

UNITED STATES PATENT AND TRADEMARK OFFICE

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BEFORE THE PATENT TRIAL AND APPEAL BOARD

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VANGUARD PRODUCTS GROUP, INC., D/B/A VANGUARD PROTEX  
GLOBAL

Petitioner

v.

INVUE SECURITY PRODUCTS, INC.

Patent Owner

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Case No.: IPR2020-00069  
U.S. Patent No. 10,043,358

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**EXHIBIT 2016**

# Plastic Optical Fiber - an overview

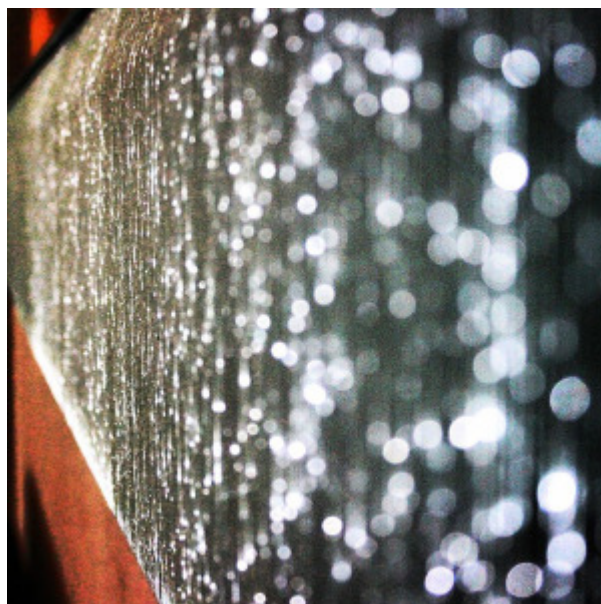
Plastic optical fibers (POF) are polymer based (typically PMMA), with a 'jacket' to force the path of the light.

## 2.5 Optical Fibers

[Plastic optical fibers](#) may be easily integrated into a textile. They have the advantage of not [generating heat](#) and are insensitive to [electromagnetic](#) (EM) radiation. [Optical fibers](#) may serve a number of functions in a smart garment—transmit data signals, transmit light for optical sensing, detect deformations in fabrics due to stress and strain, and perform chemical sensing. Plastic optical fibers can be woven into a textile; however, bending of the fibers is an issue during the manufacturing process and also with the end product as [mechanical damage](#) causes signal loss (Tao 2005). Commercially available Luminex<sup>®</sup> fabric is a textile with woven [optical fibers](#) capable of emitting its own light. While this has esthetic appeal for the fashion industry it is also used in safety vests and has the potential to be used for data transmission.

## II.E Optical Fibers

Plastic optical fibers may be easily integrated into a textile. They have the advantage of not generating heat and are insensitive to EM radiation. Optical fibers may serve a number of functions in a smart garment – transmit data signals, transmit light for optical sensing, detect deformations in fabrics due to stress and strain, and perform chemical sensing. Plastic optical fibers can be woven into a textile, however bending of the fibers is an issue during the manufacturing process and also with the end product as mechanical damage causes signal loss. Commercially available Lumigram<sup>®</sup> and Dreamlux<sup>®</sup> fabric are textiles with woven optical fibers capable of emitting their own light. Figure 3 shows the illuminated woven fabric manufactured by Dreamlux<sup>®</sup>. While this type of textile has aesthetic appeal for the fashion industry it may also be used in safety vests and has the potential to be used for data transmission.



Sign in to download full-size image Figure 3. Dreamlux® illuminated fabric incorporates optical fibers throughout the fabric. The optical fibers are grouped and inserted into a LED that spreads light all over the entire surface (Photo: Dreamlux®).

### 10.7.1 Process for manufacturing plastic optical fiber using PC as core material

The [plastic optical fiber](#) using PC as the core material has a heat resistance of 120 °C or higher which is 30 °C or so higher than that of the plastic [optical fiber](#) using PMMA as the core material. After [commercialization](#) of this plastic optical fiber by [Mitsubishi Rayon](#) in 1986, Fujitsu, Teijin Kasei, Idemitsu [Petrochemical](#) and Asahi Kasei have also successfully commercialized it.

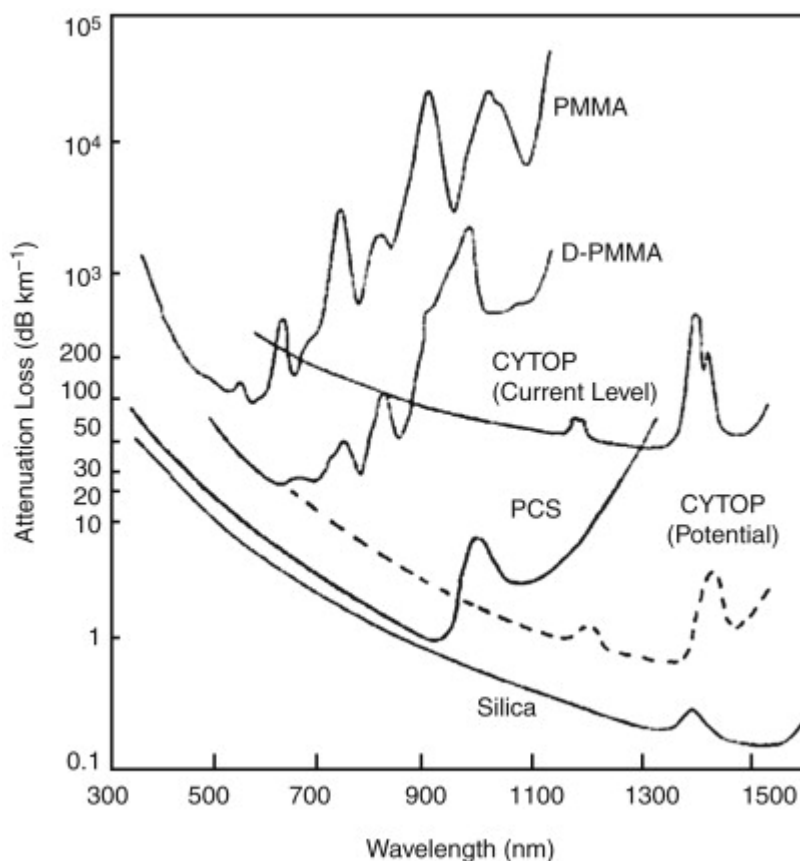
PC polymer is dissolved in an organic solvent containing [methylene chloride](#), and unreacted substances and by-products are removed from the solvent solution by washing. The polymer is recovered by removing the solvent using a spray [drying method](#). This recovered polymer is usually pelletized by [melt extrusion](#) at a temperature higher than the crystalline melting point of 245 °C, but the polymer thermally degrades at 280–320 °C. Even though pellets of such a PC polymer containing thermal decomposition products can be used for the [melt spinning](#) of plastic optical fiber, high-transmissibility product cannot be obtained.<sup>14</sup> It is, therefore, necessary to directly carry out the melt **spinning** of polymer recovered from the [polymerization](#) process without pelletizing it to produce a plastic optical fiber with high [transmissibility](#). It is also necessary to inhibit crystallization of polymer during the melt **spinning**. Since the [crystallization point](#) of PC reaches its maximum at approximately 190 °C, the [molding](#) temperature should be 210 °C or higher.

### 13.03.10.1 Polymer Optical Fiber Sensors

Research in polymer [optical fiber](#) sensors (POFSs), also referred to as plastic optical fibers, remained stagnant until the 1990s due to their high attenuation and lack of demand for specific commercial applications. The development of graded index plastic optical fibers by Prof. Koike at Keio University has given new life to plastic optical fibers, and it is expected to increase over the years across a wide variety of applications (196). Nowadays, POFs are primarily available as [multimode](#) fibers. Apart from being a much lower cost alternative to silica-based fiber sensors, they have additional advantages such as high elastic [strain limits](#), high sensitivity to [strain, high fracture toughness](#), ductility, high flexibility in bending, and potential negative thermo-optic coefficients.

A variety of optical polymers are used in the [fabrication](#) of POFs, including [polymethyl-methacrylate](#) (PMMA), amorphous [fluorinated polymer](#) (CYTOP), [polystyrene](#) (PS), and [polycarbonate](#) (PC) (199–202). A broad overview of common POF materials and their properties can be found in Ziemann et al. (200). These polymers have excellent compatibility with organic materials, which gives them great potential for biomedical [sensor applications](#)(200).

The polystyrene POF ( $n_{co} = 1.59$ ) has similar applications to those of PMMA. Usually the core is made of PS, whereas the cladding is generally PMMA. PS has its minimum of attenuation located in the red region and is mechanically better than PMMA. However, the attenuation of PS is also significantly greater than PMMA. Polycarbonate POF ( $n_{co} = 1.5–1.59$ ), on the other hand, is a high-temperature [resistant fiber](#) with a minimum attenuation of  $600 \text{ dB km}^{-1}$  located at 770 nm. Figure 16 shows the attenuation losses for some common optical polymers as a function of wavelength.



Sign in to download full-size image Figure 16. Attenuation losses for common optical polymers as a function of wavelength. Reproduced from Zubia, J.; Arrue, J. Plastic Optical Fibers: An Introduction to Their Technological Processes and Applications. Opt. Fiber Technol. 2001, 7, 101–140.

The main drawback to the multimode POFs, however, is that these sensors are generally larger than comparable single-mode sensors and their silica-based multimode counterparts. They also suffer from lower [measurement accuracy and resolution](#) as they have far greater transmission losses compared to silica optic fibers. However, recent successes in fabrication technology should be able to eliminate these issues and enable the development of high-precision sensors. Single-mode POFs with a PMMA cladding and [copolymer](#) PS/PMMA core are commercially available from Sentel Technologies. For a detailed review on the historical evolution, properties, and examples of [chemical sensors](#) based on POFs, the reader is directed to Zubia and Arrue (203).

## 1.2 Why we made this book

There have been several publications on polymer-optical fibres throughout the last years. Especially the widely-known book on POFs for communication systems by Ziemann et al. [20] and also Koike's quite recent work on fundamentals of plastic optical fibres from 2014 [21] should be mentioned in this context. Nevertheless we discussed a new book on POF technology with a slightly different focus project when we started the book project in 2014. At that time a novel fabrication method for graded-index fibres was developed that

relied only on temperature treatment to form a [refractive-index](#) profile [22] without any additional [dopants](#). At that time we established a contact for a close collaboration between Markus Beckers and Thomas Gries of ITA at the RWTH Aachen University and Christian-Alexander Bunge of the HfT Leipzig [23].

During that time we found that there was still a lot of room for improvement and novel developments in the field of plastic optical fibres. The existing books at that time often focused on particular aspects such as communication systems, but especially aspects such as novel materials for special applications or sensing were not covered in much depth. Other important developments in recent years are [smart textiles](#) and wearable sensors, for which POFs are ideally suited. Thus we planned to cover aspects such as the integration of fibres into textiles and [sensor applications](#) that became possible by this.

The book is organised as follows:

**Physics of light propagation** We first lay the foundations to understand how light propagates through different media, what happens at [material interfaces](#), what is polarisation, etc. Without this theoretical introduction it is difficult to understand the following chapters, especially the physics of optical fibres.

**Principle of optical fibres** Although we wanted to lay the focus of the book on aspects such as manufacturing methods, materials and applications, we must introduce the different aspects of optical fibres, but in particular polymer-optical fibres. We show the differences and common aspects of ray and wave theory, introduce modes, [modal dispersion](#) and other propagation effects. A detailed review on loss mechanisms and different refractive-index profiles is given.

**Special fibres** In order to cover more advanced aspects such as sensors and illumination we decided to include a chapter on special fibres. This contains single-mode fibres, multi-core fibres, as well as micro-structured fibres and grating structures, which are essential for many sensor applications.

**Materials** Most books on POFs cover the polymer materials that are currently used. But in order to overcome the limitations of POF sensors or in other applications new materials must be found that can extend the operating temperatures, reduce the sensitivity towards humidity or provide other properties that make POFs unique.

**Fabrication techniques** This was the starting point of our project. In order to compare the novel fabrication technique one has to have an overview on the existing technologies. There is literature on this topic, but very few publications cover fabrication aspects and application with the same importance. The

review ranges from discontinuous techniques for step-index fibres to modern fabrication methods for graded-index fibres.

**Mechanical properties and failure mechanisms** Every manufacturing process and every product has to withstand certain mechanical stresses. One of POF's most prominent advantages is their robustness and ease of installation. Therefore they should be rugged and forgiving. In this chapter models for mechanical properties and for the estimation of failure mechanisms are given and discussed.

**Digital communication** Most POF literature focuses on communication. Within the last years the methods have developed considerably and very sophisticated approaches in terms of modulation formats, transmitter and [receiver](#) structures and equalisers have been introduced. In this extensive chapter the theoretical foundations of digital communication are laid and their direct application to POF communication systems are explained. Based on this framework the newest developments in 1–10 Gbit/s transmission systems are reported.

**Further applications** Polymer-optical fibres have more applications than just data communication. One of the largest markets is the illumination. Here an overview on applications beyond data transmission is given.

**Integration into textiles** POFs are ideal for the integration into textiles. Many textiles actually consist of [polymer fibres](#) so that additional optical fibres do not necessarily have to be perceived. It is a natural addition. These fibres can then be used for illumination, as wearable sensors or for communication purposes. In this chapter an overview on the most common integration techniques is provided, which is new to our knowledge.

**Market review** Finally, we wanted to provide an overview on the different market segments of polymer-optical fibres. Many papers and research proposals refer to the low cost and the great market potential of POFs. With the help of a market insider we could accumulate enough information to provide a detailed survey on the POF market in terms of regions, fibre types, applications and materials.

Finally, and definitely as important as the already listed points, we planned to join the experience and knowledge of the whole field. We cannot cover the full range of aspects in the detail as our field of expertise. Therefore we asked our colleagues from partner institutions to provide chapters or assistance on particular aspects. In this way we could add a profound study on chemicals and novel materials that provided our colleagues from TU Braunschweig. Our friends from the Basque University in Bilbao contributed a chapter on mechanical properties and testing of fibres. Dr. Brigit Lustermann helped with

information on tubular fibres and ray-tracing simulation. We also received assistance from the DTU in Copenhagen on micro-structured fibres. Dr. Kort Bremer provided the section on gratings in fibres. The detailed study of optical communication systems and modern modulation formats in POF links was made possible by the help of Dr. Grzegorz Stepniak from the TU Warsaw. Colleagues from RWTH Aachen university assisted with an overview on sensor applications and fibre integration techniques into textiles. And finally, we had the luck to receive market data from Peter Kröplin of Sojitz Europe plc., a POF-market insider that made the detailed market review possible. We would like to thank all contributors for their help and dedication.

## 8.8 Products and standards

Although there is a number of commercial products suited for 100 Mbit/s transmission in POF, the choice of 1 Gbit/s transmission systems on the market is very limited. In fact, there is one company, Knowledge Development for Plastic Optical Fibres (KDPOF)<sup>8</sup> which manufactures media-converter chips for transmission of 1000Base-X data over POF. The system is capable of transferring data via up to 50 m SI-POF with net bit rate of 1 Gbit/s and  $10^{-12}$  BER. The produced [circuit](#) can operate with low-cost POF components like RC-LED and a PD with TIA. Such components are readily available on the market from vendors like Avago, Firecomms and Hamamatsu.

To achieve 1 Gbit/s over 50 m SI-POF using only low-cost components KDPOF system uses sophisticated coding and equalisation at both transmitter and [receiver](#). The modulation format is PAM-16, transmitted at the baud rate of 312.5 Mbaud. However, due to error coding, the spectral efficiency is not 4, but 3.314 bits per symbol. KDPOF system uses multilevel coset coding (MLCC) [85], a scheme where the error correction coding is integrated with multilevel modulation. MLCC is based on observation that during detection the errors fall almost entirely between adjacent symbols in the constellation. Hence, MLCC protects the neighbouring symbols using error coding. Symbols which are further apart are not protected by error code but rather by the larger Euclidean distance between them. MLCC encodes bits to a quasi QAM-128 2D constellation. Each symbol of the constellation is time domain multiplexed into two PAM-16 symbols. Such way of coding prevents application of DFE, which makes a decision based on each received PAM symbol. Therefore, instead of DFE, THP (cf, Section 8.6.11.0.3) is applied, which moves the decision feedback loop to the transmitter, where the symbols are known. At the receiver remains the adaptive feedforward part of DFE. In addition, PAM-16 scheme due to a large number of symbols is highly susceptible to nonlinearity coming from RC-LED source, and THP makes it even worse. To counteract this effect a Volterra equaliser up to the third-order is applied at the receiver, a similar one to the



shown in Schueppert et al. [13]. This KDPOF system was introduced in the DKE work group 412.7.1, 'Optical Data Transmission Over Plastic Optical Fibre' founded in December 2009, where a so-called German 'Anwenderregel' was developed based on the KDPOF system. Afterwards several follow-up standardisation activities for 1 Gbit/s over 50 m SI-POF were started. An IEEE task group is currently developing a PHY for POF.

In addition to this approach, another method using DMT over up to 50 m POF was introduced to the standardisation. In December 2011, a POF interface was included into G.6660 'Unified high-speed wire-line based home networking transceivers—System architecture and physical layer specification'. It is listed in Annex F 'Usage of ITU-T G.9960 for optical transmission'. This makes POF compatible to the G.hn standard and can potentially open up new market segments because of the relatively simple adaptation of the existing G.hn chipsets for POF transceivers. It has to be noted, however, that this standard does not guarantee minimum data rates as it adapts the bit and power loading to the available SNR in the transmission channel.

For lower data rates than 1 Gbit/s exist many commercial POF transmission systems. The most prominent product is probably the MOST bus, which is integrated into millions of cars to support a multimedia network in a ring-bus topology with up to 8 m maximum fibre length between two adjacent active nodes. Currently, there are also activities to raise data rates from currently 25 Mbit/s (MOST25), 50 Mbit/s (MOST50) and 150 Mbit/s (MOST150) to more than a Gbit/s. Here, first investigations identified multilevel PAM with THP as a suitable candidate.

The other strong market for POF communication systems is the automation. There is the German car-manufacturer consortium AIDA, which is a group of Audi AG, BMW AG, Mercedes Car Group, Porsche and Volkswagen AG, that have agreed to use the Profinet standard in their factories. Profinet is a standard for standard communication, factory automation and motion control in the automation industry, which also supports copper cables. It is based on Fast-Ethernet and supports 100 Mbit/s.

## Abstract

A homogeneous and reproducible fluence delivery rate during clinical photodynamic therapy (PDT) plays a determinant role in preventing under- or overtreatment. PDT in dermatology has been carried out with a variety of light sources delivering a broad range of light doses. Owing to the complexities of the human anatomy, these light sources do not deliver a uniform light distribution to the skin. The development of flexible light sources would considerably improve the homogeneity of light delivery. The integration of

plastic optical fibres (POF) into textile structures could offer an interesting alternative.

We developed a light-emitting fabric (LEF) using POF and polyester yarns. Predetermined POF macrobending leads to side emission of light when the critical angle is exceeded. Therefore, a specific pattern based on different satin weaves was developed to improve light emission homogeneity and to correct the decrease in side-emitted radiation intensity along the POF. The fluence rate of the LEF was  $18 \pm 2.5 \text{ mW cm}^{-2}$ . [Optical losses](#) were very low. Temperature elevation was  $0.6 \text{ }^{\circ}\text{C}$  after 10 min of illumination. Our LEF meets the basic requirements for PDT: homogeneous light distribution and flexibility. It also confirms that large ( $500 \text{ cm}^2$ ) LEFs can be easily produced by textile manufacturing processes.

### Yet another book about polymer-optical fibres?

With this book, you hold the most recent compendium about polymer-optical fibres (POFs) in your hands. You may already know several other books on this topic. Being its author, I would be more than happy if you happen to know 'POF-Handbuch', published in 2007 by Springer-Verlag. As an old hand, you may remember the very first German comprehensive book 'Kunststofflichtwellenleiter' by Andreas Weinert (Siemens at that time) in 1998, or the book 'Plastic Optical Fibers' by the French POF Club (edited by J. Marcou, John Wiley & Sons, Masson, 1997). In the recent past, there were books by Hari Singh Nalwa, 'Polymer Optical Fibers', Mohamed Atef, 'Optical Communication Over Plastic Optical Fibers: Integrated Optical Receiver', and of course Yasuhiro Koike, 'Fundamentals of Plastic Optical Fibers' (without intending to be exhaustive).

Did so much change since then for us to need a new book? Are 'POF-Handbuch' and the like possibly incomplete? The pleasing answer is yes, so much has changed in recent years. You may not find actual revolutions in the new book by Christian-Alexander Bunge, Markus Beckers and Thomas Gries, but many evolutions.

Up until now, various authors have mainly concentrated either on the polymer chemistry of POFs, or on their applications. In 'Polymer Fiber Optics', Mark Kuzyk writes with great detail about the theory of light propagation. Both Maryanne Large et al. in 'Microstructured Polymer Optical Fibres', and Frederic Zolla in 'Photonic Crystal Fibres', present how various processes of microstructuring are applied in polymers. This book tries to combine all of these aspects.

The first seven chapters deal solely with the theory of light propagation in optical fibres, the (polymeric) materials and their manufacturing methods. Also addressed are the various loss effects in multimode fibres and mechanisms of ageing and destruction. The next few chapters discuss active and passive components, and describe basics of digital signal transmission in a very detailed way. The final chapters cover various novel applications, eg, sensing and integration into textiles, and the global POF market.

Therewith the reader is offered an interesting new approach on the topic of POFs. But what does he gain from it? In fact, many things changed in the world of POFs in recent years. Starting off with data transmission; until the mid 1990s, no-return to zero modulation was the maximum with several 100 Mbit/s. Digital signal transmission was said to be way too expensive (at least for POFs), and the active components way too slow. At the beginning of the new millennium, many scientific institutes started to try reaching higher velocities. In 2000, the Gbit/s transmission was reached; in 2007 10 Gbit/s and in 2012 40 Gbit/s (on 1 mm POF, of course the significantly thinner perfluorinated graded-index (GI) POF is much faster). Much of this is already published multiple times. In recent years, development concentrated less on higher velocities, but more on feasible implementation. For the first time in the history of POF development, the new solutions of knowledge development POF provide a single-chip solution for fast data transmission over step-index POF. Currently, an implementation of the process is done as a new international standard in group IEEE 802.3bv. Remaining are the inexpensive components. Various acquisitions of smaller and innovative manufacturers of POF components prove that by now, big companies do also believe in the (economic) future of POF. In his dissertation, 'Large-area Photoreceivers for Bit Rates beyond 10 Gb/s over 1 mm Polymer Optical Fibers', Sven Loquai demonstrates that even large-area detectors can be very fast. Also, light-emitting diodes (LEDs) are becoming faster and faster (green LEDs already reach several 100 MHz bandwidths).

With the idea to manufacture GI-POF solely from [poly-methyl-methacrylate](#) without additional doping, this book's authors could improve the future possibilities for fast and inexpensive POF systems dramatically. I'm already looking forward to the POF book after this one.

**Olaf Ziemann**

*POF-AC Nürnberg*

*April 2016*

## **6.6. Conclusion**

In this chapter we have dealt with ultra-short-reach [optical interconnects](#) ranging from the [interframe](#) down to the interchip level. Most remarkably, the vast majority of experimental demonstrations nowadays is based on vertical-cavity [surface-emitting laser](#) devices, which can thus be considered the key [enabling technology](#). High-performance intersystem links almost routinely employ well-established graded-index [silica multimode](#) fibers and approach 10 Gbit/s per channel signaling rates. Continued development of [high-bandwidth plastic optical fibers](#) might bring about further cost savings in some application areas. Within a computer box, competition between traditional electrical and emerging optical interconnects is much more intense. [Guided-wave](#) approaches relying on polymer channel [waveguides](#) integrated into hybrid electrical/optical backplanes and printed [circuit](#) boards have already reached high levels of maturity. Free-space interconnects could offer some additional advantages but alignment and [stability requirements](#) will most probably be met in custom design and special purpose rather than in mainstream signal [processing systems](#). Optical chip interconnects in a long-term view hold great promise for the [realization](#) of new computing architectures exploiting massively parallel [three-dimensional](#) off-chip data transport. Over a shorter timeframe, the focused efforts that are being made in the fields of heterogeneous integration and packaging will at least result in very compact transceiver modules for space-parallel two-dimensional data communication. In any case the prospects of cost-effective optical [interconnection](#) over increasingly shorter distances are bright and it will be exciting to witness the expected rapid progress in all aspects of this highly dynamic discipline.

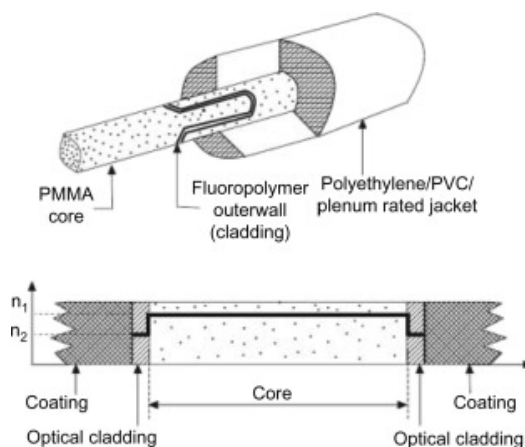
### 18.2.10 Other applications

Another attractive application of LCPs is in surface mount technology mainly in the field of electric printed circuit boards (PCBs). Instead of attaching the electronic elements of the circuit using the traditional method of anchoring leaded components using holes, the electronic elements using surface mount technology are directly attached to the surface of the PCB. This method will directly decrease the separations among the electronic elements, which lead to higher density and lower overall physical size of the board. Using this mounting method makes it possible to attach components on both sides of the PCB.

As the general trend in electrical and electronics systems is to reduce the physical size to the minimum possible while maintaining the system performance and the component's maximum possible density, special and creative solutions needed to be invented. LCPs were one possible solution that found applications in electric switches. One example is the use of LCP to replace the diallyl phthalate (DAP) [thermoset](#) in rotary switch for military radios. The high thermal and flame resistances LCPs have made them suitable for hard

soldering techniques during the switch wiring. Together with the attractive electrical properties, made the use of LCPs in such applications very useful.

Polymer composites find an important role in optical technology to serve as plastic optical fibers (POFs). Amorphous [fluoropolymers](#), poly(methyl methacrylate) (PMMA), [polycarbonate](#), and [polystyrene](#) are the most common polymers used in POFs. The diameter of these fibers is usually determined by the application it is intended to perform. The diameter could range from few millimeters down to tens of microns. Fig. 18.13 below demonstrates the basic structure of a polymer optical fiber. This POF consists of highly purified PMMA coated with fluorinated polymer as the clad. The jacket used in such POFs is polyethylene/PVC/plenum rated jacket (Chanda and Roy, 2008). In addition to its simplicity of handling and processing, POFs possess the excellent properties of polymeric materials including very low CTE, high [flame retardant](#), the low-melt viscosity and the high-melt strength, and acceptable barrier properties. Although glass optical fibers dominated the market of high bit-rate long distance transmissions, POFs are found to be very attractive to low bit-rate short-distance applications especially in the automotive industry, industrial controls, and high-energy particles detection. Graded-index plastic optical fiber (GI POF) comes with high transmission bandwidth that makes it appropriate for low cost real-time communication with high definition television systems (Chanda and Roy, 2008).



Sign in to download full-size image Figure 18.13. The core-cladding structure of a typical polymer optical fiber.

In addition to all very important applications mentioned above, [organic polymers](#) can be found in a wide diverse range of applications including;

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Medical uses including mouthpieces, intravenous fluid bags and containers, inhalation masks, blood bags, catheters, goggles, thermal blankets, caps, dialysis, gloves, medical [sealants](#), Ear Protectors, and valves.

- Construction industry including; roofing, fencing, siding and window frames, gutters and down spouts, piping for water distribution, fire sprinkler piping, coverings for walls and floors, sewage, electrical conduit, irrigation systems, landfill liners, railing, and decking, [insulation](#) of wiring.
- Automobile industry including; car body moldings, interior upholstery in cars, floor mats, under-hood wiring and cables, constructing dashboards and armrests, antiabrasion coatings, windshield wiper systems.