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Published in:
Optical Sensors 2019

Link to article, DOI:
10.1364/SENSORS.2019.STh5A.1

Publication date:
2019

Document Version
Peer reviewed version

Polyurethane Optical Fiber Sensors

Simon Fleming[1], Maryanne Large[1] and Alessio Stefani[1,2]

1 Institute of Photonics and Optical Science, School of Physics, University of Sydney, NSW 2006, Australia

2 DTU Fotonik, Department of Photonics Engineering, Technical University of Denmark, DK-2800, Kgs. Lyngby, Denmark

simon.fleming@sydney.edu.au

Abstract: Optical fiber sensors drawn from polyurethane are demonstrated. Polyurethane's Young's Modulus is orders of magnitude lower than traditional optical fiber materials, permitting more sensitive optical detection of mechanical perturbations.

OCIS codes: 060.2290, 060.2370

1. Introduction

Optical fiber can be used to sense a wide range of physical parameters. The sensitivity is determined by a combination of the intrinsic material parameters, how the material varies with the parameter of interest, and the fibre structure. Whilst there are many clever approaches from fibre and device design to modify sensitivity, the material properties are fundamental. For sensors of mechanical perturbations, such as strain, bending, twist, the material's Young's modulus is fundamental; it describes the stiffness, the amount of strain (stretch) that is produced for a given stress (force applied). Optical fibres have generally been made of high stiffness materials, such as silica glass (Young's modulus ~75GPa) or PMMA (Young's modulus ~3GPa). Large amounts of force produce small amounts of elastic deformation to perturb the guidance of light in a fibre. Furthermore, these materials have relatively low breaking strains (silica ~2%). Optical fibres made with a low Young's modulus material with a high breaking strain would offer greater sensitivity, and greater robustness. Polyurethane has a Young's modulus around 1-10MPa, three to five orders of magnitude lower, and a breaking strain as high as 600%, around two orders of magnitude higher. This suggests that optical fibres fabricated from polyurethane would have extraordinary performance.

2. Polyurethane Fibres – Properties and Fabrication

Despite the significant potential benefits for sensing, polyurethane is not an obvious material to choose for making fibres. The very low Young's modulus appears incompatible with the drawing process, where tension is applied to draw the fibre from the necked-down preform. Furthermore, the optical loss of polyurethane is ~50dB/m. These two facts appear to suggest it will be extremely hard to make, and if successfully made it will perform extremely poorly. On the other hand, an approximately four order of magnitude increase in sensitivity is very encouraging.

However, an approach is needed to reduce the impact of the high loss, and an air-core is an apparent solution. Ideally an anti-resonant fibre would allow a significant reduction in loss. We have fabricated preforms by stacking polyurethane tubes and drawn them on a (Heathway) draw tower into fibre with a variety of fairly complex geometries (Figure 1).

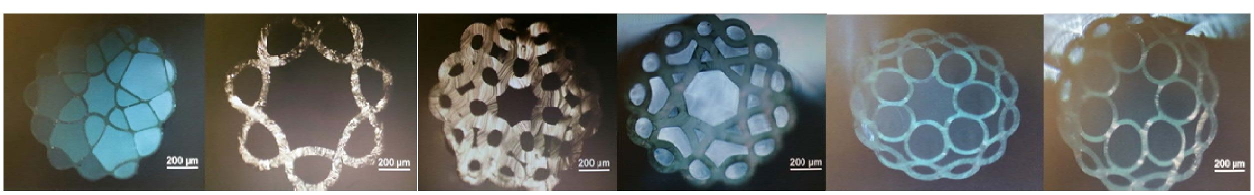

Fig. 1. Images of transverse cross-sections of a range of microstructured fibres drawn in polyurethane

Whilst this is clearly promising for anti-resonant fibres, polyurethane is very challenging to draw and as yet we have not fabricated fibres with thin enough features to operate at short wavelengths (we have realized antiresonant fibres at THz frequencies [1]). However, for many potential applications, sensing over short distances, capillary guidance is adequate.

We have also fabricated these structures with wires drawn into some of the holes. The original rationale for this was to fabricate tunable metamaterials [2], however it also permits other devices including electrical sensors in fibre form.

3. Applications and Performance

There are many potential applications, including robotics [3]. However, probably the most exciting are applications are for sensors on the body, or wearables [4]. The low cost, ruggedness and ability to combine with textiles of polyurethane is well suited to these applications, and sensing distances below a meter are not a problem.

Initial tests on a range of different simple capillary polyurethane fibres used to measure pressure demonstrated promising sensitivity of ~0.51 dB/N. [5]

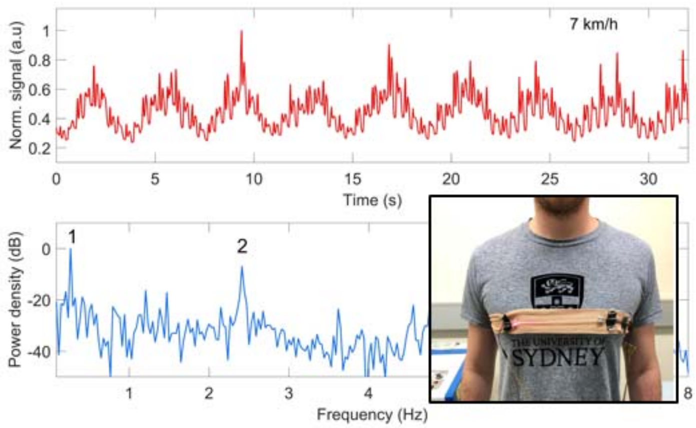

Figure 2 Time and frequency domain signals from polyurethane sensor in chest bandage (inset). Frequency plot - peak 1 is respiration, peak 2 step rate [6]

We have demonstrated a breathing monitor using simple capillary polyurethane fibre mounted in a cloth bandage together with a 633nm CW laser diode and detector. This was strapped to the torso of a test subject at diaphragm level, and the subject walked, jogged and ran on a treadmill. The signal from the detector was captured, and simple Fourier analysis was readily able to recover both the respiration signal and the rate of footfalls. [6]

The electrical form of these sensors also shows great promise. The capacitance between the fine internal conductors is readily measured and changes with mechanical perturbation of the fibre. [7] Good repeatability was observed, and the possibility of measuring magnitude and direction of applied force.

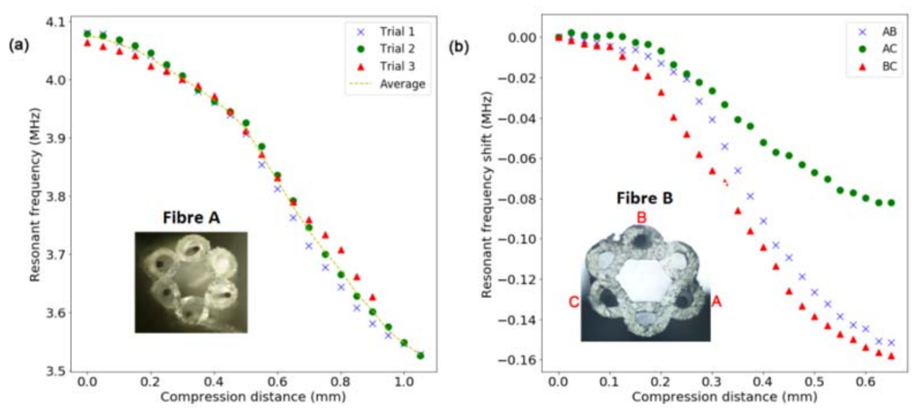

Figure 3 Response of two designs of polyurethane metal composite fibre capacitive pressure sensor [7]

4. Conclusion

Polyurethane is a very unconventional material for optical fibres as it has relatively high loss. However, it's very much lower Young's modulus and much higher breaking strain create novel opportunities for sensors of mechanical perturbation over short distances – well suited to sensors for use on the body.

5. References

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