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INDUCED BIREFRINGENCE IN OPTICAL FIBRES: PHENOMENOLOGY AND APPLICATIONS

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Abstract

Recent work has shown that the birefringence induced in optical fibres by exposure to linearly polarized light can be used to realize novel self-organised birefringent rocking filters that act as narrow-band polarization mode convertors. The present understanding of the effect is reviewed and these devices discussed.

1. Background

Photorefractive behaviour at 488 and 514.5 nm, leading to grating formation via two-beam interference, was first reported in optical fibres in 1978 [1] and in thin film waveguides of sputtered GeO_2 in 1983 [2]. In 1985 [3], it was further recorded that, for exposure to linearly polarized light, the induced index change is significantly anisotropic, lining up with the oscillating electric field of the exposing light. For some years these effects remained something of a curiosity until Meltz and coworkers [4] in 1989 demonstrated side-writing of strong stable gratings using two-beam interferometry with UV laser light in the vicinity of 245 nm. This important development has allowed production of efficient distributed Bragg reflectors with customised wavelengths of operation, devices which are of great interest in optical fibre lasers and sensors. The success of this work has somewhat overshadowed the equally intriguing matter of the induced birefringence, the subject of this paper.

2. Characteristics of photosensitivity

Whereas the mechanism for the induced refractive index change is gradually becoming clearer, the physical origins of the observed anisotropy are not yet well understood.

2.1 Induced refractive index

Further evidence has recently emerged [5] in support of a Kramers-Kronig model (first proposed in 1990 [6]) suggesting that they are related to changes in the relative populations of three defect/colour-centre populations with transitions in the UV. Although the core glass is nominally $Ge_xSi_{1-x}O_2$, in practice it is nearly always oxygen-deficient as evidenced by an absorption band at 245 nm associated with Ge-Si defects. These bonds are ruptured by one or two photon absorption, leading to the release of an electron and the creation of a positively charged GeE' centre. The released electron gets trapped at two other types of Ge dopant site, forming negatively charged colour-centres with centre-band absorptions at 217 nm and 281 nm. The longer wavelength band is very broad and much the weaker, extending out into the green where increases in absorption as high as 1000 dB/km can result, these scaling with the Ge concentration and level of oxygen deficiency. This model [7,8] explains the substantial index changes ($>10^{-4}$) that are observed experimentally out into the infra-red.

2.2 Induced birefringence

The original work of Parent et al. [3] developed from studies of Hill grating formation, and so was carried out at 514.5 nm. Ouellette et al. have recently investigated the effect at 532 nm in low-birefringence (Lo-Bi) germanosilicate fibre [9]. Reported levels of induced birefringence lie in the 10^{-5} to 10^{-6} range, i.e., between 1 and 2 orders of magnitude smaller than the associated refractive index changes. Bardal et al. [10], in a recent comparative study of Lo-Bi and bow-tie (stress-induced) Hi-Bi germanosilicate fibres exposed to frequency-doubled mode-locked Nd:YAG light at 532 nm, discovered some interesting differences suggesting that stress plays an important role (see Figure 1). The Hi-Bi fibres responded with a permanent change in birefringence that a) grew in strength only when the light was polarized parallel to the bow-tie axis, and b) lined up predominantly parallel to the existing intrinsic axes of birefringence, with a small deviation towards the local field direction. In contrast, the Lo-Bi fibres displayed a fully reversible change in birefringence that always lined up parallel to the exposing field. Intriguingly, the sign of the induced birefringence was measured to be negative along the exposing field.

As regards the wavelength dependence of the effect, the evidence is conflicting, probably indicating that it is highly specific to fibre fabrication conditions, dopant levels and built-in stress. The effect was first observed at CW 514.5 nm [3], and it has subsequently been seen at pulsed 532 nm by Ouelette et al. [9] and Bardal et al. [10]. The fibre in [9], however, was much less sensitive at CW 514.5 nm and CW 488 nm, in contrast to recent work on elliptical core (un-stressed) Hi-Bi fibre from Andrew Corporation [11].

3. Devices

The ability to write a birefringence optically into the core of a fibre permits self-organised formation (by two-mode interference) of a range of different resonant polarization convertors/wavelength filters. How does this work? A basic requirement for interference is that the participating modes should be non-degenerate. For pure polarization interference (as opposed to the more usual amplitude interference), a further requirement is that they should be orthogonally polarized. If both conditions are fulfilled, the result is a set of fringes with zero visibility but a strongly modulated polarization state, which is the ideal field for formation of birefringence gratings; where the field is circularly polarized, no birefringence is induced, and where it is linear, the opposite is true. The resulting structure converts power between orthogonally polarized modes at a specific "Bragg" wavelength. An analysis of this type of mode conversion was published in 1979 by Yeh [12].

The first self-organising device of this kind to be reported was a distributed feed-forward (DFF) rocking filter [13] in Hi-Bi fibre. The interfering modes in this case are the co-propagating non-degenerate fast and slow eigenmodes of the Hi-Bi fibre. The device was formed simply by launching linearly polarized CW 488 nm light at 45° to the birefringent axes of the fibre. After exposure, the result is a gently rocking net birefringence that couples from one eigenstate to the other within a narrow wavelength band. Using stress-induced bow-tie Hi-Bi fibre, the highest efficiency attained in 30 cm was around 10%, which is not surprising in view of fact that in these fibres the induced birefringence rocks in an angular range considerably less than 45° owing to the relative insensitivity for optical fields polarized normal to the bow-tie axis (Figure 1). In stress-free elliptical core Hi-Bi fibre, on the other hand, 100% efficiencies have been reported [11], which accords with the constraining effect that stress has on the reconfigurability of the induced birefringence [10].

Rocking filters in Hi-Bi fibres were first proposed and investigated by Stolen et al. in 1984 [14]. Their approach was to rock the preform periodically during the fibre pulling process. The self-organising phenomenon is clearly much simpler to implement and more attractive - if questions as to its long term stability are satisfactorily resolved, and if operation at any desired wavelength can be achieved. This second point has been answered by Hill et al., who have successfully employed a spot-writing technique (in which the fibre core is exposed through the cladding to collimated polarized UV laser light) to produce efficient DFF filters at 1.3 microns in elliptical core Hi-Bi fibre [15].

Recently, a further type of self-organised device has been reported [16]. This is a distributed feed-<u>back</u> (DFB) polarization state converter that <u>reflects</u>, within a narrow wavelength range, a linearly polarized mode into the orthogonal counter-propagating mode. The interfering modes in this case are two orthogonally polarized counter-propagating modes of a single-mode fibre, which need not now be Hi-Bi since non-degeneracy is guaranteed. The resulting fine-period polarization fringe pattern is transferred into a corresponding fine-period rocking pattern of induced birefringence, which acts as a DFB polarization filter. The fibre used in this experiment was the elliptical-core Hi-Bi fibre from Andrew Corporation used in [9]. An in-line quarter wave plate was fashioned by fusion-splicing two pieces of fibre with Hi-Bi axes at an angle of 45°. By placing a dielectric mirror against the end face, this arrangement resulted in two counter-propagating beams each confined to one of the fibre's polarization eigenmodes. Owing to high splice losses (90%), an efficiency of only 0.8% was achieved. This has since been substantially improved upon in Lo-Bi fibre fabricated at Southampton [17] (Figure 2). Average changes in birefringence as high as 10^{-5} have been induced [10] by uniform exposure, compared to modulation depths in the range 10^{-7} to 10^{-6} for backward filters (1.4×10^{-6} for the fit in Figure 2). This suggests that substantial improvements in DFB filter efficiencies should be possible.

4. Discussion and Conclusions

Without indulging in rank speculation, it is difficult at this stage to reach any firm conclusions as to the physical origins of the induced birefringence. However, a number of general comments may be made. Its negative sign suggests the depletion (rather than the creation) of some polarizable species, and seems to preclude the possibility that a macroscopic space-charge field, through the Kerr effect, produces the anisotropy. The ability to write very fine pitch (~180 nm) DFB filters across a fibre core ~1 micron in diameter also suggests that macroscopic space-charge fields are unlikely to play a role. It is interesting to speculate (but we won't) on a possible link with photo-induced $\chi^{(2)}$ gratings in fibres. In bow-tie Hi-Bi fibre, the induced anisotropy is irreversible and strongly influenced by the high stress fields across the core. In Lo-Bi, stress-free fibre a picture based simply on reversible bond breakage seems to be most appropriate. Light-induced absorption in germania-doped silica fibres has been modelled previously [8,18] and is attributed to the quasi-reversible redistribution of electrons between the different species of colour-centre. A detailed study of the dynamics of the induced birefringence will however be necessary before direct comparisons can be made.

In conclusion, changes in birefringence (some two orders of magnitude smaller than the associated refractive index change) can be induced in Ge-doped optical fibres by exposure to blue/green and UV laser light, and a range of novel photo-generated DFF and DFB rocking filters realised by polarization interference between orthogonally polarized non-degenerate guided modes.

Acknowledgements

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References

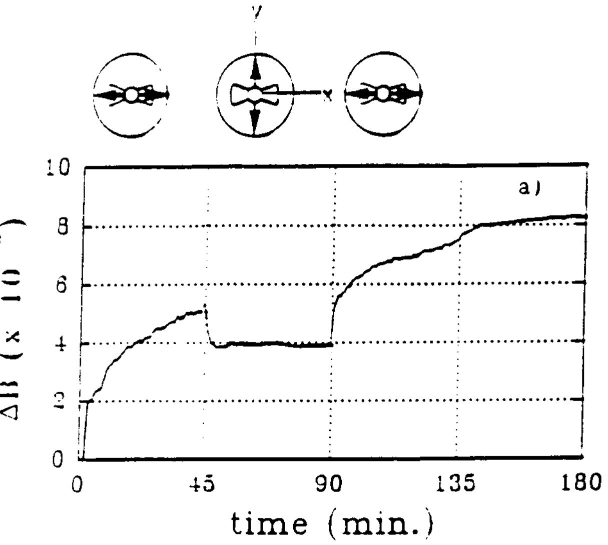
1. K.O. Hill, Y. Fujii, D.C. Johnson and B.S. Kawasaki, "Photosensitivity in optical fiber waveguides: Application to reflection filter fabrication", Appl. Phys. Lett., **32** (647-649) 1978.
2. Z.Y. Yin, P.E. Jessop and B.K. Garside, "Photoinduced grating filters in GeO_2 thin film waveguides," Appl. Opt. **22** (4088-4092) 1983.
3. M. Parent, J. Bures, S. Lacroix and J. Lapierre, "Propriétés de polarization des réflecteurs de Bragg induits par photosensibilité dans les fibres optiques monomodes", Appl. Opt., **24** (354-357) 1985.
4. G. Meltz, W.W. Morey and W.H. Glenn, "Formation of Bragg gratings in optical fibres by a transverse holographic method," Opt. Lett. **14** (823-825) 1989.

5. D.L. Williams, S.T. Davey, R. Kashyap, J.R. Armitage and B.J. Ainslie, "Direct observation of UV induced bleaching of 240 nm absorption band in photosensitive germanosilicate glass fibres," Electron. Lett. **28** (369-371) 1992.
6. D.P. Hand and P.St.J. Russell, "Photoinduced Refractive Index Changes in Germanosilicate Fibres," Opt. Lett. **15** (144-146) 1990.
7. L.J. Poyntz-Wright and P.St.J. Russell, "Spontaneous relaxation processes in irradiated germanosilicate optical fibres," Electron. Lett., **25**, (478-479), 1989.
8. P.St.J. Russell, D.P. Hand and L.J. Poyntz-Wright, "Frequency Doubling, Absorption and Grating Formation in Glass Fibres: Effective Defects or Defective Effects?," Fibre Laser Sources and Amplifiers II, SPIE **1373** (126-139) 1990.
9. F. Ouelette, D. Gagnon and M. Poirier, "Permanent photoinduced birefringence in a Ge-doped fiber," Appl. Phys. Lett., **58** (1813-1815) 1991.
10. S. Bardal, A. Kamal and P.St.J. Russell, "Photoinduced birefringence in optical fibres: a comparative study of low-birefringence and high-birefringence fibres," Opt. Lett. **17** (411-413) 1992.
11. S.E. Kanellopoulos, L.C.G. Valente, V.A. Handerek and A.J. Rogers, "Photorefractive polarisation couplers in elliptical core fibres," IEEE Photon. Tech. Lett., **3** (806-808) 1991.
12. P. Yeh, "Electromagnetic propagation in birefringent layered media," J. Opt. Soc. Am. **69** (742-756) 1979.
13. P.St.J. Russell and D.P. Hand, "Rocking filter formation in photosensitive high birefringence fibres," Electron. Lett. **26** (1846-1848) 1990.
14. R.H. Stolen, A. Ashkin, W. Pleibel and J.M. Dziedic, "In-line fiber polarisation rocking rotator and filter," Opt. Lett. **9** (300-302) 1984.
15. K.O. Hill, F. Bilodeau, B. Malo and D.C. Johnson, "Birefringent photosensitivity in monomode optical fiber: Application to the external writing of rocking filters," Electron. Lett. **27** (1548-1550) 1991.
16. A. Kamal, S. Bardal, P.St.J. Russell, Yuk-Tak Chow and D.P. Hand, S.E. Kanellopoulos, V.A. Handerek and A.J. Rogers, "Holographically written reflective polarisation filter: A new optical fiber grating device," Paper CMG7, Conference on Lasers and Electro-Optics (CLEO'92), Anaheim, California, May 1992.
17. In preparation; for submission to Optics Letters.
18. P.St.J. Russell, D.P. Hand and L.J. Poyntz-Wright, "Optically-induced creation, transformation and organization of defects and colour-centres in optical fibres," International Workshop on Photoinduced Self-Organisation in Optical Fibres, SPIE 1516-29, Quebec 1991.

Figure Captions (to be incorporated in text)

1. Comparison of birefringence induced at 532 nm in a) bow-tie Hi-Bi and b) Lo-Bi fibres (after [10]). When the polarisation is aligned along the bow-tie axis, the birefringence changes rapidly; when aligned normal to it, no change is perceptible. In the Lo-Bi fibre, however, the birefringence could be written and reconfigured in a different direction (normal in the figure) as often as desired.

2. Measured reflection as a function of frequency for a backward rocking filter. The filter was produced using 10 $mW/\mu m^2$ of CW single frequency light at 514.5 nm, and read out using the same laser running low at power, multi-frequency. The spectrum analyser resolves the individual laser modes, visible in the plot. An efficiency of ~5% was achieved. The fit uses a grating length of 8 cm and a birefringent modulation depth of 1.4×10^{-6}.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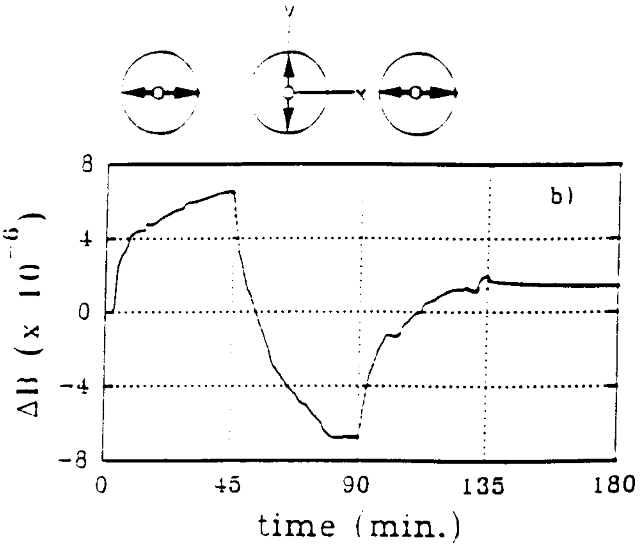
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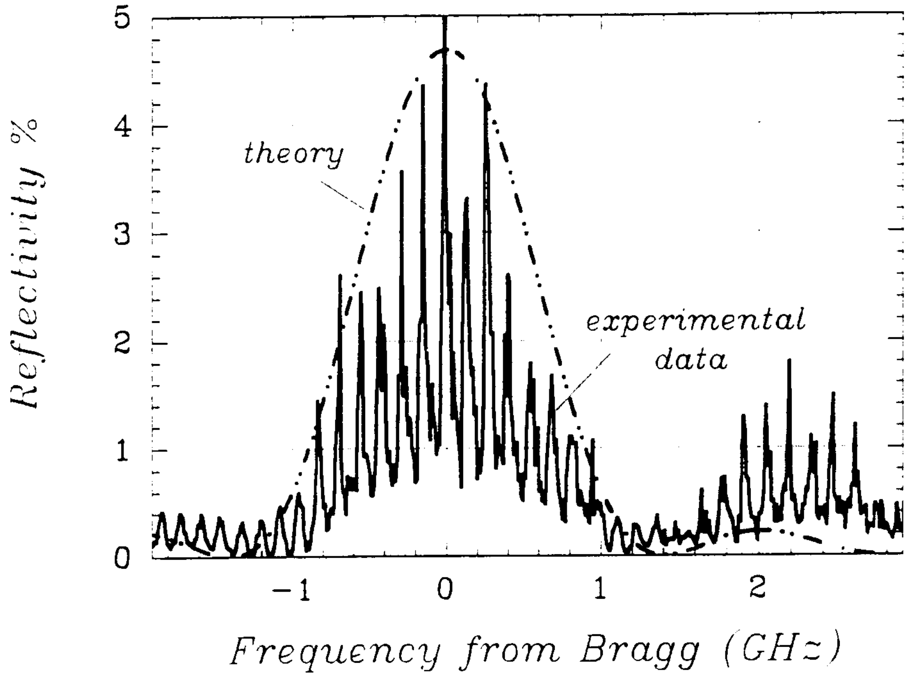
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