ROCKING FILTER FORMATION IN PHOTOSENSITIVE HIGH BIREFRINGENCE OPTICAL FIBRES

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Parent *et al.* observed that the refractive index changes induced in optical fibres by Hill grating formation (at 488 and 514·5 nm) were birefringent. A wavelength filter, formed in a simple and novel way by exposing high birefringence fibre to linearly polarised 488 nm light, is reported. Narrow bandwidth operation and high conversion efficiencies are achieved experimentally between the two orthogonal polarisation states of the fibre.

Introduction: We report an in-line polarisation rotator and filter formed in a highly birefringent (HiBi) single-mode fibre by launching light of 488 nm polarised at 45° to the fibre's principal axes. Photosensitivity in the fibre core gives rise to an induced birefringence that lines up with the oscillating electric field of the light. This periodically perturbs the intrinsic birefringence of the HiBi fibre, causing its principal axes to rock to and fro at the intrinsic beat period. The power conversion between the unperturbed principal axes is wavelength selective and, in combination with a polariser, the device acts as a filter.

Background: Holographic grating formation at 488 and 514·5 nm in standard communications optical fibre was first observed a decade ago by Hill *et al.*[1] Since then this photosensitivity has been seen in a wide range of different fibres, all of which have the presence of Ge as a core dopant in common.[2,3] There is still speculation as to the origins of the index change. We have proposed a Kramers–Krönig mechanism,[4] quantitatively linking the measured index change to the creation and bleaching of known defects and colour-centres in the UV spectral region. Two-photon absorption to a band centred at 240 nm causes breakage of oxygen deficient bonds (Ge–Ge, Ge–Si), releasing electrons that diffuse away and are trapped at two types of Ge dopant sites in the glass, with absorption bands (when occupied) at 213 and 281 nm. This model is qualitatively supported by the results of Meltz *et al.*,[5] who have extended the practicality and importance of the effect by holographically writing gratings into the core through the cladding, using 244 nm laser light. Their technique permits fabrication of distributed Bragg reflectors that operate at any desired wavelength — in the original experiments the operating wavelength was restricted to the wavelength of writing. The available index change can be as high as 5×10^{-4} at high dopant concentrations.

A further feature of this index change (one that has not received much attention since it was first noticed by Parent *et al.*[6]) is that it is birefringent, the extraordinary axes lining up with the electric field polarisation of the exposing radiation. The induced birefringence $B_i = (n_s - n_f)$ can approach 10^{-6}, and through dynamic realignment can cause polarisation instabilities in low-birefringent fibres at quite modest CW threshold power levels.*

Analysis: We make use of this effect to form wavelength selective polarisation couplers in HiBi fibres. Our technique relies on the periodic evolution of the polarisation state with distance for a launched optical electric field linearly polarised at 45° to the eigen axes of the intrinsic birefringence. As the light propagates the polarisation state evolves through left-circular, linear (orthogonal to the incident direction) and right circular back to the initial linear state. This pattern repeats at the beat period of the HiBi fibre

$$L_b = \lambda / B_o$$

where λ is the vacuum wavelength and $B_o = (n_s - n_f)$ where n_s and n_f are the effective phase indices of the intrinsic slow and fast eigenmodes.

The induced birefringence B_i aligns parallel to the linear polarisation axis, or to the major axis in the case of elliptical polarisation. The orientation of B_i will thus switch to and fro at half the beat period, L_b, between parallel to and normal to the input polarisation. This additional periodic birefringence, when added to B_0, causes the principal axes of the net birefringence to rock to and fro over a beat period, L_b. The resulting dielectric tensor, evaluated relative to the intrinsic principal axes, may be shown to take the form

$$[\varepsilon] = \begin{pmatrix} [\varepsilon_f + \Delta\varepsilon_i + (\Delta b_i/2)\cos Kz] & (\Delta b_i/2)\cos Kz \\ (\Delta b_i/2)\cos Kz & [\varepsilon_s + \Delta\varepsilon_i + (\Delta b_i/2)\cos Kz] \end{pmatrix} \tag{1}$$

where ε denotes the relative dielectric constant, ε_s and ε_f are its intrinsic fast and slow values, $\Delta\varepsilon_i$ the isotropic and Δb_i the anisotropic changes induced by exposure. Δb_i is oriented parallel to the launched polarisation, i.e., at 45° to the intrinsic principal axes. The grating vector $K = 2\pi B_0/\lambda_0 = 2\pi/L_{b0}$ where L_{b0} is the beat period at the writing wavelength λ_0.

In evaluating this expression, the transformation $R^{-1}[\varepsilon_i]R$ was used to refer the induced $[\varepsilon_i]$ to the intrinsic HiBi axes, with the rotation matrix R given by

$$R = \begin{bmatrix} \cos\phi & -\sin\phi \\ \sin\phi & \cos\phi \end{bmatrix}$$

where ϕ is the angle between the induced and the intrinsic birefringences (45° in the present case).

The perturbation induced by exposure is axially periodic, and permits a small component of the electric field in the fast (slow) mode to radiate into the orthogonal slow (fast) mode at positions (spaced $L_b/2$ apart) where the two modal fields are in phase. The result is phase-matched power conversion between the modes. The cos (Kz) in the on-diagonal elements of $[\varepsilon]$ is a periodic self-coupling term, and can be neglected.

At wavelengths different from the writing wavelength, the intrinsic beat length will not match the period of the induced birefringence, and phase-matching no longer occurs. The operation of this device is conceptually identical to that of the rocking-filter described by Stolen *et al.*[7]

The electric field is expressed as

$$\{E\} = \begin{bmatrix} V_f(z)\exp(-j\beta_f z) \\ V_s(z)\exp(-j\beta_s z) \end{bmatrix} \tag{2}$$

where V_f and V_s are slowly varying amplitudes, $\beta_f = 2\pi\surd(\varepsilon_f + \Delta\varepsilon_i)$ and $\beta_s = 2\pi\epsilon(\varepsilon_s + \Delta\varepsilon_i)$. Putting eqn. 2 into the wave equation, and invoking Floquet's theorem to relate β_f and β_s

$$\beta_f = \beta_s - K \tag{3}$$

neglecting second order derivatives of V_f and V_s and equating coefficients of $\exp(-j\beta_f z)$ and $\exp(-j\beta_s z)$ separately to zero leads to a standard coupled wave equation pair with the solution

$$\eta = \{\kappa^2/[\kappa^2 + (\theta/2)^2]\}\sin^2\{L\surd[\kappa^2 + (\theta/2)^2]\} \tag{4}$$

where η is the conversion efficiency between the principal eigen states, $\kappa = \{\pi\,\Delta b_i/4\lambda\surd(n_f n_s)\}$ is the coupling constant, $\theta = 2\pi\,\Delta\lambda/L_{bo}\lambda_0$, the dephasing parameter, and L the interaction length.

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Experiment: The fibre used in our experiments had a core Ge concentration of 13·9mol%. Its beat length and V-value at 488 nm were 0·69 mm and 2·22, respectively, giving a spot-size diameter of 1·74 μm. We exposed 1 m of the fibre to an in-core intensity of 30 mW/μm^2 for 5 min. The resulting experimental bandwidth measurement, taken using a white light source with a monochromator and appropriate polarisation filters, is plotted in Fig. 1. Also plotted in this Figure is a theoretical fit to the expression in eqn. 4. The fit was obtained for $L = 0{\cdot}1$ m and $\kappa L = 0{\cdot}32$, corresponding to $\Delta b_i = 2{\cdot}9 \times 10^{-6}$ or $B_i = 9{\cdot}9 \times 10^{-7}$. Only 10 cm of the fibre is involved in the coupling process, illustrating that the grating is not formed along the whole fibre length. This is probably because of spatial non-uniformities and temporal fluctuations in exposure caused by interactive coupling between the exposing eigen states in the slowly forming grating structure.

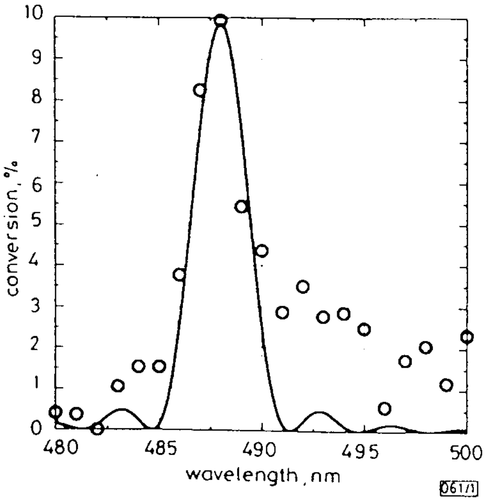

Fig. 1 *Conversion efficiency against wavelength detuning*
Full line is a theoretical fit

Conclusions: We have shown for the first time that the birefringence induced in germanosilicate optical fibres by exposure to 488 nm light can be used to form polarisation convertors/filters in HiBi fibres. The devices operate by inducing a periodic rocking perturbation of the principal eigen axes of the fibre. They have applications as wavelength and polarisation selective filters.

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