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BIREFRINGENCE AND POLARIZATION MODE DISPERSION PHENOMENA OF COMMERCIAL OPTICAL FIBER IN TELECOMMUNICATION NETWORKS

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ABSTRACT

The development of optical fibers from attenuation and absorption of fiber material for efficiency and quality has produced several positive results. However, several natural negative factors and environmental errors cause problems such as birefringence and dispersion mode variations. This article therefore proposed a simulation of birefringence and polarization mode dispersion (PMD) to investigate the emergence of interference and efforts towards finding a solution to the problem of optical fiber. Moreover, a single-mode fiber was investigated at the core refractive index and cladded with a core radius and fixed sample for a wavelength of infrared regimes. The performance of fibers was also evaluated through the determination of the PMD value of the fibers. The simulation results showed the difference observed in birefringence produced the power affecting the output. Meanwhile, the PMD also produced the light waves discovered to be experiencing widening pulses in the cladding.

Keywords: single-mode fiber, birefringence, polarization mode dispersion.

1. INTRODUCTION

The growth and application of telecommunication hardware and software components have rapidly developed over the last 30 years [1-3]. This is observed in the conduct of studies to obtain easier, cheaper, accurate, clear, and low-power solutions and products to transform network components with the expectation of ensuring no interruption while sending photonic signal information [4,5]. However, there are scientific challenges and environmental error optical fiber products carrying waves of information observed in the waveguide medium. It is therefore important to investigate these problems from the perspective of both the material and environmental factors [6,7].

One of the media components of telecommunications is optical fibers and a difference in its refractive index from the orthogonal polarization was observed due to the changes or damages to the size of its cylindrical symmetry. This further leads to a change in its propagation speed. This phenomenon is often called birefringence and mostly leads to Differential Group Delay (DGD) between two polarized waves and this is not desirable in the long-haul telecommunication system. Moreover, the variation in this concept causes random changes in the PMD [8]. Birefringence can be caused by intrinsic factors such as geometric and stress as well as extrinsic ones such as laterals stress, bending, and twist. This study considered the extrinsic factors and their possible effects on the intrinsic ones in each fiber but they are kept constant to determine the level of wave disturbance produced. However, the PMD parameter has been reported to influence the bit rate for optical communication systems such that when it has a small value, a higher bit rate is produced on the fiber [9]. The restrictions on the extrinsic factors were presumed to be placed in order to clearly understand the physical function of intrinsic factors such as the contribution of geometry and stress of the material to the interference of waves propagated in single-mode optical fibers and to provide commercial recommendations for fiber products to be designed and fabricated. Meanwhile, extrinsic factors are better understood from environmental disturbance and human errors on the fiber path used.

The inevitable imperfections in the manufacture of optical fibers lead to birefringence, which has been discovered to be one of the causes of pulse broadening in fiber-optic communications. Such imperfections can be geometrical such as lack of circular symmetry, due to the stress applied to the optical fiber and/or bending of the fiber. Birefringence is also intentionally introduced, for instance, by making the cross-section elliptical in order to produce polarization-maintaining optical fibers.

This paper, therefore, proposed the simulation of optical fiber with due consideration for several factors and physical quantities of controllable and readily variable parameters to mathematically and physically interfere with wave propagation. This simulation is required during the experiment due to its low cost, ability to manipulate and control several variables, and applicability in fibers production. It also aids the determination of the effect of

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polarization on the cylindrical fiber imperfect core as well as to prevent the significant effect of the dispersion magnitude determined. In Single-Mode Fibers (SMF) pulses, light waves have a limited spectral in a single state with the output usually widened while the polarization spreads throughout the whole series of fibers [10]. However, it is possible to explain this state of polarization using birefringence capital as observed in the effective difference in the index for orthogonal polarized normal modes [1]. The dispersion observed is PMD due to its small value compared to the others. Therefore, it is very important to conduct further study on the development of fiber design in communication systems to ensure better performance. This paper, however, investigated the characteristics of birefringence and PMD of commercial optical fiber using the Optifiber system.

2. THEORETICAL CONSIDERATION

The original optical fiber does not have a perfect cylindrical core due to its varied diameters and this causes voltage unevenness along the fiber. It also led to the difference in the propagation constant of the two polarization components and, consequently, making the fiber becomes birefringence. Moreover, the incorporated linear polarized light caused an assumption of the same amplitude for the two polarization components with no phase difference observed at the output end. However, the propagation of the light along the fiber led to the exit of one mode in the other phase due to the propagation constant of different phases. Therefore, at each point along the fiber (for random phase differences), the two components have the ability to produce elliptically polarized light while at π/2, it is circular. This means there is the development of the polarization from linear to an ellipse to circle to ellipse and back to linear and this alternating sequence has been reported to be continuing along the fiber [11].

Birefringence is caused by both intrinsic and extrinsic factors. For example, intrinsic disturbance accidentally occurs in the manufacturing process and becomes a permanent feature of the fiber. This includes the noncircular core causing the geometric aspect and the asymmetrical fields producing the stress aspect in the fiber around the core region. The external forces found to be causing the birefringence include lateral pressure, bending, and twisted fibers during handling and cabling process. These three mechanisms are, however, usually present to some extent in telecommunications fiber [12-13]. Birefringence is the difference between the polarization eigenmode propagation constants shown as [7],

$$\Delta\beta = \beta_x - \beta_y \tag{1}$$

Birefringence caused by lateral stress can be expressed by,

$$\Delta\beta_{Lateralstress} = -8\frac{Cpk_0}{\pi d}\left[1-\left(\frac{a}{d}\right)^2 H(V)\right] \tag{2}$$

While birefringence caused by bending is defined as follows,

$$\Delta\beta_{Bending} = -\frac{1}{8}\left(\frac{d}{R}\right)^2 ECk_0\left[1-\frac{1}{3}\left(\frac{a}{d}\right)^2 H(V)\right] \tag{3}$$

Birefringence caused by stress can be expressed by,

$$\Delta\beta_{Tension-coiled} = -2\frac{2-3v}{1-v}C\frac{f}{\pi dRc}k_0 \tag{4}$$

where,

$$H(V) = 2 + \frac{4(U^2-W^2)}{U^2V^2W^2} + \frac{4}{U}\frac{J_0(U)}{J_1(U)}$$

$$U = a\sqrt{n_1^2k_o^2 - \beta^2}$$

$$W = a\sqrt{\beta^2 - n_2^2k_o^2}$$

$$V = (U^2 - W^2)^{1/2} = k_0a(n_1{}^2 - n_2{}^2)^{1/2} = \frac{2\pi a}{\lambda}(n_1{}^2 - n_2{}^2)^{1/2}$$

where V is normalized frequency, β = propagation constant, C = Photo-elastic constant, p = lateral force, k_o= wave propagation constant in vacuum, E = the Young modulus, a = core radius, d = the outer diameter of the fiber, f= axial tension, c = speed of light in vacuum, υ = Poisson's ratio, n_1 = core refractive index, n_2 = cladding refractive index, and λ= wavelength.

The widening of the pulse in SMF is caused by birefringence. This happens when the input pulse moves the two orthogonal polarized components of the basic fiber mode at different group speeds and group velocities of V_{gx} and V_{gy}, to arrive at the ends of the fiber with length z. The delayed time, ΔT, between the two orthogonal polarized components is calculated by,

$$\Delta T = \left|\frac{z}{V_{gx}} - \frac{z}{V_{gy}}\right| \tag{5}$$

This difference in propagation time leads to an expansion of pulses called PMD which is a limiting factor especially in long-distance optical fiber communication systems operating at high bit rates. However, assuming the fibers have a constant birefringence, it applies only to those maintaining polarization.

PMD is a form of modal dispersion where two different polarizations of light in a waveguide, normally traveling at the same speed, travel at different speeds due to random imperfections and asymmetries, causing random spreading of optical pulses. Unless it is compensated, which is difficult, it ultimately limits the rate at which data can be transmitted over a fiber. Moreover, in an ideal optical fiber, the core has a perfectly circular cross-section and, in this case, the fundamental mode has two orthogonal polarizations (orientations of the electric field) traveling at the same speed. The signal transmitted over the fiber is randomly polarized through a haphazard superposition of the two polarizations but since

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it is in an ideal situation, an identical degeneration of the polarization occurs. However, in a realistic fiber, there are random imperfections breaking the circular symmetry and causing the propagation of the polarization at different speeds. In this case, the components of a signal slowly separate and this, for example, causes the pulses to spread and overlap. Due to the randomness of the imperfections, the pulse spreading effects in SMF correspond to a random walk, and thus have a mean polarization-dependent time-differential ΔT which is also known as the Differential Group Delay or DGD proportional to the square root of propagation distance *L*.Therefore, thePMD-induced pulse widening estimates are made using the following relationship [11]:

$$\Delta T = D_{PMD}\sqrt{L} \tag{6}$$

For long SMF, PMD values are calculated in the form of average DGD values using the following Equation [10],

$$\langle \Delta\tau \rangle = \sqrt{\frac{8}{3\pi}}\Delta\beta'\sqrt{l_c}\sqrt{z} \tag{7}$$

PMD can be also be calculated as a root mean square, (RMS),

$$\sqrt{\langle \Delta\tau^2 \rangle} = \Delta\beta'\sqrt{l_c}\sqrt{z} \tag{8}$$

where$T$ = total time delay, D = dispersion parameter, z = length of fiber, l_c= length of coupling, τ= time delay.

3. RESEARCH METHODOLOGY

The SMF parameters input simulated by Optifiber is shown in Table-1. The simulations were conducted to determine the SMF birefringence and PMD profile using the core and cladding parameters of each fiber with core diameter and cladding kept constant at 4.1µm and 62.5µm respectively. Moreover, the normalized frequency was maintained while the core and cladding refractive indices differentiating the fibers are presented in Table-1.

Table-1. SMF fiber optic refractive indices.

Fiber Optic	Core (n)	Cladding (n)
SMF 28	1.45213	1.44692
SMF 28e	1.4677	1.4624
SMF 28e+	1.45173	1.44602
SMF 28e+LL	1.45223	1.44702
SMF 28 ULL	1.44525	1.44002

The SMF profile was determined using the Refractive Index type Profile with regions 0 and 1 which served as the core and cladding parameters of optical fiber and pure Silica while Germanium material was used as positive dopants and Florin as negative. Moreover, the optical fiber mode used to produce an index capital at a given wavelength and to determine the fiber field capital was LP or Matrix Method with cutoff wavelength parameter indicated in the LP_{01} and LP_{11}. In addition, the fundamental property mode simulation was also set to determine the default values of the material, bending, and loss parameters. Meanwhile, in the scan section, the wavelength was adjusted by a fixed option and the values used for the part of the parameters were 1.2 to 1.6 with 100 iterations.

The birefringence caused by parameter disturbances started with the determination of the photo-elastic constant of the fiber and was found to be of 3.44×10^{11} m^2/kg.W, the Young modulus value of 7.75 x10^9kg.W/m^2, and the Poisson ratio of 0.164 extrinsic factors even though it was not counted as a dominant factor. Moreover, bending and stress in the fiber were also observed to have effects with the bending discovered to be 0.12m with a rolled fiber tension force of 0.5N. At the output section, a 0.4µm spectral range with 51 iterations was used while the PMD was obtained by adjusting the fiber length to 1000m, coupling length by 20m, and the spectral length was 0.1µm with 201 iterations.

4. RESULTS AND DISCUSSIONS

The birefringence caused by extrinsic factors was simulated with bending and tension force of the circular fiber kept constant on all types of fibers with these parameters considered to have the same disturbance of all the samples to evaluate the effect of intrinsic factors. The results at SMF 28, 28e, 28e +, 28e + LL and 28 ULL are shown in Figure-1 respectively.

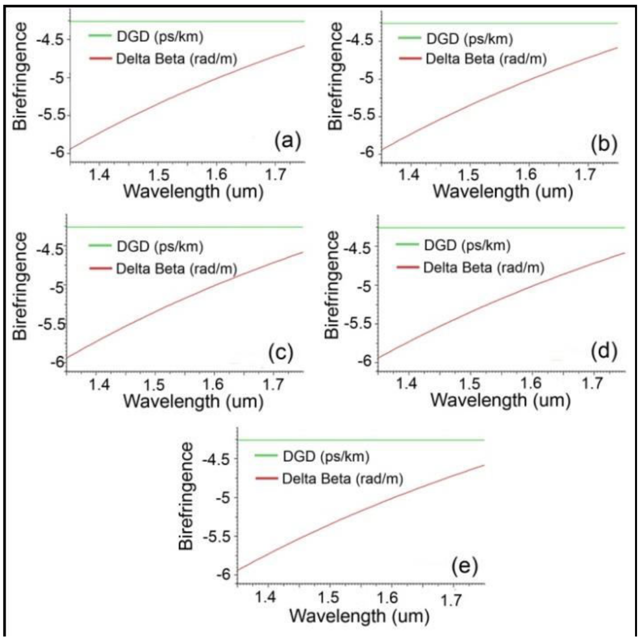

Figure-1. Birefringence SMF: (a) 28, (b) 28e, (c) 28e +, (d) 28e + LL, and (e) 28 ULL.

Figure-1 shows slight changes in all curves and by describing the discrepancies using factor 10^{-3}, the

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birefringence value was observed to be increasing with the wavelength (as the photon energy decreases) due to the difference in the second phase of the polarized wave while the DGD was discovered to be constant. The magnitude of birefringence at the wavelength of 1550nm fiber SMF 28 was -5.1753668 rad/m, SMF 28e had -5.17534 rad/m, SMF 28e + had -5.17539 rad/m, SMF 28e + had -5.14879 rad/m, and SMF 28e + had -5.175397 rad/m. In addition, at SMF 28 ULL, the value was recorded to be greater than others and this means there was a large power reduction at this optical fiber output. It is important to note that the SMF polarized light was contributed by the magnetic and electric field. Furthermore, a greater value of birefringence or the difference in wave propagation constant was found to be causing more polarization in the optical fibers and this further led to a greater phase difference between the magnetic and electric field of light. Hence, the core is imperfectly shaped in a circle due to the bending and stress force when the fiber is rolled.

The simulation showed the extrinsic parameters of birefringence used in the same fiber produced different values due to the variations in the modes of each fiber and core as well as the cladding refractive indices as shown in Table-2.

Table-2. Birefringence and DGD values.

Fiber optic	Birefringence (rad/m)	DGD (ps/km)
SMF 28	-5.1753668	-4.2590604
SMF 28e	-5.17534	-4.25504
SMF 28e+	-5.17539	-4.25901
SMF 28e+LL	-5.14879	-4.25906
SMF 28 ULL	-5.175397	-4.25906

These perturbations were accidentally introduced in the manufacturing process and later become a permanent feature of the fiber. Moreover, a noncircular core was found to have produced a geometric birefringence while the nonsymmetrical field caused stress birefringence. The refractive index of isotropic fibers depended on the polarization and propagation direction of light and the maximum difference between these indices was exhibited by non-cubic crystal structures. In addition, their phenomena have double refraction divided into two rays with slightly different paths by polarization. The curves representing anisotropic fibers generally refract a single incoming ray in two directions and these correspond to the two different polarizations, uniaxial or biaxial fiber. In the uniaxial one, the ray behaves according to the normal law of refraction with correspondence to the ordinary refractive index and this further makes the incoming ray to be normal at both incidence and refracting surface. However, as previously explained, the other polarization deviated from normal incidence and this means impossible to describe it using the law of refraction. In this case, the polarization components are perpendicular or ordinary and not perpendicular or extraordinary to the optic axis respectively, even in situations without double refractions.

The fiber with a single direction or optic axis of symmetry in its optical behavior was also observed to be symmetrical to the index ellipsoid, a spheroid in this case and was described according to the refractive indices, n_α, n_β and n_γ, along three coordinate axes. However, two of these were discovered to be equal, therefore, if $n_\alpha = n_\beta$ corresponding to the *x* and *y* axes, the extraordinary index is n_γ corresponding to the *z*-axis, which is also called the *optic axis* in this case. The wave consists of two polarization components generally governed by different effective refractive indices, and the material with the higher was discovered to have a slower phase velocity whole the other with the lower value was the *fast ray*.

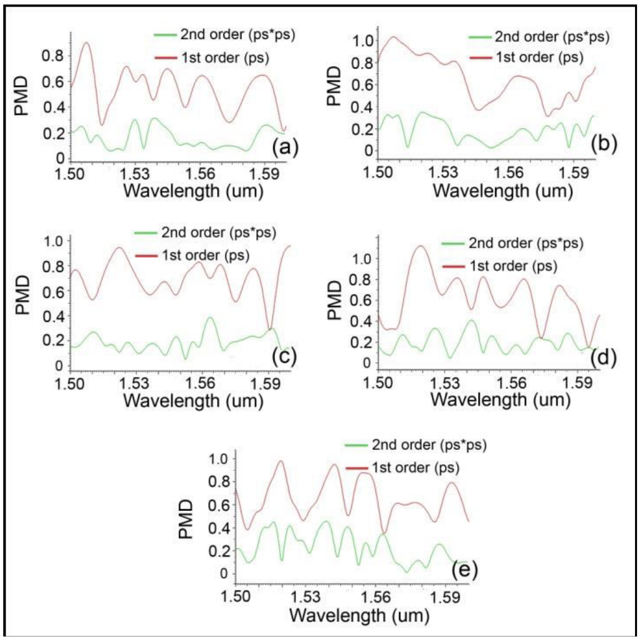

Figure-2. PMD SMF: (a) 28, (b) 28e, (c) 28e +, (d) 28e + LL, and (e) 28 ULL.

As depicted in Table-2, the birefringence is positive when the extraordinary index of refraction n_e is greater than the ordinary index n_o while a negative value shows that $\Delta n = n_e - n_o$ is less than zero. This, therefore, means the polarization of the fast (or slow) wave is perpendicular to the optic axis at a positive birefringence (or negative, respectively).

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Table-3. Average of DGD and RMS values.

Fiber optic	Average of DGD (ps)		RMS (ps)	
	1st order	2nd order	1st order	2nd order
SMF 28	0.6977	0.1893	0.7106	0.2003
SMF 28e	0.6630	0.1835	0.6940	0.2054
SMF 28e+	0.6977	0.1893	0.7106	0.2003
SMF 28e+LL	0.6247	0.1889	0.6639	0.2053
SMF 28 ULL	0.6523	0.2288	0.6706	0.2586

The circular cores did not maintain a polarization input state for more than a few meters, and this means they are not perfectly circular. Moreover, the PMD value of the single-mode optical fiber was caused by the birefringence of the fiber and this means a variation in this factor led to the random changes in the PMD [8,9] based on the difference in the mode field diameter (MFD) of each fiber. In Figure 2, the PMD value fluctuated due to the variation in the birefringence value along the fiber with the wavelength. In addition, the polarization of the fiber was also discovered to have caused its dispersion while the difference in the birefringence was caused by the imperfections of the fiber core. Therefore, a greater value of birefringence led to more significant polarization as well as a great delay in the polarized wave at the output.
Table-3 describes the values of DGD and RMS for first and second-order dispersion. In the frequency domain, PMD caused the state of polarization at the output of the fiber to vary with frequency for a fixed input polarization in a cyclic fashion. Moreover, on the Poincare sphere display, the polarization at the output moves in a circle on the surface of the sphere as the optical frequency was varied. In addition, in the spectral simulation, a set of concatenated fiber trunk was randomly generated while the PMD was calculated over a range of wavelengths and DGD evaluated based on a stochastic fiber model (first-order PMD) to quantify the first order of PMD. However, the second-order showed the expression of first frequency derivative of the dispersion vector as a function of frequency and position. This means the first order curves explained more fluctuations as observed in the reduction in the PMD as the wavelength increases, but, the second-order curves are more slightly fluctuated over the wavelength and was recorded to have produced trends nearly constant compared to the first order.

The symmetry-breaking random imperfections were classified a geometric asymmetry as observed in the slightly elliptical cores or stress-induced material birefringence, in which the refractive index itself depends on the polarization. Both of these effects can stem from either imperfection in manufacturing (which is never perfect or stress-free) or from thermal and mechanical stresses imposed on the fiber in the field - moreover, the latter stresses generally vary over time.

A related effect is a polarization-dependent loss (PDL) which involves two polarizations suffering different rates of loss in the fiber due to asymmetries. This factor similarly degraded the signal quality. It is important to note that a circular core is not required to have two degenerate polarization states but there is a need for a core with a symmetry group that admits a two-dimensional irreducible representation. For example, a square or equilateral-triangle core has two equal-speed polarization solutions for the fundamental mode and these general shapes also arise in photonic-crystal fibers. However, any random imperfections that break the symmetry have the ability to cause PMD in such a waveguide.

The PMD has random and time-dependent effects; therefore, there is a need for an active device to respond to feedback over time. Such systems are expensive and complex combined with the fact PMD is not of the most commonly used limiting factor in the lower data rates. Therefore, PMD-compensation systems have not been widely deployed in large scale telecommunications systems. The output of the fiber was essentially divided into two principal polarizations (no first-order variation of time-delay with frequency), and a differential delay was applied to re-synchronize them. Such fibers currently have practical problems such as higher losses and costs. An extension of this idea is a single-polarization fiber where only a single state is allowed to propagate along the fiber while the others escape because they are not guided.

5. CONCLUSIONS

The occurrence of birefringence in optical fibers is influenced by internal and external factors such as bending and tension forces. This, therefore, changes the cores from circular to ellipses and this makes light waves experienced an elliptical or circular polarization to produce two waves in different phases. Moreover, SMF 28 ULL was discovered to have the highest birefringence value while the lowest was recorded at SMF 28e + LL. Birefringence can cause PMD. SMF 28 has the largest PMD value with a value of 0.69770237ps compared to other optical fibers and this consequently led to a large pulse widening at cladding with a low bit rate.

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