A Comparative study of eccentric circular core and elliptical core optical fibers

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Abstract:

We present in this paper a comprehensive study of eccentric circular core and elliptical core fibers and then a comparison is drawn between these two classes of optical fiber on the basis of modal characteristics parameters calculated by different researchers. Comparative study reveals that eccentric circular core fibers is superior to elliptical core fibers on the basis of its large modal birefringence at the same operating wavelength and hence two orthogonal modes gets widely separated and preserve polarization maintaining capability to a great extent. For this purpose, optimum consideration of eccentricity is taken into account for better polarization maintenance and low loss in order to have good transmission capability. In addition to above basic property for better transmission eccentric circular core fiber can be fabricated easily in comparison to elliptical core fiber.

Keywords:

Eccentricity/ core ellipticity; normalized cutoff frequency; anisotropy; birefringence; evanescent field;

1. Introduction:

Optical fibers have become the backbone of information era. This paper comprehensively describes eccentric circular core and core optical fibers and their comparison along with superiority of one over the other. It would be pertinent to mention here that both show birefringence and presence of evanescent field.

The high value of birefringence is required in single mode polarization maintaining fibers over long distance communications. Further presence of evanescent field can be tapped for fiber optic sensing applications i.e. in fiber optic sensors.

i. Eccentric Circular Core Optical Fibers :

The eccentric location of the core relative to cladding, arising due to application of stress through ultrasonic drilling, stress rods (PANDA fibers), side grooving etc., improves the modal characteristics over that of concentric circular fiber. Ref. [1-4] have investigated the eccentric configuration and analyzed core & cladding modes & determined cut off wave numbers for low values of eccentricities using analytical method and also including numerical results. For certain values of parameters such as dielectric constants of core and cladding, the ratio of core & cladding radii, it is possible to increase the operating bandwidth of the fundamental HE_{11} mode over the conventional concentric fiber.

Alphones et al [5] have calculated large modal birefringence i.e. large separation between propagation constants of the two orthogonally polarized modes and hence the fiber can be used as a single mode polarization maintaining fiber.

N. Singh et al [6] have tried to study eccentric core fibers with any order of eccentricity analytically showing a correct limiting behaviour for concentric double clad fiber and dielectric rod problem on substitution of eccentricity parameter 'd' = 0. From the works of above researchers, we note that the cut off frequency (or V-parameter) and the birefringence increases with eccentricity.

References [7-9] have calculated modal fields, propagation constants, fundamental core mode cut off frequency Vc, and fractional power of evanescent field for different eccentricities, wavelengths, core radii and coating refractive indices using conformal mapping technique. Evanescent field in the coating has been tapped for use in fiber-optic sensing devices.

ii. Elliptical Core Fibres :

Many researchers have investigated the propagation characteristics of optical fibers with elliptical cross-section, as an extension over the conventional optical fiber with circular cross-section of the core having concentric [10] or eccentric location relative to the cladding.

Elliptical cross-section fiber also posses good modal behaviour [11- 26] in respect of fundamental mode cut off frequency, modal birefringence, evanescent field etc.

The cut off frequency is found to increases with eccentricity [12-14]. With increase in cut off frequency, the single mode operation increase & hence dispersion decreases.

Elliptical core fibers exhibit birefringence due to ellipticity of the core as well as thermally induced stress [15, 16] during its development from its perform.

Birefringence is found to vary with ellipticity, various thermal stress conditions, relative refractive index difference, Δ, thickness of cladding and number of claddings as observed by different researchers working on optical fibers having elliptical cross-section.

Birefringence is found to increase with ellipticity as reported by different researchers [17-26]. However high value of modal birefringence is obtained even with relatively small ellipticity in an optical fiber with three layer elliptical cross section [19].

M. Kuroda [20] has investigated a three layer fiber for realizing a single mode single polarization fber with large values of modal birefringence. The above mentioned 3-layer structure having W-type refractive index profile exhibit HE_{11} mode having a cut off region i.e. different cut off frequencies are obtained for the two orthogonally polarized modes & thereby eliminating one of the two polarized modes one can achieved absolute single polarization.

T.Okoshi [21] has also observed that cut off region appears for HE_{11} mode in side-pit fiber. One can be eliminated to get absolute single polarization single mode fiber. Reference [22, 23] exhibit strong evanescent and therefore it is of importance for potential applications as gas & biochemical sensors.

2. Formulation of the Problem:

i. Mathematical Formulation For Eccentric Circular Core Optical Fiber

The geometrical configuration of the cross sectional plane of the eccentric core optical fiber in shown in fig (1)

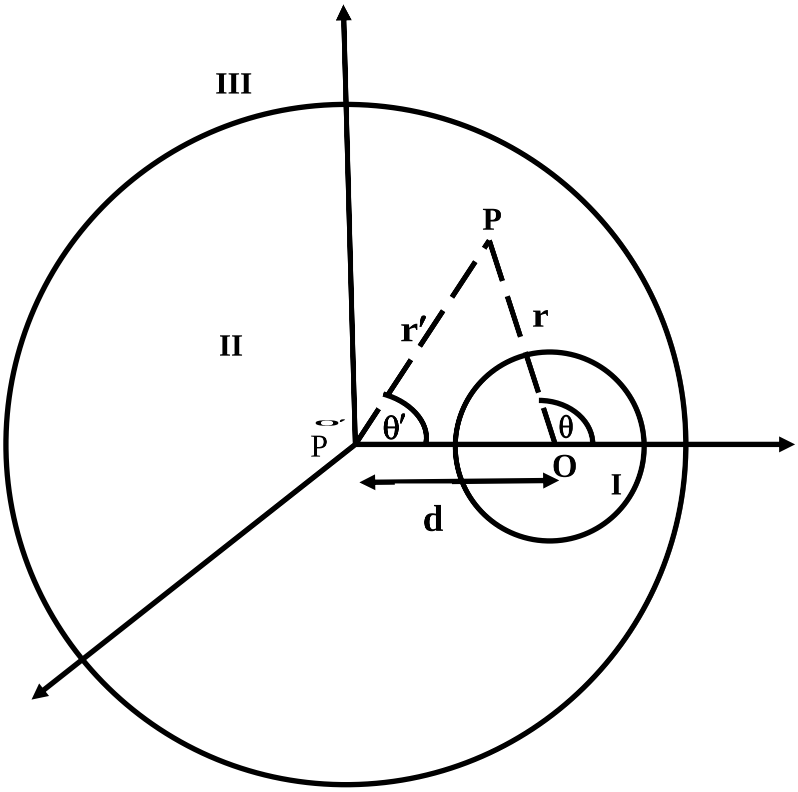

Fig 1: Cross sectional view of eccentric core optical fiber

We present the expression of cutoff condition for eccentric core double clad (three layered) optical fiber.

Let O and O' be centers of outer & inner boundaries & ‘d’ be the eccentric distance / eccentricity.

A point P in between the inner boundary & outer boundary is considered.

The fields satisfy the scalar wave equation

$$\left[\nabla_t^2 + \left(\omega^2\mu_i\varepsilon_i - \beta^2\right)\right]\psi^i_{r,\theta} = 0 \qquad (1)$$

with $\alpha_i^2 = \omega^2\mu_i\varepsilon_i - \beta^2$ and $i = 1, 2, 3$, α_i^2 is positive for region- I and negative for region-II and III

We obtain the following expressions for fields satisfying the scalar wave equation for three regions as

$$\psi_m^1 = A_m^1 J_m\left(\alpha_1 r\right) \qquad (2)$$

$$\psi_m^2 = A_m^2 I_m\left(\alpha_2 r\right) + C_m^2 K_m\left(\alpha_2 r\right) \qquad (3)$$

$$\psi_m^3 = C_m^3 K_m\left(\alpha_3 r\right) \qquad (4)$$

&

$$\phi_m^1 = B_m^1 J_m(\alpha_1 r) \quad (5)$$

$$\phi_m^2 = B_m^2 I_m(\alpha_2 r) + D_m^2 K_m(\alpha_2 r) \quad (6)$$

$$\phi_m^3 = D_m^3 K_m(\alpha_3 r) \quad (7)$$

Where $J_m(x)$ is the Bessel's function of the first kind & $I_m(x)$ & $K_m(x)$ are the modified Bessel's function of the first & second kinds respectively

Here ψ_m 's & ϕ_m 's correspond to electric & magnetic field respectively. α 's are mode characteristic parameter & expressed as

$$\alpha_i^2 = \omega^2 \mu_c \varepsilon_i - \beta^2 \quad (8)$$

Where i = 1, 2, 3 for the three regions.

We then employ Graf's Addition Theorem for Bessel Functions for shifting of centre in eccentric core system and the boundary conditions of continuity of tangential components of electric & magnetic fields at the two interfaces & then by mathematical manipulations we obtain the cutoff condition from the following characteristics equation expressed as

$$\begin{vmatrix} P_{mn} & Q_{mn} \\ R_{mn} & S_{mn} \end{vmatrix} = 0 \quad (9)$$

where the elements within the determinant are the transpose of matrices as given in Ref.[6]. Elements involve $J_m(x)$, $I_m(x) \& K_m(x)$, fiber parameters namely permittivity, permeability, radii of core and cladding and eccentric distance 'd' . The eigen values of characteristics matrix equations are the propagation constants β . For odd and even modes, we get elements of matrices which are different and hence the corresponding characteristic matrix equations will yield propagation constant β_o & β_e for the two orthogonally polarized modes. The difference $\Delta\beta$ of β_o & β_e is known as modal birefringence. i.e.

$$\Delta\beta = \beta_o - \beta_e \quad (10)$$

The normalized modal birefringence is given by

$$B = \frac{\Delta\beta}{k} = \frac{\lambda}{2\pi}(\beta_e - \beta_o) \quad (11)$$

ii. Mathematical Formulation For Elliptical Core Optical Fiber

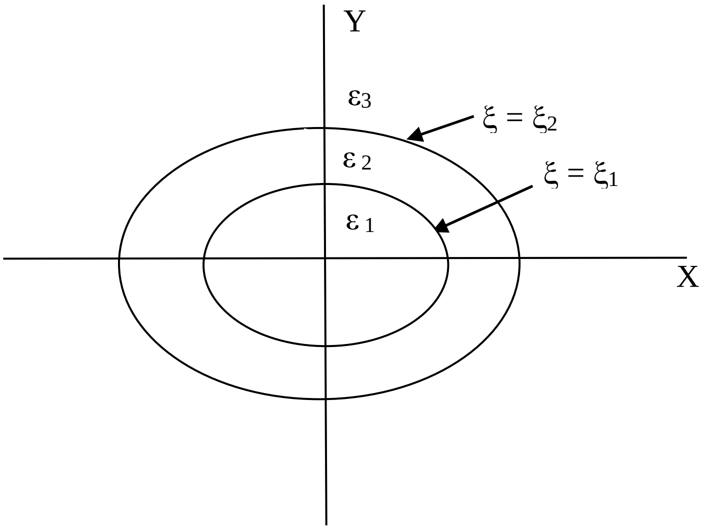

Fig 2 : Cross sectional view of elliptical optical fiber.

Fig (2) shows the cross section of the three layer elliptical fiber having a common confocal point. The outer cladding extends to infinity. The elliptical fiber has W-type refractive index profile.

$\varepsilon_1, \varepsilon_2$ & ε_3 are the permittivities of the three layers & μ_o is the permeability. Refractive indices n_1, n_2 & n_3 are related by the following relation

$n_1 k_o > \beta > n_3 k_o > n_2 k_o$

Where β is the z- component of the propagation constant and $k_o = \omega(\mu_o \varepsilon_o)^{\frac{1}{2}}$.

The electromagnetic wave propagation can be described in terms of scalar function ψ satisfying the Helmholtz eqn. in the (ξ, η, z) elliptical coordinate system.

The wave eqn. in (ξ, η, z) elliptical coordinate system

$$\frac{\partial^2 \psi_i}{\partial \xi^2} + \frac{\partial^2 \psi_i}{\partial \eta^2} + \frac{k_i^2 h^2}{2}(\cosh 2\xi - \cos 2\eta)\psi_i = 0 \qquad (12)$$

Where 2h is the absolute length of elliptical section and k_i^2 are

$$k_1^2 = n_1^2 k_o^2 - \beta^2$$
$$k_2^2 = \beta^2 - n_2^2 k_o^2 \qquad (13)$$
$$k_3^2 = \beta^2 - n_3^2 k_o^2$$

$b_i = a_i\sqrt{1-e^2}$ where i = 1, 2, 3 for core $(0 \le \xi \le \xi_1)$, cladding $(\xi_1 \le \xi \le \xi_2)$ and outer layer region $(\xi_2 \le \xi < \infty)$.

In elliptical coordinates the Mathieu function is employed for solution (omitting the z and t dependent term $e^{j(\omega t - \beta z)}$).

Eqn. (12) is separated in elliptical cylindrical coordinates

The scalar wave function can then be written as

$$\psi(\xi,\eta,z,t) = \phi(\xi,\eta)e^{j(\omega t - \beta z)} \qquad (14)$$

Where ψ represents either E or H fields. $\phi(\xi,\eta)$ is the radial function describing the field in $\xi - \eta$ plane & β is the longitudinal component of propagation constant.

Using the boundary conditions of continuity of tangential electric & magnetic field components & their derivatives at the interfaces we obtain 8 x 8 determinantal equation which can be simplified to 2x2 determinantal equation as in case of ECOF [6]. The matrix elements involve Mathieu function & modified Mathieu function.

The characteristic eqn. is derived from the determinantal equation for the two orthogonally polarized mode. Eigen values of these characteristic equations are the propagation constants of the two orthogonally polarized modes.

General expression for normalized frequency and normalized propagation constant and birefringence are

$$\mathrm{V} = \mathrm{k_o a_o}\sqrt{\mathrm{n_1^2 - n_3^2}} \qquad (15)$$

$a_o =$ semi major axis of the core & the normalized propagation constant as

$$b = \frac{\left(\frac{\beta}{k_o}\right)^2 - n_3^2}{n_1^2 - n_3^2} \qquad (16)$$

Normalized modal birefringence

$$B = \frac{\Delta\beta}{k} = \frac{\lambda}{2\pi}(\beta_e - \beta_o) \quad (17)$$

3. Results & Discussion:

Many important results in respect of cut off wave number, birefringence, polarization preservation, bandwidth, evanescent field power are obtained with low values of eccentricity. Cut off wave numbers [1, 4] have been found to increase with validity for low eccentricities.

Ref [3] discusses the possibility to enhance monomode operating bandwidth of the basic HE_{11} mode at low eccentricities over the conventional concentric fiber.

Alphones et al [5] have calculated large normalized modal birefringence ΔB approximately equal to 10^{-4} at e = 35μm, μm λ=1.3 μm, $\frac{r_2}{r_1} = 8$, r_1 = = 5μm, Δ= 0.1%. This value of normalized modal birefringence is large enough for the fiber to be used as single mode polarization maintaining fiber.

The birefringence increases with eccentricity as noted in reference [5,6].

Workers [8, 9] have calculated core mode cut off frequency V_c and evanescent field power for different eccentric distances, wavelengths, core radii and coating refractive indices. The fractional power of evanescent field finds its application in fiber optic sensing devices. It is observed that the higher the coating ref. index, the stronger is the evanescent field power & larger the eccentric distance, the weaker is the evanescent field power. The maximum power of evanescent field is desirable for enhancing sensing applications such as in gas and biochemical senses for coal mine safety applications.

The introduction of ellipticity and multilayer elliptical structure provide additional parameters for controlling the propagation properties of the fiber [12].Cut off values for e = 0.1 are V = 6.1797, 6.4031 for four & six layers respectively. For e = 0.5 are 6.825 & 7.147 for e = 0.9 are 12.831 & 13.8982. Thus the cut off values increases with increase in ellipticity from e = 0.1 to e = 0.9. The cut off frequency also increases by increasing the no. of layers at a particular value of eccentricity. Hence with increase in normalized cut off value for a particular mode, the single mode operation increases due to which the intermodal dispersion decreases.

With an elliptically cored fiber Vivek Singh et al[10] have shown that the number of guided modes decreases with increase in ellipticity from 0.6 to 0.9. As 'e' increases from 0.1 to 0.9,the cutoff 'V' values increases, a common feature in elliptical core fibers. Thus the case of e= 0.9 is desirable for having fewer modes. Finally from the variation of birefringence with 'V' parameter for different 'e', maximum birefringence is observed that at V=0.9. The results so obtained similar in nature to that reported by Adam[14].

Miyamoto [18] obtained modal birefringence having magnitude of the order of 10^{-4}.

M. Kuroda [20] describing a 3-layer elliptical structure having W-type ref. index profile have shown that HE_{11} mode have a cut off frequency region. Large values of birefringence ΔB, the difference of propagation constants have been obtained for n_1 = 1.46, Δ = 1%, & λ = 1.3 μm, ΔB ~ 1086 radian/m is obtained with ξ_1 = 0.6. For higher ellipticity ξ_2 = 0.8, ΔB = 3808 radian/m. This value is sufficient to achieve long distance transmission with polarization preservation in the 3-layered fiber.

Fibers with B value of 3 x 10^{-4} have been achived by I. P. Kaminow [24].

1.5 μm operating wavelength region shows low loss, dispersion free and larger bandwidth (250 GHz km nm) in single mode fiber compared to 1.3 μm operating wavelength having 26 GHz km nm bandwidth [25].

Ref [26] observed in non-circular core single mode fibers.

Bs > Bg when Δ is small i.e. $\Delta \approx$ 0.2 to 0.4%.

Bg > Bs when Δ is large i.e. $\Delta \approx$ 1.5%

Where Bg = geometrical birefringence

Bs = stress induced birefringence.

The optimum waveguide parameters such as index difference Δ, core ellipticity 'e', cut off frequency Vc have been determined to obtain

(i) large modal birefringence

(ii) zero polarization mode dispersion

& (iii) low-loss transmission

When borosilicate (B_2O_3) is used as a material of stress applying parts [27].

Shibata et al [28] have observed that normalized modal birefringence Δ B is markedly decreased with 'λ' for different 'e' in core fibers compared to stress induced PANDA fibers showing thereby the superiority of eccentric core circular fibers over elliptical fibers in respect of large modal birefringence at the same operating wavelength.

Thus optimum values of core as well as clad ellipticity, number of cladding layers, relative refractive index difference, operating wavelength, normalized cut off frequency (V-parameter), one can develop highly birefringent, with ignorable polarization mode dispersion, single mode polarization maintaining fibers with low loss over long distance transmission.

Comparison between ECOF & Elliptical fibres :

We have comprehensively discussed eccentric core circular fibers and elliptical core fibers correlating the works done by different workers. Birefringence is introduced when we move from conventional concentric circular cylindrical fibers to eccentric circular core fibers & elliptical core fibers which is needed in polarization maintaining fibers.

Both ECOF & elliptical core fibers predict higher normalized frequency i.e. V-parameter, high birefringence & hence polarization preservation, power of evanescent field etc. because of the introduction of new parameter eccentricity/ ellipticity. Comparative study reveals that eccentric circular core fibers are superior to elliptical core fibers on the basis of its large modal birefringence at the same operating wavelength. [28]

With large modal birefringence, the two orthogonally polarized modes gets widely separated & preserve the input stage of polarization. For this purpose, optimum consideration of eccentricity is taken into account of better polarization maintenance, sensing applications and low loss in order to have good transmission capability.

In addition to above basic property for better transmission, eccentric circular core fiber can be fabricated easily in comparison to core fiber.

4. Conclusions:

Both eccentric circular core optical fiber and elliptical core fiber exhibit high value of normalized modal birefringence having magnitude of the order of 10^{-4} which is large enough to maintain the input state of polarization over long distances with ignorable polarization mode dispersion. However eccentric core optical fiber is superior to elliptical core fiber from fabrication point of view. Eccentric core optical fiber having circular cross-section can be fabricated easily compared to optical fibers with elliptical cross-section.

In case of eccentric circular core single mode fiber, normalized cut off frequency Vc ≤ 2.405 whereas in elliptical core fiber Vc ≤ 1,85. Hence ECOF is superior to elliptical core fiber in respect of normalized cut off frequency Vc.

In ECOF we get enhanced evanescent field which result in higher sensitivity compared to elliptical core optical fibers. The potential application of ECOF is to develop new style evanescent field absorption sensor.

Normalized modal birefringence increases with eccentricity. However accompanying losses are greater in elliptical core compared to eccentric circular core optical fiber. Loss in fibers will be such that cannot be compensated.

The availability of such mode controlling parameters & the variety of new modal properties are indicative of future technological use.

We are confident that the work done in this paper will stimulate further theoretical and experimental research which will be useful in the fabrication of new photonic devices.

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