The University of Kansas

Information and
Telecommunication
Technology Center

Technical Report

PMD Characterization of Installed Fiber: Final Report

Pradeep Kondamuri and Chris Allen

ITTC-FY2004-TR-33750-01

June 2004

Project Sponsor:
Sprint

Final progress report

Pradeep Kumar Kondamuri, Dr. Chris Allen May 21st, 2004

This report summarizes the PMD research work done in the last year at the Lightwave laboratory, University of Kansas. Over the last year,

- We made PMD measurements using EXFO PMD analyzer obtained on loan from Dr. David Harris, Sprint ATL. Our analysis of measured data showed that it is very noise and not very reliable compared to the data measured using Agilent polarization analyzer.
- We made progress in modeling PMD which is very important for predicting PMD-induced outages on long-haul optical fiber links, the goal of this research work. Through modeling we showed that the spectral drift of DGD with time is due to temperature changes. However, our modeling results also showed that temperature alone is not responsible for all of the DGD temporal and spectral characteristics observed on measured data.
- We also made significant progress in understanding the temporal behavior of differential group delay (DGD). We showed for that the time derivative of DGD has a Laplacian pdf and using this we simplified the expression for calculating the first-order PMD-induced outage rates given by Caponi et al. into a simple analytical expression which depends only on the mean DGD and the Laplacian parameter. This a significant step forward in PMD outage analysis which resulted in a journal publication.

Three documents are attached to this report which explains the progress mentioned above in detail. The last document is an Electronics Letters publication which appeared in April 15th, 2004 issue.

We are on track to achieving our goal which is to develop a numerical PMD model based on measured data that can predict first-order PMD-induced outages on long haul optical fiber links. This goal, once accomplished, will greatly help network engineers at Sprint in anticipating the impact of PMD on various fiber routes and there by take steps to ensure network reliability. However, for us to achieve the goal we need financial assistance for at least one more year and we are hoping that Sprint would understand the value of our work and extend funding for one more year.

PMD measurements on Topeka fibers using the EXFO PMD analyzer

Pradeep Kumar Kondamuri, Dr. Chris Allen Aug. 29th, 2003

Introduction:

PMD was measured on three loop-back fibers that terminate in our research lab and extend to Topeka, KS. What follows is a summary of the DGD data measured on each of three individual links and on three combinations of concatenating two fiber links during the months of June and July of year 2003. This data was collected using the EXFO PMD Analyzer (FPMD-5600) while on loan to us from Dr. David Harris, Sprint-ATL.

Experimental Setup:

Single fiber link:

Concatenated fiber link:

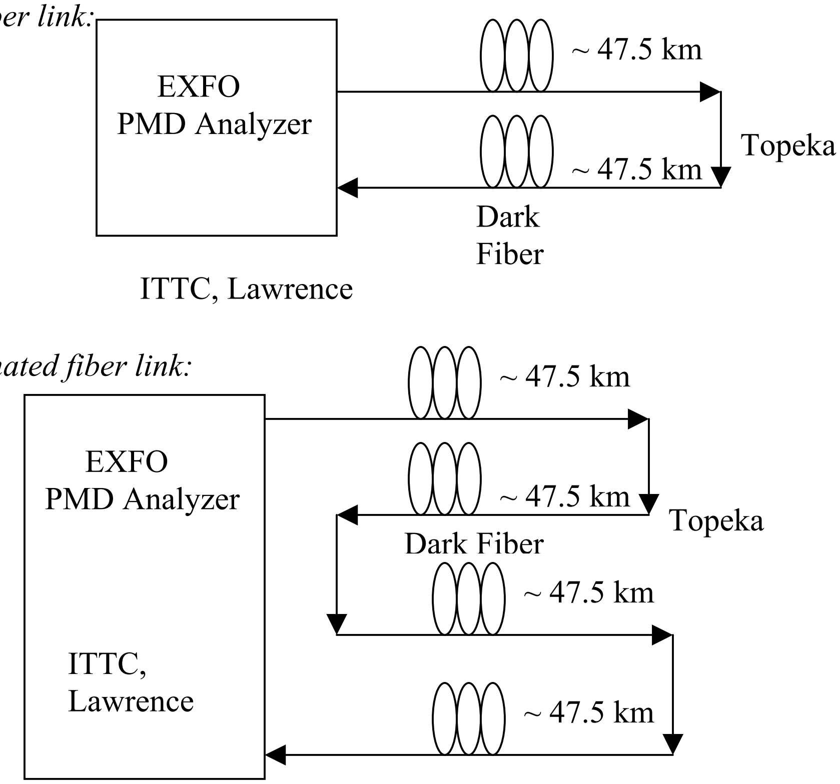

Figure 1: Experimental setup for (top) single fiber link measurements and (bottom) concatenated fiber link measurements.

Table1. Measurements' specifications

	# of days (# of meas.)	Wavelength Band (nm)	# of λs in the band	# of measured data points
Link 1	5.4 (3780)	1530 –1600	2281	8622180
Link 2	1 (701)	1530 –1600	2281	1598981
Link 3	1 (701)	1530 – 1600	2281	1598981
Links 1 and 2	4.6 (3241)	1535 – 1565	997	3231277
Links 1 and 3	4.1 (2887)	1535 – 1565	997	2878339
Links 2 and 3	4.8 (3331)	1535 – 1565	997	3321007

Plots from preliminary analysis of measured DGD data:

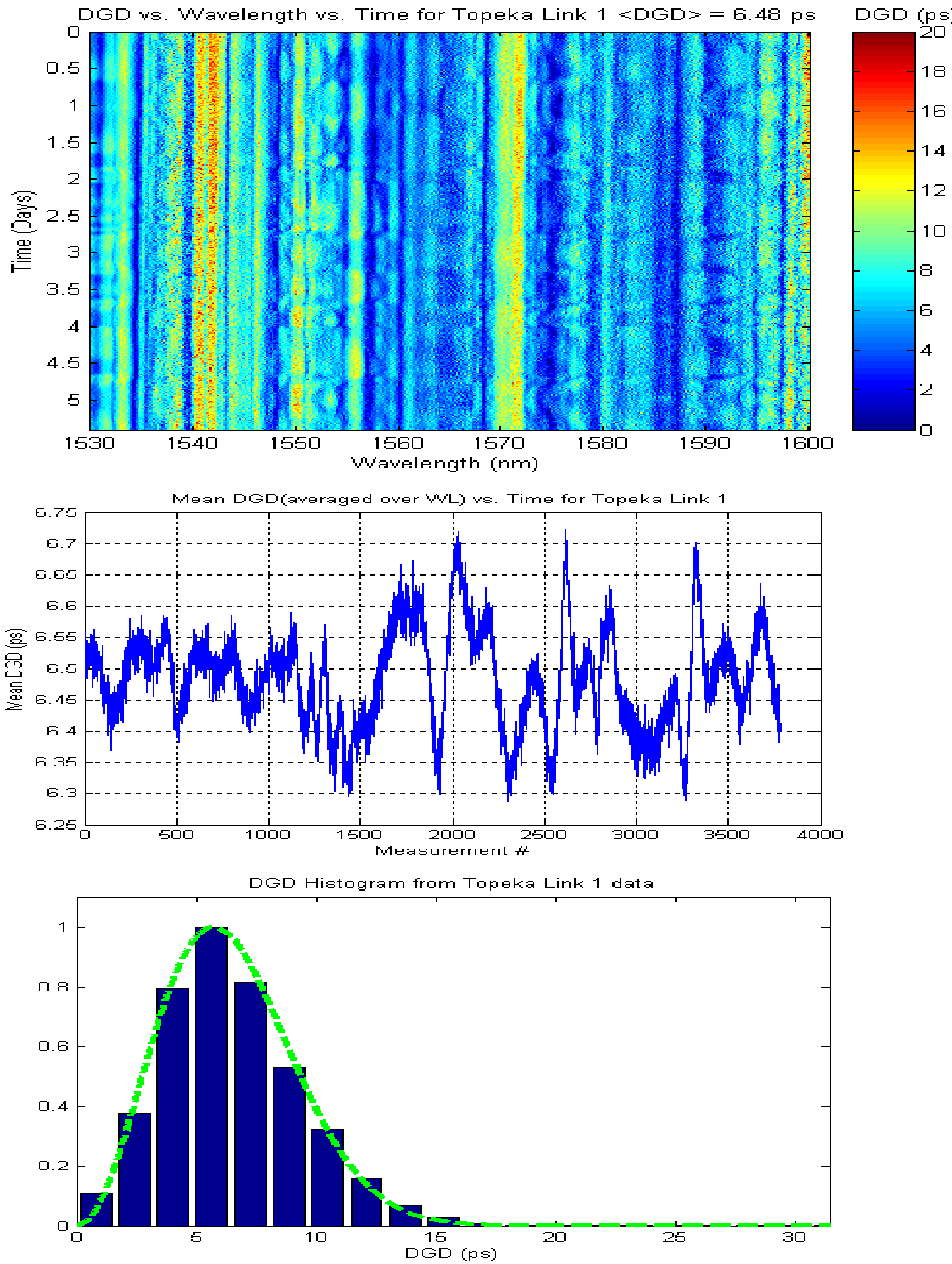

Figure 2. Measured DGD data for link 1.
(top) Color map showing measured DGD vs. time and wavelength.
(middle) Measured mean DGD vs. time.
(bottom) Histogram of measured DGD data.

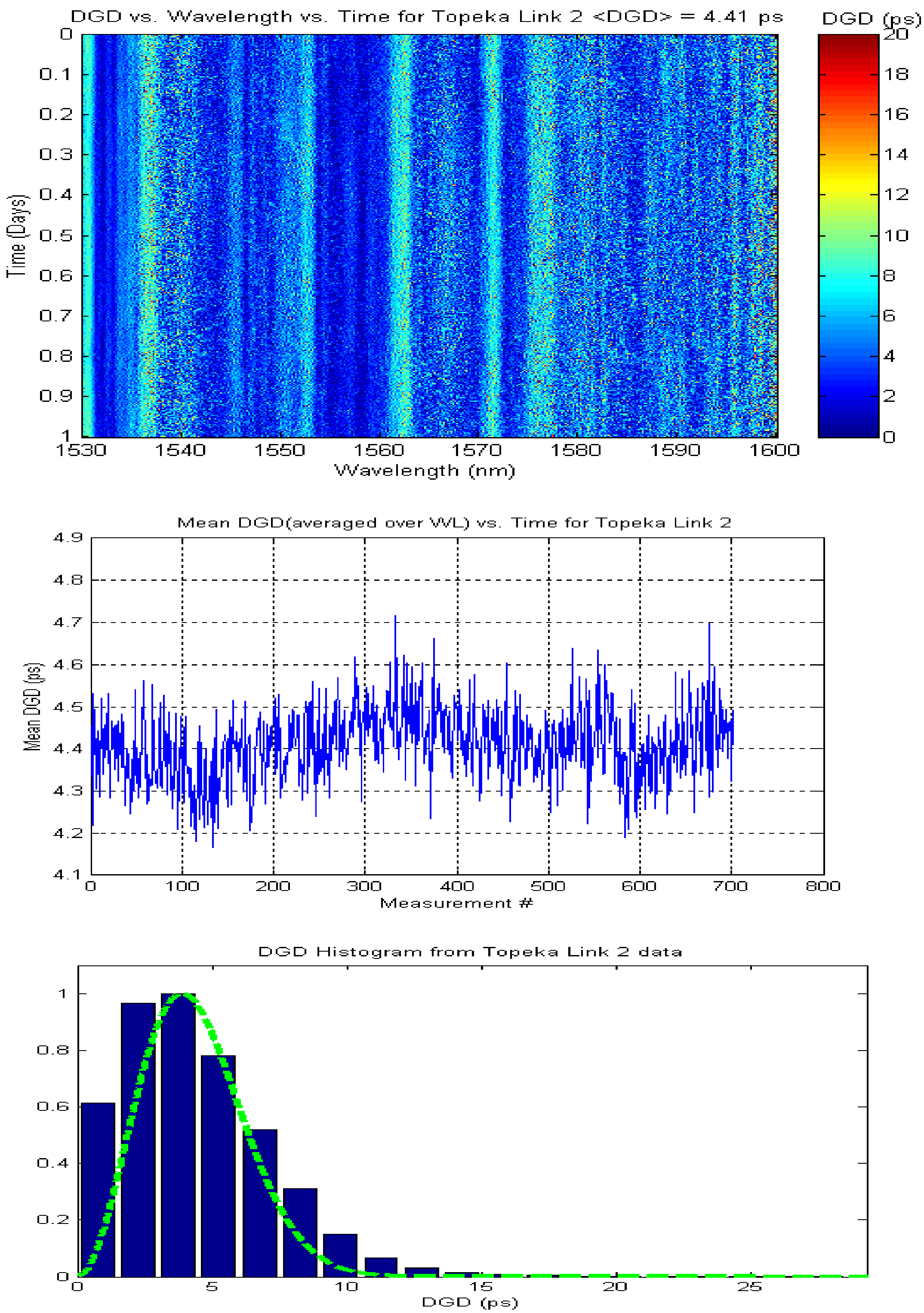

Figure 3. Measured DGD data for link 2.
(top) Color map showing measured DGD vs. time and wavelength.
(middle) Measured mean DGD vs. time.
(bottom) Histogram of measured DGD data.

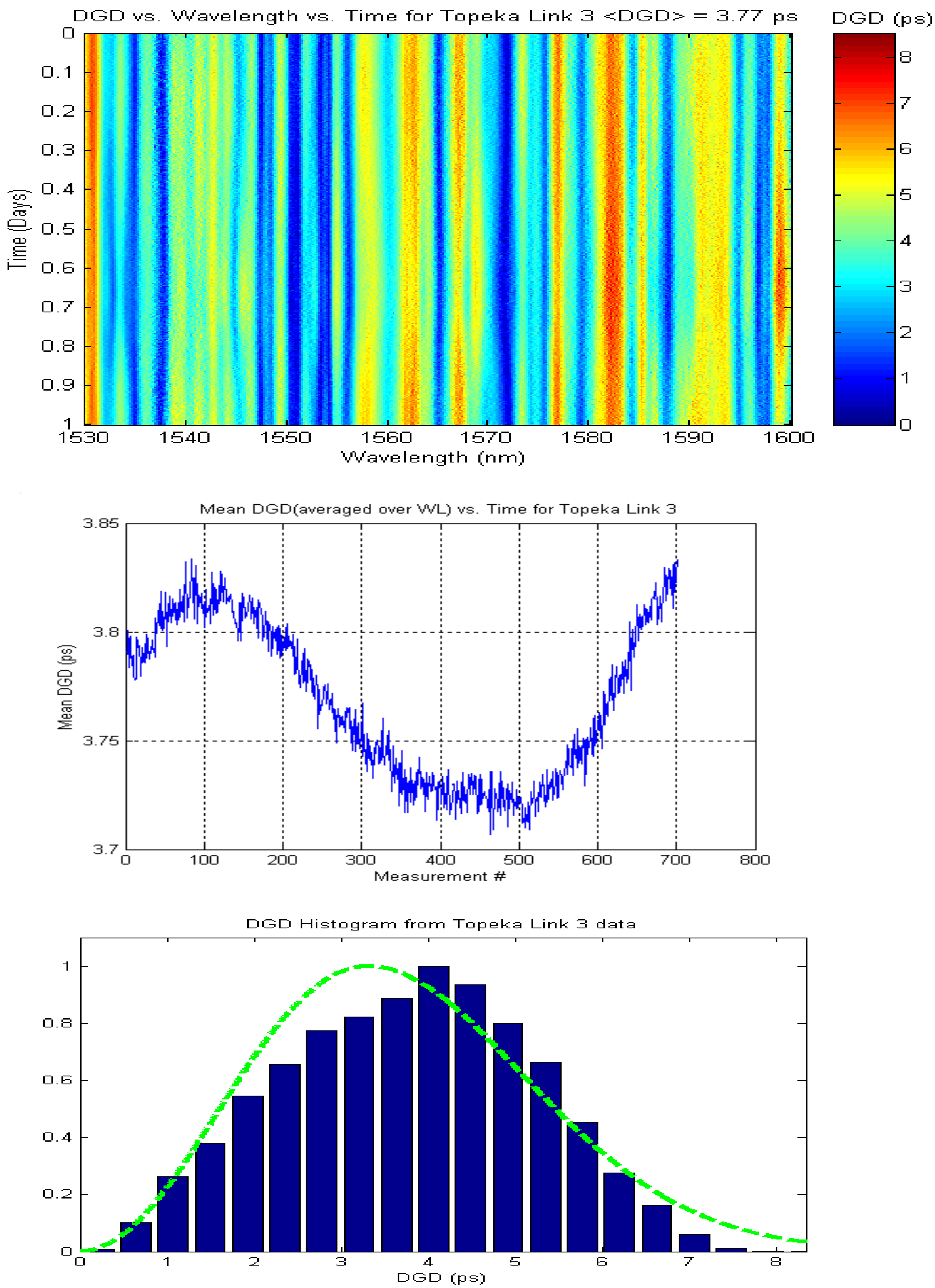

Figure 4. Measured DGD data for link 3.
(top) Color map showing measured DGD vs. time and wavelength.
(middle) Measured mean DGD vs. time.
(bottom) Histogram of measured DGD data.

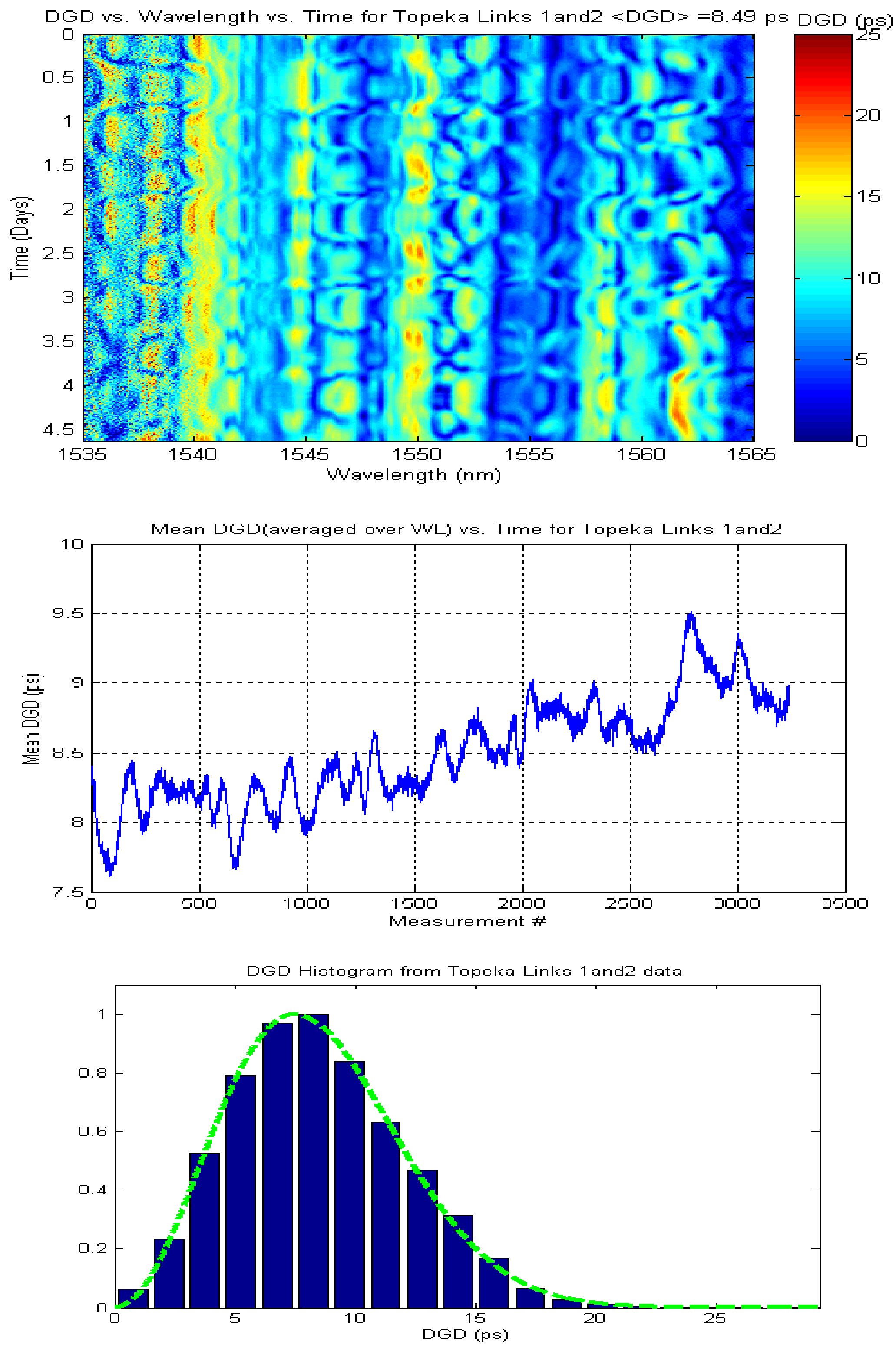

Figure 5. Measured DGD data for links 1 and 2.
(top) Color map showing measured DGD vs. time and wavelength.
(middle) Measured mean DGD vs. time.
(bottom) Histogram of measured DGD data.

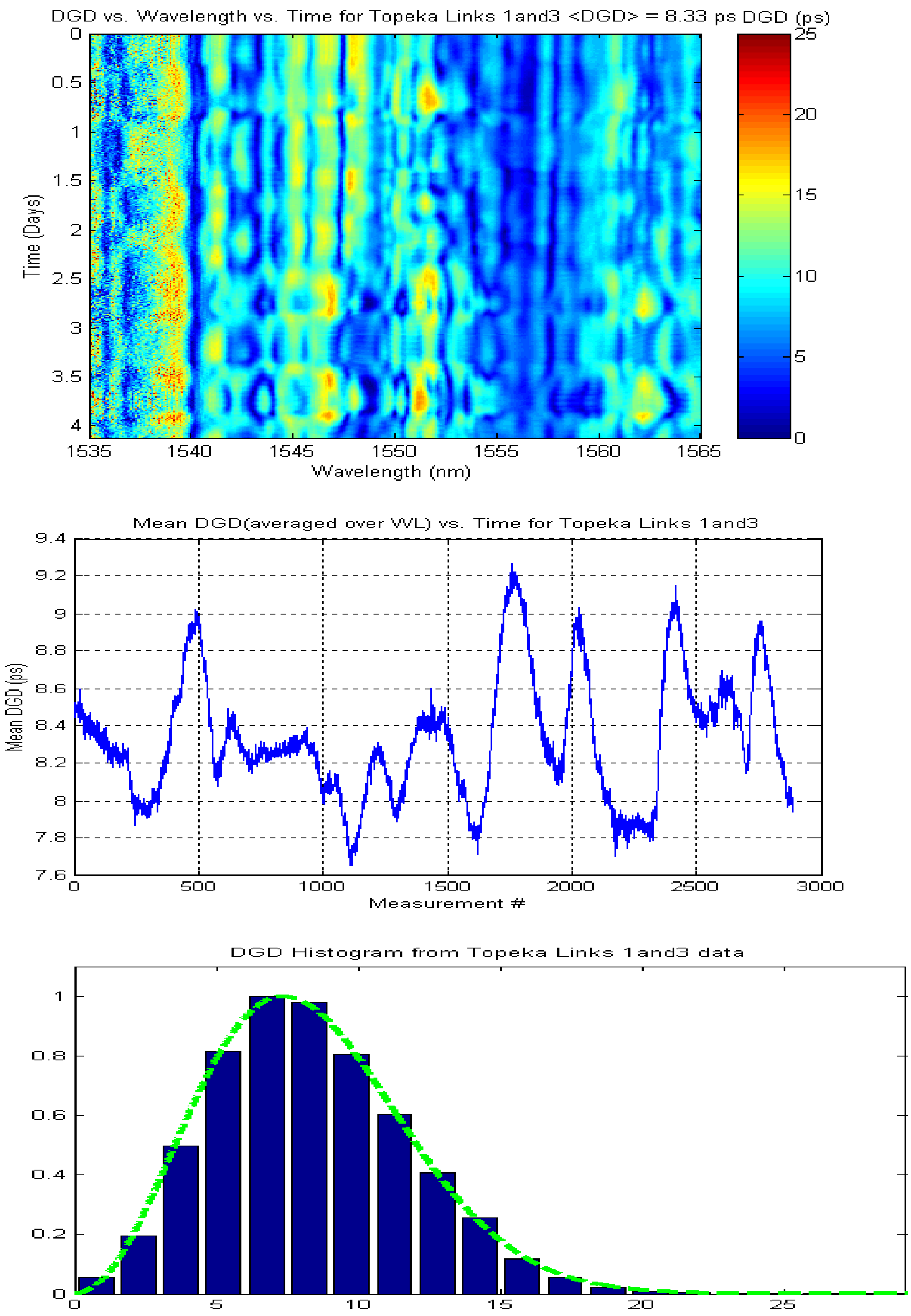

Figure 6. Measured DGD data for links 1 and 3.
(top) Color map showing measured DGD vs. time and wavelength.
(middle) Measured mean DGD vs. time.
(bottom) Histogram of measured DGD data.

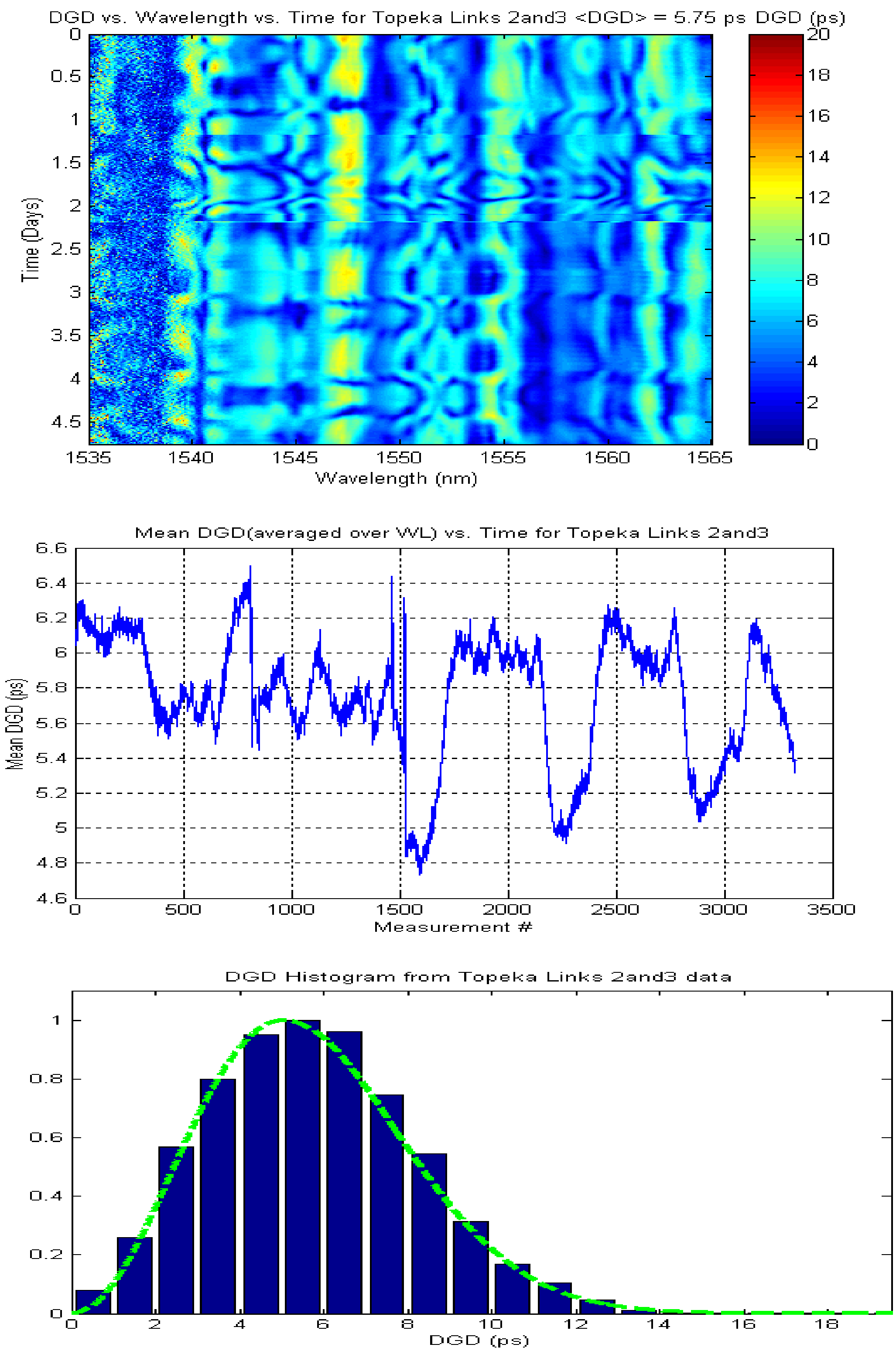

Figure 7. Measured DGD data for links 2 and 3.
(top) Color map showing measured DGD vs. time and wavelength.
(middle) Measured mean DGD vs. time.
(bottom) Histogram of measured DGD data.

Conclusions:

The measured DGD data look interesting as well as intriguing. The measured data are in accordance with our earlier observation that DGD varies rapidly along wavelength but drifts slowly with time. Also, the measured DGD follows a Maxwellian distribution. However, the mean DGD variation observed on Link 3 is quite intriguing. From this data we hope to understand better how PMD (DGD in particular) varies with link length. We have only recently begun to analyze this data. We also have PSP and second-order PMD data measured during these same periods, but we have not examined this data.

In parallel with the analysis we are developing a model that would allow us to simulate the spectral and temporal PMD behavior of buried fiber, and will thus help us to better understand the PMD phenomenon.

Numerical modeling of temporal and spectral characteristics of PMD in single-mode fibers

Pradeep Kondamuri and Christopher Allen, The University of Kansas, Nov. 24th 2003

Introduction

Using statistical analysis of measured temporal and spectral DGD variations on a 95-km buried fiber link, we have demonstrated an ability to predict PMD-induced outages. Prediction of PMD-induced outages on realistic link lengths (> 500 km) would require long-term access to such a link and is not economically feasible at this time. Another approach to obtain PMD-induced outage statistics is to develop numerical models that realistically reflect the PMD-characteristics of buried fiber. While PMD numerical models exist, they do not include the necessary temporal variations needed for PMD-induced outage analysis. Therefore we are attempting to incorporate temporal variations in the model parameters to accurately emulate the temporal nature of PMD on real fibers. Our objective is to adjust the variables in the simulation model based on known environmental factors (such as soil temperature and atmospheric pressure) and simulate results comparable to what we obtained from measurements using a polarization analyzer. Such a model will help us predict the behavior of PMD on any-length of fiber links. This report summarizes the progress that we made thus far in achieving the above-mentioned objective.

Theoretical model

Dal Forno et al. [1] describe a model for numerical simulation using coarse-step method. It considers a SMF as a concatenation of unequal length segments with a given mean birefringence and random coupling angles. The Jones matrix T (ω) that describes a concatenation of unequal sections of birefringent fiber can be expressed as [1]

$$T(\omega) = \prod_{n=1}^{N} B_n(\omega) R(\alpha_n) \tag{1}$$

$$B_n(\omega) = \begin{bmatrix} e^{j\left(\sqrt{\frac{3\pi}{8}} b\,\omega\sqrt{h_n}/2+\phi_n\right)} & 0 \\ 0 & e^{-j\left(\sqrt{\frac{3\pi}{8}} b\,\omega\sqrt{h_n}/2+\phi_n\right)} \end{bmatrix} \quad (2)$$

$$R_n(\alpha_n) = \begin{bmatrix} \cos\alpha_n & \sin\alpha_n \\ -\sin\alpha_n & \cos\alpha_n \end{bmatrix} \quad (3)$$

where N is number of segments, $B_n(\omega)$ represents the birefringence matrix of n^{th} segment with h_n length, $R(\alpha_n)$ is the matrix of a rotator that represent the random coupling angle between the segment axes, b is the fiber PMD coefficient (in ps /√km) and ω is the optical frequency.

For a given value of total PMD and fiber length L, the size of the each segment is randomly generated from a Gaussian distribution around the mean length L/N with standard deviation varying from 0-30% of the mean length. N should be chosen in such a way that the mean segment length be between 100 m and 1 km, which is the coupling length of a SMF. The phase ϕ_n in (2) accounts for the small temperature fluctuations along the fiber and it is a stochastic variable with a uniform distribution between 0 and 2π. α_n is the random coupling angle between the segment axes and is a random variable with uniform distribution between 0 and π. The DGD, Δτ, for a single wavelength can be calculated by calculating the Eigen values of the matrix $T_\omega(\omega)*T^{-1}(\omega)$, where $T_\omega(\omega)$ is the frequency derivative of the transmission matrix. T_ω can be approximated as $[T(\omega+\Delta\omega)-T(\omega)]/\Delta\omega$ for a small frequency step, Δω. The DGD is determined using the expression [2],

$$\Delta\tau = \left| \frac{\tan^{-1}\left(\frac{e1}{e2}\right)}{\Delta\omega} \right| \quad (4)$$

where e1 and e2 are the Eigen values described above.

The above model, if used as described in [1], would give insight into the Maxwellian nature of DGD and the non-periodical DGD spectral dependence. However, to match the temporal and spectral characteristics measured on a particular fiber, the free variables in the model (namely b, ϕ_n, and α_n) should be varied in accordance with the temperature and pressure variations over the measurement period. ϕ_n in (2) is included in the model to account for small temperature fluctuations, but we think a better way to model temperature fluctuations is by varying the PMD coefficient 'b' accordingly. This would allow us to observe the effects of temperature on spectral behavior of DGD.

Relative temperature sensitivity of DGD

To measure the variation in the mean DGD (and hence the PMD coefficient, 'b') with temperature we conducted some experiments using EXFO PMD analyzer and a temperature chamber. The setup used for the experiments is shown in Figure 1 below.

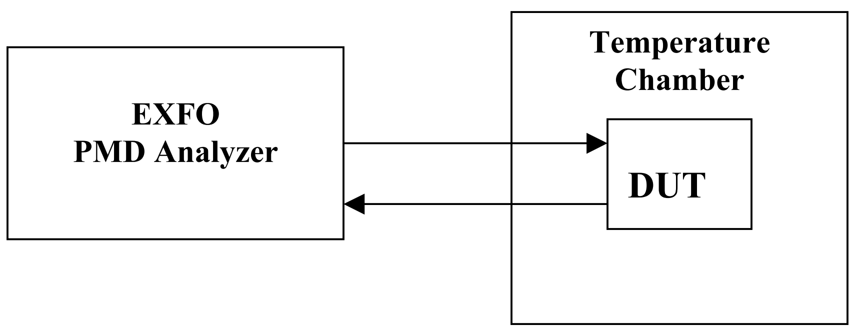

Figure 1: Experimental setup.

Two polarization-maintaining (PM) fibers each of length 10 m connected together by a connector are used as the DUT. Temperature was varied from –30°C to +30°C in steps of 5°C and at each step PMD vs. wavelength was measured using the EXFO PMD analyzer over 1530 – 1600 nm wavelength band with a very small wavelength step size (yielding around 2300 measurements over the band). From the measured PMD data, DGD was averaged over the entire measurement band at each temperature step and is plotted as a function of temperature, as shown in Figure 2.

The overall mean DGD (DGD averaged over the wavelength band and the temperature) was found to 30.65 ps. From Figure 2, we observe a change of 1.08 ps in the wavelength-averaged DGD over 60°C temperature variation. Expressed as a percentage of the overall mean DGD, this corresponds to a change of 3.5% over 60°C. From this we determined the relative temperature sensitivity of DGD to be around 6 x 10^{-4} °C^{-1}. This value is consistent with that reported by others; Fontaine et al. [3] found a value of 7 x 10^{-4} °C^{-1} using a high-birefringence fiber and Ren et al. [4] found a value of 5.7 x 10^{-4} °C^{-1} using a low-birefringence fiber. It is also worth mentioning that the wavelength-averaged mean DGD decreases with an increase in temperature which is also consistent with that reported in [3]. Finally, although we used PM fiber in our experiments to measure the relative temperature sensitivity of DGD, we expect that SMF also have a relative sensitivity of the same order.

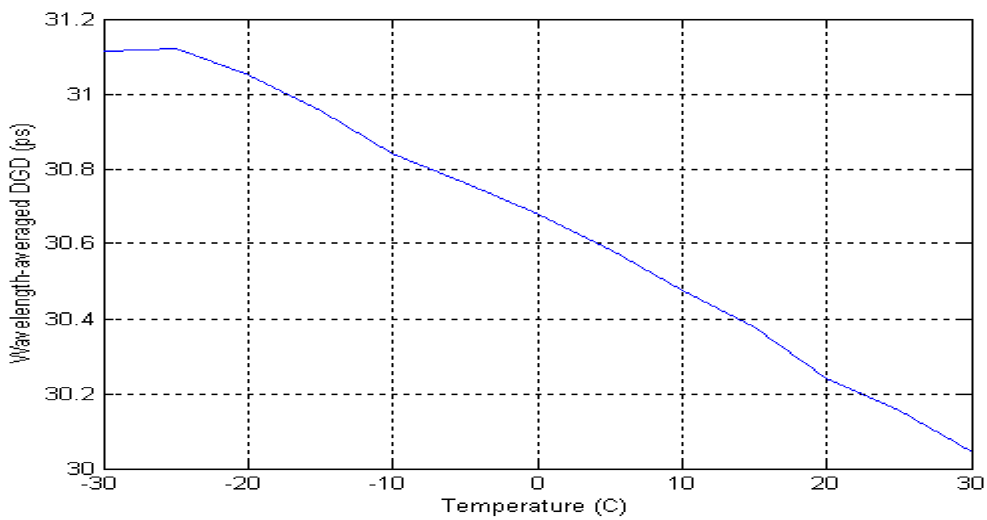

Figure 2: Wavelength-averaged DGD vs. temperature.

Effects of temperature variation on DGD

Having determined the relative temperature sensitivity of DGD, our next step was to incorporate this information in to our model to simulate the effects of temperature variation on DGD. To do this, we obtained actual soil temperature data (at a depth of 40 inches) at a location called Powell Gardens in Missouri (obtained from National Resources Conservation Services website, http://www.wcc.nrcs.usda.gov/scan/). Based on this data we varied the PMD coefficient in our model assuming a value of 6 x 10^{-4} $^{o}C^{-1}$ for the relative temperature sensitivity of the PMD coefficient.

Figure 3 shows the soil temperature at Powell Gardens, MO from Oct. 1, 2003 to Oct. 18, 2003 measured at 1-hour intervals. Figure 4 shows the modeled variation in PMD coefficient corresponding to the variation in the soil temperature. A value of 0.7 ps/√km is assumed as the initial value of the PMD coefficient. Using this profile for the PMD coefficient in the model discussed in the previous section, simulations were run and a colormap showing the DGD variation with wavelength and time (in terms of measurement number) was obtained. Figure 5 shows the DGD vs. wavelength and time colormap obtained using the model with the following parameters: 95 km link length; 100 sections of fiber, the size of the each segment randomly generated from a Gaussian distribution around the mean length of 0.95 km (coupling length); 35 nm wavelength band (1535-1565 nm); single set of α_n and ϕ_n. It is clear from the colormap that DGD drifts either to the left or right along the wavelength axis corresponding to a change in the PMD coefficient induced by the soil temperature variation. This is an important observation as it helps us understand of the effects of soil temperature variations on the DGD.

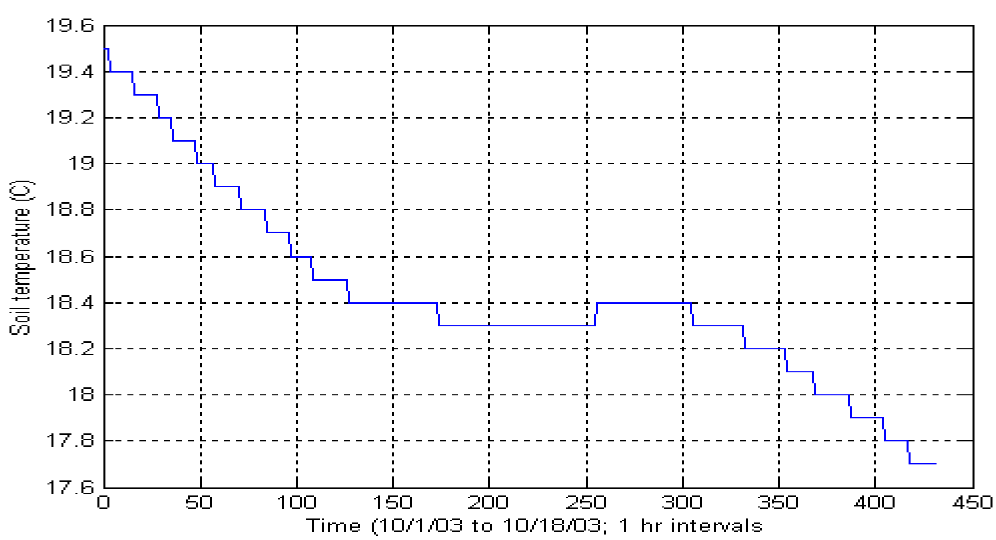

Figure 3: Hourly soil temperature (depth 40") at Powell Gardens, MO from 10/1/03 to 10/18/03.

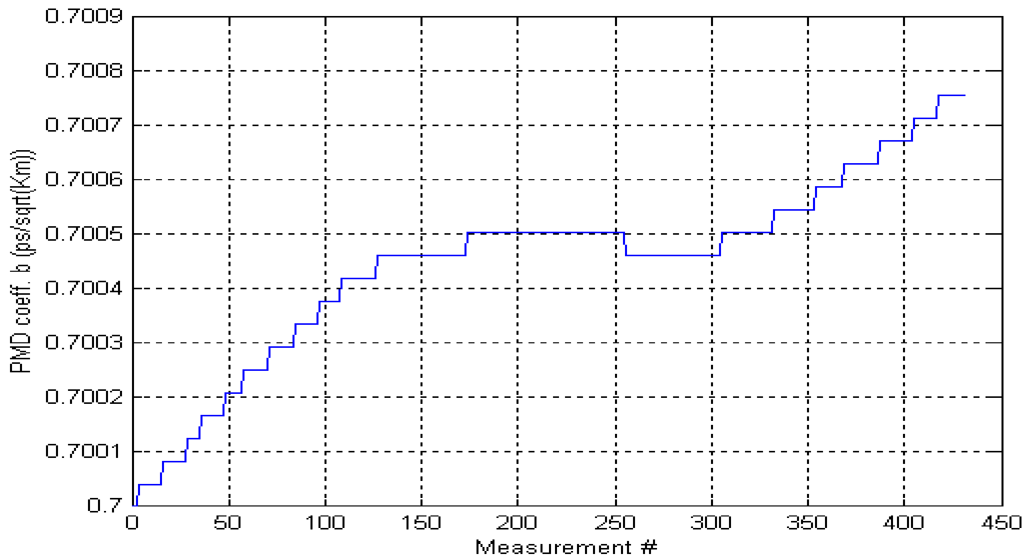

Figure 4: PMD coefficient variation modeled based on the soil temperature variation.

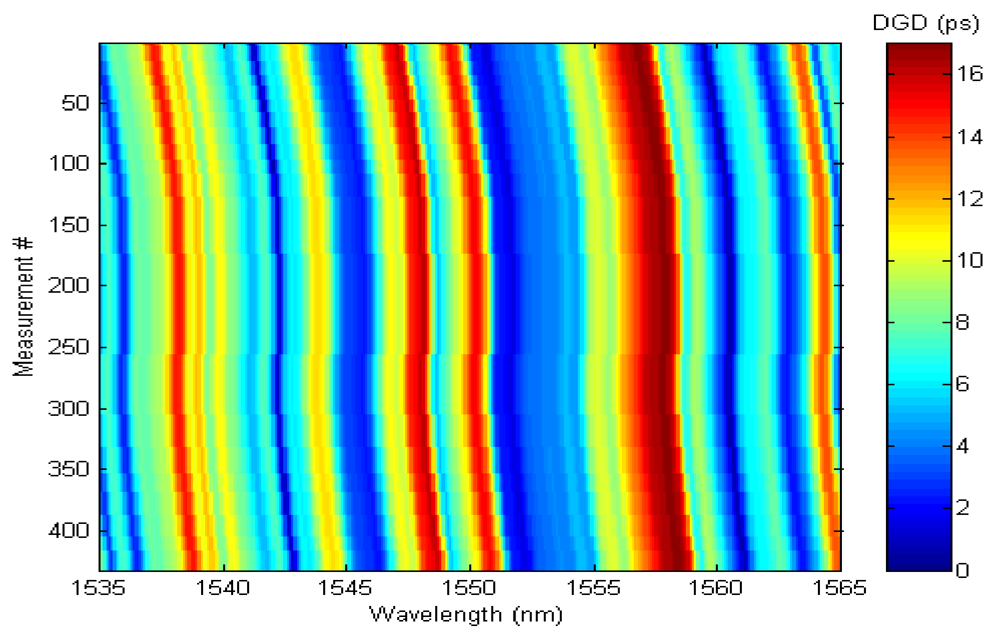

Figure 5: DGD vs. wavelength and time using the modeled PMD coefficient.

After understanding the effects of temperature on DGD, we re-examined the DGD vs. wavelength and time colormap that we obtained by measuring DGD on a 95-km buried fiber link (reported in [5] and [6]) to observe any temperature effects. For this, we needed measured soil temperature data over the measurement period. Unfortunately, this data was not available from NRCS website. However, we believe soil temperature will have the same long-term trends as that of air temperature and so we used air temperature in our analysis. Figure 6 shows the above-mentioned 86-day DGD colormap and the variation of air temperature over the measurement period.

Looking at the plots in Figure 6 closely, particularly between 50 – 60 day period (Figure 7), we observe a dip in the temperature over that period and a drift in the DGD towards right on the wavelength axis. This is in good agreement with that predicted by the simulations discussed earlier in this section. This also supports our assumption that SMF has relative temperature sensitivity similar to that of a PM fiber.

However, temperature alone does not explain the occurrences of localized high DGD events and other features that we observe in the measured colormap of Figure 6. Our finding is one part (a significant one) of a puzzle and currently we are working on resolving the rest of it. We will be reporting on our new findings in the future.

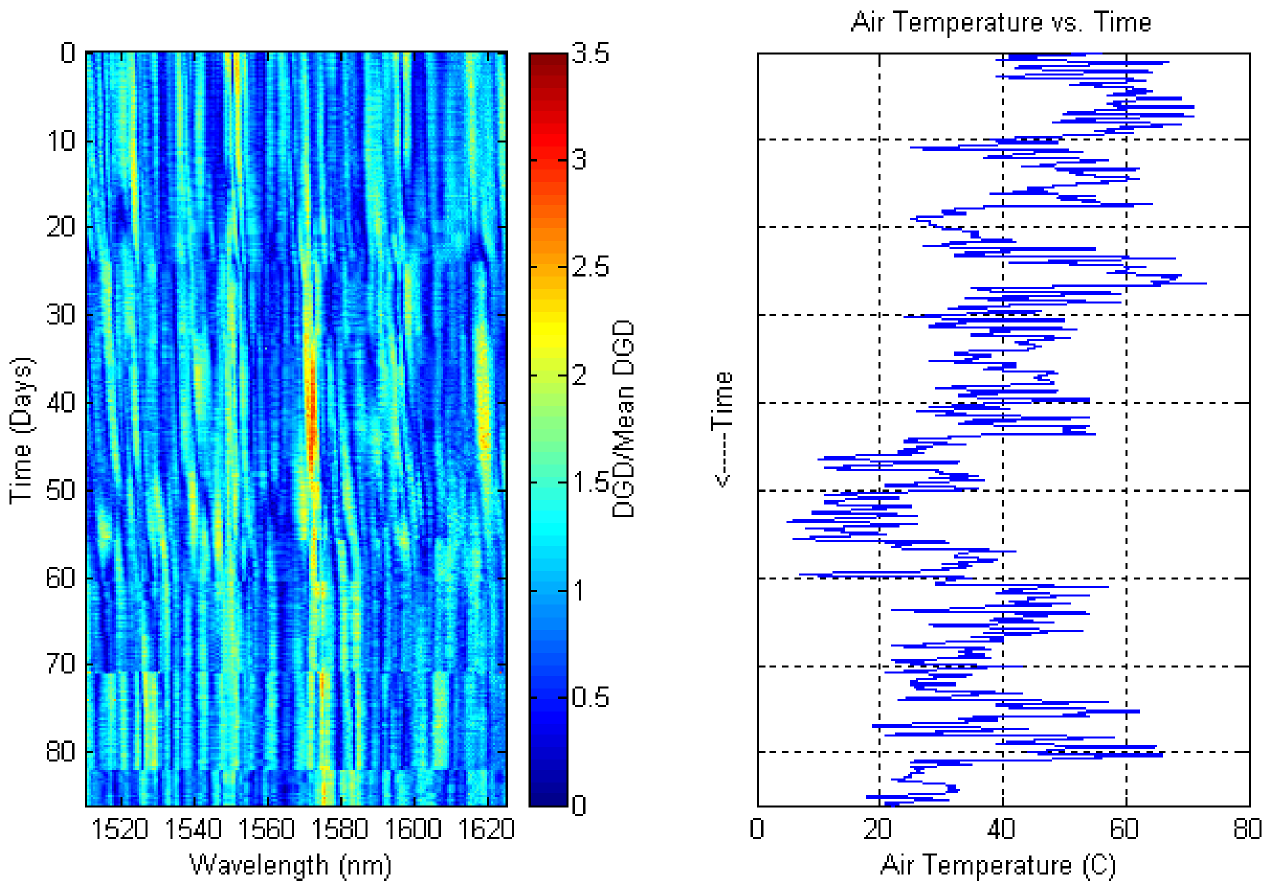

Figure 6: DGD colormap measured over a 95-km buried fiber link [5, 6] and hourly air temperature vs. time over the same 86-day measurement period.

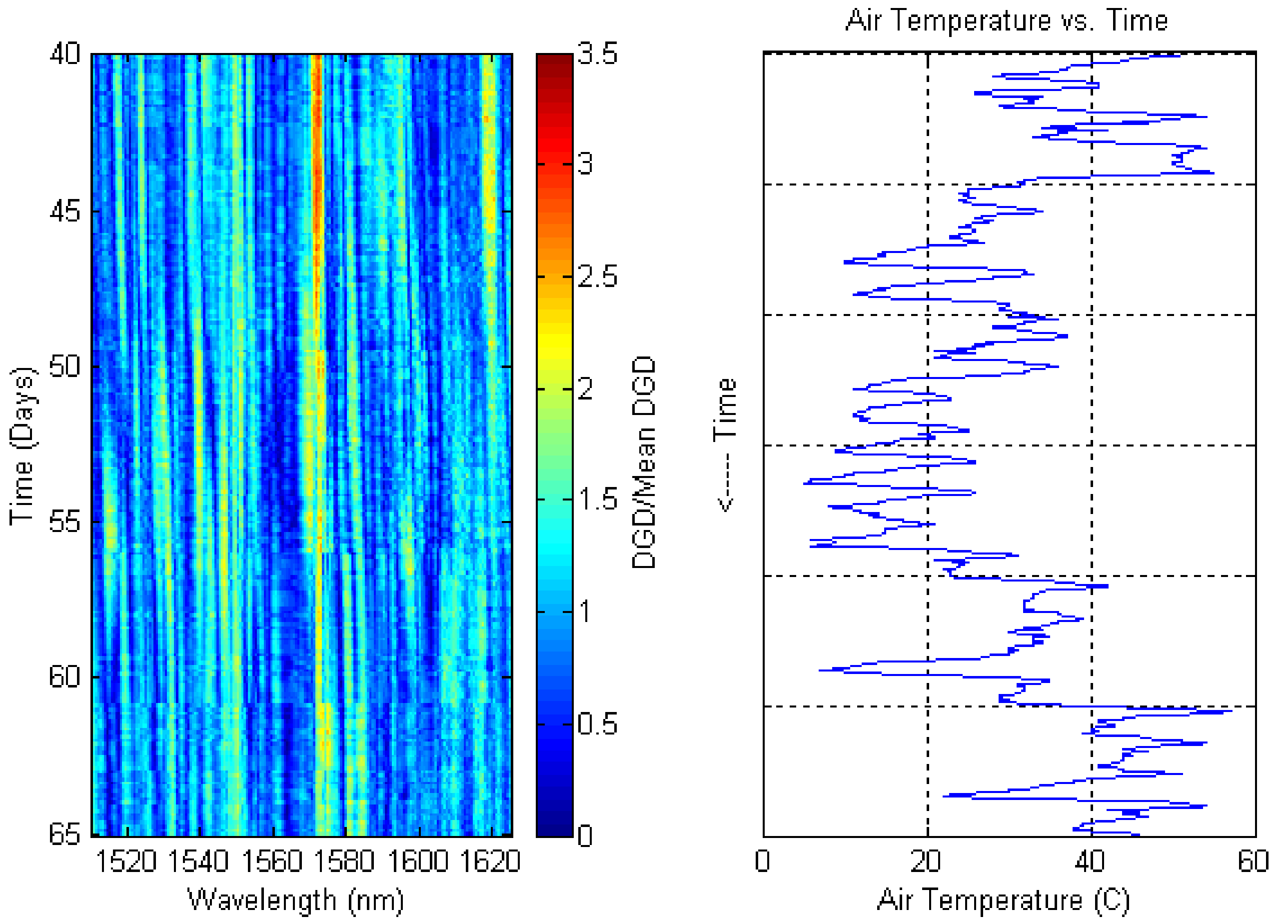

Figure 7: Figure 6 zoomed to show the period including days 40 to 65.

Conclusions

In this document we reported three different findings. First, the mean DGD will decrease with the increase in temperature. Second, SMF has relative sensitivity on the same order as that of a PM fiber and finally, the most important one, the effect of temperature on DGD. Varying temperature will cause a drift in DGD along the wavelength axis, the extent of which depends on the exact value of the relative temperature sensitivity of the fiber under test. We are currently working on improving our model further, which would enable us to explain the other features observed on the measured colormap shown in Figure 6.

References

1. Dal Forno, A. O, et al., "Experimental and theoretical modeling of polarization-mode dispersion in single-mode fibers", *Photonics Technology Letters*, 12(3), pp. 296-298, March 2000.
2. P. Hernday, "Dispersion measurements", *Fiber optic test and measurement*, Eds. D. Derickson, New Jersey: Prentice Hall PTR, pp. 502-504, 1998.
3. Marie Fontaine et al., "Theoretical and experimental analysis of thermal stress effects on modal polarization properties of highly birefringent optical fibers", *Journal of Lightwave Technology*, 14(4), pp. 585-591, April 1996.
4. Z. B. Ren et al., "Temperature dependence of bend- and twist-induced birefringence in a low-birefringence fiber", *Optics Letters*, 13(1), pp. 62-64, January 1988.
5. C. Allen, 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, January 2003.
6. C. Allen, 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, NIST conference*, Boulder, CO, pp. 195-198, Sept. 2002.

Laplacian pdf of DGD time derivative and application to predicting PMD-induced outage rates

P.K. Kondamuri, C. Allen and D.L. Richards

It is reported for the first time that the time derivative of differential-group delay (DGD) on buried fibres has a Laplacian pdf. Using this, the previously reported expression for predicting the polarisation-mode dispersion (PMD)-induced outage rate is simplified and it is shown that it is a function of the mean DGD and the fibre's Laplacian parameter only.

Introduction: Polarisation-mode dispersion (PMD) is a major impediment for network operators seeking to increase the per channel data rate to beyond 10 Gbit/s on long-haul fibre-optic links. To ensure the reliability of their fibre-optic network at higher bit rates, network engineers must be able to predict PMD-induced outage rates.

A PMD-induced outage is one which the instantaneous differential-group delay (DGD or $\Delta\tau$) exceeds a given threshold value, $\Delta\tau_{th}$, while the outage probability P_{out}, expressed in minutes/year, can be calculated using

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

where $f_\tau(\cdot)$ is the Maxwellian probability distribution function (pdf) of DGD, P_{out} represents only the annualised outage probability and reveals nothing regarding outage rate or duration. Accurate estimation of the impact of PMD on network availability requires statistical analysis of DGD temporal variability. Caponi *et al.* [1] showed how the mean time between PMD-related outages for a given link could be estimated from its DGD temporal variations and the Maxwellian probability density function. They showed that 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 [1]

$$R_{out} = \frac{1}{2} f_\tau(\Delta\tau_{th}) \int_{-\infty}^{\infty} f_{\tau'}(\Delta\tau')|\Delta\tau'|d\Delta\tau' \qquad (2)$$

where $\Delta\tau'$ is the time derivative of DGD, and $f_{\tau'}(\cdot)$ is the pdf of $\Delta\tau'$. While P_{out} is the same for all random variables with a Maxwellian pdf, it has been reported that R_{out} is not the same since differences in cable and installation affect the DGD temporal characteristics [1, 2]. In this Letter, we first show that $\Delta\tau'$ has a Laplacian pdf by curve-fitting the histogram obtained from measured data. We then simplify the R_{out} expression by analytically reducing the integral in (2) using the Laplacian pdf of $\Delta\tau'$. Finally, remarkably good agreement is shown between the values of the PMD-induced outage rate obtained using the original and simplified expressions.

pdf of time derivative of DGD: Measurements were made of the instantaneous DGD on a 190 km direct buried, standard singlemode fibre-optic cable made available by Sprint. A polarisation analyser employing the Jones-Matrix-Eigenanalysis (JME) method provided instantaneous DGD data for wavelengths from 1535 to 1565 nm with a spectral resolution of 0.1 nm. These measurements were repeated approximately every 23 minutes and for about 18 days providing 339 000 measured DGD values. $\Delta\tau'$ data were obtained by numerically differentiating the measured DGD data.

A histogram of the $\Delta\tau'$ data is shown in Fig. 1. Through curve-fitting we found that this histogram closely resembles a Laplacian pdf (a two-sided, first-order exponential) of the form

$$f_{\tau'}(\Delta\tau') = \frac{\alpha}{2} e^{-\alpha|\Delta\tau'|} \qquad (3)$$

where $\alpha = \sqrt{2}/\sigma$ and is the Laplacian parameter with units of hours/picosecond and σ is the standard deviation of $\Delta\tau'$. This is the first time that the Laplacian nature of $\Delta\tau'$ is being reported. For comparison, a curve representing a Laplacian pdf with $\alpha = 0.6$ h/ps (obtained using the variance of $\Delta\tau'$ data) is also shown in Fig. 1.

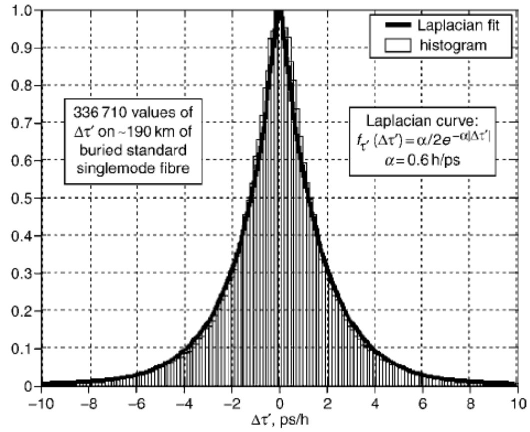

Fig. 1 *Histogram of $\Delta\tau'$ data and its Laplacian fit*

Similar agreement was seen between similar Laplacian fits and $\Delta\tau'$ histograms measured on other 95 and 190 km fibre spans. However, we have observed that α value decreases as the fibre length increases.

Closed-form expression for R_{out}: Using the Laplacian distribution as the $\Delta\tau'$ pdf, a closed form solution for the integral in (2), and hence R_{out}, can be obtained. Substituting (3) for the pdf of $\Delta\tau'$, the integral in (2) evaluates to $1/\alpha$. Then the expression for R_{out} in (2) reduces to

$$R_{out} = \frac{1}{2\alpha} f_\tau(\Delta\tau_{th}) \qquad (4)$$

The significance of (4) is that the mean outage rate due to PMD on any fibre route can be readily estimated given its mean DGD and Laplacian parameter α, greatly simplifying the route's PMD-induced outage analysis.

Whereas the fibre's mean DGD may be known from its PMD coefficient (ps/$\sqrt{}$km), the Laplacian parameter α must be estimated from a time series of DGD measurements made on each fibre. We have observed that estimation of α is observation time-independent. While the uncertainty in the α estimate decreased as the observation time increased, the estimated value for α was consistently close to 0.6 h/ps regardless of whether the observation time was one day or 18 days.

A comparison of R_{out} values for different normalised thresholds (threshold/mean DGD) obtained using numerically determined $\Delta\tau'$ pdf in (2) and the analytical expression of (4) is shown in Fig. 2. Excellent agreement between the values of the two cases is evident.

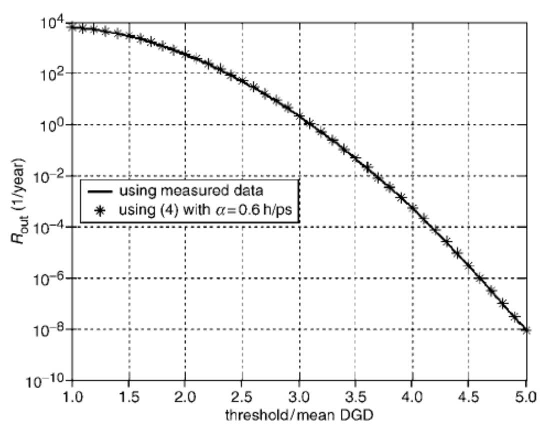

Fig. 2 *R_{out} values for different normalised thresholds using (a) numerically determined $\Delta\tau'$ pdf in (2) and (b) using (4)*

Conclusions: In this Letter, we have; (i) shown for the first time that the time derivative of DGD has a Laplacian pdf, the characteristics of which are determined exclusively by the Laplacian parameter α that has units of h/ps; (ii) simplified the expression for the mean PMD-induced outage rate reported earlier by Caponi *et al.* [1] using the above-mentioned finding, resulting in an expression for mean outage rate that depends only on the fibre's mean DGD and its Laplacian parameter α that represents its temporal characteristics; (iii) shown excellent agreement between the outage rates obtained using the original expression and the simplified closed-form expression; (iv) noted that α values decrease as the fibre length increases; (v) reported that estimation of the Laplacian parameter α from measurements is largely observation time-independent. These findings simplify the PMD-induced system outage analysis and will help network operators predict system downtime.

Acknowledgments: This work was funded by Sprint Corporation Company, L. P. and NSF grant ECS-0116213.

19 February 2004
Electronics Letters online no: 20040336
doi: 10.1049/el:20040336

P.K. Kondamuri and C. Allen (*Lightwave Communication Systems Laboratory, Information and Telecommunications Technology Center, The University of Kansas, Lawrence, Kansas 66045, USA*)

E-mail: pradeep@ittc.ku.edu

D.L. Richards (*Sprint Corporation, Overland Park, Kansas, USA*)

References

1 Caponi, R., Riposati, B., Rossaro, A., and Schiano, M.: 'WDM system impairments due to highly correlated PMD spectra of buried optical cables', *Electron. Lett.*, 2002, **38**, (14), pp. 737–738
2 Allen, C., Kondamuri, P.K., Richards, D.L., and Hague, D.C.: 'Analysis and comparison of measured DGD data on buried single-mode fibers'. Symp. on Optical Fiber Measurements, NIST Conf., Boulder, CO, USA, September 2002, pp. 195–198