Plastic Optical Fibers Branch Out

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[DRAFT 6]

Abstract

Plastic Optical Fibers(POF) have been overshadowed in the last decade by the success of glass optical fibers. As a result, POF had been relegated to low bit rate and short distance applications. Recent technological advances and the emergence of a killer application in the automotive industry have propelled POF into the limelight of a lower cost alternative to glass fiber or copper at medium distances and bit rates of 10 gbps. This paper reviews the history of POF , the technical developments that have created a buzz about POF, and the applications which are propelling POF into the mainstream. In addition, POF technology exhibits similar properties attributed to "Disruptive technologies".

When people hear of optical fibers, they immediately think of glass. Few people, including professionals in the business, know about plastic optical fibers (POFs), which predate those made of glass. Because glass fibers have certain advantages, they have dominated the market, while POFs have remained largely in the background. Recent developments in technology and applications, however, have burnished the image of POFs, and they are finding a larger market with technology companies worldwide. Today, a new enthusiasm permeates the plastics side of optical fibers. The paper reviews the development if plastic optical fibers, emerging applications, and technological developments.

Overview

POFs compete with copper wires, coaxial cables, glass optical fibers, and wireless, and they require a transmitter, receiver, cables, and connectors similar to those used in glass optical-fiber links (see ref. 1) Manufacturers form POFs out of plastic materials such as polystyrene, polycarbonates, and polymethyl methacrylate (PMMA). These materials have transmission windows in the visible range (520-780 nm). However, the loss of light transmitted at these wavelengths is high, ranging from 150 dB/km for PMMA to 1,000 dB/km for polystyrene and polycarbonates. These losses often handicap plastic fibers in competing against high-quality glass fibers, which have losses of 0.2 dB/km for a single-mode fiber and less than 3 dB/km for multimode fibers. Hence, plastic fibers have been relegated to short-distance applications, typically of a few hundred meters or less, compared with the hundreds of kilometers for glass. Nonetheless, POFs have found many applications in areas such as industrial controls, automobiles, sensors for detecting high-energy particles, signs, illumination (including lighting works of art in museums), and short data links. Basically, POF applications divide into data-communication and non-data applications (sensors and signs, for ex a mple). Today, the surge in POF production stems from its use in data transmission.

Advantages and disadvantages of POF

Certain users find POF systems provide benefits compared to glass fiber or copper wire, which include:

- simpler and less expensive components,
- lighter weight,
- operation in the visible,
- greater flexibility, and resiliency to bending, shock and vibration
- immunity to electromagnetic interference (EMI),
- ease in handling and connecting (POF diameters are 1 mm compared with 8-100 mm for glass),
- use of simple and inexpensive test equipment, and
- greater safety than glass fibers or fiber slivers that require a laser light sourc
- transceivers require less power than copper transceivers

With these advantages come disadvantages that researchers, the Plastic Optical Fiber Trade Organization (POFTO) and manufacturers are working to overcome. They include:

- high loss during transmission,
- a small number of providers of total systems,
- a lack of standards,
- a lack of awareness among users of how to install and design with POFs
- limited production, which has kept customers from realizing the full potential of POFs.
- Small number of systems and suppliers
- applications research
- certification program from POF installers
- high temperature fibers (125˚C)

History of POF

Plastic Optical Fibers (POF) using polymethacrylates (PMMA) had their origin in the early 60's, first reported by Pilot Chemical of Boston and later major developments by Du Pont in the late 60's. The history of the developments in POF are shown in the Table 1. After many years of development, Du Pont decided in 1978 to sell the POF business to Mitsubishi Rayon of Japan. The losses of the PMMA POF were 1000dB/km when Du Pont sold the business to Mitsubishi Rayon. Mitsubishi Rayon over the next few years, was able to reduce the loss of the PMMA fibers to close to the theoretical limit of 150dB/km at 650nm. This was a step index fiber with a bandwidth of 50 Mbps over 100 meters..

The next major development was by Prof. Koike and colleagues at Keio University who developed a process to manufacture graded index **POF** (GI-POF) using PMMA material in 1990. Koike and his colleagues reported a bandwidth of 3GHz-km with losses of 150dB/km. The development by Koike solved the bandwidth problem of the step index PMMA POF but losses were still 150dB/km at 650nm.

The next major development was a graded index the perfluorinated polymer which was also developed by Koike and colleagues at Keio University in 1995. The perfluorinated polymer had losses of less than 50dB/km over a range of 650nm to 1300nm. The theoretical limit of the perfluorinated material was reported as 10dB/km. Bell Laboratories reported at OFC-1999 that they had achieved 10Gbps transmission over 100m of Lucina ® fiber. (Trade name for the perfluorinated polymer fiber developed commercially by Asahi Glass)

The next major development was the simultaneous reporting in 2001 of a microstructured polymer optical fiber (Holey fiber) by groups in Australia and Korea.

The first commercially available data link using graded index fiber was announced by Fuji Photo Film in 2005.. The link was a 30 meter DVI link operating at 1Gbps using a 780nm VCSEL. The link used PMMA GI-POF developed by Fuji Photo under license from Keio University, In early 2007, PMMA, became commercially available from the Optimedia Company of Korea.

Although Asahi Glass was wiring buildings in Japan with its PF GI-POF Lucina® fiber since 2002, PF-GI-POF fiber cable by itself was not available until fiber cable alone was introduced commercially in 2005 by Chromis Optical Fiber. Chromis Optical Fiber, a spin-off of OFS and Bell Laboratories, had licensed the manufacture of Lucina fiber from Asahi. Chromis has developed a continuous extrusion process for the manufacture of PF-GI-POF compared to the batch process developed by Asahi, for Chromis fiber process produces higher quality fibers at a lower cost.

Although this section has described the historical development of Plastic Optical Fibers, comparable developments have occurred in low cost, low profile connectors, optical sensors and detectors. These developments are described later in this paper.

Table 1

1968:	Dupont first to develop PMMA1977: PMMA - d8 developed by DuPont
1978:	DuPont sold all products and patents to Mitsubishi Rayon (MR)
1990:	Professor Koike of Keio University announced development of GI POF with BW of 3GHz/km

1990: POF Interest Group (POFIG) formed in the US

1992: Bates of IBM shows 500Mbps over 100m of SI-POF possible

1992: 2.5Gbps over 100m of POF using Red Laser reported by Koike et al.

1992: Professor Koike reports GI-POF with bandwidth of greater than 19GHz at ECOC-96

1993: Sasaki et al. of Keio University report POF Optical Amplifier

1994: ARPA announced award for High Speed Plastic Network (HSPN)

1994: 2.5Gbps 100m transmission with GI-POF demonstrated using high-speed 650nm LD

1995: Proposal on a POF based ATM PMD Subworking Group: Physical Layuer

1995: Keio University & KAST develop fluoropolymer fiber

1997: ATM Forum approves POF PMD for 155Mbps over 50 meters

1997: Yamazaki of NEC reports 400Mbps POF link for 1394 over 70m

1997: Asahi Glass reports on perfluorinated POF GI-POF with one third the loss of conventional PMMA POF

1997: DARPA funds PAVNET, on to HSPN, with Lucent Technologies added to consortium

1997: Imai of Fujitsu reports 2.5Gbps over 200m using 1.3nm FP-LD, InGaAs and FP GI-POF

1998: Asahi Glass reports at OFC-98 new PF fiber CYTOP(r) with attenuation of 50 dB/km from 650-

1300 with further improvements in bus possible. Bandwidth of 300-500MHz-km. Theory shows the possibility 10GHz/km. Fiber stable over the temperature range of -40 to 90˚C.

1998: MOST Standard for Automobiles Started

1999: Lucent reports 11Gbps over 100m of Lucina fiber (GI PF POF)

2000: Lucent announces that they are developing a perfluorinated fiber using Asahi materials

2000: European Commission starts POF program under name of “Optomist” which consists of 3 programs Agetha, I/O, and Home Planet

2001: First “POF Applications Center” established in Nuremberg, with grant from the Bavarian Government

2001: Redfern Optics and KAIST of Korea announce developments of Photonic Crystal POF

2001: European Commission I/O Project and Home Planet initiated

2002: IEEE 1394B Standard ratified, IDB-1394 for Automobiles completed

2002: Fuji Film announces availability of GI-POF

2004: SMI Connector Introduced

2004: First DVI Link Introduced by Fuji Photo Film Using GI-POF

2004: First Commercially Available PMMA based GI-POF announced at POF-2004

2005: First Commercially Available PF GI-POF announced by Chromis Fiberoptics

POF Data Link

In its simplest form, a POF data link consists of a transmitter, receiver, cable, and connectors. The transmitters and receivers are electrical-to-optical and optical-to- electrical converters, respectively. More complicated data-link configurations include rings (each receiver on a network responds only to its address), stars (signals go to a hub for relay), and meshes (all receivers are interconnected in a manner similar to the Internet). As when glass-fiber systems were introduced, simple pointto- point POF links were installed first, followed by rings and stars. Today, fashion favors a combination of rings and meshes.

The high-loss problem is being addressed with new perfluorinated polymer materials, which have brought losses down to potentially 10 dB/km; and European automobile manufacturers have united to solve the production-volume issue. Table 2 compares the different transmission media-glass, plastic, and copper.

Table 2: Comparison of Plastic Optical Fiber, Glass Optical Fiber and Copper Wire

	PLASTIC	GLASS	COPPER
Component costs	Potentially low	More expensive	Low
Loss	High–medium (short distance)	Medium–low (long distance)	High
Connections	Easy to connect, requires little training or special tools	Takes longer, requires special tools and training	High
Handling	Easy	Requires training and care	Easy
Flexibility	Flexible	Brittle	Flexible
Wavelength operating range	Visible	Infrared	NA
Numerical aperture	High (0.4)	Low (0.1–0.2)	NA
Bandwidth	High (11 Gbps over 100 m)	Large (40 Gbps)	Limited to 100 m at 100 Mbps
Test equipment	Low cost	Expensive	High
System costs	Low overall	High	Medium

Different Types oF POF (PMMA, Perfluorinated Polymers, and Microstructerd POF)

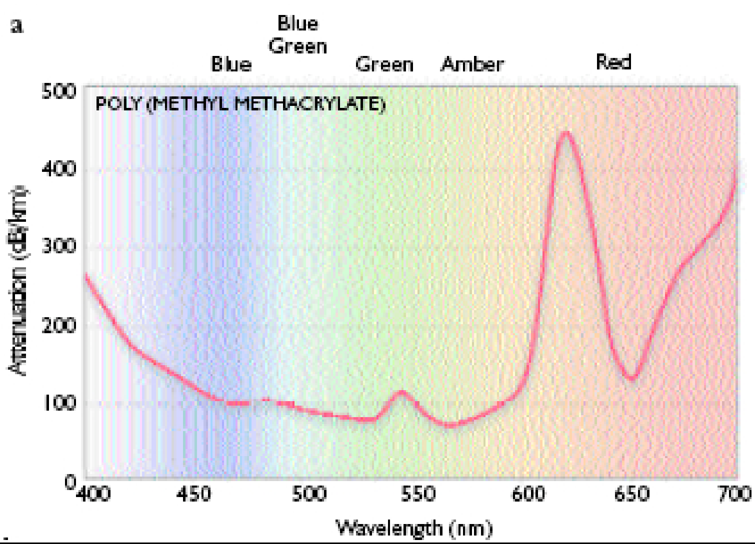
The main attributes of any transmission medium are the length over which it can transmit and the speed over that length. Loss of signal strength in an optical fiber can result from absorption or scattering of the light. Absorption is caused by impurities in the fiber, such as metals and water molecules. Light can scatter off impurities in the material, defects in the fiber such as voids, and at core-cladding interfaces and end faces. Each of these loss mechanisms is a function of the wavelength. Figure 1a shows a typical loss curve for a PMMA fiber. For this loss spectrum, the transmission windows are 530, 570, and 650 nm, all in the visible range. The window at 650 nm is narrow and, hence, could cause problems if a 650-nm source shifted with temperature. The windows at 530 and 570 nm are broader and, thus, less sensitive to shifts in source wavelength resulting from temperature changes. Note that the losses of 125 dB/km at 650 nm and of less than 90 dB/km at 530 and 570 nm limit the use of PMMA plastic fibers for transmitting light to less than 100 m.

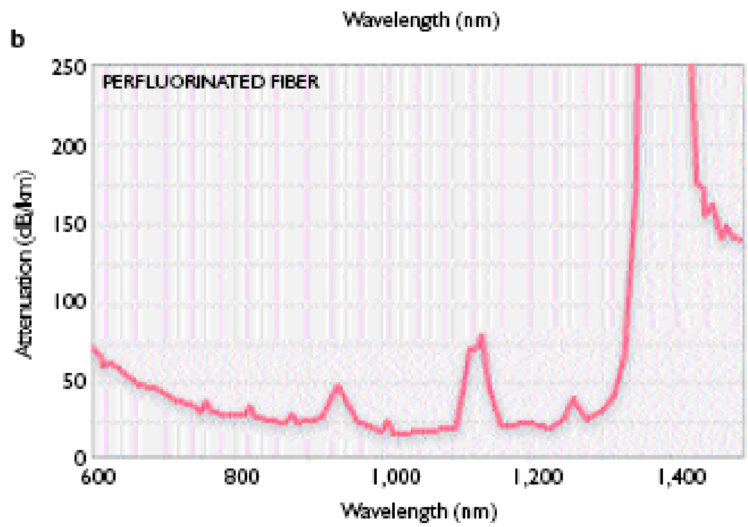
Newer plastic fibers made from perfluorinated polymers exhibit greater transmission of light over a wider wavelength range. (see ref. 2, 3) Figure 1b shows a typical loss spectrum for a perfluorinated fiber. Compared with the loss spectrum of PMMA, perfluorinated polymer fiber has two notable features. First, its spectrum ranges from 650 to 1,300 nm, and, second, the loss is less than 50 dB/km over this wavelength range. This reduction in loss allows fiber links made from this material of up to several kilometers. Thus, perfluorinated fiber overcomes the distance limitation of PMMA, and it can operate using the less expensive components developed for glass optical fibers at 850 to 1,300 nm.

An optical fiber's bandwidth is the highest number of pulses from a modulated light source that a receiver can detect. Light pulses can suffer broadening (dispersion) because of the different paths that light rays can take as they move along the fiber (Figure 2). There are two ways to characterize light transmission in a fiber: classical ray tracing , as shown in the figure, and the wave nature of light. A fiber consists of a core and cladding, with the core's index of refraction greater than that of the cladding. Containment of light in a fiber results from the reflection of light at the core-cladding interface. Each ray is considered a mode. Fiber bandwidth can be increased by reducing the number of modes or by changing the index- of- refraction profile. Reducing the diameter of a fiber allows it to transmit only a few modes, and yields what is called a single-mode fiber, which has the lowest dispersion and, hence, the largest bandwidth. Most POFs have a uniform, or step, index of refraction that is the same across the width of the fiber, and step-index multimode fibers have the lowest bandwidth. In a graded-index fiber, the index of refraction is highest at the center of the fiber and, thus, its profile has a parabolic shape. A graded-index fiber has a medium bandwidth. Various types of plastic fibers can be manufactured with step-index or graded - index cores using PMMA or perfluorinated polymers

<u>Figure 1a</u>

Loss spectrum for a poly(methylmethacryclate) fiber (a) shows minimums at 530, 570, and 650 nm, all in the visible range. Loss spectrum for a perfluorinated fier (b) is broader (650 to 1,300 nm) and the loss is less than 50 dB/km across this range.





Microstructured POF (m POF)

Microstructured POF (m POF)is a recent development in POF similar to "Holey or "Bandgap" glass fibers. m POF was first reported by van Eijkelenborg in 2001 (11). Since then, there has been considerable interest in identifying applications for which they have a competitive advantage over the technologies. Some of the features that have been explored in this context are the ability to tailor the refractive index profile by changing the hole structure; the ability to make highly birfringent or high numerical aperture fibers; and most recently to guide light in low index material through photonic bandgap guidance.

Most m POF activity to date has focussed on short distances, high bandwidth applications, which represent the main future applications of POF in general. Initial studies have been restricted bandwidth measurements over short distances. The measured bandwidth was 6 GHz over 9 meters, corresponding to 2.4 Gbps over 100 m (assuming strong mode coupling). A more recently produced fiber had a loss of 0.5 dB/m/at/650nm, compared to 0.87dB/m for earlier samples. A 25 m sample of the newer fiber was tested using the same experimental set up. It was found to have a bandwidth of 4.4GHz, corresponding to 4.4Gbps over 100 meters again with the assumption of strong mode mixing.

Finally, a record low loss of 192dB/Km at 650 nm has been achieved for a suspended core on POF produced in a draw tower employing radiative heating that provides an essentially isothermal profile in the radial direction.

Figure 2

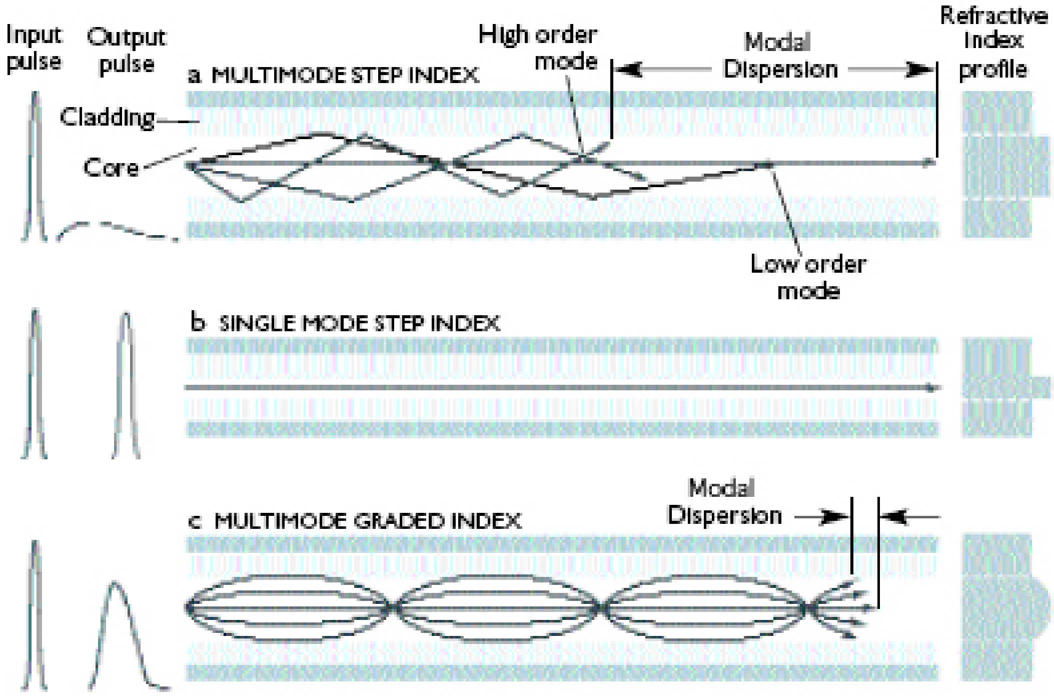


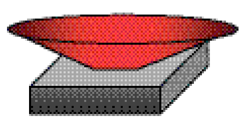
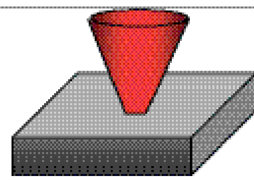
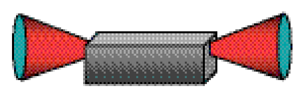
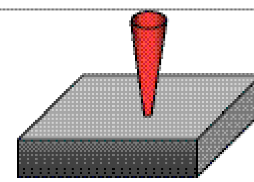
Figure 2. In optical fiber, light is reflected at the interface between the cladding and the core, which has a higher refractive index. Step-index multimode fibers (a) have the lowest bandwidth (highest number of pulses from a modulated light source that a receiver can detect). Reducing the diameter of the fiber (b) reduces the dispersion and increases the bandwidth. A graded-index fiber (c) has the highest index of refraction at the center, and medium bandwidth.

Light Sources(see ref. 5)

Several types of light sources can transmit data through POFs, including resonant cavity light emitting diodes (RC-LEDs), laser diodes, and vertical-cavity surface-emitting laser (VCSELs) diodes. These sources are compared in Table 3 for PMMA plastic fibers. As noted above, the three transmission win-dows for PMMA optical fibers are 530, 570 and 650 nm. LEDs, including surface-lightemitting diodes, can be modulated at speeds of up to 250 megabits per second (Mb/s) and laser diodes up to 4 gigabits per second (Gb/s). VCSELs at 650 nm are still in the development stage, but new resonant- cavity and near-resonant - cavity sources can be modulated at speeds of up to 600 Mb/s and 1.2 Gb/s, respectively. Perfluorinated fibers, which can operate at wavelengths from 650 to 1,300 nm, work with the light sources developed for 650-nm POFs and the 850- and 1,300-nm laser diodes used with glass optical fibers, which can transmit up to 10 Gb/s. Because POFs have larger diameters (~1 mm) than glass fibers (8-100 µm), their connectors are less complex, cost less, and are less likely to suffer damage than connectors for glass optical fibers. The reduced damage risks result from POF connectors undergoing less lateral offset and angular misalignment, and being exposed to less dirt than glass connectors. Because POF connectors have lower tolerances, makers can mold them from inexpensive plastics rather than the precision-machined stainless steel or ceramics that glass fibers require.

Table 3 : Optical Source Elements for Optical fiber Systems

Tab. 1: Optical source elements for optical fiber systems

	LED	**RCLED**	**Edge-emitting LD**	**VCSEL**
				
Typical wavelength	650nm	650nm	1310-1550nm	850nm
Efficiency	1 to 10%	5 to 20%	10 to 50%	10 to 30%
Emitting area	300x300 μm^2	20x2 μm^2	3x0.5 µm2	10x10 μm^2
Farfield angel (vertical/horizontal)	$\pm 60^o$	$\pm 30^o / \pm 10^o$	$\pm 50^o / \pm 20^o$	$\pm 10^o$
Threshold current	n/a	n/a	20 to 50 mA	1 to 5 mA
Temperature dependence of output power	Medium	Medium	High	Medium
Data rate	100 Mb/s	200 Mb/s	> Gb/s	> Gb/s
Fabrication and testing cost	Very low	Low	High	Low
Packaging cost	Low	Low	High	Low
Compatible optical fiber	POF	POF	SM Fiber	MM Fiber, PCS Fiber, New POF (PF)

Finally, because of the ease of coupling light from a light source, it is possible to embed the source and drive electronics into the connector housing (Figure 3), such as for transceivers used in automotive and consumer products.

Figure 3

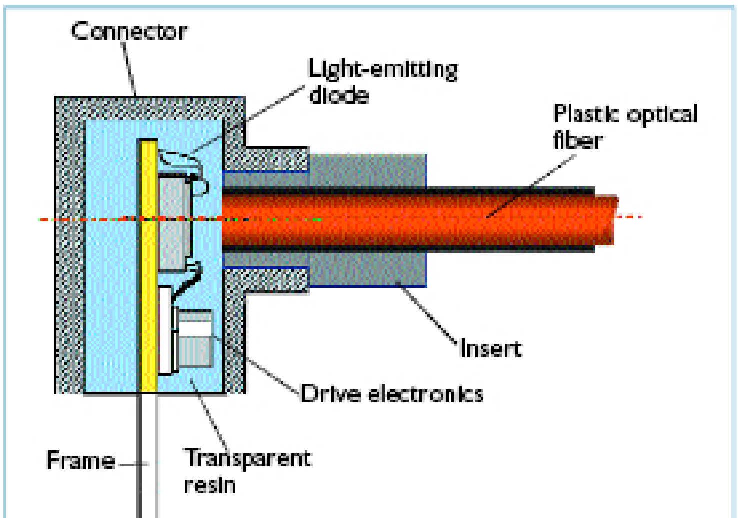


Figure 3. Connector, light source, and plastic optical fiber are easily interfaced.

POF Connectors

All transmission systems require connectors for coupling fibers to active equipments as well as for coupling fibre to fibre in a patch panel or an outlet. The connector design must allow for repeated connection and disconnection, have good loss performances and also protect the fibre from damage.

For glass optical fibre, most and probably the simplest optical fibre connectors are based on a ceramic ferrule, which can also be made of metal, ceramic or plastic. The fibre to be connected is permanently bonded with epoxy inside the ferrule (ST, SC, FC or LC types). Some systems with crimped fibre or mechanical splice inside the connector (with a built-in piece of fibre) also exist. The fibre usually has to be polished to give good performances in insertion loss and return loss. Due to the small size of glass optical fibre cores (8µm for single mode, 50µm or 62.5µm for multimode), the tolerance on the ferrule dimensions is critical for a good insertion loss value.

In this regard, a major advantage of POF is its core size. With a core size dimension of .1 to 1mm, which is higher than in MM GOF, POF require less precise parts to align the fibre than MM GOF.
This makes it possible to have a low cost and quick and easy to assemble connector.
A number of connectors have been developed and are in wide use. The most popular are the TOSLINK FCO5 (simplex) and FOC7 (duplex) developed by Toshiba and adopted by the Japanese Institute of Standards (JIS). JIS C55974 and JIS C5970 respectively. Hewlett-Packard has developed a simple "snap on" connector called the Versalink. SMA connectors have also been adopted for POF.
All of these connectors use a simple cleaving tool (razor blade) or Hot Plate to produce a high quality finish.

There have been two recent POF connector developments worthy of notice, (1) a new Small Multimedia Interface(SMI) developed by Molex and (2) a "do it yourself" connector developed for PF GI-POF by Nexans.

Small Multimedia Interface (SMI) Connector

The small multimedia interface connector system has been developed specifically for 1394b consumer applications but is finding use in other applications as well. This duplex style connector system can operate at S200 (250Mbps) for up to 50m today and S400 (500 Mbps) in the future. The connector has a small foot print of 11 mm wide and 24 mm in height making it suitable for consumer electronics.

"Do It Yourself" Connector for PF GI-POF

Nexans Cable Solutions has been active in developing PF-GI-POF cables and systems under a license from Asahi Glass. Nexans Cabling Solutions is currently developing a new SC connector compatible for this new fibre, targeting a very low cost and easy "do it yourself" type installation.
This development is based on a new patented system for fixing the fibre into the connector and cutting the fibres without the need for polishing.

For a field installable connector, a key factor is the mounting time of the connector. Compared with the cost of a connector, the installation cost is so great that it is essential to reduce the assembly time as much as possible. So one of the development target was to avoid using a glue system to use a completely new patented system instead.

The second important objective of the development was to avoid the need for any specific tool such as a crimping tool. The new NEXANS connector doesn't need any tools, and is a fully integrated system.
Finally, to avoid the need for polishing, which is a long and delicate process, a low cost cutting tool has been developed. This tool allows anyone to assemble and terminate the connector without specific training.

In conclusion, the new NEXANS connector is low cost, very easy to assemble by anyone in less than 2 minutes, doesn't need specific tool or polishing and gives a measured loss of less than 0.5dB.
This new design, now available for SC, is currently being developed for all standard connectors such as ST, LC and MTRJ.

Applications(see ref. 6)

Market researchers project a compound annual growth in POF sales of more than 20% from 2003 through 2006 (Table 3). Unlike glass optical fibers, which are mainly used in telecommunications, POFs have applications in many industries. Thus, a slowdown in the telecommunications field can have a less severe impact. The two major applications of POFs are in the industrial-controls and automotive fields. Controls remained the biggest and most stable market for the POF industry until last year, when sales to automotive companies rose to become the single largest source of revenue for POF makers. The main driver for POF in the industrial-controls market is the need for data links that resist EMI caused by high-voltage and high-current devices, such as arc welders, and high voltage apparatuses, such as X-ray machines and ion-implantation units. Today, the major source of excitement in the POF business lies in the innovative uses of its products by automobile companies.

Table 4 - Worldwide POF Market in Millions

	Auto	Consumer Electronics	Industrial Controls	Home	Inter-connect	Medical	**Total**
2002	119	90	133	25	42	42	**451**
2003	163	103	155	35	46	53	**555**
2004	201	126	194	45	54	64	**684**
2005	254	151	235	60	73	70	**843**
2006	297	173	282	75	90	84	**1001**
2007	357	198	310	83	99	100	**1147**
2008	427	228	341	91	109	120	**1316**
2009	512	250	375	100	119	144	**1500**
2010	614	300	412	110	130	162	**1728**

See Reference 5

Automobiles(see ref. 7)

Promoters of new technologies look for "killer" applications that would make the launch of their product a huge success. For POFs, the automobile industry supplied the needed killer application. In 2000, German auto manufacturer Daimler-Benz recognized that the increasing use of digital devices in automobiles increased the weight, susceptibility to EMI, and complexity of wiring harnesses. Until recently, each auto manufacturer developed its own proprietary wiring standards, which hampered them from achieving the economies of scale provided by mass production. Daiml e r-Benz realized that the way to reduce costs was to develop and buy to a common standard, and its analysis indicated that POF-ring networks would meet the needs of future automobiles. The auto maker convinced six other European auto manufacturers, including BMW and Volkswagen, to join it in developing a standard called MOST (Media Orientated Systems Transport) and to agree to purchase against the standard. The seven companies also formed an organization called the MOST Cooperation to coordinate the standard's development and promotion. The MOST Cooperation now consists of 16 auto manufacturers, including General Motors, and more than 60 POF suppliers worldwide. At the end of 2003, only 24 months after the introduction of the first vehicles with POF networks, 19 European models came equipped with POF data buses. The num-ber of terminals, or nodes, in the vehicles sold totaled 9.5 million, and 15 million nodes per year are expected to be installed from 2005 onward. The original MOST system was designed for 25 Mb/s. The next generation will transmit at 50 Mb/s, and the speed is planned to increase to 150 Mb/s by 2006. Although MOST was developed for nonmission- critical applications in automobiles, BMW also developed a separate, 10-Mb/s POF star network, called Byteflight, for critical elements such as airbag sensors. BMW now has 7 million Byteflight transceivers installed in its vehicles. A third auto network now under consideration, called Flex r a y, would use POFs as part of an automotive fly-by-light system. Flexray, for example, would replace the mechanical linka g e between the brake pedal and brakes with a plastic fiber. When a driver presses on the brake pedal, the resulting force would be converted to a light signal and transmitted to an actuator, which would convert the signal and apply the correct amount of braking to the wheels. The combination of an accepted standard and the agreement by a group of auto manufacturers to purchase against the standard has created the economies of scale needed by the industry. A transceiver for the MOST system operating at 25 Mb/s presently costs automakers $4.50, and that price is expected to fall to $3.00 in 2006, when the speed increases to 150 Mb/s. Similar transmitters for glass optical-fiber systems would cost $50-100. In the United States and Japan, automobile manufacturers are planning a more advanced system that would operate at 400 Mb/s using the IBD-1394 standard. This system is expected to be compatible with the MOST standard.

<u>Interconnects</u>

Recent studies by Intel indicate that if Moore's Law holds true and processing speeds continue to double every 18 months, it is almost certain that a PC built in 2015 will require some form of internal optical data bus to wire up its different chipsets. Over the next decade the bandwidth of interconnects inside a computer is expected to increase by an order of magnitude from 1 Ghz to 10 Ghz thanks to developments such as the PCI Express bus. This increase will require a shift in technologies from electrical to the optical domain. the fundamental problem facing computer manufacturers is that as bandwidth rise, the attenuation of copper tracks in printed circuit boards(PCBs) made from conventional dielectric material(known as FR$) starts to soar. For example, calculations suggest that at 10Ghz a typical 20 inch long interconnection may have an effective insertion loss as great as 50db whereas a plastic optical fiber of the same dimension would have a loss of .075db. With these issues in mind, Intel and others are busy exploring the option of using photons and optical waveguides to transfer data around a computer's motherboard. The big attraction of this approach is that the optical link supports much higher data rates than its electrical counterpart-potentially many tens or even hundreds of gigabits per second-over far greater distances. This means that subsystem and systems designers can consider the interconnection of circuit boards in back planes of computers, routers, switches, storage devices and other types of electronic boxes, box-to-box , rack-to-rack, and within switching and data centers.

Supercomputers and Servers

A number of applications are now being developed for large data centers, server farms, and supercomputers, all requiring large amounts of interconnection over relatively short distances on the order of 50 meters or less. As an example of this growth, supercomputers in the 1980s were a few fast processors in a single rack. By the 2000's, supercomputers, consisted of 10,000s of CPUs in 100 racks of equipment. By 2010, Top-tier machines, 3-6 petaflop machines will require 128-256 computer racks, 50-100 switch racks, and 64,000-128,000 CPU cores all requiring interconnection. These might require 50,000-100,000 fiber ribbon cables of 24 fibers each. The total cost of transceivers for one machine would cost $20-40 million. There is a precedent for this. The Earth Simulator has 83,000 copper cables (220 tons!) at (2x2) Gbps. The cost and time to terminate the fibers would seem to favor the use of POF.

Another aspect favoring POF is the cooling required for these large machines and servers. The dissipation of heat is a major problem in costs of cooling required as well as the electricity costs. Transceivers for 10G copper require 15 watts of power whereas a 10G POF link requires 1.5 watts

Local Area networks for Homes and Business

Local Area Networks (LANS) are becoming ubiquitous in small to medium size enterprises (SMEs), divisions of large companies, and in homes. For small businesses and homes, LAN with speed of 10 Mbps to 100 Mbps are quite common with 1Gbps now being considered. Recently several POF optical source companies have announced transceivers for 10-100 Mbps applications using technology developed for the MOST automotive applications. These transceivers have recently been introduced at a price of $12 per transceiver pair. With the availability of new plastic optical fibers, small form factor connectors and low cost transceivers, it can be expected that suppliers of ethernet LANS will soon be providing options using POF.

Aerospace and Applications

Because of their small size, low weight, resiliency to shock and vibration, and high bandwidth capabilities over short distances, POF's is now seriously being considered for application in aircraft, tanks, ships, helicopters, missiles, and spacecraft. In the mid 1990s, DARPA invested heavily in POF technology to develop high speed links for military applications. Unfortunately, the technology was not at that time ready for commercialization. Major companies such as Honeywell, Delphi Electronics, Boeing and Lucent Technologies were involved in the program. Now, the technology has evolved and is ready for military and aircraft applications. For example, in the new 737 follow-on, Boeing is considering POF for use in its audiovisual system in order to save weight. The POF industry is rising to the challenge by developing higher temperature fibers (125^{o}C) and flame retardant cables for other military and aerospace applications.

Future Prospects

Some writers have characterized POF as the type of innovation that Clayton M. Christensen termed a disruptive technology in his book The Innovator's Dilemma (see ref. 9). Typically, such technologies are significantly less expensive and are ones that established companies could develop, but the companies cannot decide whether the effort is worth the necessary resources or how to market the product. The history of POFs exhibits some of the characteristics described by Christensen: a developing technology, low cost, a lack of initial applications, manufacturers who followed the high-end uses recommended by their customers, and a lack of awareness by end users. It remains only a matter of time before the benefits of large-scale production in the auto industry start to permeate consumer electronics, medical instruments, and other fields, and bring the benefits and cost structure of plastic optical fibers to bear on these industries (see ref. 6,8)

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