Gb/s and beyond will most likely require some form of mitigation in long-haul applications, such as robust modulation schemes or PMDC.

To ensure signal quality on their fiber at higher bit rates, network engineers must anticipate the impact of PMD on the various fiber routes. Design of a reliable network requires a good model of the PMD characteristics on each link. An understanding of the variability of both the DGD and the PSPs is required to specify appropriate transmission parameters. Factors such as the mean DGD, PMD correlation time and bandwidth, as well as second-order effects together with performance prediction models can provide this understanding.

While PMD is a vector quantity, with a magnitude (DGD) and a direction (PSP), we are deliberately focusing exclusively on DGD as this is a readily measured parameter on installed optical networks. The statistical distribution and behavior of PSPs has been extensively studied and reported elsewhere.

PMD STATISTICS

Mean DGD

For long optical fibers, the PMD figure of merit typically specified is its mean DGD, $\langle\Delta\tau\rangle$, (having units of ps) or its PMD coefficient, $\langle\Delta\tau\rangle/\sqrt{L}$, (having units of ps/$\sqrt{\text{km}}$) where L is the fiber length. The PMD for an installed (buried) fiber-optic cable is dominated by the inherent PMD of the bare fiber; however, the level of relaxation provided by the cabling and installation techniques also affect PMD. While the PMD in bare fiber is determined largely by the core-cladding concentricity achieved during manufacture, we have found that loose-tube cabling results in a lower PMD than other cabling methods, such as slotted core cabling. In addition, mechanical stresses introduced during cable installation (burial) also contribute to the PMD and will be affected by the installation practices used and whether the cable is in a protective conduit.

The mean DGD for a given fiber is a constant that represents both the average of DGD values at one time across a broad spectral bandwidth

$$\langle\Delta\tau\rangle = \frac{1}{N_\lambda}\sum_{i=1}^{N_\lambda}\Delta\tau(\lambda_i, t) \quad (1)$$

and the average of DGD values for a single wavelength over a long time period

$$\langle\Delta\tau\rangle = \frac{1}{N_t}\sum_{i=1}^{N_t}\Delta\tau(\lambda, t_i) \quad (2)$$

where $\Delta\tau(\lambda, t)$ is the DGD value at wavelength λ and time t. Although the mean DGD for an installed fiber is constant, changing environmental factors (e.g., temperature) cause the instantaneous DGD at a given wavelength, $\Delta\tau(\lambda, t)$, to vary randomly about that mean.

When various fiber segments are concatenated to form a single long fiber, the mean DGD of the overall fiber is found by

$$\langle\Delta\tau_{total}\rangle = \sqrt{\sum_i^N \langle\Delta\tau_i^2\rangle} \quad (3)$$

where N is the number of segments.

Maxwellian distribution

The DGD for a given wavelength at any moment in time, $\Delta\tau(\lambda, t)$, is a random variable with a Maxwellian probability density function [4,5]

$$p(\Delta\tau) = \sqrt{\frac{2}{\pi}}\frac{\Delta\tau^2}{\sigma^3}e^{\left(\frac{-\Delta\tau^2}{2\sigma^2}\right)} \quad (4)$$

for $0 < \Delta\tau < +\infty$, where

$$\langle\Delta\tau\rangle = \sigma\sqrt{8/\pi} \quad (5)$$

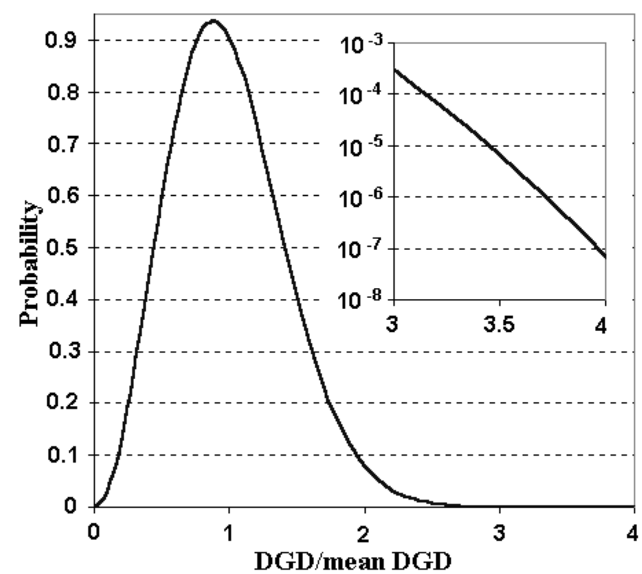

Figure 1. Maxwellian probability density function.

Therefore the single parameter <Δτ> fully specifies the distribution. Figure 1 shows the Maxwellian probability density function normalized by the mean DGD.

Using this distribution, the probability of $\Delta\tau$ exceeding a particular value can be found using

$$P(\Delta\tau \geq X) = 1 - \int_0^X p(\Delta\tau)\, d\,\Delta\tau \quad (6)$$

For example, the probability of $\Delta\tau/\langle\Delta\tau\rangle$ exceeding 3.7 is 1.3×10^{-7}. Expressed another way, if the mean DGD of a fiber link is 10 ps, 99.99999% of the time the DGD will be less than 37 ps.

NETWORK DESIGN CONSIDERATIONS

In the design of a robust, long-haul fiber-optic network, the relationship between the maximum achievable link length and bit rate must be considered. For link designs where the maximum tolerable DGD is exceeded, techniques for coping with the effects of PMD must be explored.

Receiver DGD tolerance

The maximum link DGD that a receiver can tolerate before the signal degradation becomes unacceptable depends on a variety of factors, including modulation format, optical signal-to-noise ratio, and receiver design. For intensity-modulated, direct-detected (IM-DD) systems, Iannone et al. [6] found that when the transmitted signal excites both PSPs equally (a worst case condition), a 1-dB receiver sensitivity penalty results when the instantaneous DGD is about 23% of the signaling time period, T_{bit}. For a 2.5-Gb/s NRZ signal (T_{bit} is 400 ps), this corresponds to a tolerable DGD value of about 92 ps; at 10-Gb/s, about 23 ps is tolerable; and for a 40-Gb/s NRZ signal, this corresponds to about 5.7 ps. This maximum tolerable DGD level is representative of the NRZ IM-DD case; receiver DGD tolerance can be improved through careful receiver design, use of PMD-tolerant signaling formats, and the use of forward-correction codes (FEC). Khosravani and Willner [7] showed that RZ, chirped RZ, and dispersion-managed soliton signaling formats are much more tolerant of PMD effects compared to NRZ formats. Shieh et al. [8] and Xie et al. [9] have demonstrated a substantial increase in receiver tolerance of DGD when FEC is used. Modern long-haul, 10-Gb/s receivers using FEC or RZ modulation can tolerate about 40 ps of DGD with a 1-dB power penalty.

Probability of signal outage

For occurrences of high instantaneous DGD, signal quality may be intolerable resulting in a PMD-induced outage. Such outages may significantly affect network availability for higher bit rates (10 Gb/s, 40 Gb/s, and higher). For a network to operate with an overall availability of "five nines" (i.e., 99.999% of availability), the desired PMD-related availability factor may be "seven nines" (i.e., 99.99999%) which corresponds to a maximum tolerable DGD 3.7 times the mean DGD. For a 2.5-Gb/s IM-DD NRZ system with a DGD tolerance of 92 ps, this results in an acceptable mean DGD value of 25 ps; for a 10-Gb/s system with a DGD tolerance of 23 ps, the acceptable mean DGD is 6.2 ps; and for 40-Gb/s with a tolerable DGD of 5.7 ps, the acceptable mean DGD level is 1.5 ps. For DGD-tolerant receivers (40 ps at 10 Gb/s) this results in an acceptable mean DGD of 10.8 ps.

Coping with PMD

For network operators faced with the challenge of upgrading the channel data rate on a high-PMD link in the network, a handful of solutions exist that will preserve the signal quality at increased data rates.

One alternative cost solution is to selectively replace those fiber segments in the link known to be the dominant contributors to the overall link DGD, if they can be identified.

Another alternative cost solution is to regenerate the optical signal by placing a back-to-back terminals at the point in the link where the DGD affects approach an intolerable level, thus effectively reducing the optical link length.

Still another approach is to introduce error correction codes, such as FEC. In this approach the optical data payload is reduced incrementally in exchange for a marginal gain in PMD tolerance.

Yet another solution is to incorporate an adaptive PMD compensation system [8, 9, 10, 11, 12], typically located at the receiver. Typical PMD compensation systems are effective at minimizing the effects of first-order PMD, and, in some cases, second-order PMD. However both first- and second-order PMD compensation systems suffer the drawback that they reduce the effects of signal degradation over a very narrow optical bandwidth. This is a significant drawback for dense wavelength-division multiplexing (DWDM) systems. For a long-haul fiber-optic link carrying 100s of wavelengths, a separate PMD compensation system may be required for each wavelength to provide the desired seven nines availability.

For DWDM systems, another potential solution exists. Särkimukka et al. [13] proposed a method for mitigating PMD effects in a multichannel system by moving traffic off of PMD-impaired channels onto spare channels that are not experiencing PMD degradation.

One may also rely upon more traditional protection techniques (e.g. SONET ring or IP routing at layers 1 & 3, respectively). This protection can easily provide a guard against occasional PMD-induced outages of limited duration. However, for this approach to be viable, the episodes of abnormally high DGD events must be infrequent and spectrally localized. To evaluate the feasibility and limits of this solution, an understanding of the temporal and spectral nature of PMD is required.

Finally, there are also efficient optical networking solutions offering varying degrees of protection by using an optical cross-connect with a DWDM system. Operators may then construct a mesh-protected network and provide managed wavelength services that are protected against a possible PMD induced outages. Similar to the traditional protection methods, these more recent techniques will only be viable with infrequent and spectrally localized outages.

TEMPORAL BEHAVIOR OF DGD

Given the dynamic nature of PMD and the low probability of excursions to intolerable levels, measurements of $\Delta\tau(\lambda,t)$

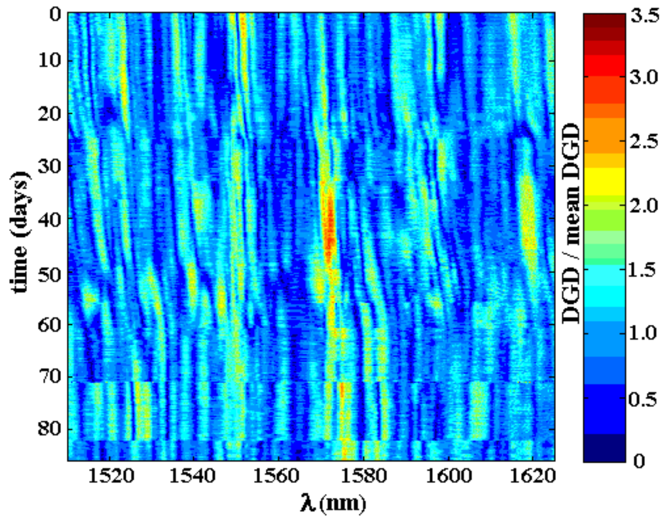

Figure 2. Map of normalized DGD vs. wavelength and time.

on buried fiber spans were made over long periods to enable prediction of the potential impact of PMD on network availability. Of particular interest are the frequency and duration of these rare events. The Jones Matrix Eigenanalysis (JME) technique was used to measure the DGD data on a 95-km span of slotted-core, direct buried fiber-optic cable made available by Sprint.

DGD was measured roughly every 3 hours at wavelengths from 1510 nm to 1625 nm with a spectral resolution of 0.1 nm (about 12.5 GHz). Over 86 days (from November 9, 2001 through February 2, 2002) 692 measurements were made on the 1150 discrete wavelengths. Figure 2 shows in a color-coded format this normalized DGD data (i.e., $\Delta\tau/\langle\Delta\tau\rangle$) representing 795,800 measured values. Expressed another way, if the 0.1-nm spectral samples and 3-hour time samples are statistically independent, then this data set would represent about 272 years of DGD data.

A histogram of this normalized DGD data is shown in Figure 3, and is seen to have shape consistent with a Maxwellian distribution, as expected. A curve representing a Maxwellian distribution normalized to the mean is also plotted for comparison.

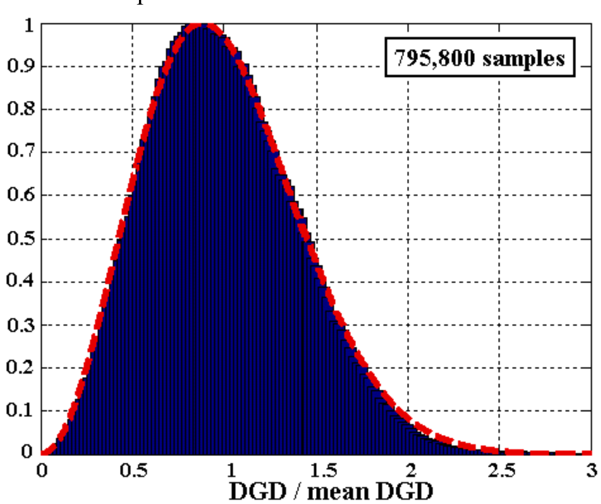

Figure 3. Normalized histogram of measured DGD data.

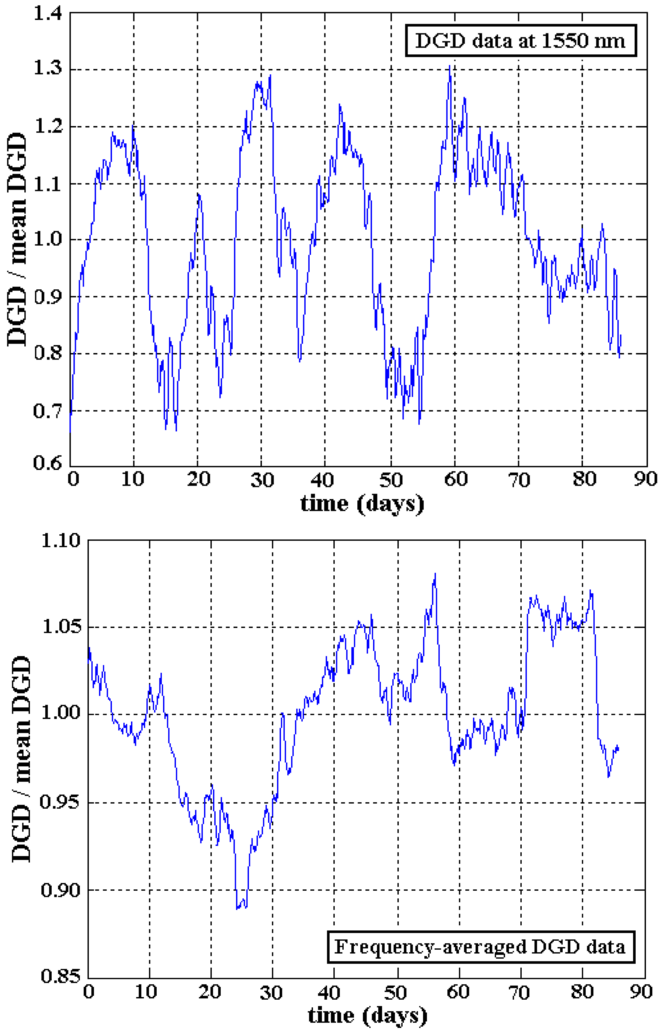

Figure 4. Measured temporal variations in normalized DGD over 86 days (top) at 1550 nm and (bottom) averaged over all 1150 frequency measurements.

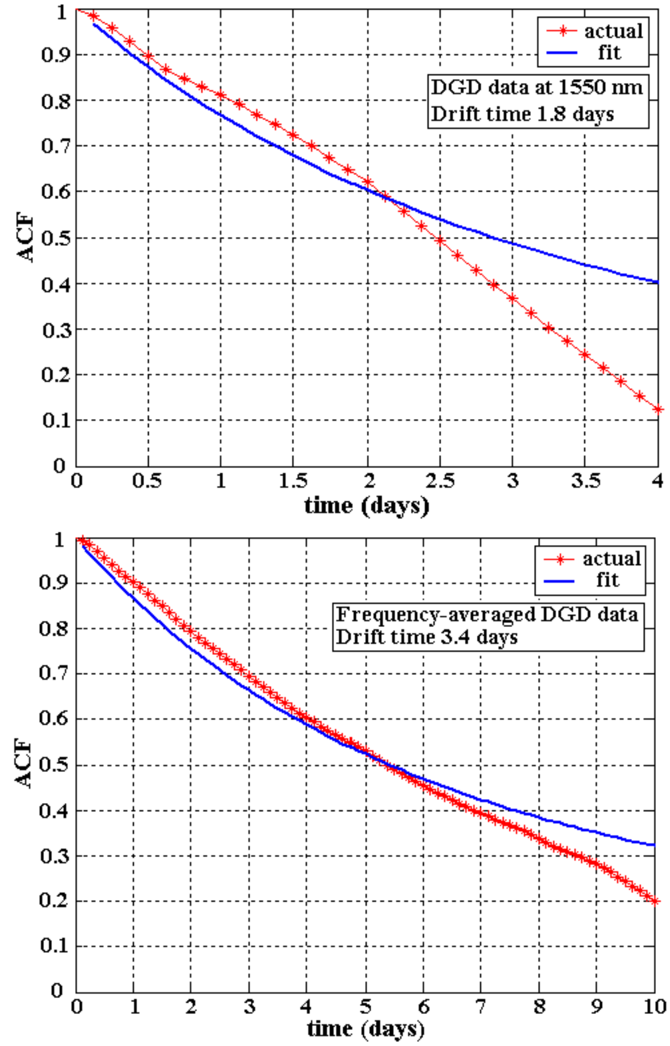

Figure 5. Normalized temporal autocorrelation functions (ACFs) of normalized DGD data measured (top) at 1550 nm and (bottom) across 1150 frequencies. Theoretical ACF curves are fitted to the measured temporal ACFs.

From Figure 2 it is apparent that for buried fiber DGD values do not change rapidly. Figure 4 shows time histories of measured DGD data over the 86-day period. The top plot is DGD data at 1550 nm and the bottom plot is frequency-averaged data. While the mean value of the bottom plot is one (by definition), the mean value of the top plot is 1.088. This should not be interpreted to mean that the mean DGD is changing; rather since fewer data were used to estimate the mean, there is more uncertainty in that estimate compared to the estimate using all of the data.

To determine the DGD rate of change, an autocorrelation analysis was performed on the DGD time histories. Figure 5(top) shows the normalized temporal autocorrelation function (ACF) of the DGD data measured at 1550 nm. Figure 5(bottom) shows the ACF for the DGD time history for the frequency-averaged DGD data. Also shown in Figure 5 are curves representing the theoretical temporal autocorrelation function for DGD [14] which has the form

$$\mathrm{AFC}(\Delta t) = \frac{1-\exp\left(-|\Delta t|/t_d\right)}{|\Delta t|/t_d} \qquad (7)$$

where t_d is the average drift time of DGD. The drift time indicates the timescale over which the DGD changes. Furthermore, when outages occur, the outage duration will be related to the drift time [14,15]. Based on data collected over the 86 days, the drift time for this fiber is estimated to be around 3.4 days. Expressed another way, samples should be collected about once every three days to obtain statistically independent DGD values on a specific wavelength; measurements collected more often are correlated.

For comparison, others have reported a range of DGD correlation times under various fiber conditions. For spools of fiber in a laboratory environment, correlation times of about 30 minutes on 31.6 km of fiber [16] and 3 hours on a 10-km fiber [17] have been reported. DGD variations on a 48-km aerial cable exhibited time scales ranging from 5 to 90 minutes depending the air temperature rate of change [18]. For submarine cables, a DGD correlation time of about an hour was observed on a 119-km cable [19], and [20] observed

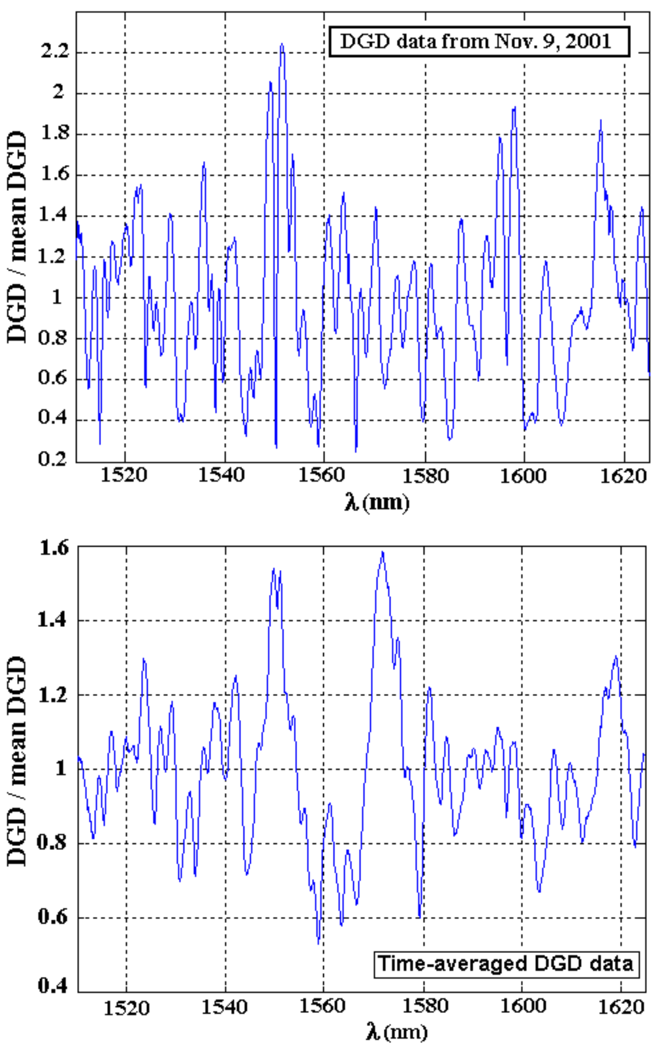

Figure 6. Spectral variations in normalized DGD over 1150 wavelengths (top) measured on Nov. 9, 2001 and (bottom) time-averaged over all 692 time measurements.

PMD changes with a period of about two months on a 62-km fiber-optic cable. On buried fibers, correlation times of at least 20 minutes (17 km) [21], 1-2 hours (48.8 km) [18], 3 and 5.7 days (127 km) [14], and 19 hours (114 km) [22] have been reported. Thus our observation of 3.4 days is consistent.

With knowledge gained from the ACF analysis, we can now interpret realistically our DGD data set. Over the 86 days of observation, about 25 independent samples were collected.

SPECTRAL BEHAVIOR OF DGD

From Figure 2 we note that the DGD varies significantly with wavelength. Figure 6(top) shows the normalized spectral variation of the first DGD data (measured on Nov. 9,2001) and the bottom plot shows the spectral variation of the time-averaged, normalized DGD data.

To determine the DGD bandwidth, spectral autocorrelation analysis was performed on the normalized DGD spectral data. Figure 7(top) shows the resulting normalized spectral ACF for one spectral measurement (data collected on

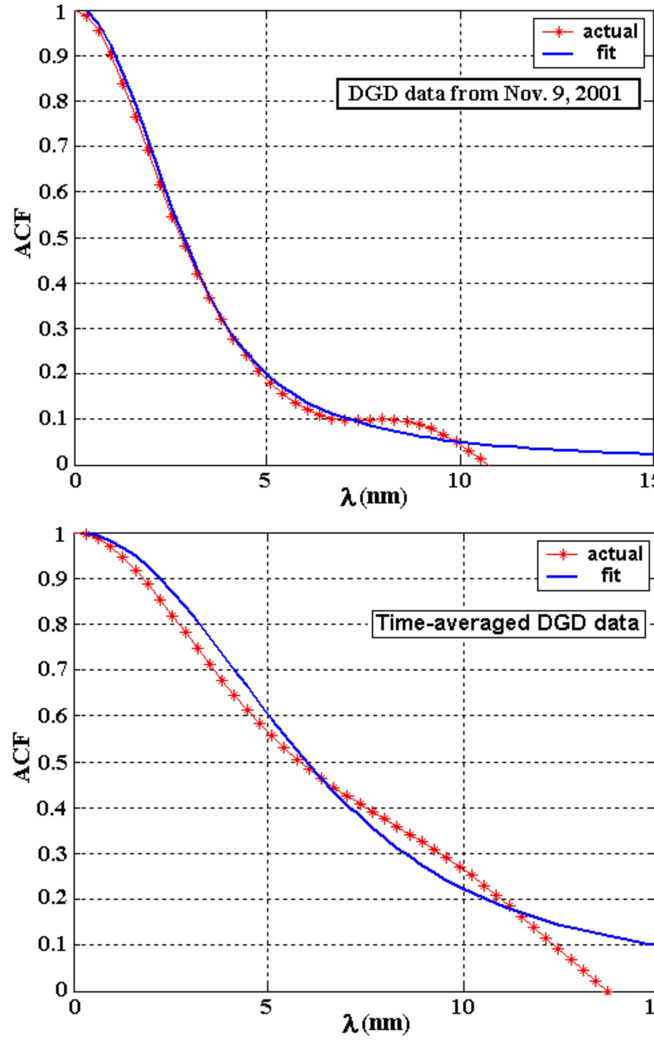

Figure 7. Normalized spectral autocorrelation functions (ACFs) of normalized DGD data measured (top) on Nov. 9, 2001 and (bottom) time-averaged over all 692 measurements. Theoretical ACF curves are fitted to the measured spectral ACFs.

Nov. 9,2001) and Figure 7(bottom) shows the normalized spectral ACF for the time-averaged data. Also shown in Figure 7 are curves representing theoretical spectral ACFs for DGD, with the form [23]

$$\mathrm{ACF}(\Delta\omega) = 3\frac{1-\exp\left(-\left\langle\Delta\tau^2\right\rangle\Delta\omega^2/3\right)}{\Delta\omega^2} \qquad (8)$$

where $\Delta\omega$ is the radian frequency and $<\Delta\tau^2>$ represents the variance of the DGD.

From the measured data the bandwidth for the normalized DGD is estimated to be about 7.5 nm or 936 GHz. Therefore if the mean DGD is 1 ps and an optical channel is affected by significant DGD, nearby channels (within about 7.5 nm) may also experience this effect.

Theory and experiments [23] have demonstrated that the DGD bandwidth is inversely proportional to the mean DGD.

$$\omega_c = 4\sqrt{2}\Big/\left\langle\Delta\tau\right\rangle \qquad (9)$$

Thus fibers with a high mean DGD have a narrower DGD bandwidth than fibers with a low mean DGD. Thus for a fiber with a mean DGD of 1 ps, the predicted DGD bandwidth is 900 GHz which agrees well with bandwidth found using the spectral ACF fit in Figure 6(bottom). Note that normalized DGD bandwidth in the Figure 6(top) is about 4 nm which is significantly less than the approximately 7.5 nm bandwidth seen in Figure (bottom). This should not be interpreted to mean that the DGD bandwidth is varying; rather the bandwidth estimate obtained using all of the data will be more accurate as it is based on significantly more data points.

IMPLICATIONS FOR NETWORK AVAILABILITY

Mean time between PMD-related outages

The mean time between PMD-related outages can be estimated from the temporal characteristics of DGD variations and the Maxwellian probability density function. The DGD rate of change is characterized by the DGD drift time, t_d. This drift time may be thought of as "rolling the dice" every t_d to obtain a new, statistically independent DGD value. Therefore the mean time between high-DGD events (i.e., DGD exceeding a value X) can be estimated as

$$T_X = t_d / \left(k \cdot P(\Delta\tau > X)\right) \qquad (10)$$

where k is a proportionality constant.

For example, Nagel et al. [22] observed a DGD correlation time of 19 hours, and predicts that the DGD will exceed three times its mean value once every 3.5 years. Since the probability of the DGD exceeding three times its mean is about 4.2×10^{-5} we can determine a value of 15 for k.

Applying (10) with a drift time of 3.4 days and a threshold of three times the mean DGD, the mean time between high-DGD events is about 14.8 years. For a PMD-induced outage probability of 1.3×10^{-7} (network availability of seven nines) the receiver should tolerate $3.7\text{x}\langle\Delta\tau\rangle$. With a DGD drift time, t_d, of 3.4 days, the estimated mean time between high-DGD events will be about 4,700 years, making it an extremely rare occurrence!

Duration of high-DGD events

Again from the DGD drift time, the Maxwellian probability density function, and the temporal ACF, the average duration of a high-DGD event can be estimated. While the correlation time represents the time delay resulting in a 63% reduction in the normalized ACF, smaller variations in the ACF require significantly shorter times. Again Nagel et al. [22] estimated a mean outage duration between 10 and 20 minutes for their link having a DGD correlation time of 19 hours. Bülow and Veith [15] found that while unusually long duration outages occur, the probability of occurrence decreases almost exponentially with outage duration. In other words, when outages occur, most will be of short duration.

Based on these findings, for the 95-km link we observed, we anticipate the typical duration of an outage to be between 1 and 2 hours with the possibility that a prolonged outage could persist for 1 to 1.5 days.

Impact of high-DGD events on adjacent channels

When a high-DGD episode occurs, how many DWDM channels will be affected? For a link with a mean DGD of 5 ps, the DGD bandwidth will be about 180 GHz or 1.44 nm. Therefore for a DWDM system with a 50-GHz channel spacing, during a $3.7\times\langle\Delta\tau\rangle$ event, the DGD in adjacent channels may also experience PMD-induced signal degradation, (i.e., only two or three channels will likely be affected by a single high-DGD episode).

Design rules

Based on these observations and analyses, certain rules may be developed. An important parameter in making decisions regarding PMD in a network is the ratio between the receiver's DGD tolerance, $\Delta\tau_{RX}$, and the link's mean DGD.

$$M = \frac{\Delta\tau_{RX}}{\langle\Delta\tau\rangle} \qquad (11)$$

For cases where M > 3, the frequency of PMD-induced outages will be low, and their duration may be brief. In these cases the approach proposed by Särkimukka (or one utilizing new protection techniques) may be viable. The occurrences when switching this traffic may be required will likely be infrequent (spanning years), and may only be required for a few minutes or as long as a day.

For cases where 2 < M < 3, PMD-induced outages may occur about once a month with typical durations measured in 10s of minutes.

For cases where M < 2, chronic PMD-induced outages will result. In these instances the option of applying PMD compensation, interrupting the link with a back-to-back terminal regenerator, or even replacing particular fiber segments may be appropriate.

Example scenarios

10-Gb/s, $\langle\Delta\tau\rangle$ = 10 ps, receiver's DGD tolerance 40 ps

In this scenario the DGD margin, M, is 4. The probability of the DGD exceeding the receiver's DGD tolerance level is about 7.4×10^{-9}, or effectively zero. In this case it is quite unlikely a PMD-induced outage will ever be observed. The DGD bandwidth will be about 90 GHz or about 0.72 nm.

10-Gb/s, $\langle\Delta\tau\rangle$ = 10 ps, receiver's DGD tolerance 23 ps

In this case the margin will be 2.3 meaning that the probability of the DGD exceeding the receiver's limit is about 0.37%. For a buried cable with a DGD drift time of about 2 days, PMD-induced outages typically will occur about once a month and last less than an hour. The DGD bandwidth will again be about 90 GHz.

40-Gb/s, $\langle\Delta\tau\rangle$ = 3.2 ps, receiver's DGD tolerance 5.7 ps

The DGD margin in this case is 1.8 so the probability of the DGD exceeding the receiver's limit is 4.4%. For a link with a drift time of 2 days, PMD-induced outages typically will occur about every third day. The typical duration will be 1 to 2 hours, however outages persisting for a day may occur. The DGD bandwidth is about 2.2 nm or 280 GHz so in a DWDM application with 50 GHz channel spacing, two or three channels may be affected during each outage.

CONCLUSIONS

By examining the statistical behavior of DGD in an optical fiber, and using measured DGD data on a buried optical cable, predictions regarding the probability, frequency of occurrence, and spectral extent of high-DGD episodes can be made. Reports by others confirm our observation that DGD excursions of three or more times the mean DGD are infrequent and relatively short lived. This finding is significant for network operators who may consider providing a few spare channels in a DWDM environment to ensure high network availability.

For cases where the mean DGD is comparable to the receiver's maximum tolerable DGD, approaches for ensuring network availability include inclusion of PMD compensation systems, shortening the link length by strategically introducing back-to-back terminal regenerators, replacing fiber segments found to have excessively high DGD levels, or by utilizing an optical networking solution whereby traffic may efficiently share protection bandwidth.

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PMD-Insensitive SCM Optical Receiver Using Polarization Diversity

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***Abstract*—Subcarrier multiplexing (SCM) optical systems with high subcarrier frequencies are susceptible to power fading caused by fiber polarization-mode dispersion (PMD). In this letter, an SCM optical receiver free of carrier fading is proposed and demonstrated using polarization diversity. Unlike conventional PMD compensators, this setup does not require a tunable optical delay line.**

***Index Terms*—Optical communication, optical modulation, polarization, polarization-mode dispersion, subcarrier multiplexing (SCM).**

IN HIGH-SPEED long-distance optical transmission systems using subcarrier multiplexing (SCM), to minimize the impact of fiber chromatic dispersion, optical single-sideband (SSB) modulation has been used, which also increases the spectral efficiency [1]. For this case, system tolerance to chromatic dispersion depends on the data rate on each individual subcarrier channel. However, polarization-mode dispersion (PMD) may become a limiting factor in this type of optical system.

In an optical fiber with PMD, two distinct orthogonal polarization modes exist with different propagation constants and different group velocities. This is described as the differential group delay (DGD) between the two orthogonal principal states of polarization (PSPs) of the fiber. Due to the statistical nature of the perturbations along the fiber, instantaneous DGD has a random value that generally follows a Maxwellian probability distribution. While SCM optical modulation distributes the total capacity of each laser transmitter into a number of subcarriers, and therefore, the data rate carried by each subcarrier is relatively low, the impact of PMD on SCM systems is determined mainly by the frequency of each RF subcarrier, rather than by the bandwidth of each individual subcarrier.

If we assume that the RF frequency of a subcarrier is $\Delta\omega$, this will also be the frequency separation between the carrier and the subcarrier in the optical domain. During fiber transmission, both the carrier and the subcarrier are decomposed into fast and slow PSPs. This causes a PMD-induced signal fading if the fiber DGD is sufficiently high. To illustrate this in a simple way, we assume that the optical field of both carrier and subcarrier are equally split into the fast and the slow PSPs and denote E_{cx}, E_{cy}, E_{sx}, and E_{sy} as carrier and subcarrier optical field components on the fast (x) and slow (y) PSP, respectively. At the receiver photodiode, the optical carrier beats with the optical subcarrier creating two photocurrent components: $i_x(t) = |E_{cx}E_{sx}|\cos(\Delta\omega t)$ and $i_y(t) = |E_{cy}E_{sy}|\cos[\Delta\omega(t+\Delta\tau)]$, where $\Delta\tau$ is the relative propagation delay between the fast and the slow PSPs, i.e., DGD. Therefore, the total received subcarrier component in the RF domain is

$$I(t) = |E_{cx}E_{sx}|\cos(\Delta\omega t) + |E_{cy}E_{sy}|\cos(\Delta\omega t + \Delta\omega\Delta\tau).$$

Because of the assumption of equal power splitting, $a(t) = |E_{cx}E_{sx}| = |E_{cy}E_{sy}|$, and we have

$$I(t) = 2a(t)A(\Delta\tau)\cos[\Delta\omega(t + \Delta\tau/2)].$$

The term $a(t)$ represents the digital data carried by the subcarrier, $\cos[\Delta\omega(t+\Delta\tau/2)]$ is the recovered RF subcarrier with a phase shift $\Delta\omega\Delta\tau/2$, and $A(\Delta\tau) = \cos(\Delta\omega \cdot \Delta\tau/2) \le 1$ represents the PMD-induced subcarrier fading. A complete fading happens when $\Delta\tau = \pi/\Delta\omega$. A complete signal fading occurs in this case because $\Delta\tau = \Delta T/2$ where ΔT is the period of the subcarrier. PMD-induced carrier fading happens to both double-sideband and single-sideband modulated optical SCM signals [2], and it is indeed one of the biggest problems preventing long-distance, high-capacity applications of optical SCM systems. For an SCM system with the highest subcarrier frequency of 20 GHz, although the data rate on the subcarrier may be low, the accumulated DGD in the transmission fiber has to be much smaller than 25 ps in order to avoid carrier fading. Therefore, for most practical applications of reasonable transmission distance, active PMD compensation will have to be used.

PMD compensation is currently an active area of fiber-optic system research. In many adaptive PMD compensating systems [3], [4], as shown in Fig. 1(a), a polarization beam splitter (PBS) is used to separate the signals carried by the two PSPs. A polarization controller (PC) precedes the PBS to align the PSPs with the principal axes of the PBS. Following the PBS is a variable delay line to compensate for the link DGD. Finally, the two optical paths are recombined, and the effects of PMD can be entirely compensated in the optical domain. Continuous monitoring of the residual PMD can be derived from the signal to provide feedback signal parameters for controlling the PC and the variable delay line. A liquid-crystal-based PC is commercially available with small footprint (such as the E-TEK FPCR series), which provides endless polarization autotracking. However, the variable optical delay line in such a PMD compensator is often implemented using a mechanical system to provide the needed

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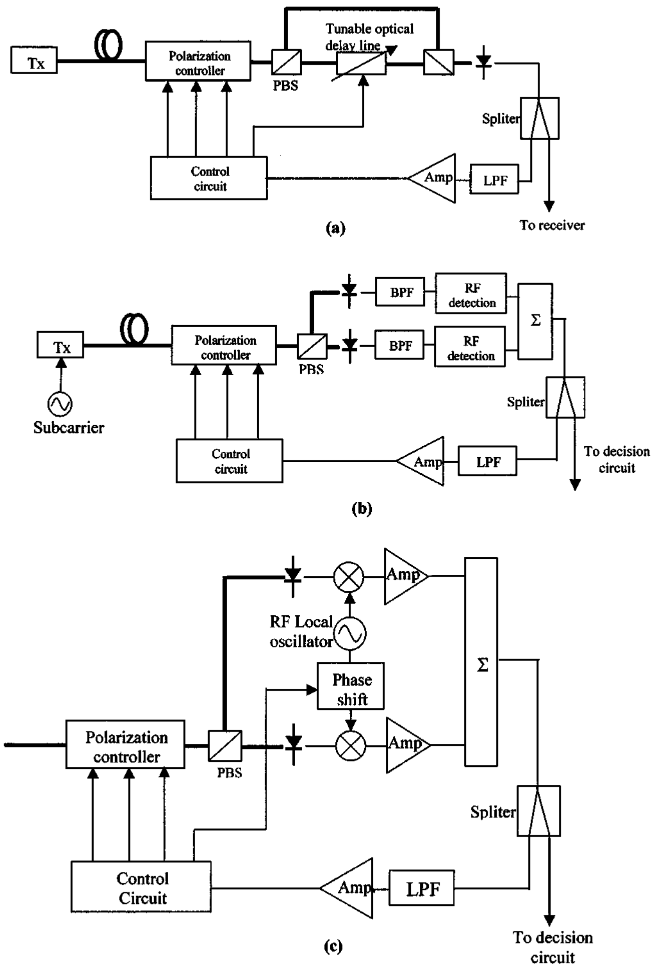

Fig. 1. Block diagrams. (a) Optical-domain PMD compensation using a tunable optical delay line. (b) PMD-insensitive SCM optical receiver using polarization diversity with RF envelope detection. (c) PMD-insensitive SCM optical receiver using polarization diversity with RF-coherent detection.

DGD range. The speed, size, and reliability of this mechanism raise concerns.

Another PMD-compensating scheme in time-division-multiplexing (TDM) optical systems is to shift the tunable delay line to the electrical domain using a polarization diversity receiver [5]. In this method, a tunable RF delay line has to be used after one of the two photodiodes to correct the PMD-induced DGD. Compared with the optical compensation method shown in [3] and [4], the tunable RF delay line required in [5] is not necessarily easier to implement than is an optical delay line.

Since PMD-induced carrier fading is the major concern in SCM optical systems, we will show that polarization diversity optical receivers shown in Fig. 1(b) and (c) are effective in eliminating this carrier fading, making an RF delay line unnecessary. The setup shown in Fig. 1(b) works for amplitude shift keying (ASK) SCM modulation scheme. Two photodiodes are used to detect the two PSP components at the output of the system. In order to ensure the alignment between the principal axis of the PBS and the PSP of the fiber, a PC is used before the PBS. If the principal axis of the PBS is properly aligned with the PSPs of the optical fiber system at the carrier wavelength, the amplitude of signals detected by both photodiodes will not be affected by PMD-induced fading. The effect of PMD will be shown as

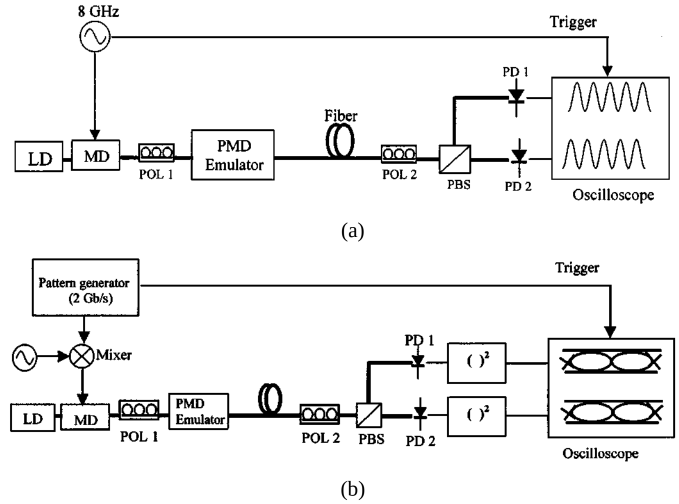

Fig. 2. Experimental setups. (a) An SCM system transmitting a nonmodulated 8-GHz subcarrier only. (b) An SCM system transmitting 2-Gb/s pseudorandom nonreturn to zero (NRZ) data carried on an 8-GHz subcarrier. LD: Laser diode. MD: Optical modulator. POL: PC. PBS: Polarization beam splitter. PD: Photodiode. $(\,)^2$: Square-law detector.

a relative time delay between the waveforms carried by the two PSP components. An RF bandpass filter is used after each photodiode to select the desired subcarrier channel, followed by an RF detector to detect the signal envelope and remove the high-frequency subcarrier. The signals carried by the two PSPs are recombined after the subcarrier is removed, and therefore, PMD-induced carrier fading is eliminated.

For phase-shift-keying-modulated SCM systems with coherent RF detection, an RF local oscillator is used to detect the baseband signal that is carried as phase information on each subcarrier component. To eliminate PMD-induced carrier fading in this type of system, a voltage-controlled phase shifter can be used, as shown in Fig. 1(c). Since PMD is a relatively slow process, the phase-tuning speed does not have to be very fast. This type of voltage controlled phase shifter is available commercially.

To verify this concept, we have first built a system transmitting only a subcarrier tone without any data on it. As shown in Fig. 2(a), in this experiment, an 8-GHz sinusoid was applied to an external optical modulator. A PMD emulator was used to create the desired amount of DGD. A PBS was used to separate the two orthogonal PSPs and a PC was used to align the principal axes of the PBS to the system PSPs. Two high-speed photodiodes were used to detect optical signals from both output arms of the PBS. A two-channel digital oscilloscope was used to display the detected signal waveforms.

With the DGD value of the PMD emulator set to zero, the two waveforms detected by both photodiodes are exactly in phase. Adjusting the angle of the PBS only resulted in amplitude redistribution between the two waveforms. By introducing a DGD using the PMD emulator, these two waveforms are no longer in phase, and the relative time delay between them is equal to the value of the DGD. Fig. 3 shows the measured waveforms when a fixed DGD is set at 62.5 ps, causing the two waveforms to be exactly out of phase. Fig. 3(a) was measured when the optical input is launched into the fiber with 50/50 splitting between the two PSPs and the principal axes of the PBS are aligned with the

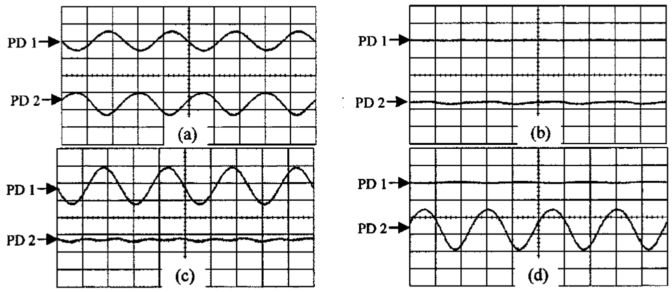

Fig. 3. Measured RF waveforms at the two photodiodes using the experimental setup shown in Fig. 3(a). Fiber system has 62.5-ps DGD. Horizontal scale: 50 ps/div. (a) PBS aligned with fiber PSPs; signal SOP is midway between the fast and the slow PSPs. (b) PBS is midway between the two fiber PSPs; the signal SOP is also midway between the two PSPs. (c) PBS is aligned with the fiber PSPs; the signal SOP is aligned with the fast PSP. (d) PBS is aligned with the fiber PSPs; the signal SOP is aligned with the slow PSP.

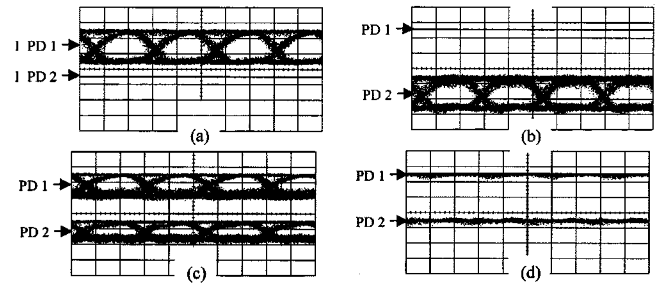

Fig. 4. Measured signal eye diagrams at the two photodiodes using the experimental setup shown in Fig. 3(b). Fiber system has 62.5-ps DGD. Horizontal scale: 200 ps/div. (a) PBS aligned with the fiber PSPs; signal SOP aligned with the fast PSP. (b) PBS aligned with the fiber PSPs; signal SOP aligned with the slow PSP. (c) PBS aligned with the fiber PSPs; signal SOP is midway between the fast and the slow PSP. (d) PBS is midway between the two fiber PSPs; the signal SOP is also midway between the two PSPs.

PSPs. In this case, the two waveforms have equal amplitude and opposite phase. Fig. 3(b) was obtained when the optical input was launched into the fiber with 50/50 splitting between the two PSPs, but the principal axes of the PBS is aligned halfway between the two PSPs. This is the worst case in terms of PMD effect, and complete carrier fading happens at both photodiodes.

Fig. 3(c) and (d) show the measured signal waveforms when the input optical signal is aligned with the fast and slow fiber PSPs, respectively. To avoid carrier fading at each diode, it is essential to align the principal axes of the PBS with the PSPs of the fiber system. In this case, since the optical-phase information is removed during photodetection, the sum of the RF signal power detected by the two photodiodes will be constant. The signal power partitioning in the two photodiodes will depend on the polarization alignment between laser source and the fiber PSPs.

In order to demonstrate the application of this concept in SCM digital systems, a digital transmission experiment was conducted using the setup shown in Fig. 2(b). In this experiment, a 2-Gb/s pseudorandom nonreturn-to-zero (NRZ) signal was carried by an 8-GHz RF subcarrier. Again, a 62.5-ps fixed DGD was artificially inserted by the PMD emulator. For simplicity, the fiber length between transmitter and receiver is short, and no chromatic dispersion is involved in the experiment. When the principal axes of the PBS are aligned with fiber system PSPs, no PMD distortion of signal waveforms results, but the relative amplitude of the waveforms detected by each photodiode depends on the signal state of polarization (SOP). Fig. 4(a) and (b) show the detected waveforms when the signal SOP is aligned with the fast and slow PSP, respectively, and Fig. 4(c) shows the waveforms when signal SOP is midway between the two PSPs. In this measurement, even though the amount of system DGD is 62.5 ps, which is equivalent to a π phase shift of the RF carrier, the sum of the signal eye diagrams detected at the two receiver arms remains independent of the signal SOP. Because of the RF envelope detection after each photodiode, which eliminates the RF carrier, carrier fading is suppressed when combining the signal waveforms from the two branches.

On the other hand, if the principal axes of the PBS are not aligned with the fiber system PSPs, PMD-induced carrier fading would happen at both of the two detection arms. Fig. 4(d) shows the detected waveforms when the principal axis of the PBS is set midway between the two PSPs of the fiber. In this worst case, complete signal fading results.

It is important to note that there is no tunable delay line used in this receiver. Even though carrier fading can be avoided by removing RF phase information before adding signals from each photodiode, the relative delay between the two branches still exists, which is determined by the fiber system DGD. For typical SCM optical systems, where the data rate carried by each subcarrier is relatively low, a moderate amount of DGD will not significantly degrade system performance.

In conclusion, we have demonstrated a carrier-fading-free optical receiver for SCM optical systems using polarization diversity. Since a tunable optical delay line is not required in this setup, it may have advantages over optical-domain PMD compensation.

ACKNOWLEDGMENT

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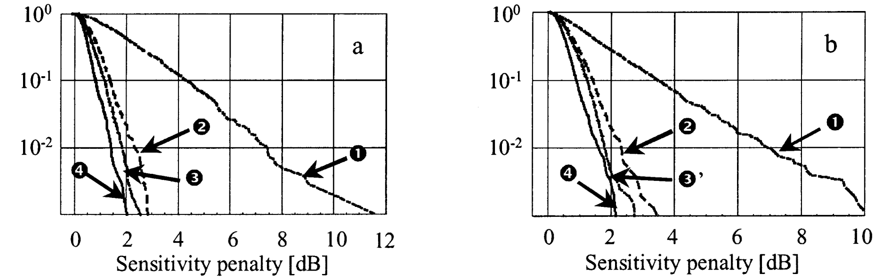

WQ3 Fig. 2. Experimental (a) and numerical (b) cumulative probabilities of sensitivity penalty. The emulated PMD is 39 ps. 1 W/o comp.; 2 W/simple first-order comp.; 3 Transient-state during comp.; 3′ Absolute max tracking comp.; 4 ISOP control + first-order comp.

pensation based on local maximum tracking, with compensation based on absolute maximum tracking and with compensation using ISOP control. The improvement brought by the latter in comparison with an absolute maximum tracking is obvious even if slight. Figure 3 plots DOP versus DGD with and without compensation. The advantage of the relevant ISOP control lies in the removal of the residual worst cases that appears for total DGD greater than 60 ps. Thanks to this new scheme of compensation the tolerable PMD increases up to 37% of the bit-time (obtained by extrapolation).[4]

Actually the issue of sub-optimum, in the case of these high-DGD conditions, steps from higher-order effects which make the maxima of the function DOP(Ω_C) not to be equivalent and make the system wander slightly from PSP alignment. To this regard the degree of freedom brought by PC1 is used to decrease the second-order effects. Indeed Figure 4 shows that these cases undergo the most important fading of the second-order parameter in comparison with ones of low DGD which seem to remain the same. The trade-off between PSP alignment and second-order is not so tight and becomes in favor of the former, leading to a better DOP.

5. Conclusion

A new scheme of compensation combining first-order compensation and relevant ISOP control was proposed. Its interest lies in the fact that it avoids staying a long time on sub-optimum, yielding poor performance of the compensator. It has proved to be a good and a simple means to improve the value of tolerable PMD in the line up to 37% of bit-time.

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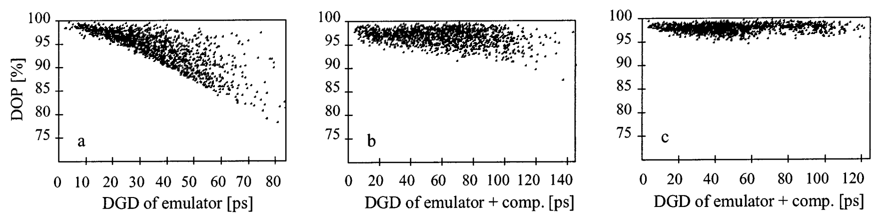
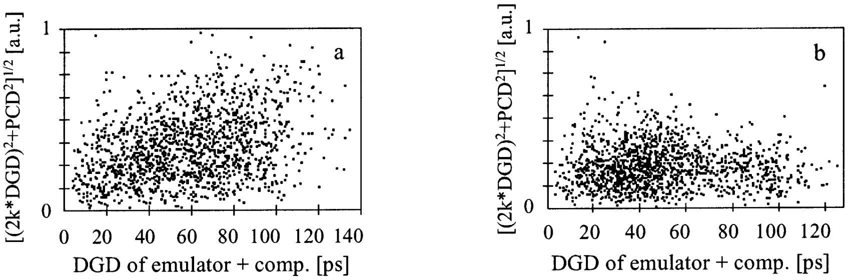


WQ3 Fig. 3. Numerical assessment of DOP versus total DGD for three cases: without compensation (a), with first-order compensation (b) and with first-order compensation and ISOP control (c).



WQ3 Fig. 4. Second-order parameter $[(2k^*DGD)^2 + PCD^2]^{1/2}$ versus total DGD in the case of first-order compensation (a) and ISOP control with first-order compensation (b).

WQ4 **4:45 pm**

Combating PMD-induced signal fading in SCM optical systems using polarization diversity optical receiver

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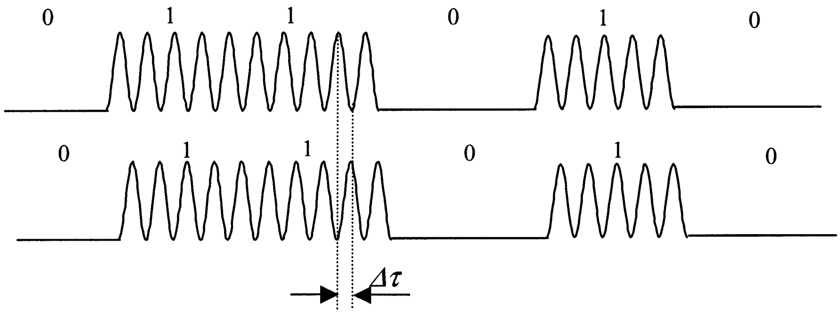
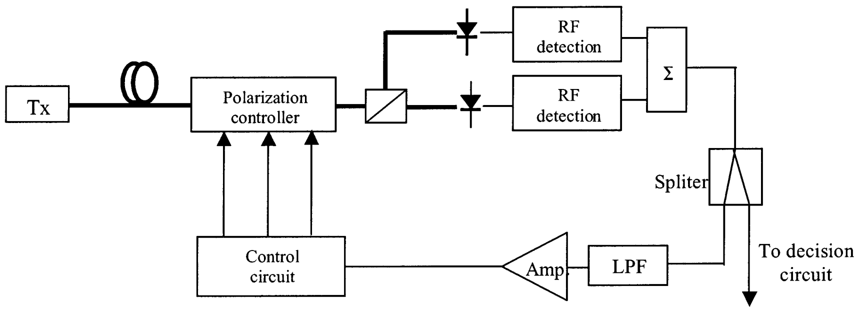
Optical sub-carrier multiplexing (SCM) is a modulation scheme where multiple signals are multiplexed in the RF domain and transmitted on a single optical carrier. A significant advantage of SCM is that microwave devices are more mature than optical devices: the stability of microwave oscillators and the frequency selectivity of microwave filters are much better than their optical counterparts. While a popular application of SCM technology is analog CATV distribution,[1] SCM is also considered for use in high-speed digital transmission because of its flexible bit rate granularity and bandwidth efficiency.

In high-speed long distance optical transmission using SCM, in order to minimize the impact of fiber chromatic dispersion, optical single-sideband (SSB) modulation has been used which also increases the optical bandwidth efficiency.[2] In this case, system tolerance to chromatic dispersion depends on the data rate on each individual sub-carrier channel. However, the impact of PMD is mainly determined by the frequency of each RF sub-carrier because the subcarrier frequency is usually much higher than the datarate it carries. Fig. 1 illustrates the waveforms of a binary coded SCM signal along the fast and the slow principal states of polarization (PSPs) of the fiber, respectively. Adding these two PSP components on the photodiode, a complete signal fading may occur when the differential group delay (DGD) approaches half of the RF sub-carrier period. PMD-induced carrier fading happens to both double sideband and single sideband modulated optical SCM signals,[3] and it is one of the biggest problems which prevents long distance applications of optical SCM systems.

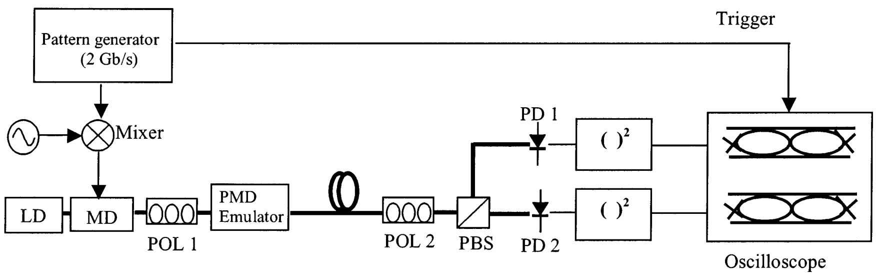
PMD compensation is currently an active area of fiber-optic system research. In many PMD compensator systems[4,5] a polarization beam



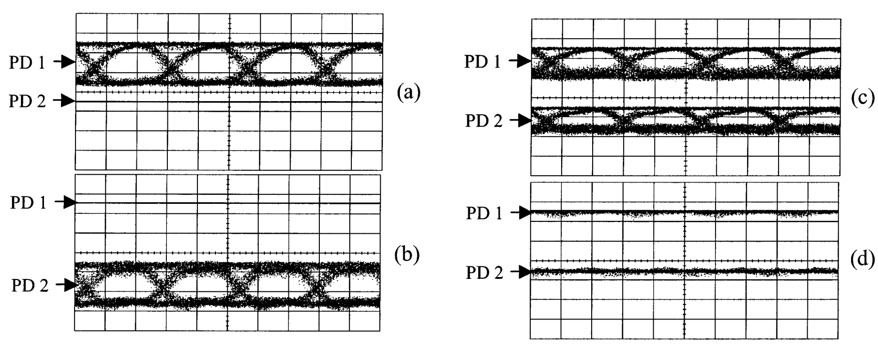
WQ4 Fig. 1. Illustration of signal waveform of an SCM system carried by two PSPs of the optical fiber.



WQ4 Fig. 2. Block diagram of PMD insensitive optical receiver using polarization diversity



WQ4 Fig. 3. Measurement setup. LD: laser diode, MD: optical modulator, POL: polarization controller, PBS: polarization beam splitter, PD: photodiode, $()^2$: square-law detector.



WQ4 Fig. 4. Measured eye diagrams at the two photodiode branches.
(a) PBS aligned with fiber PSP, signal SOP aligned with the fast PSP
(b) PBS aligned with fiber PSP, signal SOP aligned with the slow PSP
(c) PBS aligned with fiber PSP, signal SOP is in the middle between the fast and the slow PSPs
(d) PBS is in the middle between the two fiber PSPs.

splitter (PBS) is used to separate the signals on the two PSPs. A polarization controller (PC) precedes the PBS to align the PSPs with the principal axes of the PBS. Following the PBS is a variable delay line to compensate for the link DGD. Finally the two optical paths are recombined and the effects of PMD have been compensated entirely in the optical domain. Continuous monitoring of the residual PMD can be derived from the signal to provide feedback signal parameters for controlling the PC and the variable delay line. In such a system, the variable delay line is often implemented using a mechanical system to provide the needed DGD range. The speed, size, and reliability of this mechanism are raise concerns.

In order to eliminate PMD-induced carrier fading in SCM systems, we propose to use a polarization diversity optical receiver as shown in Fig. 2. In this setup, two photodiodes are used to detect the two PSP components at the output of the system. In order to ensure the alignment between the principal axis of the PBS and the PSP of the fiber, a polarization controller is used before the PBS. If the principal axis of the PBS is properly aligned with the PSPs of the optical fiber system, the amplitude of signals detected by both photodiodes will not be affected by PMD. The effect of PMD will be shown as a relative time delay between the waveforms carried by the two PSP components.

To verify the concept, an experiment was conducted using a setup shown in Fig. 3. A 2-Gb/s pseudo random NRZ signal was mixed with an 8-GHz RF carrier, this composite signal was used to drive an external modulator. A 62.5-ps DGD was created by a PMD emulator. Two polarization controllers were used in the system: the first controller (before the emulator) was used to adjust signal SOP and the second controller (after the emulator) was used for the alignment between fiber system PSP and the principal axis of the PBS. A dual-channel oscilloscope was used to display the waveforms detected by both photodiodes.

When the principal axis of the PBS is aligned with fiber system PSP, PMD does not distort the signal waveforms, but the amplitude of the waveforms detected by each photodiode depends on the signal SOP. Fig. 4(a) and (b) show the detected waveforms when the signal SOP is aligned with the fast and the slow PSP, respectively, and Fig. 4 (c) shows the waveforms when signal SOP is in the middle between the two PSPs. In this measurement, even though the amount of system DGD is 62.5-ps, which is equal to a half period of the RF carrier, the sum of the signal eye diagrams detected at the two receiver arms remain independent of the signal SOP. Because of the square-law detection after each photodiode, which eliminates the RF carrier, carrier fading can no longer happen when combining signal waveforms of the two branches.

On the other hand, if the principal axis of the PBS is not aligned with the fiber system PSP, PMD-induced carrier fading would happen at both of the two detection arms. Fig. 4(d) shows the detected waveforms when principal axis of the PBS is set in the middle between two fiber PSPs. In this worst case a complete carrier fading happened.

In conclusion, we have demonstrated a carrier fading free optical receiver for SCM optical systems using polarization diversity. Since a tunable optical delay line is not required in this setup, it may be more practical than optical domain PMD compensation.

This work was supported by Sprint Communications Company LP.

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WQ5 **5:00 pm**

Optical compensation of PMD-induced power fading for single sideband subcarrier-multiplexed systems

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1. Introduction

Polarization mode dispersion (PMD), caused primarily by the random birefringence of single-mode optical fiber, is a critical challenge in the transmission of high speed digital baseband channels (≥10 Gbit/s). A key feature of PMD is its statistical behavior, since the relative orientation between the state-of-polarization (SOP) of the input signal and the principal-states-of-polarization (PSPs) of the fiber varies randomly with time. Moreover, the differential group delay (DGD) between the fast and slow PSP, i.e. first-order PMD, is a random process with a Maxwellian probability distribution. Note that even for very-low-PMD fiber, there is still an accumulation of PMD caused by small contributions of many in-line components.

Subcarrier multiplexing has several important applications in optical systems, including: cable television, antenna remoting, LANs, and header control information for packet-switched networks. Importantly, it has been reported that the transmission of analog and digital subcarrier-multiplexed (SCM) signals over fiber will also be severely affected by PMD.[1,2] For example, in 40-GHz optical SCM systems, the RF power is completely faded with ~12.5-ps instantaneous DGD. The deleterious PMD-induced power-fading effect in SCM is as follows. The DGD between the fast and slow PSP of an optical sideband in a SCM signal causes a phase difference in the corresponding received subcarrier signals in the photodetector. Superposition of the photo-currents may lead to serious power fading of the recovered subcarrier signal due to destructive interference that is a function of subcarrier frequency and accumulated DGD.[3] Furthermore, higher-order PMD can cause additional distortion and degradation of the transmitted signal.[4,5] Although single sideband (SSB) SCM system is relatively immune to chromatic dispersion, the PMD-induced RF power fading remains as an important problem.[2]

For many system conditions, robust transmission of an SCM data channel or tone necessitates the use of some type of technique to compensate or mitigate the power fading effects of PMD. One published method of compensation used a typical first-order PMD compensator, which consists of a polarization controller, a differential-group-delay element, and a monitoring feedback loop.[2] However, that method was limited since real PMD is far from being first order and has many higher-order components.[4,5] Moreover, that technique was valid only for a specific average link DGD.

We experimentally demonstrate a novel technique for compensating the PMD-induced power fading that occurs in single sideband SCM transmission systems. PMD-induced power fading can be understood in the optical domain as caused by the polarization state of the optical carrier being different from that of the SSB. After transmitting through a fiber link with PMD, we split the optical carrier and SSB signal, realign their polarization states to each other, and then combine them at the receiver. Thus the first-order and higher-order PMD-induced RF power fading could be completely compensated. Our experiment shows that RF power fading was compensated to be less than 1.5 dB, compared to 3% of the samples exhibiting greater than 15 dB of fading without compensation. The new technique is a simple and complete solution for PMD-induced RF power fading, independent of the DGD of the optical fiber link or the subcarrier frequency. It can expand to multi-channel SCM operation when the total signal bandwidth of subcarrier frequencies does not exceed a specified limit.

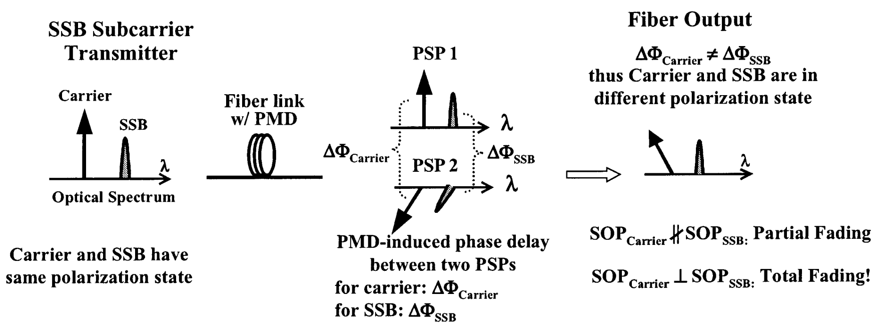
2. Concept and experiment setup

Figure 1 shows the concept for the explanation of RF power fading induced by PMD in SSB SCM systems. At the transmitter, the optical carrier and SSB have the same polarization state. After propagating through the optical fiber link, PMD induces a phase delay between two PSPs for both the optical carrier ($\Delta\Phi_{Carrier}$) and the SSB ($\Delta\Phi_{SSB}$). In general, $\Delta\Phi_{Carrier}$ is not equal to $\Delta\Phi_{SSB}$, so the optical carrier and SSB are in different polarization states at the output of the fiber, which causes RF power fading after the detection. In particular, if the polarization state of optical carrier is orthogonal to that of the SSB, the RF power will be completely faded. If the polarization states can be realigned such that they are the same for both the optical carrier and the SSB, the PMD-induced RF power fading can be completely removed.

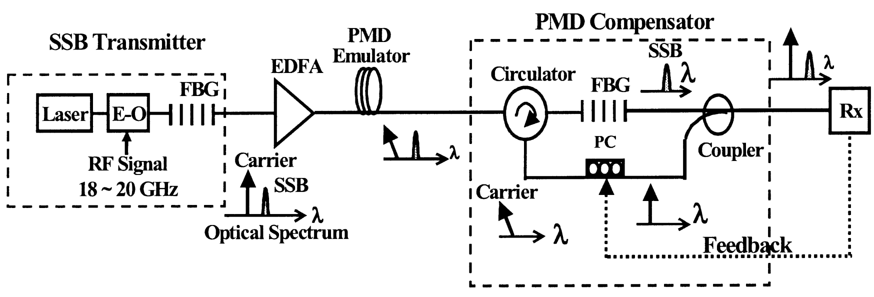
Figure 2 shows the experimental setup. We first generate an 18 ~ 20 GHz double sideband signal by externally modulating the 1550 nm optical carrier. A SSB signal is obtained by using a fiber Bragg grating (FBG) to filter out the lower sideband. After propagation through a PMD emulator, the optical carrier and SSB are separated by another FBG. The FBG has a reflection of 99.7% for the optical carrier at the wavelength of 1550 nm, with a bandwidth of 0.1 nm. The reflected optical carrier passes through a polarization controller (PC) so that its polarization state can be aligned to be the same as the SSB. Then the optical carrier and SSB are recombined at the receiver. By adjusting the PC to maximize the received RF power, the faded RF signal can be completely recovered after the detection.

3. Results and discussion

For the PMD emulator in the experimental setup, firstly we used a PC and a polarization-maintaining (PM) fiber with varying lengths to simulate the first-order PMD (DGD). The power splitting ratio was 0.5. Figure 3 shows the measured RF power fading compared to the theoretical value, and the compensated result. We can see that the RF power fading is reduced to less than 1 dB after compensation.



WQ5 Fig. 1. Explanation of PMD-induced RF power fading in a SSB SCM system in optical domain.



WQ5 Fig. 2. Experimental setup.

US006459830B1

(12) **United States Patent**
Pua et al.

(10) **Patent No.: US 6,459,830 B1**
(45) **Date of Patent: Oct. 1, 2002**

(54) **METHOD AND APPARATUS TO COMPENSATE FOR POLARIZATION MODE DISPERSION**

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(73) Assignee: **Sprint Communications Company L.P.**, Oakland Park, KS (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **09/500,092**

(22) Filed: **Feb. 8, 2000**

(51) **Int. Cl.**[7] **G02B 6/28**

(52) **U.S. Cl.** **385/24**; 385/11; 359/156; 359/161; 359/192

(58) **Field of Search** 385/11, 24, 123, 385/29; 359/156, 161, 192, 140

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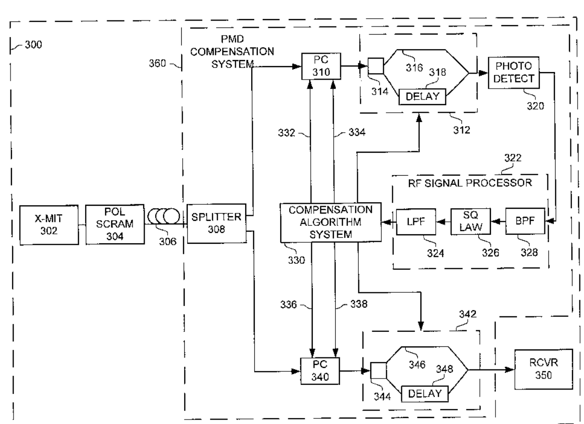
(74) *Attorney, Agent, or Firm*—Harley R. Ball; Steven J. Funk; Kevin D. Robb

(57) **ABSTRACT**

A polarization scrambler and a polarization mode dispersion (PMD) compensation system compensate for PMD on an active optic fiber. The polarization scrambler scrambles a state of polarization of an optical signal that carries user information. The PMD compensation system then receives the optical signal over the active optic fiber. The PMD compensation system measuring a differential group delay and principal states of polarization of the PMD in the active optic fiber. The PMD compensation system then determines a modification of the optical signal based on the differential group delay and the principal states of polarization of the PMD. The PMD compensation system modifies the optical signal in the active optic fiber to compensate for PMD based on the determination of the modification. The PMD compensation system then transmits the optical signal. By measuring the differential group delay and the principal states of polarization, the PMD compensation system adapts to changes in the PMD in the active optic fiber.

29 Claims, 4 Drawing Sheets



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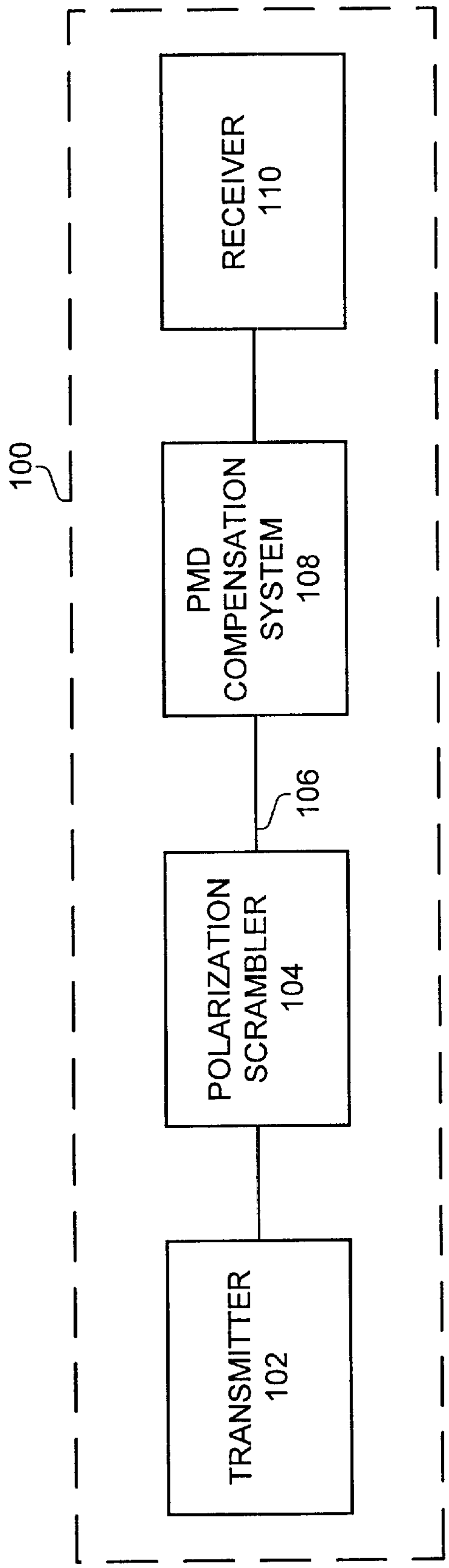
100
TRANSMITTER 102
POLARIZATION SCRAMBLER 104
106
PMD COMPENSATION SYSTEM 108
RECEIVER 110

FIG. 1

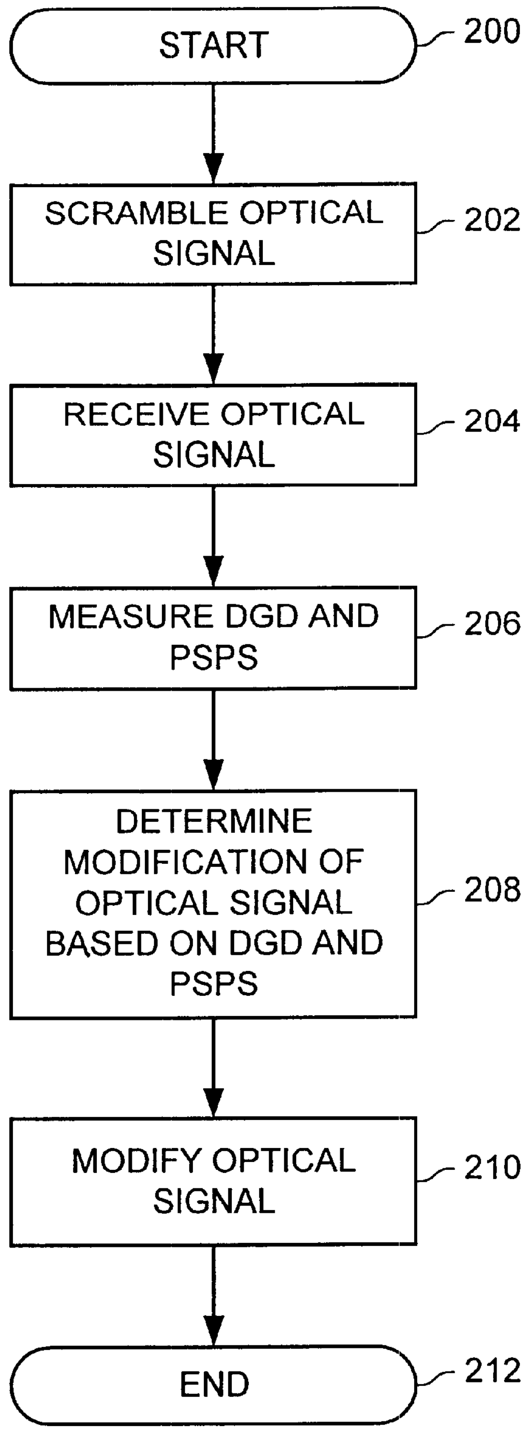
START
200
SCRAMBLE OPTICAL SIGNAL
202
RECEIVE OPTICAL SIGNAL
204
MEASURE DGD AND PSPS
206
DETERMINE MODIFICATION OF OPTICAL SIGNAL BASED ON DGD AND PSPS
208
MODIFY OPTICAL SIGNAL
210
END
212

FIG. 2

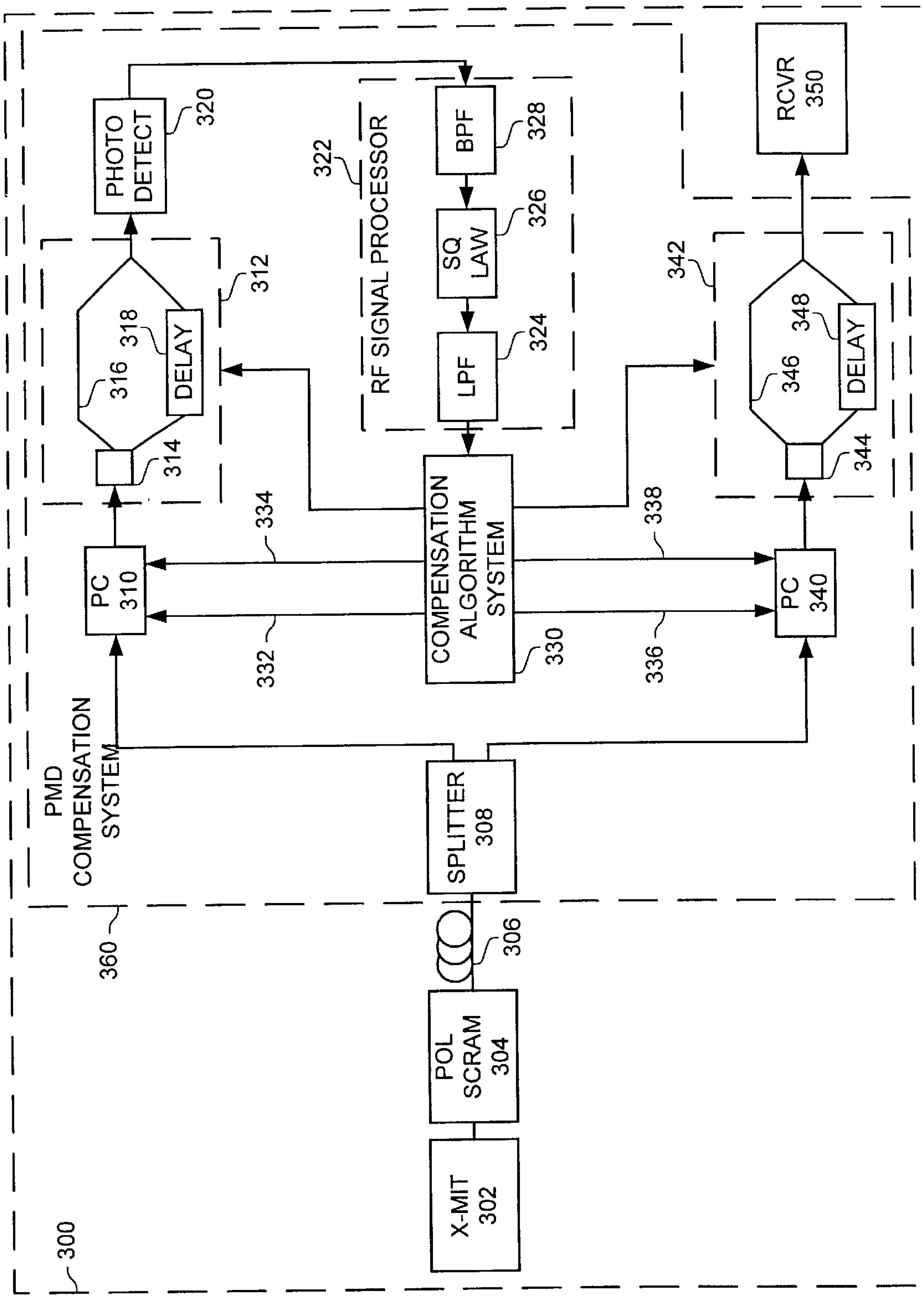

PHOTO DETECT
320
322
RF SIGNAL PROCESSOR
BPF
328
SQ LAW
326
LPF
324
RCVR
350
312
316
318
DELAY
314
342
346
348
DELAY
344
COMPENSATION ALGORITHM SYSTEM
330
334
332
338
336
PC
310
PC
340
PMD COMPENSATION SYSTEM
SPLITTER
308
360
306
POL SCRAM
304
X-MIT
302
300

FIG. 3

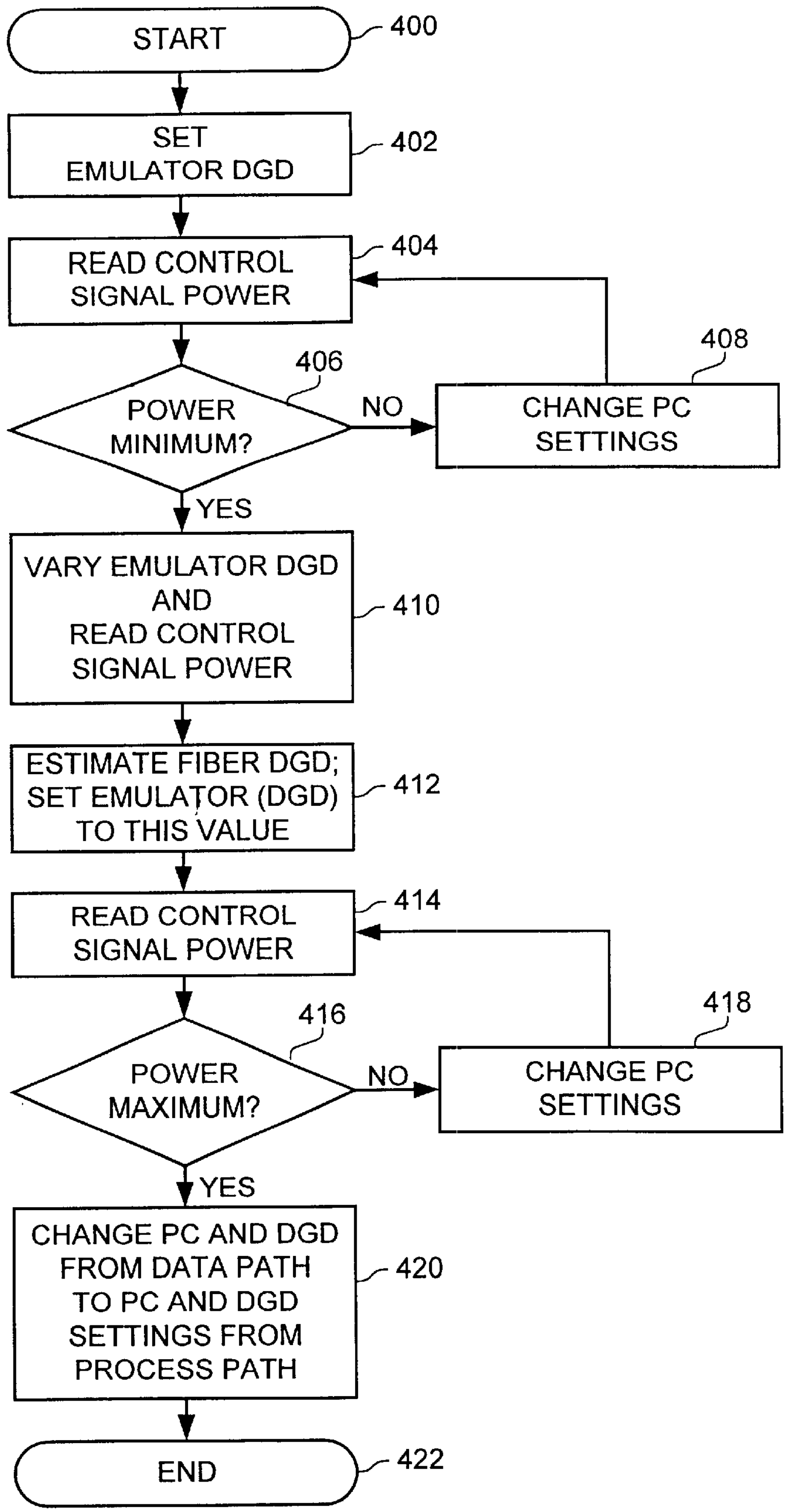
START
400
SET
EMULATOR DGD
402
READ CONTROL
SIGNAL POWER
404
POWER
MINIMUM?
406
NO
CHANGE PC
SETTINGS
408
YES
VARY EMULATOR DGD
AND
READ CONTROL
SIGNAL POWER
410
ESTIMATE FIBER DGD;
SET EMULATOR (DGD)
TO THIS VALUE
412
READ CONTROL
SIGNAL POWER
414
POWER
MAXIMUM?
416
NO
CHANGE PC
SETTINGS
418
YES
CHANGE PC AND DGD
FROM DATA PATH
TO PC AND DGD
SETTINGS FROM
PROCESS PATH
420
END
422

FIG. 4

METHOD AND APPARATUS TO COMPENSATE FOR POLARIZATION MODE DISPERSION

RELATED APPLICATIONS

Not applicable

FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

Not applicable

MICROFICHE APPENDIX

Not applicable

BACKGROUND OF THE INVENTION

1. Field of the Invention

The invention is related to the field of communication systems, and in particular, to a system that compensates for polarization mode dispersion in an optic fiber.

2. Description of the Prior Art

In fiber optic communication systems, a fiber that carries optical signals contains asymmetries. These asymmetries result in the optical properties of the fiber not being the same in all directions. Thus, the fiber is birefringent, where the material displays two different indices of refraction. This fiber birefringence causes polarization mode dispersion (PMD).

PMD is measured like a vector quantity, where a differential group delay is the magnitude of the vector and the principal state of polarization (PSP) are the direction. There are two PSPs associated with PMD. The two PSPs propagate at slightly different velocities with the distribution of signal power varying with time. PMD is a time varying stochastic effect. PMD varies in time with ambient temperature, fiber movement, and mechanical stress on the fibers. Compensating for PMD can be difficult because of the time varying nature and randomness of PMD.

Prior systems that involve taking the fiber out of operation to compensate for PMD are expensive. There have been few systems that have attempted to compensate for PMD on active fibers. A fiber is active when the fiber is operational to exchange user information. One prior system uses a polarization controller at the transmitter. The polarization controller aligns the input state of polarization of the input optical signal to the PSP of the fiber to reduce the signal distortion. One disadvantage of this system is the requirement of timely knowledge of the PSPs, which is difficult at best. Another disadvantage is the PSP of the fibers are different for each receiver. When optical add/drops are involved, this system is ineffective.

Another system uses a polarization controller prior to the receiver. The polarization controller aligns the polarization of one of the PSPs with a polarization filter. The polarization controller also receives control signals from a feedback arrangement. This system processes one of the PSPs which is essentially free from the PMD effects.

Another system uses a polarization controller and a length of polarization-maintaining fiber prior to the receiver. The length of the polarization-maintaining fiber is selected so a fixed value of differential group delay is equal to the average differential group delay of the long fiber to minimize the PMD effects. A disadvantage is this system only works for a fixed value of differential group delay. When differential group delay varies, the system does not fully compensate for the PMD effects.

Another system monitors the effect of PMD on an input optical signal. The power level of a non-return-to-zero (NRZ) optical signal's spectral component corresponding to one-half of the data rate indicates the PMD in a fiber link. In one example, to monitor the PMD on a 10 Gb/s NRZ optical signal, the system monitors the power of the spectral component at 5 GHz. This system comprises a narrowband filter centered at 5 GHz followed by a square-law detector and a lowpass filter.

One problem is that none of the prior systems track changes in the differential group delay, which is a component of PMD. Another problem is the degraded ability to monitor for DGD and PSPs when the input state of polarization of the input signal is nearly aligned with one of the PSPs. A system is needed that can compensate for PMD which accounts for changes in the PMD and the problems when the input state of polarization of the input signal is nearly aligned with one of the PSPs.

SUMMARY OF THE INVENTION

The invention solves the above problems by compensating for PMD. A polarization scrambler scrambles a state of polarization of an optical signal that carries user information. A PMD compensation system then receives the optical signal over an active optic fiber. The PMD compensation system then measures a differential group delay and principal states of polarization of the polarization mode dispersion in the active optic fiber. The PMD compensation system then determines a modification of the optical signal based on the differential group delay and the principal states of polarization of the polarization mode dispersion. The PMD compensation system modifies the optical signal in the active optic fiber to compensate for PMD based on the determination of the modification. The PMD compensation system then transmits the optical signal.

In various embodiments of the invention, the PMD compensation system measures the differential group delay and the principal states of polarization of the PMD in the active optic fiber by estimating the differential group delay and the principal states of polarization of the PMD in the active optic fiber. The PMD compensation system modifies the optical signal by changing the polarization state of the optical signal. The PMD compensation system modifies the optical signal by changing the differential group delay of the PMD in the active optic fiber.

Advantageously, the invention adapts to the time varying nature of the PMD in the active optic fiber by measuring the differential group delay and the principal states of polarization. Also, the invention is applied to active optic fibers so the fiber optic communication system does not have to be taken out of operation to compensate for PMD. The invention advantageously scrambles a state of polarization of the optical signal to greatly improve the measurement of the differential group delay and the principal states of polarization.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a system level block diagram of an example of the invention.

FIG. **2** a flow chart of the operation of a polarization scrambler and a PMD compensation system in an example of the invention.

FIG. **3** is a system level diagram of a fiber optic communication system with a PMD compensation system including a feedback arrangement in an example of the invention.

FIG. **4** is a flow chart of an operation of a compensation algorithm system in an example of the invention.

A particular reference number refers to the same element in all of the other figures.

DETAILED DESCRIPTION OF THE INVENTION

FIG. **1** depicts a system level block diagram of a fiber optic communication system **100** in an example of the invention. In FIG. **1**, a transmitter **102** is connected to a polarization scrambler **104**. The polarization scrambler **104** is connected to a PMD compensation system **108** via an active optic fiber **106**. The PMD compensation system **108** is connected to a receiver **110**.

The transmitter **102** could be any device configured to transmit optical signals. The transmitter **102** typically modulates the optical signals to carry user information. The receiver **110** could be any device configured to receive optical signals. The receiver **102** typically derives data from the optical signals.

The polarization scrambler **104** is any device or group of devices configured to scramble the state of polarization of the optical signal that carries user information. The PMD compensation system **108** is any device or group of devices configured to (1) receive the optical signal over the active optic fiber **106**, (2) measure a differential group delay and principal states of polarization of the polarization mode dispersion in the active optic fiber **106**, (3) determine a modification of the optical signal based on the differential group delay and the principal states of polarization of the polarization mode dispersion, (4) modify the optical signal in the active optic fiber **106** to compensate for polarization mode dispersion based on the determination of the modification, and (5) transmit the optical signal.

In operation, the transmitter **102** transmits the optical signal to the polarization scrambler **104**. FIG. **2** shows a flow chart of the operation of the polarization scrambler **104** and the PMD compensation system **108** in an example of the invention. FIG. **2** begins with step **200**. In step **202**, the polarization scrambler **104** scrambles a state of polarization of the optical signal. The PMD compensation system **108** then receives the optical signal over the active optic fiber **106** in step **204**. In step **206**, the PMD compensation system **108** measures a differential group delay and principal states of polarization of the PMD in the active optic fiber **106**. In step **208**, the PMD compensation system **108** then determines a modification of the optical signal based on the differential group delay and the principal states of polarization of the PMD. In step **210**, the PMD compensation system **108** modifies the optical signal in the active optic fiber **106** based on the determination made in step **208** to compensate for PMD. The PMD compensation system **108** then transmits the optical signal. The operation of the PMD compensation system **108** ends in step **212**. The receiver **110** receives the optical signal from the PMD compensation system **108**.

FIG. **3** discloses one embodiment of the invention, but the invention is not restricted to the configuration provided below. Those skilled in the art will appreciate numerous variations in a fiber optic communication system configuration and operation that are within the scope of the invention. Those skilled in the art will also appreciate how the principles illustrated in this example can be used in other examples of the invention.

FIG. **3** depicts a system level diagram of a fiber optic communication system **300** with a PMD compensation system **360** including a feedback arrangement in an example of the invention. In FIG. **3**, the PMD compensation system **360** comprises a splitter **308**, a first polarization controller **310**, a PMD emulator **312**, a photodetector **320**, a RF signal processor **322**, a compensation algorithm system **330**, a link **332**, a link **334**, a link **336**, a link **338**, a second polarization controller **340**, and a PMD emulator **342**. A transmitter **302** is connected to a polarization scrambler **304**. The polarization scrambler **304** is connected to the splitter **308** via an active optic fiber **306**. The splitter **308** is connected to the first polarization controller **310** and the second polarization controller **340**.

The first polarization controller **310** is connected to the PMD emulator **312**. The PMD emulator **312** comprises a splitter **314**, a link **316**, and a delay component **318**. The first polarization controller **310** is connected to the splitter **314**. The splitter **314** is coupled to the photodetector **320** via the link **316** and is coupled to the photodetector **320** via the delay component **318**. The photodetector **320** is connected to the RF signal processor **322**. The RF signal processor **322** comprises a lowpass filter **324**, a square law detector **326**, and a bandpass filter **328**. The photodetector **320** is connected to the bandpass filter **328**. The bandpass filter **328** is connected to the square law detector **326**. The square law detector **326** is connected to the lowpass filter **324**. The low pass filter **324** is connected to the compensation algorithm system **330**. The compensation algorithm system **330** is coupled to the first polarization controller **310** via the links **332** and **334**. The compensation algorithm system **330** is connected to the PMD emulator **312** and the PMD emulator **342**. The compensation algorithm system **330** is coupled to the second polarization controller **310** via the links **336** and **338**.

The second polarization controller **340** is connected to the PMD emulator **342**. The PMD emulator **342** comprises a splitter **344**, a link **346**, and a delay component **348**. The second polarization controller **340** is connected to the splitter **344**. The splitter **344** is coupled to the receiver **350** via the link **346** and is coupled to the receiver **350** via the delay component **348**.

A process path comprises the first polarization controller **310**, the PMD emulator **312**, the photodetector **320**, the RF signal processor **322**, and the compensation algorithm system **330**. The components in the process path collectively measure the differential group delay and determine the modification of the optical signal based on the differential group delay. The data path comprises the second polarization controller **340** and the PMD emulator **342**. The components in the data path collectively modify the optical signal based on the determination from the process path.

In operation, the transmitter **302** transmits the optical signal to the polarization scrambler **304**. In some embodiments of the invention, the transmitter **302** includes a laser diode. The polarization scrambler **304** then scrambles the state of polarization of the optical signal that carries user information. Scrambling the state of polarization of the optical signal provides the greatest probability of having the power split between the two PSPs, while all of the power propagating along one of the PSP has the lowest probability. When the power is equally split between the two PSPs, the measurements of the DGD and PSPs are greatly improved. Thus, the polarization scrambler's **304** scrambling of the optical signal greatly improves the measurements of the DGD and PSPs. In one embodiment of the invention, the polarization scrambler's **304** rate of scrambling is greater than the response time of the low pass filter **324** to provide each sample of the low pass filter **324** multiple alignments of the optical signal.

The splitter **308** then receives the optical signal over the active optic fiber **306**. In some embodiments of the invention, the active optic fiber **306** includes chromatic dispersion compensation systems, optical amplifiers, or multiple spans of optical fiber. Also, in other embodiments, the active optic fiber **306** carries wavelength division multiplexed (WDM) optical signals. The WDM optical signals are de-multiplexed prior to entering the splitter **308** in order for the operation of the PMD compensation system **360** to work properly. The PMD compensation system **360** may be required for each channel for a WDM signal.

The splitter **308** splits the optical signal. The splitter **308** transfers the optical signals to the first polarization controller **310** and the second polarization controller **340**. The first polarization controller **310** receives the optical signal from the splitter **308**. The first polarization controller **310** then changes the state of polarization of the optical signal based on signals received from the links **332** and **334**. In one embodiment, the first polarization controller **310** aligns the active fiber link's **306** output principal state of polarization with the principal state of polarization of the PMD emulator **312**. The first polarization controller **310** transfers the optical signal to the PMD emulator **312**. The splitter **314** in the PMD emulator **312** receives the optical signal and splits the optical signal into two optical signals with orthogonal polarizations. The splitter **314** transmits one optical signal with the orthogonal polarization to the link **316**. The splitter **314** also transmits the other optical signal with the orthogonal polarization to the delay component **318**. The delay component **318** delays the optical signal with the orthogonal polarization based on signals received from the compensation algorithm system **330**. The PMD emulator **312** recombines the two optical signals with orthogonal polarizations from the link **316** and the delay component **318** before transferring the optical signal to the photodetector **320**.

The photodetector **320** receives the optical signal. The photodetector **320** converts the optical signal to an electrical signal before transferring the electrical signal to the RF signal processor **322**. The bandpass filter **328** receives the electrical signal. The bandpass filter **328** is a narrow pass band centered at half the signal data rate. The bandpass filter **328** then transfers the electrical signal to the square-law detector **326**. The square-law detector **326** processes the electrical signal and transfers the electrical signal to the lowpass filter **324**. The lowpass filter **324** receives the electrical signal. The lowpass filter **324** converts the electrical signal to a control signal before transferring the control signal to the compensation algorithm system **330**.

FIG. **4** is a flow chart of an operation of the compensation algorithm system **330** in an example of the invention. FIG. **4** begins in step **400**. In step **402**, the compensation algorithm system **330** sets the emulated differential group delay of the PMD emulator **312** to an arbitrary but fixed value. In this embodiment, the initial emulated differential group delay is 15 picoseconds. Also, the compensation algorithm system **330** sets the initial PMD emulator **342** differential group delay to 0 picoseconds. In step **404**, the compensation algorithm system **330** reads the power of the control signal. In step **406**, the compensation algorithm system **330** checks if the power at the control signal is at a minimum.

If the power at the control signal is not at a minimum, the compensation algorithm system **330** proceeds to step **408**. In step **408**, the compensation algorithm system **330** changes the first polarization controller **310** values via the link **332** and the link **334**. The link **332** carries signals that control the θ value of the first polarization controller **310**. The link **334** carries signals that control the ϕ value of the first polarization controller **310**. Once the first polarization controller **310** values are changed, the compensation algorithm system **330** returns to step **404**.

If the power at the control signal is at a minimum, the compensation algorithm system **330** proceeds to step **410**. In step **410**, the compensation algorithm system **330** varies the emulated differential group delay in the PMD emulator **312** and measures the power at the control signal. In step **312**, the compensation algorithm system **330** determines the maximum power of the control signal based on the measurements from step **410**. The compensation algorithm system **330** estimates the differential group delay of the active optic fiber **306** by using the differential group delay value at the maximum power of the control signal. The compensation algorithm system **330** then sets the emulated differential group delay value of the PMD emulator **312** with the estimated active optic fiber **306** differential group delay value.

In step **414**, the compensation algorithm system **330** reads the power of the control signal. In step **416**, the compensation algorithm system **330** checks if the power at the control signal is at a maximum. If the power at the control signal is not at a maximum, the compensation algorithm system **330** proceeds to step **418**. In step **418**, the compensation algorithm system **330** changes the first polarization controller **310** values via the link **332** and the link **334**. Once the first polarization controller **310** values are changed, the compensation algorithm system **330** returns to step **414**.

If the power at the control signal is at a maximum, the compensation algorithm system **330** proceeds to step **420**. In step **420**, the compensation algorithm system **330** changes the polarization controller values and the differential group delay value from the data path from the polarization controller values and the emulated differential group delay value from the process path. The link **336** carries signals that control the θ value of the second polarization controller **340**. The link **338** carries signals that control the ϕ value of the second polarization controller **340**. The compensation algorithm system **330** sets the θ value of the link **336** to the θ value of the link **332**. The compensation algorithm system **330** sets the ϕ value of the link **338** to the ϕ value of the link **334**. The compensation algorithm system **330** sets the differential group delay of the PMD emulator **342** to the emulated differential group delay of the PMD emulator **312**. The operation of the compensation algorithm ends at step **422** and returns to step **400** to continually compensate for PMD.

The second polarization controller **340** receives the optical signal from the splitter **308**. The second polarization controller **340** then changes the state of polarization of the optical signal based on signals received from the link **336** and the link **338**. In one embodiment, the second polarization controller **340** aligns the active fiber link's **306** principal state of polarization with the principal state of polarization of the PMD emulator **342**. The second polarization controller **340** transfers the optical signal to the PMD emulator **342**. The splitter **344** in the PMD emulator **342** receives the optical signal and splits the optical signal into two optical signals with orthogonal polarizations. The splitter **344** transmits one optical signal with the orthogonal polarization to the link **346**. The splitter **344** also transmits the other optical signal with the orthogonal polarization to the delay component **348**. The delay component **348** delays the optical signal with the orthogonal polarization based on signals received from the compensation algorithm system **330**. The PMD emulator **342** recombines the two optical signals with orthogonal polarizations from the link **346** and the delay component **348** into the optical signal to compensate for PMD. The PMD emulator **342** then transfers the optical signal to the receiver **350**. The receiver **350** receives the optical signal to derive data from the optical signal.Those skilled in the art will appreciate variations of the above-described embodiments that fall within the scope of the invention. As a result, the invention is not limited to the specific examples and illustrations discussed above, but only by the following claims and their equivalents.

We claim:**1**. A method for compensating for polarization mode dispersion on an active optic fiber, the method comprising:

receiving a first optical signal that carries user information;

scrambling a state of polarization of the first optical signal;

splitting the first optical signal into a second optical signal along a process path and a third optical signal;

in the process path, measuring a differential group delay and principal states of polarization of the polarization mode dispersion in the active optic fiber based on the second optical signal;

in the process path, determining a modification of the third optical signal based on the differential group delay and the principal states of polarization of the polarization mode dispersion;

modifying the third optical signal in the active optic fiber wherein the third optical signal is polarization mode dispersion compensated and carries user information based on the determination; and

transmitting the third optical signal.**2**. The method of claim **1** wherein the optical signal is a wavelength division multiplexed optical signal.**3**. The method of claim **2** further comprising de-multiplexing the wavelength division multiplexed optical signal.**4**. The method of claim **1** further comprising changing the state of polarization of the third optical signal.**5**. The method of claim **1** further comprising delaying the third optical signal.**6**. The method of claim **1** further comprising converting the second optical signal to an electrical signal.**7**. The method of claim **6**, further comprising filtering the electrical signal with a band-pass filter. **8**. The method of claim **6**, further comprising processing the electrical signal through a square-law detector.**9**. The method of claim **6**, further comprising filtering the electrical signal with a low pass filter.**10**. The method of claim **9** wherein scrambling a state of polarization of the optical signal is at a rate greater than a response time of the low pass filter.**11**. The method of claim **1** wherein measuring the differential group delay of the polarization mode dispersion in the active optic fiber comprises estimating the differential group delay of the polarization mode dispersion in the active optic fiber. **12**. The method of claim **1** wherein modifying the third optical signal in the active optic fiber based on the determination comprises changing the state of polarization of the third optical signal.**13**. The method of claim **1** wherein modifying the third optical signal in the active optic fiber-based on the determination comprises changing the differential group delay of the polarization mode dispersion in the active optic fiber.**14**. A system for compensating for polarization mode dispersion on an active optic fiber, the system comprising:

a polarization mode dispersion compensation system coupled to the active optic fiber and configured to receive a first optical signal that carries user information, scramble a state of polarization of the first optical signal, split the first optical signal into a second optical signal along a process path and a third optical signal, in the process path, measure a differential group delay and principal states of polarization of the polarization mode dispersion in the active optic fiber based on the second optical signal, determine a modification of the third optical signal based on the differential group delay and the principal states of polarization of the polarization mode dispersion, modify the third optical signal in the active optic fiber wherein the third optical signal is polarization mode dispersion compensated and carries user information based on the determination, and transmit the third optical signal. **15**. The system of claim **14** wherein the optical signal is a wavelength division multiplexed optical signal.**16**. The system of claim **15** wherein the polarization mode dispersion compensation system is configured to de-multiplex the wavelength division multiplexed optical signal.**17**. The system of claim **14** wherein the polarization mode dispersion compensation system comprises a splitter coupled to the active optic fiber and configured to split the first optical signal into the second optical signal along the process path and the third optical signal.**18**. The system of claim **14** wherein the polarization mode dispersion compensation system comprises a polarization controller configured to change the state of polarization of the third optical signal. **19**. The system of claim **14** wherein the polarization mode dispersion compensation system comprises a polarization mode dispersion emulator configured to delay the third optical signal.**20**. The system of claim **19** wherein the polarization mode dispersion emulator comprises a splitter configured to split the third optical signal into two optical signals with orthogonal polarizations.**21**. The system of claim **19** wherein the polarization mode dispersion emulator comprises a delay component configured to delay the third optical signal.**22**. The system of claim **14** wherein the polarization mode dispersion emulator comprises a photodetector configured to convert the second optical signal to an electrical signal.**23**. The system of claim **22** wherein the polarization mode dispersion emulator comprises a radio frequency signal processor configured to process the electrical signal.**24**. The system of claim **22** wherein the radio frequency signal processor comprises a bandpass filter configured to filter the electrical signal.**25**. The system of claim **22** wherein the radio frequency signal processor comprises a square-law detector configured to process the electrical signal.**26**. The system of claim **22** wherein the radio frequency signal processor comprises a low pass filter configured to filter the electrical signal.**27**. The system of claim **26** wherein the rate of the polarization mode dispersion compensation system scrambling the state of polarization of the optical signal is at a rate greater than a response time of the low pass filter.**28**. The system of claim **14** wherein the polarization mode dispersion compensation system is configured to estimate the differential group delay of the polarization mode dispersion in the active optic fiber.**29**. The system of claim **14** wherein the polarization mode dispersion compensation system is configured to change the differential group delay of the polarization mode dispersion in the active optic fiber.

* * * * *

An Adaptive First-Order Polarization-Mode Dispersion Compensation System Aided by Polarization Scrambling: Theory and Demonstration

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***Abstract*—An adaptive polarization-mode dispersion (PMD) compensation system has been developed to cancel the effects of first-order PMD by producing a complementary PMD vector in the receiver. Control parameters for the PMD compensation system comprised of a polarization controller and a PMD emulator are derived from the nonreturn-to-zero (NRZ) signal in the channel to be compensated. Estimates of the link's differential group delay (DGD) and principal states of polarization (PSP's) based on this signal are reliable when the signal power is equally split between the link's two PSP's; however this condition cannot be assumed. To meet this requirement, we scramble the state of polarization (SOP) of the input signal at a rate much greater than the response time of the PMD monitor signal so that each sample represents many different SOP alignments. This approach allows the effective cancellation of the first-order PMD effects within an optical fiber channel.**

***Index Terms*—Compensation equalizers, optical fiber communication, optical polarization-mode dispersion, polarization scrambling.**

I. Introduction

DISPERSION in optical fiber communication systems degrades the optical channel signal quality by distorting signal waveforms. In digital systems dispersion can produce intersymbol interference (ISI). As the signal bandwidth is increased, the effects of dispersion become more significant. If not dealt with, dispersion represents a barrier to increasing the channel capacity. Effective techniques have been developed either to avoid or compensate for the dominant dispersion phenomena (e.g., modal, waveguide, and chromatic). However, among the dispersive phenomena in optical fiber, the effect of polarization-mode dispersion (PMD) is particularly difficult to compensate as its characteristics vary temporally. Fluctuating environmental factors (such as temperature, wind, and atmospheric pressure) can change the characteristics of PMD and hence its impact on optical channel quality.

The birefringence of optical fiber supports two degenerate modes, each having different propagation velocities, giving rise to PMD. To gain a better understanding of PMD, models have been developed that successfully predict the statistically observed effects in fiber. In these models, a long fiber link is modeled as a concatenated series of linearly birefringent, optical-fiber segments, each having a fixed birefringence, a fixed segment length corresponding to the fiber's random mode coupling characteristic length (L_h). The orientation of the principle axes from one segment to the next is treated as a random variable [1]. At every junction between segments, the energy from each incident pulse is split into two orthogonally polarized pulses, representing the mode coupling that occurs in fiber due to perturbations in local birefringence. After several such perturbations, the original pulse becomes a large ensemble of small pulses, dispersed in time. For the special case of a system using a light source whose coherence time is greater than the PMD-induced delays and a fiber whose optical loss is polarization independent, the PMD phenomenon in a long fiber link behaves in accordance with a high-coherence model, which incorporates the concept of principal states of polarization (PSP's). This means that, over a limited bandwidth, the link will behave as a randomly birefringent optical fiber such that an input optical pulse whose state of polarization (SOP) is aligned with one of the link's two input PSP's will emerge from the fiber's far end as a single pulse, unchanged in shape and polarized along the fiber's corresponding output PSP. From this model, we know that an input pulse aligned with neither input PSP will emerge as two orthogonally polarized pulses, separated in time by the link's differential group delay (DGD).

This model is frequency independent and valid to first order only. For wider bandwidths higher order effects must be considered resulting in frequency dependent polarization and dispersion [1], [2]. The bandwidth over which the PSP's can be assumed constant depend on the properties of the fiber and has been shown to vary inversely with the mean differential group delay (DGD) [3]. While the minimum bandwidth of the PSP's in single-mode fibers was found to be always over 50 GHz [3], this bandwidth for standard single-mode fiber is of the order of 100 GHz [1].

Time-varying environmental factors can change the mechanical stress on the fiber, causing localized changes in the birefringence characteristics of the fiber. This, in turn, affects the orientation of the PSP's and the DGD of the fiber link. For an optical transmitter with a fixed SOP, as the link's input PSP's change orientation, the relative intensities of the two orthogonal pulses will vary, and, at times, all of the energy will appear in only one pulse (resulting in no discernable PMD effects).

For long fiber links (lengths $\gg L_h$), the mean PMD increases with the square root of the link length.For example, in standard single-mode fiber, the typical random mode coupling characteristic length (L_h) is 100 m and the PMD is typically

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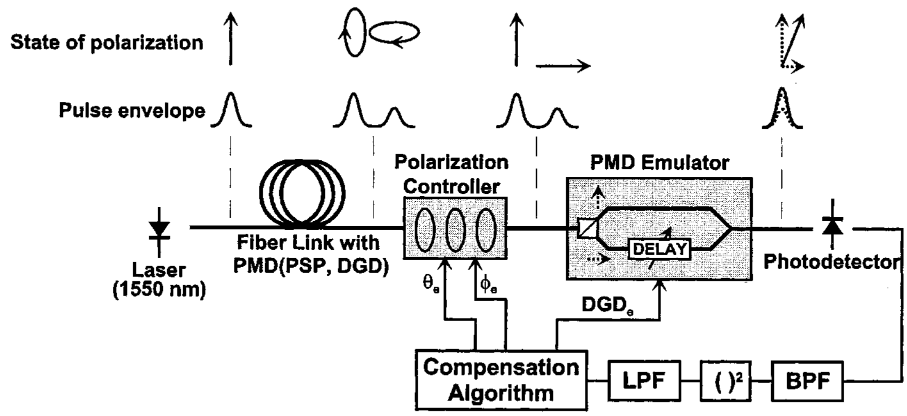


Fig. 1. Functional block diagram illustrating the adaptive PMD compensation system showing the evolution of the envelope and state of polarization for a single transmitted pulse as it progresses from the transmitter through the link, after the polarization controller, and as it emerges from the PMD emulator. BPF: bandpass filter; $(\,)^2$: square-law detector; LPF: low-pass filter.

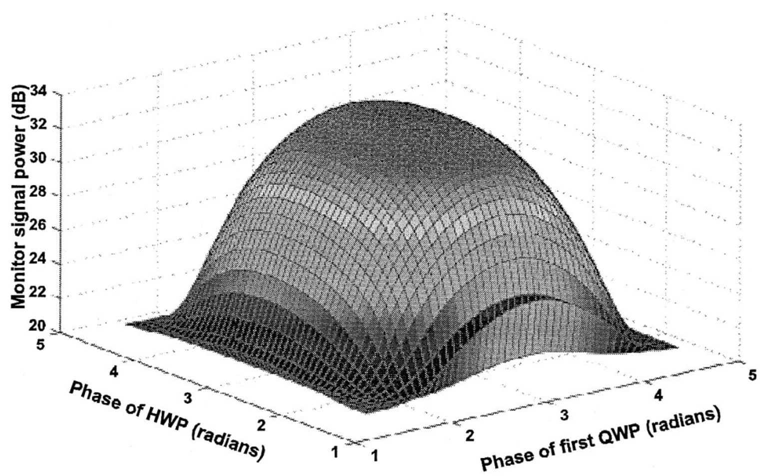


Fig. 2. Example of a simulated transfer function of monitor signal power versus polarization controller settings. The input signal power is assumed to be equally split on the two input PSP's and the DGD in both the link and the PMD emulator is 50 ps.

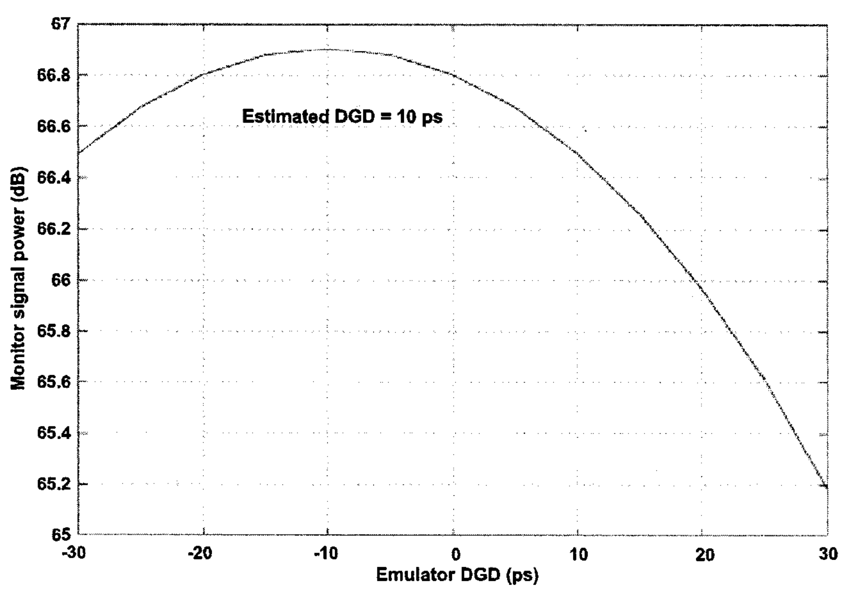


Fig. 3. Simulated transfer function relating the monitor signal power versus emulator DGD that is used to estimate the link DGD. For this case the link DGD is 10 ps and the signal power is equally split on the input PSP's.

0.1 ps/(km)$^{1/2}$ [1]. Therefore, for a typical terrestrial fiber link length of 500 km, the mean anticipated PMD would be 2.24 ps. This level of PMD is generally insignificant for channel data rates of 2.5 Gb/s or less, but would certainly be significant for data rates of 10 Gb/s, 40 Gb/s, and above.

In order to use a fiber link with PMD to carry optical signals at ever increasing data rates without channel degradation, compensation for PMD is necessary. While several PMD compensation approaches have been reported [4]–[6], only those that fully compensate PMD in a link by tracking variations in the DGD and PSP's are viable. The approach presented here attempts to compensate fully for the effects of PMD on a single optical channel over a fiber link.

II. Active PMD Compensation

In the system we developed, the PMD adaptive compensation system treats the PMD on the link as a vector quantity, with DGD as the magnitude and PSP as the direction. A PMD component of equal magnitude but opposite in direction is applied to the signal in the receiver so that the vector sum results in zero PMD. To accomplish this, an accurate and reliable technique for monitoring the PSP's and the DGD of the fiber link was developed, together with a means of producing a complementary PMD vector in the receiver. A block diagram of our system, shown in Fig. 1, illustrates the elements of the adaptive PMD compensation system and shows the evolution of the envelope and state of polarization for a single transmitted pulse as it progresses from the transmitter through the link, after the polarization controller and as it emerges from the PMD emulator. The control parameters $(\theta_e, \phi_e,$ and $\mathrm{DGD}_e)$ correspond to the settings for compensating the effects of PMD in the link.

To monitor the effect of PMD on the received signal, we adopted the method presented by Takahashi *et al.* [4]. The power level of a nonreturn-to-zero (NRZ) signal's spectral component corresponding to one-half of the data rate can serve as an indicator of PMD in a fiber link. For example, to monitor the PMD on a 10-Gb/s NRZ signal, the power of the spectral component at 5 GHz is monitored. Implementing this approach involves a narrowband bandpass filter centered at 5 GHz followed by a square-law detector and a low-pass filter. The output signal is maximized when the PMD affecting the optical NRZ signal is minimized. The shape of the transfer function relating PMD (more specifically, DGD) to the level of this *monitor signal* is approximately quadratic (as shown in Fig. 3).

The compensating PMD introduced in the receiver is set by a polarization controller and a PMD emulator. The polarization controller rotates the link's output PSP's to align with the input PSP's of the PMD emulator (which turn out to be linearly polarized). The PMD emulator introduces the desired time delay (DGD) between two orthogonally polarized optical paths by splitting the input signal based on its polarization and preferentially delaying one of the two paths before recombining the two orthogonally polarized signals. Through this approach, the two output pulses that result from PMD on the link are precisely superimposed in time, effectively undoing the effects of the link's PMD.

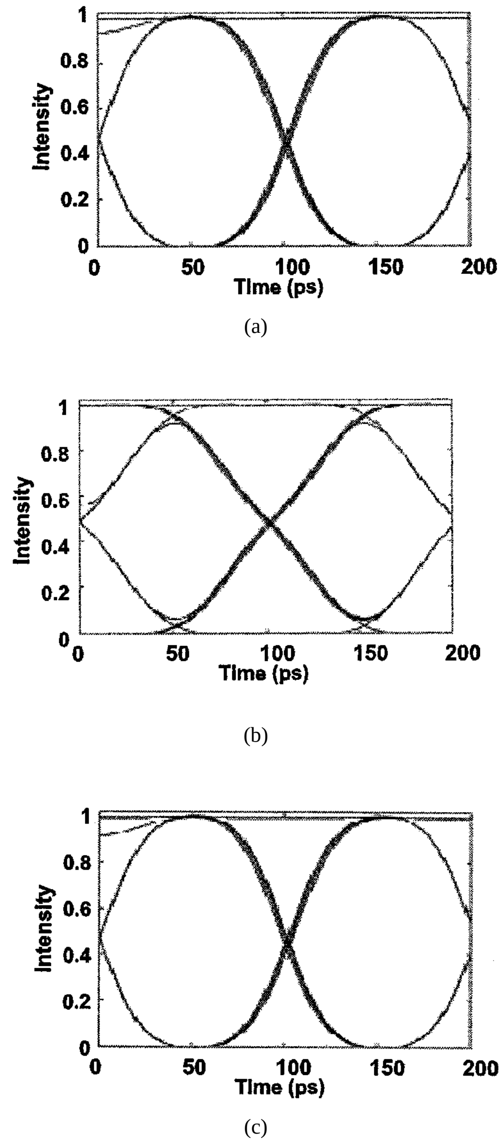


Fig. 4. Eye diagrams at different locations along the link in a simulated 10-Gb/s NRZ system: (a) transmitter output, (b) optical link output, and (c) PMD compensation system output. Assumes equal power on the link's input PSP's and 50 ps of DGD in the link. The adaptive PMD compensation system is set to compensate fully for the effects of PMD in the link.

III. Computer Simulation

Computer simulations were conducted to determine the effectiveness of this approach. In the simulation, a 10-Gb/s NRZ signal having a known SOP was launched into a fiber link having a selectable PMD (PSP's and DGD). At the receiver, the signal was passed through our PMD compensation system and the power of the 5-GHz spectral component (the monitor signal) was determined. The polarization controller was modeled as a combination of two quarter-wave plates (QWP's) and a half-wave plate (HWP), arranged as QWP-HWP-QWP. For this arrangement, the polarization controller can be simulated using a transformation matrix associated with only two free parameters, the phase angle of the HWP and that of the first QWP, since the phase angle of the first QWP and that of the last QWP are always180° apart.

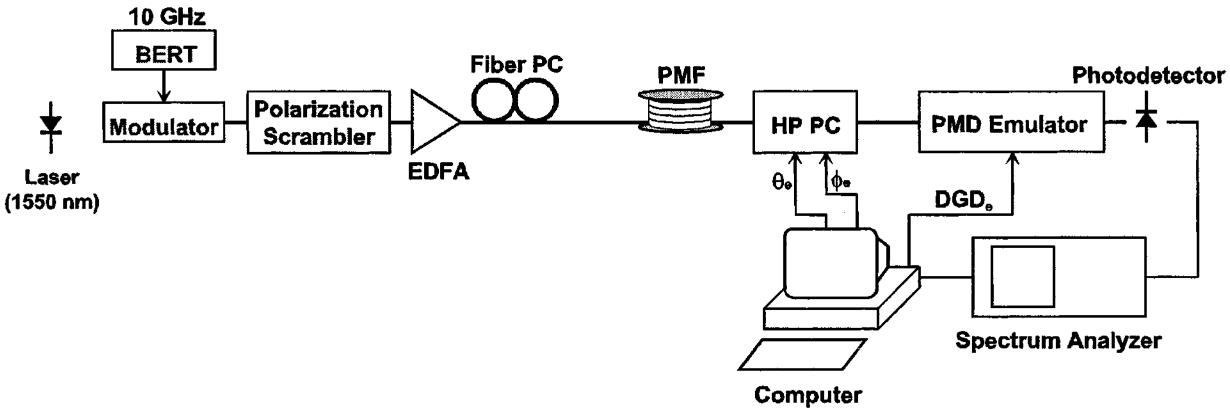


Fig. 5. Experimental setup for evaluation of the adaptive PMD compensation system. EDFA: Erbium-doped fiber-optic amplifier; fiber PC: fiber polarization controller; PMF: polarization-maintaining fiber; HP PC: HP polarization controller.

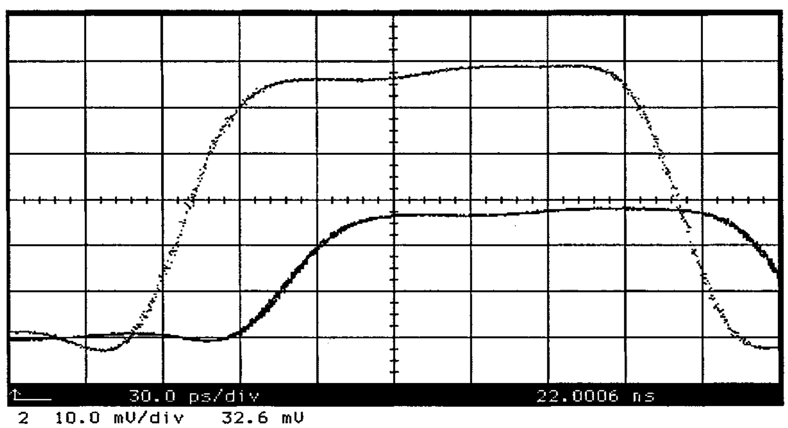


Fig. 6. Timing relationship of two orthogonal pulses obtained from the output of the PMD emulator showing the induced DGD of 48 ps. The different pulse levels of the signal traces indicate an unequal power splitting (approximately 70/30) between the emulator's PSP's.

To examine how the monitor signal power varies with polarization controller setting, we assumed a priori knowledge of the link's DGD (50 ps in this case) and set the emulator's DGD to correspond. The monitor signal power was determined for all possible settings of the polarization controller (with two degrees of freedom) to produce a surface. The coordinates of the peak of the surface correspond to the polarization controller settings that align the link's PSP's with the PSP's of the emulator. For the case where the input signal's SOP aligned such that its power is equally split between the link's PSP's, this procedure produces a surface with a single peak as shown in Fig. 2.

We next examined how the monitor signal varies with DGD in the PMD emulator. We began by setting the emulator's DGD to an arbitrary (but nonzero) value of 15 ps. In an effort to maximize the sensitivity of the monitor signal to DGD variations, we deliberately misaligned the PSP's of the link with those of the PMD emulator by setting the polarization controller such that the monitor signal is minimized. This approach is necessary to resolve small values of link DGD and to accommodate unequal power splitting between the PSP's. For example, in the case where the transmitter SOP is aligned with one of the link's input PSP's and consequently the link effectively exhibits no PMD, this polarization controller setting yields an unambiguous link DGD estimate of zero; otherwise variations in the PMD emulator DGD produces no change in monitor signal power.

We then varied the emulator's DGD and observed changes in the monitor signal level. Fig. 3 illustrates the transfer function relating emulator DGD and monitor signal level for the case where the link DGD was 10 ps and the input SOP was aligned such that its power is equally split between the link's PSP's. The resulting curve has the expected shape, with a maximum (representing a minimization in the overall PMD) when the emulator DGD exactly cancels the DGD in the link; that is, -10 ps.

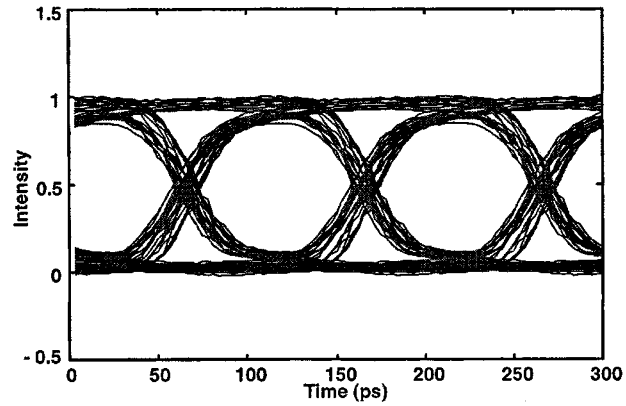
To show the effectiveness of the simulated PMD compensation system, eye diagrams of a 10-Gb/s NRZ signal were produced for the signal at the transmitter, at the output of the fiber link (but prior to the PMD compensation system), and at the output of the PMD compensation system, as shown in Fig. 4. The eye-diagrams produced from the computer simulations include an 8-GHz, fifth-order low-pass Bessel filter used as a post-detection filter to suppress high frequency components. In the link, the DGD is 50 ps and the input SOP is oriented such that the power is equally split between the link's input PSP's. The eye at the output of the fiber link is clearly distorted, most notably by the reduced slope at the bit transitions, resulting in an eye closure penalty of 0.8 dB compared to the eye diagram at the transmitter. Assuming a jitter window width of 10 ps centered on the eye opening, the eye-closure penalty is computed by comparing the vertical dimension of the eye opening with that of the eye measured at the transmitter. The difference between the eye diagram at the transmitter and that at the output of the PMD compensation system is negligible (0 dB eye-closure penalty), demonstrating the effectiveness of the compensation technique.

IV. EXPERIMENTAL VALIDATION

Laboratory tests were conducted to validate the results of the computer simulation. Fig. 5 shows the block diagram of the laboratory test setup. A 10-Gb/s NRZ signal was produced with a bit-error rate tester (BERT) driving a Mach–Zehnder modulator to intensity modulate a 1550-nm continuous-wave (CW) optical signal followed by a lithium-niobate phase shifter that serves as the polarization scrambler. (The SOP input is deliberately aligned midway between the phase shifter's fast and slow axis so that an applied voltage results in a phase shift between the two propagating waves producing a change in the output SOP.) Next is an erbium-doped fiber amplifier (EDFA) to boost the signal level. A link DGD of 48 ps was created using 23 m of polarization maintaining fiber (PMF). To vary the power distribution between the two PSP's in the PMF when the polarization scrambler was not activated, a manually controlled (paddle-type) fiber polarization controller was placed immediately between the EDFA and the PMF. Fig. 6 shows the signal output from the PMF when a 200-ps-long pulse is launched with its SOP aligned relative to the PSP's to yield an unequal power split of approximately 70/30 in this case.

Orientation control of the receiver's PSP's relative to the PSP's of the PMF was achieved with an HP 11896A computer-controlled polarization controller. The polarization controller is followed by a computer-controlled PMD emulator to introduce the compensation DGD. In this device, the incoming optical signal is decomposed into its two orthogonal, linear polarization components, which propagate along separate optical paths that are ultimately recombined with their polarization states preserved. As the path length of one of the two paths is variable while the path length of the other is constant, various amounts of DGD can be produced, both positive and negative. The computer-controllable JDS PE3050 PMD emulator used in our experiments has a DGD range of -30 to $+125$ ps and a resolution of 0.002 ps.

The output of the PMD emulator is connected to a photodetector to convert the signal from the optical domain to the electronic domain. Following the photodetector is a 7.5-GHz LPF. The signal is then split, one portion going to a high-speed oscilloscope to monitor the signal's eye diagram, and the other portion sent to an HP 8592L microwave spectrum analyzer where the power of the 5-GHz spectral component (the monitor signal) was measured. The spectrum analyzer was configured to provide a digital output signal representing the bandlimited (300 kHz bandwidth) power of this spectral component. This monitor signal is then used by a computer to determine the control parameters for the polarization controller and the PMD emulator, through a sequential search process aimed at maximizing the monitor signal power.



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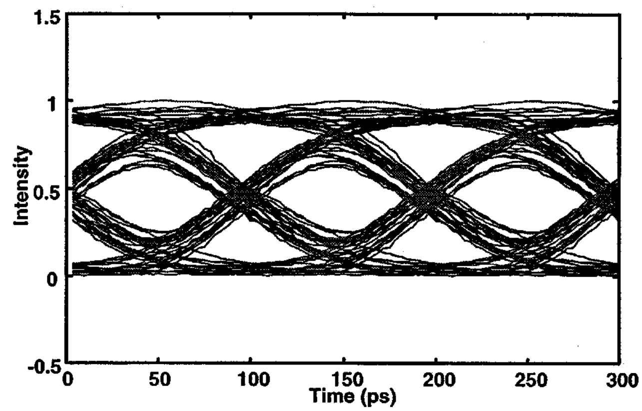

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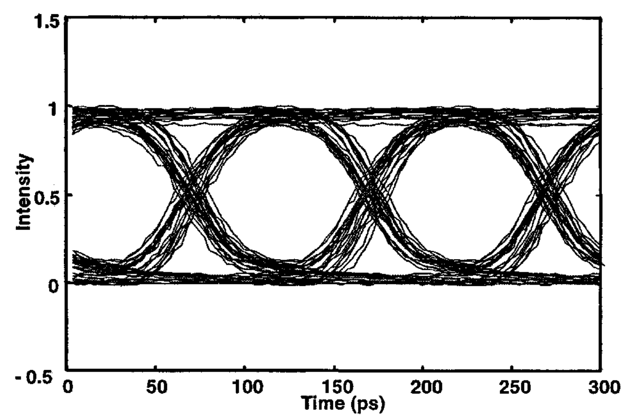


(c)

Fig. 7. Eye diagrams for a 10-Gb/s NRZ system with equal power distribution on the link's input PSP's and 48 ps of DGD in the link measured at different locations along the link: (a) transmitter output, (b) optical link output, and (c) PMD compensation system output.

Fig. 7 shows the eye diagram for the signal at various points in the system. First is the eye diagram of the signal output from the transmitter. Next is the eye diagram of the signal output from the PMF for equal power splitting between the PSP's. The most

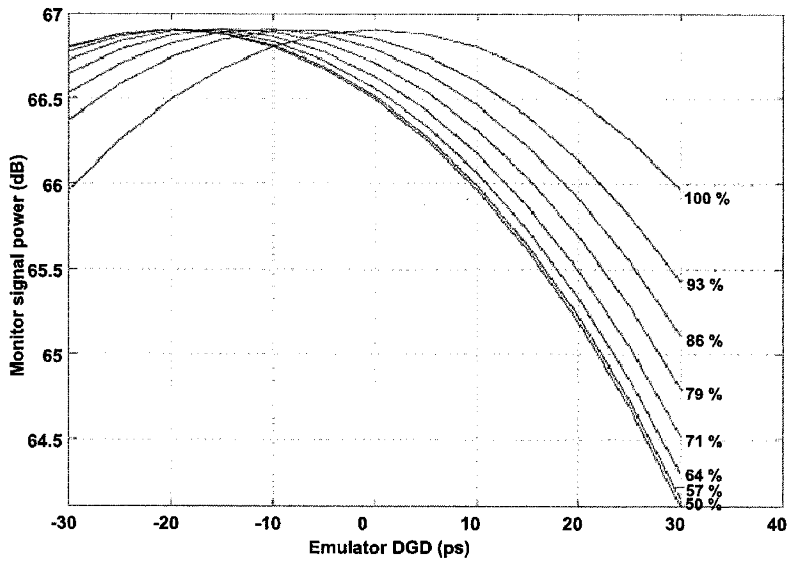


Fig. 8. Collection of curves representing the monitor signal power versus link DGD for various signal power distributions on the input PSP's. Power ratio at the input PSP's vary from 50/50 to 100/0 in increments of 7.14. The simulated link DGD is 20 ps.

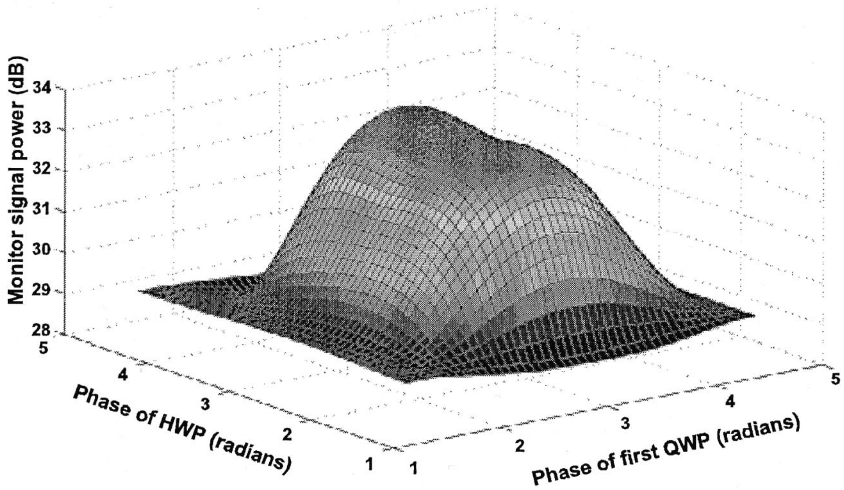
notable effect of the 48 ps of DGD introduced by the PMF is the reduced slope at the bit transitions. Finally, we show the eye diagram of the signal output from the PMD compensation system, where the quality of the eye has been largely restored to its original shape. Using the transmitter output eye opening as a reference and a 10-ps jitter window width, the eye-closure penalty of the signal at the output of the PMF is 3.8 dB, while at the output of the PMD compensation system the eye-closure penalty is 0.07 dB. The difference in eye-closure penalties between the simulation and the laboratory measurements may be attributed to amplitude and phase ripple in the system transfer function (including the modulator, photodetector, electrical post-detection filter) in the hardware but not accounted for in the simulation.

V. SOP/PSP Alignment Effects

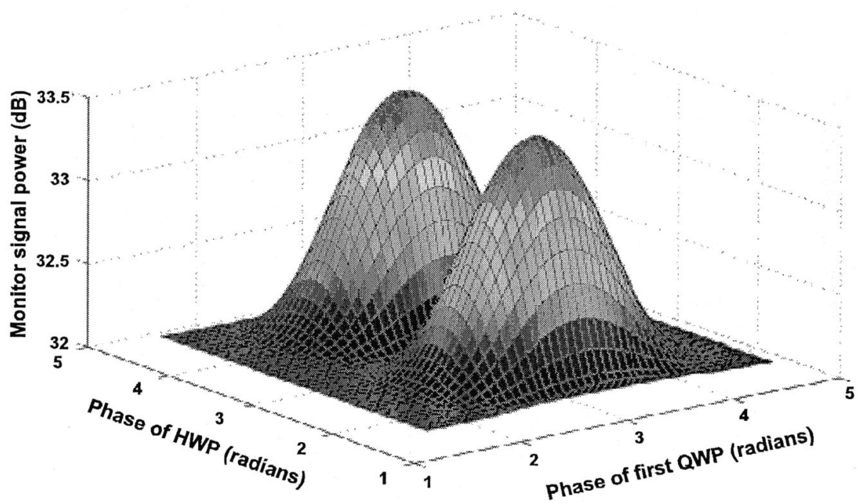
As mentioned above, the ability to monitor the state of the PSP's and DGD on a link reliably is somewhat dependent on the input SOP exciting both PSP modes in the link. Instances where the input SOP is nearly aligned with one of the link's input PSP's significantly degrades the ability of the monitoring system to track the PSP's and the DGD.

To investigate the effects of various SOP / PSP alignments, computer simulations of the PMD compensation system were conducted. As before, a 10-Gb/s NRZ signal having a known SOP is launched into a fiber link having a selectable PMD (PSP's and DGD). At the receiver, the signal is passed through the PMD compensation system and the power of the monitor signal is determined. Setting the polarization controller so that the link's PSP's and the PSP's of the PMD emulator are misaligned as before, we estimate the DGD in the link by varying the emulator's DGD and observe changes in the monitor signal level. With the link DGD set at 20 ps, Fig. 8 shows results for several cases representing various alignments of the input SOP with the link's input PSP's. For the case where the SOP is aligned such that the input power is nearly evenly split, the location of the maximum approximates the actual link DGD, i.e., 20 ps. However, as the splitting ratio becomes more and more unbalanced, the emulator DGD that maximizes the monitor signal power moves progressively toward zero. Finally the case where all of the power is launched along one PSP results in a curve that peaks at zero DGD in the emulator, despite the fact that the link's DGD is 20 ps. Hence the use of this parameter to estimate the link's DGD is sensitive to the relative alignment of the input signal's SOP and the link's input PSP's.

The relative alignment of SOP and PSP's also affects the transfer function relating the monitor signal power to the state of the polarization controller. To illustrate this, we again present computer simulations of the PMD compensation system as before. For this evaluation, we assume *a priori* knowledge of the link's DGD and set the emulator's DGD to correspond. The monitor signal power is determined for all possible settings of the polarization controller with two degrees of freedom to produce a surface plot. The coordinates of the peak of the surface corresponds to the polarization controller settings that align the link's PSP's with the PSP's of the emulator. For the case where the input signal's SOP is aligned such that its power is equally split between the link's PSP's, a surface with a single peak is produced as was shown previously in Fig. 3. However, as the alignment between the input SOP and the link's input PSP's is changed, the shape and nature of the surface changes also. In Fig. 9(a) the alignment producing a 70/30 distribution of the signal power on the PSP's results in a surface with two unequal peaks. In Fig. 9(b) the alignment is changed so that all of the signal power is coupled into a single PSP. In this case, two peaks of equal amplitude are observed, each corresponding to a case where 100% of the signal is routed through only one branch of the PMD emulator, as would be expected, and the two peaks represent two orthogonal polarization controller settings.

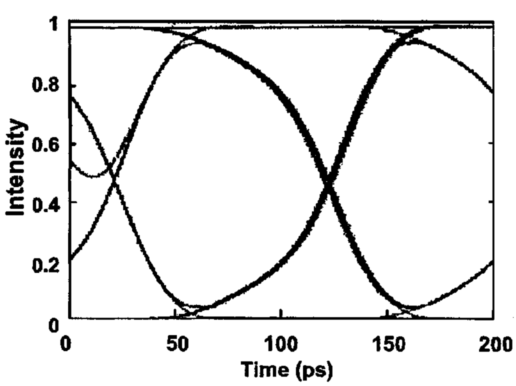


(a)

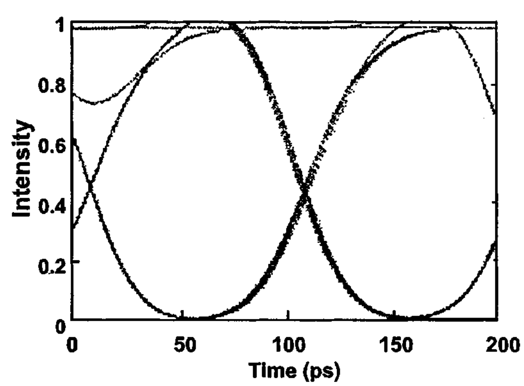


(b)

Fig. 9. Three-dimensional presentation of how the monitor signal varies with polarization controller setting with the input SOP fixed relative to the fiber PSP: (a) 70/30 signal power split onto the input PSP's and (b) all power is launched onto one of the input PSP's.



(a)



(b)

Fig. 10. Eye diagrams for a simulated 10-Gb/s NRZ system with a 70/30 power distribution on the link's input PSP's and 50 ps of DGD in the link measured at: (a) optical link output and (b) PMD compensation system output. The adaptive PMD compensation system is set to compensate fully for the effects of PMD in the link and there is no polarization scrambling at the transmitter.

VI. Polarization Scrambling

Based on these results, it is clear that the use of the monitor signal alone to determine the proper PMD compensation system settings is inadequate; knowledge of the relative alignment between the input signal's SOP and the link's input PSP's is also needed. Since the link's input PSP's are time varying, tracking with the launched signal's SOP orientation is not possible without additional information. To overcome this challenge, we scrambled the SOP of the input signal at the output of the transmitter. While the relative alignment between the SOP and the link's input PSP's is still not known at any instant, we do know that over a given interval determined by the frequency of the polarization scrambler a variety of relative alignments is realized. Additionally, for truly random SOP scrambling, the alignment having the greatest probability is where the power is equally split, and the lowest probability is where all of the power propagates along a single PSP. Therefore the estimate of the proper settings for the PMD compensation system based on the monitor signal is greatly improved when the input SOP is scrambled.

Simulation results confirm the effectiveness of this approach. When the input signal's SOP is scrambled at a rate much greater than the response time of the lowpass filter and each sample represents multiple alignments, the estimate of the compensating DGD and polarization controller setting agrees with the estimates obtained when the input SOP is static and aligned such that the power is evenly split between the PSP's. Fig. 10 shows the simulated eye diagrams for the case of an unequal power split (70/30) without polarization scrambling. The eye diagram shown in Fig. 10(a) represents the signal at the link output, prior to the PMD compensation system. The eye-closure penalty compared to the transmitted signal as shown in Fig. 4 is 0.5 dB. Fig. 10(b) shows the eye diagram of the signal output from the PMD compensation system that has been configured to maximize the monitor signal power. While the PMD compensation system has improved the signal, some distortion of the eye remains and the eye closure penalty is 0.25 dB. When polarization scrambling is present, the eye diagram at the PMD compensation system is identical to that shown in Fig. 4(c), with a negligible eye-closure penalty.

Experimental results also demonstrate that polarization scrambling improves the effectiveness of the PMD compensation system. The experimental setup described previously was configured to produce an SOP alignment that resulted in a power split of approximately 70/30 between the PSP's in the PMF. The eye diagram at the output of the PMF is shown in Fig. 11(a) and has an eye-closure penalty of 2.5 dB compared to the transmitted eye. The eye diagram at the output of the PMD compensation system configured to maximize the monitor signal is shown in Fig. 11(b). While the resultant eye diagram is improved compared to the uncompensated eye, the eye-closure penalty is 0.79 dB. Finally, the eye diagram shown in Fig. 11(c) represents the case where the polarization scrambler at the output of the transmitter is activated and the PMD compensation system again determines the appropriate settings that result in a maximum monitor signal power. The eye closure penalty for this eye diagram is 0.15 dB. Hence in this case, polarization scrambling improves our ability to compensate for PMD by more than 0.6 dB.

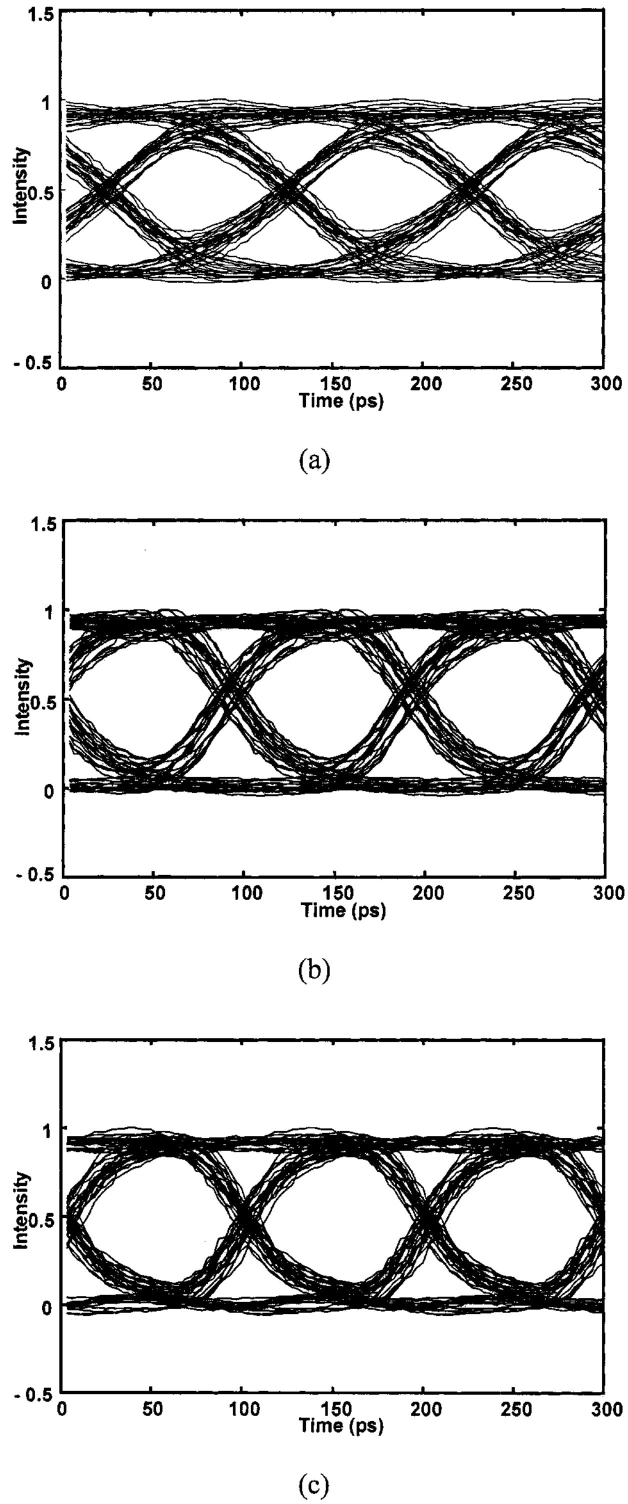


Fig. 11. Eye diagrams of the signal received from a link having 48 ps of DGD and a 70/30 power split: (a) before the PMD compensation system, (b) after the PMD compensation system without polarization scrambling, and (c) after the PMD compensation system with polarization scrambling.

In this experiment, the polarization scrambler was driven by a sinusoidal voltage with an amplitude sufficient to produce an

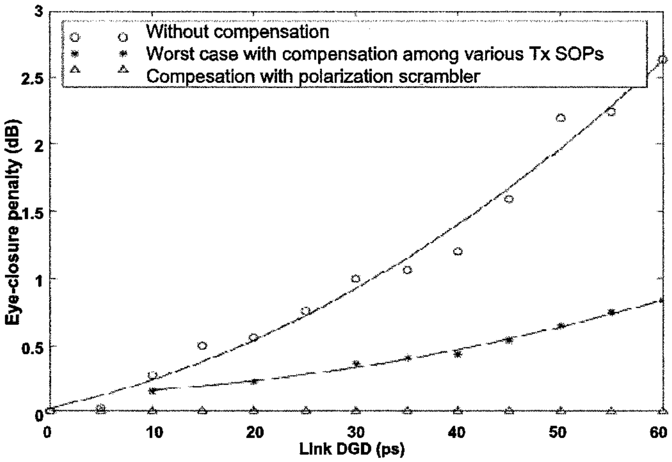


Fig. 12. Overview of signal eye-pattern degradation due to PMD effects for various degrees of PMD compensation.

orthogonal polarization. When viewed on the Poincare sphere, the resulting SOP's would ideally map out a great circle. While an ideal polarization scrambler would result in a uniform SOP distribution on the Poincare sphere, this approach sufficiently weights monitor signal with samples where the SOP is equally split between the PSP's so as to improve the DGD estimate. The frequency of this signal was approximately 1 GHz in this experiment.

To summarize the effectiveness of the PMD compensation system both with and without the benefit of a polarization scrambler at the transmitter, Fig. 12 presents the eye-closure penalty for various fiber DGD cases for a simulated 10-Gb/s NRZ signal. Three compensation modes are presented: no compensation system; compensation system active but no SOP scrambling; and active compensation with SOP scrambling. Symbols denote particular simulation results and the curves represent a best-fit interpolation. For the case of no compensation and variable power splitting between the PSP's, the eye degradation increases monotonically with increasing link DGD. For the case of active compensation without SOP scrambling, the eye degradation is substantially improved; however the degradation is not eliminated. For the case of active compensation with SOP scrambling, the eye degradation due to PMD is essentially eliminated.

VII. Conclusion

An adaptive PMD compensation system has been developed that cancels the effects of first-order PMD by producing a complementary PMD vector in the receiver. Control parameters for the PMD compensation system comprised of a polarization controller and a PMD emulator are derived from the NRZ signal in the channel to be compensated. Estimates of the link's DGD and PSP's based on this signal are reliable when the signal power is equally split between the link's two PSP's; however, this condition cannot be assumed. To meet this requirement, we scramble the SOP of the input signal at a rate much greater than the response time of the PMD monitor signal so that each sample represents many different SOP alignments. This approach allows the effective cancellation of the PMD effects within an optical fiber channel. As this approach relies on the PSP concept, this compensation technique addresses only first-order PMD; consequently in a wavelength-division multiplexing (WDM) application, a separate PMD compensation system would be required for each optical channel.

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Hok Yong Pua, photograph and biography not available at the time of publication.

Kumar Peddanarappagari, photograph and biography not available at the time of publication.

Benyuan Zhu, photograph and biography not available at the time of publication.

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A Poincare Sphere Method for Measuring Polarization-Mode Dispersion Using Four-Wave Mixing (FWM) in Single-Model Optical Fiber

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Abstract: A nonlinear Poincare sphere method for measuring polarization-mode dispersion (PMD) using the four-wave mixing (FWM) effect in single-mode optical fibers is presented. This method is based on the FWM-power transfer function on the polarization states of the input signals. Average PMD can be obtained by using this method with measurements in just a narrow optical bandwidth.

Key words: Polarization Mode Dispersion, PMD measurement, Poincare-Sphere Method, Four-wave mixing (FWM)

I. Introduction

Polarization-mode dispersion (PMD) is one of the major limiting factors of ultrahigh-bit-rate optical fiber communication systems. Currently, PMD is a big concern when upgrading legacy networks of installed fiber to 10 Gb/s (OC-192) rates and higher. For example, at 10 Gb/s (OC-192), the limit on PMD is about 10 ps [1]. Knowledge of the PMD in the fiber plant is becoming very critical for system designs, evaluations and installations.

Measuring PMD for installed fiber still is not an easy task. The time-domain methods are degraded by polarization state fluctuations, caused by polarization mode coupling in the fiber [2]. On the other hand, the frequency-domain method is limited by the motion-less condition. Any motion of the measurement apparatus, especially at the ends the fibers, can totally destroy the measured results [2, 3]. Maintaining a motionless condition is often difficult, especially with field measurements.

Recently, a novel nonlinear method was presented for measuring PMD using four-wave mixing (FWM) [4]. It alleviated the strict requirement for a motion-less condition. This paper presents a new technique for measuring PMD that is based on the same nonlinear effect (four-wave mixing, FWM) as in [4], but uses the Poincare sphere method to calculate PMD. In this method, two signals at different frequencies are launched into the fiber under tested. The output signals are then input to a dispersion-shifted fiber (DSF) to produce FWM. The FWM power in the DSF is related to the arc length on the Poincare sphere and is measured to determine the PMD value of the fiber under test. Theoretically, this method can produce a PMD value from each measurement point on FWM power, thus it greatly reduce the signal wavelength scanning range in the optical spectrum, though multiple measurements may be still needed to reduce the influence of FWM power fluctuation.

II. The theory of the method

FWM is a nonlinear process induced by Kerr effect in optical fiber. If three signals at frequencies f_i , f_j and f_k co-propagate through a single-mode fiber, the new frequency generated through FWM would be $f_l = f_i + f_j - f_k$. For the partially degenerate case, $f_i = f_j$, the newly generated frequency is $f_l = 2f_i - f_k$. The generated FWM power depends not only on the signal frequency separations, input signal power and fiber loss and nonlinear characteristics [5, 6, 7], but also on the input signal polarization states [4, 8]. The FWM power transfer function on the state of polarization (SOP) of the input pump signals can be written as [4]

$$F(SOP_1, SOP_2) = \frac{1}{2}[1 + \bar{s}_1(\omega_1)\cdot \bar{s}_2(\omega_2)]$$
$$= \frac{1}{2}[1 + s_1^{(1)}s_1^{(2)} + s_2^{(1)}s_2^{(2)} + s_3^{(1)}s_3^{(2)}] \quad (1)$$

Where $\bar{s}_1(\omega_1) = [s_1^{(1)} \quad s_2^{(1)} \quad s_3^{(1)}]^T$ and $\bar{s}_2(\omega_2) = [s_1^{(2)} \quad s_2^{(2)} \quad s_3^{(2)}]^T$ are the normalized vectors representing the two polarization states of the two input signals at frequencies ω_1 and ω_2, repectively. (1) is valid when the PMD in the fiber (measurement fiber) is small. This transfer function has been verified by both simulation and experiments in [4].

On the surface of Poincare sphere, we can write (1) as

$$F(s) = \frac{1}{2}[1 + \cos(\phi)]$$
$$= \frac{1}{2}[1 + \cos(s)] \quad (2)$$

where ϕ is the angle between the two polarization vectors and s is the arc length between the two end points of the two polarization vectors on the Poincare sphere. From (2), we can write s as a function of F, that is

$$s = \cos^{-1}(2F - 1) \quad (3)$$

By definition, the first-order PMD is calculated by [9]

$$PMD = \left|\frac{ds}{d\omega}\right| \quad (4)$$

where ω is the signal angular frequency. Substituting (3) into (4), we get

$$PMD = \frac{1}{\sqrt{F(1-F)}}\left|\frac{dF}{d\omega}\right| \quad (5)$$

If we use wavelength instead of frequency, (5) becomes

$$PMD = \frac{\lambda^2}{2\pi c\sqrt{F(1-F)}}\left|\frac{dF}{d\lambda}\right| \quad (6)$$

where λ is the wavelength and c is the speed of light.

The FWM transfer function, F, is obtained by measuring the FWM efficiency as a function of the signal wavelength separation. In real measurements, F needs to be calibrated with the zero-PMD case to reduce the effects of chromatic dispersion in measurement fiber. The derivative in (6) should also be replaced by a difference equation and we get

$$PMD = \frac{\lambda^2}{2\pi c\sqrt{F(1-F)}}\left|\frac{\Delta F}{\Delta\lambda}\right| \quad (7)$$

where ΔF is the change in FWM efficiency inside the small wavelength window $\Delta\lambda$. To reduce the influence of FWM power fluctuation, multiple measurements are needed either at one wavelength or at multiple wavelengths.

III. Experimental results

An experimental setup for measuring PMD using FWM is shown in Fig. 1. Here, a PMD emulator was used to generate a known amount of PMD in the system and served as the fiber under test. A 17.5-km dispersion shifted fiber (DSF) with a zero-dispersion wavelength of 1551 nm was used as the measurement fiber to produce FWM. The FWM power was measured by an optical spectrum analyzer. In our measurements, the wavelength of one input signal was fixed at 1554.0 nm, and the other signal wavelength was varied, where the range of variation chosen depended on the expected PMD values. During measurements, the PMD emulator was first set to zero PMD and the FWM efficiency was measured and recorded, where the FWM efficiency is defined as the FWM power normalized by its maximum value which occurs when the polarization states of two input signals are aligned. This data was used for calibrating the FWM efficiencies for the non-zero PMD cases. Fig. 2(a) and (b) show the measured FWM efficiency vs. the signal wavelength separation for two PMD values, 10 ps and 20 ps, after calibration. The PMD-induced periodic variations on FWM power is clearly observed when signal wavelength is swept. The minimum measurable FWM level was limited by ASE noise.

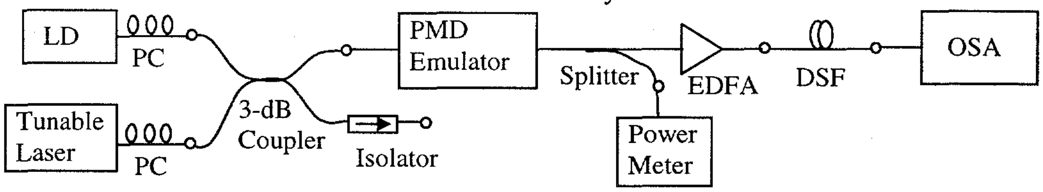

Fig. 1 Experimental setup for measuring PMD using FWM.
LD--Laser diode; PC--Polarization controller; EDFA--Erbium-doped fiber amplifier; DSF--Dispersion-shifted fiber; OSA--Optical spectrum analyzer

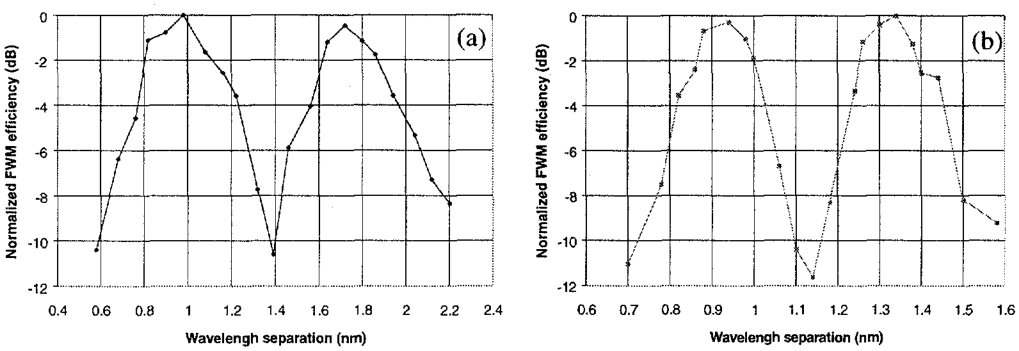

Fig. 2 Normalized FWM efficiency for PMD =10 ps and PMD = 20 ps after calibrated with zero-PMD case. (a) PMD = 10 ps, (b) PMD = 20 ps.

Fig. 3 shows measured average PMD for different given PMD. The measured mean PMD values were obtained by averaging the measurements in different wavelength ranges, represented by the periods of variations of FWM efficiency on wavelength, as show in Fig. 2. Four cases in Fig. 3 correspond to 0.5, 1, 1.5 and 2 periods. The measured results for all four cases follow well with the given values, but are mostly a little bit lower than the true PMD. This is due to measurement errors around the notch areas of the measured FWM efficiency curve. Theoretically, the notches of the FWM efficiency curve should have approached zero, but in experiments these points are non-zero due to the amplified spontaneous emission in the erbium-doped fiber amplifier (EDFA).

To estimate the optical bandwidth needed for this method, Table 1 gives the calculated width in nanometer for each period of the FWM power variations with different PMD values. It agrees well with measured FWM data in Fig. 2. For high PMD (> 10 ps), the period is quite narrow. Thus the nonlinear Poincare sphere method can measure PMD without scanning measurement signals in a wide optical bandwidth.

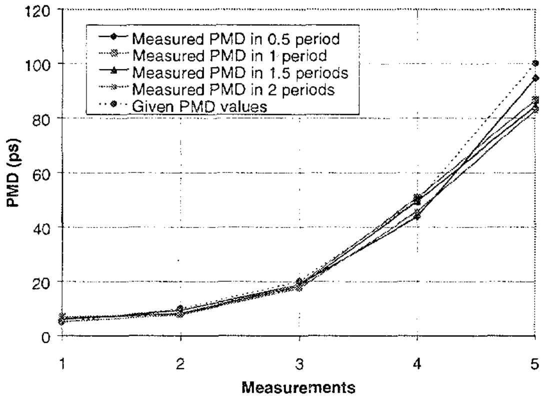

Fig. 3 Measured mean PMD and the given PMD.

Table 1 The wavelength width of one period of FWM power variations for different PMD values

PMD (ps)	5	10	20	50	100
Wavelength width (nm) per FWM period	1.6	0.8	0.4	0.16	0.08

IV. Conclusion and discussion

In summary, we have presented a new Poincare sphere method for measuring PMD by using FWM generation in single-mode optical fiber. It is based on the FWM power transfer function vs. the polarization states of the pump signals. Compared to the traditional Poincare sphere method, this method does not require measurement of the Stokes vectors and is less insensitive to mechanical vibration of measurement apparatus. Compared to the nonlinear fixed polarization analyzer method, this method does not need to scan a wide optical bandwidth and thus has fewer requirements on the measurement fiber.

Similar to the nonlinear method in [4], this technique may also be used as an in situ PMD measurement or monitoring method on dense wavelength-division multiplexed (DWM), traffic-carrying fibers. If the polarization states of the transmitted signals are fixed, the FWM products in the measurement fiber generated by wavelength channels may provide an estimate of the PMD. This can be done either span-by-span or over several spans.

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A Novel Method for Measuring Polarization-Mode Dispersion Using Four-Wave Mixing

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***Abstract*— A method for measuring polarization-mode dispersion (PMD) on fiber links using four-wave mixing (FWM) generation is presented. This method uses a probe signal to analyze the signal polarization state via FWM generation. The FWM power transfer function is derived in terms of the Stokes parameters, and is validated using both simulated and experimental results. Based on this transfer function, PMD measurements are presented that agree well with the actual PMD values. Compared to the traditional frequency-domain methods, this new method does not require a motionless condition for the measurement apparatus.**

***Index Terms*— Four-wave mixing (FWM), nonlinear effects, polarization-mode dispersion (PMD) measurement.**

I. Introduction

POLARIZATION-MODE dispersion (PMD) is one of the major limiting factors of ultrahigh-bit-rate optical fiber communication systems. Currently, PMD is a big concern when upgrading legacy networks of installed fiber to 10 Gb/s (OC-192) rates and higher. At OC-192 bit rates, the maximum acceptable amount of PMD is about 10 ps [1].

Existing PMD measurement techniques fall mainly in two categories [2]. One involves time-domain measurements, and includes the interferometric and optical pulse methods. The other involves frequency-domain measurements, based on the evolution of states of polarization (SOP) as a function of frequency or wavelength. Included in this category are the fixed-analyzer method, the Jones-matrix method, and the Poincare-sphere method. A major drawback of the time-domain methods is that their results are degraded by polarization state fluctuations, caused by polarization mode coupling in the fiber [2]. On the other hand, a limitation of the frequency-domain methods is that any motion of the measurement apparatus, especially at the ends the fibers, can totally destroy the measured results [2], [3]. Maintaining a motionless condition is often difficult, especially with field measurements.

This paper presents a novel method for determining PMD in a fiber link by measuring four-wave mixing (FWM) products. In this method, a constant wavelength "probe" wave and a variable wavelength "signal" wave are launched into the test fiber of unknown PMD. The output signals are then input to a low-dispersion, low PMD "measurement fiber" where FWM products are generated that depend on the PMD of the test fiber. Average PMD can then be determined by measuring the power of the FWM products as the difference frequency of the two signals is varied, since the magnitude of FWM products depends upon the polarization states of the two waves. This technique is insensitive to mechanical vibrations and instabilities in the test equipment, since the measured PMD depends only on the relative SOP change between the probe and signal waves in the measurement fiber, not the position coordinates of fiber or the equipment.

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II. The Theory of the Nonlinear Method

A. Dependence of the FWM Transfer Function on the State of Polarization (SOP)

FWM is a nonlinear process induced by the Kerr effect in optical fibers. If three signals at frequencies f_i, f_j, and f_k copropagate through a single-mode fiber, the newly generated frequency through FWM will be $f_l = f_i + f_j - f_k$. For the partially degenerate case, $f_i = f_j$, the newly generated frequency is $f_l = 2f_i - f_k$. The generated FWM power depends not only on the signal frequency separation, the input signal powers, the fiber loss, and nonlinear characteristics, but also on the signal polarization states. The dependence of the FWM power on these parameters for the partially degenerate case can be expressed as [4]–[6]

$$P_{\text{FWM}}(L) = F_1(\gamma, \alpha, P_1, P_2, L) F_2(D, \Delta\lambda, \alpha, P_1, P_2, L) \cdot F_3(\text{SOP}_1, \text{SOP}_2). \quad (1)$$

Here, the first term, F_1, is called the power term, which is a function of the fiber nonlinear coefficient γ, the fiber attenuation coefficient α, the fiber length L, and is the input signal powers P_i $(i = 1, 2)$. The second term, F_2, is called the FWM efficiency factor, which depends on the fiber dispersion D, the signal wavelength separation $\Delta\lambda$, the fiber loss α and length L, and the signal power [6]. The third term, F_3, is the FWM state of polarization (SOP) transfer function, where SOP_i $(i = 1, 2)$ are the states of polarization of signals 1 and 2, respectively. If $E_1 = [\cos(\phi_1),\ \sin(\phi_1)e^{j\Delta_1}]^T$ and $E_2 = [\cos(\phi_2),\ \sin(\phi_2)e^{j\Delta_2}]^T$ are the complex polarization vectors of signals 1 and 2, respectively, and the fiber length is much longer than the coupling length (10–100 m in most communication fiber), then F_3 can be written as [7]

$$F_3(\mathrm{SOP}_1, \mathrm{SOP}_2) = \cos^2(\phi_1)\cos^2(\phi_2) + \sin^2(\phi_1)\sin(\phi_2) + \tfrac{1}{2}\sin(2\phi_1)\sin(2\phi_2)[\cos(\Delta_1)\cos(\Delta_2) + \sin(\Delta_1)\sin(\Delta_2)]. \quad (2)$$

This equation is valid for fiber with small PMD, since PMD may significantly change the relative polarization states of the two signals along the fiber when the frequency separation between the two signals becomes large.

From the definitions of Stokes vectors [8], we can write the sine and cosine functions in (2) as

$$\cos(\phi_i) = \sqrt{\frac{1}{2}[s_0^{(i)} + s_1^{(i)}]} \quad (3a)$$

$$\sin(\phi_i) = \sqrt{\frac{1}{2}[s_0^{(i)} - s_1^{(i)}]} \quad (3b)$$

$$\cos(\Delta_i) = \frac{s_2^{(i)}}{\sqrt{(s_2^{(i)})^2 + (s_3^{(i)})^2}} \quad (3c)$$

$$\sin(\Delta_i) = \frac{s_3^{i}}{\sqrt{(s_2^{(i)})^2 + (s_3^{(i)})^2}}, \quad (3dc)$$

where s_0, s_1, s_2, and s_3 are the four normalized components of Stokes vector, with the superscript i standing for the signals 1 and 2, respectively. The normalized Stokes components satisfy the relation

$$s_0^i = \sqrt{(s_1^{(i)})^2 + (s_2^{(i)})^2 + (s_3^{(i)})^2} = 1 \qquad (i = 1, 2). \quad (4)$$

Substituting (3a) to (3d) into (2), we obtain

$$F_3(\mathrm{SOP}_1, \mathrm{SOP}_2) = \tfrac{1}{2}[1 + s_1^{(1)}s_1^{(2)} + s_2^{(1)}s_2^{(2)} + s_3^{(1)}s_3^{(2)}] = \tfrac{1}{2}[1 + \overline{s}_1 \cdot \overline{s}_2], \quad (5)$$

where $\overline{s}_1 = [s_1^{(1)}\ s_2^{(1)}\ s_3^{(1)}]^T$ and $\overline{s}_2 = [s_1^{(2)}\ s_2^{(2)}\ s_3^{(2)}]^T$ are the two vectors representing the polarization states of the two input signals on the Poincare sphere.

To see how FWM power generated in a low PMD, low dispersion measurement fiber can be used to measure the PMD in an arbitrary test fiber, we first note that, according to the fixed polarizer method [3], the first-order PMD of a fiber can be measured by launching a fixed SOP "signal" wave into the test fiber and then passing the output through a fixed polarizer. The output power from the polarizer is given by the expression,

$$T = \tfrac{1}{2}[1 + \overline{s}(\omega) \cdot \overline{P}] \quad (6)$$

where $\overline{s}(\omega)$ is the SOP of the light incident on the polarization analyzer and $\overline{p}$ is the unit vector specifying the transmission state (i.e., the pass axis of the polarization analyzer). First order PMD is then estimated using the formula [3]

$$\langle \Delta\tau \rangle = k\frac{\pi\langle N_e \rangle}{\Delta\omega} \quad (7)$$

where $\langle \Delta\tau \rangle$ is the mean PMD, $\langle N_e \rangle$ is the mean number of maxima and minima of the T curve in the frequency band $\Delta\omega$, and k is the polarization coupling factor (which equals 1.0 when the fiber under test is a PMD emulator).

Comparing (5) with (6), we see that they are the same function, except that the polarization state of the 2nd, fixed frequency "probe" signal in (5) replaces the polarizer transmission state $\overline{p}$ in (6). This suggests that an alternative to the fixed polarizer method would be to launch two, fixed SOP signals into the test fiber and pass the output through a short measurement fiber that has both low PMD and dispersion. According to (5), the FWM power generated in a low PMD measurement fiber will vary with frequency changes of the test signal exactly as would the output of the test signal alone passing through a fixed polarizer. This means that we can use the FWM transfer function (5) in place of the T function (6) when calculating PMD using calculating first order PMD using (7).

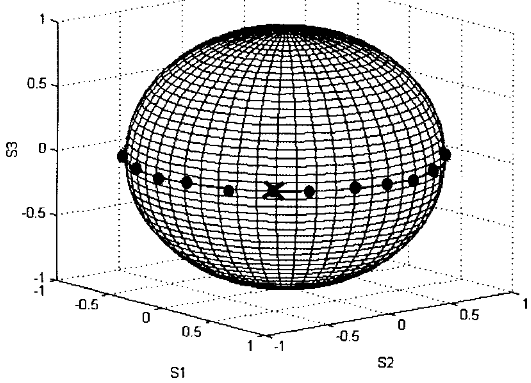
The advantage of calculating PMD using the FWM power produced in a separate, measurement fiber is that no special care need be taken to maintain a strict spatial orientation between the test fiber and the measurement equipment (such as a polarizer). This is because the probe wave follows the signal wave through both the test and measurement fibers and, therefore, automatically establishes the polarization reference in the measurement fiber.

B. Experimental Verification of the FWM Transfer Function

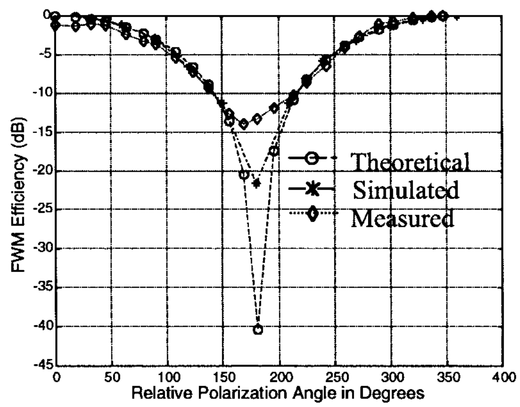
In order to verify (5), both experiments and numerical simulations were performed and compared with (5). A 17.5 km length of dispersion-shifted fiber (DSF) was used to produce FWM. The zero-dispersion wavelength of this fiber was 1551 nm. Two CW signals were input to this fiber, with wavelengths 1552.0 nm and 1552.8 nm, respectively. The polarization states of the two input signals were varied by polarization controllers, and a polarization analyzer was used to measure and record the input polarization states of the two signals on the Poincare sphere. The numerical calculations were performed using the Split-Step Fourier-Transform Method [9].

Fig. 1 shows the results for the case of when both signals were linearly polarized. Here, the SOP for one signal was fixed and the SOP for the other signal varied along the equator of the Poincare sphere. Fig. 1(a) shows the polarization states on the Poincare sphere. Fig. 1(b) shows the FWM efficiency in dB as calculated numerically, measured experimentally, and predicted by the FWM transfer function (5). For these plots, the FWM efficiency is defined as the FWM power, normalized by its maximum value. These results agree well except in the notch area, where the analytical curve from (5) goes to zero ($-\infty$ dB) when the two signals have orthogonal polarization states. The simulated results at this point do not approach zero due to the second-order FWM effects. The minimum measured FWM power is limited by the ASE noise level. Even so, the difference between measured maximum and minimum FWM efficiency is roughly 15 dB, which is more than enough to distinguish the minima and maxima needed for determining PMD.

Fig. 2 shows the variation of the FWM efficiency when the polarization state of one signal is a fixed, linear state, and the other signal's polarization state is varied from linear, to elliptical, to circular, and back to the original linear polarization

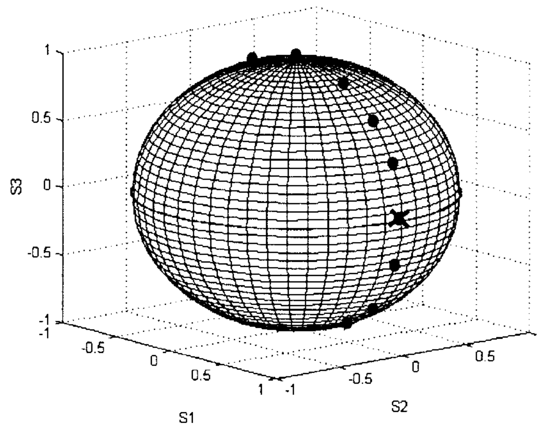


(a)

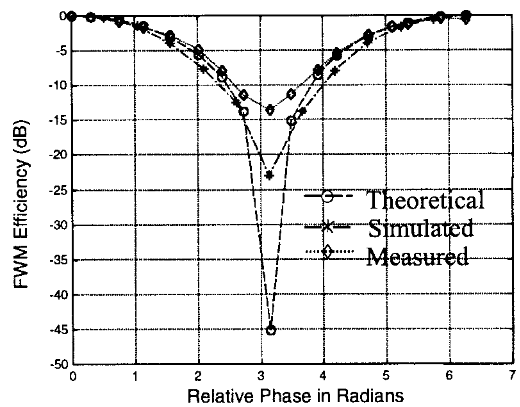


(b)

Fig. 1. The dependence of FWM on the input signal polarization states for linear polarization. × signal 1; • signal 2.



(a)



(b)

Fig. 2. The dependence of FWM on the input signal polarization states for linear, elliptical and circular polarization. × signal 1; • signal 2.

state, as shown in Fig. 2(a). Numerically calculated, measured, and analytical predictions (5) of FWM efficiency are shown in Fig. 2(b) and, again, show excellent agreement.

III. Measuring PMD Using FWM

An experimental setup for measuring PMD using FWM is shown in Fig. 3. Here, the device under test is a PMD emulator. The DSF measurement fiber is the same as that used above for verifying the FWM transfer function. An erbium-doped-fiber amplifier (EDFA) was used to boost the signal power to produce FWM in the DSF. The FWM power was measured with an optical spectrum analyzer. During the measurements, the wavelength for one input signal was fixed at 1554.0 nm and the other wavelength was varied over a range that depended on the expected PMD values. Fig. 4(a) and (b) shows the measured FWM power versus the signal wavelength separation for PMD values of 20 and 10 ps, respectively, where each is compared with the zero-PMD case. The PMD-induced variations of the FWM power are clearly observed as the signal wavelength changes, and look similar to the transmission curves obtained when using the fixed-polarizer PMD method. For the zero-PMD case, there are some fluctuations in FWM power, but the magnitudes of the variations are quite small and easily distinguished from PMD-caused FWM magnitude variations. Fig. 5 shows the measured PMD values for different settings of the PMD simulator. Here, it can be seen that the measured PMD values agree well with the actual PMD values.

IV. Conclusion and Discussion

We have demonstrated a method for determining PMD by measuring FWM generation in a section of DSF measurement fiber placed after a test fiber. Both numerical simulations and experiments were performed to verify the FWM power-transfer-function dependence on the polarization states of two waves launched into a fiber. PMD measurements were also performed, with good agreement with the given PMD values.

Like the well-known fixed polarization-analyzer method, this method uses a frequency-domain transfer function to determine SOP changes with frequency and, consequently, the PMD. The difference, however, is that this technique uses the FWM power generated in a separate measurement fiber to track the changes of polarization of a wave with frequency. This makes this technique relatively insensitive to mechanical vibrations and upset, since both the probe and signal waveforms are subjected to the same mechanical environments. Hence, the accuracy of this technique is limited only by the additional PMD and dispersion added by the measurement fiber itself, which is typically small in short lengths of DSF fiber. In addition, errors can be further reduced by first calibrating the measurement with the zero-PMD case

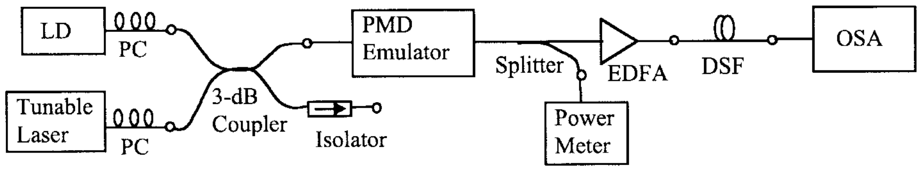


Fig. 3. Experiment setup for measuring PMD using FMD.

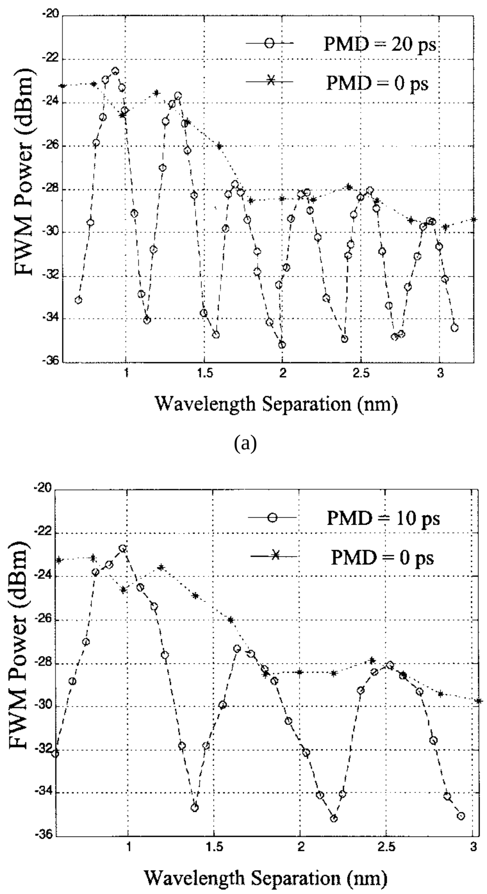


Fig. 4. Measured FWM power versus wavelength separation for different PMD values. DSF fiber length: 17.5 km, zero-dispersion wavelength: 1551 nm, Loss: 0.25 dB/km.

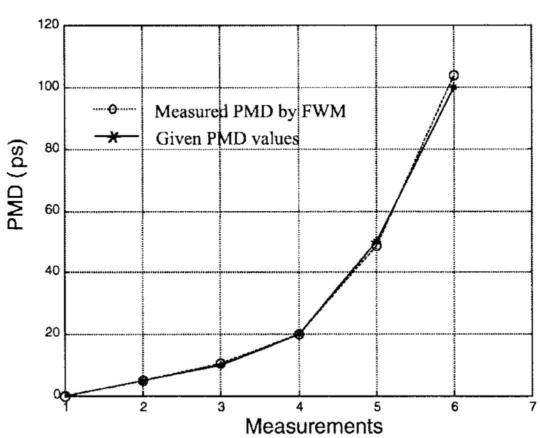


Fig. 5. Comparison of measured PMD using FWM and the given PMD.

(i.e., the test device or fiber under test removed), so that the frequency dependence of the FWM in the measurement fiber can be subtracted out.

An additional advantage of this technique is that it may be possible for it to provide in situ PMD measurement or monitoring on dense wavelength-division multiplexed (DWM), traffic-carrying links. If the polarization states of the transmitted signals are fixed, the FWM products generated throughout the bandwidth of the channels in a separate measurement fiber may provide an estimate of the PMD, either span by span or over several spans.

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Shuxian Song (M'98), for a photograph and biography, see p. 2290 of the November 1999 issue of this JOURNAL.

Christopher T. Allen (M'94–SM'95), for a biography, see p. 2290 of the November 1999 issue of this JOURNAL.

Kenneth R. Demarest (S'78–M'79–SM'99), for a biography, see p. 2290 of the November 1999 issue of this JOURNAL.

Rongqing Hui (A'94–M'97–SM'97), for a biography, see p. 2290 of the November 1999 issue of this JOURNAL.

Appendix B

Polarization Mode Dispersion, PMD Bibliography

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