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Birefringence for Elliptical-Core Fibers with Low Ellipticities

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Abstract

Model birefringence was measured for elliptical-core fibers with low ellipticities, note the birefringence depends strongly on the frequency, especially when fiber is being operated near the higher mode cutoff where $v \leq 2.4$ for circular fiber of the single-mode type that correspond to the birefringence maximum. When $v > 2.4$ this also correspond to the birefringence maximum that can be introduced in an elliptical core fiber while still operating in the single-mode regime near the higher mode cutoff. Also the birefringence is proportional to the fiber core ellipticity when core ellipticity is much less than unity, but this birefringence deviates from the linear for the large core ellipticities.

Keywords: Modal Birefringence, Frequency, elliptical-Core Fibers, Single-Mode Fiber, Mode Cutoff.

1. Introduction

The possibility of using polarization-sensitive components in optical systems based on single–mode fiber waveguides accounts for the great interest that elliptic fibers are now attracting .Ellipticity of the core cross section is on of the main imperfections in real optical fibers, which frequency lifts the degeneracy between the two main orthogonally polarized modes of an ideal circular fiber end give rise to birefringence .In the case when specific polarization characteristics of optical waveguides are achieved by geometric effects it would be of interest not only to study other axially asymmetric fibers, but also to investigate more fully the phenomenon of mode birefringence of elliptic fibers[1]. We shall obtain an approximate formula for the mode birefringence of a low-ellipticity fiber. The formula is derived using approximate vector solutions of the Maxwell equations for two dominant orthogonally polarized modes. It is shown that there are considerable changes in the mode birefringence due to changes in the parameters of the single–mode modes. It is shown that the ranges of the approximate of a single-mode elliptic fiber in which the mode birefringence is maximal and the intermodal dispersion minimal overlap near the limit of the single–mode regime [2, 3]. An experimental study was conducted in which the geometry of an optical fiber with a hollow core with a high ellipticity results in a high geometric refraction in the optical fiber at a wavelength of 1550 µm [4].There was a theoretical study that included numerical analysis using the finite element method. The high birefringence of photonic crystal fibers with an elliptical air hole resulted in better than using a circular hole to obtain high birefringence in photonic crystal fibers, and it was later compared with ordinary optical fibers. It has an elliptical air hole and a circular hole, where the highest birefringence was obtained for the photonic crystal fiber [5]. A theoretical study was used to fabricate an elliptical gap optical fiber with a compressed lattice that results in high binary refraction with a wide frequency of terahertz [6], the directional losses of this fiber are effectively reduced by the absorption of the material, as long as there is a partial dominance of the modular power distribution in the air gaps inside the dielectric material [7]. A new study was proposed to measure sea water temperature sensor based on the Sagnac Loop of high birefringent elliptical fibers. After optimizing the test parameters at a wavelength, it achieves the highest sensitivity and the highest detection range with low cost, small size and ease of manufacture of this type of fiber [8].

A numerical analysis was used by applying the finite element method FEM to design two models of optical crystal fibers, each containing five rings of air holes of circular and oval shapes. As a result, we will obtain high binary refraction and negative scattering at wavelength 1.55 µm and nonlinearity with Small loss of optical crystal fibers It was found that the elliptical model gives more small confinement loss than the circular model at wavelength [9]. The fibers have been designed with a fiber with a highly elliptical core surrounded by a trench designed to obtain the optimum effective indicators. In addition to the manufacture of asymmetric structures to increase the birefringence in the fiber through thermal stress that occurs during the manufacturing process, this results in a high birefringence in the fiber for all guided spatial modes, which can be used in the multiplex-input transmission system.Also in the same year, two types of fibers with semi-circular holes were designed in the Sagnac ring, where the design is designed to coincide with torsion, malleability and temperature. This new combination of fibers results in a high sensitivity to torsion-induced binary breakage at a certain temperature. The presence of such physical parameters as torsion, axial pressure and temperature allows resonance depressions in the interference pattern with different rates of wavelength shift [10, 11]. A high-birefringence fiber was designed due to the stress-induced polarization -maintaining fibers (PMF) fibers, which are designed from an elliptical core, in addition to four elliptical side holes distributed around it, and two symmetrical parts in a circular. What was compared to the typical birefringence of conventional polarization -maintaining fibers (PMF) as Panda fibers,this type of PMF proposed design improves the ability to maintain polarization, as it is considered a promising candidate that can be used in a wide range in high quality optical fiber sensors and also in optical communication systems [12].

In this paper, the effect of a change in the ellipticity of the core on the value of the birefringence modal was studied. We note that the ellipticity of the core of the fiber changes through the fast and slow propagation axes and results in retardation that depends on the degree of ellipticity, and also the phase difference strongly depends on the frequency.

The paper is organized as follows. In section 2, the theoretical part about birefringence in the optical fiber and the design of the elliptical core fibers is presented. Then, the practical section is presented in Section 3, which includes the optical system for conducting the workflow, followed by the most important findings and discussions in Section 4, and then finally, the most important conclusions that we reached through the workflow are presented in Section 5.

2. Theory Part

2.1 Birefringence insingle –mode fiber

The birefringence normally-exhibited by single-mode optical fibers is the result of a difference $\delta\beta$ between the propagation constant of the two orthogonally polarized state of the fundamental mode.Each mode travels at different velocity, known as birefringence. The fiber model birefringence is defined as [13, 14].

$$B = \frac{(\beta_X - \beta_Y)\lambda}{2\pi} \tag{1}$$

Where β_X, $\beta_Y$is the mode propagation constants, the difference in phase velocities cause the fiber to exhibit linear retardation, the value of which depends on the fiber length. This leads to a polarization state which is, in general,elliptical but which varies periodically along the fiber with characteristiclength L where

$$L = \frac{2\pi}{\delta\beta} \tag{2}$$

Typical single- mode fibersare found to have a period of a few centimeters.

2.2 EllipticalCore Fibers

Since the stress layer is separated from the core by more than five times the core radius, the influence of stress layer on the geometrical anisotropy can be ignored. **Figure 1**shows the geometry of the elliptical core fiber. The relative difference in refraction indexes between core and cladding Δ and the ellipticity of the core ϵ are defined as [15, 16].

$$\Delta = \frac{n_1^2 - n_2^2}{2n_1^2} \tag{3}$$

$$\varepsilon = \frac{a-b}{a} \tag{4}$$

where n_1 is the refractive index of the core, n_2 is the refractive index of the cladding, and a, bare the semi major and semi minor axes of the core, respectively .The two dominant modes of the ellipticalcoresfiber are the HE_{11}^{X} (HE_{11}^{odd}) mode, in which the direction of the electric field vector lies along the major(x-coordinate) axis **Figure 2** (a), and the HE_{11}^{Y} (HE_{11}^{even}) mode , in which the electric field vectoralong the minor(y-coordinate) axis **Figure 2**(b).

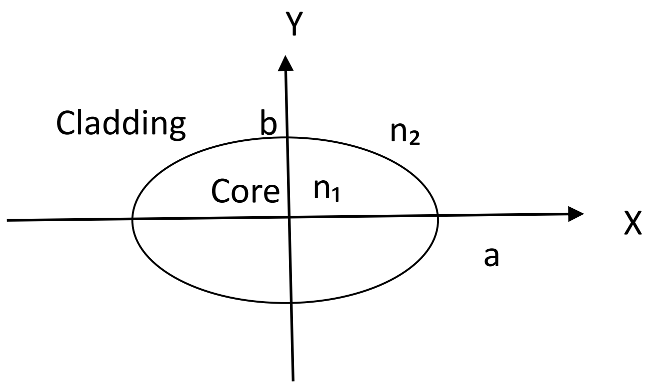
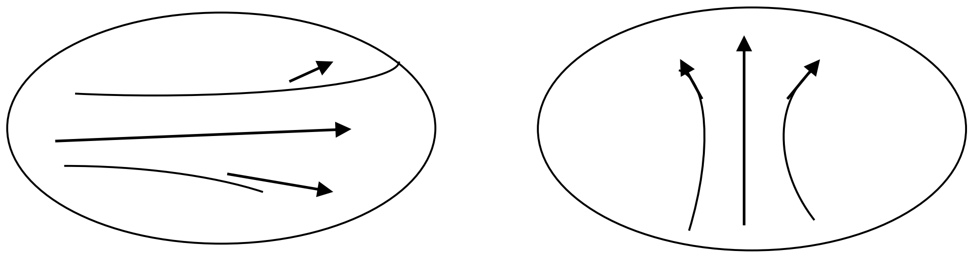


Figure 1 .Cross section of elliptical core.



(a) $\mathrm{HE}_{11}^{\mathrm{X}}$ Mode

(b) $\mathrm{HE}_{11}^{\mathrm{Y}}$ Mode

Figure 2.Field pattern for $\mathrm{HE}_{11}^{\mathrm{X}}$ (left), and $\mathrm{HE}_{11}^{\mathrm{Y}}$ (right) modes [17].

In calculating propagation constant, delay time, waveguide dispersion, a numerical method was used based on the point-matching principle. The point-matching method is a useful technique to analyze dispersion characteristics for homogeneous optical fibers with deformed core boundaries[18] .The hybrid electromagnetic fields were expanded in terms of linear combination of circular harmonics (Bessel's functions) and the boundary conditions are imposed on the field at a finite number points on the boundary. The propagation constant is given as the eigenvalue of the determinant equation whose elements are obtained by using Bessel's functions. For a fiber having slightly elliptical core(Δ <<1, ϵ<< 1), the normalized birefringence B is expressed approximately in a form [14, 18,19]:

$$B = \frac{a\delta\beta}{e^{2}(2\Delta)^{3/2}} \tag{5}$$

$$\frac{a\delta\beta}{e^2(2\Delta)^{3/2}} \approx \frac{3\pi^2\nu^2}{(\nu+2)^4} \tag{6}$$

The normalized phase difference $\delta\beta$ is expressed as a function of the normalized frequencyν for elliptical core fibers with various ellipticties.

$$\delta\beta = \frac{e^2(2\Delta)^{3/2}}{a} \cdot \frac{3\pi^2\nu^2}{(\nu+2)^4} \tag{7}$$

Where $\nu = k\,n_1 a\sqrt{2}\Delta$

(k=$2\pi/\lambda$is a wavelength of light in vacuum).

3. Experimental Part

The experimental apparatus setup used for the measurement is shown in **Figure 3**. Linearly polarized light from a He-Ne laser operating at (632.8) nm is focused on a Fresnel rhombus adjusted to transform the state of polarization from linear to circular. The circularly polarized light is focused on polarizer to select the polarization plane of the emergent linearly polarized beam. The light with selected plane of polarization is coupled to the fiber through a microscope objective. The emerging light of the optical fiber end is focused on analyzer through a microscope objective .The light beam then reaches the detection system,which constants of a PIN-SI photo detector connected to a low-noise pre-amplifier. The electric signal from the detection system fed a lock-in amplifier whose reference is the signal of the optical chopper placed in front of laser [18, 19]. A fiber was used having the characteristics shown in the **Table 1**, the deviation from circularity was determined by etching the fiber end in hydrofluoric acid and examining it under a high- power optical microscope to ensure from deformed that obtain in the fiber end. Also, we take various value of core ellipticitywith small ellipticity of fiber core (0.19, 0.227, 0.38, 0.45, 0.77) and index differentbetween core and cladding is (Δ=2.3$\times 10^{-3}$) [20].

Table 1 . Properties of used optical fiber [21**]**

Property	Fiber GSB2
Core composition	GeO_2/SiO_2
Core diameter	5 µm
Cladding composition	B_2O_3/SiO_2
Cladding diameter	16.5 µm
Substrate tube	Silica
Relative index different	2.3$\times 10^{-3}$
Overall fiber diameter	210 µm
V-Value at 632.8 nm	2.4

The experimental procedure for the determination of the linear birefringence consists to obtain the polarization state of the emerging light beam for a specific polarization plane of the coupled light beam. The polarization plane is obtained turning the polarizer (45°) with respect to the principle axes of the fiber , so that the two electric field components will be equally excited a long these axes .The principle axes of the fiber are the polarization planes a long of which ,the linear polarization state of propagation beam is preserved. Therefore these axes can be determined adjusting the polarizer and verifying the polarization state of emergent beam through the analyzer [20, 22].

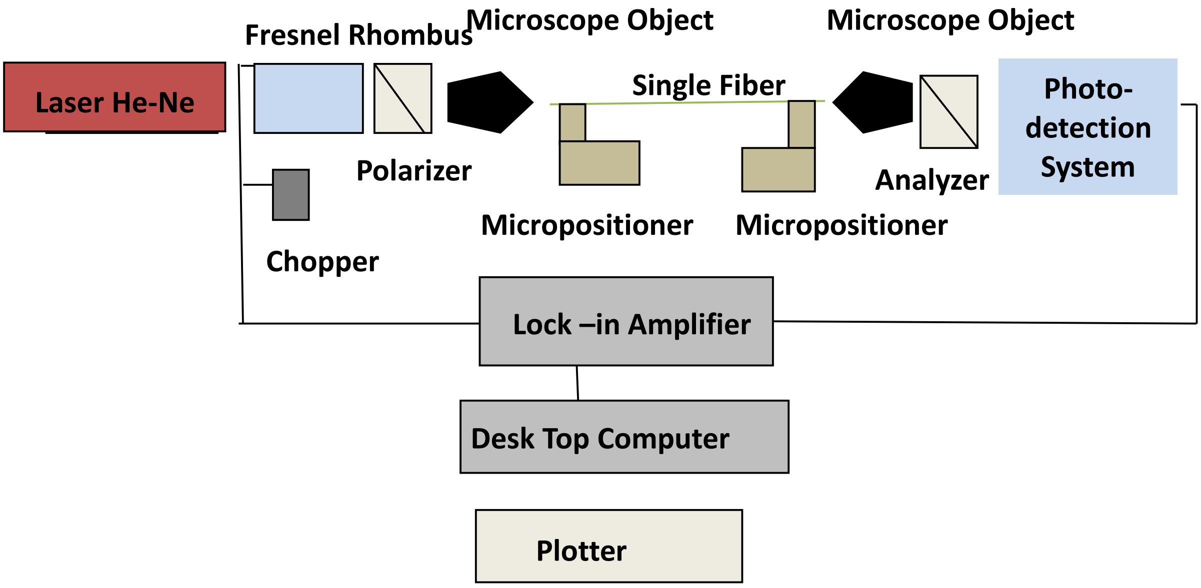


Figure 3 .Experimental apparatus used to perform the measurements [20].

4. Results and Discussion

The phase difference between the two polarization states of the fundamental mode on an elliptical fiber in the limit of small ellipticity and weak guidance. However, calculation the phase difference $\delta\beta$ as a function of normalized frequency ν for small values of Δ, a and ϵ from equation (7) as shown in **Table 2**. Also **Figure 4**show the phase difference as a function of normalized frequency for various valuesof ellipticity core(0.185,0.227,0.37,0.45,0.77) and index different between core and cladding (Δ=2.3×10^{-3}), this birefringence depends strongly on the frequency or ν value. These graphs demonstrate that when the parameters of elliptic fiber vary only within the limits of the single –mode fiber regime, the maximum $\delta\beta$ near $2< \nu < 2.4$ at which the single -mode fiber is being operated near the high mode cutoff are considered ($\nu\approx 2.4$ for step –index fiber). **Figure 4** also shows dependence of the absolute value of the relative difference Δ between different the two propagation constants are very and sensitive, when the different between the refractive indices is few. For value ν slight greater than 2.4 this is typical of elliptic fibers with small ellipticity of the core, while still near the limit of the single-mode regime, the difference between the group velocity is zero and consequently, the dispersion of a signal transmitted by a single –mode fiber with the parameters for this range is minimal .Moreover, in this range modal birefringence is close to its maximum value. By increasing ν value give lower figures than all other graphs this mean reach to implies that the birefringence produced by a given core ellipticity is here found, by a considerable margin in some cases.

In addition that, The phase difference δβ as a function of The core ellipticity in fiber having ν=2.4 at λ=0.632.8 nm show in **Figure 5**, the birefringence for fiber with small- core ellipticity is proportional to ellipticity when ϵ is much than less unity (ϵ<<1) for operation at the high mode cutoff normalized frequency ν=2.4 for near-circular step –index fibers. But for more elliptical cores(ϵ >>1) the birefringence is not proportional to ellipticities, then that the birefringence is no longer very sensitive to the core ellipticity and,in the range still near the high mode cutoff.

Table 2 . Show phase difference δβ as a function of normalized frequency for various values of core ellipticity, Δ=2.3× 10^{-3} and a=2.55 µm

ν	δβ $\epsilon^2 = 0.185$	δβ $\epsilon^2 = 0.227$	δβ $\epsilon^2 = 0.37$	δβ $\epsilon^2 = 0.45$	δβ $\epsilon^2 = 0.77$
0	0	0	0	0	0
0.2	0.011	0.014	0.022	0.034	0.04
0.4	0.031	0.052	0.063	0.085	0.1305
0.6	0.051	0.071	0.104	0.138	0.209
0.8	0.067	0.101	0.138	0.188	0.267
1	0.08	0.125	0.164	0.233	0.328
1.2	0.089	0.145	0.184	0.274	0.365
1.4	0.099	0.156	0.194	0.299	0.389
1.6	0.1	0.168	0.202	0.308	0.405
1.8	0.1016	0.177	0.206	0.314	0.413
2	0.1012	0.178	0.2079	0.315	0.415
2.2	0.099	0.176	0.207	0.313	0.414
2.4	0.098	0.168	0.2043	0.306	0.408
2.6	0.095	0.157	0.2007	0.302	0.401
2.8	0.093	0.142	0.1962	0.29	0.392
3	0.091	0.134	0.1912	0.284	0.382
3.2	0.088	0.125	0.186	0.271	0.372
3.4	0.085	0.117	0.18	0.262	0.361
3.6	0.082	0.111	0.175	0.253	0.3501
3.8	0.08	0.107	0.169	0.237	0.339
4	0.077	0.102	0.164	0.228	0.328
4.2	0.075	0.098	0.158	0.215	0.316
4.4	0.072	0.092	0.153	0.205	0.306
4.6	0.069	0.087	0.148	0.188	0.296
4.8	0.067	0.083	0.143	0.172	0.286
5	0.065	0.081	0.138	0.165	0.276

5.2	0.063	0.075	0.133	0.154	0.267
5.4	0.061	0.072	0.129	0.148	0.258
5.6	0.058	0.069	0.125	0.139	0.25
5.8	0.056	0.065	0.12	0.134	0.241
6	0.055	0.062	0.116	0.13	0.233
6.2	0.053	0.059	0.112	0.124	0.226
6.4	0.05	0.057	0.109	0.122	0.219
6.6	0.048	0.054	0.105	0.119	0.211
6.8	0.047	0.053	0.102	0.114	0.205
7	0.045	0.052	0.099	0.109	0.198
7.2	0.044	0.051	0.096	0.102	0.192
7.4	0.042	0.05	0.093	0.101	0.186
7.6	0.041	0.048	0.09	0.099	0.181
7.8	0.039	0.046	0.087	0.098	0.175
8	0.038	0.044	0.081	0.093	0.17

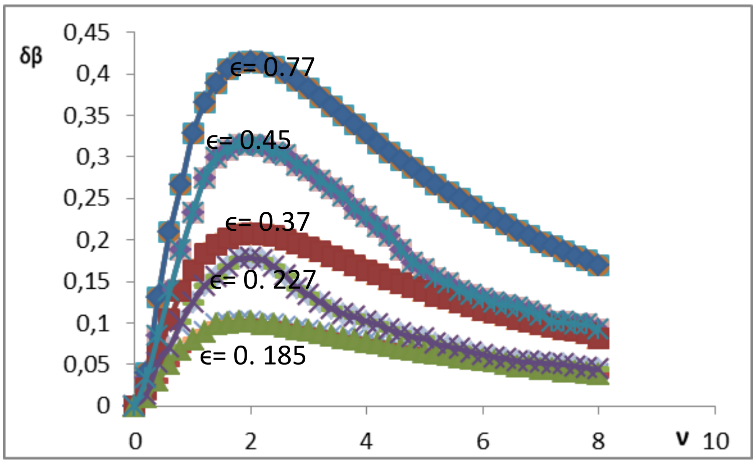


Figure 4 . Phase difference δβ as a function of normalized frequency for various values of core ellipticity (0.185, 0.227, 0.37 0.45, 0.77) and $\Delta=2.3\times 10^{-3}$.

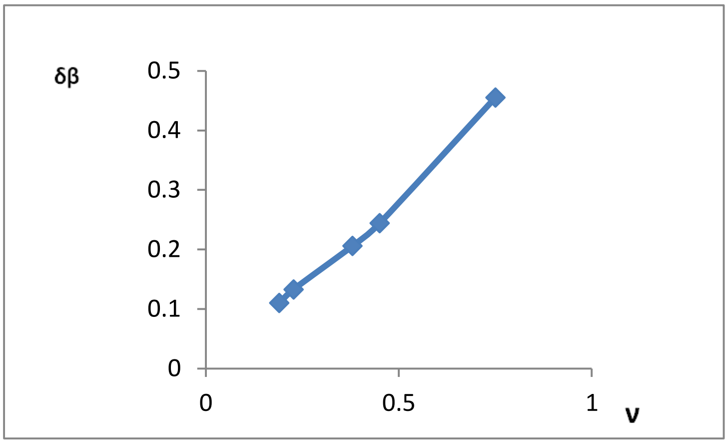


Figure 5. Phase difference δβ as a function of core.ellipticity in fiber having ν=2.4 at λ=0.632.8 nm.

5. Conclusion

An ellipticity in the fiber core establishes preferred fast and slow axes of propagation and produces a retardance which depends on the degree of ellipticity and also the phase difference depends strongly on the frequency. The maximum δβ near ν value 2< ν < 2.4 is consistent with the usual operating condition for conventional single –mode fibers. When ν > 2.4 this is also the maximum birefringence that can be introduced in an elliptical core fiber while still operating in the single mode regime. Increase ν value, the mode birefringence decrease until reach to implies near the limits of the single –mode fiber regime, then the parameters of elliptic fiber is very sensitive because of the small absolute difference between the two propagation constants. When core ellipticity is much than less unity, the phase difference is proportional to core ellipticity and for elliptical cores more than unity phase difference is no longer very sensitive to the core ellipticity is not proportional to core ellipticity and deviation from linearity for the large core ellipticity.

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