POLYMER OPTICAL FIBRE SENSING

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Abstract: This paper explores the different physical and chemical properties of silica and polymer fibre and how these impact on the behaviour of sensors based on these fibres. It identifies circumstances where the use of POF ought to be advantageous, such as where the sensor needs to survive high levels of strain. Recognising that POF sensors have not so far had anything like the commercial success of their silica-based counterparts, it also explores possible reasons for that discrepancy.

Keywords: Polymer optical fibre, sensing

1. Introduction

Research into optical fibre sensing dates back to 1967[1], if not before, and by 2020 the technology had grown to become the basis for a $3B industry[2]. Development of both silica and polymer based optical fibres was underway in the early 1950s, however silica fibre has gone on to dominate commercially in both the communications and sensing fields, probably as a result of the pioneering work of Charles Kao in the 1960s, who paved the way for obtaining low attenuation in silica fibre, which was needed to make optical fibre communications a commercial reality[3]. The market for optical fibres has been estimated at around $5B in 2022[4], with polymer optical fibre (POF) making up only around 10% of the total. In sensing too, when it comes to commercialized devices, those employing polymer fibre are very much in a minority. This paper examines the different properties of silica and polymer based fibre, uses this information to identify those applications that ought to be better suited to POF and attempts to understand why POF sensors have struggled to achieve the same commercial success as their silica counterparts.

Before going further, it may be useful to those relatively new to the field to acknowledge some of the other reviews of POF sensor technology in the literature. Although now rather old, there are two reviews by Peters[5] and Bilro et al[6] that together provide a very good introduction to the wider field. More focused (and more recent) reviews are available, dealing with distributed and quasi distributed POF sensing[7], POF based fibre Bragg gratings[8, 9], POF sensors for healthcare[10], strain sensors[11], refractive index sensors[12], liquid level sensors[13] and sensors exploiting surface plasmon resonance[14].

2. Silica vs polymer

Table 1 summarises the different properties of silica glass and poly(methyl methacrylate) (PMMA), which is perhaps the most common polymeric material from which POF is fabricated (later we shall examine how PMMA differs from some of the other polymers used in fibre production). It should also be understood that some of the properties of POF not only depend on the polymerization process employed (which can influence the average polymer chain length and degree of cross-linking), but also on the conditions under which the POF is drawn[15] and any annealing carried out on the fibre after drawing[16]. As an example, drawing under higher tension tends to align the polymer molecules with the fibre axis, making the optical properties of the polymer more anisotropic[17].

2.1. POF advantages

Situations where POF has a potential advantage over silica fibre are then as follows:

- Elasticity. The modulus of polymer fibre is roughly twenty times less than that of silica. This offers two potential advantages. Firstly, this makes POF based sensors more sensitive to stress, so for example the effect of a certain force applied to a POF based strain sensor will be twenty times as great as for an equivalently sized glass fibre. Secondly, POF based strain sensors will have less of a reinforcing effect when embedded in some compliant structure, so they are less likely to disrupt the strain field in the surrounding medium.
- Weight. Polymer fibres are almost half the weight of an equivalently sized glass fibre, though there are few situations where weight is likely to be the deciding factor in choice of fibre.

- Chemical resistance. Generally, polymer fibres are at a disadvantage as they can be attacked by a number of chemicals. One potential advantage though is the affinity some polymers (including PMMA) have for water. The absorption of water is an equilibrium process with the amount of water in the fibre being determined by the degree of saturation with water of the surrounding environment. The process seems to be reversible and repeatable and the absorption of water causes both a swelling of the fibre and an increase in its refractive index, which can be easily monitored using, for example, a fibre Bragg grating (FBG) sensor[18]. Where sensitivity to water is undesirable, optical polymers are available that exhibit negligible water absorption, such as the cyclic olefin polymers/copolymers Zeonex and Topas[19].

Table 1: Comparison of properties of silica and PMMA.

Property	Silica fibre	Citation	PMMA	Citation
Density	2200 kg/m^3	[20]	1170-1200 kg/m^3	[20]
Modulus of elasticity	72 GPa	[21]	~3.3 GPa	[22]
Absorption @600nm	5 dB/km	[23]	100 dB/km	[23]
Absorption @800nm	1.5 dB/km	[23]	>1000 dB/km	[23]
Absorption @1300nm	0.23 dB/km	[23]	>1000 dB/km	[23]
Absorption @1550nm	0.2 dB/km	[23]	>1000 dB/km	[23]
Chemical resistance	Highly inert to most chemicals. Attacked only by a few substances, such as hydrofluoric acid and potassium hydroxide.	[24]	Attacked by high concentrations of oxid acids. Soluble in ketones, esters, aromatic and chlorinated hydrocarbons. Can absorb up to 2% water.	[20, 22]
Failure strain	5-10%	[25]	Up to 100%	[15]
Temperature limit	Melting point ~1700 °C	[26]	Glass transition temperature - 105 °C	[27]

- Concentration of solution. This is another feature of the water affinity of PMMA. Consider the situation where the POF is surrounded by pure water, so that once equilibrium is reached the fibre is fully saturated with water. If a solute is then added to the water, e.g. NaCl, then osmotic pressure will tend to draw some of the water out from the fibre to dilute the solution[28]. Once again this is an equilibrium process where the amount of water in the fibre depends on the concentration of the surrounding solution. This effect has been demonstrated with both salt and sugar solutions. It follows from this description though that, whilst this effect offers good potential for sensing solution concentration, it is non-specific in nature.

- Failure strain. Carefully handled silica fibres can survive strain of several percent and for many applications in strain sensing this is easily sufficient. However certain materials, e.g. plastics, can survive much higher strains and for monitoring structures fabricated from such materials, POF based strain sensors may be attractive. Depending on the drawing conditions, POF can survive strains in excess of 50%[15], though it needs to be born in mind that such strain levels significantly exceed the quasi-elastic regime, so that POF strained to this degree will not return to its original length when stress is removed.

- Minimum bend radius. Related to the higher failure strain is the ability of POF to tolerate a smaller bend radius than a silica fibre of equivalent diameter. This could be advantageous for bend sensing but is more of a positive feature when it comes to the installation of optical fibre cables.

- Temperature sensitivity. The very large negative thermooptic coefficient of PMMA means that sensors relying on the monitoring of the optical length of fibre, as is the case with interferometric or FBG sensors, exhibit a much higher sensitivity than their silica counterparts. Of course, when sensing other measurands, the large cross-sensitivity to temperature can be highly undesirable.

- Ease of handling. This is a rather qualitative factor, that reflects the general ease of use of POF and encompasses several components. It is associated with conventional, large core diameter (highly multimode) POF and not with the rather more exotic single mode POF typically used for interferometric and FBG sensing. Large core POF can be cut-to length and terminated with simple, low-cost equipment requiring no special skills. The typical use of visible light sources with POF simplifies trouble shooting of connectorized links. As noted earlier, the tolerance of POF to small bend radiuses can simplify installation in confined spaces.

- Low cost. This is often mentioned as an advantage, but needs some qualification. The cost of POF is not necessarily cheaper than silica fibre, particularly when one considers single mode silica fibre, which, although requiring a very complex production process, is made in such high quantities (~500 million km in 2019 [29]) that economies of scale prevail. Cost can become an advantage when one considers the cost of installation, as mentioned above, and the typical use of low cost sources and detectors with POF. It is likely that for sensors, the cost of the fibre itself will not be the factor dominating the overall system cost.
- Biocompatibility. For biomedical applications, biocompatibility is often mentioned as a feature of POF based sensors. PMMA is already extensively used in medicine in dental devices, bone cements, intraocular lenses and bone screw fixations. Silica is also non-toxic, except when inhaled as a powder, when it can cause silicosis. When implanted in the body for long periods, silica will become surrounded by non-bonded scar tissue (an issue that has been overcome with the development of bioactive glasses) but this is unlikely to be an issue for a silica fibre based sensor system. Where POF may have an advantage is in situations where there may be a chance of fibre breakage and where, with silica fibre, such a breakage would likely lead to an irregular and sharp surface that could easily damage surrounding tissue. With regards to biocompatibility, for future research it should be mentioned that progress has been made towards creating implantable optical devices that will decompose safely in the body, offering the potential of inserting sensors to monitor the outcome of an operation, that would not need to be removed later [30].
- Surface chemistry. This is not something that has been widely exploited, but for chemical and biochemical sensing, it is often necessary to bind certain molecules to the fibre surface to provide a specific response to a target species. Binding to silica can be quite challenging, whereas the use of POF opens up the possibility of exploiting a wide range of organic chemical processes to modify the fibre.

2.2. Alternative fibres

A number of other polymers have proven to be suitable for fibre manufacture: properties of some key ones are listed in Table 2. Their use can be advantageous in certain situations, for example Topas, polycarbonate and Zeonex can be used at significantly higher temperatures than PMMA and are all much less affected by the presence of water in the fibre environment. CYTOP is a perfluorinated polymer, where the replacement of hydrogen with the much heavier fluorine atoms results in a shift of the absorption peaks to much longer wavelengths, meaning the loss in the NIR spectral region is orders of magnitude less than for conventional polymers.

Table 2: Comparison of properties of various polymers used for fibre manufacture.

Property	PMMA	Topas	Polycarbonate	Zeonex	CYTOP
Chemical resistance	Attacked by high concentrations of oxid acids. Soluble in ketones, esters, aromatic and chlorinated hydrocarbons. Can absorb up to 2% water. [22]	Resistant to hydrolysis, acids, alkalis and polar solvents. Attacked by non-polar organic solvents. Water absorption 0.01%. [31]	Susceptible to methyl alcohol, acetone, ketones, ethers, aromatic and chlorinated hydrocarbons, aqueous or alcoholic alkaline solutions, or ammonia gas.[32] Water absorption 0.15% [33]	Attacked by aromatic solvents, chlorinated hydrocarbon solvents, hydrocarbon solvents, ethers and ketones. Water absorption 0.014% [34]	Highly resistant but can be dissolved in fluorinated solvents. Water absorption <0.01% [35]
Glass transition temperature	105 °C [27]	Up to 180 °C [31]	145 °C [36]	123-156 °C [34]	108 °C [35]
Light absorption					13 dB/km @ 1300nm [23]

2.3. POF disadvantages

For balance it is important to note the advantages of silica fibre-based systems. Perhaps the main factor is of course the transparency of silica fibre, which for example enables sensing systems to function in some cases beyond 100km. Having said that, the far higher attenuation of polymer fibre is not necessarily such a great problem since the majority of sensing systems may well require fibre leads only of the order of 10m or so. If operation in the near infra-red is required, it is worth noting that the development of perfluorinated fibre has enabled low enough attenuation to allow fibre downlead lengths of many 10s of meters (see table 2). Alternatively, it is possible to attach short lengths of polymer fibre to a silica fibre to enable remote operation [37].

Other disadvantages of POF based systems are firstly, the much lower upper working temperature of POF than silica fibre, though as Table 2 shows, some polymers have significantly improved performance in this regard than PMMA; secondly, the chemical resistance of silica and thirdly, the fact that whilst the highly elastic nature of POF compared to silica fibre can be an advantage when wanting to measure forces or pressure on the fibre, it can be a disadvantage when trying to sense other measurands.

3. Commercialisation hurdles for POF based sensors

As noted in the introduction, silica fibre-based sensors exploiting a huge range of approaches to measurement have been commercialized; these include many quite sophisticated techniques, e.g. those based on interferometry, those making use of fibre gratings or those employing distributed sensing. In the case of POF based systems, commercial examples are few and far between. There are simple, extrinsic sensing systems, where the POF is just acting as a convenient “light pipe”, e.g. systems designed to detect the presence of an object on a conveyor belt in an automated manufacturing setting. There are even a very few more sophisticated examples, such as the POF based FBG sensing systems supplied by SHUTE[38]. However, these are all few a far between; so what is limiting the take up of POF based technology?

Reproducibility. Silica is a highly predictable and reproducible material, so the intrinsic sensing behaviour of fibre from different manufacturers will generally be extremely similar. This means that mass production of sensors requiring minimal (if any) individual calibration is feasible. This should be contrasted with POF based sensors where, as already noted, the physical and chemical properties can vary significantly depending on the polymerization process and the fibre drawing conditions.

Availability. Silica based fibre sensing system development and commercialization have for decades benefitted from the commercial success of optical communications, which has led to the development of sophisticated components and devices at reasonable cost. These include single mode fibre components, such as couplers, switches, isolators and circulators as well as a variety of active devices, such as laser or broadband sources, amplifiers and detectors. By contrast, due to its high attenuation in the NIR, POF is not well placed to take advantage of the 1550nm technology developed for communications, and in the case of single mode technology, some components are either difficult to source commercially, such as single mode fibre itself, or are simply not available, as is the case with single mode couplers or circulators.

Those intrinsic optical fibre sensors that are currently enjoying commercial success all tend to exploit fibre properties where silica fibre has an advantage. These include fibre gyroscopes, hydrophones and geophones, distributed sensing systems and FBG sensing, mostly relying on mature single mode fibre technology.

4. Conclusions

For the reasons highlighted in the previous section, it seems unlikely that POF sensors will displace silica fibre sensors where the silica-based sensors are already establishing themselves. The best commercial opportunities are likely to come in applications where one or more of the different material properties of POF are key. Although low cost is often mentioned when justifying POF sensor development, it is important to remember that ultimately it is the cost of manufacturing the whole system, including any calibration, plus installation and running costs that is important – not just the cost of individual components. This makes it challenging for POF sensors to compete with silica technology just on price – particularly when it comes to the more sophisticated intrinsic sensors.

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