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Comparative PMD Ensemble and Spectral Simulation of Fiber

Prof D. B. Bobade[1], Dr C. M. Jadhao[2]
[1]Associate Professor in Electronics, Shivaji College of Science, Chikhali
[2]Principal, Mauli College of Engineering and Technology, Shegaon.

Abstract

The polarization-maintaining fiber designs presented are of dispersion-shifted, dispersion-flattened, and dispersion-unshifted types. 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. The comparison is carried out and 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, PMD, Ensemble and Spectral Simulation, Birefringence.*

1. Polarization Mode Dispersion Models

In ideal single-mode fibers, propagation constants of the two polarization Eigen modes are degenerate. In real telecommunications fibers, perturbations act on the fiber in a way that it induces a birefringence, which splits this degeneracy. Consequently, when a pulse is launched in a fiber, it gives rise to a differential group delay between the two polarization Eigen modes. The stochastic behavior of these perturbations is an issue because it yields to the phenomenon of random mode coupling which makes impossible the basic definition of the differential group delay.

1.1 Principal states of polarization

The Principal States of Polarization (PSP) model[1] is based on the observation that at any given optical frequency, there exists a set of two mutually orthogonal input states of polarization for which the corresponding output states of polarization are independent of frequency to first order. The Differential Group Delay (DGD) resulting from Polarization Mode Dispersion (PMD) is then defined between the two output principal PSPs. The birefringence in telecommunication single-mode fibers varies randomly along the fiber length, an artifact of variation in the drawing and cabling process. Furthermore, owing to the temperature dependence of many of the perturbations that act on the fiber, the transmission properties typically vary with ambient temperature. In practice, fluctuations in temperature strongly affect PMD time evolution. To evaluate properties of long fiber spans, one adopts a statistical approach. In this case of long span fibers, the polarization Eigen states can only be defined locally and the birefringence vector has to be considered as stochastic.

1.3 Dispersion vector definition

In the time domain, the Polarization Mode Dispersion (PMD) induces a time shift between the two Principal States of Polarization (PSP). In the frequency domain, the output state of polarization undergoes a rotation on the Poincaré sphere[2] about an axis connecting the two PSPs.

The rate and direction of rotation is given by the dispersion vector Ω (ω, z) given by:

$$\mathbf{\Omega}(\omega, z) = \Delta\tau \cdot \mathbf{P}_{b-} \qquad \text{………} (1)$$

Where Pb- represents the negative output principal state.

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The strength of the dispersion vector Ω (ω, z) is equal to the differential delay time Δτ between the two output principal states, where its combined Stokes vector corresponds to the Stokes vector of the negative output principal state. The direction of the Dispersion Vector Ω defines an axis whose two intercepts with the surface of the Poincaré sphere correspond to the two principal states of polarization at the fiber output.

1.4 Poincaré sphere

The Poincaré sphere[2] is a graphical tool that allows convenient description of polarized signals and polarization transformations during propagation. A point within a unit sphere can uniquely represent any state of polarization, where circular states of polarization are located at the poles. The coordinates of a point within or on the Poincaré sphere are the normalized Stokes parameters.

1.5 Ensemble simulation

Based on the Principal States of Polarization (PSP) model, one can model the whole fiber as a sum of N trunks where each trunk represents a uniform and constant birefringent device. A recursive formula[3] describing the evolution of the dispersion vector for N and N-1 concatenated trunks is the basis for the calculus of the first and second order of the Differential Group Delay (DGD) induced by the Polarization Mode Dispersion (PMD). In the ensemble simulation model, the PMD calculation is repeated in a number of runs. First, a set of concatenated fiber trunks is generated randomly. Then the polarization mode dispersion is calculated. In the second run, a second set of trunks is generated, followed by the PMD calculations. The process is repeated as many times as it is required. Statistics[4] of the PMD are calculated using the same number of runs as the ensemble representation.

1.6 Spectral simulation

In the frequency domain, the Polarization Mode Dispersion (PMD) causes the state of polarization at the output of a fiber to vary with frequency for a fixed input polarization, which occurs in a cyclic fashion. When displayed on the Poincaré sphere, the polarization at the output moves on a circle on the surface of the sphere as the optical frequency is varied. In the spectral simulation, a set of concatenated fiber trunks is generated randomly. The calculations[4] of polarization mode dispersion are performed over a range of wavelengths.

1.6.1 First order dispersion definition

The Differential Group Delay (DGD) that is calculated based on a stochastic fiber model (first order PMD) quantifies the first order Polarization Mode Dispersion. This latter represents the discrete model for Polarization Mode Dispersion (PMD) and is given by the following recursive formula[5]:

$$\mathbf{\Omega}_N(\omega) = \frac{\partial(W_N \Delta z \mathbf{S}_N)}{\partial\omega} + \left(\mathbf{S}_N \cdot \mathbf{\Omega}_{N-1}(\omega)\right)\mathbf{S}_N$$
$$+\cos(W_N\Delta z)\left[\mathbf{\Omega}_{N-1}(\omega) - \left(\mathbf{S}_N \cdot \mathbf{\Omega}_{N-1}(\omega)\right)\mathbf{S}_N\right]$$
$$+\sin(W_N\Delta z)\mathbf{S}_N \times \mathbf{\Omega}_{N-1}(\omega) \quad \text{... (2)}$$

Where

$$\mathbf{S}_N = \frac{1}{W_N}\begin{pmatrix} \Delta\beta + \delta\beta_1^N \\ \delta\beta_2^N \\ \delta\beta_3^N \end{pmatrix}$$

$$\mathbf{W}_N = \begin{pmatrix} \Delta\beta + \delta\beta_1^N \\ \delta\beta_2^N \\ \delta\beta_3^N \end{pmatrix} = W_N \mathbf{S}_N$$

In the above, the symbol W with index N represents the birefringence of the fiber. It consists of a background linear birefringence Δβ on top of which is added a perturbation birefringence δβ. On the Poincaré sphere, the δβ. On the Poincaré sphere, the Δβ vector is (Δβ, 0, 0) and the δβ vector is (δβ1, δβ2, δβ3), respectively. The above recursive formula represents the discrete version of the Poole's dynamical equation[5].

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Mean value of the first order PMD

For a long fiber span, the average Differential Group Delay (DGD) has a square root dependence on fiber length z as follows[6]:

$$< \Delta\tau >= \sqrt{\frac{8}{3\pi}} \Delta\beta' \sqrt{l_c} \sqrt{z} \quad \text{......... (3)}$$

Root Mean Square (RMS) of the first order PMD

The root mean square differential delay time has also a square root of length dependence[3]:

$$\sqrt{\left\langle \Delta\tau^2 \right\rangle} = \Delta\beta' \sqrt{l_c} \sqrt{z} \quad \text{......... (4)}$$

The Probability Density Function (PDF) of the differential delay time is Maxwell

$$PDF(\Delta\tau, z) = \sqrt{\frac{2}{\pi}} \frac{\Delta\tau^2}{\sigma_W^3(z)} e^{-\frac{\Delta\tau^2}{2\sigma_W^2(z)}} \quad \text{... (5)}$$

Second order dispersion definition

The second order Polarization Mode Dispersion (second order PMD) is defined by the following expression[3]:

$$\Delta\tau_{\omega}(\omega, z) = |\Omega_{\omega}(\omega, z)| \quad \text{... (6)}$$

Where $\mathbf{\Omega}_{\omega}$ (ω, z) the first frequency derivative of the dispersion vector $\mathbf{\Omega}$

$$\Omega_{\omega}(\omega, z) = \frac{\partial\, \Omega(\omega, z)}{\partial\omega}$$

2. Analysis of Polarization Mode Dispersion:

A statistical specification on PMD, however, can lead to a statistical boundary on the DGD values for the population as a whole. This boundary, defined in terms of probability, leads to a value for use in system design that is approximately 20% lower in DGD value and two orders of magnitude less in probability than the values that would be obtained without a statistical specification. From 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. An upper confidence limit at some probability level is such a metric.

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. 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[7]. 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. The upper confidence limit is named PMDQ, 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. IEC 61282-3 describes a method[8] of determining a maximum (defined in terms of probability) so that if a distribution passes the Method 1 requirement, the DGD across links comprised of only optical fiber cable will exceed the maximum DGD with a probability less than 6.5x10 –8. The DGDmax value is established for a broad range of distribution shapes. This DGDmax 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.

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3. Experimental Results

The calculations are done with PMD values that are representative of a given cable construction and manufacturing time period. 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. One means of such augmentation is to generate several possible cable values from the value of each uncabled fiber[2]. 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 PMDQ. The statistical analysis is applied to all fibers as under consideration by applying both First and Second order Ensemble and Spectral Simulation. The results obtained are as shown in Figure 1-4. 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 1.The PANDA[9] fiber is LEAF Dispersion shifted fiber. 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

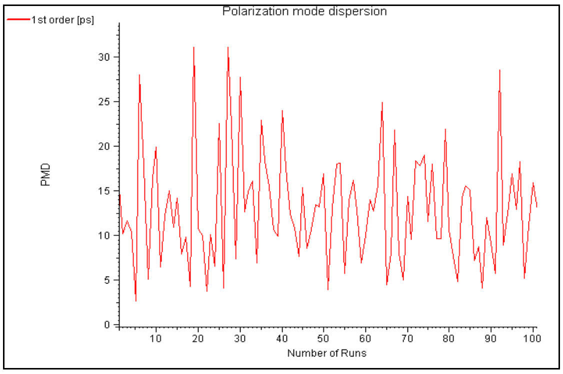

Figure 1: PMD Ensemble Simulation of Fiber-I

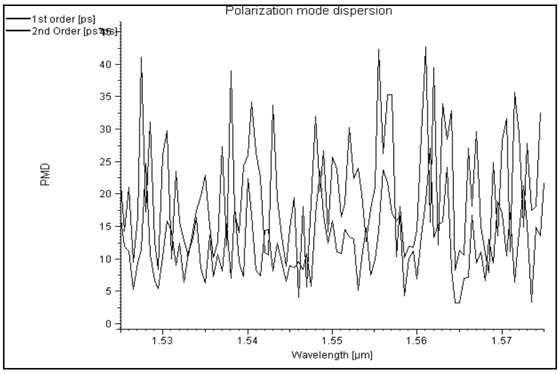

Figure 2: PMD Spectral Simulation of Fiber-I

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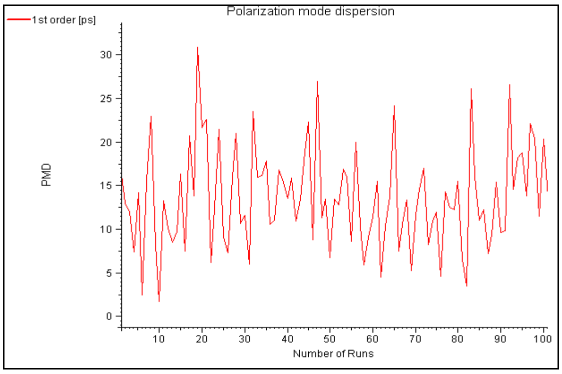

Figure 3: PMD Ensemble Simulation of Fiber-II

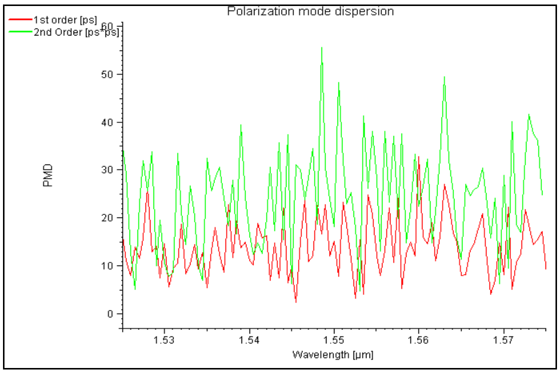

Figure 4: PMD Spectral Simulation of Fiber-II

Table 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 2: Ensemble Simulation of fiber (1st Order)

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Fiber	Mean Value (ps)	RMS (ps)
I	13.125986	14.566336
II	13.553486	14.712772

Table 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	14.011563	15.188719	24.635112	26.717287

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[10] Thermal stress has a much larger effect on polarization dispersion in an elliptical core fiber than does the geometrical anisotropy as long as Δ is chosen to be relatively small. It has been reported that this model provides a good estimate of birefringence for an extremely elliptical core fiber with e = 0.1.

Table 4: Bit rate and PMD coefficient of ITU Standard

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

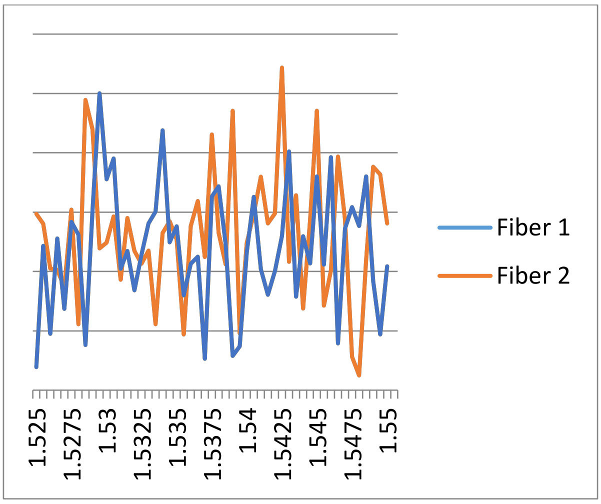

Figure 5: 1st Order PMD Vs Wavelength

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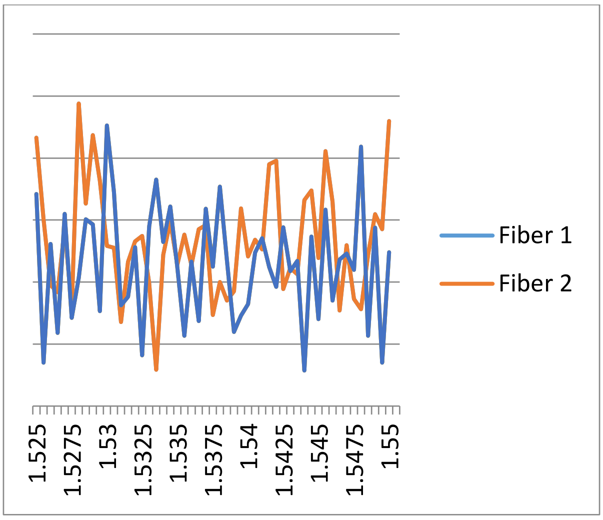

Figure 6: 2nd Order PMD Vs Wavelength

The Birefringence and polarization dispersion caused by thermal stress in single-mode fibers were formulated in terms of fiber structure and thermo elastic parameters by using a modified coupled-mode theory. They are proportional to core ellipticity, thermal expansion difference between core and cladding, Young's modulus, and photoelastic constant[6]. Taking electric field distributions taking into account derived normalized frequency dependence of these characteristics. Numerical comparison was made for germanosilicate, borosilicate, and phosphosilicate fibers. Thermal stress rather than geometrical anisotropy plays an essential role in estimating the birefringence characteristics values of the elliptical core fiber for a relatively small relative index difference.

The issues of maintaining polarization and polarization-mode dispersion in fibers have been discussed. Analysis and design of optical fibers that maintain polarization over long lengths provide zero polarization-mode dispersion, and function as polarizes or mode filters have been presented. The solution to maintaining polarization in fibers is achieved by optical fiber designs that provide either high birefringence with single-mode operation or single-polarization single-mode operation. 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. Also a wedge-shape waveguide structure with arbitrary wedge angles has been proposed for applications as a mode filter and polarizes. It employs mixed boundaries of metal and dielectric materials. In the first part of the work, designs for high-birefringence and single-polarization single-mode fibers have been addressed. The designs are based on multiple-clad geometries with the core and inner cladding regions being anisotropic due to induced stress. Refractive-index profiles with double and triple-clad structures were studied and optimized. The fiber designs were optimized for the two types of polarization-maintaining fibers in order to achieve high-birefringence fibers and single-polarization single-mode fibers with zero or very small dispersion at about 1.3 μm and 1.55 μm wavelengths. For the optimum designs, the propagation constant, cutoff wavelength, and dispersion characteristics are evaluated.

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