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RESEARCH ARTICLE

Consideration of chiral optical fibres

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Abstract Circular birefringence is a property of chiral materials. In this work, we consider the use of chiral materials in optical fibres to produce circularly birefringent optical fibres and in fibres where a contrast in circular birefringence contributes to forming the waveguide. (–)-menthyl methacrylate is also investigated as a possible material for the fabrication of such fibres.

Keywords microstructured optical fibres, microstructured polymer optical fibres, photonic crystal fibres, chirality, chiral waveguides, birefringence

1 Introduction

Polymer optical fibres (POFs) [1] and microstructured polymer optical fibres (mPOFs) [2–4] have allowed a large variety of dopants and structures to be investigated beyond what is possible with silica fibres, owing to the different fabrication methods and processing temperatures employed. This includes examples of multimode and hollow-core mPOF and organic and particulate dopants, as well as the use of different polymers altogether [4].

In this work, we consider the control of polarisation in optical fibres. Two-fold symmetric cross-sections have been thoroughly investigated and are known to induce a linear birefringence [5,6] to the fibre through structural (form birefringence) or stress (stress-induced birefringence) asymmetries. Breaking the symmetry of the fibre longitudinally rather than in the cross-section can induce circular birefringence. This has been achieved by spinning fibres with an off-set core or microstructured fibres so as for the core or hole structure to take on a helical shape [7–9]. Thus the fibre structure is "chiral" and cannot be superimposed on its mirror image. Alternatively, the fibre may be made of chiral materials that display optical activity. Both these methods create circular birefringence in the fibres, as a result of geometric effects in the former and material properties in the latter.

Circular birefringence breaks the degeneracy of circularly polarised modes, causing them to travel with different phase velocities in the fibre. The result is to rotate the plane of polarisation of linearly polarised light. This may be described as a birefringence B (difference in mode effective index between right- and left-hand circularly polarised light), an optical activity α describing how rapidly the plane of polarisation rotates in °/length, or as a beat length l_B that describes the length of propagation required to reproduce the input polarisation (i.e., a rotation of 180°). The use of chiral polymers also allows waveguide designs where differences in optical activity contribute to forming the waveguide.

Spun fibres can be produced from ordinary polymers, but chiral fibres require the production of chiral polymers, either through the use of chiral dopants or the polymerisation of a chiral monomer. The optical activity of the materials must be incorporated into numerical methods used to model microstructured fibres in order to study designs incorporating those chiral materials. In this paper, we consider the use of chiral materials in fibres and report on the development of materials and theoretical modelling of fibres incorporating chiral materials.

2 Fibres with chiral materials

The simplest incorporation of chiral materials in an optical fibre is in a step-index fibre geometry with a chiral core and achiral cladding, as shown in Fig. 1, where l_B is the beat length, and l_B' is the beat length in bulk. The optical activity will depend on the optical activity of the material used in the core and amount of light confined to the core and, hence, on the V parameter of the fibre [10].

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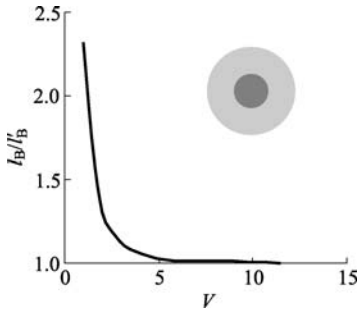

Fig. 1 Normalised beat length of a step-index fibre consisting of a high-index chiral core and a low-index achiral cladding, as a function of V parameter for fibre

Calculations indicated that a multimode fibre with $V > 6$ will have an optical rotation for the fundamental mode approaching the bulk value of the chiral material used in the core. For smaller V, the mode field extends into the cladding, and the optical rotation decreases; for a single-mode fibre, this can typically be approximated as a value of 50% of the bulk optical rotation.

Alternatively, considering a microstructured fibre equivalent, as shown in Fig. 2, the circular birefringence of the fibre would approach the bulk optical rotation under all conditions, given that the very high confinement of light in the solid material (as opposed to the air holes). Similar calculations showed a deviation from the bulk optical rotation of less than 2%, even when the air fraction of the cladding approached 60%.

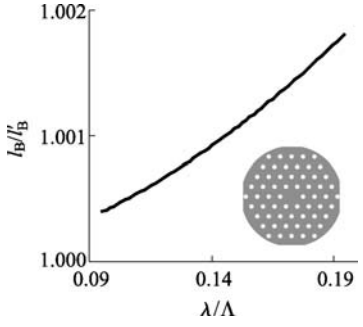

Fig. 2 Normalised beat length for a microstructured fibre composed of a solid chiral material and air holes as function of wavelength normalised by distance between adjacent holes Λ

Another possibility is to consider an optical fibre where the waveguide is defined not by a contrast in the refractive index but rather by a difference in optical activity of two materials, for example, using a right-handed and a left-handed material. Right-hand circularly polarised light will experience a refractive index of $n + \Delta n$ in one material and $n - \Delta n$ in the other (and vice versa for left hand circularly polarised light). If this were arranged in a step-index fibre geometry with a right-handed core and left-handed cladding, one circular polarisation will see a conventional waveguide with a high index core and low index cladding (with a contrast of $2\Delta n$), whereas the other will see an "antiguide" with a low index core and high index cladding. Hence, only one circular polarisation will be guided, and the fibre will be a circularly polarising fibre (this would be analogous to linearly polarising fibres which guide only one linear polarisation).

The simple description above is complicated however by scatting from the surface between the two chiral media, the core/cladding interface, which will mix the circular polarisations. The guided mode will thus consist of light in both left and right circularly polarised states. However, when the optical activity is small (as expected in chiral polymer materials), this effect is minimized, and we can assume that a single polarisation state will in fact be guided as a bound mode of the fibre [11].

Considering such a step-index fibre, we can define a normalised frequency V to describe its strength as a waveguide as follows:

$$V = 4\pi r_{co} \sqrt{\frac{n\alpha(\lambda)}{3.6\lambda}}, \quad (1)$$

where r_{co} is the core radius, n is the refractive index of the material, and λ is the free-space wavelength. Here, α is measured in °/cm. The optical activity α will typically depend strongly on wavelength. Analogous to V for conventional step-index fibres [10], a fibre will become increasingly ineffective as a waveguide as V approaches 0 and will support an increasing number of modes at increasing V. The range of parameters required in this case (particularly the range of α) is shown in Fig. 3.

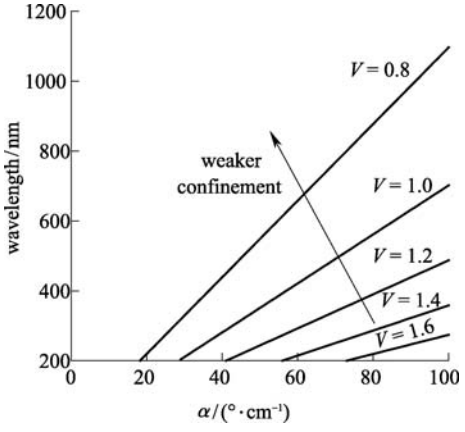

Fig. 3 Contours of different values of V calculated using Eq. (1) as function of wavelength and optical activity α (values of r_{co}= 10 μm and n = 1.6 were assumed)

Figure 3 shows that, as expected, large optical activities and short wavelengths are required to increase confinement. Furthermore, optical activity typically increases at

short wavelengths as $1/\lambda^2$, meaning such fibres will preferably be designed for short wavelengths. This is likely to result in a trade-off with material absorption as the wavelengths approach the ultra violet (UV). By inspecting Fig. 3 and assuming operation in the visible, a value of $\alpha = 50$ °/cm can be taken as an estimate of the minimum optical activity that can be used to create such a waveguide.

3 Chiral polymers

The above fibre designs all require the availability of chiral polymers that must be transparent and have the ability to be drawn into a fibre. This will require the correct molecular weight and polydispersity and a very low level of cross-linking—the polymer chains must be free to slide past one another in order for the polymer to be drawable.

Very little literature exists that considers the use of chiral polymers in such applications, and one notable report is on the copolymerisation of methyl methacrylate (the monomer for commonly-used polymethylmethacrylate, PMMA) and cholesteryl methacrylate [12]. This approach was deemed inappropriate for this work, as only one handedness of cholesteryl methacrylate would be easily available, and it was difficult to ascertain the transparency of this polymer.

The first candidate material to be considered is menthol, functionalised with methacrylate group (as shown in Fig. 4), and was chosen for its transparency and availability of both right and left handed materials, as required for the design discussed in the previous section. The monomer, (–)-menthyl methacrylate ((–)-MnMA), was prepared by replacing the hydroxyl group of (–)-menthol with a methacrylate group from methacryloyl chloride. Once polymerised, the backbone of the polymer would be identical to PMMA, but it will have the additional chiral pendent group. The optical activity of (–)-menthol is known to be $[\alpha]_D^{20} = -50° \pm 1°$, $c = 10\%$ in ethanol.

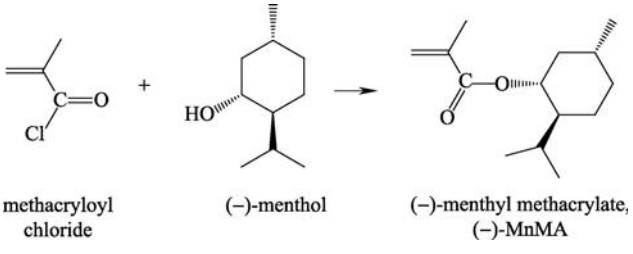

Fig. 4 Reaction used to create chiral monomer (methacryloyl chloride is reacted with menthol to create (–)-menthyl methacrylate, (–)-MnMA)

Optical rotation of (–)-MnMA synthesised was measured by using a broad spectrum (supercontinuum) source set to pass through two linear polarisers into an optical spectrum analyser. Experimental specific rotation value of

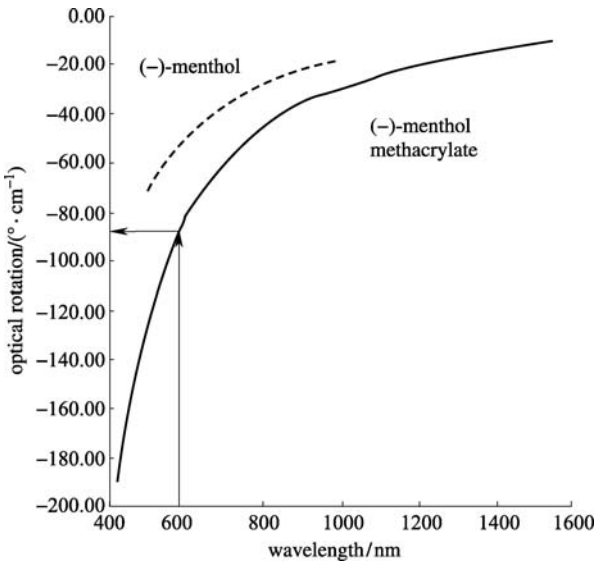

Fig. 5 Optical rotation of (–)-menthyl methacrylate, (–)-MnMA, and (–)-menthol (optical rotation of both species was measured neat, in their liquid state, at 20°C for (–)-menthyl methacrylate and at approximately 50°C for (–)-menthol)

(–)-MnMA was $[\alpha]_D^{20}(\text{neat}) = -90°$ (as shown in Fig. 5), which is in good agreement with the literature values [13] of $[\alpha]_D^{20}(\text{neat}) = -91°\text{--}90°$.

The optically active monomers are able to endow optical activity to other achiral monomers via copolymerisation, as shown in Fig. 6. Methyl methacrylate (MMA) was copolymerised with 5 or 10 mol% initial feed ratio of (–)-MnMA in bulk. MMA (3.8 g, 3.8×10^{-2} mol), (–)-MnMA (0.45 g, 2.0×10^{-2} mol), lauroyl peroxide (LP, 1.48×10^{-5} mol) as initiator, and 1-butanethiol (6.64×10^{-5} mol) as chain transfer agent were degassed via freeze-pump-thaw several times. The reaction mixture was polymerised in an oil bath at 60°C over 24 h. Copolymers containing 5 and 10 mol% initial ratio of (–)-MnMA were thus successfully synthesised.

Preliminary optical rotation measurements on the resulting polymer were consistent with expected values based on the concentration of the (–)-MnMA in the initial reaction mixture. The samples were however noted to be slightly cloudy in appearance and hence scattered the light to some degree. This is believed to be due to inhomogeneities arising from the clustering of the two monomers used and can be eliminated by altering the polymerisation conditions.

4 Conclusion

We have considered the incorporation of chiral materials in optical fibres. Using opposite signs of optical activity to define a waveguide can result in confining a single circularly polarised mode; however, this will require the

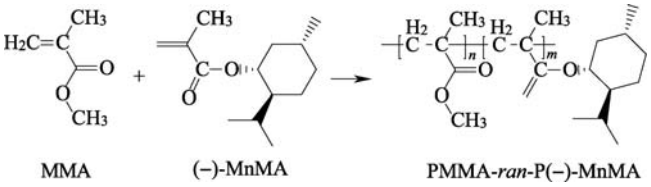

Fig. 6 Scheme of copolymerising MMA and (–)-MnMA in bulk

use of short wavelengths and large values of optical activity. As an initial candidate, (–)-menthyl methacrylate was copolymerised with methyl methacrylate to produce a chiral polymer. Further work will look to optimize the transparency of the chiral polymer and increase the optical activity.

References

1. Ziemann O, Krauser J, Zamzow P E, Daum W. POF Handbook: Optical Short Range Transmission Systems. 2nd ed. Berlin: Springer, 2008
2. van Eijkelenborg M A, Large M C J, Argyros A, Zagari J, Manos S, Issa N, Bassett I, Fleming S, McPhedran R C, de Sterke C M, Nicorovici N A P. Microstructured polymer optical fibre. Optics Express, 2001, 9(7): 319–327
3. Large M C J, Poladian L, Barton G W, van Eijkelenborg M A. Microstructured Polymer Optical Fibres. Berlin: Springer, 2007
4. Argyros A. Microstructured polymer optical fibres. Journal of Lightwave Technology, 2009, 27(11): 1571–1579
5. Noda J, Okamoto K, Sasaki Y. Polarization-maintaining fibers and their applications. Journal of Lightwave Technology, 1986, 4(8): 1071–1089
6. Russell P St J. Photonic-crystal fibers. Journal of Lightwave Technology, 2006, 24(12): 4729–4749
7. Birch R D. Fabrication and characterisation of circularly birefringent helical fibres. Electronics Letters, 1987, 23(1): 50–52
8. Argyros A, Pla J, Ladouceur F, Poladian L. Circular and elliptical birefringence in spun microstructured optical fibres. Optics Express, 2009, 17(18): 15983–15990
9. Michie A, Canning J, Bassett I, Haywood J, Digweed K, Aslund M, Ashton B, Stevenson M, Digweed J, Lau A, Scandurra D. Spun elliptically birefringent photonic crystal fibre. Optics Express, 2007, 15(4): 1811–1816
10. Snyder A W, Love J D. Optical Waveguide Theory. London: Chapman and Hall, 1983
11. Li J, Cao Y. Investigation of guided modes for a fiber filled with chiral media. In: Proceedings of the 8th Asia-Pacific Conference of Fundamental Problems of Opto- and Microelectronics. 2008, 182
12. Pujari N S, Kulkarni M R, Large M C J, Bassett I M, Ponrathnam S. Transparent chiral polymers for optical applications. Journal of Appllied Polymer Science, 2005, 98(1): 58–65
13. Shi Y T, Yu B, Ding M X, Wang F S. Stereocomplex formation between (+)- and (–)-poly(menthyl methacrylate) in bulk. Polymer Journal, 1996, 28(5): 465–466