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POLARISATION IN SINGLE MODE OPTICAL FIBRES

Conleth D. Hussey

Department of Electronics & Information Engineering,

The University,

Southampton,

SO9 5NH,

Hampshire

Summary

Starting with concepts of polarisation inherited from bulk optics, the lecture will introduce the concepts of "modal polarisations" in weakly-guiding optical fibres. Thereby certain limitations in measurement systems which employ plane polarisation, as opposed to modal polarisation are considered.

The need for highly-birefringent fibres is outlined. Recent research on fibres, having large levels of birefringence, for polarisation dependent applications is reviewed. Particular emphasis will be placed on some recent techniques, developed at Southampton, for incorporating large levels of circular birefringence into optical fibres.

Some speculative ideas about possible geometries for future polarisation-dependent applications are introduced.

1. Introduction

In most applications, an optical fibre is a means for transmitting signals in the form of optical power with pulse code or intensity modulation; the signal is detected by a photodiode that is insensitive to optical polarisation or phase. Recently, however, attention has been directed to applications which do depend upon the optical polarisation of the wave within a fibre or at its output. Yet nominally-circular fibres do not maintain the input state of polarisation for more than a few metres[1] so that fibres must be specially designed to maintain polarisation.

As in bulk media, the evolution of the polarisation state in an optical fibre can be described in terms of a "modal birefringence", i.e. the difference in effective indices for the orthogonally-polarised normal modes. It is our purpose to review the experimental progress in maximising the modal birefringence as required for various applications; we will put special emphasis on the recent achievements of high circular birefringence in optical fibres. We will be concerned with those fibres which support only one mode in each polarisation.

Before moving on to these topics, however we will briefly review the concepts of polarisation which we have inherited from bulk optics[2].

2. Polarisation

Light when travelling in free space or in a medium of constant refractive index may be treated as a transverse electromagnetic (TEM) wave. **Linearly-polarised** or **plane-polarised** light, is light for which the orientation of the electrc field is constant although its magnitude varies in time (Figure 1). The electric field or optical disturbance therefore resides in what is known as the plane of vibration. That fixed plane contains both $\underline{E}$ and $\underline{k}$, the electric field vector and the propagation vector in the direction of motion. Imagine now that we have two harmonic, linearly-polarised light waves of the same frequency, moving through the same region of space, in the same direction. If their electric field vectors are co-linear, the superimposing disturbances will simply combine to form a resultant linearly-polarised wave. Its amplitude and phase give rise to the phenomenon of interference. In contradistinction, if the two light waves are such that their respective electric field directions are mutually perpendicular, the resultant wave may or may not be linearly polarised. Exactly what form the light will take (i.e. its **state-of-polarisation**) is what concerns us in this section.

2.1 Linear Polarisation

We can represent the two orthogonal optical disturbances which were considered above in the form.

$$E_x(z,t) = \underline{\hat{i}}\ E_{ox} \cos\ (kz - \omega t) \qquad (1)$$

$$E_y(x,y) = \underline{\hat{j}}\ E_{oy} \cos\ (kz - \omega t + \zeta) \qquad (2)$$

where k is the wave number (= $2\pi n/\lambda$) and ω the frequency of the light. ζ is the relative phase difference between the waves both of which are travelling in the z-direction. The resultant optical disturbance is then simply

$$\underline{E}(z,t) = \underline{E}_x(z,t) + \underline{E}_y(z,t) \qquad (3)$$

If ζ is zero or an integral multiple of $\pm 2\pi$ then the waves are said to be in phase and

$$\underline{E} = (\underline{\hat{i}}\ E_{ox} + \underline{\hat{i}}\ E_{oy})\cos(kz - \omega t) \qquad (4)$$

the resultant wave therefore has a fixed amplitude equal to $(E_{ox}{}^2 + E_{oy}{}^2)^{\frac{1}{2}}$ i.e. it too is linearly polarised as shown in Figure 1. This process can equally well be carried out in reverse, that is, we can resolve any plane polarised wave into two orthogonal components.

If ζ is an odd multiple of $\pm\pi$, we again have linearly polarised light but now with the plane of polarisation rotated from that of the previous condition.

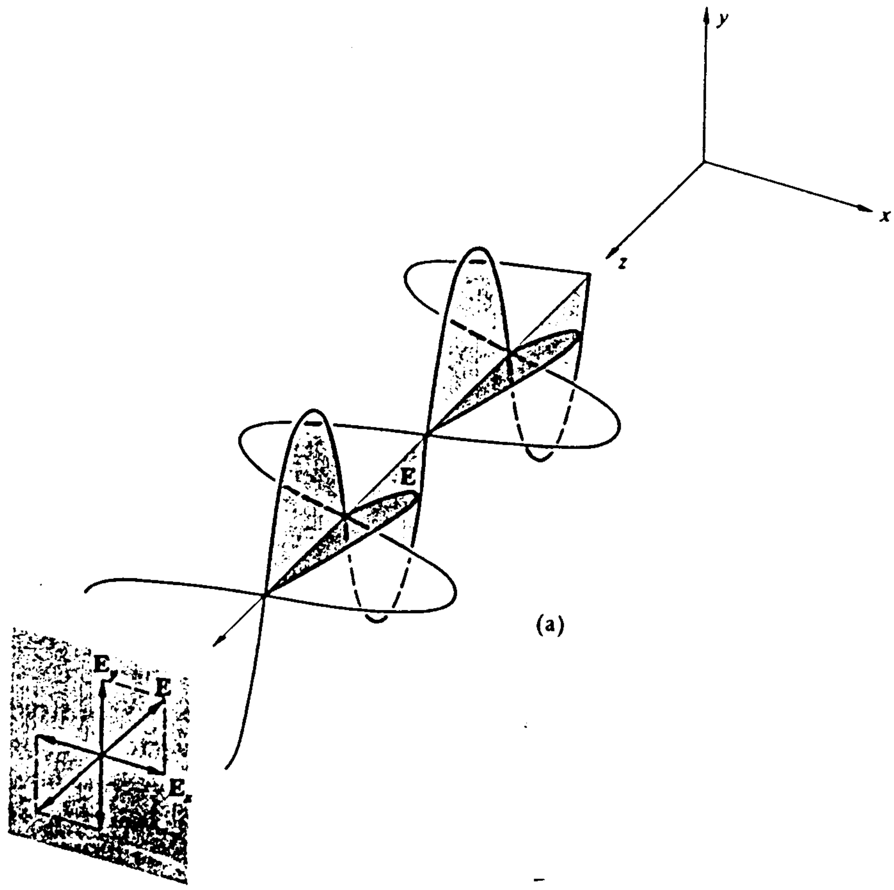


Figure 1 Linearly-Polarised Light

2.2 Circular Polarisation

Another special case of particular interest arises when both constituent waves have equal amplitudes i.e. $E_{0x} = E_{0y} = E_0$ and in addition their relative phase difference $\zeta = -\pi/2 + 2m\pi$ where $m = 0, \pm1, \pm2, \ldots$ Accordingly

$$\underline{E}_x(z,t) = \underline{\hat{i}}\, E_0 \cos(kz - \omega t) \qquad (5)$$

$$\underline{E}_y(z,t) = \underline{\hat{j}}\, E_0 \sin(kz - \omega t) \qquad (6)$$

The consequent wave is given by

$$\underline{E} = E_0 \,[\underline{\hat{i}} \cos(kz - \omega t) + \underline{\hat{j}} \sin(kz - \omega t)] \qquad (7)$$

(Figure 2). Notice that the scalar amplitude of $\underline{E}$ which is equal to E_0, is a constant. But the direction of $\underline{E}$ is time varying and it is not restricted as before to a single plane. The resultant electric field vector $\underline{E}$ is rotating clockwise at an angular frequency ω as seen by an observer towards whom the wave is moving. Such a wave is said to be **right circularly polarised.** The $\underline{E}$ vector makes one complete rotation as the wave advances through one wavelength. If $E = \pi/2, 5\pi/2 \ldots$ then

$$\underline{E} = E_0 \,[\underline{\hat{i}} \cos(kz - \omega t) - \underline{\hat{j}} \sin(kz - \omega t)] \qquad (8)$$

then the wave rotates counter clockwise and is referred to as **left circularly polarised.**

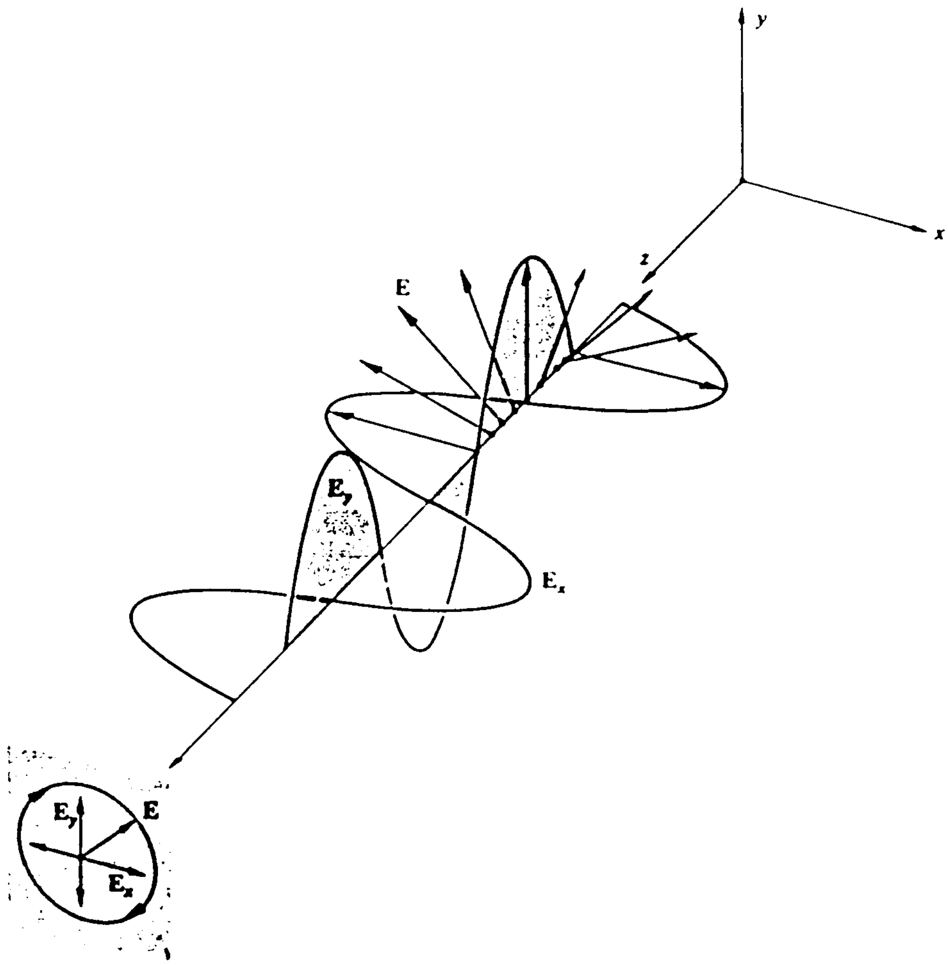


Figure 2 Circularly-Polarised Light

A linearly polarised wave can be synthesised from two oppositely-polarised circular waves of equal amplitude. In particular if we add the right circular wave of equation (7) to the left circular wave of equation (8), we obtain

$$E = 2E_0 \, \underline{\hat{\imath}} \cos(kz - \omega t) \tag{9}$$

which has a constant amplitude vector of $2E_0 \, \underline{\hat{\imath}}$ and is therefore linearly polarised. If there is a relative phase difference ζ between the right and left circular waves then the resultant wave is linearly polarised but rotated through an angle $\zeta/2$. The direction of rotation depending on the sign of the phase difference.

2.3 Elliptical Polarisation

As far as the mathematical description is concerned, both linear and circular light may be considered to be special cases of **elliptically polarised** light. By this we mean that the resultant electric field vector $\underline{E}$ will both rotate and change in magnitude as well. In such cases the end point of $\underline{E}$ will trace out an ellipse in a fixed plane perpendicular to $\underline{k}$ as the wave sweeps by. We can see this if we write the expression for the curve traversed by the tip of $\underline{E}$. If

$$E_x = E_{0x} \cos(kz - \omega t) \tag{10}$$

$$E_y = E_{0y} \cos(kz - \omega t + \zeta) \tag{11}$$

then we can show that

$$\left(\frac{E_y}{E_{oy}}\right)^2 + \left(\frac{E_x}{E_{ox}}\right)^2 - 2\left(\frac{E_x}{E_{ox}}\right)\left(\frac{E_y}{E_{oy}}\right)\cos\zeta = \sin^2\zeta \qquad (12)$$

This is the equation of an ellipse making an angle α with the E_x, E_y co-ordinate system (Figure 3) such that

$$\tan 2\alpha = \frac{2E_{ox}\, E_{oy} \cos \zeta}{E_{ox}^2 - E_{oy}^2} \qquad (13)$$

Figure 4 displays various polarisation configurations corresponding to specific values of ζ. When E is some multiple of π then the light is linearly polarised and if ζ is some multiple of $\pi/2$ together with $E_{ox} = E_{oy}$ the light is circularly-polarised.

2.4 State-of-Polarisation (SOP)

We are now in a position to refer to a particular light wave in terms of its **state-of-polarisation.** We shall say that linearly polarised light is in a P-state while right and left circular light is in an R- or L-state, respectively. Similarly the condition of elliptical polarisation corresponds to an E-state. We have already seen that a P-state can be represented as a superposition of P-states or as a superposition of R- and L-states. We have also seen that an E-state can be represented as a superposition of P-states, it can also be represented as a superposition of R- and L-states where the amplitudes of the two circular waves are different.

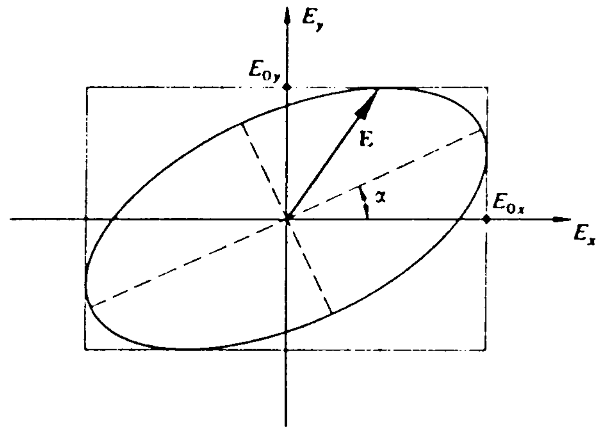


Figure 3 Elliptically-Polarised Light

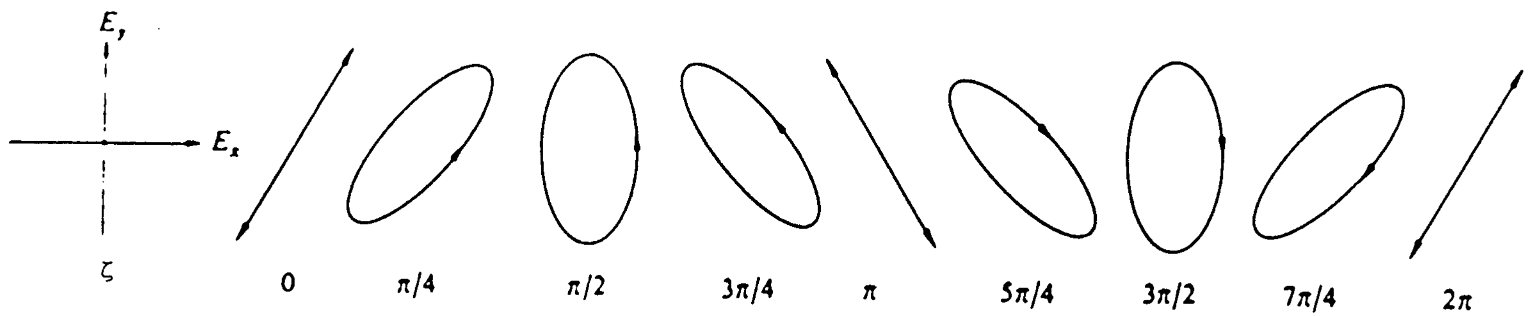


Figure 4 Various polarisation configurations corresponding to specific values of ζ. Here E_x leads E_y by ζ. The light would be circular when $\zeta = \pi/2$ or $3\pi/2$ if $E_{ox} = E_{oy}$.

3. Polarisation in Optical Fibres

The fundamental (or HE_{11}) mode of a circularly symmetric optical fibre consists of two modes whose "polarisations" are orthogonal[3]. In general the orthogonal "modal polarisations" do not correspond to the two plane polarised cartesian components (equations (1) and (2)) which apply to waves in a uniform medium. However, most optical fibres are "weakly-guiding"[4,5], i.e. they have refractive index profiles n(r), where the variation between the maximum and minimum values are small, typically less than 1%. It turns out that the electric fields are then approximate solutions of the **scalar wave equation** and can therefore be approximated by plane polarised waves.. This can be appreciated by the following arguments[6].

The propagation constant β of the fundamental mode must lie somewhere between two extremes given by the value of β (or wave number) for a z-directed plane wave propagating in an infinite medium of refractive index equal to the maximum or minimum values of the fibre profile n(r). If we define these maximum and minimum values of n(r) as

n_{co} = maximum refractive index of n(r)

n_{cl} = minimum refractive index of n(r) then β is bounded by

$$\frac{2\pi\, n_{c\ell}}{\lambda} < \beta < \frac{2\pi\, n_{co}}{\lambda} \qquad (14)$$

where λ is the wavelength in vacuum. Because fibres are "weakly-guiding" i.e. $n_{co} \simeq n_{c\ell}$ it follows that $\beta \simeq 2\pi n/\lambda$ which is the propagation constant of a z-directed plane wave in an unbounded medium of refractive index $n_{c\ell} \simeq n \simeq n_{co}$.

Accordingly, one of the polarisations of the fundamental mode of an optical fibre must be nearly a transverse electromagnetic (TEM) wave, the simplest being a wave polarised uniformly in one direction only[6]. Taking this direction to be x, the fields of an optical fibre are given by

$$\underline{E} = \underline{\hat{i}}\; E(r)\, \cos(\omega t - \beta z) \qquad (15)$$

$$\underline{H} = \underline{\hat{j}}\; (\varepsilon/\mu)^{\frac{1}{2}}\, E(r)\, \cos(\omega t - \beta z) \qquad (16)$$

while the other field components are negligible, E(r) specifies the spatial variation in the plane perpendicular to the fibre axis. μ is the permeability of the medium, $\varepsilon = \varepsilon_0 n^2$, where $n \simeq n_{co} \simeq n_{c\ell}$ and ε_0 is the dielectric constant of vacuum.

Because $n_{co} \simeq n_{c\ell}$, the fields are only weakly influenced by the polarisation properties of the fibre structure. If this is not obvious, then recall that plane wave reflection from a dielectric interface is nearly insensitive to the polarisation of the incident wave when the two dielectrics are similar[7]. Accordingly, the spatial dependence, E(r) of the fields must be insensitive to polarisation effects so that E(r) is a solution to the scalar wave equation

$$\left\{ \frac{d^2}{dr^2} + \frac{1}{r}\frac{d}{dr} + \left(\frac{2\pi}{\lambda}\right)^2 n^2(r) \right\} E(r) = \beta^2 E(r) \qquad (17)$$

The solution corresponding to the fundamental mode is that with the largest β and with E(r) independent of the polar angle.

Figure 5 shows schematically the decomposition of the "modal polarisation" of the HE_{11} mode when analysed by a bulk polariser, generally the minor field component is present at a -70dB intensity level so that for most purposes the plane polarisation approximation is valid[8,9,10].

The two polarisations of the fundamental mode can therefore be expressed in terms of the two orthogonal cartesian components (x,y) as

$$E_x(z,t) = \underline{i}\ E(r) \cos(\beta_x z - \omega t) \qquad (18)$$

$$E_y(z,t) = \underline{j}\ E(r) \cos(\beta_y z - \omega t) \qquad (19)$$

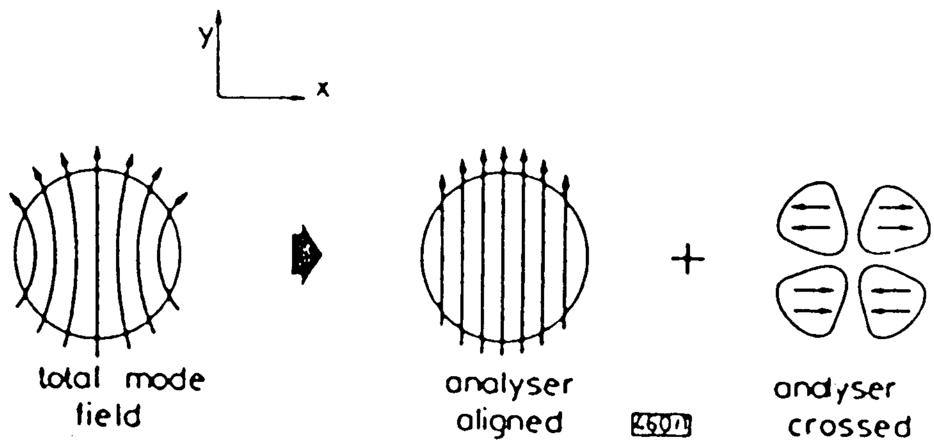


Figure 5 Schematic decomposition of the modal polarisation of the HE_{11} mode into its major y- and minor x-plane polarised components.

in complete analogy with equations (1) and (2) where $\beta_x = \beta_y$. Similarly the two polarisations of the fundamental mode can be written in terms of the two orthogonal right (R) and left (L) circularly polarised components.

$$E_R(z,t) = E(r)\ [\underline{\hat{\imath}}\ \cos(\beta_R z - \omega t) + \underline{\hat{\jmath}}\ \sin(\beta_R z - \omega t)] \qquad (20)$$

$$E_L(z,t) = E(r)\ [\underline{\hat{\imath}}\ \cos(\beta_L z - \omega t) - \underline{\hat{\jmath}}\ \sin(\beta_L z - \omega t)] \qquad (21)$$

where $\beta_R = \beta_L$.

In summary then, so called "single-mode" fibres with nominally circular symmetry about the fibre axis are in fact bimodal in that they can propagate two degenerate modes with orthogonal polarisations these are the $HE_{11}{}^x$ and $HE_{11}{}^y$ modes or the $HE_{11}{}^R$ and $HE_{11}{}^L$ modes.

4. Birefringent Fibres

Even though an ideal round-core single-mode fibre should maintain the state-of-polarisation propagating in the guide indefinitely, most real fibres scramble polarisation. This is because inherent birefringence removes the degeneracy between the two orthogonal polarisations of the fundamental mode and any defects (such as core deformations) and strains which are either built into the fibre or introduced by bending, twisting or mounting will scatter light between these two polarisations. Thus the state-of-polarisation at the fibre output is arbitrary and can, in fact, vary with time in response to temperature and pressure changes along the length of the fibre[1,11,12,13,14].

This time varying state-of-polarisation becomes a serious problem in the interconnection of single-mode fibres with polarisation sensitive devices such as integrated optical multiplexers and switches and interferometric devices since they require the interacting beams to have identical polarisations. These depolarisation effects also degrade the performance of devices based on non-linear interactions in fibres, such as Raman oscillators[11,14].

The general approach to maintaining polarisation in a single-mode fibre is to increase the fibre birefringence so as to reduce the interchange of power between the two polarisations.

4.1 Modal Birefringence

4.1.1 Linear birefringence

Linear birefringence arises from the breaking of the degeneracy between the $HE_{11}{}^{x}$ and $HE_{11}{}^{y}$ modal polarisations. This means that the propagation constants β_x and β_y

are no longer equal in equations (18) and (19). The principal axes, x and y, are determined by the symmetry elements in the cross section as in Figures 8-13. The larger the anisotropy of the cross section the greater the difference in propagation constants β_x and β_y for the two normal modes. If the fibre cross section is independent of the fibre length z, then the fibre behaves like a linearly birefringent medium with a modal birefringence B_L given by

$$B_L = (\beta_x - \beta_y)/(2\pi/\lambda) \qquad (22)$$

where λ is the optical wavelength. Light polarised along one of the principal axes will retain its polarisation for all z. Light polarised at an angle θ with respect to the x-axis at $z = 0$ will pass through various states of elliptic polarisation as the phase retardation

$$\Phi(z) = (\beta_x - \beta_y)z \qquad (23)$$

varies with length, provided the two normal mode components maintain phase coherence (cf Figure 4 for a continuously varying ζ).

For incident linear polarisation with $\theta = 45^o$ at $z=0$, the polarisation becomes circular for $\Phi = \pi/2$, linear with $\theta = -45^o$ for $\Phi = \pi$, circular for $\Phi = 3\pi/2$ and linear with $\theta = 45^o$ for $\Phi = 2\pi$ as shown in Figure 6. The length L corresponding to $\Phi(L) = 2\pi$ is called the "beat length".

$$L = \lambda/B_L \qquad (24)$$

The beat length can be observed directly by means of dipole (Rayleigh) scattering from the fibre[15]. Since the radiation pattern of a dipole has a null along the dipole axis and a maximum normal to the axis, a fibre viewed along the direction of the incident polarisation will exhibit a series of dark and bright bands with period L as shown in Figure 6. It is also thus possible to determine B from the observed beat length. The beats in the fibre shown in Figure 7 have L = 1.2mm at λ = 633nm; therefore $B_L = 5.7 \times 10^{-4}$.

Breaking the circular symmetry of the core to remove the degeneracy of the two polarisations of the fundamental mode was one of the earliest suggestions to achieve linear birefringence in a single-mode fibre[16,17] (see Figure 8). However it was shown that only a slight improvement in polarisation performance is obtained using fibres with extremely elliptical cores. It has been found that anisotropic strain is more important than non circular geometry for maintaining linear polarisation over long lengths[18,19,20]. This effect can be achieved with a stressed elliptical cladding surrounding a circular core[11,19] (see Figure 10). Strain is introduced because of the different thermal expansion between the borosilicate cladding and the silica substrate tube. Strain is introduced in the fibre drawing stage due to different cooling rates during the draw. Perhaps the best known of

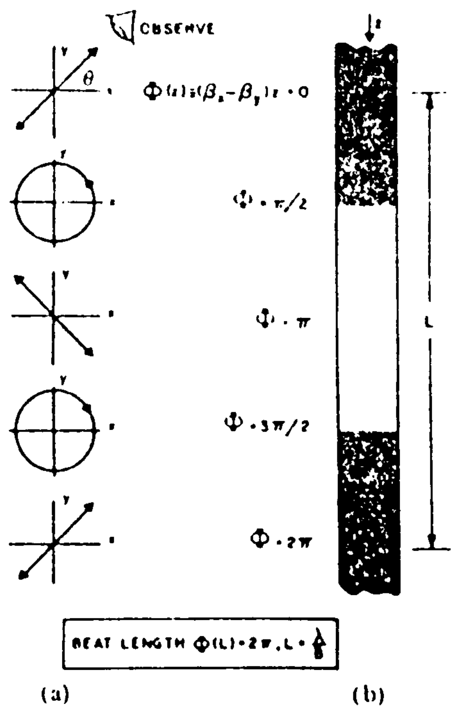


Figure 6   Beat length

(a) states of polarisation versus the phase retardation $\phi(z)$ and

(b) scattered intensity observed normal to fibre at angle θ.

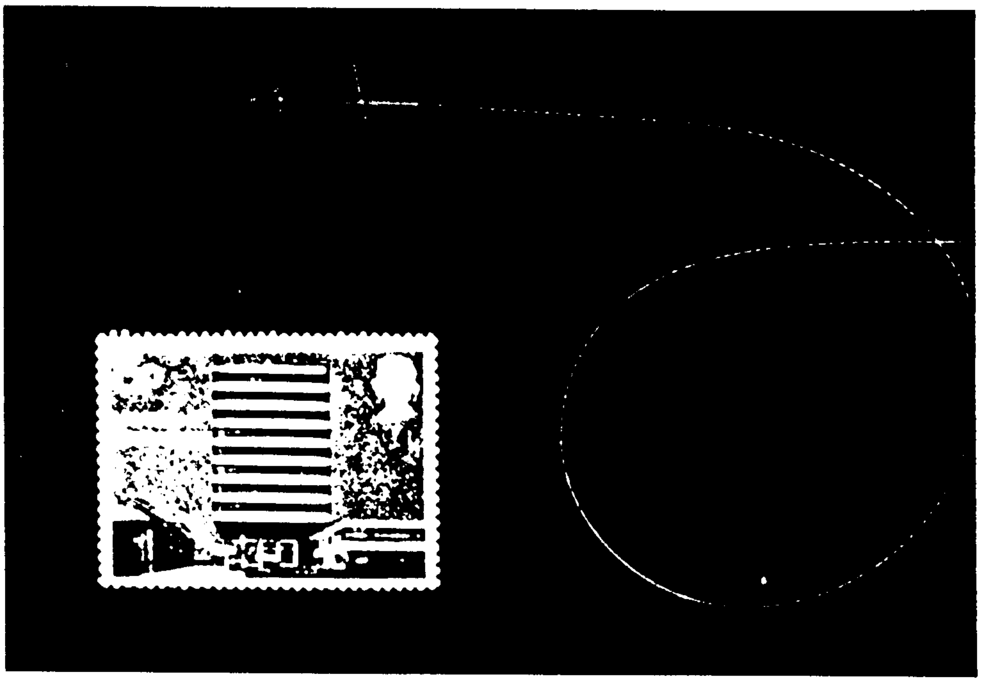


Figure 7 Polarisation Beats : L = 1.2mm at λ = 633nm.

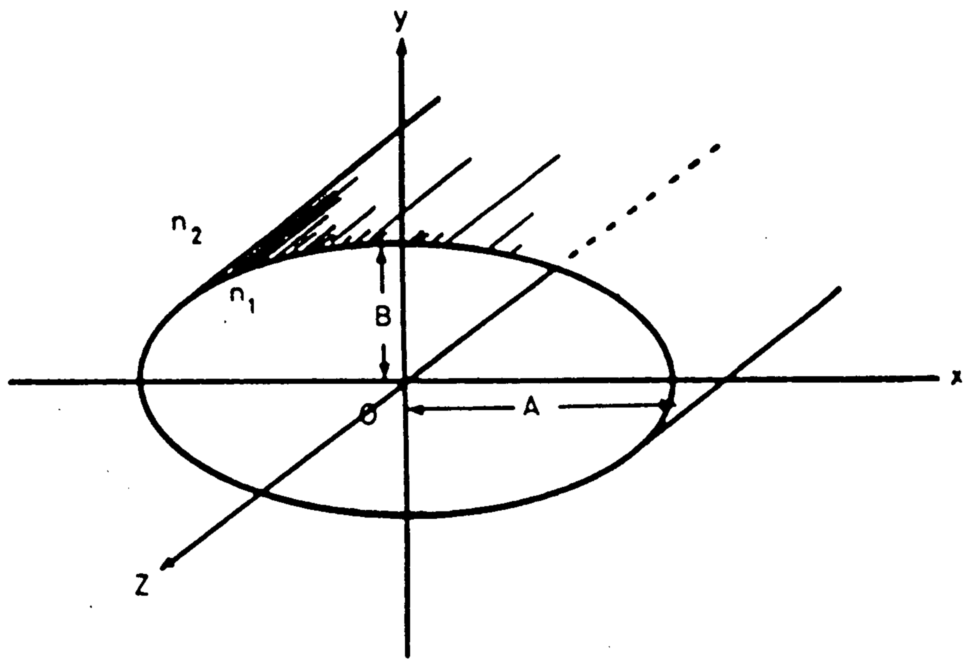


Fig. 8 *Orientation of the Oxyz-axis system in the cross-section of an elliptical dielectric cylinder with core and cladding refractive indices of* n_1 *and* n_2*, respectively*

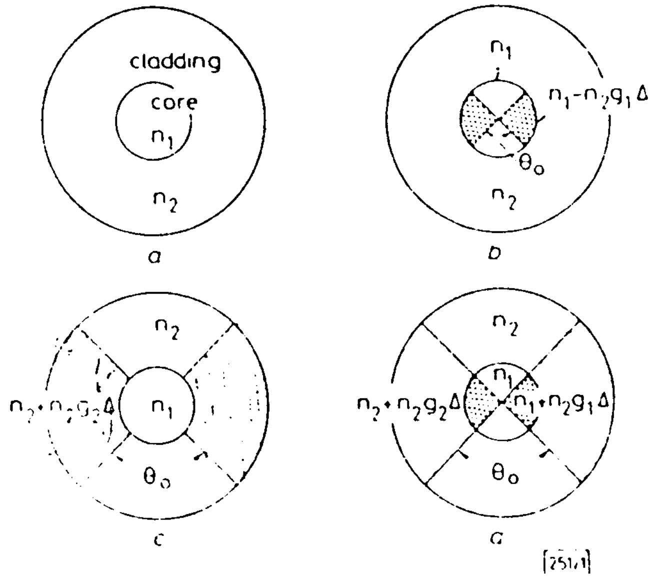
The major and minor semiaxes have lengths A and B as shown the strained fibres is the highly-birefringent (hi-bi) polarisation-maintaining fibre, the two most common forms[21,22] are shown in Figures 11 and 12. The birefringence is induced by means of anisotropic thermal stress produced by the two regions of high expansion glass disposed on either side of the core. The fabrication and performance of these fibres is now discussed in detail.

(a) Elliptical core fibres (Figure 8)

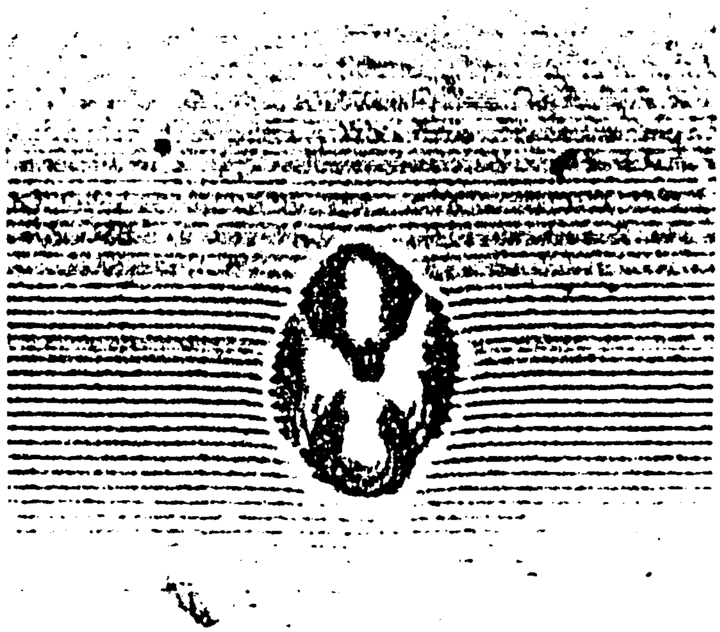
Core deformation and core ellipticity give rise to what is known as **shape birefringence**. For weakly-guiding fibres the birefringence is not predicted from solving the scalar wave equation irrespective of the ellipticity of the core[9,10]. Polarisation effects due to the finite $\Delta(=(n_{co}^2-n_{cl}^2)^{\frac{1}{2}}/n_{co})$ need to be taken into account. The birefringence is thus found to be of order Δ^2 in magnitude[16], viz;

$$B = C.e^2\Delta^2 \quad (25)$$

where e is the core ellipticity [$e^2 = 1 - a^2/b^2$, a and b the major and minor core diameters] C is some function of the fibre parameters and the modal field. Large Δ elliptical fibres (i.e. not weakly-guiding) have also been proposed[17].



(a)



(b)

Figure 9 Azimuthally inhomogeneous fibres

(a) possible cross sections and

(b) photograph of such a fibre.

(b) Azimuthally inhomogeneous index profiles

Another type of shape birefringence is introduced by varying the refractive index azimuthally as shown in Figure 9 [23].

(c) Strained elliptical cladding fibres (Figure 10).

As with the following examples, the strain in this fibre introduces a **material birefringence.**

Birefringence is introduced by grinding two parallel flat sides into a substrate tube before depositing the cladding and core layers via the MCVD process[11]. During the collapse, surface tension causes the preform to be circular again resulting in an elliptical cladding and an almost circular core. The borosilicate cladding is always strained because of the difference in thermal expansion between the cladding and the silica substrate tube[18,19,20].

The birefringence can be expressed in terms of the stress in the core[19]

$$B_L = n_x - n_y = \left(\frac{\lambda}{2\pi}\right)(\beta_x - \beta_y) = -C(\sigma_x - \sigma_y) \qquad (26)$$

where C is the stress optic coefficient and $\sigma_x - \sigma_y$ the stress difference in the core.

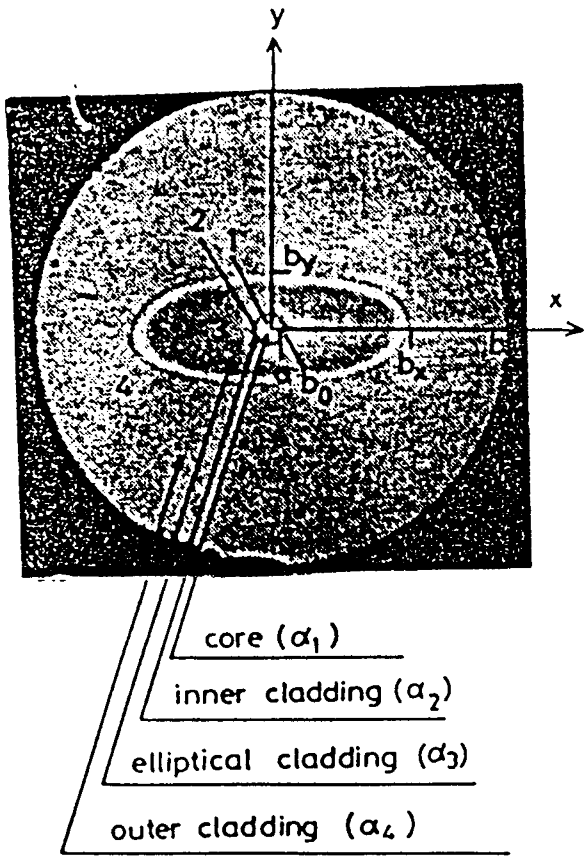


Figure 10 Stressed Elliptical Cladding Fibre

The modal fields can be obtained from the scalar wave equation but now with two different refractive indices (n_x and n_y) corresponding to each polarisation HE_{11}^x, HE_{11}^y.

(d) Bow-Tie fibres

The Bow-Tie highly-birefringent fibre is fabricated by the MCVD technique using a gas-phase etching stage in the process[21]. As in the elliptical cladding fibre, the stress-producing sectors are usually of borosilicate glass. The stages of fabrication are shown in Figure 11 and a fibre cross section in Figure 12. Analysis shows that the Bow-Tie shaped stress regions makes optimum use of available expansion coefficient mismatch[22]. This structure has given the highest linear birefringence ever reported in a single-mode fibre (L = .55mm, λ = 633nm)[21].

(e) PANDA fibres

These are very similar to the Bow-Tie fibre. The stress-producing sectors are of borosilicate glass. Fabrication is by a rod-in-tube technique, with the two borosilicate rods inserted in two ultrasonically drilled

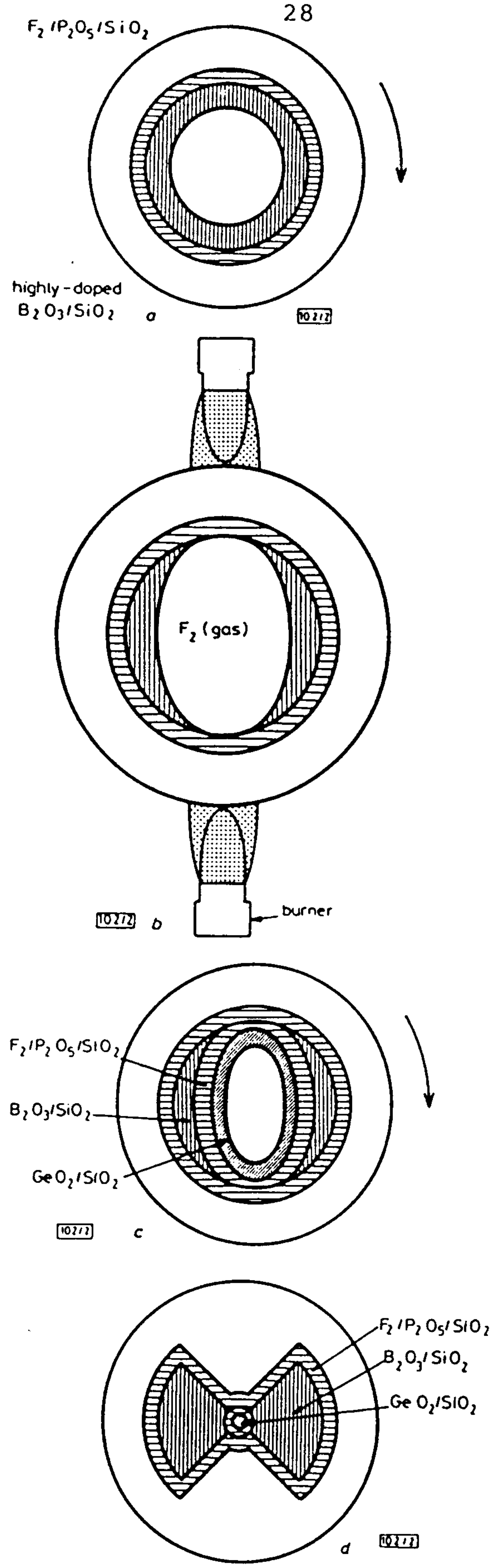
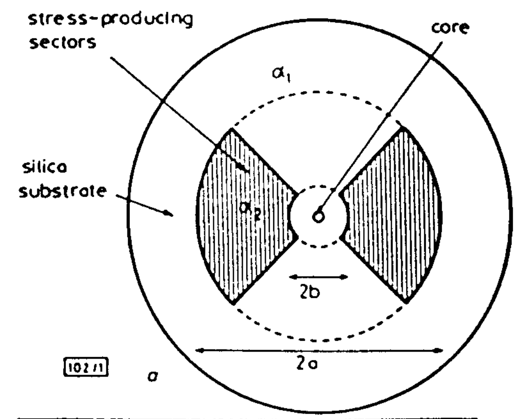


Figure 11 Schematic diagrams showing stages of fabrication of Bow-Tie fibres

(a) Deposit
(b) Etch with fluorine
(c) Deposit
(d) Collapse



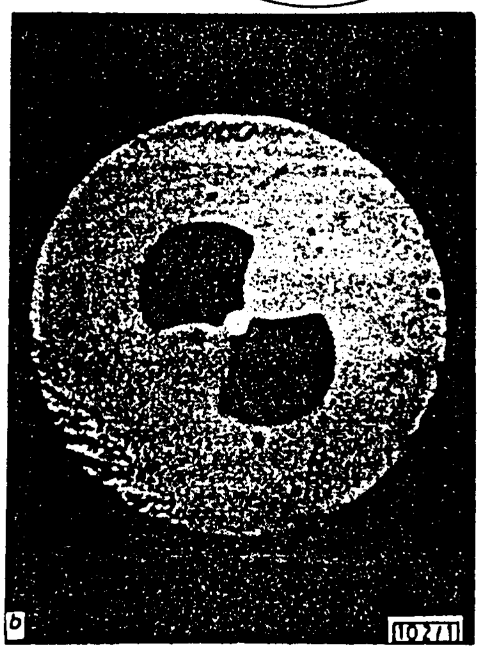


Fig. 12

a Calculated optimum cross-section geometry. The stress-producing sectors are highly doped to give a large expansion coefficient α_2

b Cross-section of bow-tie fibre manufactured by gas-phase etching

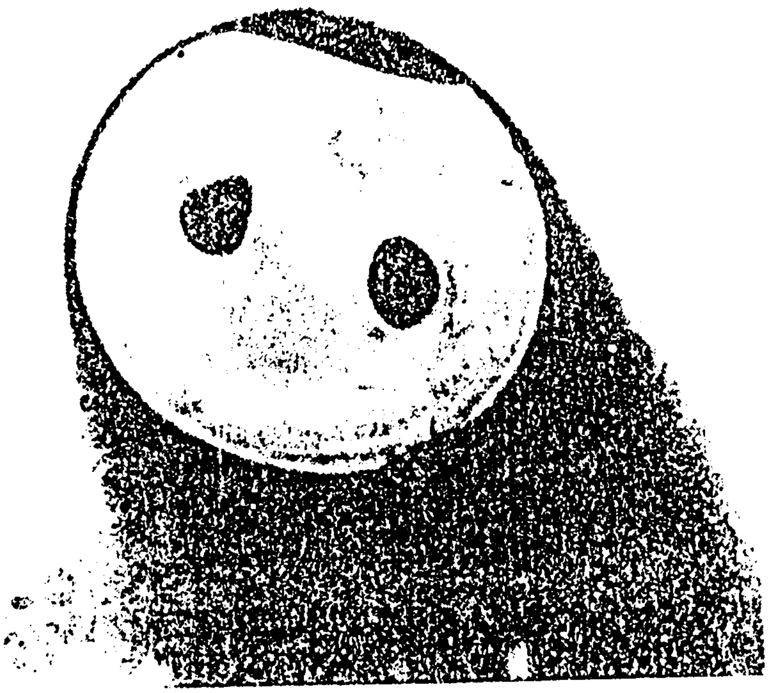


Figure 13 Cross section of a PANDA high-birefringent fibre

holes disposed on either side of the core in a standard single-mode preform. A cross section of such a fibre is shown in Figure 13 [23].

Some comments on Modal Polarisation in Hi-Bi Fibres

One difference between the "modal polarisation" on the hi-bi fibre as compared with a conventional fibre is that the additional minor field components are now present at power levels between -45 and -38dB which is two to three orders of magnitude higher the level of -70dB estimated for conventional fibres[25]. This fact is important in the fibre gyroscope where polarisers and fibre components having extinction ratios greater than 120dB may be required. However if the analysing arrangement employed fibre polarisers, which would discriminate "modal polarisation" as opposed to bulk optics polarisers which discriminate plane polarisation, then the above problems may be avoided.

4.1.2 Circular birefringence

As with linear birefringence, circular birefringence arises from breaking the degeneracy between the HE_{11}^{R} and HE_{11}^{L} modal polarisations, i.e. $\beta_R \neq \beta_L$ in equations (20) and (21).

We saw earlier that a phase difference between two orthogonal circularly-polarised waves produces a rotation of linear polarisation. Similarly a circular birefringence

$$B_c = (\beta_R - \beta_L)/(2\pi/\lambda) \qquad (27)$$

will produce a phase retardation of

$$\Phi(z) = (\beta_R - \beta_L)z \qquad (28)$$

which varies with z, with the result that the input state-of-polarisation is rotated at a rate

$$\tau = (\beta_R - \beta_L)/2 \qquad (29)$$

per unit length. The state-of-polarisation does not change along the length of the fibre it is simply rotated.

If the input is linearly polarised then this polarisation is rotated at a constant rate, τ. The length for half a complete rotation is called a beat length, L_c, which can be observed through Rayleigh scatter along the fibre, where

$$L_c = \lambda/(2B_c) = \pi/\tau \qquad (30)$$

The first technique for producing circular birefringence in fibres has been through twisting the fibre[12]. The twist averages out the linear birefringence to zero but it introduces torsional stresses which induce circular birefringence. The net result is an optical rotation $\tau_t = g\zeta$ (rads/m) where $g \approx 0.073$ for silica based fibres and ζ is the twist rate in rads/m. Unfortunately, the torsion induced by twist is at present limited to below

100 turns/m because higher torsions can break the fibre. Even at these twist rates the long term survival of the fibre is open to question. For this reason, and because the circular birefringence so obtained is not high enough, torsion-induced circularly-birefringent fibres are not really viable.

Two more techniques for achieving high levels of circular birefringence in fibres have recently been proposed and developed at the University of Southampton. The first is the **helical fibre**[26,27] whose operation is based upon the rotation of polarised light which occurs when light is constrained to follow a helical or non planar path[28,29,30]. The second is the **spiral fibre**[31,32] which exploits the fact that polarised light will rotate in a twisted anisotropic medium[33,34]. These are now dealt with in detail.

(a) Helical-core fibre

If light is constrained to follow a non planar curve the polarisation of that light will experience a rotation per unit length equal to the geometric torsion of the curve[28]. In a helical curve this torsion is a constant given by P/S^2 where P is the pitch of the helix, S the arc length for one pitch where $S = ((2\pi Q)^2 + P^2)^{\frac{1}{2}}$ and Q is the offset from the helix axis. Relative to the helix axis

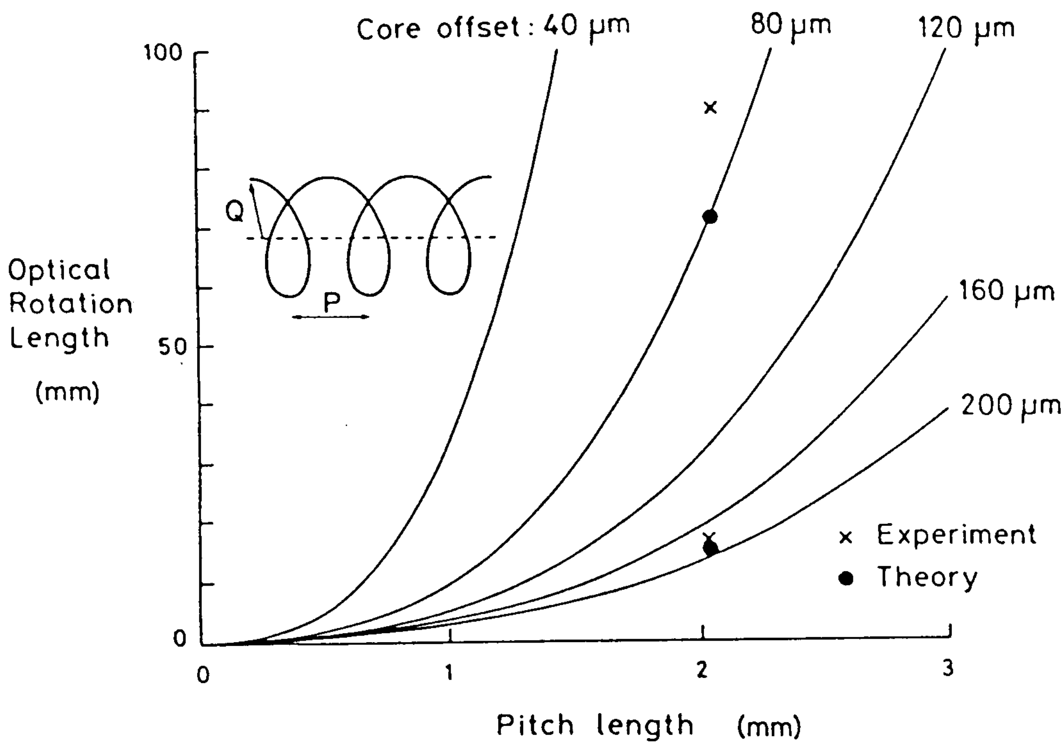


Fig. 14 Optical rotation in helical-core fibres calculated for various pitch and core offsets.

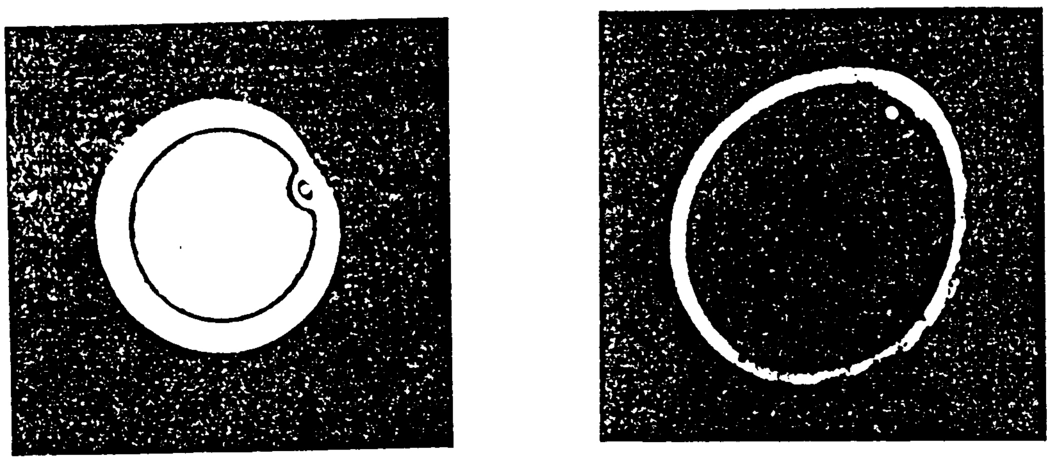
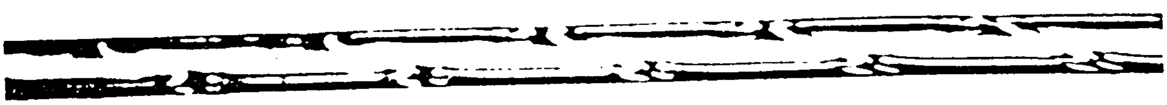


Figure 15
(a) Helical-core fibre cross-sections showing hollow tube and core structure.



(b) Transverse view of helical core fibre.

the rotation per turn (or per pitch) has been shown to be[26]

$$H = 2\pi(1 - P/S) \qquad (31)$$

and the beat length or optical rotation length is given by

$$L = P^3/2\pi^2Q^2, \; P \gg Q \qquad (32)$$

For large levels of birefringence (short beat length) we therefore require a large core offset Q, and a short pitch P. Figure 14 shows the optical rotation length for various helix parameters while a transverse and a cross-sectional view of the fibre is shown in Figures 15(a) and (b).

One of the problems with this fibre is that to achieve a high birefringence the fibre dimensions need to be very large. For instance if L = 13mm and P = 2mm then the core offset Q = 184μm so that the overall fibre diameter would need to be greater than 2 x Q = 368μm. Another difficulty is the pronounced skew angle at which light needs to be injected to and extracted from the fibre.

(b) Spiral fibres

If a linearly birefringent fibre is twisted the polarisation of light polarised along one of the birefringent axes at the input to the fibre will be found to follow the twist[34]. Clearly this phenomenon is not circular birefringence since the evolution of the state-of-polarisation along such a fibre will be the normal evolution along a straight linearly birefringent fibre, with the rotation due to the twist superimposed. However with careful design of the core the rotation of polarised light that occurs in a twisted birefringent or twisted anisotropic medium can be exploited to produce circular birefringence.

If a twist is to have any influence on the polarisation of the propagating field it is necessary to introduce some azimuthal inhomogeneity into the core. For high levels of circular birefringence it is necessary to consider some very large inhomogeneities and core structures which have single lobe and multiple lobe configurations as shown in Figure 16[31,32].

It is important that these structures do not have any inherent linear birefringence so that certain symmetries need to be observed. For instance if the lobes are coupled then the overall core structure must not have distinguishably different orthogonal axes e.g. cases I, II and III of Figure 16. If the lobes are uncoupled then each lobe must independently have no linear birefringence. To achieve high levels of circular birefringence the lobe

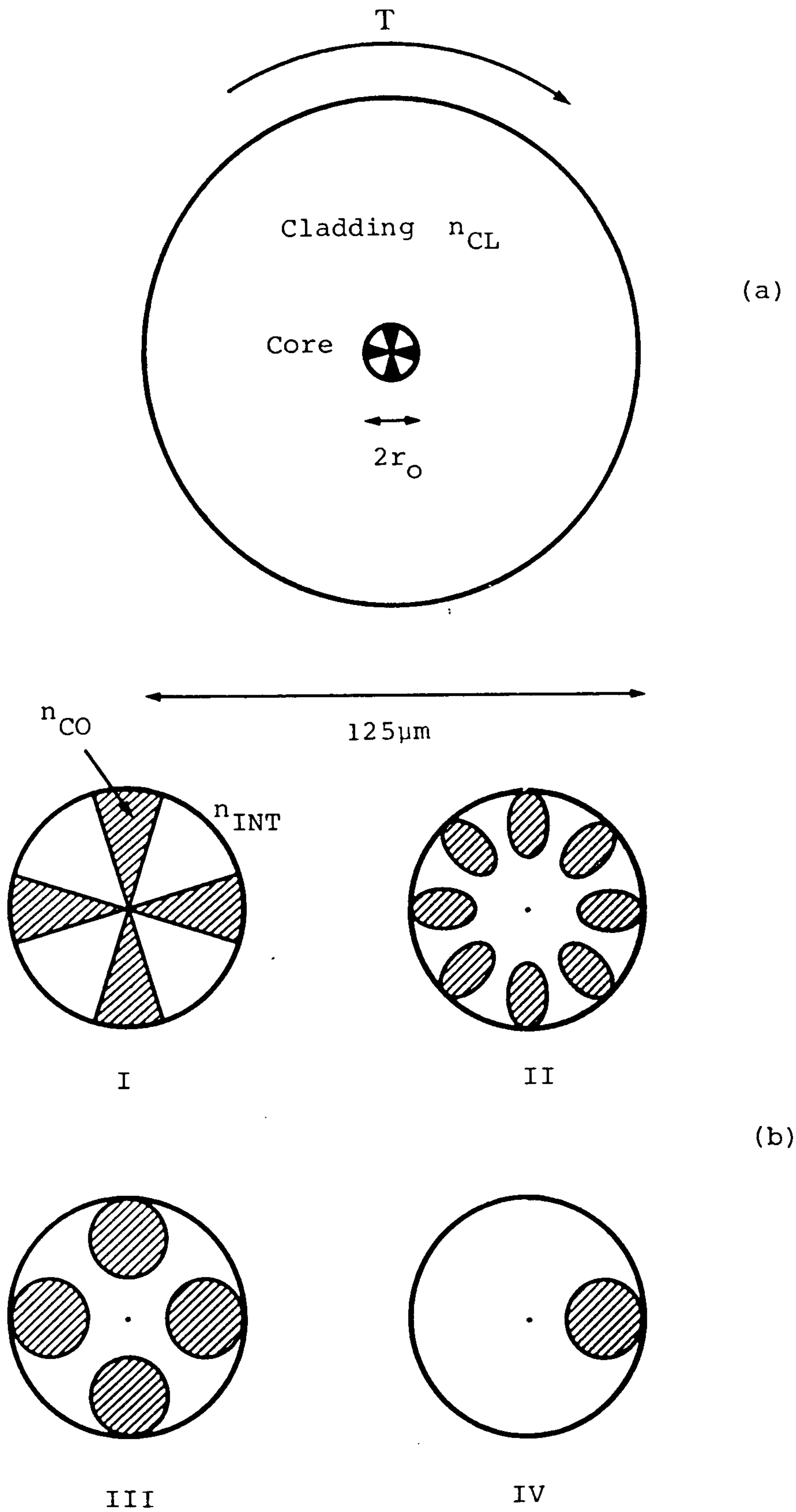


Figure 16 (a) Typical fibre cross section defining fibre parameters.

(b) Possible azimuthally inhomogeneous core structures.

refractive index should be much greater than both the immediately adjacent core refractive index and the cladding refractive index[31].

If these structures are twisted along the axis of the fibre then the polarisation can be made to rotate at the twist rate and under certain conditions the polarisation can be made to rotate at a slower rate.

Figure 17 shows some design curves for a twisted cross structure (Case I of Figure 15)[31]. The curves show the optimum core radius to obtain the maximum twist rate. The optimum appears as a compromise between poor capability of field confinement at the small radii and the spilling out of the field at the outermost radius when the peripheral twisting speed is high. The optimum radius decreases as $(\Delta n/n)^{-\frac{1}{2}}$.

The spiral fibres can be fabricated by a rod-in-tube technique. The preform is then spun as the fibre is drawn using standard drawing procedures. Some results for a fibre with the simplest single lobe structure are quoted in Table 1[32]. A single MCVD preform was used to provide the lobe. The fibre parameters were: $\Delta n = 0.01$, core radius $10\mu m$, $n_{c\ell} = n_{INT}$ and an unspun length of fibre was single moded at $\lambda = .633\mu m$. Fibre diameter was $110\mu m$.

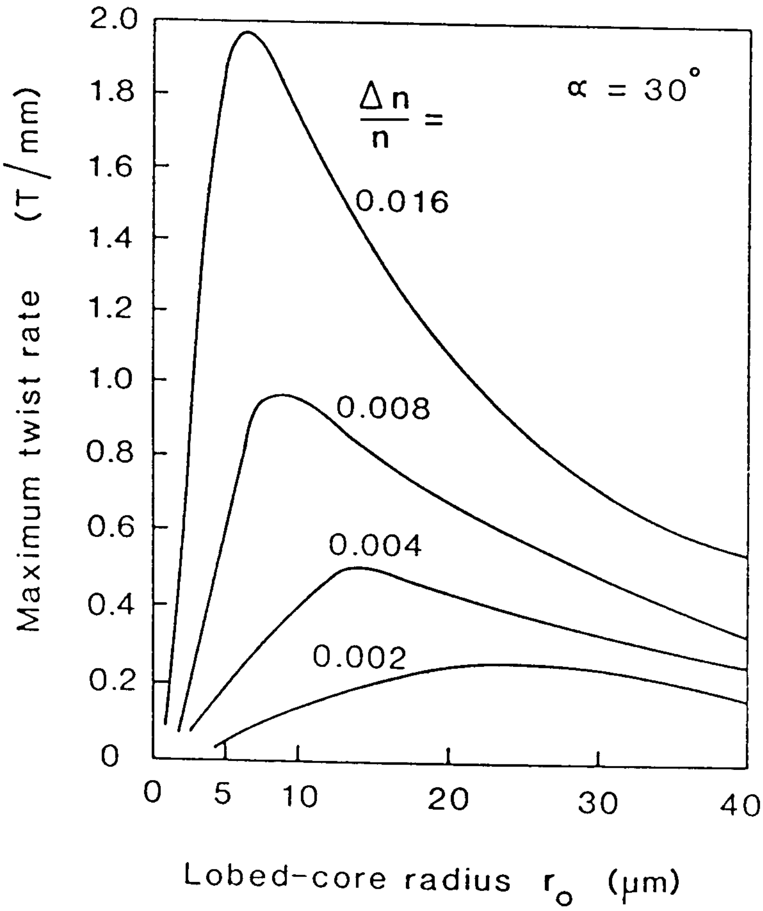


Figure 17 Design curves for the "twisted cross" structure showing the maximum obtainable twist rate versus core radius for different values of refractive index.

Twist rate T/m	Optical rotation rate T/m	Beat length mm
50	50	10
83	83	6
100	100	5
116	116	4.3
160	14	35
250	10	50

Table I : Measured twist rates and beat lengths on our sample fibre

From Table 1 it is clear that the polarisation follows the twist rate up to some critical point, the beat length of 4.3mm corresponds to the highest level of circular birefringence ever yet reported in single-mode fibres.

4.1.3 Elliptical birefringence

In general fibres are elliptically birefringent so that the two polarisation eigen modes of the fibre are elliptical in form. Any elliptical birefringence may be resolved into linear and circular components and the elliptical birefringence can be written as[12]

$$B_E^2 = B_C^2 + B_L^2 \qquad (33)$$

In most applications the fibre will be predominantly linearly birefringent ($B_L \gg B_C$) or circularly birefringent ($B_C \gg B_L$) so that we do not need to take the elliptical polarisations into account although their behaviour is well understood[12].

5. Ring core fibres as possible futuristic fibres for polarisation dependent applications

So far in this lecture I have introduced the idea of "modal polarisation" in contrast with the plane polarisation of bulk optics. In the fibres that have been considered so far the modal polarisation bears a very great resemblance to plane polarisation so that with care the modal polarisation can be approximated by plane polarisation. I am now going to introduce a single-mode fibre where the modal polarisation bears no resemblance to our conventional bulk optics ideas of polarisation[35,36]. This fibre is a ring core fibre as shown in Figure 18. The fibre comprises a thin layer of high refractive index sandwiched between an outer and inner "cladding" of lower refractive index.

It has been shown that such a fibre[36], which has the layer of higher refractive index (n_2 = 1.455) 2μm thick at a radius of 250μm and cladded (n_1 = 1.449) to give an overall diameter of about 800μm, has an unusual dispersion behaviour. The fundamental modes (i.e. they propagate for all wavelengths) are now the TE_{01} (and TM_{01}) modes while the HE_{11} modes are cutoff at short wavelengths.

The polarisations of the TE_{01} mode on the tubular waveguide is a pure circumferential electric field (i.e. in cylindrical coordinates it is θ directed) while the TM_{01} polarisation is purely radial (i.e. r directed). These are shown in Figure 18.

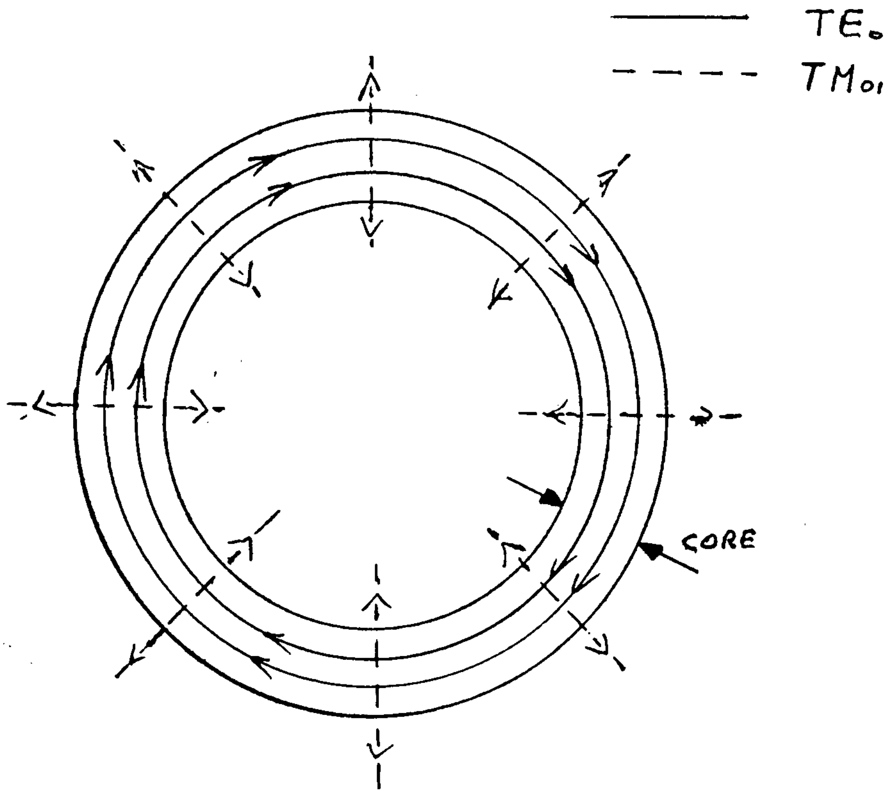


Figure 18 The ring core fibre showing the two pure TE_{01}, TM_{01} modal polarisations.

Given the cylindrical nature of an optical fibre it seems reasonable to consider these cylindrical polarisations as the "natural" polarisations. Modal birefringence could be introduced very simply with radial stress thereby introducing a birefringence

$$B = (\beta_r - \beta_0)/(2\pi/\lambda) \tag{34}$$

where β_r is the propagation constant of the TM_{01} mode and β_0 is the propagation constant of the TE_{01} mode.

Fibre polarisers with a metal cylindrically disposed in the fibre where it can interact with the modal fields will completely extinguish the TM_{01} mode thereby supplying complete modal polarisation discrimination required for fibre sensors. One other advantage of the ring core fibre as a birefringent fibre is that it should be very immune to the normal external perturbations of bends and pressure since these generally impart a preferred cartesian axis to the fibre so that their effects should distribute themselves equally over the TE_{01} and TM_{01} modes.

Conclusions

The exploitation of polarisation effects in optical fibres is really only beginning. Applications which use fibres in conjunction with bulk-optic components require us to be alert to the differences between the fibre's "modal polarisation" and the bulk-optic's "plane polarisation" and also to understand the limitations which this imposes on our measurements. It is only with the development of fibre based devices such as fibre polarisers, fibre couplers and fibre switches etc. that such restrictions will be removed.

The use of novel fibre geometries, such as the ring core fibre, forces us to consider "modal polarisations" which are radically different to our conventional conceptions of polarisation. Yet, such fibres may prove, in the long term, to be much more "practical" for polarisation dependent applications than fibres that have, so far, been developed. Time will tell.

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