DISTRIBUTED WATER SENSING USING PLASTIC OPTICAL FIBRES

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Abstract: We describe the design and an experimental proof of principle of a POF based distributed sensor to detect leaks and spills.

1. Introduction

This paper presents an evaluation of graded index plastic optical fibre as a potential transducer for distributed water sensors based upon microbend induced loss. The work originated in similar sensors based on silica fibre which have now been demonstrated and the principles are well understood [1]. When based upon silica these sensors have a range of up to several kilometres and respond to and can locate a spill of the order of one metre in extent. However, for many applications a much simpler configuration requiring a lower range system and possibly even only on/off response is required. This is one motivation for examining the prospects for plastic fibres. The second is that – again in some applications – exposure to moisture, even from a high humidity atmosphere can be damaging to the reliability of silica fibres especially when the secondary coating may have suffered during fabrication or installation processes. There are, of course, other benefits to plastic fibres – all well rehearsed – which include predominantly ease of handling and overall significantly relaxed mechanical tolerances. In the remainder of the paper we shall highlight the essential theoretical aspects of microbend phenomena in plastic fibres and present both an experimental characterisation of this phenomena and a demonstration sensor.

2. Microbending in Plastic Optical Fibres – the Essential Theory

Microbend loss was first recognised as an important phenomenon in optical fibre transmission systems approaching 40 years ago and the essential theory is well established. The basic conclusions of this theory (and indeed of the practice) are that single mode fibres require microbend periods which are sub-millimetre in order to induce significant loss and consequently, unless deliberately introduced by the much vaunted long period grating, single mode fibres are relatively immune to this phenomenon.

For multimode fibres however, the situation is very different, most notably with the graded index fibres which in fact dominated the communication system application in the era during which microbend was first characterised. Graded index fibres are designed to exhibit very low intermode dispersion and so the intermode beat length is carefully controlled and indeed is, in principle, the same for all adjacent pairs of modes within the fibre. Consequently, any perturbation introduced at this beat length can rapidly induce significant losses. For optical fibre telecommunications cables this had a profound impact on cable design. For sensors it facilitates the realisation with standard silica 62.5/125 graded index fibre of microbend structures which respond to displacement measured in microns. Indeed this essential principle has been exploited in earlier versions of the sensor principles incorporated here. For the step index fibre the situation is very different in that there is a threshold beat length below which no coupling occurs, but for any beat length the total coupling is relatively limited since the intermode beat varies throughout the mode spectrum.

The same basic principles apply to plastic fibres though the detailed values are significantly different. Figure 1 shows for graded index fibres the beat length as a function of core diameter for various numerical apertures and Figure 2 presents the minimum beat length for step index fibres under similar parametric conditions. Depending on the fibre the consideration the actual beat lengths required are significantly different to those applicable to standard silica graded index fibre.

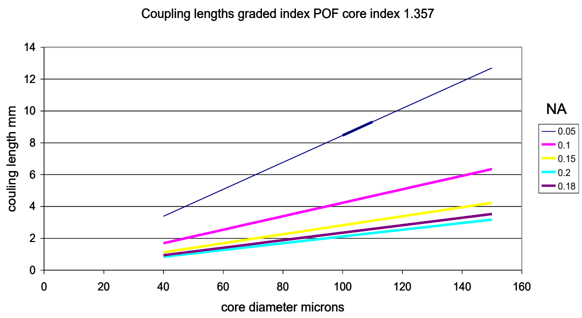

Figure 1: Calculated coupling lengths *vs* core diameter for graded index optical fibres with a peak core index of 1.357 (typical for POF) and with numerical aperture as a parameter.

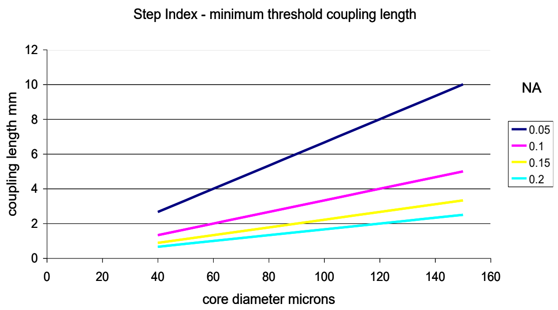

Figure 2: Calculated coupling lengths *vs* core diameter for step index optical fibres with numerical aperture as a parameter. These minima are independent of core index – simply depending on NA and core diameter.

This basic analysis does not of course take account of displacement sensitivities. For silica periodic displacements of microns transverse to the direction of propagation at the appropriate period are sufficient to induce significant (many 10's dB per km) loss. Plastic fibre is, however, significantly more robust to transverse displacement – a combination of both the mechanics of the interface since the polymer is much softer than silica and the optical properties of the core itself.

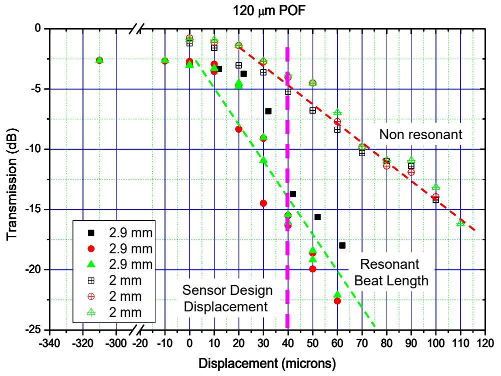

Figure 3: A direct comparison of induced loss *vs.* lateral displacement for a 5cm microbend section illustrating the impact of the resonant coupling length

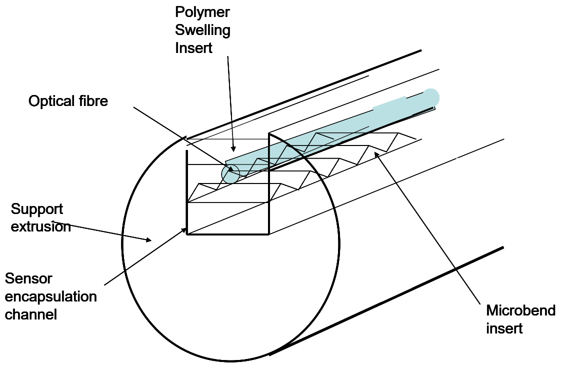

Figure 4: An extrusion compatible sensor design – note that the driving element – the swelling insert must be capable of producing a minimum of 50 microns displacement on the POF

Figure 3 presents experimental verification of these interactions showing the effect of transverse displacement at the critical beat length for graded index polymer fibres and contrasting this behaviour with equivalent displacements applied away from the critical spatial resonance. These measurements provide the basic framework through which the experimental demonstration system can be designed.

3. Demonstration Sensor System

The plastic fibre sensor system is fabricated using a process compatible with the eventual extrusion-based manufacturing. The essential features are shown in Figure 4. There are numerous important contrasts between this system and the original silica based configuration, the most fundamental of which is that the displacement required to introduce useful bending loss is significantly larger. Consequently, the thickness of the driving material (the swelling hydrogel-based polymer) is also substantially increased. The result of this (Figure 5) is that the swelling response time, which in turn corresponds approximately to the sensor response time, is now measured in minutes rather than seconds. In many applications this is perfectly acceptable.

A second consequence of the modified structure is that, perhaps paradoxically, achieving the necessary fabrication tolerances for long distance, low loss architectures is relatively difficult so that the additional induced loss inherent within the sensor configuration itself can be larger. This, in turn, limits the range of this sensor to the tens to perhaps the 100 metre level.

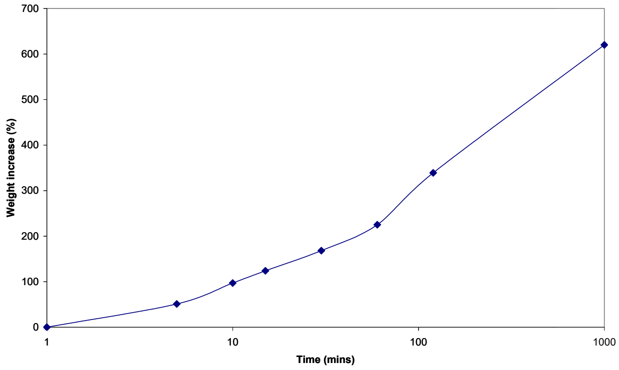

Figure 5: Swelling response *vs.* time in water of the a representative sample of the hydrogel material used as the swelling insert in figure 4.

Figure 6: Photograph of the laboratory bench mock up sensor. The red wrap is a porous tape and the sensor is approximately 8mm in diameter

A photograph of the test configuration is shown in Figure 6. Its response to a "spill", which involved moistening a few centimetres of sensor element using a hand-held spray, is shown in Figure 7. These measurements were take with a precision OTDR and do indicate that, in principle, the limited range sensor can locate and detect spillages. Again, though, we see that for most applications a simple wet/dry signal will be adequate and this (Figure 8) can be used to indicate that somewhere along the length of the sensor the moisture level has exceeded a previously calibrated average threshold value

Cursors	X	Y
◆ A	22.798	-16.24
◆ B	23.475	-15.64
◆ C	-3.988	-24.15
◆ D	-3.988	-24.15

Figure 7:High resolution OTDR trace of the attenuation introduced at 17.6m by moistening a section approximately 30 cm long using a hand-held water spray.

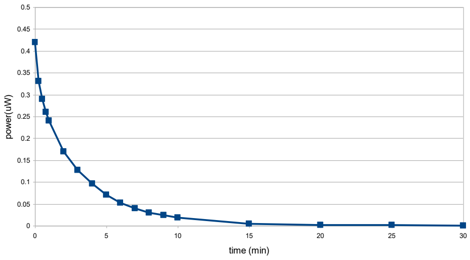

Figure 8: Optical power transmission *vs.* time for the sensor immersed in water over a length of approximately 10cm.

4. Concluding Observations

The concept of a distributed moisture sensor based upon polymer optical fibre has been demonstrated at the laboratory bench level. We have characterised the microbend response of plastic fibres, both graded and step index, and designed a suitable, extrusion compatible, sensor architecture. This simple demonstration indicates potential for the eventual application in installations such as domestic and small industrial embedded heating systems, especially those based on CHP concepts and in some types of specialised pipe line leakage monitoring.

5. References:

1. Alistair Maclean, John McCormack, Brian Culshaw, "Distributed Sensing for Liquid Leaks and Spills2, presented at SPIE DSS 2010 paper Proc SPIE Volume 7677