DEVELOPMENT OF POLYMERIC OPTICAL FIBRE FABRICS AS ILLUMINATION ELEMENTS AND TEXTILE DISPLAYS

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ABSTRACT

Polymeric optical fibre (POF) is used for simple light guide and illumination applications. The polymer optical fibre materials can be utilised in flexible lighting elements which can be combined with textile structures. The POF woven fabrics are introduced as a flexible alternative to lighting elements.

Various light-emitting woven fabric and light emission theories has been discussed. Simple poly-methyl-metacrylate PMMA and polycarbonate PC fibres have been produced experimentally through single-screw and conical extrusion. The fibre is integrated in woven structures by means of handloom, narrow fabric weaving and Jacquard technology. The manufacturing technology suitable for light-emitting textile applications and its opportunities in textile integration is discussed.

Keywords: *Polymeric optical fibre, light emitting weaving, illumination, and displays.*

BACKGROUND

Intelligent systems integration with clothing, accessories, upholstery, or industrial technical textiles should enable higher user-comfort and performance. Evidently optics should also be included among the possibilities.

Flexible display units may provide new possibilities for creative design in architectural and industrial art applications for public premises, vehicles, and other related upholstery. The woven optic fibre constructions introduced so far have been markedly too rigid and tough for wearable clothing. The field is more suitable for novel development of flexible displays based on polymeric light-emitting LED technology.

Plastic optic fibre for illumination

The main source of plastic optic fibre for illumination is core constructed with cladding, i.e. step-indexed (SI) fibre manufactured in the co-extrusion process. The fibre is manufactured in two stages: first, a macro fibre of 2 to 5 mm which is drawn in final dimensions; in the second, the melting phase [1]. Polymeric optical fibre (POF) made of PMMA, polycarbonate (PC), and polystyrene (PS) has been on the market for the past 25 years. The materials can be considered alternatives for special uses typically in illumination. Impurities limit the usage of materials other than the above in data and telecom applications.

Polymethyl methacrylate has high transmission (98% over 3mm) and also has the best window at 550 to 650 nm wavelength, with a refractive index of 1.492. It is typically used in combination with low molecular weight dopants (LMC). The PMMA is stable when used up to +85°C in dry air. Higher temperatures, especially in humid conditions, cause rapid degradation of the polymer and reduce the service age down to a few thousand hours. In ambient conditions of normal premises, however, the service life expectation is predicted at 20-30 years when copolymers are used [11].

Polycarbonate (polymers and copolymers of bis-phenol A) can be utilised in higher temperatures than the PMMA, and they are less sensitive to moisture.

Table 1. Critical values of structure and properties of various applications

Dimension, properties	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	3-5dB/m	0.5dB/m	0.25dB/m
Heat resistance	60°C	70°C	85°C

Optic fibre in woven structure

Total reflection on the inter-phase of two optic materials is simply defined by the refractive index n of each material. When the reflection angle φ is less than the critical, light will return to the same phase where it is coming from at an inverse angle φ'. This is called reflection, but when the angle φ is greater than the critical, an optic leakage will take place [2, 3]

$$\varphi_{Critical} = \arcsin(n_2 / n_1)$$

In woven structures, the weft bend angle α can be calculated when the dimension of warp and weft and the warp density are known [4]. Based on trigonometry, we have:

$$\tan \alpha = L / (2r + R)$$

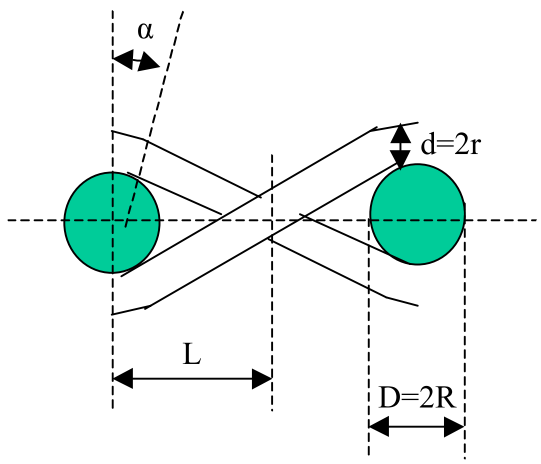


Figure 1. Schematic structure of a woven fabric

Based on the reflection law and system geometry, optic leakage will take place in weft when

$$2 \arctan L / (2r + R) > \arcsin(n_2 / n_1)$$

The model is simplified, and in the case of bent fabric the weft bend angle α will change as well in many complex ways. The effective area of light emission can be calculated, but only approximately and in a complicatedfashion. For plain 1/1 set, in modified form [5]

$$\mathbf{A = 1 -} (\phi/2 \ln [1+ \sqrt{1+\phi^{2}} /2] + \sqrt{1+\phi^{2}} /2\phi - \rho_{Warp} D - \rho_{Warp}\rho_{Weft} d^2 \sqrt{[1/\rho_{Warp} - D/d]^2 + 1})$$

Where	ρ_{Warp}, ρ_{Weft}	=	warp and weft density respectively
	ϕ	=	$1 / [\rho_{Warp} (D + d)]$

This, like the empiric result , indicates high light leakage which is already great in the first knot points, meaning great complication in adjusting steady lighting over the whole woven structure. Light emitted on the seamy side is also obvious. Some improvement will be reached with 2/1 to 5/1 structures.

Warp is an object in the woven fabric whit is significantly less able to bend than weft, and it is thus able to conduct light for longer distances in a given construction. Under lateral compression, such as that caused by weft tension forces, linear birefringence will be induced based on the strain-optic relationship, as shown below [6]:

$$B_1 = [(4n_2^3 f)/ (\lambda E \text{ R})] (1 + \nu)(p12 - p11)$$

where	λ	=	wavelength
	E	=	Young's modulus
	ν	=	Poisson ratio
	(p 12 – p 11)	=	strain optic tensor

Fibre sensitivity to torsion is small, although the polarisation response to torsion is significant. The torsion introduces shearing stress in the cross-section of the fibre, ultimately causing light wave-plates to rotate, and the azimuth ϕ to be changed.

Tension response to linear and circular birefringence is close to zero deformation.

Emission on the cladding

Emission control with geometry is complicated, especially when the weft is used as a light-guide. Alternatively, using an optic fibre with light emitting cladding as a warp is more favourable. The basic alternatives are either to scratch the surface or to include fluorescent material on the cladding [7].

In the case of controlled shatter surface, we enter the phenomenology of crystal reflections. A surface able to emit light in a controlled way has to have reflective surfaces in a harmonic lattice with a dimension which fits together with the used wavelength λ. The possibilities include very accurately manufactured dints, whose sizes and distances are in multiples of $\lambda/2$. Any notch or scratch may be too coarse and lose the whole light power at a single or a few points. In practice, the construction would be complicated to manufacture, and should be covered with mechanically protective cladding of a relatively low refractive index $n_{cladding} << n_{core}$.

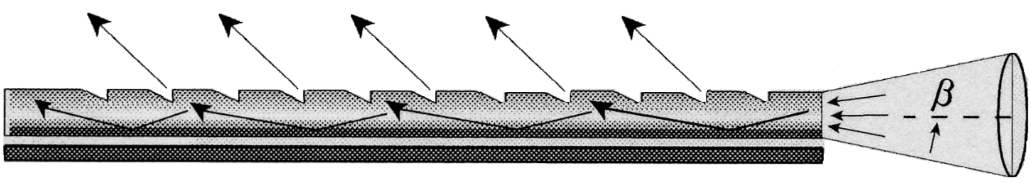


Figure 2. Optic fibre with dints

Thus, light emitting materials are a practical alternative to cladding. . In the cladding the light mode meets the active orbital, causing a state of excitation, which in time emits photon. Control of the emission is markedly better. The remaining questions are the correct layer thickness of the cladding in the magnitude of wavelength λ, and secondarily its wear resistance. The optic fibre material PMMA is UV radiation-sensitive, which favours photoluminescence instead of UV fluorescence.

Back lighting

In the application of back lighting, electronics has adopted the technology of rigid planar elements, manufactured on the basis of different atomic layer technologies. The disadvantage of such components is their relatively high manufacturing costs and poor mechanical robustness. Additionally, the liquid crystal film used as a dimming layer to form the patterns displayed is sensitive to low temperatures.

Woven back lighting elements have been commercially adopted in only a few applications, e.g. lighting for dental surgery. In electronic devices, fibre-optic back lighting is used for high brightness and low power 30ft-l and 10-20mA, combined with long lifetime (up to 100 000 hours) [8].

Alternative technologies for flexible displays are based on novel conductive and light emitting polymers. Research and development of polymer light emitting diodes P-LED is active. Constructions on flexible film substrates have been introduced. Most fascinating with the P-LED is the possibility of producing them with gravure printing, or alternatively with ink jet technology [9].

Mass illumination

The amount of light power which can be transmitted through a single optic fibre is directly related to the optic opening Na (and cross sectional area) of the fibre. For plastic optic fibre, the acceptance angle is typically large $\varphi_{Critical} > 35^o$, and the core dimensions are large, from 500 to 1800μm.

$$Na = \sin \varphi_{Critical}$$

Light power transmission also depends on the attenuation of the fibre. In plastic, the attenuation is even at its best 10 to 50 times higher than that of typical silica glass. However, the flexibility of plastic is superb compared to that of glass, especially at the temperature range 0 to 80 ^oC. PMMA becomes especially brittle at sub-zero temperatures.

Nevertheless, a limiting factor in the usage of POF in mass illumination is the light power threshold value which limits polymer degradation. Increasing the constant light power from 30-50mW/mm^2 will rapidly decay the fibre. Especially hazardous is the extensive UV component <400nm.

Transmission of bulk light power is thus complicated. However, the development of a holey fibre may improve the performance [10]. Intensive light sources can be obtained only at the end of the fibre. As a result of the factors mentioned, POF illuminations are suitable for limited signal panels and sign elements.

Signal panel prototypes

Optic fibre of 400 μm was manufactured by means of extrusion in the TUT Fibre Material Science extrusion line. Both traditional single screw Fourne and novel Conex technologies were used.

POF Extrusion

The material used for extrusion had MFR2 = 1...2 g/10min. The material was markedly higher in molecular weight and viscosity than typical fibre grades. The aim was to reach maximum toughness and tensile properties for the application. The fibre design was a simple monofilament, which was produced using a 1mm-round die targeting 400-μm fibre.

The fibre was collected using as little orientation as possible. Practically all orientation is caused by and crystalline structures that may cause light scattering in the fibre. The cooling of the fibre was also typically slow, using 1.5 m high cooling section and <25 m/min spinning speed. As a result, the fibre manufactured by means of conical extrusion showed better mechanical properties.

Weaving

In the woven prototype 400 µm PC polycarbonate fibre showed superior toughness. Commercially structured 1000 µm SI PMMA fibre and laboratory-spun 400 µm PMMA were used as a reference fibre. In this case, the fibre toughness is at the limit regarding the forces required for the process.

The first fabrics were woven by means of a handloom. The result most clearly showed the need for a high tensile force for POF as warp. The weaving speed has to be low, or the fibre should be warmed during weaving, in order to reach the required toughness for the process. The POF also slips due to its monofilament structure.

Prototyping was continued with a narrow fabric weaving machine. In this case, both the warp alone and warp and weft were of polycarbonate. The strength of polycarbonate was sufficient, but new complications were observed. Due to the non-oriented structure of POF, the fibres elongated under the required tension. Polycarbonate showed markedly reduced optic properties later in testing. When using POF as warp and weft, a positive shedding mechanism is needed to control the harnesses. It seems that the only possible filling insertion system in POF weaving is the positive rapier.

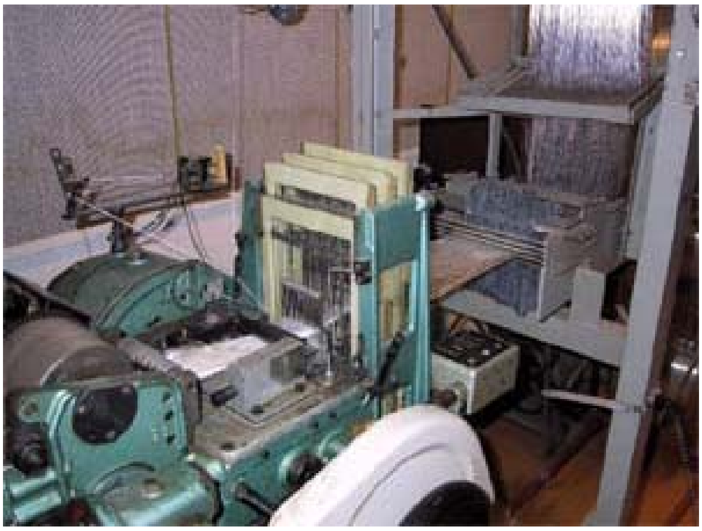


Figure 3. Narrow fabric weaving unit for POF fabric sample preparation in TUT

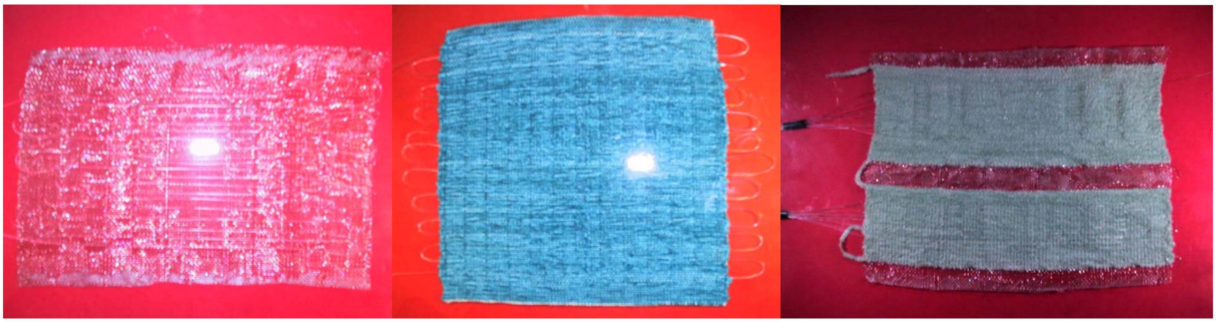
Utilising the polycarbonate POF as a weft in Jacquard weaving caused no marked problems. Several different sample fabrics were manufactured.

A
Warp: Trevira CS
Weft: Steel with POF (1.0 mm PC) floating
POF density: 9.0 fibre/cm

B
Warp: PES
Weft: Steel with POF (1.0 mm PMMA) floating
POF density: 1.3 fibre/cm

C
Warp: PES
Weft: Glass fibre and POF (0.5 mm PMMA)
POF density: 5.0 fibre/cm

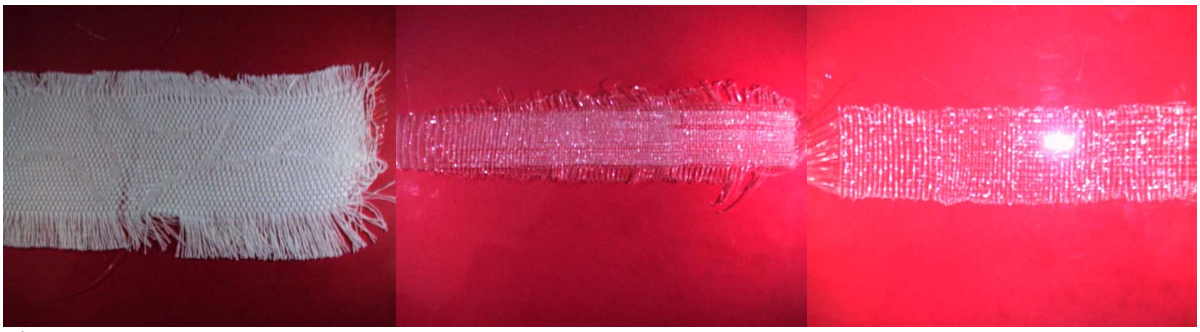
Typical of all the cloths produced was their toughness and considerably robust structure. This was understandable because of the POF monofilament size. However, the minimum diameter of POF which remains useful in the application is 60 or 125 μm, reducing the emitting light power per fibre to 5 to 20 per cent from the actual values.



D
Warp: Steel
Weft: Steel with POF (0.5 mm PMMA) floating
POF density: 2.9 fibre/cm

E
Warp: PES
Weft: Trevira CS with POF (1,0 mm PMMA) floating
POF density: 1.7 fibre/cm

F
Warp: Steel
Weft: Trevira CS with POF (0.5 mm PMMA) floating
POF density: 2.5 fibre/cm



G
Warp: CO
Weft: : POF (0.5 mm PC)
POF density: 18 fibre/cm

H
Warp: POF (1.0 mm PC)
Weft: POF (1.0 mm PC)
POF warp density: 20 fibre/cm
POF weft density: 8 fibre/cm

I
Warp: POF (1.0 mm PC)
Weft: POF (1.0 mm PC)
POF warp density: 10 fibre/cm
POF weft density: 6 fibre/cm

Figure 4A-I. POF woven structures: Samples A – F were manufactured by a hand loom, sample G by a Jacquard weaving machine, and samples H & I by a narrow fabric weaving machine

Finishing

The woven cloths were finished with different methods in order to produce optically active surfaces. The mechanically abraded structure was manufactured simply, first manually with sandpaper, causing extensive scratches on surfaces.

In order to control the procedure, Stoll abrasion testing equipment was utilised. Cloth was attached in the tester for a short period, 20 rounds, and the surface of the fabrics was abraded on one side.

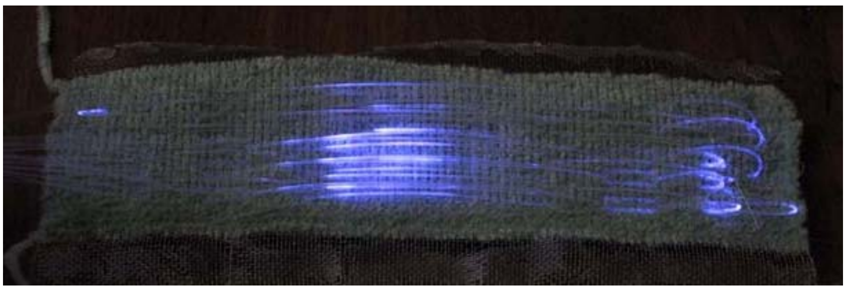


Figure 5. Fabric woven from steel (warp) and Trevira CS (weft) with Stoll abrasion treated 0.5mm PMMA POF weft floatings.

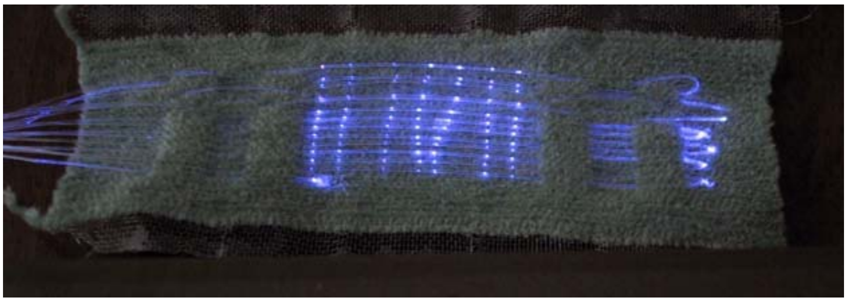


Figure 6. Fabric woven from steel (warp) and Trevira CS (weft) with 0.025mm notched 0.5mm PMMA POF weft floatings

Side notching was performed with a motion-limited press, equipped with a cutting knife of a particular shape. When closing the press, the knife cut the POF warp. The weft was not markedly destroyed while it had higher flexibility, and it was thus able to move under the knife, contrary to the tough POF monofilament.

Chemical abrasion was not tested; the required chemicals may also harm the weft fibre materials.

Results

Use of POF as a light-emitting weft proved impossible in most cases, because the warp is unable to carry the required tension for the creation of bend angle α. When reached, the bend angle α was already so extensive that it lost the light power in the fibre after the first 5 to 10 knots.

The abraded result was uneven, but indicated the theory to becorrect. In order to control the process, there is need to develop equipment suitable for this task.

Side-notching the POF weft made it possible to manufacture simple figures of light dots. When the light was fed from each side, it was possible to create figures with fairly high light power. The alternative is simple to perform, and thus possible to be used.

Fluorescent cladding was not manufactured in this test. However, the performance of the technology is known from references.

CONCLUSION

Illumination woven structures are used in only a few commercial applications, such as dental surgery light sources, and in back lighting applications when high brightness and low power are combined with long lifetime. Cloths with reasonable light emission are tough and considerably robust in structure.

Use of polymeric optic monofilament as a light-emitting weft is limited because of the complex control of the bend angle α. Light-emitting weft is simpler. Side-notching the POF weft makes simple figures of light dots possible. The abraded monofilament distributes the emitted light more evenly. The latter, together with fluorescent cladding, has to be abrasion protected for use. Other limitations derive from the limited mechanical properties at sub-zero temperatures, especially with the most common PMMA fibre.

Woven illumination systems are suitable for architectural and industrial art applications for public premises, vehicles, and other related applications. Their advantage is that the light source and emitting surface can be separated. The best light power is achieved at the fibre end. Side-notched emission is also effective (dot light), but fluorescent warp is practical as well (side illumination). The light-emitting wovens are suitable for indoor use. Woven illumination is not recommended either for bulk light sources or flexible high definition displays.

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