Analysis of Polarization Maintaining Optical Fibers under External Stress

Farzana Rahmat Zaki *

Nazia Nusrat **

Abstract

This present study is on detailed physical explanation of stress-induced birefringence in step index polarization maintaining elliptical core optical fibers. The birefringence is a quadratic function of the effective index change, which may occur due to changes of stress distribution within a material. In this study, changes in birefringence have been observed by applying lateral pressures. The effects on birefringence with changing ellipticity of core of the fiber have been observed by applying no pressure, pressure along x-axis and y-axis on the optical fiber. Finally, the birefringence of an optical fiber resulting from an asymmetry of the index profile has been numerically evaluated using finite-element method (FEM).

Key Words: Birefringence, FEM, Polarization maintaining fiber.

1. Introduction

Single mode optical fiber that can maintain a state of polarization over a long length area is desirable for use in coherent optical communications and fiber optic sensing element. Single mode fibers, capable of transmitting power in only one polarizing state, also have an advantage in interconnecting single mode fibers and polarization sensitive devices such as integrated optical multiplexer and switches [1]. The required birefringence is usually achieved by geometrical effects (elliptical cores) or the elasto-optic effect [2]. Here, the birefringence arises from asymmetrical distribution of refractive indices.

Birefringence in optical fiber can be classified into two categories such as intrinsic and extrinsic. Intrinsic birefringence is caused by geometric asymmetry [3]-[6], often referred to as birefringence, and by stress asymmetry [7], which is introduced permanently into the fiber during the fiber manufacturing process. Stress anisotropies often are contributed by a geometric asymmetry of the index profile in combination with thermal mismatches of the different glass regions including the core segment and the cladding glasses. They can also be affected by fiber draw-induced rapid quenching. Note that for silica clad fibers, the draw induced birefringence can be opposite in sign to that caused by the thermal expansion mismatch [5]–[7]. On the other hand, extrinsic birefringence is caused by external factors such as micro- and macro-bending, lateral load, fiber twist, etc. These external factors can also cause deformation and asymmetry stresses in the fiber.

* *Assistant Professor, Department of EEE, Eastern University, Bangladesh*

** *Phd Student, Brunel University, London, United Kingdom*

Preservation of the state of polarization of the guided light can be achieved by destroying the circular symmetry of its refractive index distribution in the core region, such as occur in elliptical core fiber [8]-[9]. However, the birefringence properties of this kind of fiber are much more limited when compared with that which can be achieved with the stress inducer birefringence. Recently, a variety of structures has been proposed for the polarization maintaining optical fibers with stress induced birefringence, most of which is designed to maintain differential stress in the fiber core region. There are many such successful fiber structure designs, such as PANDA [10], bow-tie , side tunnel, side pit fiber etc. Theoretical studies have shown that the bow type fiber is the most effective in terms of polarization maintaining property [11].

In this present study, the effect of core ellipticity on birefringence has been observed. The simplest form of optical fiber, the single mode step index optical fiber, has been considered. To keep polarization-maintaining property, there should be present the birefringence property resulting from an asymmetry of the index profile. The investigation is done under different pressure conditions such as under no pressure, applying external pressures along only x direction and along only y direction of the fiber.

2. Theoretical Formulation

The energy principle states that the total potential energy should be a minimum when thermal stress and/or an external force is applied to the body. The total potential energy of the body is given by

$$\Pi = (\text{internal work}) - (\text{external work}) = U - V, \tag{1}$$

where U and V denote strain energy and work done by the external force, respectively.

Strain energy per unit length is obtained by

$$(\text{strain energy}) = \frac{1}{2}\iint(\text{stress}).\ [(\text{strain}) - (\text{initial steain})]\ dx\,dy.$$

Then,

$$U = \frac{1}{2}\iint\{\sigma\}^T[\{\varepsilon\} - \{\varepsilon_0\}]\,dx\,dy\ , \tag{2}$$

Where $\{.\}^T$ represents the transpose of the vector and integration is over the cross-section of the actual structural body under strain and stress. Since strain and stress do not penetrate into the air region, the actual boundary of the body becomes the boundary of the FEM analysis. The displacements u(x, y) and v(x, y) along the x- and y-axis directions in the eth (e = 1–N) element is approximated by the linear function of x and y:

$$u(x,y) = p_0^e + p_1^e x + p_2^e y\ , \tag{3}$$

$$v(x,y) = q_0^e + q_1^e x + q_2^e y\ , \tag{4}$$

where p_0^e, p_1^e, p_2^e and q_0^e, q_1^e, q_2^e are expansion coefficients. Assuming the displacements at nodal points i, j, and k in the eth element are given by (u_i, v_i), (u_j, v_j) and (u_k, v_k), respectively, the expansion coefficients p's and q's are obtained by solving the linear equations which can be obtained from (3, 4) for the nodal displacements corresponding to the 3 nodal points i, j, and k of the eth element. Thus, one can obtain

$$\begin{bmatrix} p_0^e \\ p_1^e \\ p_2^e \end{bmatrix} \quad \left[C^e\right] \begin{bmatrix} u_i \\ u_j \\ u_k \end{bmatrix} \tag{5}$$

$$\begin{bmatrix} q_0^e \\ q_1^e \\ q_2^e \end{bmatrix} \quad \left[C^e\right] \begin{bmatrix} v_i \\ v_j \\ v_k \end{bmatrix} \tag{6}$$

where [C^e] is given by

$$\left[C^e\right] = \begin{bmatrix} 1 & x_i & y_i \\ 1 & x_j & y_j \\ 1 & x_k & y_k \end{bmatrix}^{-1}.$$

$$\text{i.e.,}\quad \left[C^e\right] = \frac{1}{2s_e} \begin{bmatrix} (x_j y_k - x_k y_j) & (x_k y_i - x_i y_k) & (x_i y_j - x_j y_i) \\ (y_j - y_k) & (y_k - y_i) & (y_i - y_j) \\ (x_k - x_j) & (x_i - x_k) & (x_j - x_i) \end{bmatrix}. \tag{7}$$

Here, the coordinates of the nodal points of the triangular element are expressed as (x_m, y_m) (m = i, j, k). Hence, the cross-sectional area se of the eth element is given by

$$2s_e = (x_j - x_i)(y_k - y_i) - (x_k - x_i)(y_j - y_i).$$

Now, we find the strain components in the *eth* element as

$$\varepsilon_x = \frac{\partial v}{\partial x} = p_1^e = \frac{1}{2s_e}\left[(y_j - y_k)u_i + (y_k - y_i)u_j + (y_i - y_j)u_k\right],$$

$$\varepsilon_y = \frac{\partial v}{\partial y} = q_2^e = \frac{1}{2s_e}\left[(x_k - x_j)v_i + (x_i - x_k)v_j + (x_j - x_i)v_k\right],$$

$$\gamma_{xy} = \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} = q_1^e + p_2^e = \frac{1}{2s_e}\left[(y_j - y_k)v_i + (y_k - y_i)v_j + (y_i - y_j)v_k\right] +$$

$$\frac{1}{2s_e}\left[(x_k - x_i)u_i + (x_i - x_k)u_j + (x_j - x_i)u_k\right].$$

Therefore, we get the strain vector in each element as

$$\begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{bmatrix} = \frac{1}{2s_e} \begin{bmatrix} (y_j - y_k) & 0 & (y_k - y_i) & 0 & (y_i - y_j) & 0 \\ 0 & (x_k - x_j) & 0 & (x_i - x_k) & 0 & (x_j - x_i) \\ (x_k - x_j) & (y_j - y_k) & (x_i - x_k) & (y_k - y_i) & (x_j - x_i) & (y_i - y_j) \end{bmatrix} \begin{bmatrix} u_i \\ v_i \\ u_j \\ v_j \\ u_k \\ v_k \end{bmatrix}. \quad (8)$$

This is rewritten in matrix form as

$$\left[\varepsilon^e\right] = \left[B^e\right]\left[d^e\right], \quad (9)$$

where [B^e] is a 3 6-element matrix in the right-hand side of (8) and {d^e} represents the displacement vector, a 6 1 column matrix having six degrees of freedom for eth element, i.e.,

$$\left[B^e\right] = \frac{1}{2s_e} \begin{bmatrix} (y_j - y_k) & 0 & (y_k - y_i) & 0 & (y_i - y_j) & 0 \\ 0 & (x_k - x_j) & 0 & (x_i - x_k) & 0 & (x_j - x_i) \\ (x_k - x_j) & (y_j - y_k) & (x_i - x_k) & (y_k - y_i) & (x_j - x_i) & (y_i - y_j) \end{bmatrix}$$

and $$\left[d^e\right] = \begin{bmatrix} u_i \\ v_i \\ u_j \\ v_j \\ u_k \\ v_k \end{bmatrix}.$$

The strain energy in the eth element is then expressed as

$$U^e = \frac{1}{2} \iint \left[\sigma^e\right]^T \left[\left[\varepsilon^e\right] - \left[\varepsilon_0^e\right]\right] dx\, dy. \quad (10)$$

Now, the total potential energy is given by

$$\Pi = U - V = \frac{1}{2}\{d\} - \{d\}^T[\{H\} + \{f_L\}]. \quad (11)$$

For the thermal stress analysis of birefringent fibers and waveguides without external force, we simply make $\{f_L\} = \{0\}$.

Potential energy should be a minimum by the energy principle. Therefore, the partial derivative of Π with respect to the displacement of each nodal point should be zero:

i.e., $$\frac{\partial \Pi}{\partial \{d\}} = [A]\{d\} - \{H\} - \{f_L\}].$$

We then have the 2nth-order linear simultaneous equations:

$$[A]\{d\}=\{H\}+\{f_L\}. \qquad (12)$$

For the global system, now it can be written that

$$\{A\}=\sum_{e=1}^{N}\iint_e [B^e]^T\,[D^e]\,[B^e]\,dxdy.$$

$$\{H\}=\sum_{e=1}^{N}\iint_e [B^e]^T\,[D^e]\{\varepsilon_0^e\}dxdy.$$

The solution of (12) gives the displacements at all nodal points of the fiber or waveguide under thermal stress and/or external forces. The solution of the displacement vector can be easily obtained as:

$$\{d\}=[A]^{-1}\left[\{H\}+\{f_L\}\right]. \qquad (13)$$

General sparse matrix solver may be employed to solve the system of linear simultaneous equations in order to find the displacement vector. Once the displacement of each node is known, the stress in each element is calculated by

$$\{\sigma^e\}=[D^e]\qquad [B^e]\,\{d^e\}-\{\varepsilon_0^e\}). \quad (e = 1—N). \qquad (14)$$

In optical fibers or waveguides under stress or strain, the original refractive index of the material changes due to the photoelastic effect. The new refractive index for x- and y-polarized light can be calculated from the equation.

$$\begin{bmatrix} n_x(x,y) \\ n_y(x,y) \\ n_z(x,y) \end{bmatrix}=\begin{bmatrix} n_{x0}(x,y) \\ n_{y0}(x,y) \\ n_{z0}(x,y) \end{bmatrix}-\begin{bmatrix} C_1 & C_2 & C_2 \\ C_2 & C_1 & C_2 \\ C_2 & C_2 & C_1 \end{bmatrix}\begin{bmatrix} \sigma_x(x,y) \\ \sigma_y(x,y) \\ \sigma_z(x,y) \end{bmatrix}.$$

Here C_1, C_2 are the elasto-optic (photoelastic) coefficients of the fiber or waveguide material, n_{x0}, n_{y0}, and nz0 are the unstressed refractive indices of the material and n_x, n_y, and n_z are the main diagonal elements of the anisotropic refractive index tensor. Since the material considered here is silica, an isotropic material for the fiber, having a refractive index, n, we have in this case

$$n_{x0}(x,y)=n_{y0}(x,y)=n_{z0}(x,y)=n.$$

However, after the stress analysis, the birefringence can be calculated from the refractive indices for the x- and y-polarizations. Because the stress is distributed across the whole cross section of the fiber or waveguide, the birefringence is evaluated from the average tensor refractive indices in the core region and also the values at the center of the core. Thus,

$$\overline{n}_x=\frac{1}{A}\iint_A n_x(x,y)dxdy,$$

$$\bar{n}_y = \frac{1}{A}\iint_A n_y(x,y)\,dxdy,$$

where A is the area of the core region. Therefore,

$$B_{average} = \bar{n}_x - \bar{n}_y = \frac{C_2 \quad C_1}{A} \iint_A (\sigma_y - \sigma_x)\,dxdy \ .$$

Sometimes, the birefringence of the fiber is approximated by the difference of refractive indices at the center of the fiber core. Assuming that the center of the core is the origin of the coordinate system, we can write

$$B_0 = n_x(0,0) - n_y(0,0) = (C_2 \quad C_1)(\sigma_y - \sigma_x)\big|_{x=0,\,y=0}$$

3. Experimental set-up/methodology

The birefringence properties of a single mode optical fiber with a silica cladding have been investigated numerically. The calculations were performed at the wavelength of 1.55 μm, refractive indices of unstressed fiber are assumed 1.5 in core region and 1.48 in cladding region. The effective index of the modes polarized along the fast and the slow axis are calculated, using FEM, as a function of the asymmetry coefficient. The main advantage of the FEM presented here is that it could be easily adapted to the study of other asymmetric index profiles, including anisotropy due thermal stress effects. To achieve the required accuracy in the calculations, a large number of elements were needed, particularly at the core-cladding interface, to precisely evaluate the polarization effects. The core and cladding region are divided into triangular elements and the summation is carried over all the different finite-element triangles. Here the simulation is done for 3661 nodes and 7140 elements. All the numerical results presented in the next sections have been realized with the contour and mesh plots illustrated in the following sections.

Fibers with elliptical core and circular cladding are similar to, but simpler than, fibers made through perform deformation in structure. Here, the birefringence property of such fibers with an elliptical core and a circular cladding is analyzed under different stresses. The fiber structure is illustrated in Fig.1.

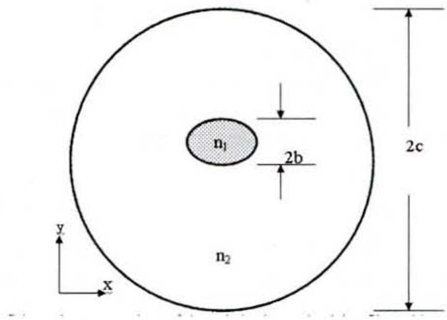


Fig 1. Schematic cross-sections of the polarization maintaining fiber with an elliptical core and circular cladding.

For a numerical analysis of the birefringence property of this type of fiber, the geometrical and mechanical parameters of the fiber are considered to be such that

$C_1 = 7.42\text{x}10^{-6}$ mm/kg^2	$C_2 = 41\text{x}10^{-6}$ mm/kg^2
$\alpha_1 = 2.0\text{x}10^{-6}$ / °C	$\alpha_2 = 1.0\text{x}10^{-6}$/ °C
E (Young's modulus)= 7380 kg/mm^2	ν (Poisson's ratio) = 0.186
Core diameter (minor axis),b = 2.5 μm	Diameter of the fiber,2c = 100 μm
x & y axis division = 30 μm, 20 μm,10 μm	ΔT = -1000 °C

The birefringence of an optical fiber resulting from an asymmetry of the index profile is numerically evaluated using a finite-element method with a full-vectorial formulation. The birefringence is a quadratic function of the effective index change. The calculated photo-induced birefringence is negligible if the index change is lower than 5e-4. However, the birefringence can reach 5e-6 for large values of index change.

4. Results and Discussions

Here, we observed the effect of various stresses on birefringence under two different conditions.

- Without any external pressure applied
- External pressure applied in two different directions
  - (a) Pressure applied along x direction, P_x
  - (b) Pressure applied along y direction, P_y

Case-1: Without any External Pressure

When no external pressure is applied and only stress is present in the core of the fiber, at that time only residual birefringence has been observed. By changing the values of ellipticity of the core (ε), linear change in birefringence (B_0) has been notified.

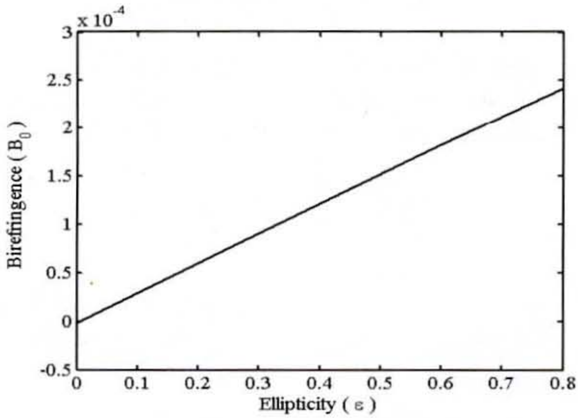


Fig. 2. Birefringence versus ellipticity when no pressure is applied

Here, changes of refractive indices of core and cladding due to change in stress with variation of ellipticity of core have been observed. Maximum change occurs due to change in ellipticity.

Birefringence is defined as a constant times the difference between horizontal and vertical components of refractive indices changes. Change of refractive index (Δn) is proportionate to change in corresponding stress vector, so birefringence is also proportional to difference between horizontal and vertical components of stress vector (σ). Stress vector and refractive index changes for different core ellipticity, therefore, change in birefringence for ellipticity, ε = 0.0, 0.3, 0.6 are shown in table-1.

Table-1: Data for When No External Pressure is Applied in Fiber Core

ε	σ_x	σ_y	$\sigma_y - \sigma_x$	Δn_x	Δn_y	$\Delta n_x - \Delta n_y$
0.0	0.00001424	0.00000153	-.0000127	-0.000893808	-0.00132027	.00042646
0.3	0.00001550	0.00000006	-.0000154	-0.000840998	-0.00135971	.00051871
0.6	0.00001677	-0.0000014	-.0000182	-0.000789944	-0.00139987	.00060993

With increase in ellipticity, horizontal(x) stress component increases and vertical stress component (y) decreases which leads magnitude of Δn_x to decrease and magnitude of Δn_y to increase. The net result is, ($\Delta n_x - \Delta n_y$) increases. For change in ellipiticity from 0.0 to 0.3, change in Δn_x is .00005281 and change in Δn_y is .0003943. Thus, the change in nx is dominating. The similar dominancy is observed for change of ellipticity from 0.3 to 0.6. The changes are shown below:

$\sigma_{x(0)} - \sigma_{x(.3)}$	126e-6	$\sigma_{y(0)} - \sigma_{y(.3)}$	-147 e-6	$\Delta n_{x(0)} - \Delta n_{x(.3)}$	528e-4	$\Delta n_{y(0)} - \Delta n_{y(.3)}$	-394e-4
$\sigma_{x(.3)} - \sigma_{x(.6)}$	127e-6	$\sigma_{y(.3)} - \sigma_{y(.6)}$	-146 e-6	$\Delta n_{x(.3)} - \Delta n_{x(.6)}$	511e-4	$\Delta n_{y(.3)} - \Delta n_{y(.6)}$	-402e-4

Again, for =0.0 and =0.3, change in birefringence is
$\{\Delta n_{x(0)} - \Delta n_{y(0)}\} - \{\Delta n_{x(0)} - \Delta n_{y(0)}\} = 0.00009225$
for ε=0.3 and ε=0.6, change in birefringence is 0.00009122

For each case change in birefringence is almost constant. These explain that how birefringence increases linearly with increase of ellipticity. Effects of ellipticity on refractive indices and stress vectors are observed in core. At ellipticity of core at 0.8, maximum change is observed. Mesh plots of stress and two dimensional stress vector plots have been shown in fig 3 to fig. 7.

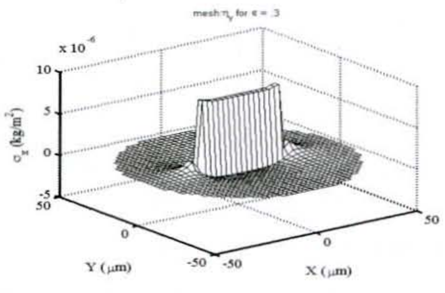


Fig. 3. Mesh of σ_x for ε = 0.8

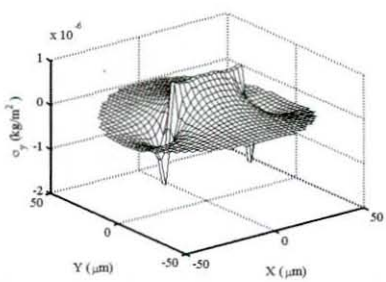


Fig. 4. Mesh of σ_y for ε = 0.8

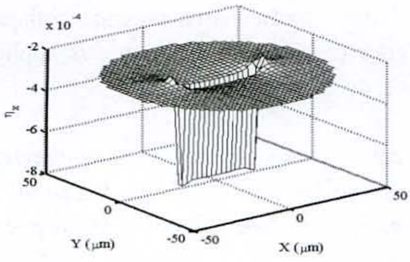


Fig. 5. Mesh of ε_x for = 0.8

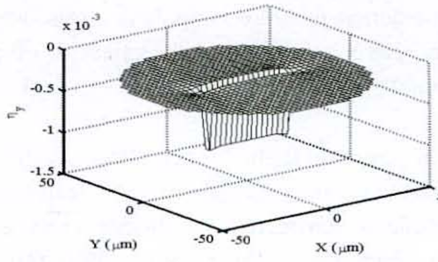


Fig. 6. Mesh of η_y forε= 0.8

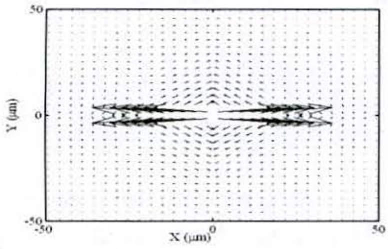


Fig. 7. Stress vector forε= 0.8

In each case maximum stress occurs within the core region. There is no stress observed in cladding region. However, the stress in core region is due to only thermal stress.

Case-2: External Pressure Applied in x Direction, P_x

When external pressure is applied along x direction and stress is also present in the core of the fiber, residual birefringence is observed due to the effect of stress for applied pressure. By changing the values of ellipticity of the core (ε), linear change in birefringence (B_0) has been notified. With the increase of ε, B_0 also increases. ε is varied from. 0.0 to 0.8. At ε = 0.8 maximum variation of stress than that of circular core is observed. Like in the case of no pressure applied, the birefringence increases linearly with increasing ellipticity. In this case, birefringences have larger value than that of the previous one when only thermal stress is remained.

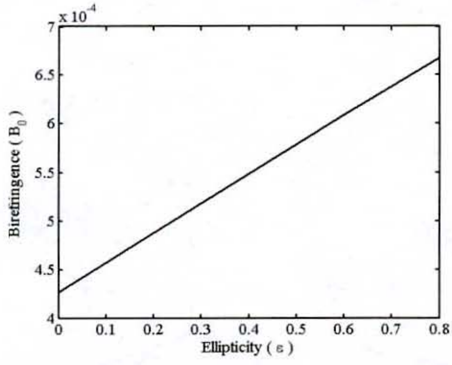


Fig. 8. Birefringence versus ellipticity when pressure is applied along x-direction.

When external pressure is applied, stress due to thermal stress and external pressure both are present. Here, we observed the effect of ellipticity of core when external pressure is applied horizontally as shown in table-2.

With increase in ellipticity, horizontal (x) stress component increases towards positive direction and vertical stress component (y) decreases from positive towards negative direction. If magnitude is considered, the change in σy is 1st decreasing and then increasing if ellipticity changes from 0 to .8. The overall result is, (Δnx -Δny) increases.

Table-2: Data for Applied External Pressure in Fiber Core at x-Direction

ε	σ_x	σ_y	$\sigma_y-\sigma_x$	Δn_x	Δn_y	Δn_x -Δn_y
0	0.00001424	0.00000153	-.0000127	-0.000893808	-0.00132027	.00042646
.3	0.00001550	0.00000006	-.0000154	-0.000840998	-0.00135971	.00051871
.6	0.00001677	-0.0000014	-.0000182	-0.000789944	-0.00139987	.00060993

For change in ellipitcity from 0 to 0.3, change in Δn_X is 0.00005281 and change in ny is 0.0003943. Thus, the change in Δn_X is dominating. The similar dominancy is observed for change of ellipticity from 0.3 to 0.6. The changes are shown in the following table.

$\sigma_{x(0)}$- $\sigma_{x(.3)}$	126e-6	$\sigma_{y(0)}$-$\sigma_{y(.3)}$	-147e-6	$\Delta n_{x(0)}$ -$\Delta n_{x(.3)}$	528e-4	$\Delta n_{y(0)}$ -$\Delta n_{y(.3)}$	-394e-4
$\sigma_{x(.3)}$ - $\sigma_{x(.6)}$	127e-6	$\sigma_{y(.3)}$ - $\sigma_{y(.6)}$	-146e-6	$\Delta n_{x(.3)}$ -$\Delta n_{x(.6)}$	511e-4	$\Delta n_{y(.3)}$ -$\Delta n_{y(.6)}$	-402e-4

For each case change in birefringence is almost constant. Mesh plots of stress and two dimensional stress vector plots have been shown in fig 9 to fig. 13.

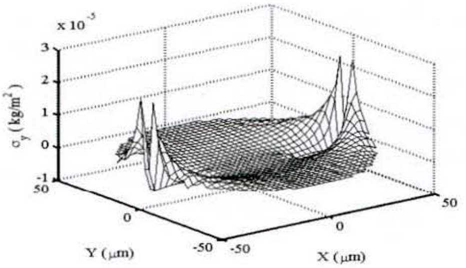


Fig. 9. Mesh of σ_y forε= 0.8

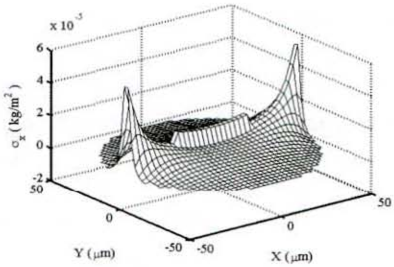


Fig. 10. Mesh of σ_x forε= 0.8

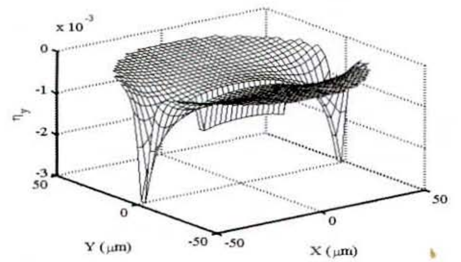


Fig. 11. Mesh of η_y forε= 0.8

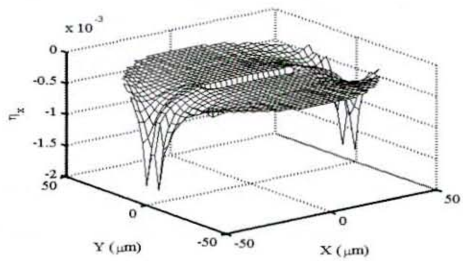


Fig. 12. Mesh of η_x forε= 0.8

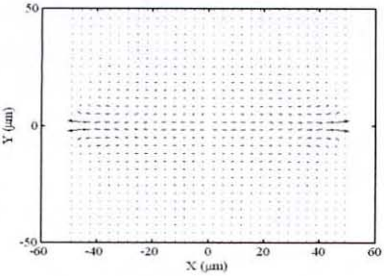


Fig. 13. Stress vector for ε= 0.8.

Observing these figures we can say that, unlike no pressure, both core and cladding region undergoes some stresses. Here, we have assumed that maximum stress occur in core region. It is also noticeable that the value of stress is much larger than that experienced for only presence of thermal stress. The effect of thermal stress is negligible in this case.

Case-3: External Pressure Applied in y Direction, P_y

When external pressure is applied along y direction and stress is also present in the core of the fiber, at that time residual birefringence is observed. By changing the values of ellipticity of the core (ε), we observed linear change in birefringence (B_0). With the increase of ε , B_0 also increases.

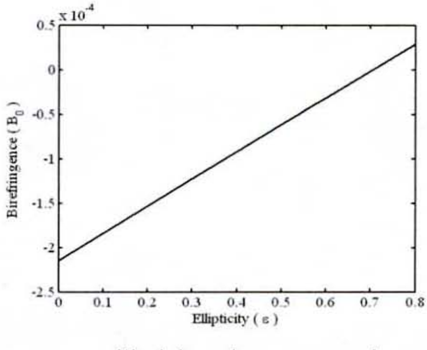


Fig. 14. Birefringence versus ellipticity when pressure is applied along y-direction.

By applying pressure along vertical direction, a special phenomenon during linear change in birefringence has been experienced. When the ellipticity is 0.64, birefringence curve intersects X-axis which signifies that up to ellipticity is 0.64, the change in vertical component of refractive index (Δn_y) is larger than the horizontal component (Δn_x). But when ellipticity exceeds 0.64,Δnx becomes larger than Δny. At ε= 0.6, no birefringence exists. This is the critical point and the phenomenon is called regenerative phenomena.

When pressure is applied along vertical i.e. y direction, the maximum stress in core region are given below for different birefringence. Effects of two stress components, horizontal (σx) and vertical (σ y) and changes of refractive indices (Δn_x and Δn_y) are shown table-3.

Table-3: Data for Applied External Pressure in Fiber Core at y-Direction

ε	σ_x(kg/m^2)	σ_y(kg/m^2)	$\sigma_y - \sigma_x$ (kg/m^2)	Δn_x	Δn_y	Δn_x -Δn_y
0.0	0.00000311	0.00000948	.00000637	-0.00111307	-0.000898920	-.00021415
0.3	0.00000437	0.00000801	.00000364	-0.001060315	-0.000938186	-.00012213
0.6	0.00000565	0.00000656	.00000091	-0.001009283	-0.000978638	-.00003065
0.8	0.00000648	0.00000561	-.0000009	-0.000975659	-0.001004897	.00029238

It is found that birefringence has negative values up to a certain ellipticity but then has a positive value at ε= 0.8. With increase of ellipticity Δn_x has negatively decreasing magnitude and Δn_y has negatively increasing magnitude. At point ε = 0.6, Δn_x = 0.97 and Δn_y = 1.00 which are almost equal. This point is the critical point. After this point, n_x in larger than Δny and so positive value of birefringence is obtained. This phenomenon is called regeneration.

$\sigma_{x(0)}$-$\sigma_{x(.3)}$	126e-6	$\sigma_{y(0)}$-$\sigma_{y(.3)}$	-147e-6	$\Delta n_{x(0)}$ -$\Delta n_{x(.3)}$	-527e-5	$\Delta n_{y(0)}$ -$\Delta n_{y(.3)}$	-393e-5
$\sigma_{x(.3)}$ - $\sigma_{x(.6)}$	128e-6	$\sigma_{y(.3)} - \sigma_{y(.6)}$	-145e-6	$\Delta n_{x(.3)}$ -$\Delta n_{x(.6)}$	-510e-5	$\Delta n_{y(.3)}$ -$\Delta n_{y(.6)}$	-404e-5

Mesh plots of stress and two dimensional stress vector plots have been shown in fig 15 to fig. 19 due to external pressure applied along y direction.

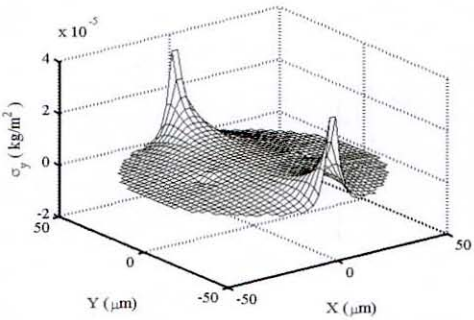


Fig. 15. Mesh of σ_y for ε= 0.8

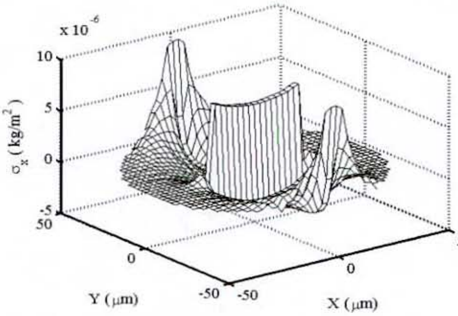


Fig. 16. Mesh of σ_x for ε= 0.8

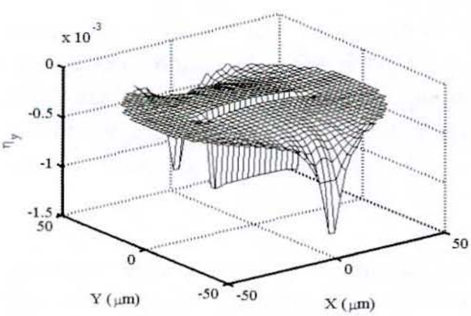
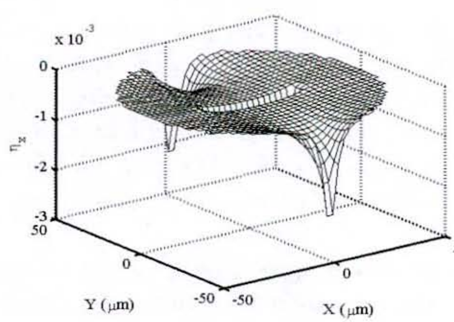


Fig. 17. Mesh of η_y for ε= 0.8



18. Mesh of η_x for ε= 0.8

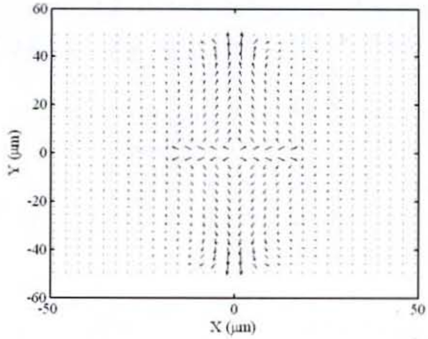


Fig. 19. Stress vector forε= 0.8

Observing these figures we can say that, both core and cladding region undergo some stresses. Here, maximum stress occurs in core region.

Comparative Analysis

For same ellipticity, birefringences are different for different conditions as induced stresses are different. Effects of various stresses on birefringence can be depicted from table-4.

Table-4: Effect of Birefringence on Variation of Core Ellipticity of Fiber

ε	B_0 (Pressure = 0)	B_0 (for P_x)	B_0 (for P_y)
0	-1.138491e-6	4.26374e-4	-2.14198e-4
.3	9.064574e-5	5.18031e-4	-1.09528e-4
.6	1.827409e-4	6.09528e-4	-3.073154e-5
.8	2.421817e-4	6.680508e-4	2.906717e-5

Birefringence due to only thermal stress is larger than that for pressure applied along y direction and smaller than that for pressure applied along x direction. Maximum stress is distributed in core when external pressure is Px. Stresses for Px are much larger than stress due to no pressure applied. As only thermal stress, which is very small, is present if no external pressure is applied, effect of residual birefringence is negligible than birefringence due the mentioned two conditions. But when pressure is applied along y direction, it shows degenerative phenomenon and its birefringence is smaller than the residual birefringence of core. This phenomenon imposes a limitation on maintaining birefringence by changing core ellipticity. At ellipticity around 0.65, the two quadratic components of refractive indices are almost same, no birefringence exists. This leads the fiber not to have polarization maintaining property anymore.

5. Conclusions

Single-mode fiber that preserves the plane of polarization of the light launched into it as the beam propagates through its length, also known as polarization-preserving fiber. The polarization is maintained by introducing asymmetry in the fiber structure, either in its shape (geometrical birefringence) or in its internal stresses (stress-induced birefringence). Here, we have analyzed over how birefringence changes with core ellipticity for three different conditions. When no pressure is applied, the changes in birefringence occur only due to thermal stresses. In all other cases, applied pressure has more or less effect. It has been observed that, the birefringence increases linearly with the core ellipticity in cases of no pressure applied, external pressure applied vertically and horizontally. A crucial point is observed at vertically applied external pressure. At this point no birefringence property is shown by the fiber. The relative index change in the core has a significant impact on fiber birefringence. The higher the refractive index change is, the higher the birefringence becomes. The sensitivity of fibers is thus depends on external forces applied on it.

References

R. A. Steinberg and T. G. Giallorenzi, "Performance limitations imposed on optical wave-guide switches and modulator by polarization," *Appl. Opt.,* vol. 15, no. 10, pp.1976.

H. Tsuchiya and J. Sakai, "Characteristics of singlemode optical fiber with elliptical core," *presented at the Tech. Meet. Opt. Quantum Electro., IECE, Japan*, Paper OQE74-86 (1974).

A. M. Vengsarkar, L. G. Cohen, and W. L. Mammel, "Theoretical analysis, of highly elliptical core fibers with arbitrary refractive index profile,"*Opt. Lett.*, vol. 17, pp. 1658-–1660, (1992).

D. Q. Chowdhury and D. A. Nolan, "Perturbation model for computing optical fiber optical fiber birefringence from two-dimensional refractive index profile," *Opt. Lett.,* vol. 20, pp.1973–1975 (1995).

D. Q. Chowdhury and D. Wilcox, "Comparison between optical fiber birefringence induced by stress-anistropy & geometric deformation," *in OFC/IOOC '99.* Tech. Dig., vol. 2, pp. 220–222 (1999).

J. Noda, K. Okamoto, and Y. Sasaki, "Polarization-maintaining fibers and their applications," *J. Lightwave Technol.,* vol. LT-4, pp. 1071-1089 (1986).

Y. Yamamoto and T. Kimura, "Coherent optical fiber transmission systems," *IEEE J.Quantum Electron*, vol. QE-17, pp. 919-935, 1981.

T. Hosaka, K. Okamoto, T. Miya, Y. Sasaki, and T. Edahiro, "Low-loss single polarisation fibres with asymmetrical strain birefringence," *Electron. Lett.,* 17, 530-531 (1981).

M. P. Varnham, D. N. Paye, A. J. Barlow, and R. D. Birch, "Analytic solution for the birefringence produced by thermal stress in polarization-maintaining optical fibers," *J. Lightwave Technol.,* vol. LT-4, pp. 332-339 (1983).

A. Kumar et al., "Birefringence calculations in elliptical-core optical fibers", *Electron. Lett.* 20, 112 (1984).

D. Mogilevtsev et al., "Design of polarization-preserving photonic crystal fibres with elliptical pores", *J. Optics A – Pure and Applied Optics 3*, S141 (2001).