FEM Study Of Elliptical Coreoptical Fibres

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Abstract

Elliptical core optical fibres have the distinct property of geometry birefringence which enables them to exhibit polarization maintainingcharacteristics. These specialty fibres are typically used to guide linearly polarised light from point to point thereby finding many specialised applications in optical sensors as well as telecommunications and sensor research.The 2D-FEM modal analysis presented in thispaper relies on solving Maxwell's equations of electromagnetic wave propagation using COMSOLMultiphysics®.The model developed in this study is adapted for FEM study of any elliptical core waveguide based on its geometry and doping concentration. The implementation of the FEM methodin COMSOL enhances an insight into the numericalmethodology and analyses factors that affect itsperformance. As a result, computational stability,convergence rate, modelling accuracy together with theinfluence of time and space step lengths can all beexamined.
Keywords – *elliptical core optical fibre, specialty fibre, birefringence, 2D-FEM, propagation mode*

1. Introduction

Conventional single mode opticalfibres used in communication systemsideally have a perfect cylindrical core, with uniform diameter. In an ideal single mode fibre, the fundamental propagation mode (HE_{11}) is a degenerated combination of two orthogonal propagation modes (H_{11}^x, H_{11}^y). Thus, if linearly polarized light is launched in such a fibre, the polarization state of the light beam should not change as it propagates. However, practically it is found that the state of polarization changes as light propagates along the fibre and hence the output state of polarization (SOP) is in general arbitrary [1,2]. The change of SOP of the light is caused by many factors, such as slight ellipticity of the core, uneven stress distributions in the fibre when the fibres are manufactured, or bends and twists when the fibre is laid on ground. In an elliptical corefibre, if light that is polarized along the major or minor axis is launched, the output from the fibre has the same polarization as the input and hence the fibre maintains this polarization[3]. Elliptical core fibresare used in applicationswhere the transmission and deliveryof polarized light is required. These include: interferometry [4], fibre optic gyroscopes [5,6], coherent communications, integrated optics[6], Optical Coherence Tomography[7], Laser Doppler Anemometry and Velocimetry[8]. In this present study we developed a 2D-FEM model of an elliptical core optical waveguide. Using the 2D-FEM modal analysistechnique, the guided fibre modes are resolved and identified in terms of the obtained mode intensity profiles.

2. Analysis Technique and Model

Optical mode in a fibre is a general concept in optics that also occurs inthe theory of lasers.Modeanalysis in optical fibres can be accomplished more rigorously by solving Maxwell's equations and applying appropriate boundary conditions defined by fibre geometries and parameters [9]. An optical moderefers to a specific solution of the Maxwell's equations that satisfy the proper boundary conditions at the core cladding interface. The mode has the property that itsspatial distribution does not change with propagation. The fibre modes can be classifiedas guided modes, leakymodes, and radiation modes [9-11].In fibreoptic communication systems signal propagationtakes place through the guidedmodes only[10-12].
The optical modal analysis is carried out assuming that thewave propagates along the *z*-direction and the electric fieldof the wave has the form:

$$\mathbf{E}(x,y,z,t) = \mathbf{E}(x,y)e^{j(\omega t - \beta z)} \quad (1)$$

where$\omega$is the angular frequency and $\beta$is the propagation constant. The fibre guide is assumed to be uniform in the direction of wave propagation. An eigenvalue equation in terms of the electric field can be obtained from the Helmholtz equation:

$$\nabla \times (n^{-2}\nabla \times \mathbf{E}) - k_0^2\mathbf{E} = \mathbf{0} (2)$$

and is solved for modal effective index,
$n_{eff} = \beta/_k$ as theeigenvalue. The boundary condition for electric field at theoutside of the cladding boundary was set to zero. In theCOMSOL Multiphysics [14], however, a module based onthe

perpendicular hybrid mode wave using transversal fieldsis used for finding the modal solutions. To do this, the crosssectional domain of the fibre is meshed with the triangular elements while the FEM is used. The birefringence propertiesand its structural dependence can be obtained easily from theorthogonal mode solutions. The orthogonal modes propagate with different phase velocities and the difference between their effective refractive indices is called the phase birefringence, given by:

$$B = \left|n_{eff}^{x} - n_{eff}^{y}\right| \quad (3)$$

The fibre birefringence is of great value serving to de-couple the propagationconstants and maintain the polarization.If light is injected into the fibre so that both the orthogonal modes are excited, then one will be delayed in phase relative to the other as they propagate. When this phase difference is an integral multiple of 2π, the two modes will beat at this point and the input polarization state will be reproduced [15,16].The length over which this beating occurs is the fibre beat length given by:

$$L_B = \frac{\lambda_0}{B} \quad (4)$$

The basic structure of a step index elliptical core fibre is shown in Figure 1. The fibre is characterized by these parameters: the semi-major radius *a*, the semi minor radius *b*, and the core cladding refractive index difference, Δn. Using n_{core} and n_{clad} for core refractive index and cladding refractive index, respectively, the normalized frequency is defined by:

$$V = \frac{2\pi b}{\lambda}\sqrt{n_{core}^2 - n_{clad}^2} \quad (5)$$

The normalized birefringence$\Delta(\frac{B}{k})/(\Delta n)^2$ is dependent on the values of *V* and the elliptical ratio[9,10,14].

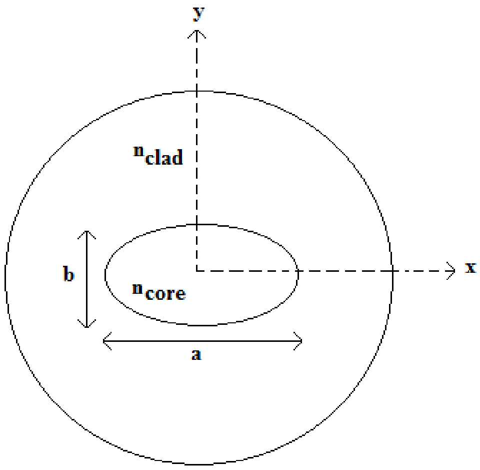

Figure 1. Transverse cross section of an elliptical core fibre

3. Modelling and Simulation Procedure

The FEM in COMSOL study employed the RF Module which combines the optics and photonics interfaces. The geometry of the elliptical fibre in Figure 1 was employed. The material properties used in the study are shown in Table 1.Throughout the study, the elliptical parameters *a* and*b* werefixed at 6 µm and 2 µm respectively.The material properties in Table 1 are valid for the free space wavelength of 1.55 µm. This is wavelengthwhere the lowest loss is achievable. [11,12,16].

Table 1.Material properties used in the study

	Core	Cadding
Material	Silica Glass	Doped Silica Glass
Refractive Index	n_{core} = 1.4457	n_{clad} = (varied from 1.4150 to 1.4290)

A modal analysis was performed and the associated parametric sweeps where done in order to investigate the influence of the refractive index difference between core and cladding, (Δn), on the properties of the elliptical core fibre. The refractive index of the core (n_{core}) was fixed at 1.4452 while the cladding refractive index (n_{clad}) was varied from 1.4150to 1.4290in steps of 0.001. The corresponding V values, electric field intensities and effective refractive indices where determined for various values ofΔn. The standard meshing tool was used with the mesh setting at physics – controlled mesh and element size set to "finer". Figure 2 shows the meshed geometry of the fibre cross section in 2D. A total of 2 924 triangular elements were used in this FEM study.

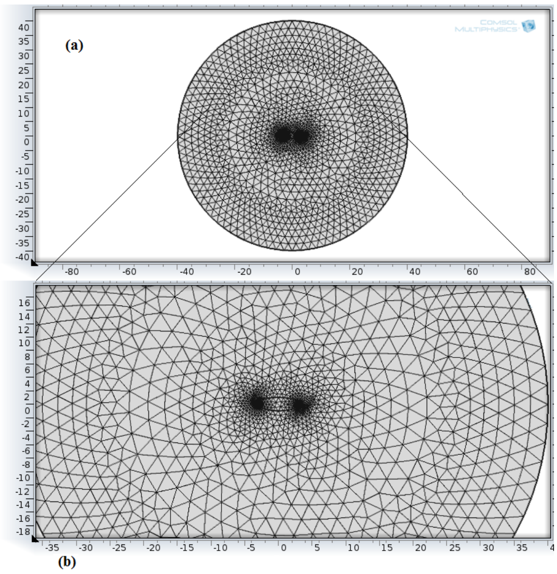

Figure 2. Structure of the triangular finite elements in COMSOL for a single mode step-index fibre

4. Results and Discussion

3.1 NormanizedBirefrigence,V and Δn

The first part of the modal study was a parametric analysis of the effect of Δnon the normalised birefringence for the fundamental mode. Figure 3 shows that an increase in Δn from around 0.016 to 0.03 corresponds to a linear decrease in the normalized birefringence from around 0.0230 to 0.144.

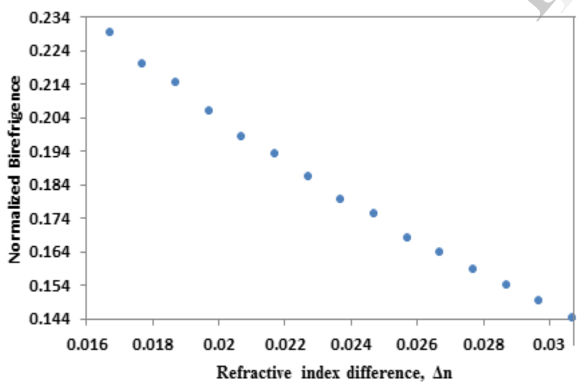

Figure 3. Normalized birefringence as a function of normalized frequency V for the fundamental mode

Figure 4 shows the dependence of normalized birefringence on the normalized frequency V for the fundamental mode. Figure 5 shows the dependence of electric field difference (i.e. $\Delta E = E^x - E^y$) on Δn for the fundamental mode. From Figure 4, Δn is accompanied by a general increase in ΔE. In other words the difference between the electric field intensity associated with the H_{11}^Xpolarisation stateand the H_{11}^y polarisation state increases as Δn is increased. Table 2 summaries results of the dependence of NA, V parameter andΔn_{eff} on the refractive index difference Δn. This may be expected since the higher Δn corresponds to a higher value of the V parameter.

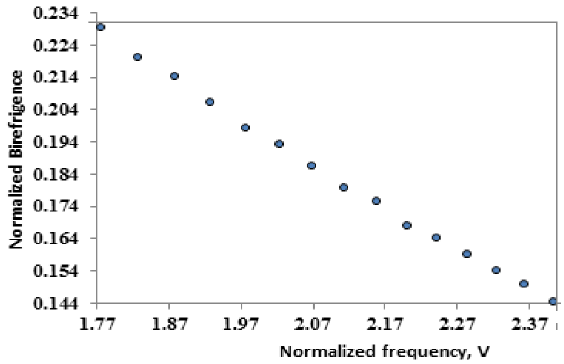

Figure 4.Normalized birefringence as a function of normalized frequency V for the fundamental mode

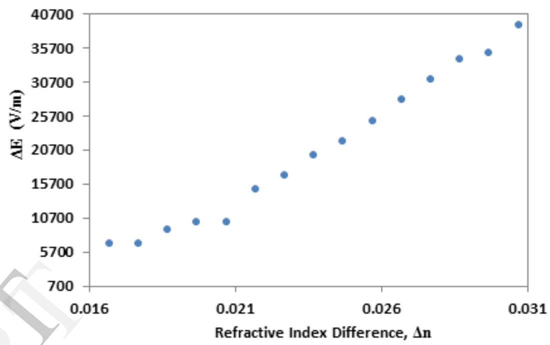

Figure 5.Dependence of electric field difference ($\Delta E = E^x - E^y$) onΔn(for the fundamental mode)

Table 2: Summary of results of the study

Δn	NA	V	Δn_{eff}	Normanized Birefringence
0.0307	0.29635	2.402611	0.000136	0.144299
0.0297	0.291535	2.36357	0.000132	0.149645
0.0287	0.286635	2.323844	0.000127	0.154184
0.0277	0.281646	2.283399	0.000122	0.159001
0.0267	0.276564	2.242195	0.000117	0.164121
0.0257	0.271383	2.20019	0.000111	0.168057
0.0247	0.266097	2.157336	0.000107	0.175384
0.0237	0.2607	2.113582	0.000101	0.179814
0.0227	0.255185	2.068872	9.6E-05	0.186303
0.0217	0.249545	2.023142	9.1E-05	0.193251
0.0207	0.243769	1.97632	8.5E-05	0.198371
0.0197	0.23785	1.928328	8E-05	0.206138
0.0187	0.231775	1.879075	7.5E-05	0.214476
0.0177	0.225532	1.82846	6.9E-05	0.220243
0.0167	0.219106	1.776367	6.4E-05	0.229481

3.2 Analysis of Modes

Figure 6(a) shows the spatial guidingmode fields for n_{core} = 1.4457 andn_{clad}=1.415 (i.eΔn = 0.0307). As shown in Figure 5, there are three pairs of degenerate modes namely: (H_{11}^{x}, H_{11}^{y}); (TE_{01}, TM_{01}) and (HE_{12}^{x}, HE_{12}^{y}). Figure 6(b) also shows the spatial guiding modes for n_{core} = 1.4457 andn_{clad}=1.429 (i.eΔn = 0.0167). The results in Figure 6 show that for the value of Δn = 0.0167, there exists only two pairs of degenerate modes: (H_{11}^{x}, H_{11}^{y}) and (TE_{01}, TM_{01}). Comparing Figure 6 (a) and Figure 6 (b), it is apparent that the elliptical core fibre can support more modes at higher values of Δn.

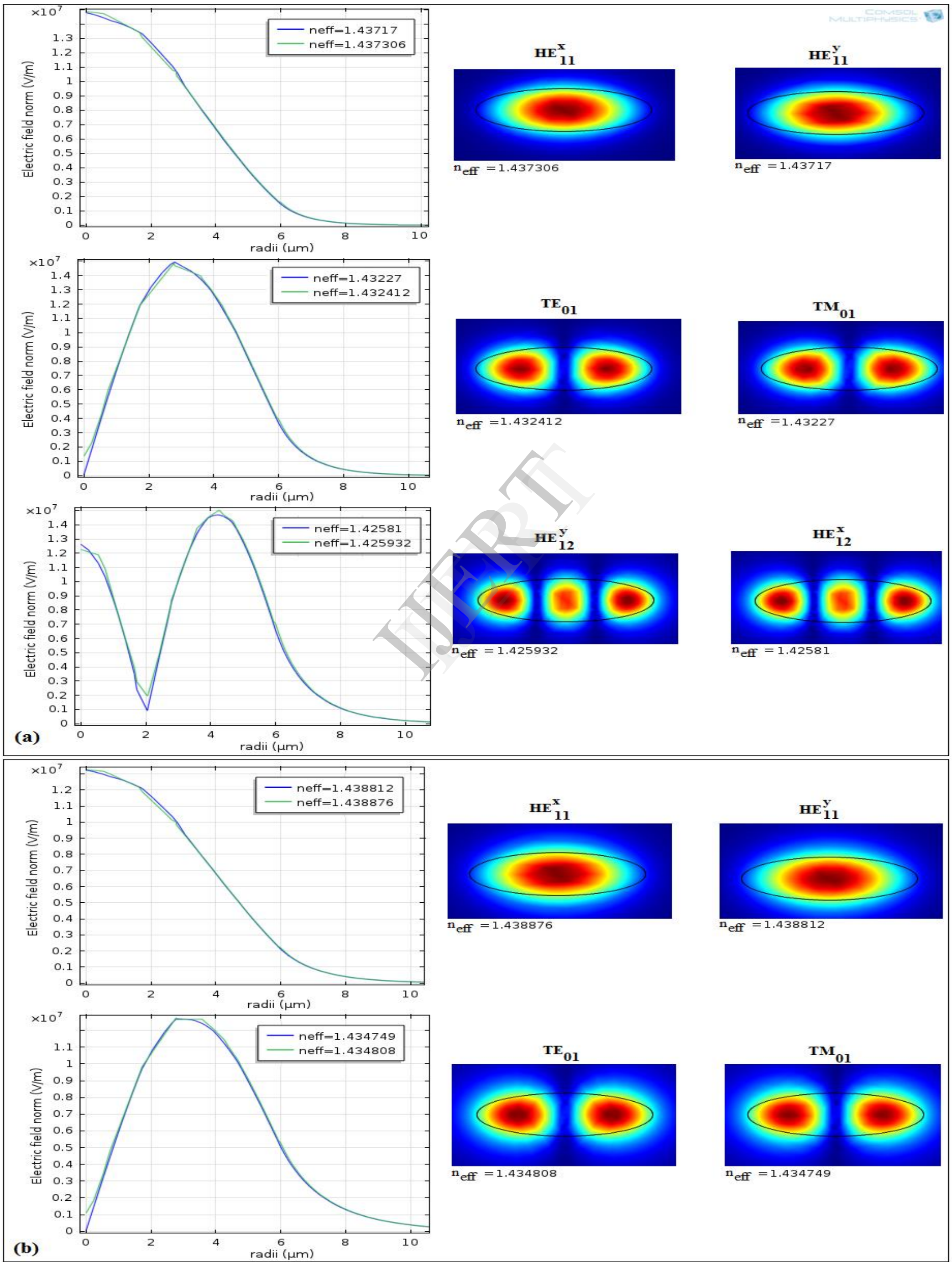

Figure 6: Calculated mode profiles and effective indices of the elliptical fibre for (a) Δn = 0.0307 (b)Δn = 0.0167. The associated E-field plots for the modes are shown to the left

It has been clearly shown that the guided modes are well confined to the core region of the fibre and presents an obvious ellipse. Figure 6 has also shown that it is possible to excite the fundamental mode with maximum electric field intensity in the middle of the core. However, two higher order modes including the second order mode (TE_{01}, TM_{01}) and third order mode (HE_{12}), with a minimum in the middle of the core, evolve as the fundamental mode (H_{11}) splits [17,18]. Because of the twofold symmetrical shape of the core, the presence of a form asymmetry in the fibre is supported by the weak birefringence caused by the refractive index difference of the propagating modes [19,20].

4. Conclusion

An elliptical core fibre with elliptical ratio *a/b* = 3 wassuccessfully analysed using the FEM in COMSOL Multiphysics®. The results confirm thatit is possible to give weak phase birefringence due to twofold symmetry in the ellipticalfibre structure. This type of specialtyfibre is likely to find applications in fibre mode converters as well as mode selective couplers.Compared to traditional analytical methods of analyzing optical waveguides, it has been shown thatthe FEM computational package, COMSOL Multiphysics® has the ability to model homogeneous elliptical core optical fiber regions with a high resolution and allows the analysis of other parameters such as the electric intensity and mode field distribution across the fiber structure.

5. References

[1] R.B Dyott, *Elliptical Fibre Waveguides*, Artech House, 1995.
[2] R.B Dyott, J.R Cozens and D.G Morris, Preservation of Polarization in optical fibre waveguides with elliptical cores, *Electron. Lett*. Vol. 15, pp. 380-382, 1979.
[3] A. Méndez and T. F. Morse, *Specialty Optical Fibers Handbook*. Academic Press, San Diego, California,2007.
[4] B.H Lee, Y.H Kim, K.S Park, J.B Eom, M.J Kim, B.S Rho and H.Y Choi, InterferometricFiber Optic Sensors, *Sensors*, vol. 12, pp. 2467-2486, 2012
[5] M. Papuchon and C. Puech, Integrated Optics: a possible solution for the fiber gyroscope, *Proc. SPIE*, vol. 157, pp 218-219, 1978.
[6] M. J. Digonnet, P. F. Wysocki, B. Kim, H. J. Shaw, Broadband fiber sources for gyros, *Proc. SPIE*, vol 1585, pp 371-382, 1991.
[7] B.P Pal(ed), *Fundamentals of Fiber Optics in Telecommunications and Sensor Systems*, New Age International Publishers, New Dehli, 2005.
[8] T. Tajikawa, M. Takeshige, W. Ishihara, S. Kohri and K. Ohba, Development of miniaturisedfiber-optic laser Doppler velocimetry sensor for measurement of local blood velocity (fabrication of convex or concave lens-like fiber tip and the characteristics of sensor optical system), *Journal of Fluid Science and Technology*, vol. 4, no. 1, pp. 62-74, 2009.
[9] R. Hui and M. O'Sullivan, *Fiber Optic Measurement Techniques*,Elsevier Academic Press, London, 2009.
[10] J. M. Senior, *Optical Fibre Communications: Principles and Practice*, Pearson, England, 2009
[11] G.P. Agrawal, *Fibre Optic Communication Systems*, Wiley, New Jersey, 2010.
[12] A. Yariv, *Optical Electronics in Modern Communications*, 5th edition, Oxford University Press, 1997.
[13] M. M. Islam, M. A. Zahid, N. B. Jamal, M. R. Parvez and M. S. Alam, Wavelength Dependence of Guiding Properties in Highly Birefringent Elliptical Ring Core Optical Fiber, *Journal of Electrical Engineering*, vol. EE 36, no. II, pp. 10-15, 2009.
[14] COMSOL Multiphysics 4.3 Documentation, COMSOL, http://www.comsol.com/, 2012.
[15] J.P. Goure and I. Verrier, *Optical Fibre Devices*, Institute of Physics Publishing, 2002.
[16] H. Kolimbiris,*Fibre Optic Communications*, Pearson Education, India , pp. 296-309, 2004.
[17] Z. Wang, J. Ju, W. Jin, Properties of elliptical-core two-mode fiber, *Optics Express*, vol. 13, no. 11, 2005.
[18] Y. Zhang, L.Ren, K. Li, H. Wang, W. Zhao, L. Wang, R. Miao, M. C. J. Large and M. A. Van Eijkelenborg, Guiding mode in elliptical core micro structured polymer optical fiber, *Chinese Optical Letters*, vol. 5, no. 4, pp. 194-196, 2007.
[19] M.S. Alam and S.R.M. Anwar,Modal Propagation Properties of Elliptical Core Optical Fibers Considering Stress-Optic Effects, *International Journal of Electrical and Computer Engineering*,vol. 5, no. 4, pp. 257-262, 2010.
[20] V.P. Tzolov and M. Fontaine, Theoretical analysis of birefringence and form-induced polarization mode dispersion in birefringent optical fibers: A full-vectorial approach, *J. Appl. Phys*, vol. 77, no. 1, 1995.