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Performance of optical fibers birefringence and its effect on wavelength

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ABSTRACT

The phenomenon of refractive index difference between two orthogonal polarization modes in optical fibers, plays as an important role in optics transmission systems and precision sensors. This study aims to analyze the effect of wavelength on the birefringence performance of five types of single-mode optical fibers, namely SMF-28, SMF-28e, SMF-28e+, SMF-28e+LL, and SMF-28 ULL. Simulations were performed using OptiFiber software with wavelengths varying from 1000 nm to 1550 nm. The results show that the birefringence value decreases significantly as the wavelength increases, in line with the propagation of the optical field into the sleeve which reduces the refractive index difference between the two orthogonal modes. The highest birefringence value was recorded for SMF-28e+ at 9.28 rad/m 1000 nm, while the lowest value was 5.79 rad/m 1550 nm. In addition, external effects such as fiber curvature showed a contribution to the change in birefringence, which is relevant for the design of precision optical systems. These findings confirm the importance of controlling wavelength parameters and geometric structure in optimizing fiber birefringence performance for polarization- based optical communication and sensor applications. Suggestions for further research is to evaluate the effect of temperature, external pressure, and voltage on birefringence in various other types of optics fibers.

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1. INTRODUCTION

The phenomenon of birefringence with delays to two different polarizations of light waves can pose serious problems, especially in systems that are highly sensitive to polarization and wavelength [1]. Birefringence in optical fibers can be natural, due to geometric asymmetry of the core, or artificial (designed), as in the case of polarization-maintaining fibers. The effect of birefringence on wavelength is very important to know, because many communication systems and sensors use optical fiber as one of the main components [2]. In temporal pulse broadening in coherent transmission systems, the birefringence value is the main component along the fiber. The advantage is that even though it has a small value, it can cause a cumulative effect that distorts the signal and degrades the overall system performance [3]. One of its uses is to potentially strengthen polarization stability in high-speed fiber optical communication applications [4].

Optical fiber is an important technology in modern communication systems. The advantage of optical fiber is that it has isolation properties that can be used as a product in the future for better and accurate information systems in a fast time [5, 6]. However, one of the challenges faced in the use of optical fibers is the phenomenon of birefringence. Birefringence can cause refractive index differences between two different polarization modes, thus affecting the wavelength of the transmitted signal [7]. Birefringence occurs when the refractive index varies based on the direction of light propagation [8]. This phenomenon can affect the quality of the transmitted signal and can cause errors in data transmission.

2. LITERATURE STUDY

Birefringence in optical fibers can be caused by imperfections in fiber geometry, mechanical stress, or changes in ambient temperature [2]. Birefringence can be measured using polarimetric techniques or fiber optic sensors [3]. The magneto-optical properties of the fiber optic material can also be used to affect birefringence [9].

The effective refractive index for different polarization modes can be calculated using the following formula [5]:

$$n_{eff} = \frac{\beta}{k_0} \tag{1}$$

where, β is the propagation constant, and k_0 is the wave number.

The difference in refractive index between two different polarization modes can lead to significant wavelength differences. The wavelength difference can be calculated using the following formula [10, 11]:

$$\Delta\lambda = \frac{\lambda}{L} \cdot \frac{dL}{d\lambda} \cdot \Delta_n \tag{2}$$

where, λ is the wavelength, L is the length of the optical fiber, and Δ_n is the difference in refractive index between two different polarization modes.

Birefringence is also highly dependent on the wavelength of light used. At shorter wavelengths, the mode field is more concentrated in the fiber core so the birefringence value tends to be higher. conversely, at longer wavelengths, the widening of the optical field across the sheath lowers the effective refractive index difference and reduces the birefringence [12, 13].

At larger wavelengths, the optical path length and phase difference between the two modes increase, which can magnify the birefringence value [14]. Research shows that birefringence is not linear to wavelength and is highly dependent on fiber structure [15, 16]. Photonic crystal fiber and polarization-maintaining fiber (PMF) show a more stable birefringent response than conventional single-mode fiber [17, 18].

3. RESEARCH METHODS

The method used is numerical simulation with OptiFiber software to see the effect of birefringence on the wavelength of several types of single-mode optical fibers, namely SMF-28, SMF-28e, SMF-28e+, SMF-28e+LL, and SMF-28 ULL. The parameters simulated on OptiFiber are shown in Table 1. The SMF profile is determined using Refractive Index type Profile with region 0 and 1 which serves as the core and sheath parameters in the optical fiber.

The difference value can be calculated using the following formula [11]:

$$B = n_x - n_y \tag{2}$$

where, B is the birefringence value, n_x and n_y are the effective refractive indices for x and y polarization modes.

The simulation process was carried out by designing the fiber geometry structure, setting the refractive index values of the core and sheath based on Germanium and Fluorine doped silica-based materials at 4.1 µm and 62.5 µm, and setting the wavelength variations at 1310 nm and 1550 nm.

Table 1. Various types of SMF Type SMF.

SMF type	Refractive index of the core	Refractive index of the cladding
SMF-28	1.45213	1.44692
SMF-28e	1.46770	1.46240
SMF-28e+	1.45173	1.44602
SMF-28e+LL	1.45223	1.44702
SMF-28 ULL	1.44525	1.44002

To find the normalization frequency, use the formula:

$$v = \frac{2\pi\alpha}{\lambda}\sqrt{{n_1}^2 - {n_2}^2} \tag{2}$$

where, v is used to determine the number of modes in the fiber, in single mode optical fibers the value of $v < 2.405$.

4. RESULTS AND DISCUSSION

Figure X shows the relationship between wavelength and birefringence for several single-mode optical fibers (SMF-28, SMF-28e, SMF-28e+, SMF-28e+LL, and SMF-28 ULL). The results indicate a clear decreasing trend in birefringence as the wavelength increases from 1000 nm to 1550 nm. The highest birefringence value occurs at 1000 nm (≈9.2 rad/m) and gradually decreases to about 6.0 rad/m at 1550 nm. This trend is consistent for all fiber types, indicating that wavelength significantly influences birefringence characteristics in single-mode fibers. Although slight differences appear between fibers, particularly at longer wavelengths where SMF-28 shows slightly lower birefringence, the overall behavior remains similar due to comparable structural parameters such as core diameter and refractive index contrast.

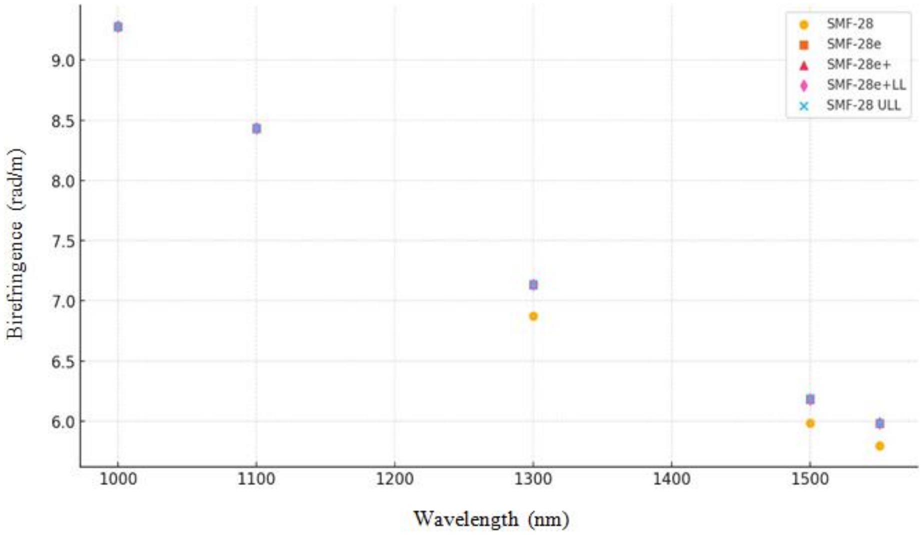

Figure 1. Birefringence as a function of wavelength for several single-mode optical fibers.

Birefringence induced by parameter perturbations is related to the fiber photoelastic constant (3.44×10^{-12} m^2/N), Young's modulus (7.75×10^{10} N/m^2), and Poisson's ratio (0.164). Previous experimental studies by Eickhoff reported birefringence values of approximately 4×10^{-5} at 632.8 nm, decreasing to 1.5×10^{-6} at 1550 nm, which is consistent with simulation and experimental results reported in the literature [19]. The decrease in birefringence at longer wavelengths occurs because the optical mode field becomes broader, reducing the influence of structural asymmetries and refractive index perturbations. As a result, polarization rotation becomes slower at larger wavelengths [20, 21]. These findings confirm that wavelength, core geometry, refractive index contrast, and external factors such as bending, pressure, and temperature significantly affect birefringence. Therefore, understanding this relationship is essential for designing optical fibers for high-speed communication systems, fiber lasers, and polarization-based sensing applications.

5. CONCLUSION

An increase in wavelength leads to a decrease in birefringence value, which impacts the performance of the optical system, understanding this is important in fiber design for communication and sensors. The decrease in Δn value at large wavelengths especially in SMF28e+ proved to have good performance in terms of polarization stability.

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