Potentialities of multimode fibres as transmission support for multiservice applications: from the wired small office/home office network to the hybrid radio over fibre concept

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1. Introduction

The aim of this chapter is to demonstrate the high potentialities of the multimode fibre to be used as transmission media for multiservice applications inside a building or even in-house (Small Office/Home Office). Most of the building networks are based on multimode fibre topology (90%) for high speed (10Gbps) – short range (<300m) optical networks. A significant increase of the data rate through the corporate Network or the Internet has been observed, due mainly to the explosion of the media exchange (music, Video on Demand (VOD), big data files,…). The IEEE802.3 Gigabit Ethernet Standard is becoming the commonly installed standard in an office network while some specific applications will require a high data rate transmission (for ex. 10Gbps). Moreover, the deployment of the Fibre To The Home concept has been already launched all over the world (Europe, United State, Asia…) under the acronym "triple play" (data, voice and TV over IP). The easy handling and connection of multimode fibre coupled to the high bandwidth capacities open the way to the "Do It Yourself" concept (DIY) for the subscriber.

The first part of this chapter deals with the description of the different candidates able to provide a low cost solution and to support the increase of the data rate through longer range. The description will focus on the fabrication processes, the physical properties and the optical performances (attenuation, optical bandwidth, numerical aperture…) obtained for glass multimode fibre (GMMF) as well as polymer ones (PMMF). In order to satisfy the growing demand of the 10Gbps applications, some manufacturers of optical fibre such as Draka Comteq, Corning or OFS optics have developed new Extended Bandwidth GMMF allowing to transmit high throughput signals (10Gbps) through more than 1000m. These fibres – principally optimized for an 850nm wavelength operation – exhibit a high Bandwidth-Length product (>6GHz.km) and the well known (more than 30 years old) fabrication process of the GMMF allows to obtain glass fibres with high purity and optimized index profile. These glass multimode fibres enable to reach a good trade-off between cost and performance. Nevertheless, in order to decrease the connection cost of an optical LAN, novel optical fibres less brittle and more flexible than silica ones, based on polymer materials (the PolyMethylMethAcrylate PMMA (Plexiglass) or the fluoropolymer Cytop® (CYclic Transparent Optical Polymer)), have been developed by Asahi Glass and Chromis Fibreoptics. The high attenuation of the polymer based optical fibres as well as their intermodal dispersion induce link length limitation that should reasonably restrict their use to home applications where, by the way, their easy handling should drive to the DIY concept.

GMMF or PMMF exhibit a high transmission capacity when high fibre bandwidth and Coarse Wavelength Division Multiplexing (CWDM) technique are combined and the concept of multiservice application is born around this idea. In fact, the idea is to re-use the existing baseband Ethernet network that is already deployed inside buildings to simultaneously transmit other services thanks to wavelength multiplexing: this is the topic of the second part of this chapter. The improvement of the indoor coverage of wireless communications signals using carrier frequencies up to 10GHz (radiocellular (GSM, DCS, EDGE, UMTS), WLAN (IEEE 802.11a, b, g,…) and WPAN (Bluetooth, Zigbee, UWB) standards…) between different offices located in a building could be realized with the radio over fibre (RoF) concept. RoF concept allows to transport by optical means a radio signal from a central office to multiple remote access points through a fibre network in order to extend the wireless range and to provide a high quality of service (QoS) in term of data rate. Each access point is composed of E/O and O/E converters for the bidirectional transmission as well as active and passive RF devices (amplifier, coupler, circulator…). The required O/E and E/O components are available. Most of them have been developed for GbE or 10GbE applications. Concerning the RF electronics, it has been developed for the different wireless systems under investigation. Different implementations that are able to transmit such signals using multimode fibre (GMMF and PMMF) will be described as well as the obtained performance (Error Vector Magnitude, eye diagram…). Using Ultra Coarse Wavelength Multiplexing (i.e. 850 nm and 1300nm) which is affordable using WDM multimode couplers, the radio over fibre technology can be coupled to the digital baseband transmission on the same multimode fibre converting so this support to a multi-service transmission media. Results of simultaneous transmission experiments will illustrate this aspect.

A last application of WDM use consists in the optical powering of the remote access points that has already been demonstrated over GMMF and can be considered as another complementary service.

All of these topics will be described in this chapter.

1. Physical links (fabrication processes, physical properties…) dealing with the further developments on the Glass Multimode Fibre (GMMF) and the new development on the Polymer Multimode Fibre (PMMF)
2. Wired links using baseband signals (topology, performance…)
3. Radio over multimode fibre systems (topology, performance…)

4. Multi-services application: Optical Powering of remote access points in Radio over Fibre systems and simultaneous transmission of baseband and radio signals

2. Description of the multimode propagation channel: from the glass fibre world to the polymer optical fibre concept

The fibres used for optical telecommunications are made of dielectric materials (here, glass or polymer) having the functionality to confine and to guide visible and infrared light over long distances. Generally, an optical fibre is composed of two concentric dielectric tubes (the core and the cladding) each of them with a specific permittivity (or refractive index) value or profile. Under some conditions, the guided propagation of the light along the fibre axis is realized; it occurs in the material having the highest refractive index (fibre core).

Regarding to the core diameter, we can define either singlemode or multimode fibres: the modal behaviour of these two fibres is related to the number of modes propagating inside the fibre core. In this chapter, we focus only on the multimode fibres due to the easiness of connection, relative large modal bandwidth available over short range (typically inside a building) and the fibre compatibility with the low cost infra-red Vertical Cavity Surface Emitting Laser (VCSEL). Because of the large core diameter of such fibres, a large number of modes propagate inside the core where the multipath propagation is governed by the refractive index profile.

The light propagate into the multimode fibre core only if the incident light in front of the fibre's input facet is concentrated inside an acceptance cone (fig. 1) defined as the Numerical Aperture (NA).

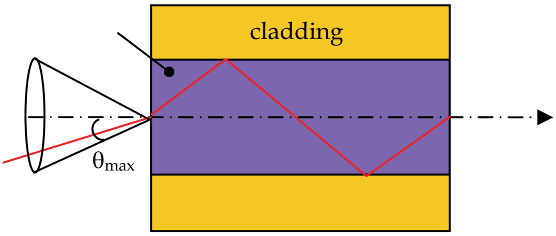

Fig. 1. Definition of the numerical aperture (NA)

The NA is related to the refractive index difference and is independent of the refractive index profile as defined in the relationship (1):

$$NA = \sin(\theta_{\max}) = \sqrt{n_{core}^2 - n_{cladding}^2} \quad (1)$$

From the geometric optics point of view, two different kinds of multimode fibres can be distinguished[1]:

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[1] The ring fibres as well as the W shape fibres do not fill with the application field of this chapter.

- the step index fibre having a step variation (fig. 2a) of the refractive index profile in the transverse plane: the rays inside the fibre core propagate by total internal reflection at the core/cladding interface (fig. 2c)
- the graded index fibre, where the index profile (fig 2b) is optimized to reduce the delays between the fastest fundamental mode (close to the fibre axis) and the higher order modes as shown in fig 2d. This graded index profile allows the enhancement of the modal bandwidth and different optimizations have been and are made to get the different types of multimode fibres particular behaviours.

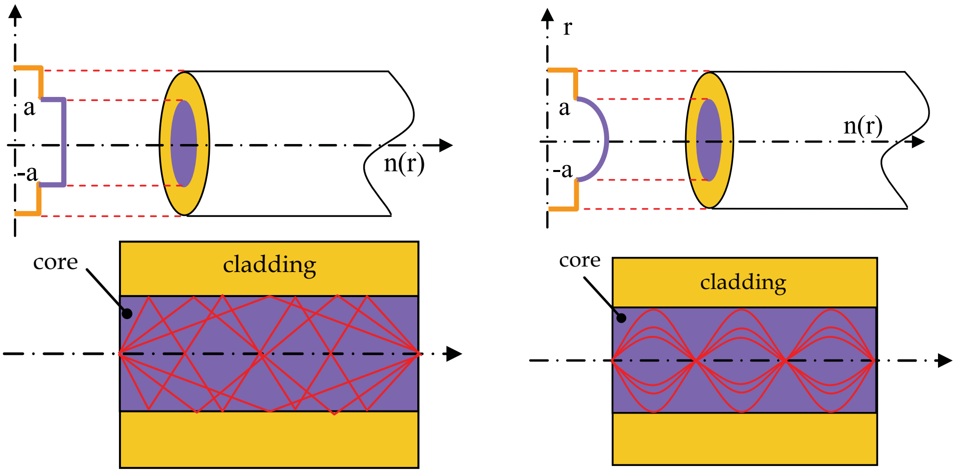

Fig. 2. Refractive index profile of step index fibre (a) and graded index fibre (b). Ray tracing of the multimode propagation inside a step index fibre (c) and a graded index fibre (d).

The graded index profile variation is described by the equation (2).

$$n(r)=\begin{cases} n_{core}\cdot\left(1-2\Delta\left(\dfrac{r}{a}\right)^{g}\right)^{1/2} & \text{if} \quad 0\le r\le a \\ n_{cladding} & \qquad\quad r\ge a \end{cases} \tag{2}$$

where n_{core} and $n_{cladding}$ are respectively the refractive index of the core and the cladding parts of the fibre and a the core radius. The constant Δ is defined by the relationship (3).

$$\Delta=\frac{n_{core}^{2}-n_{cladding}^{2}}{n_{core}^{2}} \tag{3}$$

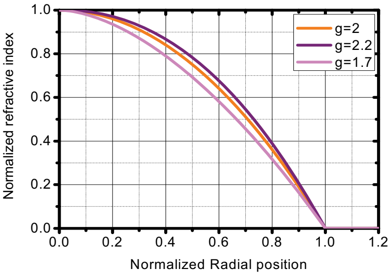

Fig. 3. Refractive index profile as a function of the core index exponent (gradient index type fibre)

In case of graded index fibre, the refractive index profile is determined by the g factor called the core index exponent. In case of the g factor is very close to 2, we define parabolic index or square law multimode fibre (fig. 3).

The ray optics theory does not take into account the relative values of both wavelength (λ) and diameter of the finite ray (Φ_{ray}): the full description of the multimode fibre propagation would be completed with the evaluation of the intensity distribution within the light beam. With the use of the Maxwell formalism related to the wave description for lightwave, the electromagnetic field (E, H) distribution inside the fibre is given by the solutions of the eigenvalue equation (4).

$$\Delta\begin{Bmatrix} E \\ H \end{Bmatrix} + \left(\omega^2\mu_0\varepsilon_0 n^2 - \beta^2\right)\begin{Bmatrix} E \\ H \end{Bmatrix} = 0 \tag{4}$$

where ω and β represent respectively the pulsation and the propagation constant and μ_0 and ε_0 , vacuum permeability and permittivity.
Theses solutions represent the mode field distribution not only in the core but also in the cladding. The full resolution of the eigenvalue equation does not cover the field of this chapter but the mode notion had to be introduced. The authors invite the reader to refer to ref [Miller, 1979] describing a detailed resolution of the equation (4). Nevertheless, the total number of propagating modes (N) inside a multimode fibre having a cylindrical revolution and defined by the core radius (a), the refractive index difference (Δ) and the core index exponent (g) is given by the equation (5) whatever the index profile is and by the equation (6) in case of step index profile (g→∞) :

$$N = \frac{V^2}{2}\cdot\frac{g}{g+2} \tag{5}$$

and

$$N_{step} \approx \frac{V^2}{2} \tag{6}$$

where V represent the normalized cut-off frequency given by the relationship (7).

$$V = \frac{2\pi a}{\lambda} \cdot NA \tag{7}$$

We can notice that the total number of modes is correlated to the core diameter, the numerical aperture, the operating wavelength and the core index exponent. The mode field distribution could be evaluated thanks to the use of the near field distribution measurement. From the communication point of view, an optical pulse travelling over an optical fibre is attenuated and spread due to respectively the material transparency of the fibre core and the fibre dispersion. Regarding to, respectively, the input optical power (P_0) and output optical power (P_L) after fibre propagation (length: L), the fibre attenuation (α) is given by the equation (8). The fibre attenuation α is generally referred to the operating wavelength in the fibre datasheets and could be evaluated over a large spectral range.

$$\alpha = \frac{10}{L} \cdot \log_{10}\left(\frac{P_0}{P_L}\right) \tag{8}$$

The fibre dispersion, that is responsible for the pulse broadening in a multimode fibre, is correlated to:

- the chromatic dispersion
- the intermodal dispersion (owing to the number of propagation modes)

If only one mode is considered (only considering chromatic dispersion), the temporal broadening of an input pulse is induced both by the material dispersion $M(\lambda)$, the spectral width ($\Delta\lambda$) of the light source and the fibre length (L) according to the formula (9).

$$\Delta t_{chromatic} = M(\lambda) \cdot \Delta\lambda \cdot L \tag{9}$$

In multimode fibre communication, the pulse broadening effects related to the intermodal dispersion are determined by both, the number of modes excited in the fibre core and the coupled power into each of these modes. Even if the main part of the optical power is coupled to the fundamental mode group LP_{01}, several groups of higher order modes propagate through the fibre with different optical paths leading to a spreading of the arrival time at the receiver side (fig. 4). The effects on the fibre bandwidth due to the intermodal dispersion caused by the different group velocities of the various modes (or groups of modes) can be minimized by optimizing the index profile versus different criteria (operating wavelength, signal bandwidth, propagation length,...).

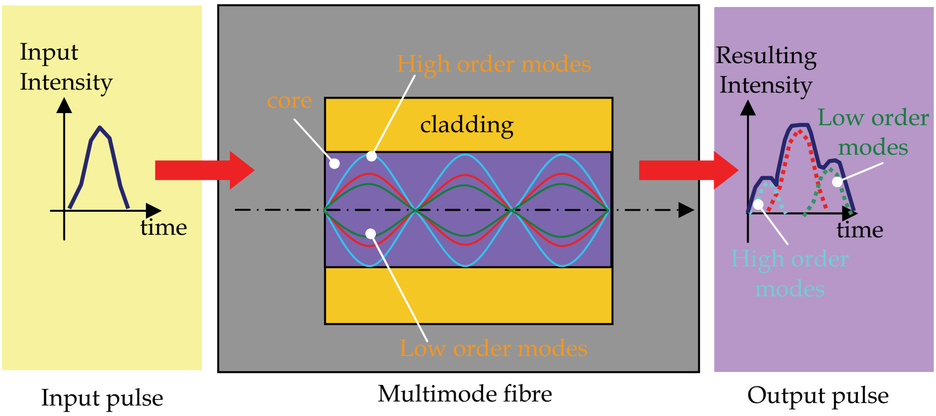

Fig. 4. Illustration of the intermodal dispersion over a multimode fibre

Depending on this index profile and so the wavelength, mode groups propagate at different velocities and the difference in travel time between the fastest and the slowest mode groups is known as the Differential Mode Delays (DMD).On fig. 5, is represented a typical DMD chart showing the pulse spreading after propagation for different launching position at the input fibre facet (0µm means launching just in the centre of the fibre, 20 µm means launching at 20 µm away from the centre, launching being made by a small spot).
This DMD parameter is very important in multimode fibre communication and needs to be reduced in order to increase the bandwidth/length product of multimode fibres. The DMD measurements allow to qualify the modal bandwidth of the multimode fibre and has been calculated thanks to the formula (10) derived from [TIA-455-220-A]:

$$DMD = \frac{\left\lfloor T_{slow} - T_{fast} \right\rfloor - \Delta T_{Short\_length}}{length} \tag{10}$$

where T_{slow} and T_{fast} represents the training edge of the slowest resultant pulse and the leading edge of the fastest resultant pulse measured at 25% of the threshold (Fig. 5). Δ_{Tshort_length} represents the pulse width (at 25% from the threshold value) obtained on a short length of fibre and the length term is used to normalize the DMD parameter by the fibre length. The DMD is related to the Effective Modal Bandwidth (EMB, also known under laser bandwidth) and the calculated effective modal bandwidth (EMBc, dealing with the "worst case EMB") defined in the fibre's datasheets.

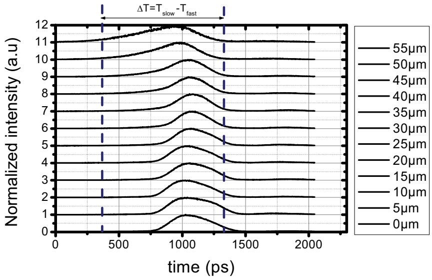

Fig. 5. DMD scanning of a polymer fibre having a 120μm core diameter [Lethien, 2008]

Contrary to single mode fibre (SMF), the modal bandwidth of multimode fibre depends strongly on the spatial distribution of the optical power and so on the modal launching conditions (see DMD chart on Fig. 5). In order to study the evolution of the fibre bandwidth regarding to the launch conditions, a high dynamic range (30dB) test setup [Lethien, 2008] allows the measurement of the response of multimode fibres in both time and frequency domains. Due to the high attenuation of several types of fibres, the test setup must also be designed minimizing extra optical losses. The test setup consists in a picosecond pulse laser (Hamamatsu PLP-10: central wavelength: 850 nm, spectral width: 4nm, pulse width: 70 ps typ.) coupled to free space optics that allow modifying the mode launching conditions at the input of the fibre under test (FUT) (Fig. 6).

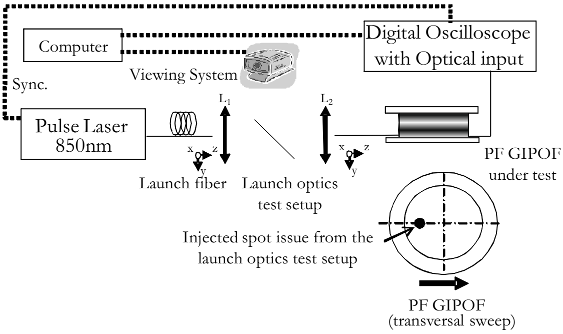

Fig. 6. Bandwidth measurement test setup at 850nm

This launching optics is composed of a launch fibre (SMF, 9 μm core, NA=0.11), two lenses, two 3-axis high precision positioners, one beamsplitter and a viewing system connected to a computer. This optical bench induces 5dB optical losses from the output of the laser source to the input of the FUT. The position of the injection spot regarding to the fibre core is displayed via the viewing system which is disposed on one light path issued from the beamsplitter. The fig. 7 illustrates the displacement of the injection spot on the input facet of the FUT. On the two pictures on the left side, the injection spot is outside the fibre core. This latter fibre is illuminated from its output facet by a visible light source. On the two pictures on the right side, the spot is launched inside the fibre core and the intensity of the back-illuminating light has been adjusted in order to distinguish the injection spot from the fibre core.

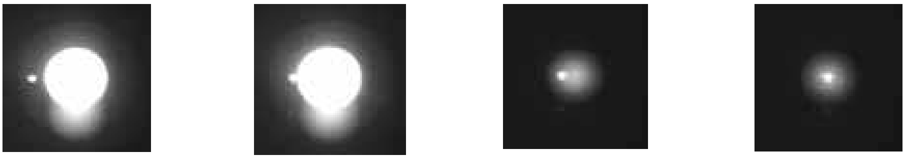

Fig. 7. Offset launch of a restricted spot into a fibre core. From left to right, this injection spot is going from outside the core up to its centre.

Based on the Lagrange-Helmholtz invariant calculus, the diameter of the launched spot as well as its numerical aperture have been determined regarding to the core diameter ($\Phi_{\text{Launch-fibre}}$), the NA ($NA_{\text{Launch-fibre}}$) of the launch fibre and the focal length, f_1 and f_2, of, respectively, lenses L_1 and L_2 as described in (11) and (12):

$$\phi_{launched-spot} = \phi_{launch-fiber} \cdot \frac{f_1}{f_2} \tag{11}$$

$$NA_{launched-spot} = NA_{launch-fiber} \cdot \frac{f_1}{f_2} \tag{12}$$

By using the adequate optical lenses and regarding to the available launch fibre (single mode fibre, 50µm and 62.5µm core diameter glass multimode fibres…), Any launching conditions, from the overfilled launch (OFL) condition (LED condition) to the restricted mode launch (RML) condition can be then simulated. The OFL conditions are used to define the OFL modal bandwidth and the RML conditions deal with both the DMD and the EMB measurements.

Time domain analysis of the output signal issued from the multimode fibre is made using an optical sampling oscilloscope; this analysis can be converted into the frequency domain using FFT (Fast Fourier Transform). The fibre bandwidth is obtained by de-embedding the frequency domain results issued from the tested length of multimode fibres from the results obtained on a short fibre length (1 m).

2.1 The Glass Multimode Fibre (GMMF): further developments

2.1.1 Manufacturing processes of GMMF

A glass multimode fibre is generally composed of a SiO_2 core doped with Ge surrounded by a SiO_2 undoped cladding layer. The aim of this part is not to present the much known glasses material but to review the three different processes involved by the 3 main manufacturer of glass multimode fibres. Most of the optical fibre is fabricated by the so-called preform methods consisting in realizing a glass rod with diameter from 1cm up to 10cm and nearly 1m length. The optical fibre is then pulled thanks to a fibre drawing tower. The heating of the preform close to the melting point in the furnace localized at the top of the drawing tower allows to pull a thin fibre where the core diameter can be adjusted according to the pulling speed and the furnace temperature (fig. 8).

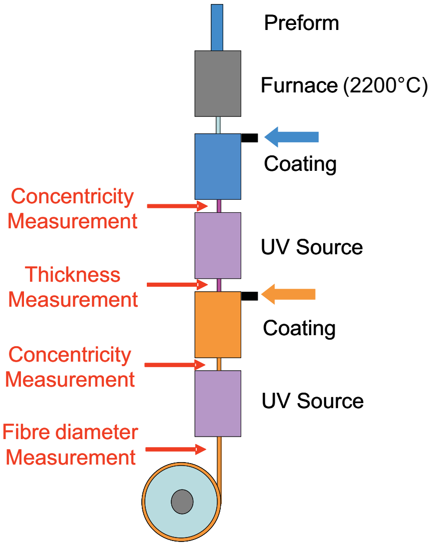

Fig. 8. Overview of a fibre drawing tower

Currently, several processes could be used to manufacture the preform before the fibre pulling:

- The Modified Chemical Vapour Deposition (MCVD) or just called CVD process developed by OFS' optics [MCVD OFS]
- The Plasma-actived Chemical Vapour Deposition (PCVD) process used by Draka Comteq [PCVD Draka]
- The Outside Vapour Deposition (OVD) manufacturing process used by Corning [OVD Corning]

The MCVD process (fig. 9a) is a patented process developed at Bell Labs in the 1970s. A mixture of ultra-pure gases composed by oxygen (O_2), silicon tetrachloride ($SiCl_4$), germanium tetrachloride ($GeCl_4$) and freon (C_2F_6) is sent inside a rotating high purity quartz tube which is heated from an outside source at a temperature close to 1600°C (flame). The chemical reactions occuring inside the quartz tube induce the formation of glass soot, resulting to the coating deposition of a thin layer of doped glass particles inside the tube as described in equation (x) and (x).

$$SiCl_4 + O_2 \xrightarrow{1600°C} SiO_2 + 2Cl_2 \quad \text{(x)}$$

$$GeCl_4 + O_2 \longrightarrow GeO_2 + 2Cl_2 \quad \text{(x)}$$

Then, the mixture of gases is progressively adjusted inside the tube and the process is done again layer by layer to form the complex structure of the fibre core (in case of gradient doping). Once the tube composed by the glass material is collapsed by heating it at 2000°C, the preform is then fully fabricated and ready for the pulling. Nevertheless, the index profile has to be controlled in order to avoid defects such as centre dips or centre line spike which significantly degrade the DMD and effective modal bandwidth performance.

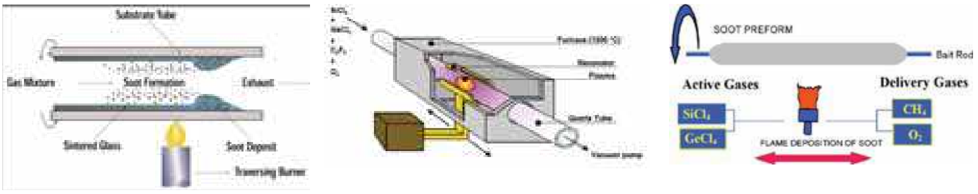

Fig. 9. Description of the MCVD [MCVD OFS], PCVD [PCVD Praka] and OVD [OVD Corning] manufacturing processes

The PCVD [Kuyt, 1999] process (fig. 9b) is similar to the MCVD method: the heating of the deposition region is now realized thanks to the use of microwaves instead of a burner (flame) to form reactive plasma used for the glass deposition.

Unlike the two processes dedicated to inside vapour deposition (external flame or plasma), the Outside Vapour Deposition (OVD) manufacturing process used by Corning consists in forming sequential layers of glass soot around a rotating target rod plunged in a mixture of gases (fig. 9c). The target rod travels through a traversing burner and reacts in the flame to form SiO_2 and GeO_2 fine soot particles. Firstly, the core material (doped silica) is deposited followed by the pure silica cladding. Both the core and the cladding materials are vapor-deposited. With the use of this OVD process, Corning can exhibit the high purity of the entire preform. When deposition is complete, the bait rod is removed from the center of the porous preform, and the preform is placed into a consolidation furnace. During the consolidation process, the water vapour is removed from the preform. This high-temperature consolidation step sinters the preform into a solid, dense, and transparent glass. Regarding to the available manufacturing process to fabricate GMMF and to the Corning point of view, the OVD process seems to provide the best uniformity in term of EMB performance (better refractive index control than the MCVD and PCVD processes). A study performed by Corning [Lopez, 2008] has reported recently that the EMB from GMMF produced by MCVD process demonstrate a 13% difference value contrary to 3% average difference for the ones produced with the OVD process. The presence of centreline dips in the refractive index profile is attenuated with the OVD process contrary to the in vapour deposition processes leading (PCVD, MCVD) to the improvement of the EMB (reduction of the DMD phenomena) as well as the transmission performance.

2.1.2 State of the art of the GMMF according to the modal bandwidth

This part deals with the comparison between the GMMF performance available on the market in term of EMB and attenuation. The GMMF are standardized by the International Electrotechnical Commission (IEC), the International Standards Organization (ISO) and the Telecommunications Industry Association (TIA). The properties of the GMMF [IEC 60793-2-10 – TIA 492AAAA – TIA 492AAAB – TIA 492AAAC – TIA 492AAAD – ISO 11801] issued from the main manufacturers Draka Communications, Corning and OFS optics, especially the OFL bandwidth (MHz.km), the high performance EMB (MHz.km), the numerical aperture, the core/cladding diameters (µm) and the GMMF attenuations (dB/km), are summarized in the table 1 [Draka – Corning – OFS optics].

	IEC	ISO	TIA	Core/ cladding diameters(μm)	α 850nm (dB/km)	α 1300nm (dB/km)	OFL 850nm (MHz.km)	OFL 1300nm (MHz.km)	EMB 850nm (MHz.km)	NA
HiCap	A1b	OM1+	492AAAA-A	62.5/125	2.7	0.6	200	600	-	0.275
HiCap	A1a.1	OM2+	492AAAB	50/125	2.2	0.5	600	1200	-	0.2
MaxCap300	A1a.2	OM3	492AAAC-A	50/125	2.2	0.5	1500	500	2000	0.2
MaxCap 550	A1a.3	OM4	492AAAD-A	50/125	2.2	0.5	3500	500	4700	0.2
Infinicor CL 1000	A1b	OM1	492AAAA-A	62.5/125	2.9	0.6	200	500	385	0.275
Infinicor 300	A1b	OM1	492AAAA-A	62.5/125	2.9	0.6	200	500	220	0.275
Infinicor 600	A1a.1	OM2	492AAAB	50/125	2.3	0.6	500	500	510	0.2
Infinicor SXi	A1a.1	OM2	492AAAB	50/125	2.3	0.6	700	500	850	0.2
Infinicor SX+	A1a.2	OM3	492AAAC-A	50/125	2.3	0.6	1500	500	2000	0.2
Infinicor eSX+	A1a.2	OM4	492AAAC-A	50/125	2.3	0.6	1500	500	4700	0.2
OFS Laser optimized 62.5	A1b	OM1	492AAAA-A	62.5/125	2.9	0.6	220	500	-	0.275
OFS Laser optimized 62.5 XL	A1b	OM1	492AAAA-A	62.5/125	2.9	0.6	350	500	-	0.275
OFS LaserWave® G+	A1a.1	OM2	492AAAB	50/125	2.3	0.6	700	500	950	0.2
OFS LaserWave® 300	A1a.2	OM3	492AAAC-A	50/125	2.3	0.6	1500	500	2000	0.2
OFS LaserWave® 550	A1a.3	OM4	492AAAD-A	50/125	2.3	0.6	3500	500	4700	0.2

Table 1. Summary of current glass multimode fibre properties

The high potentialities of the GMMF described in the table 1 allow to investigate high data rate over long haul transmission with low cost architecture and commercial off the shelf devices.

2.2 The Polymer Multimode Fibre (PMMF): new concept

Only the PMMF with a graded index profile and designed to be used for the telecommunications will be considered in this paragraph.

2.2.1 Properties of the graded index PMMF

The thermoplastic PMMA (Polymethylmethacrylate) has been the first material used for the PMMF fabrication. Known under the acronym Plexiglass®, the PMMA is an organic compound having an amorphous structure of the polymerized material and a glass transition temperature (T_g) close to 100°C. The Plexiglass® is composed of several MMA monomers, each of them showing 8 C-H bonds as described in fig. 10a. The 6th and 5th harmonic waves (occurring at 627nm and 736nm respectively) of the MMA monomer are responsible for the high level of attenuation of the PMMA based PMMF especially from the visible to the infra-red spectral ranges (110dB/km at 650nm). In order to decrease the intrinsic absorption of the PMMA based PMMF resulting particularly from the vibrational overtones, the idea is to perform the partial or complete substitution of the hydrogen compound by heavy atoms like deuterium (also called heavy hydrogen ^{2}H, a stable isotope of hydrogen having twice the atomic mass of the hydrogen atom) or fluorine atoms. Even if the use of heavy hydrogen induces a significant improvement of the fibre attenuation [Koike, 1996] over the visible spectrum (one order of magnitude), the deuterium based PMMF are very sensitive to the water vapour in the ambient air which is absorbed by the core material leading to an increase of the attenuation[2].

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[2] In fact, the deuterium is progressively replaced by hydrogen atoms resulting from the water vapour contamination inside the fibre.

Thanks to the use of fluorine atoms to realize the core material, it would be possible to reject the absorption bands (C-F bonds) of the used material into the infra-red spectra, far away from the telecommunication window (850nm – 1550nm). Regarding to the available [Murofushi, 1996] polymer materials (PTFE, PFA…)[3], the minimum fibre absorption has been obtained by Asahi Glass Company (AGC) from Japan with the use of the cyclic transparent optical polymer (CYTOP®) which contains only C-F bonds as shown in fig. 10b. The CYTOP® material is an amorphous fluoropolymer having a T_g close to 108°C and where the graded index variation inside the fibre core is realized by copolymerisation of two monomers and by a doping process (interfacial-gel polymerization method).

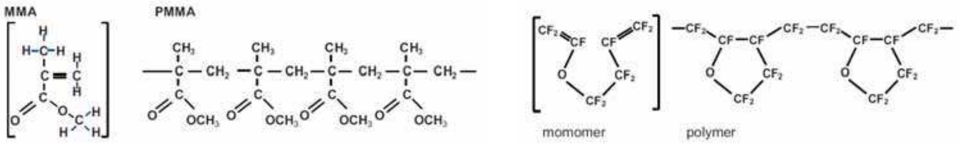

Fig. 10. Molecular geometry and bonding of the Plexiglas® (a) and the CYTOP® (b) materials

Nevertheless, even if the fibre attenuation is going to decrease till 15dB/km at 1300nm (fig. 11) with the use of the CYTOP® material, the calculated attenuation [Murofushi, 1996] threshold is not yet reached mainly due to the extrinsic losses induced by the fabrication process (impurities owing to the gas, material crystallization (scattering centres), contamination and so on). Moreover, the fluorination method using the CYTOP® material is generally expensive due to the complicated reaction steps induced during the material synthesis [Koike, 2009]. Recently, Koike *et al* [koike, 2009] have proposed the use of a partially fluorinated polymer P3FMA (poly (2, 2, 2- trifluoroethyl methacrylate)) to decrease the vibrational absorption due to C-H bonds in PMMA fibres. Thanks to this polymer, an attenuation close to 71dB/km at 650nm has been reached with P3FMA based PMMF. Several manufacturing processes have been reported for the graded index PMMF fabrication and a little synthesis is done for the three following processes:

- the interfacial gel polymerization technique
- the centrifuging process and the combined copolymerization/rotating methods
- the extrusion of several layers

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[3] PTFE : polytetrafluoroethylene and PFA : tetrafluoroethylene – perfluoroalkylvinyl – ether

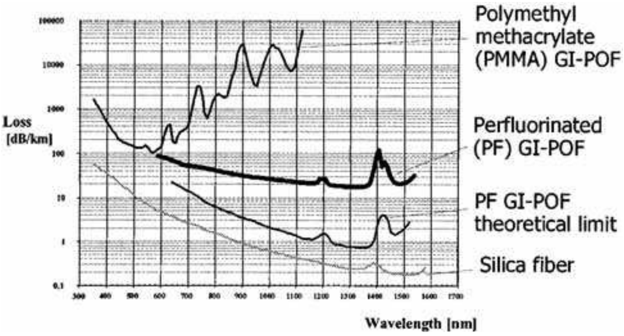

Fig. 11. Spectral attenuation of the graded index PMMF as compared to glass fibre [Van den Boom et al, 2001]

Koike *et al* [Koike, 2002 – Koike, 1995] from the Keio University (Japan) have developed the interfacial gel polymerization method to realize the preform (fig. 11). A mixture composed of two kinds of monomers (a classical one and a dopant) has been inserted in a tube (diameter equivalent to the preform diameter) and heated at 80°C to be preliminary liquefied. During this process, the formation of a gel layer is done in the inner wall of the tube (polymer gel phase) and the smaller size monomer diffuses from the edge of the preform to the centre in order to form the graded index profile. The graded index profile is correlated to the dopant distribution inside the preform.

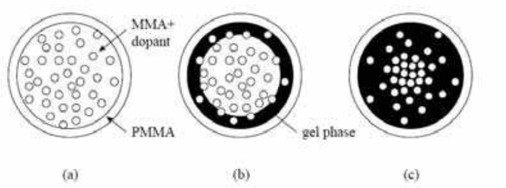

Fig. 12. Interfacial gel polymerization method used by Koike *et al* [Koike, 2002 – Koike, 1995]

Owing to the density difference between the two monomers, the centrifuging method [Duijnhoven, 1999] could be used to produce PMMF preforms. More specifically, a gravitational field is used in the process to generate and to fix compositional gradients in homogeneous mixtures of monomers, mixtures of polymers and polymer-monomer mixtures according to the molecular weight. In this manufacturing method, the rotation speed is kept below 25000 rotations per min (rpm).

The South Korea firm Optimedia head by C.W Park has developed a graded index PMMF based on the PMMA material [Park, 2006] with the use of the copolymerization/rotating methods. Here, a mixture of polymers is filled inside a tube before a polymerisation done either by UV exposure or the increase of temperature. The rotation of the filled tube is only done to provide a symmetrical UV exposure and so a uniform polymerization of the material used to make the preform (fig. 12a).

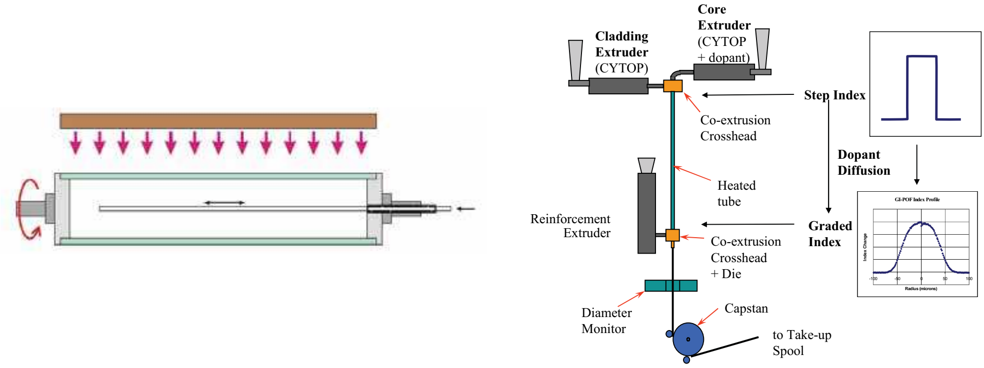

Fig. 13. Manufacturing processes used by Optimedia (Copolymerization [Park, 2006]) and Chromis fiberoptics (co-extrusion process [White, 2005])

The Chromis fiberoptics company head by W. White has performed the fabrication of PMMF based on the CYTOP® material with the use of the co-extrusion process. Two extruders containing respectively the CYTOP® material for the cladding and the CYTOP® fluoropolymer including dopant for the core are used to fill a heated tube (fig. 12b). Owing to the thermally polymerization, the dopant diffuse from the centre to the outer edge in order to form the graded index profile [White, 2005].

2.2.2 Overview of the different polymer fibres used in telecommunication for in building transmission

The fibre length inside a building is generally limited to 300m [Bennet, 2004] and for the application field of this chapter (High data rate baseband transmission, radio over fibre systems) the CYTOP® based PMMF seems to present the suitable properties to achieve the link budget requirement. In fact, the relative low attenuation (~40dB/km) in the expected spectral range [850nm – 1300nm] contrary to the PMMA based PMMF (more than 100dB/km in the visible range) as well as their bandwidth allow using them to design high speed and low losses small office/home office networks. Currently, two manufacturers have been identified for supplying the perfluorinated graded index polymer optical fibres. Asahi Glass Company has commercialized the Lucina PMMF in early 2000 with the use of the interfacial gel polymerization method and good attenuation and bandwidth performance has been obtained (table 2). This fibre has a 120µm core diameter and a numerical aperture close to 0.185. This fibre has a 120µm core diameter and a numerical aperture close to 0.185. Since April 2009, AGC company has proposed the so named Lucina-X PMMF that includes a double cladding in order to decrease the sensitivity of such fibres to bending effects. Since 2005, Chromis Fiberoptics has developed the co-extrusion process to draw the perfluorinated graded index PMMF. This process is well adapted to mass production.The core diameter of such PMMF [Chromis – Asahi Glass] varies from 50µm up to 120µm (table 2). Actually, only the 120µm core diameter based PMMF Lucina and GigaPOF-120SR have been standardized under the A4G category. A PMMF based on a 62.5µm core diameter has been standardized under the A4h acronym but this type of PMMF has only a 245µm cladding diameter contrary to the GigaPOF-62SR. An update of the IEC-60793-2-40 document [IEC-60793-2-40] will allow to standardize the 50µm and 62.5µm based PMMF from Chromis Fiberoptics manufacturer.

	IEC	ISO	TIA	Core/ cladding diameters (µm)	α 850nm (dB/km)	α 1300nm (dB/km)	OFL 850nm (MHz.km)	OFL 1300nm (MHz.km)	EMB 850nm (MHz.km)	NA
Lucina	A4g	-	-	120/490	18	18	350	-	-	0.185
Lucina - X	A4g	-	-	120/490	18	18	350	-	-	0.185
GigaPOF-50SR				50/490	40	40	300	-	-	0.19
GigaPOF-62SR	A4h?			62.5/490	40	40	300	-	-	0.19
GigaPOF-120SR	A4g	-	-	120/490	40	40	300	-	-	0.185

Table 2. Overview of the commercially available PMMF

To conclude on the glass and the polymer multimode fibres, some backscattering traces realised on 4 PMMF and 1 GMMF are presented.

The backscattering technique (fig. 13) has been used to localize the defects in the fibre core and to determine the fibre length. The main intensity peak, due to the Fresnel reflection of the propagated light at the end of the fibre (polymer or glass/air interface at the connector), is localized close to 200m for all the fibres. Defects are materialized by the smaller backscattering peaks that appear all along the propagation. The PMMF issued from the Chromis Fiberoptics manufacturer (more particularly the 50µm sample) exhibit so some defects unlike the PMMF from the Asahi Glass (Lucina). The Draka GMMF Maxcap550 exhibits an uniform shape due to the low spectral attenuation and the absence of scattering losses in the fibre core.

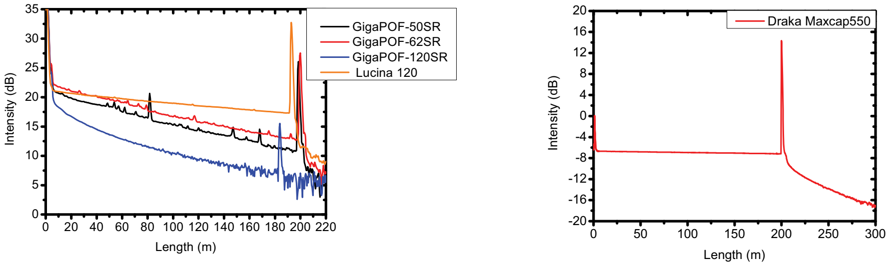

Fig. 14. Backscattering traces of the Lucina (PMMF) and the Chromis Fiberoptics fibres (PMMF) as compared to the Draka Maxcap550 (GMMF)

In spite of the attenuation, the PMMF are very challenging due to their easiness of connection. No expensive tools are required to provide a clean facet of the fibre contrary to the silica fibre world. Clip-on connectors have been developed by Nexans and Chromis Fiberoptics to be fixed on the external coating of the PMMF which favour the *Do it Yourself* concept. Nevertheless, the bandwidth potentialities of the PMMF do not reach the GMMF especially with the deployment of the new OM4 fibre designed for high speed and long haul distribution (1km) inside a fibre network. The PMMF attenuation needs also to be improved in order to increase the link budget and to be competitive against the GMMF.

Nevertheless, regarding to the promising material dispersion, the PMMF based on the CYTOP® material should provide better performance in term of bandwidth capacities. The fig. 14 presents the dispersion of the three materials used to develop either GMMF or PMMF.

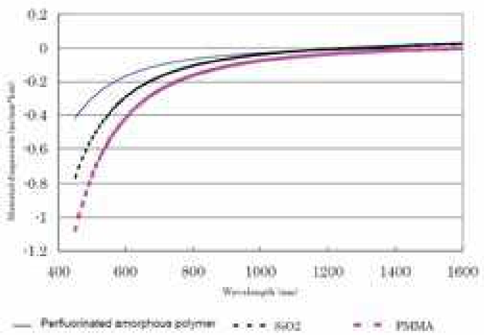

Fig. 15. Comparative study of material dispersion used in GMMF and PMMF [Asahi Glass]

3. Optical transmission of baseband multi-gigabit signals over multimode fibres

3.1 Multi-gigabit transmission over the GMMF

In 2002, Pepeljugosky *et al* [Pepeljugoski, 2002] have demonstrated the potential of high modal bandwidth GMMF to be used for a 15.6Gbps transmission over 1km at 850nm. Successful transmission of 20Gbps over 200m is also reported with the same fibre at 850nm.

The 40Gbps transmission over high modal bandwidth GMMF has been reported by Matthijsse *et al* [Matthijsse, 2006] at 1300nm over more than 400m link length. A special fibre has been pulled to optimize the bandwidth at 1300nm (5.3GHz.km) and several launch conditions have been tested from the centre launch to the radial overfill launch. A singlemode to multimode fibre coupling is realized at the emission and a multimode fibre taper is used at the receiver side in order to focus the light issued from the multimode fibre core (50µm diameter) to the active area of the used photodiode (~14µm). Good 40Gbps transmission performances were so reported over 40nm wavelength window which demonstrated the huge tolerance of the operating wavelength when using such high modal bandwidth GMMF inside a high data rate fibre network.

3.2 Multi-gigabit transmission over the PMMF

The high attenuation of the polymer based optical fibres as well as their intermodal dispersion induce link length limitation particularly at 850nm. In fact, Pedrotti *et al* [Pedrotti, 2006] report the state of art of the multi-gigabit transmission over PMMF: most of the presented works exhibit a bit rate-length product less than 1Gbps-km. Li *et al* [Li, 1999] report a high bit rate-length product but with the use of APD receivers not compatible with low cost systems. Giaretta *et al* [Giaretta, 2000] have realized an 11Gbps transmission over a range less than 100m by using a 1300nm FP laser and coupling optics which are not suited