ISSUES ON POLARIZATION MODE DISPERSION (PMD) FOR HIGH SPEED FIBER OPTICS TRANSMISSION

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Abstract

In this paper, the analysis of the first and second order PMD characteristics is presented. It is found that a pulse spread of up to 15% of the pulse width is allowed depending on the receiver sensitivity penalty tolerated the system. PMD measurement is also discussed considering Interferometric, Jones-Matrix Eigen analysis (JME) and Fixed Analyzer techniques, from the perspective of field and laboratory applications. A simulation based on realistic parameters of a fiber optic link is performed and the results show that at a 40 Gbp transmission rate, a fiber optic with a PMD coefficient of 0.5 ps/(km),$^{1/2}$ can only support up to a 10 km distance.

Keywords: PMD, JME, interferometric

Introduction

For years telecommunication companies had been given a free ride as they grew from 90 Mpbs to 270 Mbp to 435 Mbp to 2.5 Gbp. A problem began to manifest itself in 10 Gbp systems and threatens major dislocation at 40 Gbp networking. For the first time, the fiber optics industry was faced with a networking killer that is Polarization Mode Dispersion (PMD).

PMD occurs when different planes of light inside a fiber travel at slightly different speeds, making it impossible to transmit data reliably at high speed and due to the asymmetry. of the fiber strand. The problem was discovered in the early 1990s and could destroy the integrity of a network.

The PMD that is due to the asymmetry of the fiber optic strand is simply the fact that the fiber core is slightly out-of-round, or oval as shown in Figure 1. Fiber asymmetry may be inherent in the fiber from the manufacturing process, or it may be a result of mechanical stress on the deployed fiber. The inherent asymmetries of the fiber are fairly constant over time, while the mechanical stress due to movement of the fiber can vary, resulting in a dynamic aspect to PMD.

As higher transmission rates are involved, data pulse width reduces, which results in a very

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small amount of pulse spread becoming significant in deteriorating the signal quality. Therefore, PMD effect, which was neglected in analyzing slower network performances, becomes important and needs to be catered for.

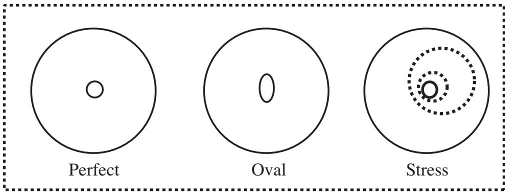

Figure 1. The mechanical stress due to movement of the fiber resulting in a dynamic aspect to PMD

PMD is the dispersion introduced when two laser Principle States of Polarization (PSP), which are orthogonal to each other, travel at different speeds in an optical fiber core and reach the receiver at different times (Francia *et al.,* 1998; Meadowlark Optics, 2002). The time difference between the two PSPs is referred to as Differential Group Delay (DGD). DGD causes the pulse width to spread as shown in Figure 2. The average pulse spread is referred to as the PMD. Although the PMD effect is very small in comparison to Chromatic Dispersion (CD), at data rates higher than 10 Gbp, it contributes a deleterious effect even if without the presence of CD (Chen *et al.*, 2000). Therefore, measures to compensate this effect become unavoidable.

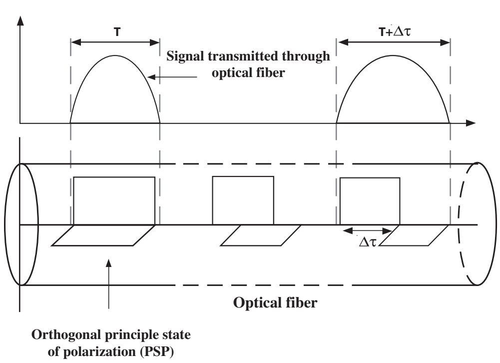

Figure 2. Effect of DGD to signal propagation in birefringence fiber that results in pulse spread

In this report, we present the theory of PMD, measurement techniques used in laboratory and field environments, PMD Compensation techniques and also simulation results.

Materials and Methods

PMD is initiated by light polarization behaviors. Basically, light is polarized in three manners. They are linear, circular and elliptical polarization (Sunnerud, 2001). These types of polarization are differentiated by the phase difference, $\varnothing$, between their orthogonal components as shown in Figure 3. Linear polarized light has a zero phase shift; circular polarized light has a $\lambda/4$ phase shift; and elliptical polarized light is produced when the two components are shifted at a phase lower or higher than $\lambda/4$. If the phase shift is at $\lambda/2$, then the light becomes linearly polarized with opposite direction. Another important property of optical waves is their polarization state. A vertically polarized light is a state where the electric field lies only along the y-axis when light propagates in the z-direction. When the electric field lies only along the x-axis, it is called horizontally polarized light (Agere Systems, 2002; Meadowlark Optics, 2002). When the light has both the x and y components of PSP, its polarization state could be described by the projection of polarization direction, e.g. 45^o polarized light, which has equal magnitudes of its PSPs as illustrated in Figure 3(a).

To understand PMD, the transmission fiber is designed as a group of concatenated birefringence sections, with each section having different birefringence values and PSP positions as shown in Figure 4. When the signal PSPs are equal to the fiber PSPs, the predecessor polarization state is maintained. However when they are not equal, polarization states in the next birefringence section will change. Therefore for a fiber with N birefringence sections the signal polarization state and birefringence values change N times. Changes in the polarization state are referred to as mode coupling (Sunnerud, 2001). The length between the two points where the same polarization state could be found is referred to as the beat length. Signal deterioration that occurs when too many mode couplings exist is referred to as signal depolarization.

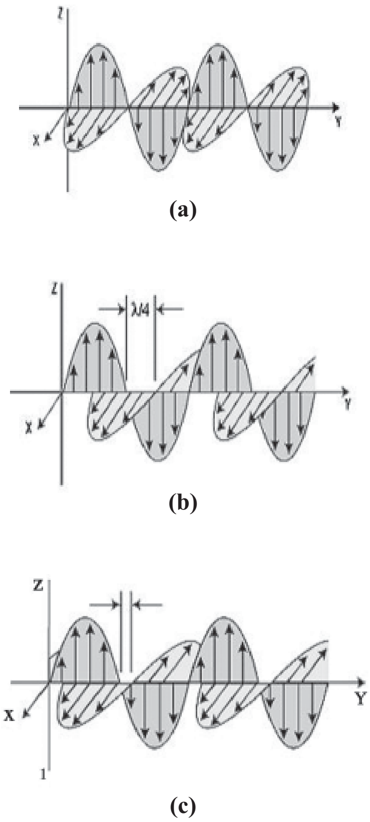

Figure 3. (a) Linear (b) circular (c) elliptical polarization (Francia *et al.,* 1998)

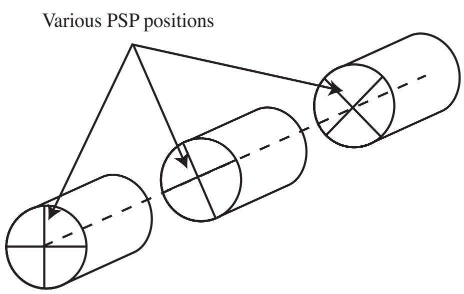

Figure 4. Transmission fiber model with 3 birefringence sections with different orientations of input PSP and birefringence values

Changes in polarization states are simply explained by the amplitude change of both PSPs. When light has both its orthogonal polarization states, DGD becomes an issue. Principally, DGD occurs due to a noncircular fiber core, which is caused by aging, stress and bending. The noncircular core has a different refractive index in x and y directions, and this difference is referred to as birefringence (Profile Inc., 2000; Sunnerud, 2001; Meadowlark Optics, 2002).

$$\beta = n_x - n_y \qquad (1)$$

The propagation difference between the two PSPs increases when β increases and therefore increases the PMD effect.

Basically PMD could be categorized into first and second order PMD. First order PMD (FOPMD) is referred to as the pulse spread that occurs resulting froms the DGD, which originated from different propagation time of the two orthogonal PSPs, regardless of the transmission wavelength. The FOPMD coefficient could mathematically be represented as (Pennickxand Lanne, 2001):

$$PMD^{first-order}_{coefficient} = \frac{1}{\sqrt{l}}\sqrt{\langle \Omega^2(\omega) \rangle}$$

$$= \frac{\Delta\tau}{\sqrt{l}}(ps/\sqrt{km}) \qquad (2)$$

where l = transmission distance
$\Omega(\omega)$ = PMD vector
$\Delta\tau$ = DGD

A typical acceptable FOPMD coefficient is from 0.1 ps/(km)$^{1/2}$ to 0.5 ps/(km)$^{1/2}$.

Second order PMD (SOPMD) behaves quite differently from the FOPMD because it is wavelength dependent (Derickson, 1998; Francia *et al*., 1998; Noe *et al*., 1999; Yu *et al*., 2001; Moller *et al*., 2002). As the transmission wavelength changes when the laser chirps (Lanne *et al*., 2000), the DGD also changes. The FOPMD compensator, which normally consists of a Polarization Controller (PC) and several birefringence sections solves the FOPMD (Moller *et al*., 2002), but residual SOPMD is left to be compensated. Mathematically the SOPMD coefficient is defined as below (Pennickx and Lanne, 2001):

$$PMD^{second-order}_{coefficient} = \frac{2\pi c}{\lambda^2 l}\sqrt{\langle \Omega^2_\omega(\omega)\rangle} \quad (ps/nm/km) \qquad (3)$$

with $\langle \Omega^2_\omega(\omega)\rangle$ = wavelength dependence DGD
λ = laser line width
l = transmission distance

From the mathematical representation, the SOPDM behaves like CD. Therefore this effect could either add or subtract the CD effect depending on the laser chirping direction.

The effect of PMD on the data quality is masked by CD in Non-Dispersion Shifted Fiber (NDSF). However, when CD is compensated by using Dispersion Compensation Fiber (DCF), PMD effects become noticeable (Pennickx and Lanne, 2001). ITU-T proposed pulse spread of 10% of the pulse width, (PW) (0.1 PW) as the maximum allowable PMD for 1 dB sensitivity penalty, in CD compensated fiber (Bulow, 1999; Sarkimukka *et al*., 2002). Some literature proved that up to 15% of PMD in comparison to PW could be allowed (Bulow, 1999). However for prevention purposes, the ITU-T standard is normally preferred. This guideline applies to all fiber types.

PMD Measurement Techniques

PMD measurement techniques are generally classified by the working environment and the result precision. In this paper, three methods are discussed. They are the Fixed Analyzer, Jones-Matrix Eigen analysis, and Interferometric techniques.

Fixed Analyzer Method

By using this method, mean DGD is obtained from the number of peaks and valleys in the optical power spectrum as the wavelength is scanned. Wavelength scanning involvement made this method to be also known as the wavelength scanning method. A typical measurement result is shown in Figure 5.

From Figure 5 it is observed that the result contained a power spectrum with several peaks and valleys, which are the resultant of fiber birefringence and random mode coupling. The mean DGD, $\Delta\tau$ could be calculated a from (Derickson, 1998):

$$\langle \Delta\tau \rangle_\lambda = \frac{kN_e\lambda_{start}\lambda_{stop}}{2(\lambda_{start}-\lambda_{stop})c} \qquad (4)$$

where N_e = number of extrema (peaks and valleys)
c = speed of light in air
k = 0.824 for random mode coupling
k = 1 for non mode coupled fiber or devices

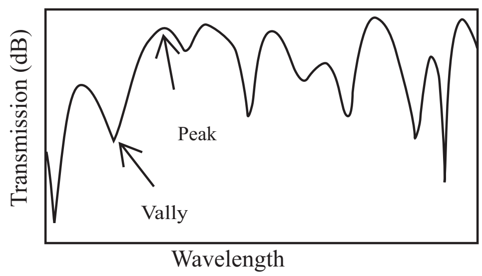

Figure 5. A typical Fixed Analyzer measurement result (Francia *et al.,* 1998)

Jones-Matrix Eigen Aanalysis (JME) Method

For the time being, the best PMD measurement method in terms of sensitivity and accuracy is the JME (Profile Inc., 2000; Sunnerud, 2001; Moller *et al*., 2002). This method determines mean DGD. Basically, a Tunable Laser Source (TLS) is used as the input signal, which is swept through a range of wavelengths at the input of the Device Under Test (DUT), e.g. fiber, isolator. For each specified wavelength the DGD is measured. At the end of the measurement, several values of DGD are obtained. Mean DGD is then calculated.

Theoretically, Jones-Matrix describes that optical components e.g. fiber and isolator, transform any input state of polarization (ISOP) into another state. Say the ISOP vector is A, the output is B, and JME the coefficient is M. Therefore

$$B = MA \tag{5}$$

The input Jones vector, which consists of two complex components, is described as

$$\vec{A}\begin{Bmatrix} E_x e^{i\Phi y} \\ E_x e^{i\Phi y} \end{Bmatrix} \tag{6}$$

From the equation, it could be observed that the output state of polarization (OSOP) strongly depends on M.

The major advantage of JME is that it simultaneously evaluates the DGD, PSP and PDL. The measurement is quite slow in comparison with other techniques, but produces the most accurate results. By analyzing the eigen values at several specified wavelengths, the PMD of DUT is completely characterized. A typical JME result is depicted in Figure 6. Beside the advantages, there are two disadvantages of JME, which are sensitivity to DUT movement and vibration, and slow measurement time. These disadvantages made JME notpreferable forfield measurement. For field measurement the popular technique used is called interferometric.

Interferometric

Interferometric is a field-application PMD measurement technique. It is designed to measure high PMD in installed fiber cable. Therefore, its sensitivity does not have to be as good as JME. It is not capable of measuring as low PMD as JME but the technique has a high tolerance to fiber movement and has a faster measurement time.

The working principle of the interferometric technique is depicted in Figure 7. LED is used as the source, followed by a polarizer that fixes the polarization state to 45°, so that the signal has the same amplitude of PSP. The signal is coupled into both paths of the interferometer. Before the signal reaches the interferometer, a Polarization Bean Splitten (PBS) is used to select only one PSP, horizontal or vertical, so that each interferometer receives only one PSP. At each interferometer, there are two mirrors, one fixed and one adjustable. The time delay or specifically DGD is determined from the moving mirror position, which is given by (Derickson, 1998):

$$\Delta\tau = \frac{2\Delta x}{c} \tag{7}$$

where Δx is the distance between the moving and fixed mirrors.

Therefore, DGD is determined from the difference between the moving and fixed mirror positions. A typical measurement result is shown in Figure 8 which is measured in randomly mode coupling fiber. The central peak occurs when both paths are at equal lengths, which represents zero DGD. The side peaks located at both sides

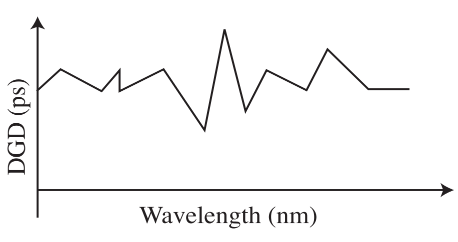

Figure 6. Typical JME measurement result

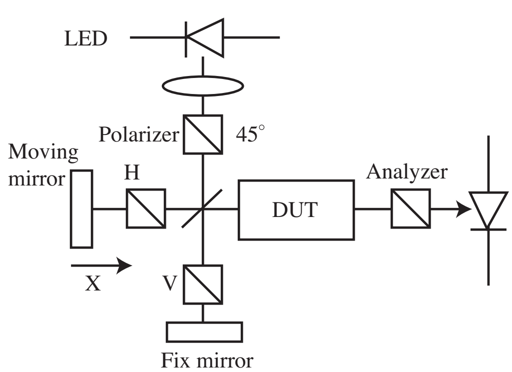

Figure 7. Interferometric working principle

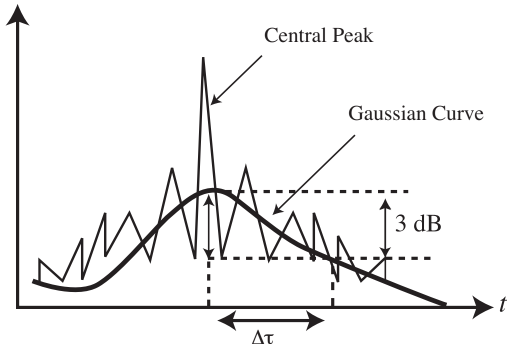

Figure 8. Typical interferometric measurement reslut

of the central peak represent the condition where both the moving and fixed paths are not at equal value, representing the PMD existence. Many side peaks are produced while the mirror is adjusted; the left hand side of the figure is the reflection of the right hand side with the center at the central peak. For simplicity, the Gaussian curve that best fits the figure, including the central peak is determined. From the Gaussian curve, 3 dB DGD value is determined as shown in Figure 8. Only one side of the curve is considered, as the other side is only its reflection.

PMD Compensation

It has been reported that PMD compensation is realized in both electrical and optical domains (Noe *et al.*, 1999; Merker *et al.*, 2000; Pennickx and Lanne, 2001; Yu *et al.*, 2001). In the electrical domain, a Transversal Electrical Filter (TEF) is used as a PMD equalizer. In the optical domain, it is a PMD compensator generally composed of highly birefringence elements (Polarization Maintaining Fiber, $LiNbO_3$ delay, Bragg Grating) separated by a Polarization Controller (PC) (Pennickx and Lanne, 2001). In general, a compensator DGD of the same value as the fiber link DGD is introduced in the oppositedirection to cancel-out fiber PMD effect.

Electrical PMD Equalizer (EPMDE)

In an electrical PMD equalizer, TEFs and an adaptive weight tap are used (Merker *et al.*, 2000). These filters work in removing Intersymbol Interference (ISI) caused by PMD. Filters with frequencies of 1.25, 2.5, and 5 GHz are used, according to the received signal frequency. It is observed that the maximum filter frequency, which is 5 GHz could only support up to 10 Gbp of NRZ and 5 Gbp of RZ signal. This observation is supported by Moller *et al.* (2002). This exposes the technique limitation in effectively compensating the PMD at a high bit rate. However, it is capable of handling the PMD effect up to the second order.

Optical PMD Compensator (OPMDC)

OPMDC compensates the PMD effect in the optical domain. With reference to the DGD introduced by the fiber link, OPMDC introduces delay to one of the PSPs, in order to align it with another PSP. By performing this, the PMD pulse broadening effect could be canceled out. Figure 9 depicts the basic setup for OPMDC. The delay line involved could be fixed (Noe *et al.*, 1999) or dynamic (Pennickx and Lanne, 2001), according to the link condition and PMD origin. For the link installed underground, the cable normally is not moving. PMD mainly originated from fiber aging and temperature fluctuation. As the fiber condition normally does not frequently and abruptly change, fixed OPMDC would be sufficient. For the aerial cable link, the cables are hanging and moving. Therefore the PMD effect which is caused by cable movement emerges. This effect changes with time and requires dynamic OPMDC. There are reports that compare fixed and dynamic OPMDC (Yu *et al.*, 2001). Most of them showed better performance in dynamic, but at a higher cost. Therefore in environments where rapid PMD changes does not involved, fixed OPMDC would be sufficient, with a significant cost saving.

Referring to Figure 9, for dynamic OPMDC, a feed back line is required with control mechanisms that are capable of determining varying fiber DGD values and compensation

DGD required, so that the PMD effect could be abolished. A OPMDC birefringence block normally consists of several birefringence sections. The simplest architecture in terms of complexity consists of only one section, while a more complex version was demonstrated with 73 sections (Noe *et al.*, 1999). In theory, the more birefringence element there are, the more efficient the OPMDC could address all orders of PMD (Pennickx and Lanne, 2001). This technique capable of managing PMD even at 40 Gbp. However its capability is limited to only first-order PMD compensation. There is still second-order PMD left to be compensated.

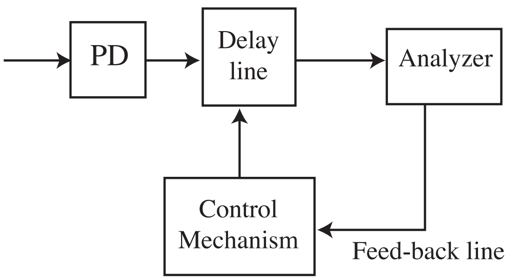

Figure 9. Block diagram of OPMDC, PD: Photodetector

Simulation Results and Discussions

The simulation is numerically realized by MSExcell by using (2). The intention of this simulation is to see the PMD characteristics with reference to fiber first-order PMD coefficient and bit rate against transmission distance. No OPMDC or EPMDE is included. DGD of 0.1 T is used as a benchmarking reference. In Figure 10, by using 40 Gbp as the transmission rate, fibers with a PMD coefficient of 0.1 ps/(km)$^{1/2}$, 0.3 ps/(km)$^{1/2}$, and 0.5 ps/(km)$^{1/2}$ are compared. The curves generated show that for a good link (0.1 ps/(km)$^{1/2}$), the PMD values could be tolerated even at a distance longer than 160 km. However at higher PMD coefficient e.g. 0.3 ps/(km)$^{1/2}$ and 0.5 ps/(km)$^{1/2}$, the transmission distance is limited to only 80 km and 10 km respectively. Therefore for 40 Gbp bit rate, very good quality of fiber is needed in order to support the long distance optical amplifier transmission system.

In Figure 11, it is observed that by using fiber with 0.5 ps/(km)$^{1/2}$ PMD coefficient, long distance transmission could be supported up to 10 Gbp transmission rate. No clear PMD threat could be noticed at 2.5 Gbp. From this curve it could be concluded that by using fiber with a PMD coefficient as high as 0.5 ps/(km)$^{1/2}$, a bitrate lower than 10 Gbp still could be supported without PMD compensation up to 160 km.

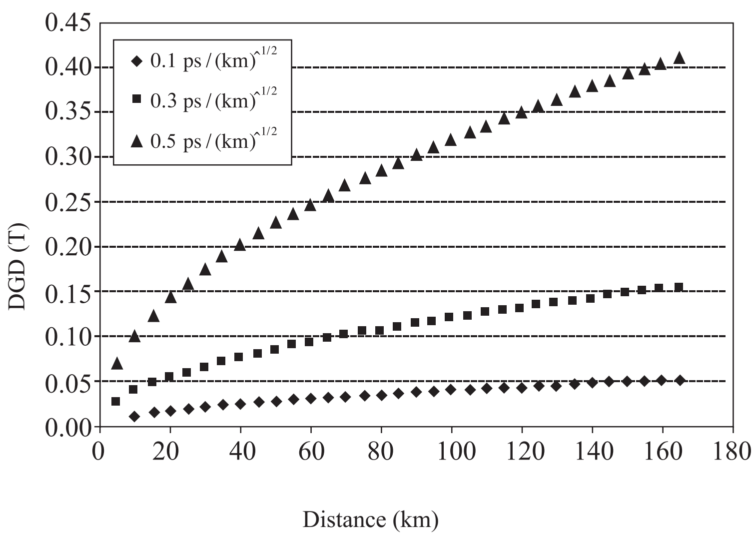

Figure 10. DGD (T) vs distance (km) for fiber with several PMD coefficients at 40 Gbp rate

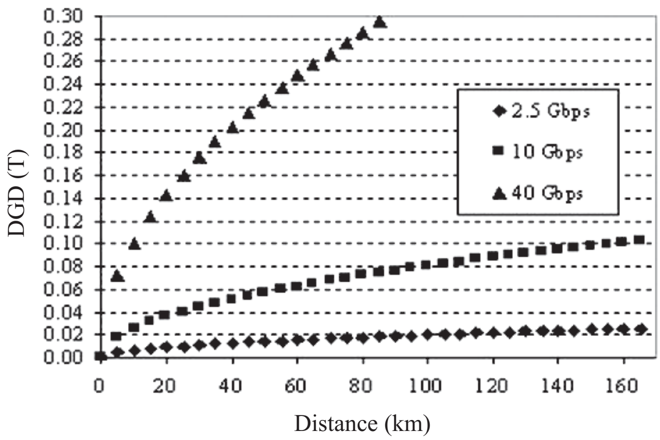

Figure 11. DGD (T) vs distance (km) for several bit rate by using 0.5 ps/(km)$^{1/2}$ PMD coefficient fiber

Conclusion

The effect of PMD is clearly shown, starting from the light characteristics. The three measurement methods discussed are among the popular and reliable PMD measurement techniques. PMD compensation which is realized in both the electrical and optical domains was briefly discussed. Finally, simulation results obtained, which strengthen the theory used, are discussed.

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