Analysis and Simulation of Polarization Mode Dispersion in SMF

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Abstract—A statistical specification on PMD, however, can lead to a statistical boundary on the DGD values for the population as a whole. The first consideration, it is desirable to define a single statistical metric for the distribution of the PMD values that are measured on optical fiber cables. The metric therefore must incorporate both aspects of process mean and process variability. The calculations are done with PMD values that are representative of a given cable construction and design. Four different samples are used of variant designs and are simulated. The PMD is created during fiber manufacturing, affected during cable manufacturing, installation and by the environment. Thus it is essential to measure PMD at every stage of the fiber life.

Keywords*-FiberOptics,Birefringes,PMD,Ensemble and Spectral Simulation.*

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1. INTRODUCTION

It is known that the PMD coefficient of a set of concatenated cables can be estimated by the computation of the quadrature average of the PMD coefficients of the individual cables. To give the upper confidence limit metric more meaning in terms of application, the upper bound for a concatenated link of twenty cables is computed [2]. This number of cables is smaller than that used in most links, but is large enough to be meaningful in terms of projecting DGD distributions for concatenated links. A probability value of 0.01% is also standardized – partially on the basis of obtaining equivalence with the probability that DGD exceeds a bound, which is required to be very low [8]. The upper confidence limit is named PMD_Q, or link design value and this specification type is known as Method 1. The probability limit for DGD is set at $6.5x10^{-8}$ based on various system considerations including the presence of other PMD generating components that may be in the links[9]. IEC 61282-3 describes a method of determining a maximum (defined in terms of probability) so that if a distribution passes the Method 1 requirement[6], the DGD across links comprised of only optical fiber cable will exceed the maximum DGD with a probability less than $6.5x10^{-8}$. The DGD_{max}value is established for a broad range of distribution shapes. This DGD_{max} method of specifying the PMD distribution of optical fiber cables is known as Method 2. Methods of combining the Method 2 parameters with those of other optical components are given in IEC 61282-3. Method 1 is a metric that is based on what is measured and is therefore somewhat more straightforward for use in trade and commerce as a normative requirement. Method 2 is a means of extrapolating the implications for system design and is therefore included as information for system design.

2. SAMPLES OF FIBERS AND DESIGN

Four different fiber samples are used for simulation and analysis, these fibers have different profiles, designs and different modes. The fiber samples are as follows:

1) Fiber-I
2) Fiber-II(a,b,c)
3) Fiber-III
4) Fiber-IV

2.1: Fiber-I

Table 2.1: Design of Fiber-I

Region	**Diameter**		**Profile**	**Refractive Index**
	a	**2a**		
Region 0 (Core)	4.15 µm	8.3 µm	Constant	1.45213
Region 1 (Cladding)	58.35 µm	125 µm	Constant	1.44692
Wavelength = 1316 nm				
Numerical Aperture = 0.123				
Normalized Frequency = 2.428				

2.2: Fiber-II

It is similar as Fiber-I except the different designs of profile; following are the designs of fibers

a) Gaussian Profile
b) Alpha-peak Profile
c) Alpha-dip Profile

2.2(a) Gaussian Profile

The Fiber-II (a) is designed by using Gaussian Profile. Its design and Profile is as follows:

Table 2.2: Design of Fiber-II (a)

Region	**Diameter**		**Profile**	**Refractive Index**
	a	**2a**		
Region 0 (Core)	4.15 µm	8.3 µm	Guassian Function	N_{max} = 1.45213 Norm FWHM (h)= 50 C.position (x_0) = 0
Region 1 (Cladding)	58.35 µm	125 µm	Constant	1.44692
Wavelength = 1316 nm				
Numerical Aperture = 0.123				
Normalized Frequency = 2.428				

2.3.2(b) Alpha-peak Profile

The Fiber-II (b) is designed by using Alpha-peak Profile. Its design and Profile is as follows:

Table 2.3: Design of Fiber-II (b)

Region	Diameter a	2a	Profile	Refractive Index
Region 0 (Core)	4.15 µm	8.3 µm	Alpha-peak Function	N_{max} = 1.45213 Norm Index Difference (Δ)=0.4 Alpha (α) = 2
Region 1 (Cladding)	58.35 µm	125 µm	Constant	1.44692
Wavelength = 1316 nm				
Numerical Aperture = 0.123				
Normalized Frequency = 2.428				

2.3.2(c) Alpha-dip Profile

The Fiber-II (c) is designed by using Alpha-dip Profile. Its design and Profile is as follows:

Table 2.4: Design of Fiber-II (c)

Region	Diameter a	2a	Profile	Refractive Index
Region 0 (Core)	4.15 µm	8.3 µm	Alpha-dip Function	N_{max} = 1.45213 Norm Index Difference (Δ)=0.4 Alpha (α) = 2
Region 1 (Cladding)	58.35 µm	125 µm	Constant	1.44692
Wavelength = 1316 nm				
Numerical Aperture = 0.123				
Normalized Frequency = 2.428				

2.3: Fiber-III

Fiber-III is a Segmented-core Triangular profile design

Table 2.5: Design of Fiber-III

Region	Diameter a	2a	Profile	Refractive Index
Region 0 (Core)	3.1 µm	6.2 µm	Linear Function Start = 1.4615 End = 1.44692	RI = 1.4615
Region 1	1.32 µm	8.84 µm	Constant	1.44692
Region 2	1.5 µm	11.84 µm	Constant	1.45000
Region 3	57.3 µm	126.44	Constant	1.44692
Wavelength = 1300 nm				
Numerical Aperture = 0.183				
Normalized Frequency = 2.74				

2.4: Fiber-IV

Fiber-IV is a Triple Clad Fiber (TC)

Table 2.6: Design of Fiber-IV

Region	Diameter a	2a	Profile	Refractive Index
Region 0 (Core)	4.2 µm	8.4 µm	Function $(RI+\Delta\,[1-(x/w)^{\alpha}]$	RI = 1.44370 Delta (Δ)=0.01 Alpha (α) = 10 Steps = 20
Region 1 (Cladding)	2.5 µm	13.4µm	Constant	1.44370
Region 2 (Cladding)	6.75 µm	26.90 µm	Function $(RI+\Delta\,[1-((2x-w)/w)^{\alpha}]$	RI = 1.44692 Delta (Δ)=0.003 Alpha (α) = 10 Steps = 20
Region 3 (Cladding)	49.05 µm	125 µm	Constant	1.44370
Wavelength = 1300 nm				
Numerical Aperture = 0.0068				
Normalized Frequency = 3.4357				

3. Experimental Results

The calculations are done with PMD values that are representative of a given cable construction and manufacturing time. Typically at least 100 values are required. The sample is normally taken on different production cables and different fiber locations within. The cable distribution can be augmented by measurements of uncabled fiber provided that a stable relationship between uncabled fiber and cable values has been demonstrated for a given construction[16]. One means of such augmentation is to generate several possible cable values from the value of each uncabled fiber. These different values should be selected randomly to represent both the usual relationship and the variability that follows from, for example, measurement reproducibility. Because the range of variations includes reproducibility error, this method of estimating the distribution of cable PMD values can lead to over-estimation of PMD_Q. The statistical analysis is applied to all fibers and by applying both First and second order Ensemble and Spectral Simulation. The results obtained are as shown in Figure 3.1-3.14. The most successful structures in preserving the polarization state are the fiber-III. As important as this issue is, a fiber with zero polarization-mode dispersion is in great need in today's expanding and vastly growing telecommunications applications. The different Polarization-Maintaining Fibers are as shown in the table 3.1.The PANDA [3] fiber is LEAF Dispersion shifted fiber profile known as Fiber-III. Review of polarization-maintaining/eliminating waveguide structures and their designs have been presented. Limiting the propagation to one polarization state can be achieved by either breaking the degeneracy between the mutually orthogonal polarization states

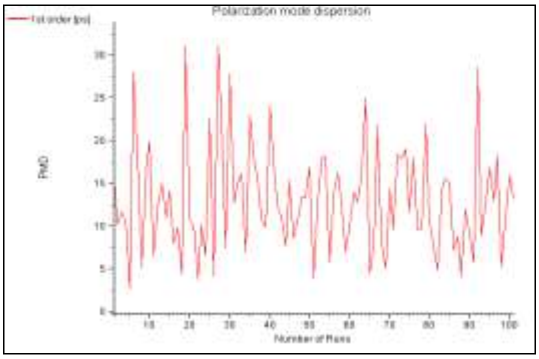

Figure 3.1: PMD Ensemble Simulation of Fiber-I

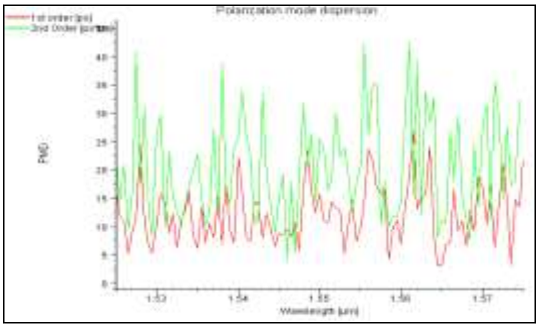

Figure 3.2: PMD Spectral Simulation of Fiber-I

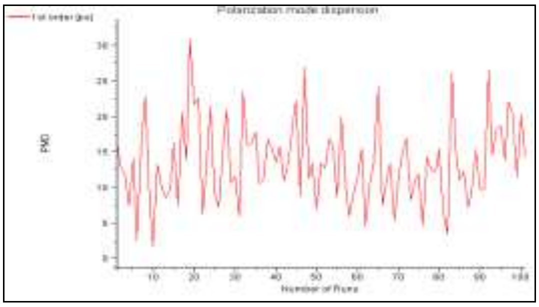

Figure 3.3: PMD Ensemble Simulation of Fiber-II (a)

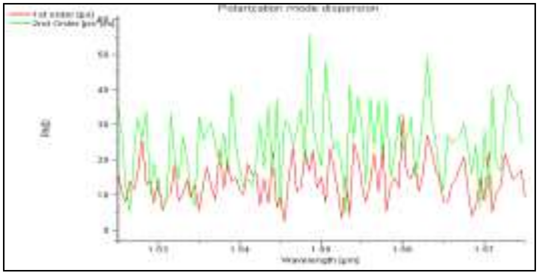

Figure 3.4: PMD Spectral Simulation of Fiber-II (a)

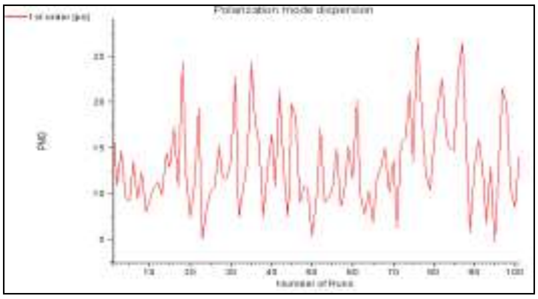

Figure 3.5: PMD Ensemble Simulation of Fiber-II (b)

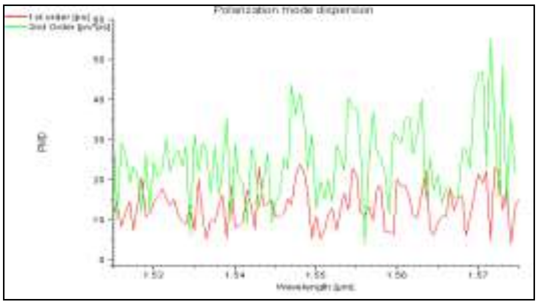

Figure 3.6: PMD Spectral Simulation of Fiber-II (b)

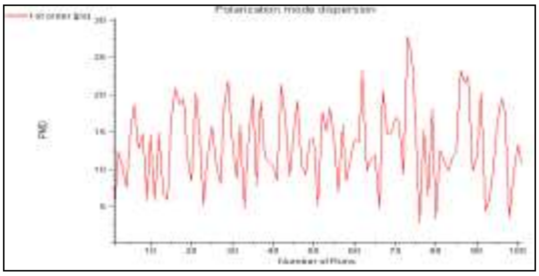

Figure 3.7: PMD Ensemble Simulation of Fiber-II (c)

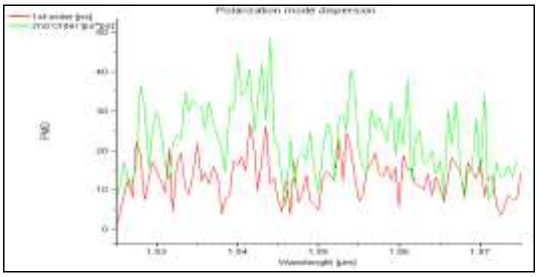

Figure 3.8: PMD Spectral Simulation of Fiber-II (c)

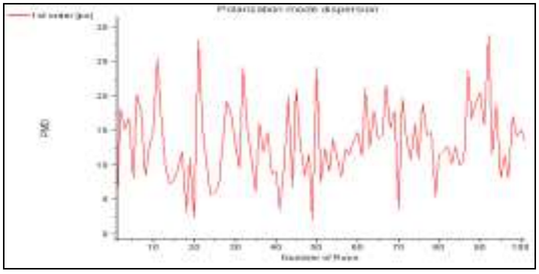

Figure 3.9: PMD Ensemble Simulation of Fiber-III

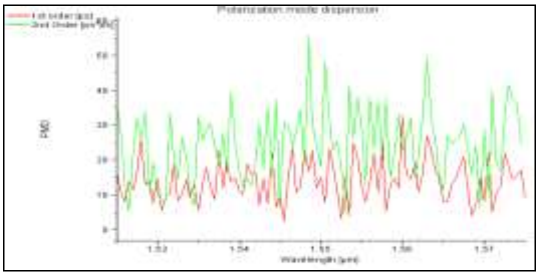

Figure 3.10: PMD Spectral Simulation of Fiber-III

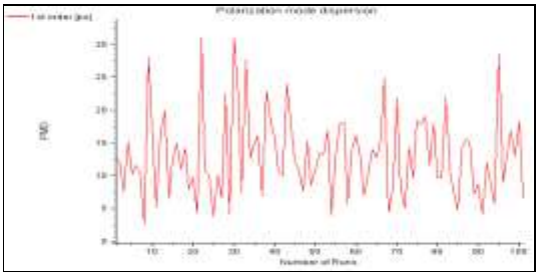

Figure 3.11: PMD Ensemble Simulation of Fiber-IV for Lower Mode

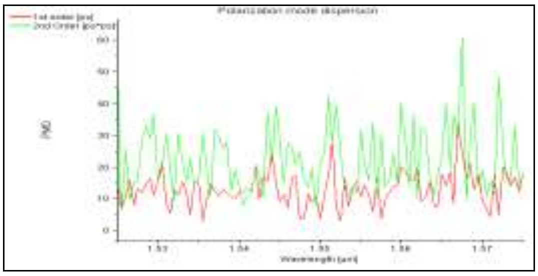

Figure 3.12: PMD Spectral Simulation of Fiber-IV for Lower Mode

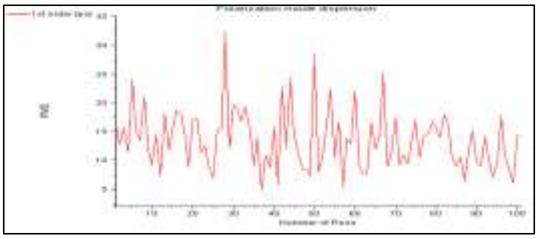

Figure 3.13: PMD Ensemble Simulation of Fiber-IV for Higher Mode

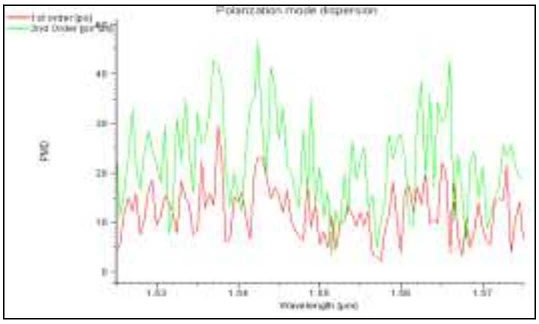

Figure 3.14: PMD Spectral Simulation of Fiber-IV for Higher Mode

Table 3.1 Classifications of Polarization-Maintaining Fibers

Fiber	**Geometry Type**	**Stress Type**
Circularly Birefringent	-Helical Core -Spun	-Twisted Round
Linear Single Polarization Differential Attenuation	-Side Pit -Side Tunnel	-Bow Tie -Flattened Depressed Cladding -Stress Guiding
Linearly Birefringent	-Elliptical Core -Dumbbell Core -Side Pit -Side Tunnel	-Elliptical Cladding -Elliptical Jacket -PANDA -Four-Sector Core -Bow Tie

Table 3.2: Ensemble Simulation of fiber (1st Order)

Fiber	**Mean Value (ps)**	**RMS (ps)**
I. I	13.125986	14.566336
II (a)	13.553486	14.712772
II (b)	13.238036	14.125211
II (c)	13.159420	14.242697
III	13.189284	14.284404
IV	13.051204	14.485852

Table 3.3: Spectral Simulation of fiber

Fiber	**1st Order**		**2nd Order**	
	Mean Value (ps)	**RMS (ps)**	**Mean Value (ps)**	**RMS (ps)**
I	12.424058	12.427580	22.054523	22.065250
II (a)	14.011563	15.188719	24.635112	26.717287
II (b)	13.339352	14.244407	24.967813	26.825545
II (c)	12.694488	13.749768	22.596157	24.396222
III	14.011563	15.188719	24.635112	26.717287
IV	12.965173	14.062667	22.511337	24.911744

Table 3.4: Bit rate and PMD coefficient of ITU Standard

Bit rate (Gb/S)	**Maximum PMD (ps)**	**PMD coefficient (ps/Km$^{1/2}$)**
II. 2.5	40	≤ 2.0
10	10	≤ 0.5
20	5	≤ 0.25
40	2.5	≤ 0.125

Through deforming the circular geometry of a fiber and/or introducing shape, stress regions, certain refractive index profiles, or by incorporating metal boundaries into the structure of waveguides. A successful structure to maintain polarization as suggested is the fiber-III (PANDA fiber). With this structure, a high birefringence can be achieved along with a low loss and low cross-talk[10]. In elliptical fibers, the birefringence is not as high as in PANDA fibers, and the required core size becomes impractical (extremely small) for the fiber to operate as a single mode waveguide. Introducing stress regions in the fiber or azimuthal variations of the refractive index can solve this problem. The ensemble and spectral simulation results are as shown in table 3.2 and 3.3.The polarization-maintaining fiber designs presented are of dispersion-shifted, dispersion-flattened, and dispersion-unshifted types.

4. CONCLUSION

The zero polarization-mode dispersion single-mode design is a dispersion-shifted fiber that provides large effective area and hence reduces signal distortions due to nonlinearity in fibers. The second order PMD is dependent of wavelength and it similar like chromatic dispersion and 2nd order coefficient is square of 1st order and the standard 2nd order PMD coefficient is less than or equal to 0.2 ps/nm Km. The proposed PMD coefficient for a 99.994% probability that the power penalty will be less than 1 dB for 0.1 of the bit period[5]

The PMD is created during fiber manufacturing, affected during cable manufacturing, installation and by the environment. Thus it is essential to measure PMD at every stage of the fiber life.

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