13

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

Christophe Lethien, Christophe Loyez,
Jean-Pierre Vilcot and Paul Alain Rolland
*IEMN CNRS UMR 8520 (**I**nstitut d'**E**lectronique, de **M**icroélectronique et de **N**anotechnologie) and IRCICA FR CNRS 3024 (**I**nstitut de **R**echerche sur les **C**omposants logiciels et matériels pour l'**I**nformation et la **C**ommunication **A**vancée),*
Université des Sciences et Technologies de Lille,
France

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).

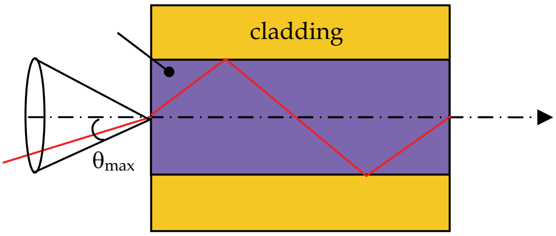


Fig. 1. Definition of the numerical aperture (NA)

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]:

---

[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.

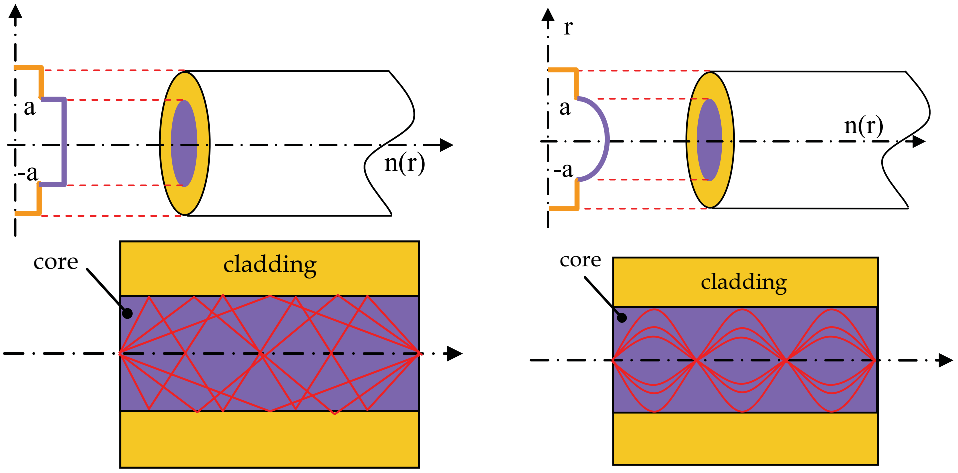


Fig. 2. Refractive index profile of step index fibre (a) and graded index fibre (b). Ray tracing of the multimode propagation inside a step index fibre (c) and a graded index fibre (d).

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

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

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).

$$\Delta = \frac{n_{core}^2 - n_{cladding}^2}{n_{core}^2} \qquad (3)$$

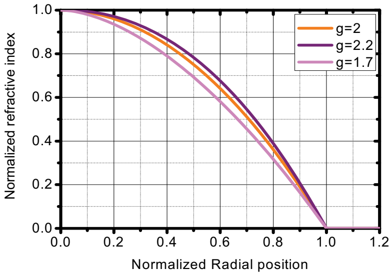


Fig. 3. Refractive index profile as a function of the core index exponent (gradient index type fibre)

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,...).

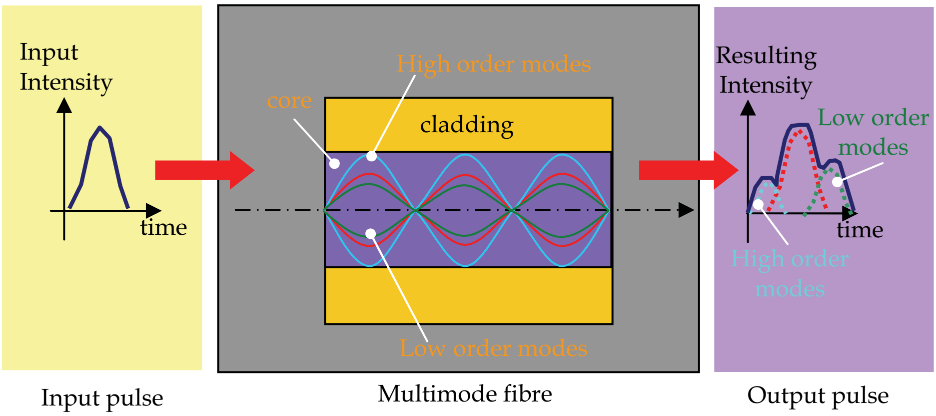


Fig. 4. Illustration of the intermodal dispersion over a multimode fibre

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]:

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

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.

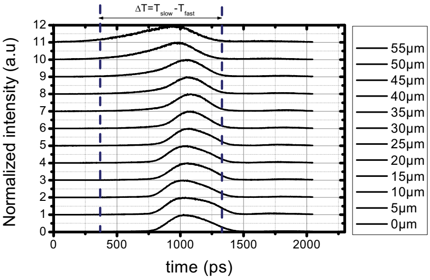


Fig. 5. DMD scanning of a polymer fibre having a 120µm core diameter [Lethien, 2008]

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).

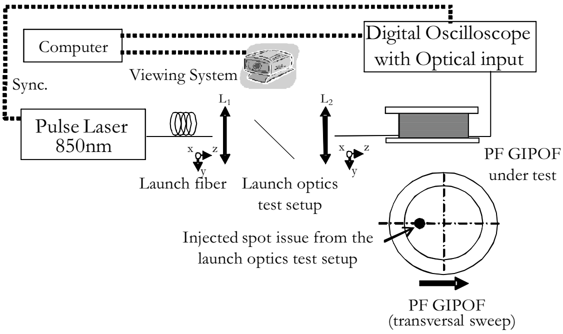


Fig. 6. Bandwidth measurement test setup at 850nm

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.

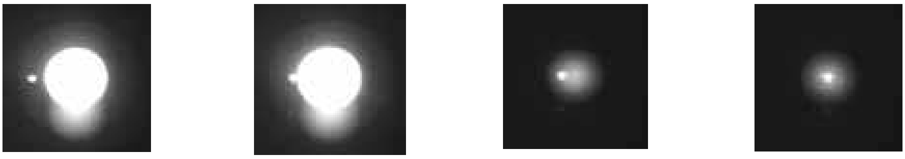


Fig. 7. Offset launch of a restricted spot into a fibre core. From left to right, this injection spot is going from outside the core up to its centre.

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 ($\Phi_{Launch\text{-}fibre}$), the NA ($NA_{Launch\text{-}fibre}$) 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).

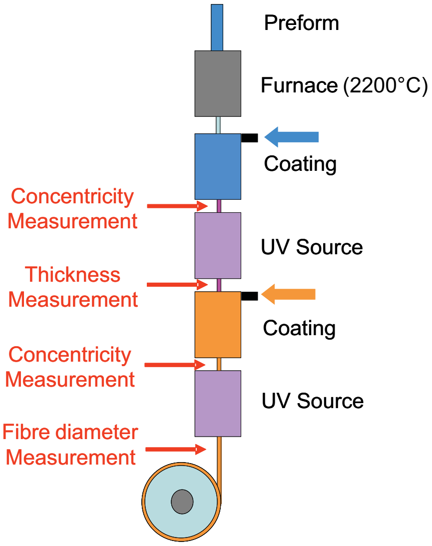


Fig. 8. Overview of a fibre drawing tower

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.

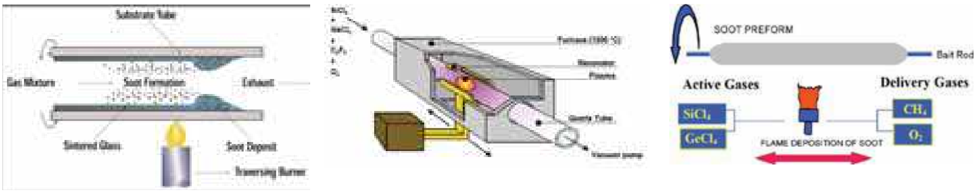


Fig. 9. Description of the MCVD [MCVD OFS], PCVD [PCVD Praka] and OVD [OVD Corning] manufacturing processes

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].

---

[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).

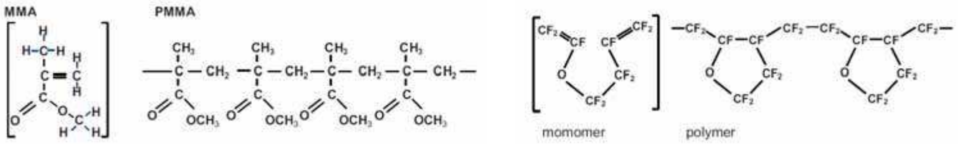


Fig. 10. Molecular geometry and bonding of the Plexiglas® (a) and the CYTOP® (b) materials

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

---

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

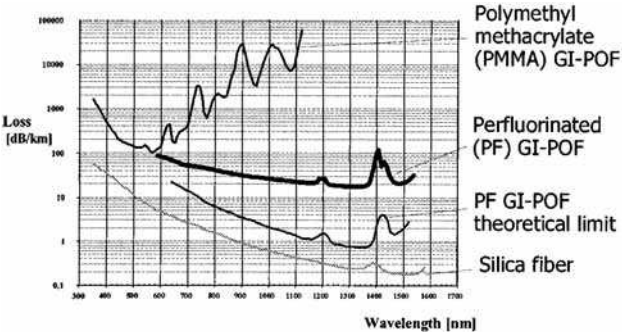


Fig. 11. Spectral attenuation of the graded index PMMF as compared to glass fibre [Van den Boom et al, 2001]

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.

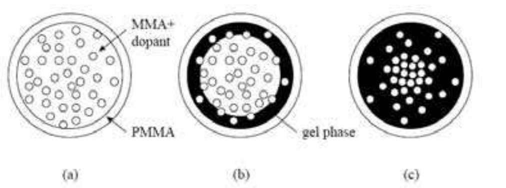


Fig. 12. Interfacial gel polymerization method used by Koike *et al* [Koike, 2002 – Koike, 1995]

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).

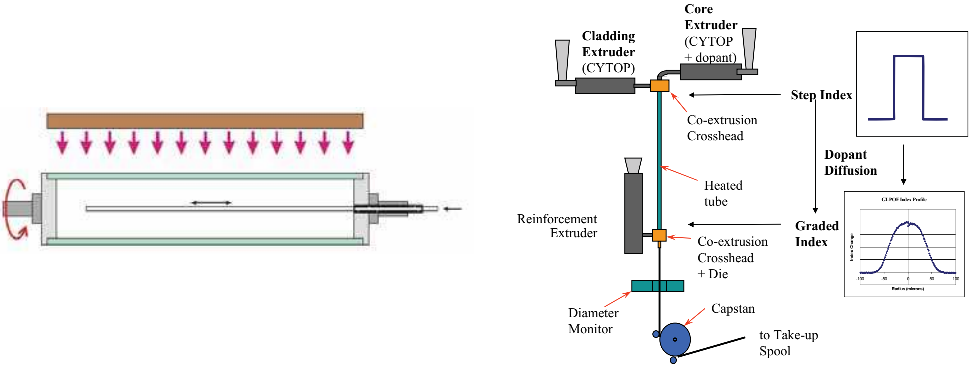


Fig. 13. Manufacturing processes used by Optimedia (Copolymerization [Park, 2006]) and Chromis fiberoptics (co-extrusion process [White, 2005])

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.

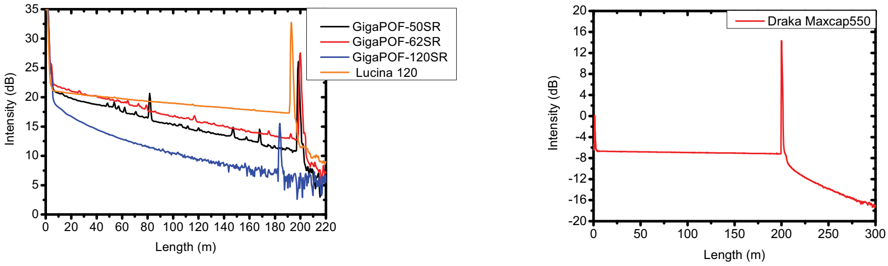


Fig. 14. Backscattering traces of the Lucina (PMMF) and the Chromis Fiberoptics fibres (PMMF) as compared to the Draka Maxcap550 (GMMF)

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.

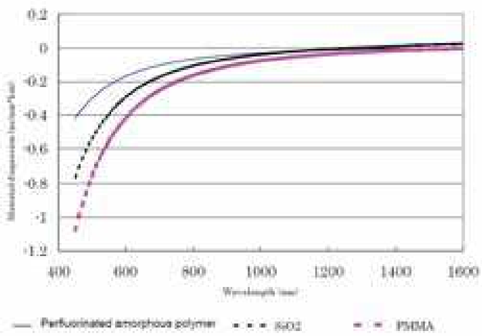


Fig. 15. Comparative study of material dispersion used in GMMF and PMMF [Asahi Glass]

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 for a low cost 10Gbps optical network.

In [Lethien, 2008], it has been proposed to investigate the use of conventional low cost devices such as VCSEL (Vertical Cavity Surface Emitting Laser) and PIN photodiodes with plastic fibre in order to have a pragmatic approach of the future high speed optical network. Phyworks technology [Phyworks], based on the use of Electronic Dispersion Compensation devices (EDC) placed at the electrical output of a conventional photoreceiver (here, a GaAs photodiode), has been used. The EDC technology allows overcoming the modal dispersion of the multimode fibres either in glass or polymer. Phyworks company wants to produce 10Gbps TX/RX module including VCSEL TOSA (Transceiver Optical SubAssembly) and driver for the TX part and photodiode ROSA (Receiver Optical SubAssembly), EDC and transimpedance amplifier (TIA) chips for the RX part with target price of less than 200$ per module. The coupling pair EDC/TIA cost should be around 55$ (low cost devices contrary to the ones used in the previous studies [Pedrotti, 2006], [Li, 1999], [Giaretta, 2000]). The EDC technology is a cost effective solution to struggle the intermodal dispersion inherent to the optical link based on the multimode fibre. The Phyworks serial EDC replaces the existing Clock Data Recovery (CDR) of a classical XFP transceiver.

The transmission of a 10.3125Gbps baseband signal over 4 polymer fibres (GigaPOF50-SR, GigaPOF62-SR, GigaPOF120-SR and Lucina) have been performed (fig. 15). As mentioned previously, the study done by Giaretta *et al* [Giaretta, 2000] has been achieved at 1300nm and with a 130µm core diameter PF GIPOF. This fibre has been excited in restricted mode launch conditions with the use of a single mode fibre coupled to the 1300nm laser in order to decrease intermodal dispersion effects. Moreover, in order not to induce mode filtering at the receiver and to reduce the coupling losses due to the large core diameter of the fibre, Giaretta *et al* have used a collimating lens and a focusing lens inducing 4.8dB coupling losses.

The study reported by Lethien *et al* [Lethien2, 2008] is realized at 850nm (low cost 10G XFP transceiver) and without adaptive optics due to the fibre core diameter. In order to exhibit the power dispersion penalties for all the fibres under test, we have measured the BER as a function of the received optical power in the back-to-back case and by inserting the required length corresponding to the 4 fibres under test.

The BER measurements realized on the GigaPOF50-SR PF fibre did not provide goods results (no error free in all case even if we remove the optical attenuator due to a default of concentricity of the fibre core regarding to the cladding). The exhibited power dispersion penalties are summarized for a BER=10^{-9} in the table 3.

	From Chromis fiberoptics manufacturer				From AGC Manufacturer
Fiber type	50A	62.5A		120A	120B
With EDC	-	3.5	4	4	3.5
Without EDC	-	6	-	>9	9

Table 3. Measurement of the power dispersion penalties (dB) of the optical link

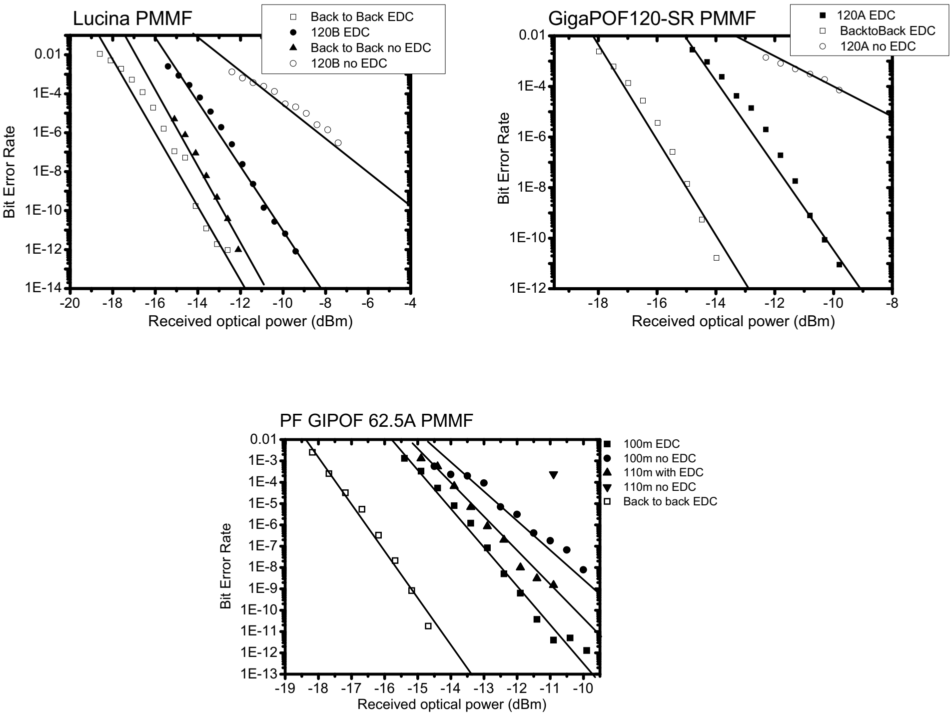
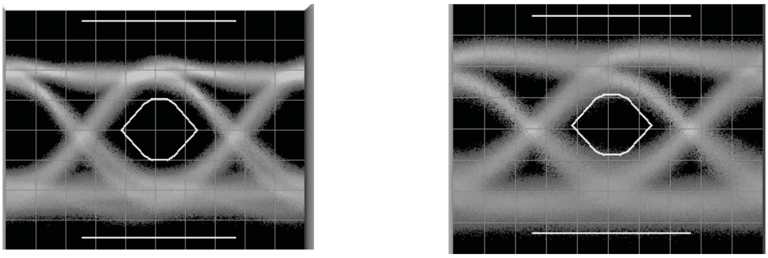


Fig. 16. BER as a function of the received optical power

The 3 presented PMMF coupled to an EDC device exhibit power dispersion penalties around 4dB. These penalties are inherent to the modal bandwidth of the fibre. As described in the datasheets of the Picolight XFP module, the worst case distance range of a 10.3125Gbps signal over a 50/125 GMMF with a Bandwidth-length product of 400MHz.km (500MHz.km) is 66m (82m). These BL products have been given in order to have a comparative reference with the measured modal bandwidth of the 4 PMMF under test. As mentioned previously, the 50µm based PMMF cannot transmit such kind of high bit rate signal. The two 120µm core diameter PMMF exhibit a power dispersion penalties around 3.5dB with the use of an EDC device and 9dB without dispersion compensation.

The number of propagation modes in an optical fibre depends on the core diameter. The 120µm PMMF owns a larger core diameter than the 62.5µm based PMMF. By the way, the propagated modes in the 120µm - core fibre are much numerous in that case. The intermodal dispersion in the large core PMMF is then much higher than in the GigaPOF62-SR fibre. These results have been demonstrated by the power dispersion penalties measurement in between the two fibres without the use of an EDC device (5dB for the 62.5µm PMMF compared to 9dB for the 120µm PMMF). Nevertheless, all these power dispersion penalties have been induced not only by the modal bandwidth limitations of the fibre but also by a mode filtering at the receiver (active area # 70µm).

The transmission of a 10Gbps signal has been achieved over 100m of the 62.5µm core diameter PMMF with a BER=10^{-12}. The length of the optical link realized with the used fibre is higher than the range of the optical link based on GMMF provided in the datasheets of the Picolight module (BL product # 400-500MHz.km – length 66m/82m). The additional range gained with the use of an EDC device at the photoreceiver side is equal to 18m which demonstrated the potential of the dispersion compensation devices coupled with the 62.5µm core diameter based perfluorinated based PMMF. In the fig. 16, the mask testing measurements regarding to the transceivers type including and not EDC devices are performed on the GigaPOF62-SR (100m length). By using the conventional photoreceiver (RX part of the low cost Picolight XFP), the BER is closed to 10^{-7} and set around 3.10^{-12} with the use of the EDC device. The eye opening is then higher with the use of the EDC device. It has been shown that the EDC device enhances the signal quality by reducing the intersymbol interference phenomena which demonstrates without any doubt the potential of this kind of device.



GigaPOF62 with EDC GigaPOF62 without EDC

Fig. 17. 10GBase-SR mask testing of the 62.5A PF GIPOF

The 40Gbps transmission over 30m of the GigaPof-50SR both at 1550nm and 850nm has already been reported by [Polley, 2007]. An increase of the link length is then realized by the same group and similar transmission over the perfluorinated based PMMF having a core diameter value close to 50µm has been yet demonstrated by Polley *et al* [Polley, 2008]. The link is limited to 100m and the laser is a FP laser operating at 1315nm.

In 2007, a precise comparative study between GMMF and PMMF has been performed regarding to the sensitivity of such fibres to the offset launch for data rate close to 40Gbps and link length less than 100m [Schöllmann, 2007]. The feasibility of error free transmission at 1550nm with either 100m of GMMF (OM3 type) or 50m of PMMF (GigaPOF50-SR) is so demonstrated for 40Gbps signal. To obtain such results, offset launches close to ±3µm for the GMMF and ±10µm for the PMMF have been exhibited.

4. Radio over Fibre (RoF) systems

Radio over Fibre (RoF) systems use optical carriers to distribute micro- or millimeter-wave signals. Contrary to the previous part dedicated to baseband signals, the RoF concept deals with narrow band or broadband signals exhibiting a modulation bandwidth between several MHz (for narrow band signal) to more than 500MHz for the future Ultra Wide Band signals. In spite of the reduced bandwidth, high data rates combined with portability could be obtained. Such systems are used on applications, such radars, on several kilometres spans. An interesting use of these systems in telecommunications is to distribute wireless telecom signals all over an indoor or shadowed area. In that case, multiple access points are needed on a coverage zone that is typically less than 1km diameter wide. The concept is then declined as a picocellular system in which each elementary cell covers a maximum of some hundreds of meters. But most of time, these elementary cells will cover a unique space or room (fig. 17). The coverage of a building can then be done using a central office which receives/emits signals either by radio or fibre optics systems and distributes them to a multitude of remote antenna units which are optically fed. These remote antenna units deliver the downlink signals and receive the uplink ones within their dedicated picocell area.

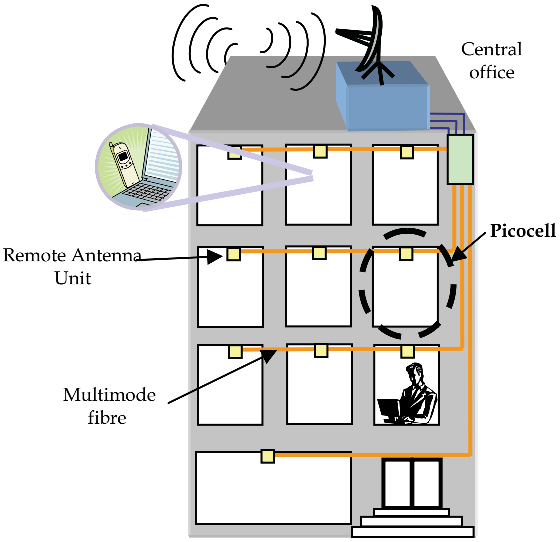


Fig. 18. Schematic of radio over fibre picocellullar indoor system.

Two kinds of systems can be distinguished. The first one deals with RF signals having a carrier frequency up to 10GHz and is mainly dedicated to the optical transport of wireless communication bands, wireless signals. In that case, the RoF system acts as a relay for these signals. The second one is more advanced and is based on an optically generated micro- or even millimetre wave signal (up to 60GHz frequency bands); the achievable data rate could be then as high as several hundred of Mbps and up to the Gbps. These systems are dedicated to the transfer of huge amount of data within the same building such as hospitals or banks. They can act as stand-alone internal systems without any external connections. This application field dealing with the millimetre wave RoF system is covered in another chapter of this book.

An overview of the wireless signals used in a radio over fibre systems will be performed just before the description of the RoF topologies and RoF systems.

4.1 Evolution of the Wireless communications networks

The radio over fibre concept complies with the radio spectrum dedicated to broadcast and wireless applications having a carrier frequency up to 1GHz (AM and FM radios, TV broadcast…). The RoF system covers also the microwave as well as the millimetre waves (radiocellular, WLAN, WPAN…) with carrier frequency from 1GHz up to 100GHz.

From a radio frequency point of view, a radio signal is disturbed when the propagation is done in a confined space, for example inside a building or a tunnel. The aim of a RoF deployment is either to improve the indoor coverage of a wireless signal or to increase the connectivity of an ad-hoc network. This chapter focuses only on wireless standards mainly created by the major normalization organisms (IEEE, ETSI, 3GPP, 3GPP2…) and generally divided into three main categories depending on the application field:

- the radio-mobile signals
- the Wireless Local Area Network (WLAN) standard
- the Wireless Personal Area Network (WPAN) standard

The radiocellular concept deals firstly with the deployment of the 2nd generation of mobile equipment (ME). Depending of the country where the mobile network is implemented, several standards have been investigated. The 2nd generation of the radio-mobile standard (IS-136 ; GSM ; PDC and PDC-P ; cdmaoneA) has a data rate limited to 14.4kbps except for the PDC with 30kbps value.

Before the deployment of the 3rd generation, an intermediary step is added and known under the 2.5 generation (IS-136+; GSM/GPRS or GSM/HSCSD ; cdmaoneB; cdma2000 phase 1) in order to provide furthers services requiring much data rate (internet, video exchange…). Theoretically, the data rate is close to 100kbps. The EDGE radiocellular standard corresponding to an improvement of the GSM one is used for data transmission at 384kbps. The 3rd generation of mobile networks is deployed with throughput up to 2Mbps all over the world for responding both to the exponential growing of video media exchanges and the internet traffic. The main problem is related to the inter-operability between the different standards deployed all over the world (IS-136HS, UMTS, cdma200 phase 2). The convergence of the three last cited standards is known under the HSDPA and HSUPA acronyms (High Speed Downlink/Uplink Packet Access) linked to the 3.5th generation deployment: the data rate is close to 14.4Mbps. In 2010, a new emerging standard is going to be deployed as the future radio-mobile standard. The Long Term Evolution (LTE) represents the future of the UMTS standard as it evolves from an architecture supporting both circuit-switched and packet-switched communications to an all-IP, packet-only system. The so-called LTE is related to the 3.9th generation and provides throughput up to 300Mbps with a specific quality of services (QoS) depending on the mobile speed (Optimized performance for low mobile speeds from 0 to 15 km/h – supported with high performance from 15 to 120 km/h - functional from 120 to 350 km/h). The QoS of mobile communications with speed comprising between 350 to 500 km/h is currently under consideration. Regarding to all the radio–mobile generations, the carrier frequency of such wireless networks is comprised between 900MHz and 2.62GHz.

The indoor coverage of a signal issued from a Wireless Local Area Networks (WLAN) is very sensitive to the material used to fabricate the building. The main WLAN standard is the Wireless-Fidelity, known under the acronym WiFi or IEEE802.11. Several declinations of such standard are related to the data rates and the operating frequency. The table 4 summarizes the basic properties of the WiFi standardized by the IEEE organism. The data rate varies from 11Mbps up to 54MBps depending on the standard release. The IEE802.11a has been used in United States. The IEEE802.11b and IEEE802.11g are dedicated to Europe. The radio range is generally close to 140m in free space configuration and is reduced for in building communications (35m) as well as the bit rate.

	IEEE802.11a	IEEE802.11b	IEEE802.11g
Carrier frequency	5.825 GHz	2.412 GHz	2.412 GHz
Modulation scheme	64QAM - OFDM	CCK - DSSS	64QAM - OFDM
Data rate	54Mbps	11Mbps	54Mbps
filter	BT = 0.5	BT = 0.5	BT = 0.5

Table 4. Overview of the IEEE802.11 standard

In June 2009, the IEEE802.11n will be expected to propose high data rate (250Mbps) and long range transmission inside a building (more than 70m) especially thanks to the use of multiple antennas (Multiple Input Multiple Output system (MIMO)).

In order to develop personal network without cable (Wireless Personal Area Network – WPAN) for computer office applications or radio mobile systems, several protocol have been created either for low or high data rates transmission. A standard created by Ericsson in 1994 (Bluetooth) for low bit rate wireless communication has been used over the unlicensed ISM band (2.4GHz). The data rate is close to 3Mbps and the radio range is limited to 10m when emitting less than 1mW RF power level. Launched by Nokia, the Wibree has been created to provide a short radio range (5m) and low data rate standard with a fewer consumption than the Bluetooth (better than a 50 factor). The Wibree is unfortunately incompatible with the Bluetooth and since June 2007, a fusion between the two standards has been created over the “Bluetooth ultra low power”. An oriented low consumption wireless sensor networks (WSN) standard known under the acronym Zigbee (IEEE802.15.4) and using the ISM 2.4GHz unlicensed frequency bands in Europe has been used for domotic applications. The data rate is well limited to 250kbps and a new modulation scheme is under development with the use of ultra wide band concept.

The Ultra-Wideband standard (UWB) is becoming the common wireless technology for short haul - high data rate wireless communications and sensor networks. Regulated by the Federal Communications Commission (FCC) in the USA since April 2002, the UWB technology operating in the frequency range between 3.1GHz up to 10.6GHz and two proposals of this standard have been investigated by laboratories and manufacturers depending on the modulation schemes in the IEEE 802.15.3a working group. The standardization of the high data rate (>200Mbps) ultra-wideband technologies has been firstly studied. The Direct Sequence (DS) and the Multiband Orthogonal Frequency-Domain Multiplexing (MB-OFDM) ultra-wideband technologies are in competition and the supporting organizations who support each proposal continue to promote them outside of the IEEE task group. The DS-UWB [Yao, 2007] is based on the use of the position, amplitude or phase modulation of a sub-nanosecond pulse and is supported by the UWB Forum. The standard jointly published by the Wimedia alliance and the Multiband OFDM alliance defines the specifications of the OFDM physical layer and is known under the name ECMA-368 (ISO specifications). This ECMA Standard [ECMA 368, 2007] specifies the ultra-wideband physical layer (PHY) and medium access control (MAC) sublayer for a high-speed short haul wireless network, utilizing the frequency range described above and supporting data rates of up to 480 Mbps. The ECMA-368 standard is divided into 14 unlicensed bands, each with a bandwidth of 528 MHz (fig. 18). The first 12 bands are then grouped into 4 band groups, each of them being composed of 3 frequency bands. The last two bands are grouped into a fifth band group. The sixth band group consists of bands 9 to 11 which overlaps band groups 3 and 4. The Wimedia standard uses the MB-OFDM modulation scheme to transmit information through a wireless personal area network (WPAN). A total of 110 sub-carriers (100 data carriers and 10 guard carriers) are used per band. In addition, 12 pilot subcarriers that allow for coherent detection bring out a total of 122 subcarriers spaced 4.125MHz apart. The occupied bandwidth is nominally 528MHz and the signal subcarrier could hop in frequency according to predetermined patterns known as Time-Frequency Code (TFC). The MB-OFDM UWB standard provides throughput from 53.3Mbps up to 480Mbps depending on the modulation schemes over 2m to 10m range. The power spectral density is closed to -41dBm/MHz over the UWB spectrum. QPSK modulation is used for data rates up to 200Mbps and Dual Carrier Modulation (DCM) scheme is dedicated to 320, 400 and 480Mbps throughput: the DCM modulation consists in the grouping of 4 bits onto two separate constellation maps to obtain the same structure that of a 16QAM modulation scheme. Each of these 16QAM constellations is then modulated onto two subcarriers spaced 206MHz apart allowing to decrease the probability that both suffer simultaneously from fading. Since March 2007, the ECMA-368 standard has been recognized as the ISO/IEC 26907 international standard (ISO/IEC 26907:2007 Information technology -- Telecommunications and information exchange between systems -- High Rate Ultra Wideband PHY and MAC Standard).

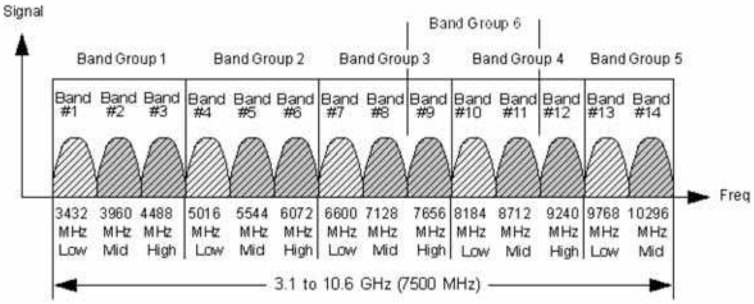


Fig. 19. Allocation of the frequency bands for UWB band groups [2]. Each band has a 528MHz bandwidth and central frequency is indicated.

All the radio standards presented in this part could be evaluated with the use of modulation quality metrics such as the Error Vector Magnitude or the Relative Constellation Error (RCE) given by the standardization organisms (ex: IEEE, ETSI…). The Error Vector Magnitude – expressed in percentage or dB – is defined as the vector difference at a given time in between an ideal reference signal and the measured signal submitted to residual noise and distortion induced by the radio over fibre system (fig. 19).

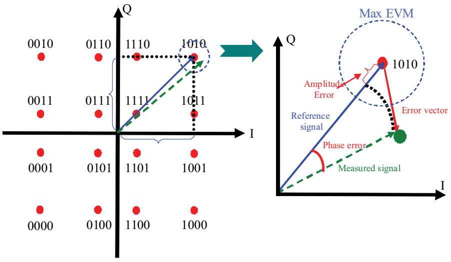


Fig. 20. 16 QAM modulation scheme and schematic view of the Error Vector Magnitude parameter

As mentioned previously, the improvement of the indoor coverage of all the presented standards could be realized with the use of the radio over fibre concept and the main topologies are described in the next part.

4.2 Topologies used for the distribution of radio signal over the optical fibres

According to A. Seeds point of view [Seeds, 2002], the availability of the first semiconductor lasers and electro-optic modulators combined with the development of the low loss silica optical fibres (either singlemode or multimode) as well as the development of PIN and avalanche photodetectors since 30 years has lead to the birth of the radio over fibre technology. For indoor or shadow area coverage of radio communications systems, picocellular RoF systems are fine alternatives since they allow distributing signals where global distribution systems are ineffective. Their coverage range is some tens to hundred meters. A typical system uses a base station which optically fed remote antenna units with the RF signal which is modulated on the optical carrier. Since the coverage is rather small, electromagnetic pollution can be greatly reduced since emitted RF power can be 30 dB lower than for classical systems, i.e. 20 mW in spite of 20W. This optical carrier is carried on optical fibre up to the remote antenna units. The application field of this chapter is related to the multimode fibre either in glass or polymer and whatever the optical carrier and wavelength are, the transmission of signals can been achieved using three main schemes.

4.2.1 Baseband over fibre (BB over Fibre)

The radio signal is received and the data are extracted (A/D) as a binary sequence in the central office. These data are used to modulate the optical emitter (EO). At the remote antenna unit, once detected (OE) they are converted (D/A) to modulate a RF carrier (provided by a Local Oscillator that is locally generated) (fig. 20). These data are use to modulate the optical emitter (EO). At the remote antenna unit, once detected (OE) they modulate again (D/A) a RF carrier (provide by a Local Oscillator) that is locally generated (fig. 20). This topology adds complexity and cost in each remote antenna due to the embedded required electronics. Anyway, it is the less stringent on optical link requirements since only the data stream (less than 1Gbps data rate) is carried on it. The GMMF or PMMF fibres are considered to be the low cost solution here but obviously SMF can be used with an increase in the connection cost. Transceivers are here digital transceivers as used in GbE transmission.

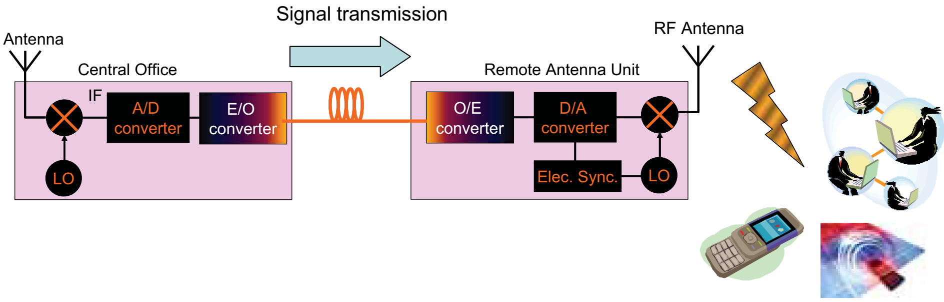


Fig. 21. Data over fibre transmission scheme

4.2.2 Intermediate Frequency over Fibre (IF over Fibre)

The radio signal is down-converted to a lower frequency and the resulting IF signal is sent through the fibre. At the remote antenna unit, this IF signal is mixed with a local oscillator one to re-generate the RF signal (fig. 21). This scheme adds lower complexity at remote antenna units that the previous one since only RF circuitry is needed. We are now dealing with an analog optical transmission link. The same comment as above concerning the type of fibre that can be used can be made.

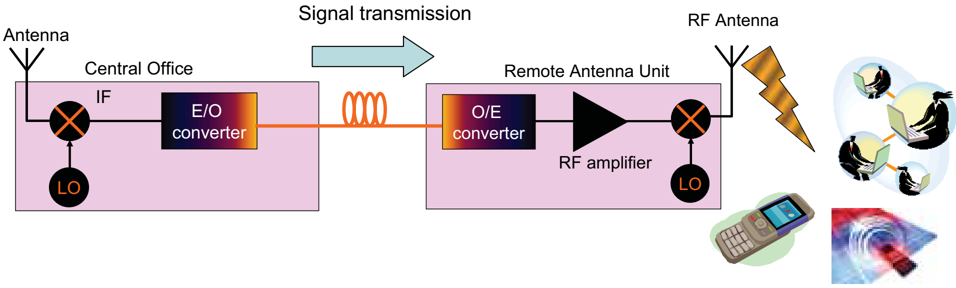


Fig. 22. IF over fibre transmission scheme

4.2.3 RadioFrequency over Fibre (RF over Fibre)

This is the simplest way of implementation as well as the lower cost for the remote antenna units. The RF signal directly modulates the emitter and is directly re-emitted at the remote antenna unit (fig. 22). But this scheme requires enhanced performance for the optical emitters and receivers since they have to transmit the carrier frequency of the radio signals.

If that one is roughly below 10 GHz, this transmission scheme shall be affordable, above 10 GHz, IF over fibre scheme shall be considered as a more potential cost effective solution.

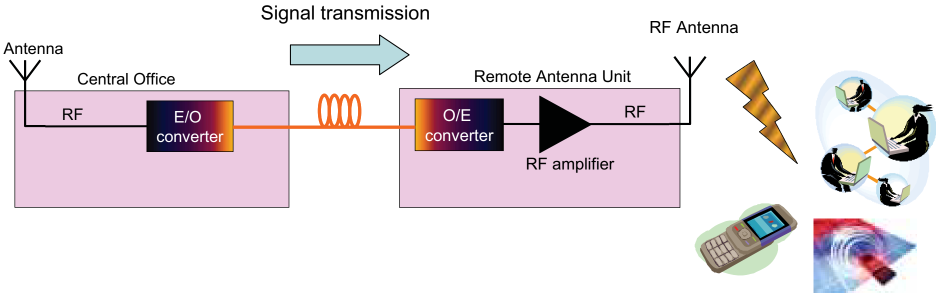


Fig. 23. RF over fibre transmission scheme

4.2.4 Architecture of a bidirectional access point

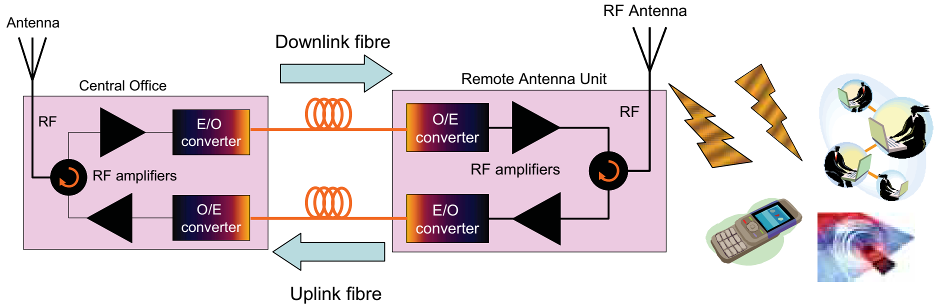


Fig. 24. Schematic view of a bidirectional access point

In order to realize the bidirectional aspect of the radio link (up and downlink), the remote antenna unit has to integrate both an E/O emitter, an O/E receiver and the RF circuitry able to achieve the corresponding topologies (BB over fibre, IF over fibre and RF over fibre). In the fig. 23, the easiest RF over fibre topology is described just with the use of a RF circulator to separate the up and down streams. Regarding to the link budget of such RoF system (mainly 30dB RF losses), RF amplification has to be done to overcome the RF losses either in downlink with the use of a Medium Power Amplifier (MPA) or with a Low Noise Amplifier (LNA) able to provide a small noise factor for the uplink.

4.3 State of the art of the Radio over multimode fibres system

The previous part has demonstrated the potential of the radio over multimode fibre technology to improve the indoor coverage of radio signals between different offices located in a building where a multimode fibre based network has been already deployed. As described, the radio over fibre (RoF) technology allows to optically transport a radio signal through an optical fibre and so to extend the wireless range beyond 10m. The pragmatic approach of these studies, based on the use of multimode fibres either in glass or polymer associated with commercial off the shelf (COTS) devices (Vertical Cavity Surface Emitting Laser (VCSEL) and photodiode), induces the use of the intensity modulation – direct detection technique (IM-DD) without sophisticated architecture.

In the following, we will consider in most of the case the RF over fibre topology since it is potentially THE low cost solution owing to the fact that very few electronics are required within the remote antenna units. This solution will be even more effective if transmission can be done on multimode fibre that constitutes the main part of the pre-installed fibres in buildings for gigabit Ethernet applications. The modal characteristic of this kind of fibre restricts the system bandwidth but high modal bandwidth multimode fibres have been developed as described previously. Therefore, Wake *et al* [Wake, 2001] demonstrated that it is possible to overcome this limitation even transmitting complex modulation schemes (32 QAM) having a bit rate of 10Mbps on a RF sub-carrier (2 GHz) trough 1 km of GMMF OM2 at 1.3µm. On fig. 24, the constellation as well as the eye diagrams of such a signal is represented before and after the optical transmission. As it can be observed, no real degradation appears even considering the bandwidth of the optical fibre is 500MHz.km. This work is considered as the beginnings of the radio over multimode fibre concept.

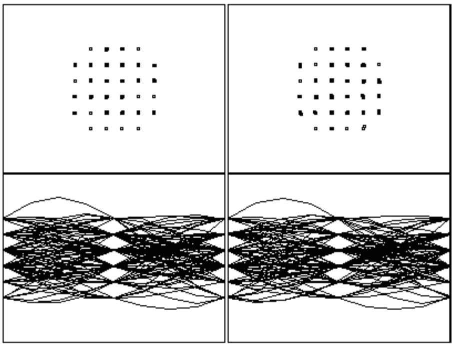


Fig. 25. IQ Constellation (top) and eye (bottom) diagrams of a 32 QAM signal on 2 GHz RF carrier before (left) and after (right) its transmission on a GMMF based RoF system [Wake, 2001]

4.3.1 RoF system developed with GMMF

The joined researches lead both by the University of Cambridge and the University College London in the Friday (Fibre Radio for In-building Distributed Antenna sYstems) project are focused on the market dealing with the extended coverage of second generation (2G), 3G mobile and WLAN networks in deployment areas such as corporate office buildings, shopping centres and airports [Wake, 2002]. The indoor coverage of such signals can only be improved using distributed antenna systems (DAS) within the building since the signal penetration from outside base stations is unreliable (fig. 25). In the Friday project, the exploitation of low-cost solutions (850nm VCSELs and subcarrier transmissions over pre-installed multi-mode fibre (MMF)) is performed to design and implement a low-cost and multi-services fibre-based DAS (GSM (900MHz and 1800MHz), UMTS (2GHz) and WLAN (5-6GHz)). The topology used for optically deport both the IEEE802.11a and IEEE802.11g

WLAN standards in the Friday project is presented on the fig. 25.

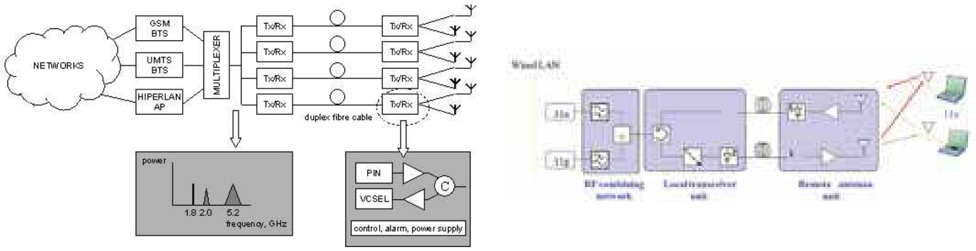


Fig. 26. RoF topology used in the Friday project (left) and for the WLAN standards (right)

Tyler *et al* have demonstrated the possibility [Tyler, 2002] to use the low bandwidth GMMF having a core diameter of 62.5µm for achieving the transmission of a 2.5Gbps Sub-Carrier Modulated signal (SCM) over 300-m length at 1300nm.

Chia *et al*. [Chia, 2003] have reported the transmission performance (error vector magnitude (EVM) variation) of the 50- m-core high bandwidth MMF (2000 MHz km at 850 nm) used in radio-over-fiber systems (RoF) for WLAN IEEE 802.11 a/b/g signals. Hartmann *et al*. have done some studies dealing with an RoF system operating at 1300 nm with 62.5- m-core MMF (500MHz km) for WLAN distribution system [Hartmann, 2004]. The performance (frequency response, spurious-free dynamic range, link gain, and noise figure) of two RF links using two 50µm-core MMF have been compared by Carlson *et al*. for the transmission of wireless telecom and local area networks signals at 840 nm [Carlsson, 2004].

In [Lethien, 2005] the transmission of digital signal modulated on radio-frequency subcarriers through GMMF by using low-cost 850nm vertical-cavity surface-emitting lasers and 50µm/62.5µm core matched receptacle photodiodes. Several mobile telecommunication (GSM, UMTS FDD) and WLAN standards (IEEE802.11a, b, g) have been transmitted over the OM2 Corning Infinicor 600 and the Corning Infinicor SXi (BL product at 850nm: 500MHz.km and 1500MHz.km) and high bandwidth OM3 Infinicor SX+ (BL product at 850nm: 2000MHz.km) GMMF. Several fibre lengths (100, 300m and 600 m) have been tested in an RF over fibre transmission scheme.. Characterization has been carried out to exhibit the error vector magnitude (EVM) variation as a function of fibre type and length. EVM minor to IEEE requirements are obtained for all standards being tested such as IEEE 802.11 g with 1.8% root-mean-square for 300 m of 50µm-OM2 GMMF at 850 nm as shown in the fig. 26. The UMTS transmission over GMMF and using a singlemode VCSEL has been realized by [Persson, 2006]. An EVM value close to 3% is reported in this paper when using the OM3 type GMMF in a link operating at 850nm. In [Nkansah, 2006], the performance measurements of different combinations of digital enhanced cordless telecommunications packet radio service, global system for mobile communications, universal mobile telecommunication service, and IEEE802.11g (54 Mbps) signals in a dual band configuration has been performed (fig. 27). The RoF system consists in the use of the RF over fibre topology with 300 m OM2 GMMF combined with low cost 850nm COTS VCSEL and photodiode.

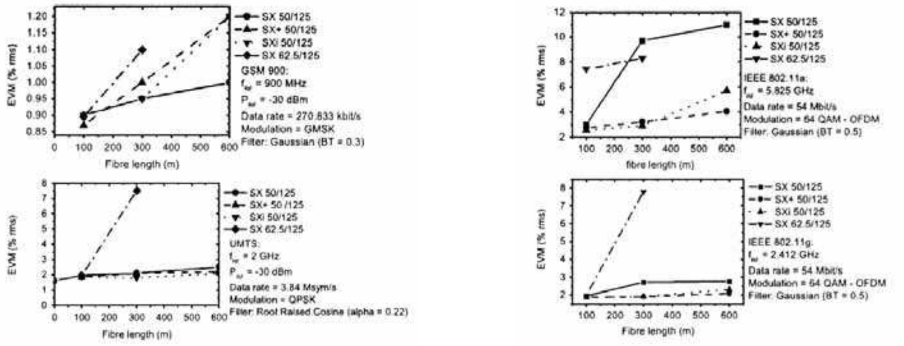


Fig. 27. Error Vector Magnitude as a function of the fibre length for the GSM, UMTS, IEEE802.11a and IEEE802.11g standards [Lethien, 2005]

The feasibility of such a system is demonstrated with error vector magnitude measurements which are within the required specifications. Inexpensive and omnidirectional multiband antennas were used in the wireless path. EVM has been evaluated both for the transmission of UMTS and IEEE802.11g standards over 300m OM2 GMMF followed by 4m wireless transmission. 8.8% and 4.7% EVM values are respectively obtained for the UMTS and the WiFi at the central unit in the uplink configuration.

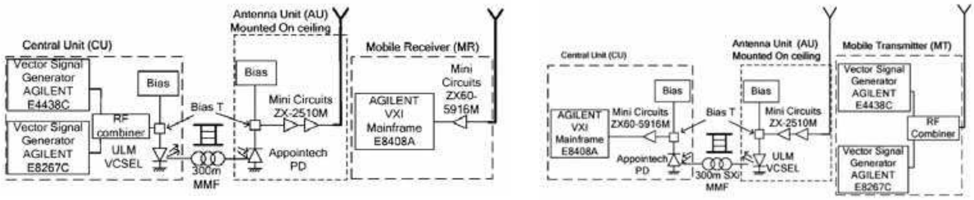


Fig. 28. Downlink (left) and uplink (right) configuration of a simultaneous transmission of dual band radio standards [Nkansah, 2006]

Today, one of the interesting topic concerns the feasibility of using the RoF concept to optically deliver the ultra-wide band signal to achieve long haul and high speed hybrid network. Previous studies have been already achieved on the UWB radio over fibre system but have been limited to one type of glass fibre (singlemode fibre: [Tabatabai, 2006] and multimode fibre [Yee, 2007], [Guo, 2008]) and packet error ratio (PER) measurement. In [Ben Ezra, 2008] paper, a theoretical modelling of a 4GHz Ultrawide Band (UWB RoF) radio over multimode fibre link operating at 850nm is presented as well as the experimental measurement over GMMF having a length more than 500m. The PER has been evaluated as a function of the fibre length. A 1m wireless path strongly degrades the overall performance of the used system developed in the framework of the UROOF European project (Photonic components for UWB over optical fiber IST-5-033615). Pizzinat *et al* [Pizzinat, 2007] have demonstrated the possibility of transmitting a MB OFDM UWB signal having a data rate of 1.92Gbps over 500m link length composed of the OM2 GMMF (BL product: 700MHz.km at 850nm). The measured BER in the two different frequency bands of the transmitted signal

(3.1GHz – 4.7GHz or 6 to 7.6GHz) are respectively 10^{-8} and 10^{-6}, values obtained with TOSA and ROSA devices (Transmitted or Received Optical Sub-Assembly) inserted in a point to point topology. The feasibility of a multipoint to multipoint architecture has been demonstrated by Pizzinat *et al* [Pizzinat, 2008] for the distribution of UWB MB OFDM signal over multimode fibre with low cost devices.

4.3.2 RoF system developed with PMMF

Regarding to the PMMF available on the market, only the perfluorinated CYTOP® based PMMF is used for the distribution of radio signals over optical multimode fibre, mainly owing to its relative low attenuation in the infrared domain (contrary to the Plexiglas based PMMF). The use of the PMMF in RoF systems is mainly exploited by two different groups localized on the one hand in Eindhoven University of Technology (The Netherlands) and on the other hand, in the University of Lille 1 (France).

Koonen's group [Koonen, 2008] has developed a special topology based on optical frequency multiplication (OFM) to transmit radio signal over the Lucina fibre as described in figure 28. The so called OFM technique is based on FM to IM conversion and is very robust against modal dispersion occurring in multimode fibre communication.

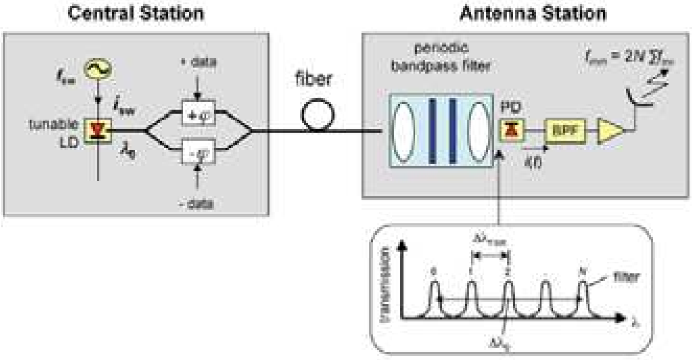


Fig. 29. Overview of the OFM method [Koonen, 2008]

The wavelength of a tunable optical source is periodically swept over a range $\Delta\lambda_0$ in the central station. The antenna station is composed of a periodic optical band-pass filter where the band-pass transmission peaks are spaced by the wavelength free spectral range ($\Delta\lambda_{FSR}$). The light issued from the frequency sweeping optical source goes back and forth inside the cavity of the band-pass filter resulting in the presence of transmission peaks. Light intensity bursts are then detected on the photodiode. A microwave signal is so generated at the fundamental frequency and also higher harmonics. An electrical band-pass filter (BPF) is used to select the specific harmonic allowing the propagation of the pure radiofrequency signal thanks to the antenna. A Mach Zehnder intensity modulator is used to modulate the frequency-swept optical carrier with the data stream: the resulting signal is not affected by the OFM process and is considered as the envelope of the optical sweeping signal before the photodetection. This OFM process could be used also with the GMMF.

In [Lethien, 2006], the improvement of the indoor coverage of radiocellular signals such as GSM and UMTS has been realized with the use of the Lucina fibre in a RoF topology based on the IMDD technique. The EVM has been evaluated after the transmission over a GMMF and PMMF in order to exhibit a different behaviour of the two fibres regarding to the radio signals. The results show that, the Lucina fibre constitutes without any doubt a promising candidate in RoF system using COTS components dedicated for GMMF. Moreover, because of its higher core diameter, PMMF does not induce modal noise penalties as occurred in GMMF link [Ishigure, 2003] and the alignment is also less critical what reduces the cost of the optical active and passive devices including the installation and maintenance costs of the connections. Its higher flexibility based on "plastic" material offers a great advantage compared to the silica fibre which is more brittle. Nevertheless, the higher core diameter of the fibre with respect to the active area of some high speed detectors is the cause of an additional power penalty.

Lethien *et al* [Lethien, 2009] has demonstrated the potential of GMMF and PMMF to transmit the Wimedia MB OFDM UWB standard over more than 1km and 200m respectively for the GMMF and the PMMF. The influence of the fibres properties (attenuation, bandwidth/length product…) on the link quality (fig. 29) has been performed and two different behaviours regarding to the core material have been exhibited.

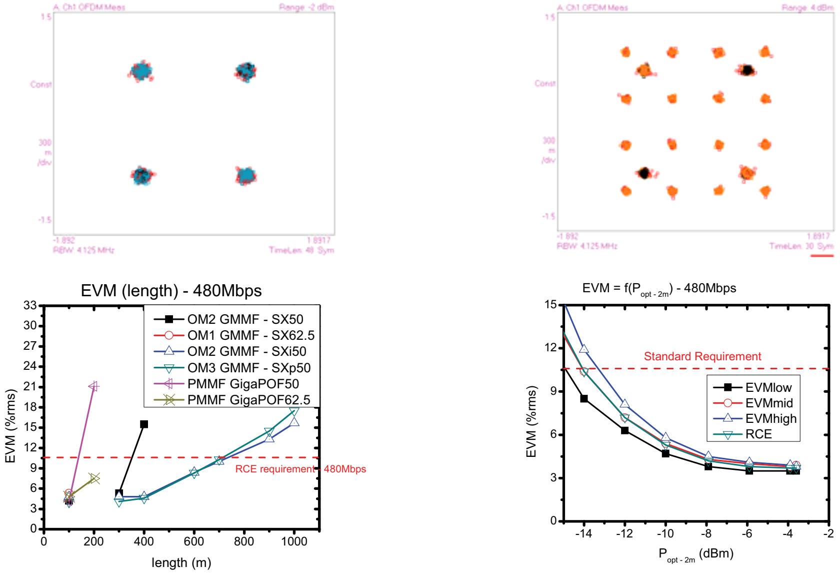


Fig. 30. IQ constellation diagrams (QPSK and Dual Carrier Modulation schemes) and evolution of the EVM as a function of the fibre length and the fibre attenuation

By using this preinstalled multimode fibre Ethernet networks, it would be possible to use the high potential of the fibre bandwidth coupled with the wavelength division multiplexing technique to successfully transmit multi-services application without impairments aiming to obtain a low cost infrastructure in term of service integration. The successful transmission on a single GMMF of the IEEE802.11g signal with the optical power used to supply the remote access points (principally composed by a laser, a photodiode and RF amplifier) is also reported by Wake et al [Wake, 2008] thanks to the use of the wavelength multiplexing method. The so obtained EVMs with electrical or optical power supplies are in the same order of magnitude.

The simultaneous transmission of a digital 10GbE signal and a radiofrequency MultiBand Orthogonal Frequency Division Multiplexing Ultra-Wide Band (band group 5) MB-OFDM UWB signal at 480 Mbps has been successfully achieved over 1.1km fiber length without any error and with RCE less than 5.5% rms, respectively by Lethien *et al* [Lethien2, 2009, Lethien3, 2009]. Concerning the radio signal, an additional 1-meter long wireless path has also been demonstrated that led to an RCE value of 7.2%.

5. Conclusion

This chapter describes an overview of the potentialities of the multimode fibre either in glass or polymer to be used for multi-services applications. The state of art of the existing GMMF and PMMF has been done with the advantages and drawbacks of the used core material. The manufacturing processes of such multimode fibres have been described to exhibit the fibre performances obtained regarding to the used processes. The transmission of multi-gigabits signal over both PMMF and GMMF is also reported for short range/high data rate wired networks. Moreover, the radio over fibre concept is introduced for the improvement of the indoor coverage of wireless signal in shadowed area with low cost and unsophisticated topologies. It has been demonstrated in this chapter that the multimode fibre constitutes, without any doubt, a promising candidate for home office/small office applications.

6. References

[Asahi Glass] Datasheets of the Asahi Glass Perfluorinated GIPOF "Lucina™", http://www.agc.co.jp/english/rd_e/e_lucina.html, 2009 (Tokyo, Japan)

[Ben Ezra, 2008] Y. Ben Ezra et al, "Experimental and theoretical investigation of the multiband OFDM Ultra Wideband Radio over multimode fiber transmission", in proceedings of the 2008 IEEE International conference on ultra-wideband (ICUWB 2008), vol. 3, pp 55-58.

[Bennet, 2004], M. Bennett, A. Flatman, B. Tolley, "Broad Market Potential of 10Gb/s Ethernet on FDDI grade MM Fiber," IEEE802.3, (2004), http://www.ieee802.org/3/tutorial/mar04/10GMMF_SG_v031604a.pdf

[Carlsson, 2004] C. Carlsson, A. Larsson, and A. Alping, "RF tranmission over multimode fibers using VCSELs—Comparing standard and high bandwidth multimode fibers," J. Lightw. Technol., vol. 22, no. 7, pp. 1694–1700, Jul. 2004.

[Chia, 2003] M. Y. W. Chia *et al*, "Radio over multimode fiber transmission for wireless LAN using VCSELs," Electron. Lett., vol. 39, no. 15, pp. 1143–1144, 2003.

[Chromis] Datasheets of the Chromis Perfluorinated GIPOF "GigaPOF", http://www.chromisfiber.com/products.htm, 2009 (Warren, USA)

[Corning] Datasheets of the Corning™ fibers, http://www.corning.com/opticalfiber/products/infinicor_fibers.aspx, May 2008 (New York, USA)

[Draka] Datasheets of the Draka fibers, http://www.draka.com/draka/DrakaComteq/Drakafibre/Languages/English/Navigation/Markets&Products/Technical_Suppo

rt/Datasheets/DCOF_MaxCap-550.pdf, September 2008 (Amsterdam, The Netherlands)

[Duijnhoven, 1999] Franciscus G.H. van Duijnhoven, "Gradient refractive index polymers produced in a centrifugal field : preparation, characterisation and properties", - Eindhoven : Technische Universiteit Eindhoven, 1999. Proefschrift. - ISBN 90-386-2581-2, http://alexandria.tue.nl/extra3/proefschrift/boeken/9902697.pdf

[ECMA 368, 2007] Standard ECMA-368, "High Rate UltraWideband PHY and MAC Standard," 2nd edition, (December 2007), http://www.ecma-international.org/publications/standards/Ecma- 368.htm

[Giaretta, 2000] G. Giaretta et. al. "High-Speed (11 Gbit/s) Data Transmission Using Perfluorinated Graded-Index Polymer Optical Fibers for Short Interconnects (<100m)," IEEE Photon. Tech. Lett. **12**, 347-349 (March 2000)

[Guo, 2008] Y.-X. Guo, V. H. Pham, M.-L. Yee, L. C. Ong, B. Luo, "Performance evaluation for WiMedia Ultra-Wide Band simultaneous Transmission with wireless LAN over cable and Fiber," in Proceedings of IEEE Radio and Wireless Symposium (IEEE, 2008), pp 259-262

[Hartmann, 2004] P. Hartmann, X. Qian, R. V. Penty, and I. H. White, "Broadband multimode fiber (MMF) based IEEE 802.11a/b/g WLAN distribution system," in Microwave Photonics Conf. Proc. (MWP 2004), 2004, pp. 173–180.

[IEC 60793-2-10] Standard IEC 60793-2-10, "Optical fibres – Part 2-10: Product specifications – Sectional specification for category A1 multimode fibres", (June 2007),

[IEC 60793-2-40] Standard IEC 60793-2-40, "Product specifications – Sectional specification for category A4 multimode fibres," 2nd edition, (March 2006), http://webstore.iec.ch/webstore/webstore.nsf/artnum/035855

[Ishigure, 1998] T. Ishigure *et al* "High bandwidth low loss Graded index polymer optical fibre for near infrared use", ECOC 1998, Madrid (Spain), September 1998

[Ishigure, 2003] T. Ishigure, K. Makino, S. Tanaka and Y. Koike, "High-Bandwidth Graded Index Polymer Optical Fiber enabling Power Penalty-Free Gigabit data transmission", Journal of Lightwave Technology, vol. 21, no. 11, November 2003, pp 2923-2930

[ISO 11801] Standard ISO 11801, "ISO 11801 - INFORMATION TECHNOLOGY - GENERIC CABLING FOR CUSTOMER PREMISES"

[Koike, 1995] Koike *et al*, "High-bandwidth, high-numerical aperture graded-index polymer optical fiber", JOURNAL OF LIGHTWAVE TECHNOLOGY, VOL. 13, NO. 8, August 1995 pp 1686-1691

[Koike, 1996] Y. Koike: "Status of POF in Japan", POF´1996, Paris 22.-24.10.1996, pp. 1-8

[Koike, 1997] Y. Koike: „Progress in Plastic Fiber Technology", OFC´1997, Dallas, pp. 103-108

[Koike, 2002] Koike *et al*, "High-Bandwidth Graded-Index Polymer Optical Fiber With High-Temperature Stability", JOURNAL OF LIGHTWAVE TECHNOLOGY, VOL. 20, NO. 8, AUGUST 2002 pp 1443-1448

[Koike, 2009] Kotaro Koike and Yasuhiro Koike, "Design of Low-loss Graded Index Plastic Optical Fibre Based on Partially Fluorinated Methacrylate Polymer", IEEE Journal of Lightwave Technology, Vol. 27, No. 1, January 2009

[Koonen, 2008] A.M.J. Koonen et al, "Radio over MMF technique – pat II: Microwave to millimetre wave systems", IEEE/OSA Journal of Lightwave Technology, vol. 26, no. 15, august 2008, pp 2396-2408

[Kuyt, 1999] G. Kuyt, P. Pleunis, A. van Bergen, and R. van Laere, "PCVD graded index multimode fibers for gigabit speed datacom applications using laser sources," in Proc. EuroCable , 1999, pp. 222–229.

[Lopez, 2008] M. Lopez and P. Ronco, "Advantages of the Corning optical fiber manufacturing process", white paper, available online at www.corning.com/WorkArea/downloadasset.aspx?id=10869

[Lethien, 2005] LETHIEN C., LOYEZ C., VILCOT J.P., « Potentials of radio over multimode fiber systems for the in-buildings coverage of mobile and wireless LAN applications", IEEE Photonics Technol. Lett., 17, 12 (2005) 2793-2795

[Lethien, 2006] LETHIEN C., GOFFIN A., VILCOT J.P., LOYEZ C., "Radio over fibre systems using perfluorinated graded index polymer optical fibre", Microw. Opt. Technol. Lett., 48, 6 (2006) 1197-1199

[Lethien1, 2008] C. Lethien, C. Loyez, J-P. Vilcot and A. Goffin, "Differential Mode Delay measurements of the fluorinated based Graded Index Polymer Optical Fibre", IEEE Photonics Technology Letters, Vol. 20, No. 18, pp 1584 – 1586, September 2008

[Lethien2, 2008] C. Lethien et al, "Potential of the polymer optical fibers deployed in a 10Gbps small office/home office network", Opt. Express, 16, 15 (2008), pp 11266-11274

[Lethien, 2009] CHRISTOPHE LETHIEN, CHRISTOPHE LOYEZ, JEAN-PIERRE VILCOT, RÉDHA KASSI, NATHALIE ROLLAND, CATHY SION AND PAUL ALAIN ROLLAND, "Review of glass and polymer multimode fibers used in a Wimedia UltraWide Band MB-OFDM radio over fiber system", IEEE/OSA Journal of Lightwave Technology, vol 27, no 10 (2009), pp 1320-1331

[Lethien2, 2009] LETHIEN C., LOYEZ C., VILCOT J.P., ROLLAND P.A., "High modal bandwidth glass multimode fibers used for the simultaneous transmission of 10GbE and band group 5 MB-OFDM ultra-wide band signals", in proceeding of the European Workshop on Photonic Solutions for Wireless, Access and in-house Networks, Duisburg, Germany, may 18-20, 2009

[Lethien3, 2009] LETHIEN C., LOYEZ C., VILCOT J.P., P.A. ROLLAND, "Multi-service applications on high modal bandwidth glass multimode fiber", IET Electron. Lett., 45, 18 (2009), pp 951-952 (august 27, 2009)

[Li, 1999] W. Li et. al. "Record 2.5 Gbit/s 550 m GIPOF Transmission experiments at 840 and 1310 nm wavelength", in *Proceedings of POF1999*, (China, July 13-16, 1999), pp 60-63

[Matthijsse, 2006] P. Matthijsse et al, "Multimode fiber enabling 40 Gbit/s multi-mode transmission over distances >400m", in proceedings of the OFC 2006, OW1-13

[MCVD OFS] D. Mazzarese, "Manufacturing multimode fiber: Precise control of production and testing ensures high performance", white paper, available online at www.ofsoptics.com/resources/fibermfgpaper.pdf

[Miller, 1979], S.E. Miller et al, "Optical Fiber telecommunications", 1979, Academic Press, ISBN : 0-12-497350-7

[Murofushi, 1996] M. Murofushi: "Low loss perfluorinated POF", POF´1996, Paris, 22.-24.10.1996

[Nkansah, 2006] NKANSAH A., DAS A., LETHIEN C., VILCOT J.P., GOMES N.J., GARCIA I.J., BATCHELOR J.C., WAKE D., Simultaneous dual band transmission over multimode fiber-fed indoor wireless network, IEEE Microw. Wirel. Compon. Lett., 16, 11 (2006) 627-629

[OFS optics] Datasheets of the OFS optics fibers, www.ofsoptics.com/resources/multimodeselectionguide%20.pdf, 2009 (Norcross, USA)

[OVD Corning] P. Bell and T. Wiggs, "Multimode fibre and the vapour deposition manufacturing process outside vapour deposition vs. Inside vapour deposition", white paper, available online at www.corning.com/WorkArea/downloadasset.aspx?id=7029

[PCVD Draka] PCVD based fibre production, available online at www.thor.edu/kvasir/2-draka.pdf

[Park, 2006] S. W. Park, "Production, properties and future of PMMA-GI-POF", 21. Meeting of the ITG-SC 5.4.1, Oldenburg, 12.05.2006

[Pedrotti, 2006] K. D. Pedrotti, R. P. Dahlgren, J. A. Wysocki, S. E. Ralph, R. Gandhi and A. Polley, "Multi-gigabit transmission over POF," in Proceedings of POF World West, (Santa Clara, June 21-22, 2006)

[Pepeljugoski, 2002] P. Pepeljugoski *et al* "15.6-Gb/s Transmission over 1km of netw generation multimode fiber", IEEE PHOTONICS TECHNOLOGY LETTERS, VOL. 14, NO. 5, MAY 2002, pp 717-719

[Persson, 2006] Persson, K.-A. Carlsson, C. Alping, A. Haglund, A. Gustavsson, J.S. Modh, P. Larsson, A., "WCDMA radio-over-fibre transmission experiment using singlemode VCSEL and multimode fibre", IEE Electronics Letters, Vol. 42, No 6, pp 372-374, march 2006

[Phyworks] Description of the Phyworks technology, http://www.phyworks-ic.com/technology.asp

[Pizzinat, 2007] Anna Pizzinat, Pierre Urvoas and Benoit Charbonnier, "1.92Gbit/s MB-OFDM Ultra Wide Band Radio Transmission over low bandwidth multimode fiber", in proceeding of the Optical Fiber Communication and the National Fiber Optic Engineers Conference 2007 (OFC/NFOEC 2007), 25-29 March 2007, pp 1 - 3

[Pizzinat, 2008] A. Pizzinat *et al*, « Low cost Transparent radio over fibre system for UWB based home network », in proceeding of ECOC 208, 21-25 september 2008, Brussels (Belgium)

[Polley, 2007] A. Polley, R. J. Gandhi, and S. E. Ralph, "40Gbps links using plastic optical fiber,"in Proc OFC, Anaheim, 2007, OMR5

[Polley, 2008] A. Polley and Prof. Stephen E. Ralph, "100 m, 40 Gb/s Plastic Optical Fiber Link", in proceeding of OFC/NFOEC 2008, OWB2

[Schöllmann, 2007] Stefan Schöllmann *et al*, "First Experimental Transmission over 50 m GI-POF at 40 Gb/s for Variable Launching Offsets", in Proceedings of the 33rd European Conference on Optical Communications, September 16-20, 2007, Berlin, Germany

[Seeds, 2002] Alwyn J. Seeds, "Microwave photonics", IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES, VOL. 50, NO. 3, MARCH 2002, pp 877 - 887

[Tabatabai, 2006] F. Tabatabai, H. Al-Raweshidy, "Performance evaluation for WLAN and UWB using radio over fibre," in Proceedings of the 9th European Conference on Wireless Technology (IEEE, 2006), pp. 147-149

[TIA-455-220-A] TIA-455-220-A, "Differential Mode Delay Measurement of Multimode fibre in the time domain", January 03

[TIA 492AAAA] Standard TIA 492AAAA, "Detail Specification for 62.5-Micrometer Core Diameter/125-Micrometer Cladding Diameter Class Ia Graded-Index Multimode Optical Fibers", (January 1998)

[TIA 492AAAB] Standard TIA 492AAAB, "Detail Specification for 50-Micrometer Core Diameter/125-Micrometer Cladding Diameter Class Ia Graded-Index Multimode Optical Fibers", (November 1998)

[TIA 492AAAC] Standard TIA 492AAAC, "Detail Specification for 850-nm Laser-Optimized, 50-um Core Diameter/125-um Cladding Diameter Class Ia Graded-Index Multimode Optical Fibers, (January 2003)

[TIA-492AAAD], Standard TIA 492AAAD, "OM4 fiber specification", in preparation

[Van den Boom et al, 2001] Van den Boom H.P.A et al, "High-Capacity Transmission Over Polymer Optical Fibre", IEEE JOURNAL ON SELECTED TOPICS IN QUANTUM ELECTRONICS, VOL. 7, NO. 3, MAY/JUNE 2001

[Tyler, 2002] Tyler E J, M Webster, R V Penty and I H White, "Subcarrier modulated transmission of 2.5Gb/s over 300m of 62.5µm-core diameter multimode fibre", IEEE Photon. Technol. Lett., Dec 2002

[Wake, 2001] WAKE D., DUPONT S., LETHIEN C., VILCOT J.P., DECOSTER D., "Radio frequency transmission of 32 QAM signals over multimode fibre for distributed antenna system applications", Electron. Lett., 37, 17 (2001) 1087-1089

[Wake, 2002] Wake, D, "Trends and prospects for radio over fibre picocells", in proceedings of MWP 2002. International Topical Meeting on Microwave Photonics, 5-8 Nov. 2002 Page(s):21 - 24

[Wake, 2008] DAVID WAKE, CHRISTOPHE LETHIEN, CATHY SION, JEAN-PIERRE VILCOT AND NATHAN J.GOMES, "An Optically Powered Radio over Fiber Remote Unit using Wavelength Division Multiplexing", in proceedings of the IEEE International Microwave Photonics conference and the Asia-Pacific Microwave Photonics conference (IEEE MWP2008/APMP2008), September 30th – October 3rd 2008, Gold Coast (Australia)

[White, 2005], W. White, "New Perspectives on the Advantages of GI-POF", POF 2005, Hong Kong, September 2005

[Yao, 2007] J. Yao, F. Zeng, Q. Wang, "Photonic generation of Ultrawideband signals," Journal of Lightwave Technology, 25, 11, 3219-3235 (November 2007)

[Yee, 2007] M.-L. Yee, Y.-X. Guo, V. H. Pham, L. C. Ong, "WiMedia Ultra-Wide Band Transmission in Radio over Fiber using Multimode Fiber," in Proceedings of the 20th Annual Meeting of the IEEE Lasers and Electro-Optics Society (IEEE, 2007), pp 335-336

Optical Fiber New Developments
Edited by Christophe Lethien

ISBN 978-953-7619-50-3
Hard cover, 586 pages
Publisher InTech

Published in print edition December, 2009

The optical fibre technology is one of the hop topics developed in the beginning of the 21th century and could substantially benefit applications dealing with lighting, sensing and communication systems. Many improvements have been made in the past years to reduce the fibre attenuation and to improve the fibre performance. Nowadays, new applications have been developed over the scientific community and this book fits this paradigm. It summarizes the current status of know-how in optical fibre applications and represents a further source of information dealing with two main topics: the development of fibre optics sensors, and the application of optical fibre for telecommunication systems.

How to reference
In order to correctly reference this scholarly work, feel free to copy and paste the following:

Christophe Lethien, Christophe Loyez, Jean-Pierre Vilcot and Paul Alain Rolland (2009). 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, Optical Fiber New Developments, Christophe Lethien (Ed.), ISBN: 978-953-7619-50-3, InTech, Available from: http://www.intechopen.com/books/optical-fiber-new-developments/potentialities-of-multimode-fibres-as-transmission-support-for-multiservice-applications-from-the-wi

INTECH
open science | open minds

InTech Europe
University Campus STeP Ri
Slavka Krautzeka 83/A
51000 Rijeka, Croatia
Phone: +385 (51) 770 447
Fax: +385 (51) 686 166
www.intechopen.com

InTech China
Unit 405, Office Block, Hotel Equatorial Shanghai
No.65, Yan An Road (West), Shanghai, 200040, China
中国上海市延安西路65号上海国际贵都大饭店办公楼405单元
Phone: +86-21-62489820
Fax: +86-21-62489821