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Polarisation effects in twin-core fibre: Application for mode locking in a fibre laser

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Abstract. **We report the first measurements of the longitudinal power distribution in a twin-core optical fibre at different input light polarisations. Experimental evidence is presented that, because of the difference in birefringence between the cores, the power in them depends on which core the beam is launched into. Experimental data are interpreted in terms of a modified polarisation model for mode coupling in twin-core fibres which takes into account the birefringence of the cores. In addition, we demonstrate for the first time the use of the polarisation properties of a twin-core fibre for mode locking in a fibre laser.**

Keywords: *twin-core optical fibre, polarisation, mode locking, fibre laser.*

1. Introduction

Owing to coupling between modes propagating in its cores, twin-core fibre (TWF) finds application in many fibre-optic devices: from couplers [1] and narrow-band filters [2] to ultrafast switches [3] and various sensors [4, 5]. Mode coupling between neighbouring cores is known to take place only when their mode fields significantly overlap and the modes have identical propagation constants. Lobach et al. [6] examined the effect of mechanical stress on the degree of mode coupling in TWFs. As shown in that study, effective mode coupling takes place only when the refractive index change induced by mechanical stress in the cores through the photoelastic effect fully compensates the unintentional index difference between the cores. In addition, the degree of mode coupling was found to depend on the polarisation state of propagating light. Coupled-mode theory with no allowance for polarisation [7] is incapable of interpreting this effect. To take into account the influence of polarisation, two mode coupling constants are introduced, instead of one, for describing the coupling between the polarisation modes involved [8]. A system of coupled modes is then written for each polarisation and solved independently, but the birefringence (BR) induced polarisation evolution in the two cores is left out of consideration.

In this paper, we demonstrate that BR may lead to effects that cannot be accounted for by existing models. Our objectives are to study the influence of polarisation on mode coupling in TWFs and construct a model capable of accounting for the experimental data obtained. We describe the first measurements of the longitudinal power distribution in a TWF by a unique method at different input light polarisations. In addition, we demonstrate for the first time the use of the polarisation properties of a TWF for mode locking based on nonlinear polarisation rotation.

2. Experimental

We studied the influence of polarisation on mode coupling in an ytterbium-doped TWF 35 cm in length. The fibre was similar to that studied previously [6], which had been shown to have an unintentional refractive index difference between the cores $\delta n \approx 10^{-4}$, with the result that very weak mode coupling took place in a straight fibre section. To increase mode coupling, the refractive indices of the cores were equalised using the photoelastic effect. To this end, the fibre was placed in a groove of constant curvature, $R \approx 16.2$ cm, so that its bending plane coincided with the plane passing through the axes of the cores and one of the cores was under compressive strain, whereas the other was under tensile strain. In addition, Lobach et al. [6] measured the coupling constant, $\Gamma \approx 7.6$ m^{-1}, which determines the distance over which all the power is transferred from one core to the other (beat length): $L_b = \pi/(2\Gamma) \approx 20.6$ cm.

Figure 1 shows a schematic of the experimental setup used to study the influence of polarisation on mode coupling. A linearly polarised 1.06-μm output of a single-frequency Nd:YAG laser was coupled into one of the cores using a three-axis positioning system. The input polarisation azimuth ϕ, measured from the plane defined by the cores, was varied using a half-wave plate. The longitudinal power distributions in the cores were measured at $\phi = 0$, 90°, 45° and –45°. Figure 2a shows the power profile $P_1(z)$ along the length of the first core when the beam was launched into it. For convenience, we indicate the power in the core the beam was launched into. The power in the second core is not indicated because the light absorption was negligible and the total power in the two cores did not vary along the fibre. In addition, we measured the longitudinal power distribution $P_2(z)$ when the beam was launched into the second core (Fig. 2b). The

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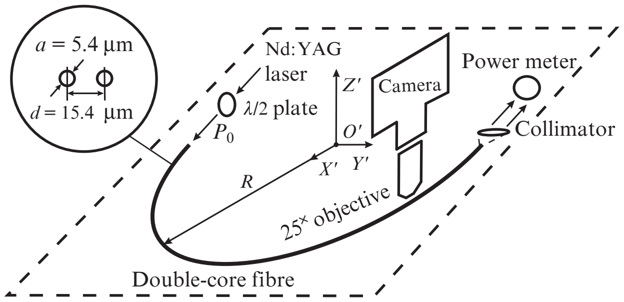

Figure 1. Experimental configuration used to study the influence of input light polarisation on the longitudinal power profile in a TWF. Inset: schematic of the fibre cross section.

power was assessed from the luminescence intensity of the ytterbium in the cores using a CMOS camera and microscope objective. To determine the power inside the fibre, we performed calibration in which the emission intensity at the extreme point at the fibre output was normalised by the power measured at the core output. The technique used to measure the longitudinal power distribution was described in greater detail elsewhere [6].

Our experimental data demonstrate that the longitudinal power profile (Fig. 2) does depend significantly not only on the input light polarisation but also on which core the beam is launched into. The distinction between the $P_1(z)$ and $P_2(z)$ profiles originates from the difference in BR between the cores. Moreover, the longitudinal profile obtained by averaging over the four input polarisation states,

$$\bar{P}_j(z) = \frac{P_j(z,-45°) + P_j(z,0°) + P_j(z,45°) + P_j(z,90°)}{4},$$

is to a good approximation independent of the core number j (Fig. 3a).

3. Theory

To describe the influence of polarisation on mode coupling, consider first a theory that leaves BR out of account. It is known [8] that there are then two orthogonal linear polarisations (a and b) that have different coupling constants (Γ_a and

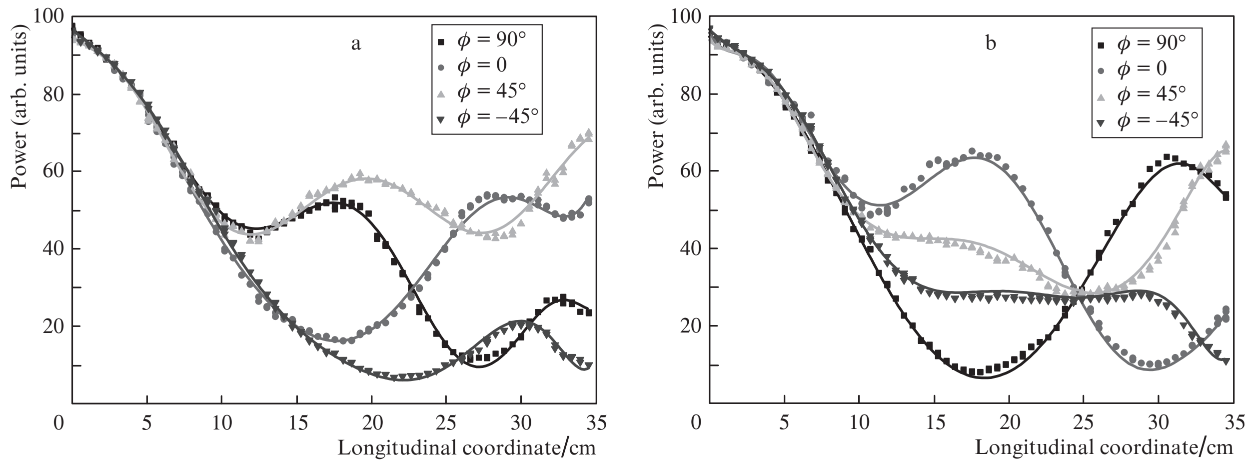

Figure 2. Longitudinal power profile at different input polarisation azimuths for the beam launched into the (a) first and (b) second cores. The points represent the experimental data and the solid lines represent the profiles calculated using Eqn (4).

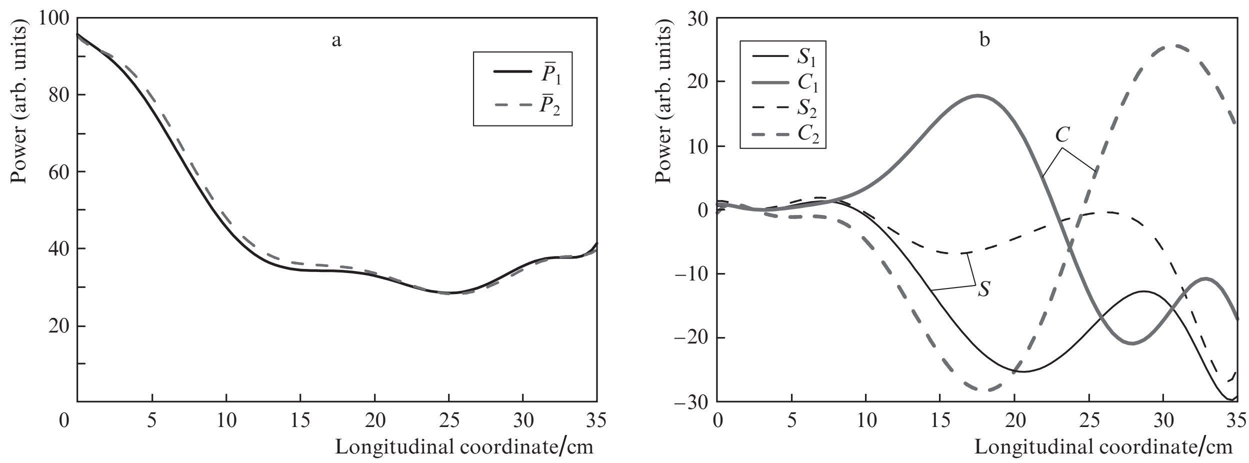

Figure 3. (a) Average longitudinal power profiles $\bar{P}_j$ and (b) functions C_j and S_j.

Γ_b). For example, when a beam polarised along the a axis is launched into one of the cores, the longitudinal power profile has the form $P_a(z) = \cos^2\Gamma_a z$. If the beam is polarised along the b axis, we have $P_b(z) = \cos^2\Gamma_b z$. It is easy to understand that the longitudinal power profile for linearly polarised light with an azimuth ϕ relative to the a axis has the form

$$P(z,\phi) = \cos^2\Gamma_a z\cos^2\phi + \cos^2\Gamma_b z\sin^2\phi. \quad (1)$$

This result is due to the fact that we leave out of account the difference in propagation constant between waves of different polarisations in the cores in the absence of BR. By virtue of the symmetry of the problem, the longitudinal power profile should be independent of which core the beam is launched into, but the present experimental data demonstrate the opposite (Fig. 2). For this reason, we propose a modified polarisation model for mode coupling in TWFs, which takes into account BR in the cores. In addition to the fact that the polarisation modes of neighbouring cores are coupled through their coupling constants, the model takes into account the coupling between the polarisation modes in the cores due to BR.

Each core supports only two polarisation modes (a and b). For generality, the cores are taken to differ in refractive index. Accordingly, they have different propagation constants, k_1 and k_2, with a half-difference $\Delta k = (k_1 - k_2)/2$. Based on coupled-mode theory [7] and the above assumptions, we derived equations for the polarisation mode amplitudes:

$$\frac{\mathrm{d}}{\mathrm{d}z}\begin{pmatrix} a_1 \\ b_1 \\ a_2 \\ b_2 \end{pmatrix} = \mathrm{i}\begin{pmatrix} \Delta k + \gamma_1^z & \gamma_1^x & \Gamma_a & \Gamma_{ab} \\ \gamma_1^x & \Delta k - \gamma_1^z & \Gamma_{ba} & \Gamma_b \\ \Gamma_a^* & \Gamma_{ba}^* & -\Delta k + \gamma_2^z & \gamma_2^x \\ \Gamma_{ab}^* & \Gamma_b^* & \gamma_2^x & -\Delta k - \gamma_2^z \end{pmatrix}\begin{pmatrix} a_1 \\ b_1 \\ a_2 \\ b_2 \end{pmatrix} \equiv \mathrm{i}\hat{M}\boldsymbol{v}, \quad (2)$$

where z is a coordinate along the fibre axis and $\hat{M}$ is the coupling matrix. The constants γ_i^x and γ_i^z describe the coupling between waves of different polarisations in core i. The BR axis direction can be expressed through γ_i^x and γ_i^z as $\tan(2\theta_i) = \gamma_i^x/\gamma_i^z$, and the BR value δn_i can be found from $\delta n_i k_i = 2[(\gamma_i^x)^2 + (\gamma_i^z)^2]^{1/2}$. The optical activity of the cores is neglected. The constants Γ_a, Γ_b, Γ_{ab} and Γ_{ba} describe the coupling between the polarisation modes of neighbouring cores and are determined by the overlap integrals of the corresponding polarisation mode fields. $\hat{M}$ is taken to be Hermitian because there is no loss in the fibre.

In the case of constant coefficients, the solution to Eqn (2) can be expressed through a matrix exponential, so we take it in the form $\boldsymbol{v}(z) = \exp(\mathrm{i}\hat{M}z)\boldsymbol{v}(0) = \hat{U}\boldsymbol{v}(0)$, where $\boldsymbol{v}(0)$ are the amplitudes at the fibre input. To calculate the matrix exponential, it is necessary to find the eigenvalues of $\hat{M}$. For arbitrary coefficients, the eigenvalue equation is an equation of the fourth degree, whose analytical solution (e.g. that found by Ferrari's method) is very cumbersome. The solutions have compact form when the two cores have identical directions of their major axes. For example, at $\gamma_1^x = \gamma_2^x = 0$ the major axes of the cores are parallel to a line connecting their centres. At the same time, the cores may differ in BR. It can be shown that the overlap integral of modes a and b is then zero because they are mutually orthogonal, i.e. $\Gamma_{ab} = \Gamma_{ba} = 0$. The power in one core as a function of longitudinal coordinate z and input polarisation azimuth ϕ then has the form

$$P(z,\phi) = |a(z,\varphi)|^2 + |b(z,\varphi)|^2 =$$

$$= 1 - \left(\frac{\Gamma_a}{\chi_a}\sin\chi_a z\right)^2\cos^2\phi - \left(\frac{\Gamma_b}{\chi_b}\sin\chi_b z\right)^2\sin^2\phi,$$

where

$$\chi_a = \sqrt{\Gamma_a^2 + (\Delta k + \delta)^2};\ \chi_b = \sqrt{\Gamma_b^2 + (\Delta k - \delta)^2};\ \delta = \frac{\gamma_1^z - \gamma_2^z}{2}.$$

This result is easy to understand given that the BR contribution is equivalent to a difference in wave vector between the core modes and reduces the coupling amplitude and length. The power is then also independent on which core the beam is launched into. It is not difficult to show that at $\Delta k = 0$ and $\gamma_1^z = \gamma_2^z$ the solution takes the form (1).

In other cases, the solutions to Eqn (2) are more cumbersome and rather difficult to analyse, so we will restrict our consideration to the general properties of the solutions. It turns out that only in special cases is the longitudinal power profile independent of which core the beam is launched into, whereas in general such a dependence exists because the cores differ in BR.

It can be shown that, when linearly polarised light with a polarisation azimuth ϕ is launched into one of the cores, i.e.

$$(a_1(0), b_1(0), a_2(0), b_2(0),) = (\cos\phi, \sin\phi, 0, 0)$$
$$\text{or } (0, 0, \cos\phi, \sin\phi), \quad (3)$$

the power as a function of z and ϕ has the form

$$P_j(z,\phi) = |a_j(z)|^2 + |b_j(z)|^2$$
$$= \bar{P}_j(z) + C_j(z)\cos 2\phi + S_j(z)\sin 2\phi. \quad (4)$$

The functions $\bar{P}_j(z)$, $C_j(z)$ and $S_j(z)$ are in general determined not only by fibre parameters but also by which core is excited. Let us show that, in the case of a Hermitian matrix $\hat{M}$, $\bar{P}_j(z)$ is independent of which core the beam is launched into. If $\hat{M}$ is Hermitian, the matrix exponential $\hat{U} = \exp(\mathrm{i}\hat{M}z)$ is unitary. The rows and columns of a unitary matrix are known to form an orthonormal system, i.e. $\sum_{j=1}^{4} U_{ij}U_{jk}^* = \delta_{ik}$. This means that the total power in the cores is constant. Summing this expression over the first two rows and the last two columns, we obtain

$$\sum_{i=1}^{2}\sum_{j=1}^{4}|U_{ij}|^2 = \sum_{j=3}^{4}\sum_{i=1}^{4}|U_{ij}|^2 = 2.$$

Expressing $\bar{P}_j(z)$ through the U_{ij} matrix elements, we find

$$\bar{P}_1(z) = \sum_{i=1}^{2}\sum_{j=1}^{2}|U_{ij}|^2 = \sum_{i=1}^{2}\sum_{j=1}^{4}|U_{ij}|^2 - \sum_{i=1}^{2}\sum_{j=3}^{4}|U_{ij}|^2$$

$$= \sum_{i=1}^{4}\sum_{j=3}^{4}|U_{ij}|^2 - \sum_{i=1}^{2}\sum_{j=3}^{4}|U_{ij}|^2 = \sum_{i=3}^{4}\sum_{j=3}^{4}|U_{ij}|^2 = \bar{P}_2(z).$$

The function $\bar{P}_j(z)$ has a clear physical meaning: it is a longitudinal power profile for unpolarised input light. Indeed, the experimental data in Fig. 3a confirm that $\bar{P}_j(z)$ is independent of the core number, i.e. $\bar{P}_1(z) = \bar{P}_2(z)$. Moreover, it follows from (4) that

$$P_j(z,0^\circ) - \bar{P}_j(z) = -P_j(z,90^\circ) + \bar{P}_j(z) = C_j(z),$$
$$P_j(z,45^\circ) - \bar{P}_j(z) = -P_j(z,-45^\circ) + \bar{P}_j(z) = S_j(z). \quad (5)$$

The present experimental data are consistent with Eqns (5). This means that relation (4) is supported by experiment.

Using the functions $\bar{P}_j(z)$, $C_j(z)$ and $S_j(z)$, we can find the longitudinal power profile at an arbitrary linear input polarisation (solid lines in Fig. 2).

It is worth pointing out that, only qualitative agreement between theory and experiment has been demonstrated to date since we failed to evaluate the BR of the cores, mode coupling constants and wave vector detunings in the fibre from the present experimental data. One possible reason for this is that the fibre parameters in our experiments might vary along the fibre because of the variation in its radius of curvature or fluctuations in the fibre fabrication process.

4. Application of TWFs

As seen from (4), the transmittance of the cores is a harmonic function of the input polarisation state. Therefore, TWFs can be used to make polarisation filters. To check this possibility, single-mode fibres were fusion spliced on both sides to one of the cores of a 21.3-cm length of TWF, and the TWF was bent in order to compensate the refractive index difference between the cores and cemented to a plate. The effective transmittance of this configuration at 1.06 μm was found to vary from 25% to 50%, depending on the input polarisation. Note that the losses are due to the radiation transfer to the second core and scattering at the slice points. All the power at the output of the second core was lost at the fusion splice. Such a filter can be used for polarisation selection, e.g. for laser mode locking based on nonlinear polarisation rotation. The basic operating principle of such a laser is that, during pulse propagation, the Kerr effect leads to an intensity-dependent rotation of the polarisation ellipse of the light [9]. As a result, the loss in a laser with a polarisation selector will depend on its power. A polarising isolator or fibre polarisation splitter is used for this purpose in fibre lasers.

Figure 4 shows a mode-locked ring laser configuration. The gain medium of the laser is a 1.7-m length of a single-mode ytterbium-doped fibre (Nufern SM-YDF-5/130) core-pumped by a single-mode laser diode through a wavelength-division multiplexer (WDM). Unidirectional lasing was ensured by a polarisation independent isolator. A key polarisation element in the laser configuration was a piece of TWF with ytterbium-doped cores. The emission was outcoupled from the cavity by a 70/30 coupler. The cavity was tuned using a polarisation controller. The total cavity length was 8.1 m (mode spacing of 25.5 MHz). The pulse duration did not exceed the response time of the oscilloscope (250 ps). The output power of the laser was up to 70 mW at a pump power of 400 mW.

At certain settings of the polarisation controller, mode-locked operation was achieved, which showed up in both the emission spectrum of the laser (Fig. 5a) and its temporal response, examined using a high-speed photodetector and oscilloscope. The transition to mode-locked operation broadened the lasing spectrum to 7 nm (against 0.5 nm in continuous mode), and the oscilloscope trace showed pulses with a repetition rate equal to the inverse of the cavity round-trip time. Figure 5b shows the pulse height distribution obtained as a histogram of 10^4 pulses. The pulse height is seen to fluctuate significantly (±5%). In the literature, this regime is known as stochastic mode locking [10].

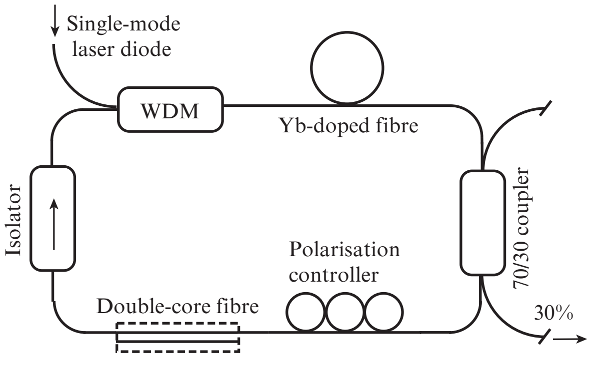

Figure 4. Mode-locked TWF laser configuration.

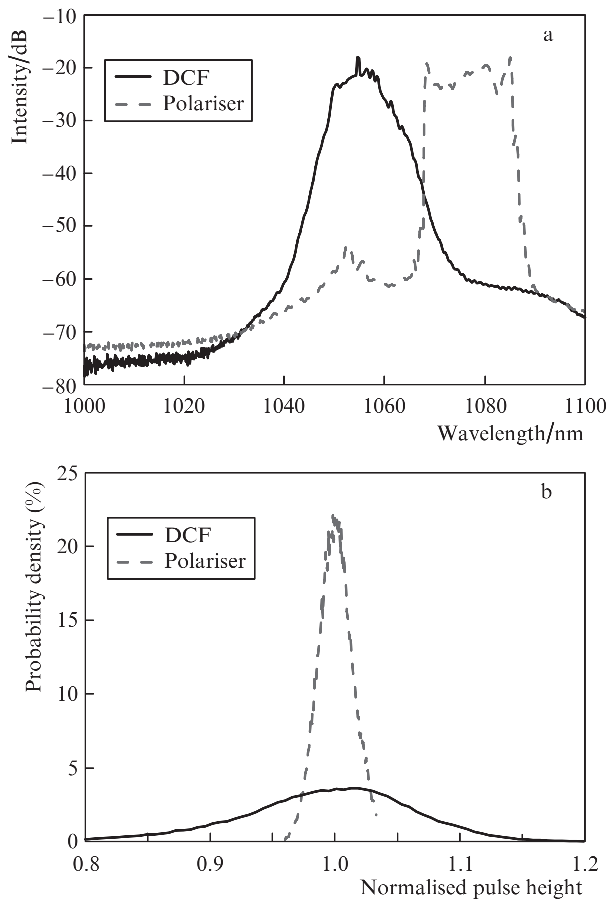

Figure 5. (a) Emission spectra and (b) pulse height distributions of the TWF laser and a laser with a polariser.

In special experiments, we verified whether mode locking could be achieved without TWF or using a single-core ytterbium-doped fibre with similar parameters instead of the TWF. In neither case was mode locking achieved. Moreover, we observed a spontaneous transition from stochastic operation to the generation of multiple chirped pulses [10], with the result that the spectrum had sharp edges and the pulse height fluctuations decreased sharply. This transition suggests that the TWF was a nonoptimal polarisation element. Indeed, replacing the TWF by a fibre polariser, which has a stronger polarisation dependence, causes the mode-locking regime to differ significantly from that of the TWF laser. In the case of the polariser, we observed stable generation (Fig. 5b) of chirped pulses, with characteristic sharp edges of the lasing spectrum (Fig. 5a) [11].

Thus, we have demonstrated for the first time the use of the polarisation properties of a TWF for mode locking in a fibre laser. The mode locking mechanism in this study differed from that assumed previously for the laser configuration in question and based on the nonlinear properties of TWFs (see e.g. Winful and Walton [12]). This was verified using the above procedure for luminescence intensity measurements at the TWF filter output. The power redistribution in the cores that would be expected for the mode locking mechanism based on the nonlinear properties of TWFs was not detected. It is quite possible that optimising the polarisation properties of TWFs will enable more stable mode locking.

5. Conclusions

We have measured the longitudinal power distribution in a TWF at different input light polarisations. Experimental evidence has been found that, because of the difference in BR, the power in the cores depends on which core the beam is launched into. At the same time, the longitudinal power profile obtained by averaging over the input polarisation states is independent of initial conditions. A polarisation model for mode coupling in a TWF with birefringent cores is proposed, and experimental data are presented that support the model. Unfortunately, no quantitative agreement between theory and the model has been reached. One possible reason for this is that the coefficients in Eqn (2) vary along the length of the fibre because a constant radius of curvature is very difficult to ensure in experiments. Moreover, unintentional, random variations in BR along the fibre in both cores also cannot be ruled out. The present results suggest that differences in BR between the cores should be precluded at the fibre development stage and that fibre parameters should be maintained constant along the length of the fibre with high accuracy at the fibre fabrication stage in order to avoid uncontrolled effects.

In addition, we have demonstrated a new application for the polarisation properties of TWFs: fibre laser mode locking based on nonlinear polarisation rotation. For stable laser operation, the polarisation properties of TWFs should be optimised. This can be achieved, e.g., by increasing the difference between the transmittances for different polarisations.

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