From Loss Test to Fiber Certification – Part II
Fiber Characterization Today
Polarization Mode Dispersion

White Paper

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Introduction

When the first discussions on polarization mode dispersion (PMD) started in 1986 [1], only a few people considered that this effect might become part of their daily business. Since then the Internet, broadband services, etc. have generated a bandwidth demand that drives high-speed transmission at rates of 10 Gbit/s and above. While research on polarization mode dispersion goes on for the next generation networks [2, 3], it is essential to know how PMD influences today’s network performance. Understanding the causes of PMD, and the advantages and disadvantages of the different measurement methods that are available for field-testing, are key for building reliable and profitable high capacity networks. Along with chromatic dispersion (CD), polarization dependent loss (PDL) and loss [4] polarization mode dispersion is an important piece of the puzzle for today’s fiber certification. Part II of our Series on fiber certification will help to understand the issues related to PMD.

Causes of PMD

Effects like chromatic dispersion, polarization dependent loss, polarization mode dispersion and also non-linear effects are a result of the refractive index not being constant in one way or the other. While for chromatic dispersion it is the wavelength dependency of the refractive index, it is the refractive index dependence on the signal power that causes non-linear effects. For polarization mode dispersion the cause is a small difference in refractive index for a particular pair of orthogonal polarization states, a property called birefringence [5]. This means that the speed of light depends on the path it takes along the fiber. The cause of the birefringence is illustrated in Figure 1. In contrast to an ideal fiber (left cross-section in Figure 1), a real fiber can exhibit several kinds of imperfections [6]. From right to left, strain, impurities in the fiber and fiber asymmetry are shown. The imperfections are partly inherent to the manufacturing process of the fiber, from cabling of the fibers and are partly caused by environmental conditions and the quality of fiber deployment. The asymmetries in shape of the fibers are nearly constant over time causing a constant PMD.

Strain in fibers can vary with time due to temperature changes and even show a diurnal (day/night) fluctuation of strain and so vary the PMD. Vibrations can cause a dynamic change in strain and so PMD for fibers that are deployed near railway tracks and aerial fibers can exhibit a change in strain due to movement caused by wind. All of those effects contribute to the PMD not being constant over time, so that the maximum PMD that might occur can only be predicted as will be explained later. When discussing polarization mode dispersion, it is important to understand that the real cause of signal degradation is the differential group delay (DGD), also called the instantaneous PMD and that the term PMD, is really the mean value of DGD over wavelength and over time.

When light is coupled into a fiber, it takes different paths traveling through the fiber. As shown in Figure 2, the differential group delay is the difference in time that the components of the light pulse need to travel along the fiber depending on the different paths it takes. The part of the light pulse indicated in blue (marked with X) travels the slow axis in the fiber. The part of the light pulse indicated in red travels the fast axis of the fiber. At the end of the fiber there is a difference in travel time for the two different parts of the light pulse, the differential group delay. In a special kind of fiber, called polarization maintaining fiber (PMF), the different parts of the light pulse travel a different path, but do not change the paths during the travel through the fiber.
This fiber one can easily compensate for the DGD (PMD) by e.g. using a polarizer to filter out one part of the light pulse, either the part indicated in red or the part indicated in blue (marked with X)\(^1\). A real telecom fiber can be represented as a series of birefringent fiber elements of the type illustrated in Figure 2, concatenated with random orientation of the axes [7]. This is shown in Figure 3.

![Figure 3: Randomly concatenated birefringent elements as representation of a fiber](image)

Each section of the fiber exhibits a fast and a slow axes which are rotated randomly in relation to one another. Between the sections the light is coupled from one pair of fast and slow axes into another pair of axes, a process called mode coupling. Because of the randomness of the orientation of fast and slow axes and the mode coupling for the different fiber elements, the PMD is of statistical nature and no simple way of compensating for the PMD is possible as will be discussed later. The DGD as well as the PMD is measured in picoseconds (ps). Because of the statistical nature of PMD, PMD is not linearly proportional to the fiber length but to its square root. This means that a 4 times longer fiber exhibits only twice the PMD and the PMD coefficient is given in ps/√km.

To illustrate the temporal behavior of DGD and PMD, Figure 4 shows a long-term measurement of the DGD/PMD on a 127 km dispersion-shifted fiber over a period of 36 days\(^2\) [8]. In Figure 4 the differential group delay is color-coded. Dark blue corresponds to low DGD of <0.5 ps and dark red corresponds to a higher DGD of >5.5 ps. The PMD can be obtained by taking the average of the DGD values over wavelength at any given point in time. In theory the PMD can also be obtained by taking the average of the DGD at a particular wavelength over time. However measurements have to be long-term enough to obtain accurate results from these averages. The change of the PMD over time (the wavelength averaged or mean DGD) is only about ±10% whereas the change of the DGD over time at a particular wavelength is much higher.

![Figure 4: Long Term DGD/PMD measurement of 127 km dispersion-shifted fiber](image)

Because of the changes of the DGD with wavelength and time, DGD statistics have to be taken into account in order to assure system performance. Assuming the probability that a certain DGD might occur has a distribution as shown in Figure 5 (Maxwell distribution [9]), one can determine the PMD test-limit for a fiber link from the system DGD limit. 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 (OSNR) and the receiver design. In Figure 5 the probabilities are shown for the differential group delays when the mean DGD (i.e. PMD) is 10 ps. The probability that the mean DGD (PMD) of 10 ps (10 ps ± 0.5 ps) actually occurs at a particular moment in time for a particular wavelength is about 10%. There are also lower DGD values than the 10 ps mean DGD that might occur with a certain probability and there are higher DGD values than the 10 ps mean DGD that might occur with a certain probability. In conjunction to the ITU-T G.691 recommendation [9], as an example let's assume that the maximum link-DGD a receiver in a certain 10 Gbit/s system can tolerate is 30 ps and lets also assume that system failure\(^3\) due to the DGD being higher than 30 ps must be less than 0.004%.

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\(^1\) Figure 2 represents the whole length of a fiber, if the fiber is a polarization maintaining fiber (PMF).

\(^2\) Figure 4 was taken with permission from [8].

\(^3\) System failure relates to a path penalty of 1 dB for receivers with signal dependent noise.
Then the red area in the inset of Figure 5 represents the probability for the DGD being higher than 30 ps (i.e. about 0.004%). The resulting PMD that the fiber-link must not exceed is then 10 ps.

Figure 5: Probability density of DGD values for a PMD of 10 ps

System impairments and PMD limits

PMD causes a number of serious capacity impairments [10] including pulse broadening. In Figure 6a the pulse pattern in time and in Figure 6b an eye-diagram for a signal without differential group delay i.e. no PMD impairments are shown. It can be seen that the pulse pattern has a good shape and that the eye-diagram is wide open resulting in a low bit-error-ratio.

Figure 6a: Pulse pattern for a signal without DGD impairment
Figure 6b: Eye-diagram for a signal without DGD impairment

Figure 7a and Figure 7b show the signal under the influence of 100 ps DGD with the power being equally distributed in the fast and the slow axes.

Figure 7a: Pulse pattern for a signal with 100 ps DGD
Figure 7b: Eye-diagram for a signal with 100 ps DGD

From Figures 6 and Figures 7 it is clear that DGD, and so PMD, influences the system performance.

It is also necessary to discuss what the system tolerances for PMD are at different bit-rates and what the qualities of fibers are that have been installed. Investigations on installed fibers show large quality differences among fibers that have been installed before and after the early 90’s [11–14]. In Ref. [11] only 13% of the fibers that have been installed after 1994 have a PMD coefficient of larger than 0.2 ps/√km. For those fibers that have been installed prior to 1994, 30% have a PMD coefficient of larger 0.2 ps/√km. In Bellcore’s fiber measurement audit of existing cable plant [12], 20% of the measured installed fibers exhibit a PMD coefficient of larger than 1 ps/√km. Table 1 summarizes some of the measurements.
As mentioned before, every transmission system has its distinct tolerance with respect to the differential group delay (corresponding to PMD). In order to get an idea of to what extent today’s fibers can impact system performance, PMD-limits for different bit rates\textsuperscript{4} are listed in Table 2, assuming that as a rule of thumb the PMD value in ps should not exceed 10% of the bit-period \[9, 15\]. In Table 2 the tolerable PMD coefficients and the PMD limits are translated into fiber lengths. It can be seen that for a 2.5 Gbit/s bitrate long fibers can be used even for poor fibers of about 1 ps/√km PMD. For 10 Gbit/s systems PMD has to be taken more seriously as the number of fibers exceeding a PMD coefficient of 1 ps/√km is not low. This might result in possible system outage due to high bit error rates caused by high PMD.

It is also important to consider measuring the fiber PMD when installing 2.5 Gbit/s systems to assure that the poor fibers (high PMD) are used for the low bit-rate systems and the good fibers (low PMD) are left for high bit-rate systems that might be installed later in time. Using the lowest PMD fiber today for low bit-rate systems can mean expensive delays in turning up future higher bit-rate systems later, since swapping fibers can be complicated, require extensive coordination, or if they are leased or leased out, can be almost impossible. Making accurate measurements and using the poorest fiber that will still reliably carry the desired bit-rate can make a contribution to profitability through better fiber usage and speed future deployments.

<table>
<thead>
<tr>
<th>Author</th>
<th>Region</th>
<th>Deployed</th>
<th>Percentage of fibers</th>
<th>PMD Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peters [12]</td>
<td>US</td>
<td>pre 1991</td>
<td>31%</td>
<td>&gt; 1 ps/√km</td>
</tr>
<tr>
<td>Noutsios [11]</td>
<td>US</td>
<td>pre 1994</td>
<td>30%</td>
<td>&gt; 0.2 ps/√km</td>
</tr>
<tr>
<td>Peters [12]</td>
<td>US</td>
<td>pre 1997</td>
<td>20%</td>
<td>&gt; 1 ps/√km</td>
</tr>
<tr>
<td>Noutsios [11]</td>
<td>US</td>
<td>post 1994</td>
<td>13%</td>
<td>&gt; 0.2 ps/√km</td>
</tr>
<tr>
<td>Barcelos [13]</td>
<td>Brazil</td>
<td>1998–2002</td>
<td>11%</td>
<td>&gt; 0.5 ps/√km</td>
</tr>
<tr>
<td>Tessmann [14]</td>
<td>Germany</td>
<td>pre 1991</td>
<td>mean over all fibers</td>
<td>0.32 ps/√km</td>
</tr>
<tr>
<td>Tessmann [14]</td>
<td>Germany</td>
<td>1992–1998</td>
<td>mean over all fibers</td>
<td>0.13 ps/√km</td>
</tr>
<tr>
<td>Tessmann [14]</td>
<td>Germany</td>
<td>post 1999</td>
<td>mean over all fibers</td>
<td>0.05 ps/√km</td>
</tr>
</tbody>
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Table 2: Summary of the measurement results from [11 - 14]

<table>
<thead>
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<td>0.05 ps/√km</td>
</tr>
</tbody>
</table>

Table 2: Tolerable PMD for different bit rates

<table>
<thead>
<tr>
<th>Bit Rate</th>
<th>SDH/SONET</th>
<th>Max. PMD</th>
<th>0.08 ps/√km</th>
<th>0.2 ps/√km</th>
<th>1 ps/√km</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5 Gbit/s</td>
<td>STM-16/OC-48</td>
<td>40 ps</td>
<td>250,000 km</td>
<td>40,000 km</td>
<td>1,600 km</td>
</tr>
<tr>
<td>10 Gbit/s</td>
<td>STM-64/OC-192</td>
<td>10 ps</td>
<td>15,000 km</td>
<td>2,500 km</td>
<td>100 km</td>
</tr>
<tr>
<td>40 Gbit/s</td>
<td>STM-256/OC-768</td>
<td>2.5 ps</td>
<td>1,000 km</td>
<td>160 km</td>
<td>6 km</td>
</tr>
</tbody>
</table>

\textsuperscript{4} Bit rates refer to single channel bit rates.
PMD measurement methods

Measuring PMD of installed fibers and links mainly has two applications:

Fiber certification
• measure fiber plant without network equipment (optical amplifiers etc.)
• assess bandwidth potential of the fibers
• design the network (e.g. regenerator spacing)

Network upgrade/network design verification
• measure fiber plant with or without network equipment
• assess bandwidth potential and upgradability of link
• verify link design (e.g. regenerator spacing)

Reliable and accurate PMD measurements require a dual-ended measurement using a PMD-tester light-source and a PMD-tester receiver as shown in Figure 8.

![Figure 8: Schematic layout of an optical network with possible measurement points for PMD-test source and PMD-test receiver. Span test, and overall link test](image)

Depending on the application, the PMD-test source may be connected to one fiber end and the receiver is connected to the other end of the fiber with no optical equipment (e.g. optical amplifiers) in-between. Another possibility is to connect the PMD-test light source at the very beginning of the line-side of the optical network and the PMD-test receiver at its very end. This way the whole network can be characterized with a single measurement.

Different test equipment exists for measuring PMD and DGD in the field, using standardized methods to determine the PMD/DGD.

• Fixed Analyzer Method [16]
• Interferometric Method [17]
• Jones Matrix Eigenanalysis Method [18]

In the following section the different methods will be described and their advantages and disadvantages will be discussed. Beginning with the fixed analyzer method, it is important to differentiate between the different implementations that are available on the market today. A low-accuracy, low-cost solution is shown in Figure 9. It consists of a broadband light source and a analyzer on the one end and an analyzer (same as the polarizer on the source side) and an optical spectrum analyzer on the other end. The light of the broad-band source, such as an LED, is polarized and is connected to the fiber under test. The PMD of the fiber causes the polarization to change as a function of the wavelength. The higher the PMD of the fiber, the faster the change in polarization over wavelength. On the receiving end a high light intensity passes the “fixed” analyzer if the light has the same polarization as the analyzer. The light intensity after the analyzer is low, if the light polarization is perpendicular to the polarization of the analyzer. As the polarization of the light changes with wavelength, this polarization change is detected as a power fluctuation with wavelength, recorded by the optical spectrum analyzer.

![Figure 9: Schematic view of a low-accuracy, low-cost implementation of the fixed analyzer method](image)

The number of occurrences of high power and low power (10 in the example from Figure 9) need to be counted and multiplied by a factor that is depending on the degree of mode coupling and that is known from the literature[5] [16]. From this the PMD is estimated. A variation sometimes seen is to calculate and display the Fourier transform of the power fluctuations with wavelength and fit the resulting graph with a Gaussian curve. The standard deviation (width) of the fitted Gaussian curve then gives the estimated PMD of the fiber [17]. This procedure is comparable to the interferometer method that will be explained later.

5 PMD = \[k \cdot Ne \cdot \frac{\lambda_1 - \lambda_2}{2 \cdot c \cdot (\lambda_2 - \lambda_1)}\].

k: mode coupling factor, Ne: number of extrema, \(\lambda_1, \lambda_2\): start and stop wavelength respectively, c: speed of light.
The limitations of the fixed analyzer method are caused by the resolution of the optical spectrum analyzer that influences the maximum measurable PMD, the bandwidth of the light source that influences the minimum measurable PMD, and the dynamic range of the measurement that limits measurement accuracy in general. A high-end implementation of the fixed analyzer method is outlined in Figure 10. The broad-band light source is replaced by a tunable laser and the receiver is based on a polarimeter. This way the power fluctuation with wavelength is recorded for three different polarizations. The PMD is estimated in the same way as done with the low-accuracy implementation. Advantages of the high-end implementation of the fixed analyzer method are that the three measurements can be averaged giving a higher accuracy for the PMD result and that there is nearly no limitation for measuring high PMD values due to the high resolution, i.e. small bandwidth of the laser source. Also more optical power is available at each wavelength, providing high dynamic range. Both implementations only measure the total PMD but give no information on the DGD versus wavelength.

![Figure 10: Schematic view of a high-end implementation of the fixed analyzer method](image)

Another way of measuring the PMD is using the interferometric method as shown in Figure 11. It is based upon the electric-field autocorrelation of two signals derived from the same wideband source. As in the low-accuracy implementation of the fixed analyzer method, a polarized broadband light source is used at one fiber end. At the receiver side the light passes a Michelson interferometer before it hits the detector. In the interferometer the light is first split into both interferometer arms.

![Figure 11: Schematic view of the interferometer method](image)

Each part of the light is then polarized (orthogonally to each other). One part hits a fixed mirror introducing a fixed time delay and the other part of the light hits a moving mirror introducing a variable time delay. If the time delays of the light in both interferometer arms are equal, the detector detects a high light intensity, because all the light waves match and add together. This way interference fringes are measured by moving the variable mirror over a wide-enough range. The center peak of the interferogram corresponds to the mirror position where both interferometer arms are of equal length.

To obtain the PMD from the interferogram, it is fit to a mathematical model. Depending on the degree of mode coupling of the fiber under test different curve fits are required. For strongly mode-coupled fibers, most commonly the interferogram is fit with a Gaussian curve. From the standard deviation (width) of the fitted curve the PMD can be obtained. The interferogram of many fibers is not however strictly Gaussian, introducing a measurement error. Discussions about the accuracy of the interferometric measurement for the field are ongoing and first attempts have been made to mitigate the observation that many of the deployed fibers show a different behavior compared to the theoretical model used by the interferometric methods. As with the fixed analyzer method, the interferometric method does not give any information on the DGD but only the PMD. For both methods, the fixed analyzer as well as the interferometric method, the 2nd order PMD is only estimated by multiplying the first-order PMD with a factor.

The third method that will be described and that standards quote as the most accurate common technique is the Jones Matrix Eigenanalysis method (JME). It is the only field method that directly measures the DGD as a function of wavelength and so measures the PMD directly by calculating its average.

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6 With the low-accuracy fixed analyzer implementation it is also possible to obtain and average measurement results for different polarizations by rotating the analyzer.
The method can be applied to short and long fibers regardless of the degree of mode coupling. The schematic of a JME instrument is shown in Figure 12.

Like all field-test instruments the JME field DGD/PMD test instrument consists of a PMD-test light source and a PMD-test receiver. The light source of the JME instrument consists of a high-end tunable laser source with polarization management components. The polarization management is used to set the different input polarizations that are used for the measurement. The receiver consists of a polarimeter. This is a sophisticated receiver that splits the received signal into polarization components and analyzes them simultaneously. The analysis is based upon the measurement of the transmission matrix of the fiber at a series of wavelength. To obtain the transmission matrix of the fiber, the instrument needs to compute the relationship between three output and three input states of polarization at each wavelength.

### Table 3: Advantages and disadvantages of different polarization mode dispersion measurement methods available for field test

<table>
<thead>
<tr>
<th>Method</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
</table>
| Fixed analyzer (low-accuracy) | Low-cost solution  
Measures loss vs. wavelength                                      | Indirect measurement  
Low accuracy  
Sensitive to degree of mode coupling  
Sensitive to input polarization  
Averaging necessary  
Low dynamic range  
Maximum PMD limited  
Minimum PMD limited  
Unreliable  
No DGD vs. wavelength  
No 2nd order PMD vs. wavelength |
| Fixed analyzer (high-end)             | Measures loss vs. wavelength                                                | Indirect measurement  
Minimum PMD limited  
Sensitive to degree of mode coupling  
Sensitive to input polarization  
Averaging necessary  
No DGD vs. wavelength  
No 2nd order PMD vs. wavelength |
| Interferometer             | Low-cost option available                                                    | Indirect measurement  
Sensitive to interference effects  
Sensitive to degree of mode coupling  
Sensitive to input polarization  
Averaging necessary  
No DGD vs. wavelength  
No 2nd order PMD vs. wavelength |
| JME                      | Direct measurement  
Most robust measurement  
Not sensitive to degree of mode coupling  
Not sensitive to input polarization  
Measures DGD vs. wavelength  
Measures 2nd order PMD vs. wavelength  
PMD troubleshooting possible  
Measures loss vs. wavelength | No low-cost option available |
From the matrix values at pairs of adjacent wavelengths, the DGD is obtained. The PMD is then given by simply averaging the obtained DGD values. Because the complete transmission behavior of the fiber is measured, 2nd order PMD in addition to the PMD can be obtained. An added measurement is to also provide loss values over wavelength.

To make the JME method usable in the field (the method is a long-established standard in the lab and factory), two challenges had to be overcome. First source and receiver had to be placed at different locations, even several hundred km apart and second, the data acquisition time had to be orders of magnitude faster to make the measurement robust against fiber movement. The traditional lab instrument needed about a second for a single wavelength measurement making it necessary to fasten all patch cords to prevent fiber movement. Today’s JME equipment [20] measures 100,000 data points per seconds making the method field suitable and extremely robust against fiber movement. The tunable laser source is also highly compact and more rugged than past available designs. In Table 3 the advantages and disadvantages of the different PMD methods that are available for field test are summarized.

Figure 13a and Figure 13b show example measurements from a field trial and illustrate the benefits of a high-accuracy and robust test instrument for today’s fiber certification.

Figure 13a: PMD measurement of a buried 65 km standard single-mode fiber with the JME method

Figure 13b: PMD measurement of a buried 65 km standard single-mode fiber with the interferometric method

The differential group delay is plotted vs. wavelength. The average of the DGD (the PMD) is shown to be 2.85 ps (bold number in Figure 13a). The same fiber has been measured with the interferometric method resulting in a PMD of 4.34 ps. The circles in Figure 13b indicate the potential cause of a too broad curve fit. As the width of the fitted curve determines the estimation of PMD, the PMD values of the interferometric method is higher compared to the PMD reading of the JME method. When planning a 10 Gbit/s system for a six-span fiber link this means that one optical-electrical regenerator needs to be planned into the network design based on the interferometric measurement and that the JME method shows that no optical-electrical regenerator is needed (with respect to the link PMD value)\(^7\) in the network design. The results are summarized in Table 4.

Looking beyond the 10 Gbit/s, to 40 Gbit/s systems PMD measurement tools are required to be accurate and reliable against the different effects that might mask the real PMD values on fibers, as very small quantities of PMD need to be resolved.

Table 4: Impact of the PMD measurement results on the network design, compared between the interferometric method and the JME method

<table>
<thead>
<tr>
<th>Measurement Type</th>
<th>Single-span PMD</th>
<th>6-span PMD</th>
<th>No. of OEO regenerators required</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interferometric method</td>
<td>4.34 ps</td>
<td>10.6 ps</td>
<td>1</td>
</tr>
<tr>
<td>JME method</td>
<td>2.85 ps</td>
<td>7 ps</td>
<td>0</td>
</tr>
</tbody>
</table>

\(^7\) For a 10 Gbit/s certification the link loss, return loss, chromatic dispersion and reflections need to be within the according limits.
With higher bit rates 2\textsuperscript{nd} order PMD plays a more serious role in network design. When looking at Figure 13a, it can be seen that the DGD is not constant over wavelength. The width of the gray bar drawn onto Figure 13a is equivalent to the optical bandwidth of a 40 Gbit/s signal. The top and bottom line in the inset of Figure 13a represent the difference in differential group delay that this signal sees over its entire bandwidth. This dependency of the DGD on the wavelength is one component of the 2\textsuperscript{nd} order PMD that is called the polarization dependent chromatic dispersion (PCD) [21]. The second component of the 2\textsuperscript{nd} order PMD is called the depolarization [21]. 2\textsuperscript{nd} order PMD is expressed in picoseconds per nanometer (ps/nm or ps\textsuperscript{2}).

For higher bit rates PMD compensation (PMDC) has been proposed as an approach to increase the tolerance of high-speed transmission systems against PMD [22]. The compensation is done either in the electrical or optical domain. The compensators need to compensate the DGD and second-order PMD in a particular channel. Looking at Figure 4 the compensator needs to account for all the color changes (DGD changes) for a particular wavelength over time. How fast these adjustments need to be made is still under investigation. For the DGD changes due to environmental changes like temperature, compensation in the order of a second is sufficient. For transients that might appear, e.g. due to shock on chromatic dispersion compensation modules, the compensators need to be much faster [23]. In the optical domain, PMD is compensated using adaptive optics. An example of such a compensator is sketched in Figure 14 according to [6].

The signal that is degraded due to DGD (separation of pulses at different polarizations) and second-order PMD (pulses have a round shape) is fed into the PMD compensator. The adaptive optics reactively adjusts for the DGD and second-order PMD in order to deliver reshaped output pulses by closing the feedback loop between optics, detector and controller. As PMD compensators become more widely spread and affordable, another application for measuring the PMD will arise. In next generation networks, network designers will need to decide whether PMD compensation will be necessary. Costs will be saved by making highly accurate and robust measurements of first- and second-order PMD.

**Conclusion**

In conclusion, PMD test equipment exists today in various flavors ranging from low-accuracy, rough PMD estimation to high-accuracy state of the art DGD/PM fiber certification instruments. PMD can potentially limit system performance in 10 Gbit/s and faster systems. When installing 2.5 Gbit/s systems, PMD measurements help to identify poor fibers with the benefit of saving low-PMD fibers for higher bit-rate systems. Next generation PMD test equipment is needed to cope with the challenges that 10 Gbit/s brings today and that higher bit-rates and new technologies like PMD compensation will bring. It is the business case of saving huge costs and preventing unnecessary expenditures by finding the most effective network design with robust and reliable measurements that make people go for state of the art test equipment.


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17. TIA/EIA FOTP-124, “Polarization mode dispersion measurement for single mode optical fibers by interferometry”.


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