POLARISATION MAINTENANCE IN CIRCULARLY BIREFRINGENT FIBRES

Indexing terms: Optical fibres, Polarisation, Birefringence

The feasibility of twisted circularly birefringent polarisation maintaining fibres is investigated. It is shown that the twist rate required to provide immunity from external effects is excessively large.

Introduction: Optical fibres capable of transmitting a single, defined state of polarisation (SOP) under conditions of bending, twisting and externally applied pressure are of interest in telecommunications and for use in interferometric sensors. The current approach[1] is to produce a fibre which exhibits a high degree of linear birefringence and to launch light along one of the principal axes. The intrinsic linear retardance can be made sufficiently large so that it far exceeds any externally induced linear birefringence (bending, pressure) and furthermore swamps the relatively small circular retardance caused by twisting. Thus, the propagating linearly polarised light remains unperturbed by normal fibre handling. In a recent publication[2] a novel alternative with a number of advantages was proposed: the fibre is made to exhibit a large degree of circular birefringence by twisting it in the hope that the circular birefringence will swamp the intrinsic and extrinsic linear birefringence. The fibre will then be capable of propagating *circularly polarised* light unchanged.

In this letter we show that, whereas sufficient circular retardance can be induced by twisting to overcome the low intrinsic birefringence in a well-made fibre (the criterion used in Reference 2), the degree of twist required to produce sufficient circular retardance to overwhelm practical bend or pressure-induced extrinsic birefringence would fracture the fibre. Moreover, the predicted reduction in polarisation mode dispersion[2] is offset by the introduction of photoelastic group-velocity dispersion of similar magnitude.

Theory and experiment: In order to calculate the degree of twist required to maintain a circular SOP, we take as a model a twisted fibre subjected to a simple bend and determine the resulting output extinction ratio. If the fibre is sufficiently twisted to overcome the intrinsic birefringence,[2,3] it can be represented[4] as a stack of pure rotator elements of thickness δz and rotation $\alpha\delta z$, where $\alpha = 0{\cdot}07 \times$ twist rate.[3] The effect of a bend (or side pressure) is to introduce linear birefringence $\Delta\beta$, which we represent by interspersing birefringent elements having retardance $\Delta\beta\delta z$ and an azimuth θ (Fig. 1). The latter is determined by the plane of the bend or applied pressure.

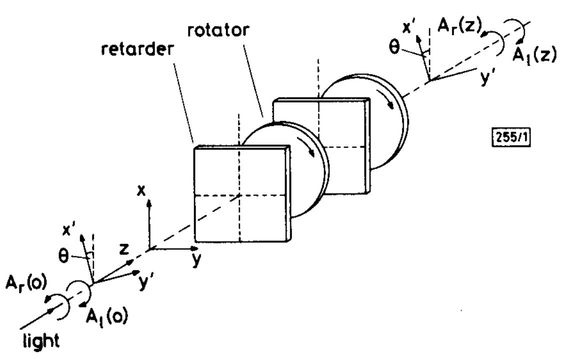

Fig. 1 *Theoretical model*

Using coupled-mode analysis,[4] we obtain analytic expressions for the amplitude of the fields in the two orthogonally polarised modes as a function of length for any input SOP. Proceeding from this result[5] the solution is cast in the form of a Jones matrix equation and adjusted to the external co-ordinate system x', y' (Fig. 1) to allow for the azimuth θ. Expressed in terms of left and right circularly polarised light components $A_l(z)$, $A_r(z)$, respectively, the matrix equation becomes

$$\begin{bmatrix} A_l(z) \\ A_r(z) \end{bmatrix} = \begin{bmatrix} P & -Q^* \\ Q & P^* \end{bmatrix} \begin{bmatrix} A_l(0) \\ A_r(0) \end{bmatrix} \tag{1}$$

where

$$P = \cos \gamma z - \frac{i}{(1+\rho^2)^{1/2}} \sin \gamma z \tag{2}$$

$$Q = \frac{-i\rho}{(1+\rho^2)^{1/2}} \sin \gamma z \, . \, e^{-2i\theta} \tag{3}$$

and the asterisk denotes complex conjugation. We have introduced

$$\rho = \frac{-\Delta\beta}{2\alpha} \tag{4}$$

$$\gamma = \tfrac{1}{2}(\Delta\beta^2 + 4\alpha^2)^{1/2} \tag{5}$$

If only, say, left circularly polarised light is launched, we obtain for the extinction ratio $R(z)$

$$R(z) = \left(\frac{A_r(z)}{A_l(z)}\right)^2 = \frac{\dfrac{\rho^2}{1+\rho^2}\sin^2 \gamma z}{\cos^2 \gamma z + \dfrac{1}{1+\rho^2}\sin^2 \gamma z} \tag{6}$$

Thus, the extinction ratio is an oscillatory function of fibre length, having minimum and maximum values of 0 and $(\Delta\beta/2\alpha)^2$, respectively. Provided the twist-induced circular birefringence greatly exceeds the extrinsic linear birefringence (i.e. $\alpha \gg \Delta\beta$) the fibre maintains circular polarisation. Unfortunately, the extrinsic linear birefringence to be found in a practical cable is relatively large, thus necessitating an impractical twist rate, as shown in the following example.

Consider a 125 μm-diameter fibre subjected to a bend of 35 mm diameter, or alternatively, to a transverse pressure of 23 Nm^{-1}. These not unlikely figures result in an induced linear birefringence[6,7] of 8·4 rads/m at a wavelength of 1·3 μm. Assuming a maximum tolerable extinction ratio of -40 dB, eqn. 6 reveals that an optical-rotation beat length of 14·9 mm would be required, i.e. a twist of $\sim$ 1 mm/turn. Such a twist is close to the theoretical strength limitation of the glass and is not therefore practical.

An experiment was conducted to verify the above predictions using a short length ($\sim$ 1 m) of low-birefringence[8] fibre ($\Delta\beta < 0{\cdot}05$ rads/m) which had been highly twisted at a rate of 47·4 rads/m, (i.e. $\alpha \gg \Delta\beta$). Left circularly polarised light from a HeNe laser was launched into the 139 μm-diameter fibre and the output extinction ratio (defined in eqn. 6) measured as a function of the bend radius R of a single loop wound near the fibre midpoint. The results are compared in Fig. 2 with the prediction of eqn. 6 and good agreement is observed. Note that a single loop of 2·4 cm radius catastrophically degrades the extinction ratio to 0 dB.

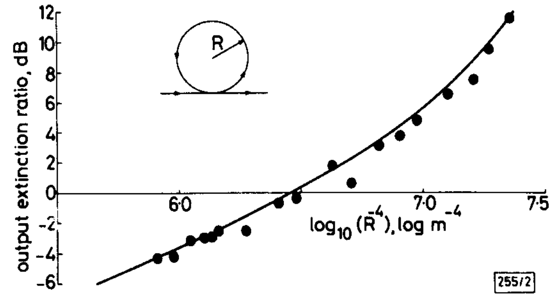

Fig. 2 *Output extinction ratio for circularly polarised light from a twisted single-mode fibre as a function of bend radius R (see inset)*

Dots are experimental values

Essentially the reason for the failure of circular-polarisation maintaining fibres is that it is not possible to induce sufficient circular retardance in the fibre to quench the extrinsic linear birefringence. On the other hand, it *is* possible to virtually eliminate intrinsic linear birefringence effects by twisting[3] or spinning the fibre during drawing.[5] This is in part due to their smaller magnitude in a well-made fibre, but also to the rotation of the intrinsic linear-birefringence axes with the twist. For

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extrinsic effects such as bends, a constant azimuth exists and the induced birefringence is quenched only by virtue of the photoelastic birefringence α induced by the twist. Since $\alpha = 0{\cdot}07 \times$ twist rate, the photoelastic rotation is an order of magnitude less effective in overwhelming linear birefringence when acting alone.

Dispersion of twisted fibres: Twisting or spinning[5] a fibre reduces the effect of polarisation mode dispersion.[2,5] However, in a twisted fibre the circular birefringence which replaces the linear birefringence is itself slightly dispersive. In the limit of large twist ($\alpha \gg \Delta\beta$) the group-delay difference $\Delta\tau$ between orthogonally polarised modes is:[5]

$$\Delta\tau = -\frac{2z}{c}\frac{d\alpha}{dk} \tag{7}$$

where c is the velocity of light and k the free-space wavenumber. The rotation α is related[3] to the elasto-optic constants of silica, the dispersion[9] in which leads to $\Delta\tau \sim 3{\cdot}5$ ps/km at a wavelength of $1{\cdot}55$ μm for a fibre twisted at 50 turns/m. A similar dispersion would, for example, occur in a fibre having a typical linear birefringence of 2·8 rads/m. Thus a twisted fibre has no dispersion advantage. Note, however, that in the case of a fibre twisted during drawing negligible residual dispersion exists.[5]

Conclusions: By analogy with linear-polarisation maintaining fibres,[1] it would appear that in a circular-polarisation maintaining fibre it is necessary to have a circular-birefringence beat length of the order of 1 mm to ensure immunity to external effects such as pressure and bends. Optical rotation of this magnitude cannot be obtained by twisting the fibre. Unless other means can be found to introduce a high rotation, the advantages[2] of a circular polarisation-maintaining fibre regretfully appear unattainable.

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