Invited paper

Polarization effects in aerial fibers

David S. Waddy *, Liang Chen, Xiaoyi Bao

Department of Physics, University of Ottawa, 150 Louis Pasteur, Ottawa, ON K1N 6N5, Canada

Received 9 October 2003
Available online 27 October 2004

Abstract
Different aerial fiber polarization effects are investigated and discussed. The state of polarization time drift is explored in different fibers. Polarization mode dispersion and polarization dependent loss time variations are reported. Fiber galloping and aerial fiber system impact issues are discussed. © 2004 Elsevier Inc. All rights reserved.

Keywords: Aerial fiber; Polarization; Polarization mode dispersion

1. Introduction
Polarization effects in optical fiber cause errors to occur in communication systems [1,2]. Polarization mitigation techniques exist [3], but are targeted at buried, ducted, and submarine fiber. Aerial fiber has special properties caused by its environmental exposure that make it more difficult to mitigate than other types of fiber. In this paper we investigate the three major polarization effects: state of polarization (SOP) change, polarization mode dispersion (PMD), and polarization dependent loss (PDL) in aerial fibers.

SOP change is caused either by change of Berry phase [4] or PMD and PDL. Berry phase changes when a fiber is moved spatially. PMD is caused by stress (birefringence) on a fiber’s core/cladding breaking the cylindrical symmetry. The PMD describes the polarization dependence of the time delay of an optical pulse as it propagates along the fiber. The propagational time difference between the fastest and slowest polarization is called the...
differential group delay (DGD). High amounts of DGD can cause pulses to overlap in an optical communications system. PDL describes the polarization dependence of the optical attenuation for different states of polarization and can occur concurrently with PMD in fibers [5].

A Stokes vector describes SOP of a lightwave. This three-dimensional vector can be arbitrarily positioned on a Poincaré sphere when measured at the output of a fiber. The principal state of polarization (PSP) vector describes the optimal polarization state that outputs a pulse with no distortion, to first order, caused by PMD [6]. The PSP vector can be chosen to be either the fast or slow polarization through the fiber. These are orthogonal in the presence of zero PDL. Changes in PMD are intrinsically linked to changes in output SOP when the input SOP is fixed. Mechanical stress physically changes the fiber and thus PMD, PDL, and SOPs change. Berry Phase is a global topological effect and is not dependent on the detailed physical make-up of the fiber [4].

Buried fiber is installed underground and thus is located in a very static environment. Note: the term buried fiber includes both ducted underground buried fiber and directly buried fiber. Stress on a buried fiber is mostly fixed at install time, assuming there is no active external perturbations (e.g., vibrations due to trains or humans), the output SOP is affected only by PMD variation.

Aerial fiber is installed above ground, usually on telephone or hydro poles and thus is located in a dynamic environment. Wind can cause the fiber-to-move (gallop) [7]. The birefringence of the fiber can change due to temperature change and wind. SOP, PMD, and PDL can all change on short time scales because the aerial fiber is in a dynamic state.

Aerial fibers have been measured by many groups in the past; Many of the published field measurements have been concerned with cable installation, stresses, and fiber lifetimes. Aerial fiber polarization effect studies have been performed by a few groups. These are of interest because they give an idea of possible system outage causes specific to aerial fibers. PMD in aerial fiber at high altitudes [8] has been measured and found to track diurnal temperature changes [9]. Correlations between simulated wind motion and modal noise have been observed in aerial multi-mode fiber cables [10]. PMD has been found to track temperature in aerial fiber when measured with a PMD interferometric test-set [11]. Aerial fiber in high-voltage transmission systems have been measured and shown to be correlated to current fluctuations and wind [12]. We have also found wind correlation in aerial fiber [13]. The stochastic random walk of aerial fiber SOP has been studied [14].

Fiber cable can be separated into two general types: tight buffered and loose tube [15]. Loose tube cable dominates aerial installations. Loose tube has the advantage of the fiber not experiencing strain immediately when the fiber is physically moved because the fiber floats in a silicon gel. There are four types of aerial cable in common use today: lashed, all dielectric self supporting (ADSS), optical ground wire (OPGW), and wrapped [15]. These four types of cable have different tolerances for strain. Detailed studies comparing polarization effects for different types of aerial fiber need to be conducted.

Optical polarization mitigation relies on changing optical components based on how the fiber changes. This means optical components must respond on a time-scale commensurate with that of the speed of the fiber changes. It is thus very important to know how fast aerial fibers fluctuate and any biases and correlations that are different from buried fiber.
We report on five experiments performed on five aerial fibers that show how polarization effects behave differently than for buried fiber. The major results of the experiments are that aerial fibers polarization changes quickly (as compared to buried) and aerial fiber exhibits a statistical polarization bias. Diurnal changes usually dominate the statistical bias. Using this information, conclusions are drawn on how to properly calculate outage probabilities for an aerial fiber and how these results differ from buried (and other types) of fiber. System impact and mitigation issues of aerial fiber polarization effects are also discussed.

2. Theory

Some mathematical constructs are needed to describe the SOP, PMD, and PDL used throughout this paper. Before we describe the mathematics it is important to give a physical description of what they are. As described in the Introduction, the SOP is a Stokes vector describing the polarization state of light of a given wavelength. This quantity can be easily measured with a polarimeter.

If a fiber is not perfectly cylindrically symmetric it has some quantity of PMD. In practice the birefringence randomly varies in all fibers whether through manufacture, cabling, or external stress. Thus all fibers have some PMD, albeit very small in some cases. When an EM wave travels through a fiber its two orthogonal polarization components, commonly defined as \( E_x \) and \( E_y \), will separate in time. The time difference between \( E_x \) and \( E_y \) at a single frequency is known as the DGD. This quantity is usually measured by launching three known polarizations, at two neighboring wavelengths, into a fiber and measuring the output Stokes vectors. Through some mathematical transforms (see [16] for details) the PMD vector can be calculated.

The PDL on a linear scale is defined as the ratio between the maximum and minimum attenuation coefficient over all polarization states. While this quantity can be measured by using polarization scrambling and recording the maximum and minimum attenuation it is usually measured using the Jones matrix [17] or Müller matrix [18] method. PDL varies across wavelength in optical fibers.

Special mention of the interaction of PMD and PDL must be made as this can be a confusing topic. Some implementations of the Jones Matrix method when measuring DGD ignore PDL by normalizing the matrices [19]. Throughout this paper when DGD statistics are presented they include the effects of PDL.

We begin by introducing the mathematical definitions of the quantities used in this paper. First, we define DGD as \( \Delta \tau \) and PDL as \( \eta \). The frequency dependent complex PMD vector can be described as \( \mathbf{W}(\omega) = \mathbf{Q}(\omega) + i \mathbf{A}(\omega) \) [5]. The imaginary term, \( i \mathbf{A}(\omega) \), occurs when PDL is present. In the absence of PDL \( \mathbf{A} \) is zero and \( \mathbf{W} \) is real and its direction corresponds to the fast PSP. When PDL is present \( \mathbf{W} \) is complex and the fast PSP and slow PSP are not orthogonal [5]. In practice, the PMD vector is always complex because PMD and PDL are always present (even if one is very small). The DGD is equal to the real part of the complex PMD vector magnitude \( \text{Re}(\mathbf{W} \cdot \mathbf{W}) \). The mean of DGD over infinite frequency or time is well known and defined as the PMD (a scalar). The differential attenuation slope (DAS) is defined as \( \Delta \alpha = \text{Im}(\sqrt{\mathbf{W} \cdot \mathbf{W}}) \). DAS arises from different attenuation on the non-orthogonal fast and slow PSP’s. DAS also has time as its unit.
“Pristine” is a terminology that describes a convenient theoretical construct used to describe quantities without the nonlinear interaction effect between PMD and PDL. These quantities are in the mathematical sense, which are not exactly what one measures experimentally. The mean square pristine DGD \( \langle \Delta \tau^2 \rangle \) is that of an equivalent system where all PDL elements are set to zero while PMD remains the same. Similarly, the mean square pristine PDL \( \langle \eta^2 \rangle \) is that of an equivalent system where all the PMD elements are set to zero while PDL remains the same. However, in a real system both PMD and PDL non-linearly interacts thus the experimentally measured mean square DGD \( \langle \Delta \tau^2_{\text{experiment}} \rangle \) is not the same as the pristine mean square DGD \( \langle \Delta \tau^2 \rangle \). Similarly the experimental mean square PDL \( \langle \eta^2_{\text{experiment}} \rangle \) could be different from the pristine mean square PDL \( \langle \eta^2 \rangle \). It is important to note the mean square pristine DGD and mean square pristine PDL can be found by the following coupled equations that are valid in the highly mode-coupled limit [20]:

\[
\langle \Omega^2 \rangle - \langle \Lambda^2 \rangle = \langle \Delta \tau^2 \rangle,
\]

(1)

where \( \langle \ldots \rangle \) indicates averaging over frequency \( \omega \).

\[
\langle \Omega^2 \rangle + \langle A^2 \rangle = \frac{3}{4} \frac{\langle \Delta \tau^2 \rangle}{\langle \eta^2 \rangle} \left[ \exp \left( \frac{4}{3} \frac{\langle \eta^2 \rangle}{\langle \eta^2 \rangle} \right) - 1 \right].
\]

(2)

Solving the above equations one can find:

\[
0 = \left[ \exp \left( \frac{4}{3} \frac{\langle \eta^2 \rangle}{\langle \eta^2 \rangle} \right) - 1 \right] - \left[ \frac{4}{3} \frac{\langle \eta^2 \rangle}{\langle \eta^2 \rangle} \frac{\langle \Omega^2 \rangle + \langle A^2 \rangle}{\langle \Omega^2 \rangle - \langle A^2 \rangle} \right].
\]

(3)

Now, by solving for the root of \( \langle \eta^2 \rangle \) we then convert it using a Maxwellian distribution:

\( \langle \eta^2 \rangle = \left( \frac{2}{3\pi} \right) \langle \eta \rangle^2 \),

which is valid for even relatively high PDL [21]. To find the mean pristine PDL in units of dB,

\[
PDL_{\text{pristine}} = 20 \sqrt{\frac{8}{3\pi}} \langle \eta^2 \rangle \log_{10}(e).
\]

(4)

The difference between the mean pristine PDL calculated in Eq. (4) and mean PDL measured with a test-set is minimal, but there is a noticeable difference. The difference is due to the interaction of PMD/PDL and is not fully described in the analytical formula.

The second-order real part of the PMD vector can be described as \( \frac{d^2 W}{d\omega^2} = \hat{\Omega} \frac{d^2 \hat{W}}{d\omega^2} + \Omega \frac{d^2 \hat{W}}{d\omega^2} \). When second-order PMD is mentioned in Ref. [2], it usually is in the case of zero PDL, thus the PMD vector \( \vec{W} \) is real and the second-order PMD or dispersion vector velocity (DVV) can be defined as \( \text{DVV} = |\frac{d^2 \vec{W}}{d\omega^2}| \). If PDL is present then the second-order PMD, or DVV is similarly defined as \( \text{DVV} = \text{Re}(\sqrt{\frac{d^2 W}{d\omega^2} \frac{d^2 W}{d\omega^2}}) \). We are using the later definition in this paper.

The autocorrelation function (ACF) is a very useful tool in quantifying PMD. An ACF can describe how correlated the PMD is to neighboring channels in the frequency domain and how correlated PMD is at a single channel in the time domain. This information is
especially useful for the mitigation of PMD. ACF’s over frequency and time for the PMD vectors magnitude and direction have been derived [19,20,22]. In aerial fibers the interesting quantity is the time drift ACF. Aerial fibers decorrelate much faster than buried fibers [9]. The directional time drift ACF [19] is described empirically as

\[
E[\vec{S}(t) \cdot \vec{S}(t + \Delta t)] = \exp\left(\frac{-|\Delta t|}{\tau_d}\right),
\]

(5)

where \(\vec{S}(t)\) is the output unitary Stokes vector as a function of time \(t\) and \(\tau_d\) is a fitting parameter. The experimental directional time drift ACF can also be found by [9]

\[
R(\Delta t) = \frac{1}{N} \sum_{t=0}^{N-1} \vec{S}(t) \cdot \vec{S}(t + \Delta t),
\]

(6)

where \(N\) is the total number of points.

We now introduce the inverse 50% point so that one can have a simple single value metric to describe how fast an ACF decorrelates. This can be defined as [9]

\[
1 - \frac{t_{1/2}}{t_{\max} - t_{\min}},
\]

(7)

where \(t_{1/2}\) is defined when the ACF drops below 0.5 and \(t_{\max} - t_{\min}\) is the length of time over which the ACF is performed.

For a given wavelength the arc-length change between two SOPs at two time instants \(t\) and \(t + \tilde{t}\) can also be calculated by using [14]:

\[
\gamma(t, \tilde{t}) = \arccos(\vec{S}(t) \cdot \vec{S}(t + \tilde{t})),
\]

(8)

where \(\vec{S}(t)\) is the measured Stokes vector at time \(t\).

### 3. Parallel state of polarization drift time autocorrelation

In this first experiment we measure the SOP drift time ACF of two fibers simultaneously. This allows one to see if they decorrelate at the same rate when undergoing the same environmental effects.

The experimental setup can be seen in Fig. 1. It consisted of a tunable laser at 0 dB m with a 3 dB coupler. Each output was launched into a fiber under test (fibers A and B). The outputs of the two fibers were connected to two identical polarimeters [23]. The polarimeters recorded the Stokes parameters at 10 ms intervals. This high-speed was used to catch any quick changes in the SOP.

Using the collected Stokes parameters and Eq. (6) we calculated the ACF’s for each fiber independently. Figure 2a shows the ACF for two fibers in the same 52.45 km fiber. The fiber is made up of 46 km of buried cable and 6.5 km of aerial (in the center of the span). The PMD was measured separately with an interferometric test-set and found to be 0.72 ps for fiber A and 0.61 ps for fiber B. Fiber A shows almost perfect environmental bias. Starting from a high correlation at noon, the fiber quickly decorrelates during the evening, but then is almost back to the same correlation the next day at noon. This phenomenon has
Fig. 1. Diagram of parallel state of polarization drift time autocorrelation experiment. PA1 and PA2 are polarimeters. FUT is the buried/aerial fiber under test and CO1 and CO2 are central offices.

Fig. 2. (a) Shows the time drift ACF of the state of polarization vector for two combined aerial/buried fibers (fiber A and fiber B). (b) Shows the arc-length ($\Delta t = 10$ ms) histograms of the same two fibers.

been seen before in a buried fiber exposed to the environment [24]. Fiber B exhibits a small environmental bias, but generally decorrelates quite slowly.

In the case of fiber A we propose that environmental stress changing over a 24 h period is causing the oscillating decorrelation, which is seen to be the same as in fiber B. However, fiber A seems to experience bigger changes in the SOP wandering than in that of fiber B. Fibers A and B have almost the same amount of PMD. If the PMD values were significantly different this could account for the different decorrelation times. Since we are measuring
the SOP and not the PSP vector, it is unknown how correlated the particular input SOP is to the PSP. It is plausible that the input SOP is closer to the PSP for fiber B than fiber A. This would cause fiber A to have a greater fluctuation.

Figure 2b displays an arc-length histogram calculated using Eq. (8) for fiber A and fiber B at a time interval $\Delta t$ of 10 ms. In this data analysis fiber A is more correlated in short time than fiber B, this might seem to contradict Fig. 2a, but as Figs. 3a and 3b will show the difference is very small and within experimental error.

Figure 3a shows the raw collected Stokes parameters from fiber A. One can observe how points 24 h apart are related. This is what causes the ACF to return to the starting point. Figure 3b shows almost horizontal lines for fiber B. This means that it stays very correlated and this is reflected in the ACF shown in Fig. 2a.

Measurement of two fibers at the same time has been performed before [19]. Different correlation times were found and attributed to the fact that one of the fibers did not enter as many central offices. Our fibers take the exact same path and thus we do not believe this to be the case. We believe the difference in correlation time is due to the difference in launching SOP relative to PSP vector. If the fibers had a larger difference in PMD then this could also be a factor. If the PSP vector could have been measured quickly then the results of this experiment would be conclusive. This is was not possible at the time.

4. State of polarization drift time correlation

This experiment investigates how the SOP drift time correlation relates to such quantities as wind, temperature, and solar intensity. Similar to the previous experiment we launch...
Fig. 4. (a) Shows arc-length change at $\Delta t$ 10 ms time interval for fiber C, (b) shows inverse 50% autocorrelation with each point corresponding to 600 s, (c) shows wind intensity, temperature, and sun altitude.

A laser at 0 dBm power into a fiber under test. The output is connected to a polarimeter and we measure the Stokes parameters at 10 ms intervals.

Fiber C is a 34 km aerial fiber with mean PMD of 7.49 ps. The PMD was measured separately with an interferometric test set. The PDL was not measured. Figure 4a shows the arc-length (Eq. (8)) change at a time interval of 10 ms over the 5 days of the experiment. Figure 4b displays the inverse ACF 50% point (Eq. (7)). Each point is an inverse ACF 50% point for 10 min of output Stokes data (60,000) points. The fastest decorrelation is indicated by a value of one and the slowest by a value of zero. Figure 4c displays wind, temperature, and sun altitude. It can be observed that a correlation exists between sun altitude and the ACF changes. Correlations also seem to exist with wind and temperature, but these are not as conclusive. It must be noted that the weather data is only collected hourly and is $\sim$30 km from the test-site. Fiber C runs in a north-south direction, so wind direction would also have an effect and not just the intensity that we show.

There is no observable correlation between Figs. 4a and 4b. This is because fast arc-length changes are caused by the wind. These SOP changes tend to fluctuate back and forth around the same spot and thus average out in any ACF calculations because they are fluctuating at a specific frequency (see Section 7). This fluctuation by the wind is a manifestation of Berry phase [4]. The change in the fiber output SOP direction autocorrelation is due mostly to stress induced by the wind and temperature changes. One must also note that Fig. 4a is 10 ms time changes and Fig. 4b is 10 min decorrelation.

Figure 5 shows a histogram of the Fig. 4a arc-length change data-points. This plot is very useful in determining how fast an SOP compensator component of an optical PMD
Fig. 5. Histogram of arc-length for fiber C and close-up of tail of same histogram (inset).

mitigation scheme would have to be. Since the data was collected at 10 ms intervals and the histogram has events that occur from 0 to $\pi$ a compensator would have to respond faster than 10 ms. Responding means being able to take the input SOP and convert it to any desired output state at less than 10 ms.

The arc-length results differ significantly between fibers A, B, and C. Fibers A and B have low PMD ($\leq 1$ ps), whereas fiber C has a high PMD (7.5 ps). The larger arc-length fluctuations in fiber C are due to its longer aerial length as compared to fibers A and B. Fibers A and B only have 6.5 km versus 34 km for fiber C. More specifically, the large arc-length fluctuations at 10 ms sample rate can only be caused by fast physical movement of the fiber. Wind would be the primary cause of the movement and how wind affects an aerial cable would depend on the cables construction, environment, and installation. In the case of fiber C, it travels through open rural fields. Fibers A and B travel through a metropolitan area. More specific information on exact cable type was not available, so more detailed analysis was not possible. A more detailed study is required.

5. State of polarization drift time bias

Using the Stokes data collected from fiber C in Section 4 we perform a directional ACF on the whole data set. Figure 6a shows the ACF decorrelates very quickly. Contrary to fibers A and B, this fiber shows no 24-h pattern of correlation. One would likely assume that this fiber is unbiased. Figure 6b is a histogram of the collected output Stokes parameters from fiber C in spherical coordinates [25]. The histogram was corrected for displaying a sphere on a flat surface by dividing by the sine of the longitudinal angle. Two points of
greater intensity in the center and a point of lesser intensity in the upper right corner, show that the histogram is not evenly distributed.

The ACF does not indicate a periodic bias, but that does not mean a bias does not exist. It is conceivable that any fiber exposed to the environment is biased. One might argue that the measurement was not taken for a long enough period to get a good picture of the statistics, but with such fast SOP changes we do not believe this to be the case.

6. Polarization mode dispersion in environmentally biased fiber

A PMD test-set was used to measure PMD on fiber D, a 52.42 km combined aerial/buried fiber (same cable as before). The measurement consisted of launching three different polarization states and wavelength scanning from 1530 to 1590 nm at 1968 discrete wavelengths. The equation of motion method [16] was used to find the PMD vector. Figure 7a shows the ACF of the normalized real part of the PMD vector (directional correlation). This is defined as the ACF of

\[
\begin{bmatrix}
\frac{\tilde{\Omega}(t)}{|\Omega(t)|} & \frac{\tilde{\Omega}(t + \Delta t)}{|\Omega(t + \Delta t)|}
\end{bmatrix}
\]

We observe that the fiber decorrelates, but then almost everyday oscillates and becomes slightly more correlated. It is quite apparent that this fiber has an environmental bias.
Figure 7b shows the mean DGD (PMD) of the fiber. Current statistical theory dictates that if one were to measure over infinite wavelength the mean PMD of a fiber would be constant no matter what decorrelation it had gone through. In our measurement we only measured 60 nm, which leads to some uncertainty in the measurement [26]. The fluctuations are too great to be experimental error and it is quite apparent that they fluctuate with the time of day. What this means is the inherent birefringence of the fiber changes throughout the day because of environmental bias such that one can think of the fiber as actually being a “new fiber” at every instance in time, but somehow still related (correlated) to the “previous fiber.”

Figure 7c is a plot of the DVV, if there were zero PDL in the fiber one could consider this as what is commonly known as second-order PMD. It must be noted that work up to this point [27] has concentrated on second-order PMD and not DVV. We observe that the DVV also fluctuates with time.

Figure 7d is a plot of mean pristine PDL as a function of time. The PDL of the fiber is observed to change in a periodic manner and thus is also biased. This fiber is observed to have a significant amount of PDL. It must be noted that the pristine PDL calculation assumes the fiber is static over the measurement time. This assumption could be false for the middle of the day when the fiber is dynamic. This would overstate the PDL magnitude at those times in Fig. 7d. The DAS is also plotted (Fig. 7e) and can be correlated to the PDL [28].
7. Aerial fiber galloping impact on state of polarization

Galloping is when an aerial cable is excited by the wind and undergoes oscillatory motion [7]. The strain induced by galloping reduces the lifetime of the cable. Galloping is a concern because it causes the state of polarization (SOP) to change and thus makes PMD mitigation that relies on tracking the SOP more difficult.

Aerial fiber links consist of an optical fiber attached to a series of poles. We will assume the poles are equally spaced and thus just consider one span consisting of two telephone poles with an attached fiber. Typical span lengths vary from \( L = 30 \text{ m} \) in urban areas to well over \( L = 100 \text{ m} \) in long haul aerial fiber only installations [13,29]. The fiber will naturally sag under its own weight, with the lowest point being at the span center. If we consider an aerial fiber strung between two poles as a catenary problem [30], then

\[
y(x) = \frac{T}{\mu g} \left[ \cosh \left( \frac{\mu g}{T} x \right) - 1 \right],
\]

where \( x \) is the distance measured from the center between the two poles, \( T \) is the tension inside the fiber at the pole, \( \mu \) is the linear density, and \( g \) is the gravitational acceleration constant. The lowest point is at \( x = 0 \). At point \( x = L/2 \) we calculate \( Y_{sag} \) which corresponds to the sag of the cable or the cables lowest point between the two poles. This value is typically 1% (= \( Y_{sag}/L \)) of the span length \( L \) [31]. One can numerically solve for \( T/\mu g L \) as a function of \( Y_{sag}/L \) in the following:

\[
\frac{Y_{sag}}{L} = \frac{T}{\mu g L} \left[ \cosh \left( \frac{\mu g L}{2T} \right) - 1 \right] - 1
\]

to determine the \( n \)th frequency harmonic [32],

\[
f_n = \frac{n}{2T} \sqrt{\frac{T}{\mu}} = \frac{n}{2} \sqrt{\frac{g}{T}} \sqrt{\frac{T}{\mu L g}}.
\]

This assumes constant tension throughout the length of the cable, which is true in cases of small sag. This equation is very sensitive to changes in the sag. We plot how the fundamental harmonic \((n = 1)\) changes in Fig. 8 from 0.5 to 5% of sag and lengths from 25 to 100 m. One can observe that as sag increases the fundamental frequency decreases.

The SOP was measured by using an external cavity tunable laser at 0 dB m and 1550 nm and a polarimeter that records the SOP of the light. A fiber (fiber E) near Montreal, PQ, Canada was measured for 3 days in October 2001. This fiber had a PMD of 0.9 ps and length of 80 km. Hourly weather data was obtained from a nearby Plattsburgh, NY, USA weather stations. Plattsburgh is about 80 km from the test site, weather data is not expected to be in perfect agreement with the weather at the fibers location. A fast-Fourier transform was performed on the Stokes parameter data sets at 10-min intervals (60,000 points). Multiplying this by its conjugate produces the power spectrum. We summed the three Stokes parameter’s power spectrum together to see the combined effects. Figure 9a shows the power spectrum for frequencies of 1.3 Hz and less. A clear band can be observed at 0.51 Hz. The band is more pronounced with sustained winds as shown in Fig. 9b.
fiber has a span length that varies between 30 and 45 m. Figure 8 shows that this corresponds to sag between 2.6 and 4.0%. These values are not exactly known for the installed fiber, but match with visual estimates of the sag.

Fiber galloping and its effect on the SOP need more investigation. It has been investigated recently in high-tension power lines and oscillations were found to be caused by wind and AC current of the power lines [12].

8. Measurement issues and system impact of aerial fibers

PMD and PDL cause errors to be generated in optical systems, thus it is very important to determine the system impact. Of most concern to optical system designers is the probability of system outage. Outage probabilities for systems with PMD have been investigated by many groups [1,33,34]. All these methods rely on knowing the PMD value accurately. As we have shown in Section 6 the mean PMD and mean PDL (and high order quantities) vary with time. This means that birefringence or stress on the fiber is changing. From the point of view of PMD theory [35] this means that at each instant of time you have a “new fiber.” So for each “new fiber” an outage probability must be calculated. For other types of fiber the DGD spectrum will change with time, but the mean DGD will stay relatively constant. Standard outage probability calculations are thus valid.

To determine the PDL and PMD of an aerial fiber, one must do more than one measurement [36]. The minimum requirement would be a 24-h measurement to catch the major diurnal variation. It would also be beneficial to measure the fiber during a period of unsettled weather (storm) to observe its behavior under maximum stress. We realize that this is
not usually practical and cost-effective in the real world. We have observed that the PMD and PDL is usually higher during the day, so one would err on the side of caution by taking measurements in the middle of the day.

We propose three different methods to calculate system impact and outage probabilities in aerial fibers:

1. **Maximum**
   Over the period measured take the maximum PMD and PDL and use these values in the outage calculation. This method will generally overestimate the outage probability if a long enough measurement is taken.

2. **Mean**
   Calculate the mean PMD and mean PDL over all measurements and use these values in the outage calculation. In the case of cyclical (diurnal) PMD and PDL changes this should give a good estimate.

3. **Weighted sum**
   For each measurement over time a separate PMD and PDL is obtained. Do many outage probability calculations based on each PMD and PDL value. By weighing and summing the different outage probability calculations one can obtain a good estimate. This method is very computationally intensive and should only be used in special situations where the PMD and PDL vary in a non-predictable manner.

To illustrate the three methods we perform a numerical simulation using computer code we have written and a commercial optical system simulation software package. Figure 10
Fig. 10. Diagram of simulated 10 GHz RZ optical system.

shows a diagram of the system modeled. The system is a 10 GHz RZ modulated system that is amplified spontaneous emission (ASE) noise loaded.

The transmitter portion is made up of a laser launched into two LiNbO$_3$ modulators driven by a clock and data source, respectively. The data source uses a $2^7 - 1$ pseudo random bit sequence (PRBS) pattern with 64 sample points. Coupled to the transmitter is an ASE noise source (erbium doped fiber amplifier (EDFA) with null input). By using optical attenuators the receiver can be set so that the ASE noise is the dominant noise. This is done to emulate a real system.

The PMD and PDL emulator is made up of 15 PMD sections and 15 PDL sections. The PMD and PDL values are Gaussian distributed over the 15 sections. The angles are randomly oriented between each of the sections to give different PMD and PDL values across frequency. Using the PMD and PDL Monte Carlo simulation technique [5,37] these angles are scrambled with each iteration of the simulation.

The receiver consists of an optical Fabry-Perot filter with a bandwidth of 37.5 GHz. A 10 GHz PIN diode is used to convert the light to an electrical signal. To amplify this signal we use a trans-impedance amplifier followed by a limiting amplifier. A 9 GHz 4th-order Bessel filter is used before the decision circuit. The optimal decision threshold point is used and the $Q$ factor is calculated. The $Q$ factor is plotted (Fig. 12) as a function of different bit period sample times.

The simulation PMD and PDL values are based on the PMD and PDL values found in Fig. 7 for fiber D. Note that we multiplied the PMD values by a factor of 10, but left the PDL values unchanged. The reason for this is the PMD values were too low to see any system impact, but yet we still wanted to show the aerial fiber PMD dynamics.

Figure 11a shows 200 iterations of the simulation using method 1 (maximum). This consisted of a mean PMD of 12.60 ps and mean PDL of 6.85 dB, which corresponds to the maximum values measured over the 13 days. A smearing can be observed which is caused by the high amount of PDL. Figure 11b shows 200 iterations of the simulation using method 2 (mean). The mean PMD is 11.48 ps and the mean PDL is 1.10 dB. Figure 11c shows the results from method 3 (weighted sum). Fifteen different values of PMD
were used by generating a histogram based on the fiber D experimental data (see Fig. 12). The PDL was left fixed at mean of 1.10 dB. Ideally one would like a joint probability PMD and PDL histogram, but having two free parameters in an heuristic simulation is too computationally intensive. The system impact difference between methods 2 and 3 is small. This is because of the symmetry of the PMD histogram.

For low PMD (<10 ps) and low PDL (<1 dB) aerial fibers standard system impact and outage probabilities can be used. For higher values of PMD and PDL one of the three presented methods could be considered. Method 1 was shown to give a worst case scenario and likely severely overestimates the system impact. Methods 2 and 3 behave in a similar manner, but if the PDL is also allowed to change the results will differ. This should be investigated further.

9. Conclusion

The SOP of aerial fiber has been shown to be biased by the environment. Two fibers measured at the same time, show the SOP change to be independent from each other, but this could be due to different launch states relative to PSP. Both are affected by environmental bias. PMD, SOP, PDL, DAS, DVV are all shown to be environmentally biased in a 24 h period. Large SOP changes are found to occur at speeds of at least 10 ms. Aerial fibers are found to gallop in the wind producing a fundamental frequency that depends on the span length and sag.

Diurnal changes: sun induced heating, temperature change, and wind are the major differences between other types of fiber (e.g., buried) fiber and aerial fiber. The effect of the
changing environment has been shown to change the mean DGD of an aerial fiber. This is the major difference from a system impact perspective between aerial and buried fiber. We have proposed three methods to calculate aerial fiber outage probabilities. While aerial fiber outage probabilities are more complicated to calculate accurately, it does not mean that aerial fibers are not suitable for 10 GHz and greater systems. In fact, for small PMD and PDL the system impact will be the same for buried and aerial fiber.

In aerial fiber links with high PMD, fast mitigation (<10 ms) is needed. Without fast mitigation, these links are unusable. We wish to note that after we completed our experiments fiber C had a 10 GHz long-haul wave division multiplexed (WDM) system deployed on it. This demonstrates that aerial fiber can be used for high bit rate systems. Aerial fiber requires careful link budgeting and planning in links with PMD capable of degrading a system. In aerial links with minimal PMD, fast SOP changes still occur. This can cause system impact issues with any polarization dependent components and should be budgeted for.

Aerial has many advantages including: cheap right-of-way, fast [38] and cheap installation, and quick repair. Aerial fiber has been found to cost 75% less than an equivalent buried solution [39]. Polarization effects in aerial fiber are only a hindrance to deployment when PMD and/or PDL is large or the system has many polarization dependent components.

Acknowledgments

The authors acknowledge D. Harris, J. Pan, P. Hernday, M. Parent, J. Stears, R. Cormier, K. Simpson, P. Lange, D. Painter, J. Cameron, P. Lu who helped in collecting the data by
supplying access to the fiber, supplying equipment, and/or aiding in the experiments. We also thank S.A. Clark for helpful discussions.

References