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Chapter

Simulation of Birefringence and Polarization Mode Dispersion Characteristics in Various Commercial Single Mode Fibers

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Abstract

Single mode optical fiber operation for long haul distance communication media has rapidly developed. Several efforts are implemented to reduce and control the attenuation and absorption of signal propagation. However, fiber parameters still experienced interference with internal and external factors that result birefringence and polarization mode dispersion such as bending power losses, signal widening and increasing wavelengths. In order to reduce and optimize the interference which is experimentally difficult to demonstrate because of the very long fibers hence a numerical simulation is set with perspective of twisted fiber disorder as a function of wavelengths and fiber geometry. The simulation evaluates the various refractive indices, radius of fibers and wavelength sources. The quality of optical fiber interference can be identified from the twisted power losses values with different variations of twisted radius. This model obtained indicates the greatest power losses occurring as a function of radius, refractive indices and wavelength. The results show that normalized frequency value has important role in determining the effectiveness the optical fiber performance and stability of power deliver. The addition of wavelength can affect the fibers experiencing birefringence and polarization mode dispersion occurring at wavelength of telecommunication regimes.

Keywords: single mode fiber, birefringence, power loss, wavelength

1. Introduction

The use of fiber optic in telecommunication circuits and networks cannot avoid the influence and appearance of waveguide geometry problems such as bending and twisting although the growth and investigation of telecommunication hardware and software components to minimize the negative effects still 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]. Fiber parameters still experience interference with internal and external factors that result birefringence and polarization mode dispersion. Not only power attenuation and signal defects but also due to material factors and the effect of the power transmitted at a certain wavelength then it can reduce the signal profile and quality. 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 discrepancy of refractive indices 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. This performance partially can be observed in fiber bending. Moreover, the variation in this concept causes random changes in the Polarization Mode Dispersion (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 one of them 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 fiber optic lead to birefringence, which has been discovered to be one of the causes of signal widening in optical fiber. Such imperfections can be geometrical such as a circular or elliptical symmetry problem, since the mechanical force applied and/or bending of the fiber. Birefringence is also intentionally introduced, for example, by using the cross-section elliptical, circular in order to produce polarization-maintaining fibers.

This chapter, 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 polarization on the cylindrical fiber imperfect core as wellas 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.

Optically, power losses due to bending in decibel unit can be expressed by:

$$\mathrm{L} = 10\log_{10}\frac{P_i}{P_o} = 10\log_{10}\left[\frac{1}{\exp(-2\propto L)}\right] = 4.342\left(-2\propto L\right) \quad (1)$$

where P_i is input power (Watt), P_o is output power (Watt), α is power loss coefficient (m^{-1}), and L is length of fiber (m) [11].

Therefore, in order to minimize power losses and geometry disturbance caused by birefringence, this chapter, however, investigated the characteristics of birefringence and PMD of commercial optical fiber using the OptiFiber system. OptiFiber is optical fiber software to design and calculate several optical parameters and functions. Fiber optics may have graded index fibers and concentric layers of lossless materials that can be estimated by using a sequence of constant index layers. In term of mode solution, OptiFiber can solve an exact solution based on terms and boundary conditions at boundaries instead of relying on meshes to estimate the geometry and structure. The mode solvers are important for single mode and multimode fiber calculations as many modes in the spectrum will occur. OptiFiber allows users to decompose any field into the fiber modes. The modes complex coefficients for any field can be calculated. In the same way, by defining the intensity or the amplitude of modes, OptiFiber can demonstrate the total (composition of modes). This is able to compute the single mode and multimode field after propagating down the fiber by a specified distance. Therefore, SMF and refractive indices ones are evaluated for wavelength sources of 1310 nm and 1550 nm in normalized frequency regimes over the radius and fiber bending. Thus, it can give a better contribution for optical application purposes of fibers.

2. Theoretical aspects

Birefringence is the optical property of a material having a refractive index depending on the polarization and propagation direction of light [1]. These phenomena can be called as birefractive (or birefringent) representing optically anisotropic materials. The birefringence is often quantified as the maximum difference between refractive indices exhibited by the material such as crystals with structures of non-cubic crystal. Those can be meant as plastics under mechanical stress. It is also responsible for the phenomenon of double refraction where by a ray of electromagnetic wave, if wave incident upon a birefringent material, is split by forming polarization into two rays taking slightly different paths. Danish scientist Rasmus Bartholin in 1669, who firstly described and observed this effect [7] in calcite, a crystal which have one of the strongest birefringence. But, Augustin-Jean Fresnel that figured out the phenomenon of polarization, understanding spectral of light as a wave with field components in transverse polarization (perpendicular to the direction of the wave vector). This event was not until the 19th century. Birefringence represents double refraction occurs if electromagnetic waves are launched to a certain material waveguide and it will split into two different signals. Two kind examples of optical material causing birefringence are Boron nitride and Calcite crystals. Birefringence can splits the signals into two images of the similar color as a "double image". It just as a prism splits waves into a large number of colors.

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 then consequently, the optical 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, 12].

Birefringence is caused by both intrinsic and extrinsic factors. For example, intrinsic disturbance accidentally occurs in a factory-made process to be 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 [13, 14]. Birefringence is the difference between the polarization eigenmode propagation constants shown as [7],

$$\Delta\beta = \beta_x - \beta_y \tag{2}$$

Birefringence caused by lateral stress can be expressed by,

$$\Delta\beta_{Lateralstress} = -8\frac{Cpk_0}{\pi d}\left[1-\left(\frac{a}{d}\right)^2 H(V)\right] \tag{3}$$

While birefringence caused by bending is defined as follows,

$$\Delta\beta_{Bending} = -\frac{1}{8}\left(\frac{d}{R}\right)^2 ECk_0\left[1-\frac{1}{3}\left(\frac{a}{d}\right)^2 H(V)\right] \tag{4}$$

Birefringence caused by stress can be expressed by,

$$\Delta\beta_{Tension-coiled} = -2\frac{2-3\upsilon}{1-\upsilon}C\frac{f}{\pi dRc}k_0 \tag{5}$$

where,

$$H(V) = 2 + \frac{4(U^2 - W^{2)}}{U^2V^2W^2} + \frac{4}{U}\frac{J_0(U)}{J_1(U)} \tag{6}$$

$$U = a\sqrt{n_1^2k_o^2 - \beta^2} \tag{7}$$

$$W = a\sqrt{\beta^2 - n_2^2k_o^2} \tag{8}$$

$$V = \left(U^2 - W^2\right)^{1/2} = k_0 a\left(n_1^{\,2} - n_2^{\,2}\right)^{1/2} = \frac{2\pi a}{\lambda}\left(n_1^{\,2} - n_2^{\,2}\right)^{1/2} \tag{9}$$

Where V is normalized frequency, β = propagation constant, C = Photo-elastic constant, p = lateral force, k_o = wave propagation constant in vacuum, E = 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.

Light is linearly polarized through SMF assuming that the two polarization components have similar amplitude and at the output end there is no difference of phase. But when light propagates along the fiber, one mode exits from difference phase due to propagation constants. Thus, at each point along the fiber (for random phase differences) the two components will produce an elliptical polarized light. In phase difference $\pi/2$, a circular polarized light can be produced. In this case, the changes of polarization are from linear to ellipse to circle to ellipse and back to linear. This alternating polarization sequence continues along the fiber. The L_p length of the polarizing fiber rotated through 2π radians angle is expressed as the length of the fiber pressure given by the equation as follows,

$$L_p = \frac{2\pi}{\delta\beta} \tag{10}$$

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 [12].

$$\Delta T = \left| \frac{z}{V_{gx}} - \frac{z}{V_{gy}} \right| \tag{11}$$

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 one of modal dispersion representing a distortion mechanism happening in multimode fibers and other waveguides, where the signal is distributed in time since the traveling velocity of the optical light is not similar to all modes. Other names for these phenomena include kinds of distortion and dispersion such as multimode distortion, multimode dispersion, modal distortion, intermodal distortion, intermodal dispersion, and intermodal delay distortion. Modal dispersion in a step-index fiber optics can be analogically compared with multipath propagation of a radio signal. Spectra of optical wave launch to the fiber with various angles to the fiber axis, until the fiber's acceptance angle. Waves transmit to a shallower angle travel by a more direct path, and arrive sooner than optical spectra those enter at a steeper angle (that reflects many times off the boundaries of the core as they propagate to the length of optical fiber). The arrival of different components of the signal at different times distorts the shape [3]. Modal dispersion limits the bandwidth of multimode fibers. For instance, a typical step-index fiber with a 50 μm core would be limited to approximately 20 MHz for a one kilometer length, then it can be said as a bandwidth of 20 MHz km. Modal dispersion can be considerably reduced, however it never completely eliminated, by the use of a core which have a graded refractive index profile. But, multimode graded-index fibers that have bandwidths exceeding 3.5GHz·km at 850 nm are nowadays commonly manufactured for use in 10Gbit/s data links.

Modal dispersion is different from chromatic dispersion, a distortion that will produce since the differences in propagation speed and direction of various wavelengths of optical spectra. Ideally, modal dispersion can occur, as monochromatic electromagnetic wave. A particular case of it is polarization mode dispersion (PMD), a dispersion phenomenon of fiber generally associated with single-mode fibers. This PMD results if two modes that normally propagate at the similar speed because of fiber core geometric and stress symmetry (for instance, two orthogonal polarizations in a waveguide of circular or square cross-section), launch at different speeds because of random imperfections that break the symmetry.

PMD has linearly effect when electromagnetic wave propagates in a resonator waveguide, namely "single-mode" fibers. Although the waveguide as a single mode, these optical fibers contribute two modes of traveling pattern distinguished by their polarization. Due to the fiber experiences the birefringence, the two modes propagate with different group velocities, and this birefringence random change along the length of fiber produces in arbitrary coupling between the modes. PMD phenomena lead to pulse distortion and system impairments in term of current practical transmission technology, resulting that limit the transmission capacity of the fiber. This study has been reviewed by researcher [3, 13], generally covering the demonstrative aspects and applications of PMD characteristics to fiber waveguide systems and the PMD effects on nonlinear fiber waveguide. In this study, it is aimed to complement the investigation and to analyze and synthesize the basic principle and concept of PMD, interweaving and linking the basic rule and mathematical formulation that emerge scattered in kind sources in the references. Author will describe the relationship between time and frequency domain analyses and the isomorphic connection between the three-dimensional (3-D) by using real-valued 3-D Stokes vectors and the two-dimensional (2-D) view using complex-valued 2-D Jones vectors. Isomorphic pairings of users such as these have been greatly applied elsewhere in photonics and optoelectronics such as in opto-mechanics, in opto-quantum mechanics [7], and also in the unification of quantum theory and general relativity [8]. Authors consider this methodology for the objective and aims.

Basically at least there are three different dispersive characteristics in fiber optics of which dispersion can occur in polarization effect and is the most complex. One of fiber mode systems, i.e., a multimode fiber system, a signal pulse can separate into multiple spatial paths or modes [13]. Each mode or component may arrive at the receiver at a certain time, widening the received signal. Another mode fiber, single-mode fiber answers the differential mode delay cases, will allow data values to be gone up until chromatic dispersion — the variation of propagation speed over the wavelength — results unacceptable signal broadening [12, 14]. The quantity of chromatic dispersion that a system can influence is inversely proportional to the square of the bit rate since an increment data values means not only narrower bit slots, but also a wider spectrum and increased spreading that are more sensitive to the widening of neighboring signals [15].

In polarization concept, namely The Principal States of Polarization model [Poole and Wagner, 1986] [15–17] is referred to the experiences that at any given optical parameters such as frequency, there exists a set of two mutually orthogonal input states of polarization effect where the relationship output states of polarization phenomena are found that it independent of frequency to first order. The Differential Group Delay (DGD) producing from PMD is then introduced for the two output principal PSPs. Generally, in telecommunication single-mode fibers system the birefringence varies randomly along the length of fiber, an artifact of variation in the drawing and cabling process. In addition, involving to the thermodynamic function and dependence of the disturbances that deal with on the fiber, the propagation properties of wave particularly will vary with ambient temperature and circumferences [16]. Practically, fluctuations in thermodynamic function such as temperature strongly influence PMD time evolution. To resolve properties of long fiber spans, one considers a statistical mechanics approach. Therefore, in this situation of long span fibers, the effects of polarization Eigenstates can only be introduced locally and the birefringence vector has to be considered as stochastic phenomena.

In fiber optics, generally there are slightly several discrepancies in the traveling characteristics of electromagnetic waves with different sates of polarization. A *differential group delay* can happen even for optical fibers which in accordance with the design will have a rotational symmetry and therefore they exhibit without birefringence. This case is able to produce random imperfections such as bending, twisting of the fiber optics, or from other kinds of mechanical perturbations stress, strain as the results of mechanical and temperature changes. Especially, because of the effect of influence of twisting and bending, the cabled fiber having PMD can be completely different from the similar to optical fiber on a spool. However, nowadays new designs can be used to optimize and apply fiber-optic links in order to reduce the disturbances or low PMD, but the mobile and handling of such cables is still able to have several disturbances. The terms PMD and DGD are misconducted in solving the dispersion or they are interchangeably often used. However, they sometimes have slightly different meanings. Several researchers use the phenomena of PMD and consider DGD to be its magnitude. Others definition of PMD is as the statistical deviation formulation of DGD in several wavelength range. It can be noted that for fiber optics, actually the DGD can have a complicated and substantial relationship over fiber optic wavelength source. Nevertheless, other researchers apply the *second-order* term of PMD for the derivative of the differential group delay in term of the angular frequency, even though there is actually no second-order derivative involved. PMD can contribute to pulse dispersion and therefore causes transmission impairment. Although PMD is usually thought of as a fiber transmission effect, it is supported by the repeater has to be taken into account since the sum of PMD in a trajectory is made up of contributions from the repeater and the transmission fiber. The objective of the repeater design is to produce the PMD contribution of the repeater smaller than optical fiber (that is <0.15 ps/km). The largest potential components of PMD are erbium-doped fiber and the isolator. Isolator components are designed and modified to have a PMD compensation element which they greatly can reduce the PMD from that found in standard single-stage devices (generally more than 1 ps). PMD is also greatly reduced by dual-stage isolators. One has to care during the manufacture of the erbium-doped fiber in order to minimize its PMD. A repeater's PMD on average can be expected to be less than 0.30 ps. On the other hand, the repeater's PMD cannot be significantly contributed by the couplers.

PMD, as a modal dispersion with two kinds polarizations of signal in the fiber, generally traveling with a similar speed, propagate at various speeds due to random asymmetries and, imperfections hence it results any distribution of signals. If it is not compensated, that is not easy; it ultimately limits the value where signals can be launched over a fiber. Moreover, in an ideal fiber, the geometry core has a perfectly circular and, the fundamental mode has two orthogonal polarizations traveling at the same speed. Also, the signal is randomly polarized through ahaphazard superposition of the two polarizations, however; since it is in an ideal situation, an identical degeneration of the polarization occurs. However, in a commercial fiber, there are uncertain imperfections having damage the cross section 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 signals to propagate and overlap. Due to the randomness of the imperfections, the signal spreading effects in SMF correspond to a random traveling, and hence have a mean polarization-dependent time-differential ΔT which is also introduced as the Differential Group Delay (DGD) proportional to the square root of propagation distance L. Therefore, the PMD-induced pulse widening estimates are made using the following relationship [16, 17]:

$$\Delta T = D_{PMD}\sqrt{L} \tag{12}$$

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

$$\langle \Delta\tau \rangle = \sqrt{\frac{8}{3\pi}}\Delta\beta'\sqrt{l_c}\sqrt{z} \tag{13}$$

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

$$\sqrt{\langle \Delta\tau^2 \rangle} = \Delta\beta'\sqrt{l_c}\sqrt{z} \tag{14}$$

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

3. Single mode fiber: performance assessment

The SMF parameters input numerically demonstrated 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 4.1 μm and 62.5 μm respectively. Moreover, the normalized frequency was maintained while the core and cladding refractive indices differentiating the fibers are presented in **Table 1**. The value of SMFs having the range of normalized frequency of LP_{01} can be defined as core and cladding refractive indices and control single mode performance as depicted in **Figure 1**. However, the discrepancies of each sample show how power is delivered to the fiber.

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

Table 1.
SMF fiber optic refractive indices.

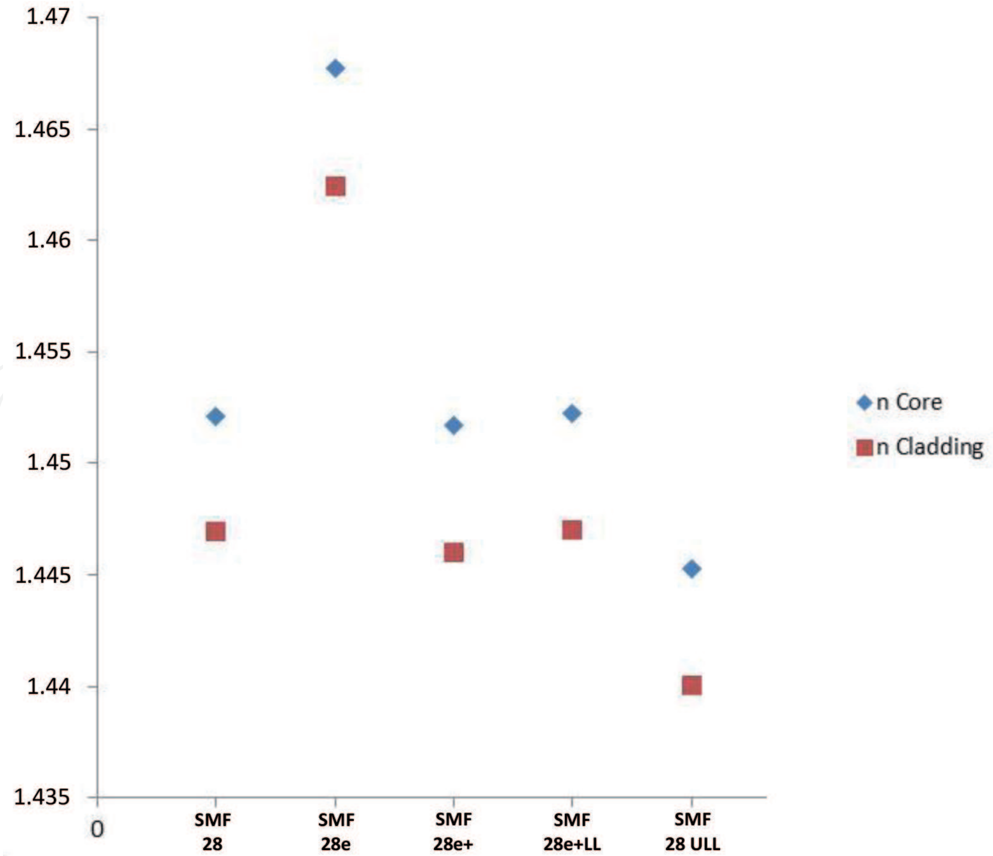

Figure 1.
Core and cladding profile for various SMFs of ***Table 1****.*

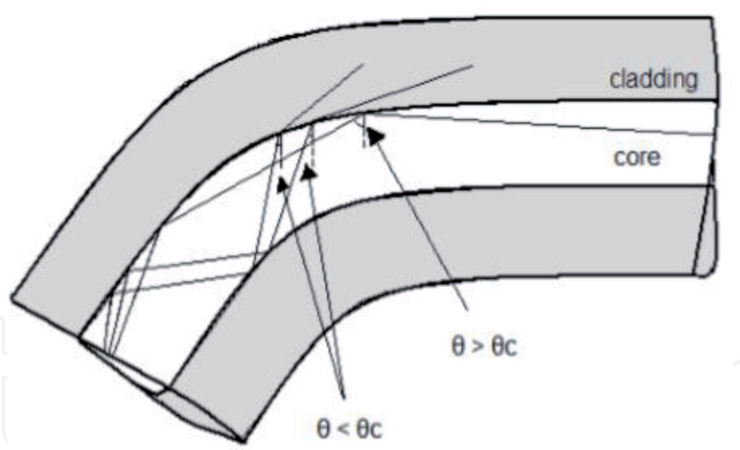

Figure 2.
Schematic profile of refractive ray due to fiber bending.

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 mode (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 determinethe default values of the material, bending, and loss parameters as illustrated in **Figure 2**. 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.

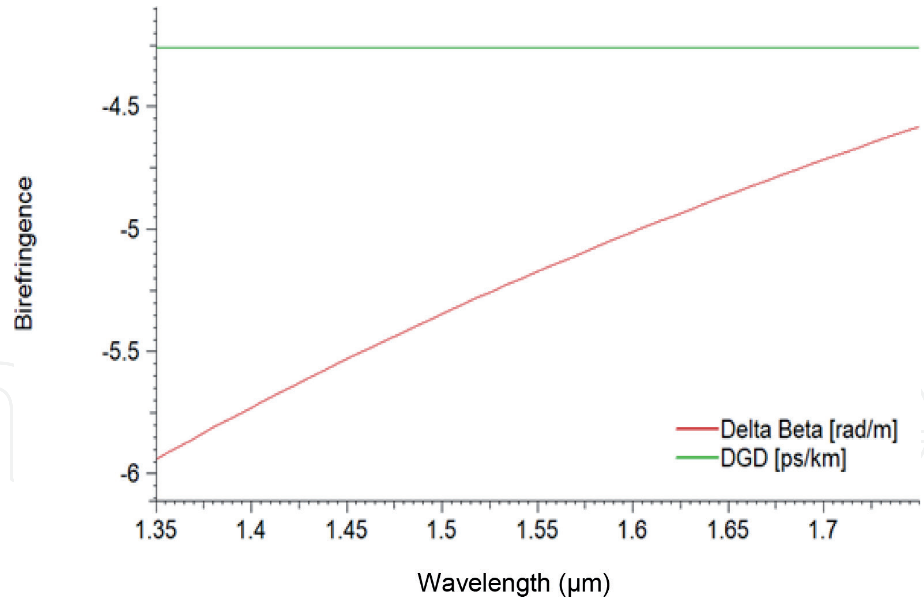

Figure 3.
Birefringence profile of SMF 28.

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 7.75×10^9kg.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 0.12 m with a rolled fiber tension force of 0.5 N. At the output section, the value of 0.4 μm spectral range with 51 iterations was used while the PMD was obtained by adjusting the fiber length to 1000 m, the coupling length by 20 m, and the spectral length was 0.1 μm with 201 iterations.

As bending induced parameters of SMF, the numerical demonstration can explain several losses over wavelength and radii. 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 nearly the same as shown in **Figure 3**.

Figure 4 shows of SMF 28 profile, which is slight change in all SMF curves and by describing the discrepancies using factor 10^{-3}. The 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 1550 nm 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.

As depicted in **Figures 5** and **6**, power losses are mostly affected by 1550 nm where this wavelength has low energy. Also it readily produces power losses even SMF 28 ULL is significant amount as a result of its normalized frequency.

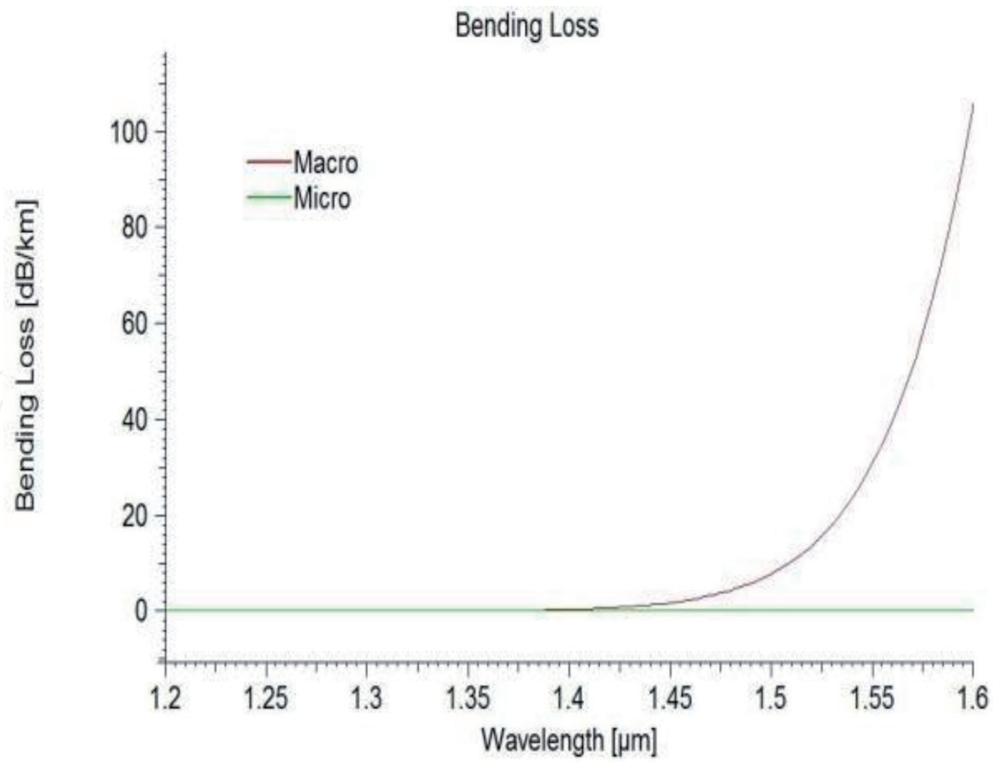

Figure 4.
Bending loss of SMF-28.

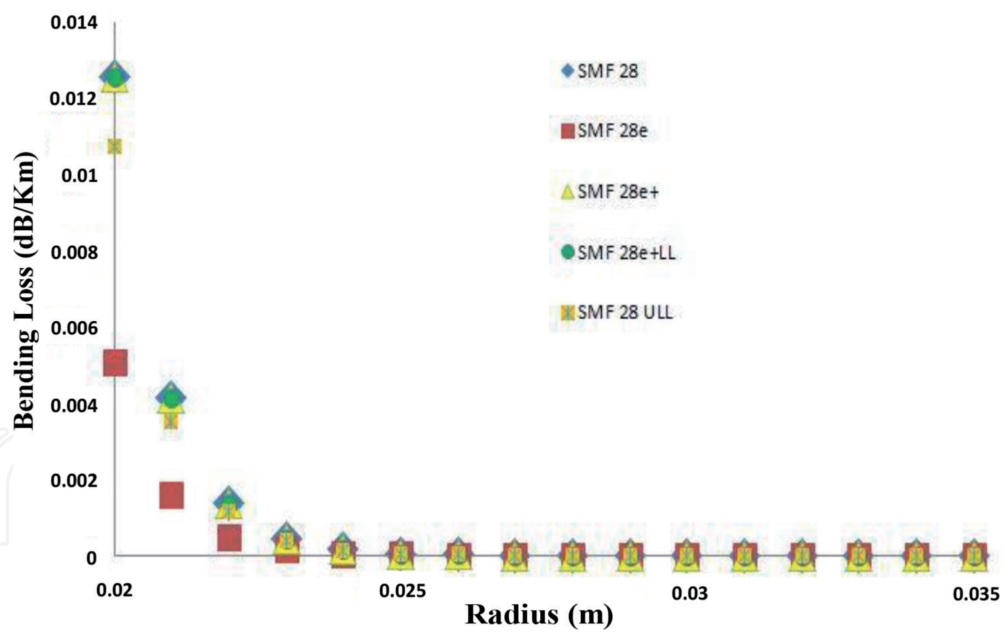

Figure 5.
Power losses due to bending of 1310 nm.

Figure 7 describes that birefringence of each fiber is nearly the same value, but they are not if corrected by 10^{-2}. They are decreased as a function of wavelength since the lower energy of wavelength source is applied, the smaller the birefringence is produced.

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**.

These perturbations were accidentally known in made factory process and later become a permanent feature ofthe fiber. Moreover, a noncircular core was found to

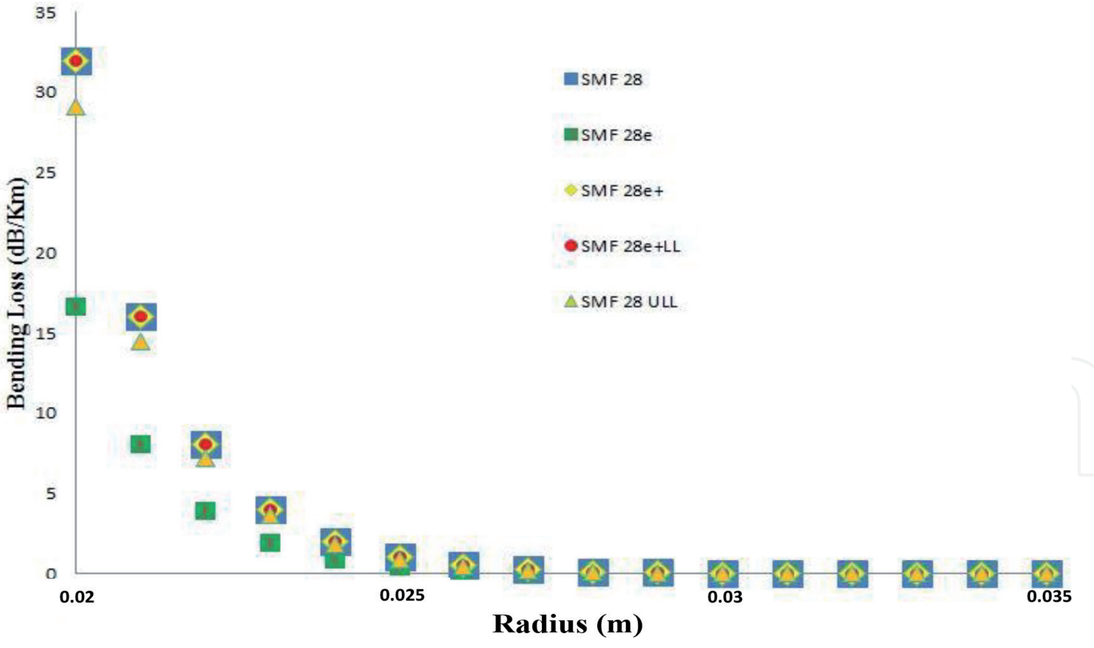

Figure 6.
Power loss due to bending of 1550 nm.

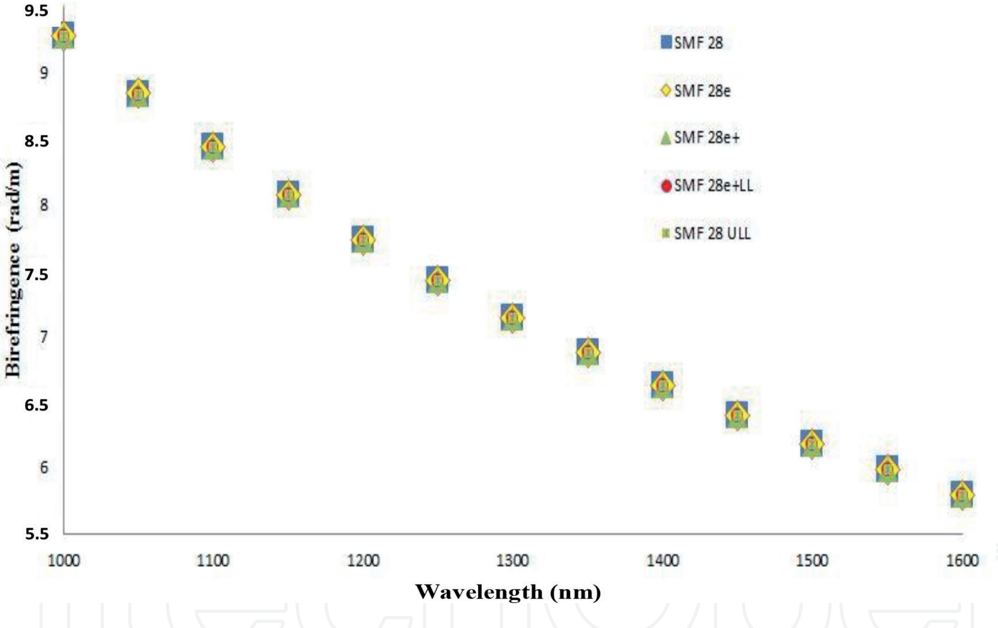

Figure 7.
Birefringences of several SMF.

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

Table 2.
Birefringence and DGD values.

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 explained based on the refractive indices, n_α, n_β and n_γ, along Cartesian coordinate. But, two of these were known to be the same, hence, if $n_\alpha = n_\beta$ corresponding to the x and y axes, the extraordinary index is n_γ over the z-axis. The signal 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*.

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 slow or fast wave is perpendicularto the optic axis at a negative or positive birefringence respectively.

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 [12, 17] based on the difference in the mode field diameter (MFD) of each fiber. In **Figure 8**, 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 output of polarization vary with frequency for a fixed input one in a cyclic fashion. Moreover, on the Poincare sphere display, the output polarization propagates in a circular pattern on the surface where the 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.

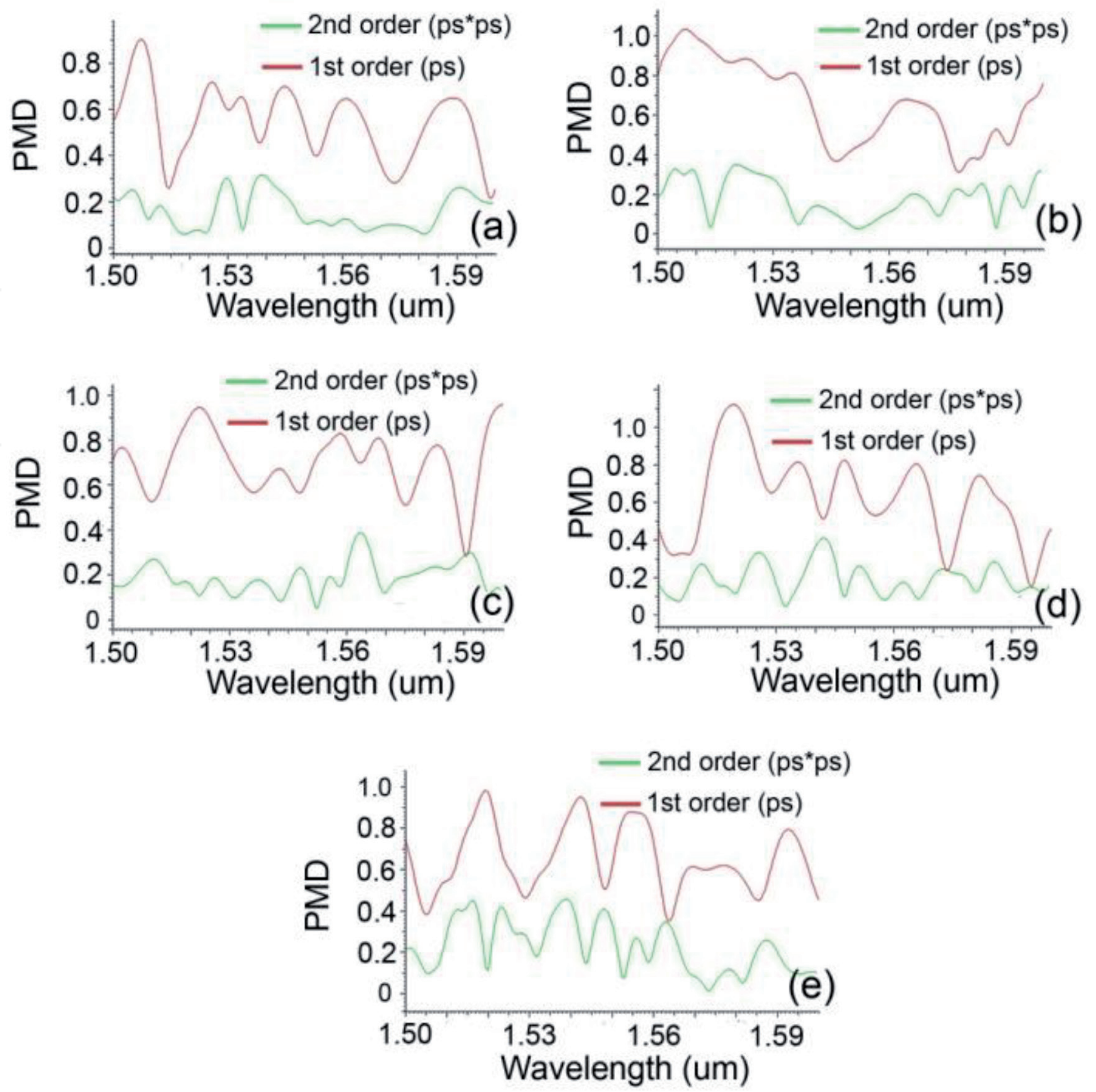

Figure 8.
PMD SMF: (a) 28, (b) 28e, (c) 28e+, (d) 28e + LL, and (e) 28 ULL.

Fiber optic	Average of DGD (ps)		RMS (ps)	
	First order	Second order	First order	Second 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

Table 3.
Average of DGD and root mean square (RMS) values.

The symmetry-breaking random imperfections were classified a geometric asymmetry as observed in the slightly elliptical cores or stress-induced fiber birefringence, in which the refractive index itself is a function of polarization. Both effects can stem from either imperfection in made factory process or from mechanical and thermal stresses imposed on thefiber in the field, moreover the latter stresses generally vary over time. A related effect is a polarization-dependent loss (PDL) that involves two polarizations suffering different rates of loss due to asymmetries. This factor similarly degraded the pulse quality. It is important to note that a circular core is not required to have two degenerate polarization states but there is a need a symmetry group which admits a two-dimensional irreducible representation. For instance in fundamental mode, an equilateral-triangle or square corehas two equal-speed polarization solutions and these common shapes also arise in crystal waveguides. However, any imperfections that make damage of 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 not low cost and complex combined with the real PMD is not of the most commonly used in a certain factor in the lower data rates. Therefore, PMD-compensation systems have not been widely deployed in large scale telecommunications systems. The fiber output was essentially separated into two principal polarizations (no first-order variation of time-delay with frequency), and a differential delay was applied to re-synchronize them. Therefore, currently fibers have practical problems economically such as higher costs and losses. This means that a single-polarization fiber is required where only a single state is allowed to transmit along the fiber while the others escape because they are not guided.

4. Summary

The occurrence of birefringence in commercially 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 *vice versa* 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 0.69770237 ps 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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