POLYMERIC OPTICAL FIBRES AND FUTURE PROSPECTS IN TEXTILE INTEGRATION

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ABSTRACT

In the era of wearable computing, intelligent systems are breaking the bounds of traditional textiles and their design. The integration of the technologies with clothing, accessories, upholstery, or industrial technical textiles provides higher user-comfort and enables their seamless use in everyday activities. Polymer optical fibre (POF) materials are suitable for short-distance data transfer and can be combined with textile structures. The manufacture of the fibre is low cost, and the products are more durable than glass optic fibres. Applications for POF today are known in the automotive industry, consumer electronics, cabling, and measuring as optodes.
Polymeric optical fibre (POF) made of polymethyl methacrylate PMMA has been on the market for the past 25 years, used for simple light guide and data transmission application. Perfluor (PF) polymers offer great new opportunities in the field of data communication because of low absorption losses. Optical polycarbonate (PC), and polystyrene (PS) are used for special applications. The POF materials are introduced, and their opportunities in textile integration are discussed.

Key words:

Polymeric optical fibre, optical polymers, manufacturing, applications.

OPTICAL POLYMER MATERIALS

Du Pont developed the plastic optical fibre in 1964, and Mitsubishi Ryon later introduced the technology for it as a commercial product. Asahi Glass has recently introduced a perfluor polymer fibre with revolutionary properties which are suitable for broadband data transmission and telecommunications.

Tampere University of Technology studies POF manufacturing methods in the Technical Textiles laboratory of Fibre Material Science. Both extrusion processes suitable for simple light guides and fibre-drawn methods for data transmission applications are under investigation.

Many electronic functions can be built into textiles based on low-tension electrical connection. However, limitations related to electromagnetic disturbances and moisture are evident. In contrast to the electric connections, light transmission is not affected by the defects of physical surroundings.

The light wave-guides may be prepared of silica glass, which are very efficient for data transmission, especially at long distances. In contrest for short distances ranging from a few to dozens of meters the dominant technology may be an overkill. In textile integration, POF is a reasonable choice because of its high mechanical flexibility and durability.

Wave-guides

Flexible wave-guide device solutions are only feasible through the use of optical polymers and, optionally, polymeric optical fibre (POF) solutions. Different kinds of flexible circuits are thus possible, even to the extent of locating them in technical textiles. Most important in the field are the flexible bus connectors between different electric devices.

The refractive profile for fibre has the highest refractive index in the core to conduct the light inside the fibre. The large difference in refractive indexes on the fibre surface leads to high diffraction losses. Thus, it is feasible to have at least one lower refractive index layer on top of the core, which is called the step-index. See **Figure 1.** When more than one layer acts in series to reduce refractive index as a function of increasing radius, the construction is called a multi-step-indexed fibre. Finally, when there is a smooth parabolic change in the refractive index, the construction is graded indexed GI.

The POF for data transmission applications typically have dimensions of 125-980 microns, when the light guides are markedly larger, say 2-5mm in diameter. Typical cable constructions are simplex, doublex, and multicore, which contain one, two, or multiple sieves of smaller fibres respectively.

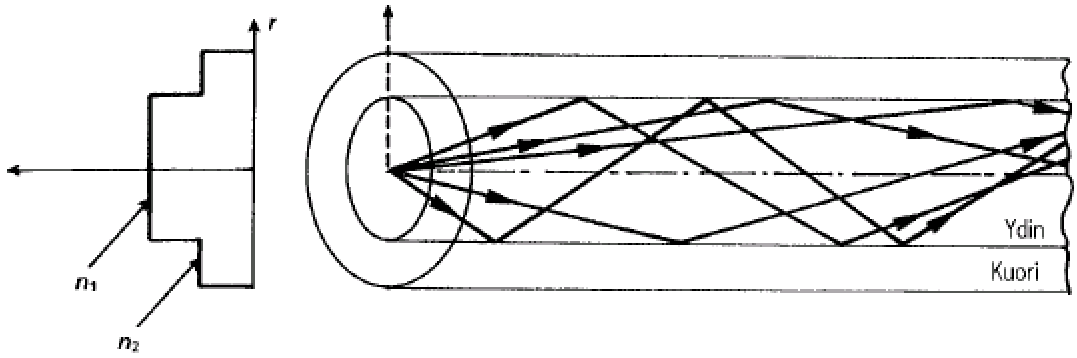

Figure 1. The principle of step-index (SI) - fibre is based on refraction on the boundary

There are also special constructions for back lighting elements *inter alia*, which can for example be the square of the cross-section. One side of the wave-guide is a reflector, which causes light leakage on the other side. Another technology producing a planar lighting element is the even waving of several optic fibres. In the waving knot points, the bending causes the light to leak out. See also **Fig. 8.**

Holey optical fibre

The newest developments are related to fibres which act optically as crystals. The fibre bundles in well-defined structures provide the macro-fibre with attractive non-linear optic behaviour. These fibres have recently also been manufactured from polymeric optical materials /18/. The area of application for these constructions has still to be found. See **Figure 2**.

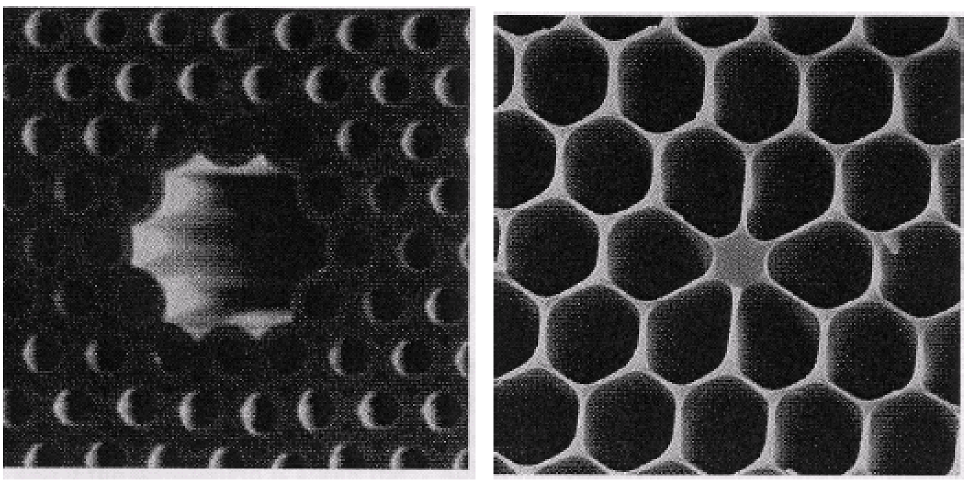

Figure 2. Crystal fibre may be either holey in the middle or contain a honey-comb structure.
(Ref. *Scientific American*, Dec 2001.)

Polymethyl methacrylate

Polymethyl methacrylate (PMMA) has a high transmission rate (98% over 3 mm) with a single window at 550-650 nm wavelength suitable for optic fibre communication at theoretically 55 dB/km @ 570 nm, and typically 100-500 dB/km (see **Table 1**). As a homopolymer, PMMA has a refractive index of n_D=1.492. Combining low molecular weight dopants (LMC) may affect the refractive index. Doping the system will evidently increase light scattering, and is a major risk for the long-term stability of the system. For details of the properties, see **Table 2**.

Alternatively, copolymers of fluorinated MMA monomers can be utilised. The advantage of this is that the chemical structure is permanently defined, but the manufacturing procedure of the preform is decidedly more complicated and time consuming.

PMMA has favourable rheological properties for drawing the fibre out of a preform. The glass transition temperature for PMMA homopolymer is 105°C. The drawing can be done at reasonable temperatures of 175-220°C, depending on the composition. These properties even make direct extrusion process possible.

PMMA is stable when used at up to +85°C in dry air. Higher temperatures, especially in humid conditions, cause rapid degradation of the polymer and reduce the service life to a few thousand hours. In the ambient conditions of normal premises, however, the service life expectation is predicted to be 20-30 years when copolymers are used.

Perfluorinated

Perfluorinated (PF) amorphous polymer materials n_D=1.335-1.344 are based on totally fluorinated diene monomers or copolymers thereof. The excess carbon-hydrogen bonding means an attractive absorption window of between 650-800 nm and around 1300 nm, excluding 1170-1230 nm. The fibre losses in this region are theoretically 0.3 dB/km, and typically 5-10 times that.

The most widely known PF is commercial CYTOP™ polymer, a chain with a serial ring structure on the backbone that leads to an amorphous structure and no diffraction on the crystals. The molecular orientation of the polymer is helical, providing excellent optical properties. The low attenuation of CYTOP™ means a marked improvement in bandwidth. See **Figure 3.**

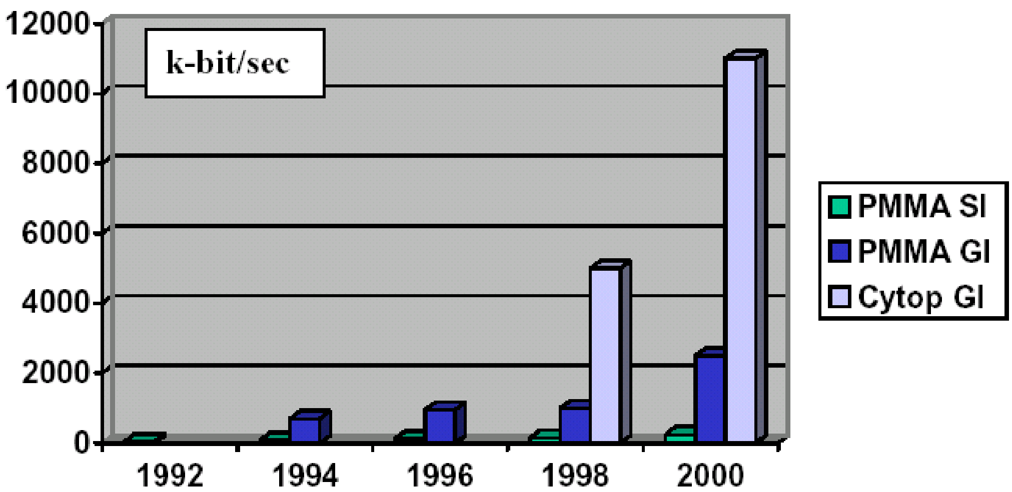

Figure 3. CYTOP™ and graded index structure increased the POF band width from 150 k-bit/s up to 11.5 Gbit/s in one decade of time

The melt processing of PF is a highly delicate task, while the processing window for fluorinated polymers is narrow. Additionally, the products of degradation processes are both corrosive and toxic.

For this reason manufacturing process takes place under highly controlled conditions typically in the interfacial gel polymerisation.

PF has minimum water diffusion. The fibre does not absorb water, and consequently increases its attenuation. Neither is its chemical structure affected by moisture, and thus does not degrade in a humid environment. Furthermore, PF materials have excellent chemical resistance to substances like sulphuric acid, sodium hydroxide and benzene. The only drawback in comparison with PMMA is in the case of freon, e.g. CFC-113.

The mechanical properties of different PF materials are insufficiently reported, but they do resemble those of PMMA systems, or 20% less tensile strength at typical usage temperatures of -40 to +85 °C.

Polycarbonate

Polycarbonate (PC) (polymers and copolymers of bis-phenol A) with refractive index n_D=1.58 and glass transition temperature of 150 °C can be utilised at higher temperatures than PMMA; say, – 40-120 °C. PC is also less sensitive to moisture than PMMA. However the attenuation properties are worse, say 700 dB/km @ 570 nm. This limits its use in special applications such as outside the passenger compartment in an automobile. Mechanically PC is as durable as PMMA, with break strength of 17.7 k Psi at 10.8% elongation (6.3% for PMMA).

Polystyrene

Polystyrene is less attractive for data applications than PMMA, due to its rather worse attenuation of 90 dB/km, compared to 55 dB/km @ 570nm. Glass transition is very much the same, namely 105°C, but the refractive index of n_D 1.59 is closer to the typical value for PC. See attenuation profiles in **Figure 4**.

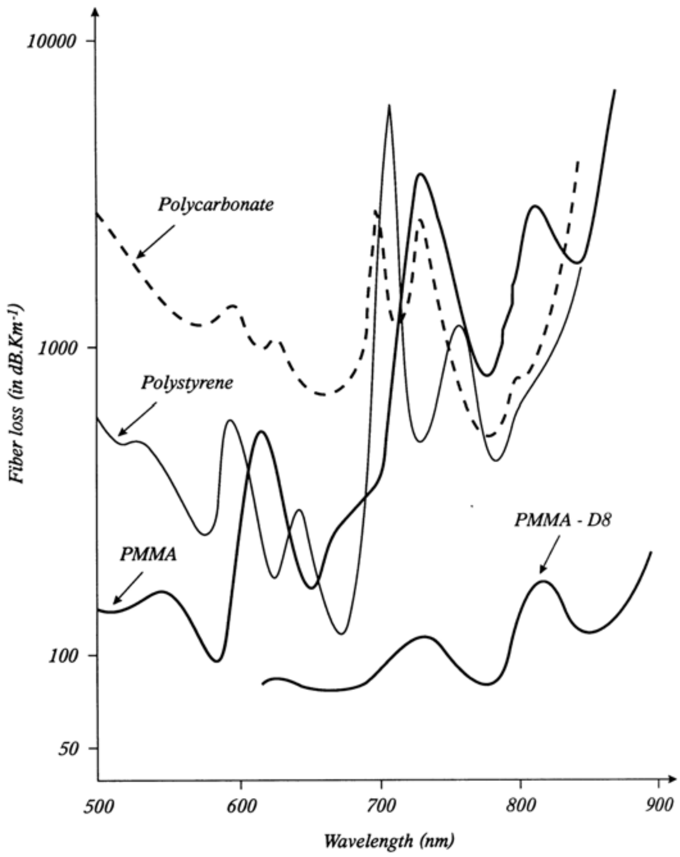

Figure 4. Different plastic materials have variations in attenuation

Polyolefin materials

The polyolefin materials can be considered as alternatives for special uses, typically in illumination. Impurities limit the usage of other materials than those mentioned above in data transmission and telecommunications applications. The polyolefin materials PMP and cyclic olefin copolymers (COC) have refractive indexes of n_D=1.46 and 1.53 respectively. The cyclic olefin copolymers contrary to PMP have shown worse extrusion properties than PMMA in The Tampere University of Technology (TUT) extrusion tests. /13/

MANUFACTURING METHODS

The extrusion process is simple and can be used for single and step-index fibre. The target in manufacturing the preform is actually to form the right refractive index profile in the preform before the actual fibre drawing process.

The optical qualities of polymers, especially for data applications, should be formed on site with fibre drawing in order to avoid unnecessary contamination. All the monomers used have to be purified of oxygen compounds, moisture, metal chelates, and other light absorbing substances. The methods used are vacuum distillation and different absorption masses. It is also advisable to initiate polymerisation with azo-initiators instead of peroxides. /14/

Extrusion

Extrusion is sensitive to contaminations and variations in layer thickness of the fibre construction. Thus, the process is suitable for less demanding applications. With a single extruder, it is simple to produce a single fibre, typically with a monofilament spinrette. Step-index fibres are produced with centre core-cladding tooling. A typical performance level for POF of kind is 400 Mbit/sec at distances of up to 100m, but not limited to that.

In the extrusion process the fibre can be directly formed close to its final diameter. However, the extrusion process is limited through tooling pressure with the small fibre dimensions. Simultaneously the fibre draw-down has to be kept in reasonable limits, while a draw-down ratio >4 may affect the optical properties trough crystal formation. Thus the dual step drawn process (Peachtree) is favourable.

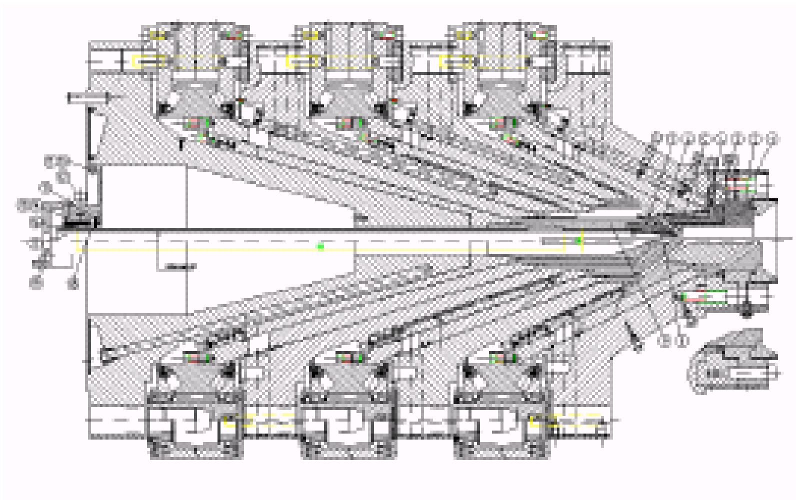

Figure 5. Conical extruder cross-section for the multi SI fibre, with core and 5 claddings

The extruder can be fed with pelleted polymer, but polymer formed in-situ in a special feeding device reduces contamination level. Over the past few years, Conex Cables Oy has collaborated with others to develop a unique new conical extrusion technology. As an exception to conventional extrusion, this technology enables multiple concentric polymer layers to be extruded with a compact machinery solution. One potential application arising from this capability is the production of graded index POF. See **Figure 5.**

To our knowledge, there is currently no commercially viable method for the continuous production of graded index plastic optical fibres. Theoretically it has been calculated that the number of layers needed to successfully imitate the graded index is around 15-20 layers. Two conical extruders with 3 rotor extruders in cascade are able to produce up to 12 layers. In practice, a core with only 3 claddings has been made, but the construction is sufficient up to 1 Gbit/sec at 100m. /13/ In our TUT Fibre Material Science, an SI fibre with conical extruder cascade has been made. The extruder used is shown in **Figure 6**.

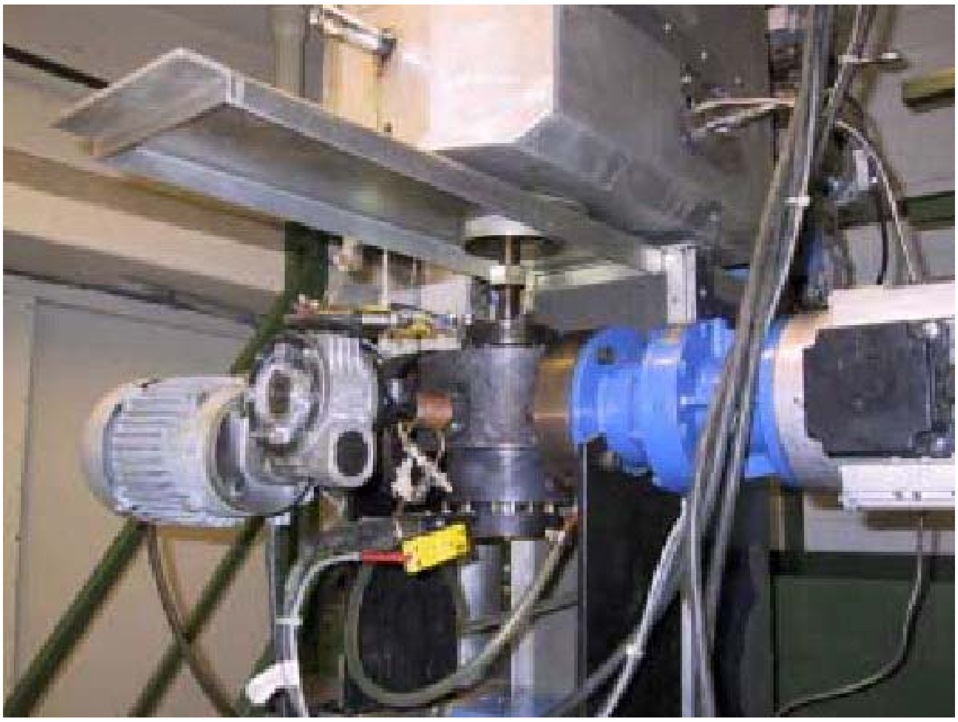

Figure 6. Pilot extrusion set-up for SI-fibre in TUT Fibre Material Science

Thermal bulk polymerisation

Bulk polymerisation of MMA and co-monomers in a rotating horizontal tube makes it possible to produce co-centric optic polymer tubes. The most practical way is to place the tube in a lathe rotating at, for example, 450-900 rpm. The time required for 100% conversion is 24h at 90°C, during which time the pressure in the tube has to be at least 25 bar (gauge). The function of the pressure is to avoid bubble formation.

The bulk polymerisation process is time-consuming. This is especially true in the case of multiplayer preform manufacture. However, thermal bulk polymerisation is suitable for simple preform core manufacturing. /14/

Photo polymerisation

Photo-initiated polymerisation is widely used, but is more typical for planar solutions requiring masking techniques. The advantage of the method is that it is very fast compared to thermal methods. The disadvantage, however, is that the initiator typically stops at a comparably low conversion, and removing the unreacted monomer minimises the former benefits and results in increased monomer consumption.

Photo polymerisation requires the right choice of initiator in order to achieve at least a reasonable monomer conversion. The outside vapour deposition OVD process is more suitable for photo polymerisation. Both are results of limited radiation penetration; typically UV @ 365-400nm is effective to only <0.1mm depth. Only very thin layers are possible as well per time. /14/ The principle of preform is expressed in **Figure 7.**

Should a step index fibre be produced, the single core can be coated with a primary coater while the core is produced. The monomer for cladding is added on the ready fibre size core and UV cured.

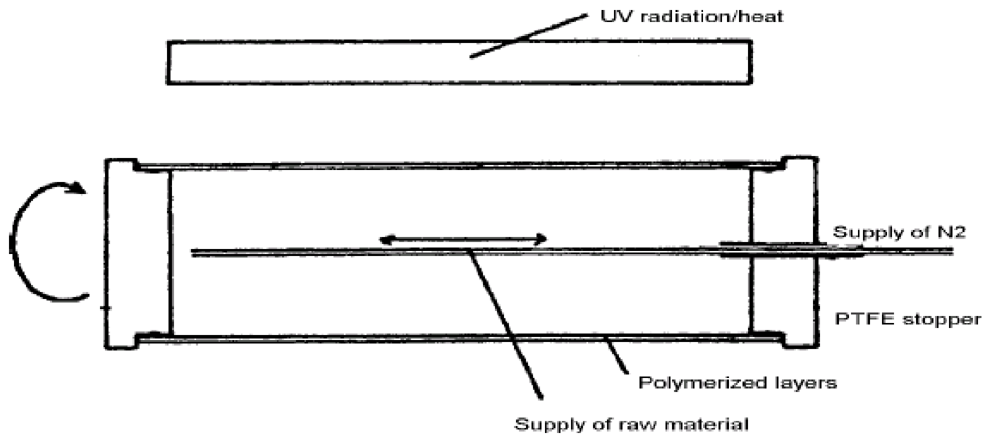

Figure 7. Preform is drown layer by layer in rotating tube and the radiator initiates the polymerisation reaction (Ref. WO87/01071)

Chemical vapour processes

The methods for manufacturing GI-POF are based on manufacturing a pre-form in a separate process, which is then continued in the fibre drawing process. The preform manufacturing processes are adopted from the production methods for glass fibre. The CVD (chemical vapour deposition) in glass tube is a typical solution.

Interfacial gel-polymerisation

The basic idea of this method is to imitate gel-effect conditions, in which the high viscosity of the reaction medium considerably reduces the rate of chain breaking and results in the growth of polymer chains. Under these conditions the refractive index profile can be affected.

The polymerisation takes place in a horizontal tube of transparent polymer with a low refractive index, such as PMMA, that must be fully compatible/soluble with the polymer formed inside. The formation of the 10-70 mm tube is made at 70 °C and at a high rotational speed of 1000-3000 rpm in the presence of a monomer, initiator and chain transfer agent.

Co-monomers are added in the actual polymerisation phase, and the gel formation is controlled at temperature in the range of 60-95°C. The hold-up time for the initial phase is typically 6 hours, after which rotation is continued for the next, say, 20 hours. Different combinations of parameters can control the refractive profile.

After polymerisation, the preform is held in a vacuum of approximately 0.2mm Hg at 80°C for 20 hours or more. During this period the content of residual monomer diminishes, and the pre-form collapses under the forces of surface tension.

There are several derivatives of the basic construction. In one invention, a pin is also rotated in the middle of the polymerisation vessel. The apparatus causes a Coulette flow, which makes formation of the graded indexed structure more controlled.

Fibre drawing

The actual fibre drawing takes place in an induction oven at 160-280 °C. The drawing procedure is controlled by a diameter control unit, which regulates the tension rollers. The process is thus remarkably similar to glass fibre drawing. Originally 35-50mm preforms are used, but possibilities up to 100mm have been studied. No fraction of a preform is allowed to have monomer conversion lower than 99.5%, while too high a free monomer concentration in the fibre drawn process would cause gas disclosures.

The drawing oven is typically an electrically heated open resistor type of round oven. It has also been proposed to replace this with an infrared oven, in order to overcome problems related to the poor thermal conductivity of the plastics. The diameter of the perform, as well as the fibre drawlength after it, are limited due to the insulating properties of the optic polymer preform. Our experience with a special IR oven is promising, while the melting time constant is in magnitude of 50-70 seconds with 40mm preforms and 2-2.5 kW input power. When 1.2 micron wavelength is used, radiation penetration depth is more than 10mm, which reduces the heat transfer and conduction limitations. The possibility of shutting down the heating power increases the safety. However, a protective gas ??[cover/filter]] at the oven section is recommended to avoid surface oxidation. /16/

Table 1. Attenuation properties of typical PMMA fibre, core 980∝m

	650 nm				1300 nm
	α_1^{iso}, dB/km	α_2^{iso}, dB/km	α^{aniso}, B/km	α^{total}, dB/km	α^{total}, dB/km
Un-doped	12.5	0	6.2	18.7	1.2
Doped	15.4	75.6	70.6	161.6	10.1

Table 2. PMMA modified fibre properties

POF	Draw T oC	Yield Strength kgf/cm^2	Tensile Strength kgf/cm^2	Elongation %
SI-POF	(220)	970	1040	67
MMA-BZMA	190-250	1060-712	1620-634	33-9
MMA-VB	190	737	638	7
MMA-BB	175-195	-1170	2050-1340	39-34
MMA-BBP	190-195	1260-960	1880-970	43-51
MMA-BEN	200	1052	1092	36

APPLICATION

Integrating electronic equipment into textile products may mean some revitalisation of the industry. Essential for POF in the field is whether consumer electronics apply the optic data channels to a greater extent. With POF, the data transmission systems may be manufactured in a markedly more robust manner than today's standard solution.

The application spectrum of POF has increased, and is developing towards technically more demanding solutions simultaneously with continuing improvements in the performance of the materials and their manufacturing methods. New polymeric materials have even been introduced, such as the previously mentioned amorphous PF in data communication fibre, or polycyanurenate as an alternative for UV curable fluor-acrylate in optical wave-guide devices. See table 3 for three different application areas.

As for communication applications, the actual growth potential in the fields of the automotive industry, consumer electronics, and later in local networks have been indicated. Special applications such as optodes and photonic sensors may also find some advanced technical applications. /15/

Table 3. POF application areas

	Illumination	Commercial	Communication
Diameter (μm)	100-5000	250-2000	500-1000
Diameter tolerance	25 %	<10 %	<10 %
Cladding	Not critical	Critical	Very critical
NA	Not critical	0.3-0.65	0.5
Attenuation	3-5 dB/m	0.5 dB/m	0.25 dB/m
Heat resistance	60 °C	70 °C	85 °C

Illumination and wave-guide applications

Fibre optic systems are used today for lighting, decoration and sign applications. It is thus simple to show different colours of light in a tight screen area, when the actual light source that emits heat can be located separately. Some POF systems emit light along the entire cable. Materials that emit visible light through fluorescence or scattering can be added to the fibre. Side-emitting fibres are commonly used in the lighting of architectural and contour buildings, hotels and entertainment centres.

In public premises and leisure areas, there is a need for light guides due to complicated routing or limited lightning. Today many of these solutions are based on bulky lamp rows or less effective taping solutions. Optical fibre makes it possible to build this function into carpets and suchlike in a most sophisticated and space-saving manner.

Light guide illumination is useful in hazardous and explosive environments. High-voltage tube devices can be replaced with fibre, thick fibre or rods. Changing particle size and concentration can even control light emission in large core-size 10mm bulky rods of POF. The material is manufactured by means of adding micro-spherical beads during the synthesis of the rods. To a certain extent illumination fibre material can be added to fabric structures. Weaving the POF into the fabric makes light leak out of the fibre, and planar flexible lighting elements can be fabricated [19]. See **Figure 8.**

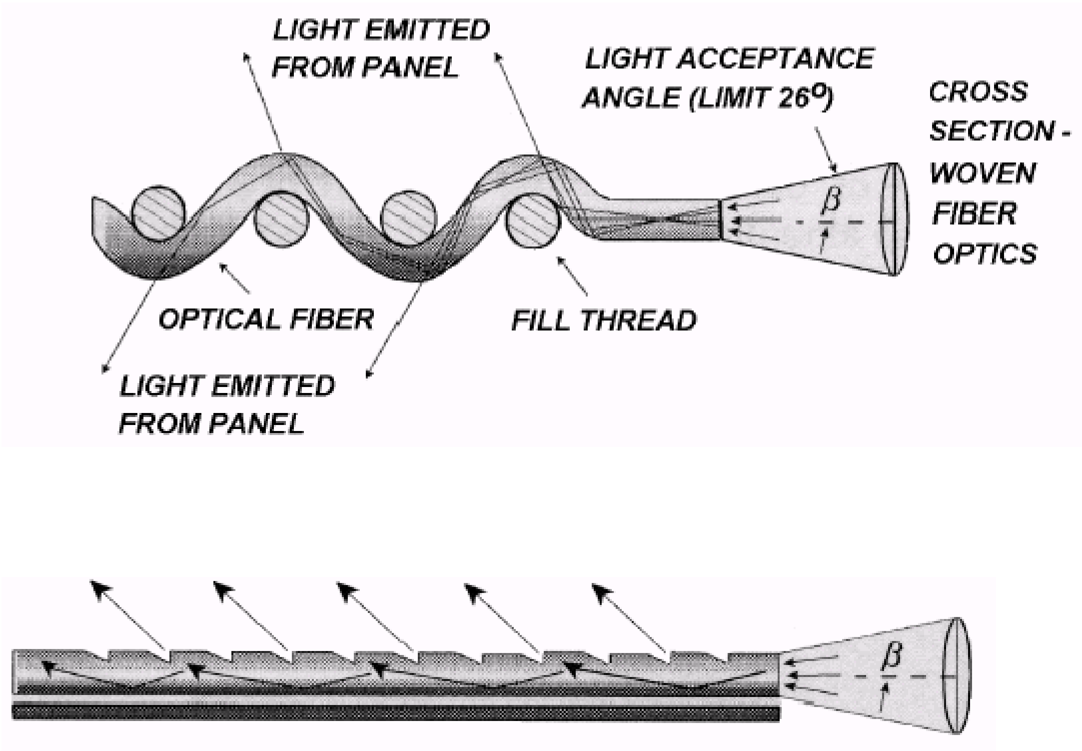

Figure 8. POF in weaving emits light, and fabric with light emission can be made, or alternatively the surface may have an abraded construction. www.lumitex.com

Sensor applications

The photonic sensors, optodes, can be located up to 100 meters away from the measuring device. No electric transmission is necessary, while the optodes either produce light for indication through luminance reactions or affect the light transmission. Electric fields, magnetic fields, radiation, moisture, harsh chemical conditions, or even high temperatures do not affect measurement.

Optical (bio-) chemical sensors are devices that convert a (bio-) chemical state into a signal via a transducer. The chemical state may be in gaseous, liquid, or solid phase, and the output signal is typically electrical, used for measurements or controlling an actuator. In the majority of optical sensors, the transduction steps are:

Electrical-optical-chemical-optical-electrical

The chemical to optical step includes chemical reactions, molecular recognition, and transferring a chemical signal into an optical signal, using indicators for example. The actual size of an optode is typically 1-3mm. With the optode chemical concentrations, pH, moisture level, temperature, and different biological species can *inter alia* be measured /17/. See **Figure 9.**

Intelligent filters make the chemical, pulp, or biochemical processes more adaptable to the process dynamics and fluctuations. The process stream can be analysed by the optode while filtered, and the filters can even be controlled by the process control systems.

The high flexibility of POF and the limited size of the fibre have made it possible to locate these sensor functions in technical textiles. It is entirely feasible, for example, to measure different concentrations of the process stream as it passes the filtering process.

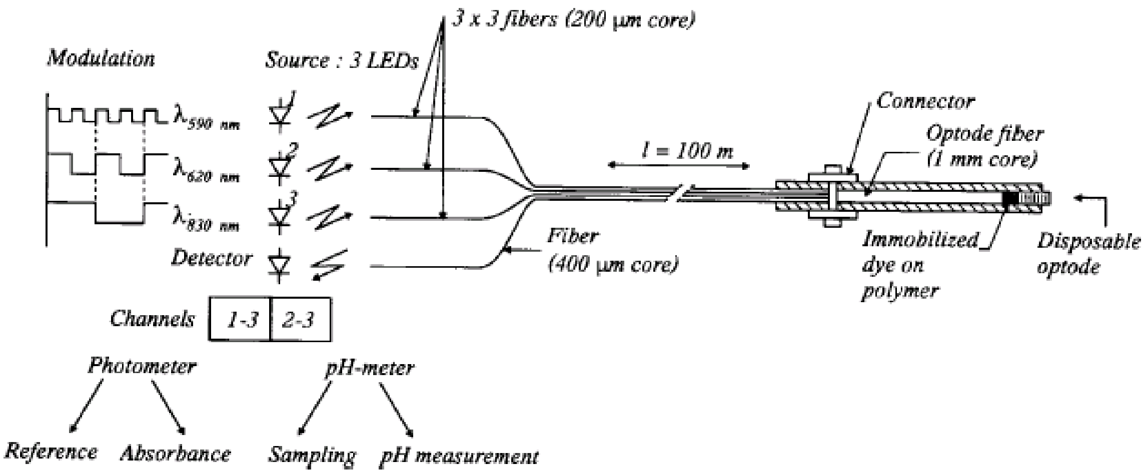

Figure 9. Optodes contain typically 1-100m of POF, a measuring cell aching optically in changes in the environment, and a reflector sending the measuring light beam back through the fibre

Consumer electronics

The novel IEEE1394 a/b standard, even more than the old standards, provides us with the possibility to create point-to-point networks between digital devices. Typical applications are found in play consoles or audio systems. Furthermore, office automation will increase POF usage in fire wires. Since the flexibility of the other optical systems is limited, POF has been studied. The 125-micron core diameter has been proposed as a compromise between the packing density and the actual device alignment, when the optimum for data transfer is in the core size range of 60-70 microns. Optical pathway blocks of 8x8 and 4x4x8 have been built with very low losses; namely, <20 dB/10 cm at 660 nm and a bandwidth of up to 10 Gbit/s.

Automotive applications

Although Mercedes Benz has been the pioneer in this field, within a few years most producers will adopt the technology, mainly in top-end vehicles. The automotive industry has applied the D2B standards to provide noise-free infotainment inside the passenger compartment, and has adopted the MOST standards. A typical requirement is 150 Mbit/s and 30 m, but 500 Mbit/s will come as IEEE1394 automotive standards are introduced.

Flat flexible cable hybrid design is one area of interest. The development opens the door for fabric-integrated solutions as an alternative to FFC. It would then be easy to integrate the data bus connection into the decorative textiles on the car body. The targets for this are installation simplicity, weight savings and integration. The need for different kinds of flat displays and illuminations is also increasing.

Multimedia & telecom applications

POF in multimedia and telecom are applicable to the final of the data highway. The competing technologies in the home and office network are RF copper cables and specific OF (miniature glass fibre cables).

POF's advantages include their low weight, inexpensive costs, and simple installation. Disadvantages are related to limited bandwidth, such as 400 Mbit/s over 100m. As an optic media the POF is insensitive to electrical and magnetic noise, thus competing with copper. There is additionally an application in data connections, when the silica OF is a technical overkill.

Optical fibre application in textiles

There is active research related to intelligent clothing. The applications combine electronics and information technology with textiles. This began with military applications, but later the solutions have been combined into leisure products and safety clothing.

Wearable computing additionally makes it possible to integrate data and telecommunication devices, play consoles, or even full time control of life functions. Polymer optic fibre applications can reasonable be expected in interior textile integration, typically in automotive vehicles and public buildings, where the data channels are to be hidden. In lighting, the new LED sources may reduce indication light use of POF, and niche architecture solutions are left.
However, the most attractive future applications are in field of para-textiles, such as chemical measurements in filters in use. As another example, we may refer to measurements integrated in different insulation constructions. When in combination with the technical textiles there is a need to measure very small volumes and aggressive environments on-line, especially chemical states, the optodes provide solutions.

CONCLUSIONS

POF technology is developing in step with the advances in electronics and communication technology. As a communication application, the actual growth potential in the fields of the automotive industry, consumer electronics, and later in local networks is indicated. There are also separate developments in the fields of sensors and illumination. Special applications such as optodes and photonic sensors may also find some advanced technical textile applications.

Essential for POF is the question ofwhether consumer electronics apply the optic data channels to a greater extent. With POF, the data transmission systems may be manufactured in a markedly more robust manner than today's standard solution. Advanced systems will be integrated with decorations, upholstery and automotive interiors, where POF is flexible and compatible with these constructions. The driving force should be higher user-comfort, which enables seamless use of the technology in everyday activities.

Furthermore, the measuring solutions in para-textile applications contain obvious possibilities. Optodes can be integrated into demanding environments, in small spaces, and not least without the necessity for electricity conduction and tension inside the textile.

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