ANALYSIS AND VIABILITY OF WDM TECHNOLOGY IN POF ACCESS NETWORKS

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To my parents because thanks to them I have given the first steps in my life, achieved most of my challenges and learnt a lot for my future.

Special thanks

I would like to thanks all the people have been there not only in the last steps with this TFG but during my university stage. I would like to say thanks to Beatriz, who has helped me to refresh my optical acknowledgement, organize the project, and for these deep reviews to have everything coherent and perfect. I would like to say thanks too to my friends because without them the last 4 years at the University would have been even harder. Specially to Aitor who has known when I needed a “slap on the wrist” and he gave it to me. He has always been there and thus, he deserves these thanks. And finally say thanks to my family and girlfriend because in spite of the distance, they have known how to support me and give me strength. They have been a fundamental pillar since I started the University.

Resumen

En este TFG analizaremos la viabilidad de implementar un sistema WDM en redes de acceso, en concreto en una red de interior del hogar, eligiendo como medio de transmisión fibras de plástico. Para abordarlo introduciremos el medio de transmisión así como los componentes actualmente disponibles en él eligiendo de acuerdo a los requerimientos de nuestro despliegue WDM aquellos más óptimos. El despliegue será caracterizado en términos de rendimiento, tasas alcanzables y posibles degradaciones que puedan aparecer en el conjunto. Compararemos el despliegue con otras tecnologías disponibles y con la trasmisión monocanal empleando el medio de transmisión, destacandolas ventajas que pueda aportar en el ámbito del hogar y planificaremos un enlace punto a punto caracterizado con los distintos planos, esquemas técnicos y equipos así como un presupuesto y pliego de condiciones que ejemplifique el desarrollo realizado. Finalizaremos el trabajo con unas conclusiones y posibles líneas futuras de investigación que ayuden a impulsar la implantación de esta tecnología en el mercado.

Resum

En aquest TFG analitzarem la viabilitat d'implementar un sistema WDM en xarxes d'accés, en concret en una xarxa d'interior de la llar, triant com a medi de transmissió fibres de nucli de plàstic. Per a abordar-ho introduirem el medi de transmissió així com els components actualment disponibles en ell triant d'acord amb els requeriments del nostre desplegament WDM aquells més òptims. El desplegament serà caracteritzat en termes de rendiment, taxes assolibles y possibles degradacions que puguen aparèixer en el conjunt. Compararem el desplegament amb altres tecnologies disponibles i respecte a la transmissió monocanal destacant els avantatges que puga aportar en l'àmbit de la llar i planificarem un enllaç punt a punt caracteritzat amb els diferents plànols, esquemes tècnics i equips així como un pressupost amb un plec de condicions que exemplifique el desenvolupament previ. Finalitzarem el treball amb unes conclusions i possibles línies futures d'investigació que ajuden a impulsar la implantació d'aquesta tecnologia en el mercat.

Abstract

In this paper we will analyze the viability of the WDM technology in access networks, especially in a house network, choosing as a transmission medium optical fibers with a plastic core. In order to address it we will introduce the transmission medium as well as components currently available there regarding our implementation requirements. The deployment will be specified in terms of performance, maximum rates and any degradation that might appear in the system. Moreover we will compare the deployment with other available technologies and with the monochannel transmission emphasizing the advantages in a house environment, planning a link point to point with its technical schemes, devices and the budged with its specifications exemplifying the previous development. We'll end up with some conclusions and future investigation guidelines that help to the implementation of this configuration in the market.

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List of Abbreviations and Symbols

Symbol	**Explanation**
α	Angle (here in an optical dense medium relative to the axis of incidence)
α	Attenuation coefficient in dB/km
α_{excess}	Excess loss
β	Propagation constant
Δ	Relative refractive index difference
$\Delta\lambda$	Expectral width
Δf	Frequency difference
Δt	Time difference generally
Δt_{mod}	Propagation time difference due to mode dispersion
Δt_{mat}	Propagation time difference due to material dispersion
D_{mat}	Material dispersion
D_{mod}	Modal dispersion
D_{wg}	Waveguide dispersion
κ	Exponent for pulse broadening
λ	Wavelength
λ_{source}	Source wavelength
$\lambda_1, \lambda_2, \lambda_3, \lambda_4$	Various wavelengths
τ_g	Group propagation time
$d\beta/d\omega$	Group propagation time
A	Fiber core radius
A/D	Analog/Digital
ADSL	Asymmetrical Digital Subscriber Line
APD	Avalange Photo Diode
AWG	Arrayed Waveguide Grating
B	Bandwidth (generally)
BER	Bit error rate
c	Velocity of light
C_{PD}	Capacity of the photo diode
CYTOP®	Cyclic Transparent Optical Polymer (Asahi Glass Comp.)
d	Fiber diameter
DEMUX	Demultiplexer
DVB	Digital Video Broadcasting
e/o	Electro/optical
f	Frequency generally (Hz)

f_{3dB}	Bandwidth at 3 dB below maximum
FEC	Forward Error Correction
FWHM	Full Width at Half Maximum
g	Index coefficient
g(t)	Pulse response
GI	Graded Index
GI-MPOF	Graded Index profile multimode MPOF
GOF	Glass Optical Fiber
h(t)	Impuls response
H(f)	Frequency response
I	Current generally
I_{ph}	Threshold current
I_d	Dark current
k	Boltzmann´s constant
L	Length
LAN	Loal Area Network
LD	Laser Diode
LED	Light Emitting Diode
Low-NA	Reduced Numerical Aperture
MC	Multi Core
MM-GOF	Multimode Glass Optical Fiber
MOST	Media Oriented System Transport
MPOF	Microstructured POF
MUX	Multiplexer
n	Refractive index
n_0	Refractive index of air
n_1	Refractive index of fiber core
n_2	Refractive index of fiber cladding
NA	Numerical Aperture
o/e	Optical/electrical
P	Power generally
P_0	Output power
P_{out}	Output power
P_{tx}	Transmitted power
P_r	Received power
P(f)	Power at the frequency f
PC	Plycarbonate

PF-POF	Perfluorinated POF
PLC	Power line communication
PMMA	Polymethylmetacrylate
POF	Polymer Optical Fiber
POF-ALL	PPaving the Optical Future with Affordable Lightning-Fast Links (EU project: www.ist-pof-all.org)
R, $\Re$	Responsivity
R	Electrical resistance
S	Sensitivity
SI	Step Index
SM	Security margin
SM-GOF	Single Mode Glass Optical Fiber
SNR	Signal to Noise Ratio
t	Time
t_1, t_2, t_3	Different propagation times
t_f	Fall time
t_r	Rise time
T	Temperature generally
V	Normalized propagation constant
V	Voltage generally
VCSEL	Vertical Cavity Surface Emitting Laser
WDM	Wavelength Division Multiplex
WDMA	Wavelength Division Multiple Access
z	Fiber position

Chapter 1. Introduction, objectives and structure

1.1 Context and motivation

Plastic optical fiber is a fiber technology developed decades ago with the purpose of providing low-data rate communication with a big advantage and plastic optical fiber (POF) links are becoming increasingly popular for applications such as computer or peripheral connections, control and monitoring, board interconnects and even domestic hi-fi. Unlike glass optical fibers (GOF), POF remains flexible while having a large diameter core and high numerical aperture, lead to a high capacity they can bring along the fiber.

POF systems have been used extensively in automatic control equipment in rugged manufacturing environments under industrial standards. In consumer data communications, the first widely used standard is *TOSLINK*, released by Toshiba to Sony-Philips-Digital-Interface (S/PDIF), used to digital audio transmission. Another sector has been the automotive industry where POF systems have been adopted for information and multimedia transmission inside vehicles. The **first industrial** standard in this field was the Digital Domestic Bus (D^2B) released in 1998 by Daimler-Ben that used 1-mm POF link offering duplex signal bus ring of 5.6 Mb/s.

D^2B evolved Media-Oriented System Transport standard with a maximum data rate increased to approximately 150 Mb/s. On the other hand, BMW introduced another standard called *"byteflight bus",* focused on more reliability with data rates around 10-50 Mb/s. An important commercialization step in POF came up with the introduction of *IDB-1394,* a combination of the *IEEE 1394b* and *Intelligent Transportation System Data Bus standards*. *IDB-1394* is designed to provide a higher data rate of 250 Mb/s for automotive as well as household Fast **Ethernet applications** through step-index POF (SI-POF)with fibers as long as 20-30 m.

During the past 40 years, the routing of electronic signals in the home has become increasingly prevalent. Most of them are crowded with many electrical wire connections, such as phone lines, coaxial TV cables and twisted-pair Ethernet cables. **Comparing them** on one hand with the size of 1-mm POF the jacketed POF cable is four times smaller in diameter (16 times smaller) than a typical coaxial cable. On the other hand the demanding of high-speed data communication, achieving speeds of 2.97 Gb/s is setting the Coaxial cable in their limits. In this context then, a POF system comes up as a **great alternative offering higher data rates, easy to install and with a better immunity to noisy electromagnetic interference** from home appliances and parallel channels. POF cable should be cheaper to purchase in the future because of its polymer material. Other attractive benefit as replacement of coaxial cable is its easy "*cut-and-plug*" termination because there's no necessity to professional skills to make a good termination. If we compare it with Wireless technology it has better performance due to it's a cable solution and the transmission medium doesn't suffer from any external electromagnetic radiation and the spectrum to use is free from any other transmissions. In Figure 1we can see current technologies with offered bit rates and link length and where POF fibers would fit in the schema.

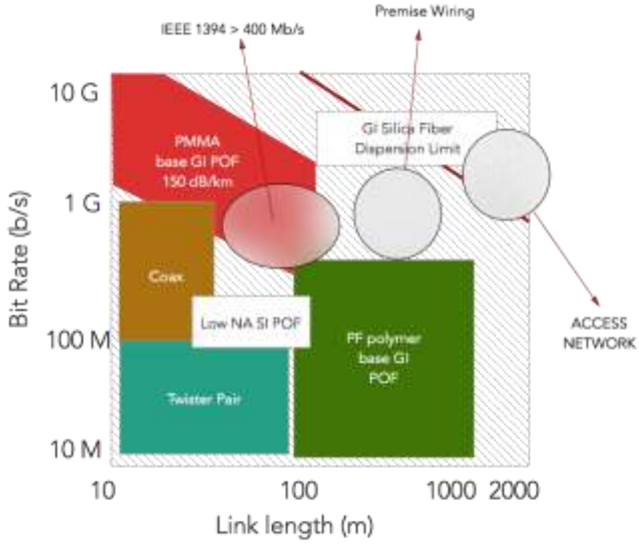


Figure 1 - Comparative of existing technologies contrasting their data rates with the light length

It is now possible to extend the data rates of POF systems by almost and order of magnitude by taking advantage of recent breakthroughs and advances. One of the most important advances has been the development of **high-speed red VCSELs** (*670 nm*) that has a cut-off frequency higher than 3GHz and a FWHM of less than 1 nm, both of which are almost 20 times better than competing LEDS. Wit the use of these VCELS, the speed bottleneck at the transmitter seems to be relaxed butnevertheless we have still there in the transmission medium. For decades, researches have been investigating how to improve these SP-POF (*Step Index Optical Fiber*) through Graded Index Optical fibers where the index n(x) decreases from the core center toward its core edge. What does this suppose? GI-POF exhibits much less multimode dispersion as compared with SI-POF (an improvement around 30 times greater).

Thanks to previous mentioned advances in transmitter and transmission fiber the current bottleneck has been moved to the receiver side, especially due to its **bandwidth limitations**. Although the limitation has been reduced minimizing active areas and parasitic capacitances there are still bandwidth limitations that occur because of the bounding-wire inductance.

The two major applications of POFs are the industrial-controls and automotive fields. The main drive for POF in the industrial controls market is the need for data links that resist EMI caused by high-voltage and high-current devices. Today, the major source of excitement in the POF business lies in the innovative uses of its products by automobile companies.

- **Automobiles:** In 200 German auto manufacturer Daimler-Benz recognized that the increasing use of digital devices in automobiles increased the weight, susceptibility to EMI and complexity wiring harnesses. Then after some research Daimler-Benz realized that the way to reduce costs was to develop and buy to a common standard, and its analysis indicated that POF-ring networks would meet the needs of future automobiles. The automaker convinced six other European automobile manufactures and they created and organization called the MOST Cooperation to coordinate the standard's development and promotion creating a standard with the same name (Media Oriented Systems Transport). The original MOST was designed for 25 Mb/s. The next generation will transmit at 50 Mb/s, and the speed increased to 150 Mb/s in 2007.
- **Interconnects:** Over the next decade the bandwidth of interconnects inside a computer is expected to increase by and order of magnitude from 1 GHz to 10 GHz thanks to developments of internal optical data bus to wire up its different chipsets. It will require a shift in technologies from electrical to the optical domain. The big attraction of this application is that the optical link supports much higher data rates than its electrical

counterpart-potentially many tens or even hundreds of gigabits per second-over far grater distances.

- **Supercomputers and servers:** A number of applications are now being developed to large data centers and supercomputers around the world. These canters require large amounts of interconnection over relatively short distances on the order of 50 meters. Thanks to fiber the number of links would decrease and the total weight offering better performance. Another aspect favouring POF are the cooling requirements in comparison to 10G copper that needs 10 times more power.
- **Local Area networks for Home and Business:** Due to the importance of LANS in small to medium size enterprises (SMEs), divisions of large companies, and in homes, POFs are being developed to offer higher data rates using the technology developed for the MOST automotive applications. With the availability of new plastic optical fibers, small from factor connectors and low cost transceivers suppliers of Ethernet LANs will soon be providing options using POF.
- **Aerospace and Applications:** POF is very interesting Aerospace because of its size, low weight, resiliency to shock and vibration and high bandwidth capabilities over short distances. POF's is now seriously being considered for application in aircraft, tanks, ships, helicopters, missiles, and spacecraft. The POF industry is rising to the challenge by developing higher temperature fibers and flame retardant cables for other military and aerospace applications.

Although during the development of POF most of companies have been focused in environments other than the house there is a big challenge there. We might think in glass fibers, traditional SMF and MMF as an alternative there. They can provide rates greater than 10 Gb/s in larger distances of almost 1 km. The performance is much bigger than in case of POF, however this performance arises from tiny glass/silica cores with delicate connectors, a makeup that imposes tight alignment requirements during termination and installation. In summary, SMF and MMF systems are **difficult to handle and installation costs** are prohibitively high for most homeowners. POF fiber could handle all these problems offering a great solution and displacing copper cables for the so-called last mile between the last distribution box of the telecommunication company and the end-consumer. Today, copper cables are the most significant bottleneck for high-speed Internet.

"Triple Play", the combination of VoIP, IPTV, and the classical Internet, is being introduced to the market with force, therefore high-speed connections are essential. It is highly expensive to realize any VDSL system using copper components, thus the future will be FTTH. As mentioned, POF can be applied in the house itself for different scenarios: "*A/V Server Network*", "*Control Server Network*" and "*Data Server network*"

Motivation

The main reason why POF are not being installed at multigigabit data rates is that due to the large dimension of the fiber core multimode transmission occurs along the POF, in fact 30,000 modes exist inside a 1-mm SI-POF core. The constant refractive index in fiber core cause different velocities for all the modes transmitted. This different time delay, also called the differential time delay (DTD) causes a narrow light pulse at the POF input to become a more widely dispersed pulse at the POF output. This phenomenon is known as multimode dispersion and it's more severe in POF due its large core size as compared with MMF and especially with SMF. This limitation can be expressed as a constant product of bandwidth and channel length. A typical value is 5 MHz · Km for step index fiber (1). This relationship between the POF bandwidth and the channel length explains the current limitations of POF transceivers that have nonequalized receivers. For graded-index POF the proportionality constant is much larger, on the order of 150 MHz · Km.

$$\text{Bandwith (MHz)} = \frac{5000\ MHz \cdot m}{Channel\ Length\ (meters)} \qquad (1)$$

Assuming then that the higher-speed light source is available at the transmitter, higher-speed SI-POF systems involve shorter channel lengths. For example 1.25 Gb/s can be achieved using red VCSEL and a channel of 10 m. The reason why most current commercial POF transceiver **do not use high-speed red lasers** are threefold:

1) A high-speed red laser diode is more expensive than a red LED
2) Most applicants did not historically require a gigabit data rate, and a rate of 100-250 Mb/s (enough for most automobiles and industrial control applications)
3) The constraints of other link components, such as the dispersive behaviour of the SI-POF channel and the speed of the receiver module.

Speed limitations caused by the receiver circuits are currently being minimized. A typical POF receiver front end consists of a transimpedance amplifier (TIA), a post-amplifier (PA), and a clock/data recovery circuit. A TIA with input impedance low enough would minimize speed limitations caused by the large parasitic capacitance of the PD. In addition, SI-POF cables exhibit DC attenuation, which is approximately 165 dB/km at around 650-nm wavelength. This translates to around 8 dB attenuation for a 50 m POF link. In summary, a receiver front end capable of driving a large CPD at data rates of a few Gb/s while exhibiting a high optical sensitivity is desired.

POF has big opportunities in house environment, however it has a big challenge to go over it, its bandwidth limitation that allows POF to achieve data rates with a higher magnitude from existing technologies and adding the main advantages of optical transmission.

Nowadays there are a lot of studies based on this purpose, improve the performance of a POF link with better fiber fabrication methods, with lens systems to overcome the problem of high numerical aperture, better devices to work in POF Grid offering a similar performance to glass fibers and look for different modulation schemes or multiplexing technologies to deploy.

WDM could be a great solution, due to the fact that the attenuation of POF presents 3 attenuation windows that we could take advantage from with a multiplex signals over the fiber, **increasing the data-rate and applying them to a real house scenario**. This project will analyse the viability of this system, from the devices we can use of this transmission scenario to the deployment defined in terms of performance, penalties and different analysis related with time dispersion and power balance.

1.2 Objectives

The objective of this TFG is to analyze the viability of WDM technology on POF to overcome the low data rates levels of a monochannel transmission that are not suitable for a house link. WDM technology in glass optical fibers offer great advantages that we are going to try to move into POF. I will propose a solution based on the available components, and I will evaluate the performance and costs in order to assess its viability for access networks.

1.3 Structure

The project will be structured in the following sections that will be covered along this document:

- **Fundamentals of POF Systems**: In this section the transmission medium will be presented: features of the transmission medium, components available there, filtering devices like for example fiber Bragg gratings (FBG) and short review of a multichannel transmission talking about the attenuation windows and giving examples of grid on different kind of plastic fibers. This section is important to know better about what happens in these fibers and why the deployment of WDM there is not as easy as it is on glass fibers.
- **Methodology**: We'll introduce here how we are going to plan the project solution and the steps we are going to follow to get the expected results including information about

the management tools we've used, the distribution of project in different tasks and a Gant chart to show the project schedule.

- **Design of a WDM system over POF**: Once refreshed the transmission medium the design of the WDM system will start with a short review with current services in a house (Digital television, Internet, Voice) and their requirements in order to know about the requirements our WDM system will have. With these requirements and keeping in mind available components we'll choose the right components starting with the fiber with its grid and following it with transceiver/receiver and mux/demux devices.
- **Specifications:** All specifications of our designed system will be summarized here with a example of link in a house giving a installation budget to have not only a performance idea but a economic one (important for a home user too). We'll give some examples of topologies that cover different services that are currently deployed with Wireless or copper solutions.
- **Conclusions and future guidelines**: We will discuss here with a personal conclusion about the results linking them with future investigation lines around WDM in POF especially these related with real tests with the designed topology.
- **Bibliography:** All documents that have helped with the development of the project will be in this section, technical papers, other projects, doctoral thesis, articles, … The project will be mostly on the information there, overall the fundamentals section.
- **Annexes:** With the designed system, we will archive here all specification documents of chosen devices.

Chapter 2. Fundamentals of POF Systems

2.1 Plastic Optical Fibers

2.1.1 Propagation in POF

2.1.1.1 *Normalized frequency (V)*

In an optical fiber, the normalized frequency, V (also called the V number), is given by

$$V = \frac{2\pi a}{\lambda}\sqrt{{n_1}^2 - {n_2}^2} \quad (2)$$

where a is the core radius, λ is the wavelength in vacuum, n1 is the maximum refractive index of the core, n2 is the refractive index of the homogeneous cladding.

The V number can be interpreted as a kind of normalized optical frequency. It is relevant for various essential properties of a fiber:

- For V values below ≈ 2.405, a fiber supports only one mode per polarization direction (*single-mode fibers*)
- Multimode fibers can have much higher V numbers. For large values, the number of supported modes of a step-index fiber can be calculated approximately as:

$$M \approx \frac{V^2}{2} \quad (3)$$

- The V number determines the fraction of optical power in a certain mode, which is confined to the fiber core. For single-mode fibers, that fraction is low for low V values (*e.g. below 1*), and reaches $\approx 90\ \%$ near the single-mode cut-off at ≈ 2.405
- A low V number makes a fiber sensitive to micro-bend losses[1] and to absorption losses in the cladding. However, a high V number may increase scattering losses in the core or at the core-cladding interface.

The expression of V can be rewritten using the numerical aperture (NA):

$$V = \frac{2\pi a}{\lambda}\, NA \quad (4)$$

[1] Micro-bend losses: These extra losses appear when the fibers are bent and rise very quickly once a certain critical bend radius is reached. This critical radius can be very small for fibers with robust guiding characteristics, whereas it is much larger for single-mode fibers with large mode areas.

2.1.1.2 *Numerical aperture*

In optics, the numerical aperture is a dimensionless number that characterizes the **range of angles** over which the system can accept or emit light. It has the property that it is constant for a beam as it goes from one material to another provided there is no optical power at the interface. In optics it describes the cone of light accepted into the fiber or existing in it *(*Figure 2).

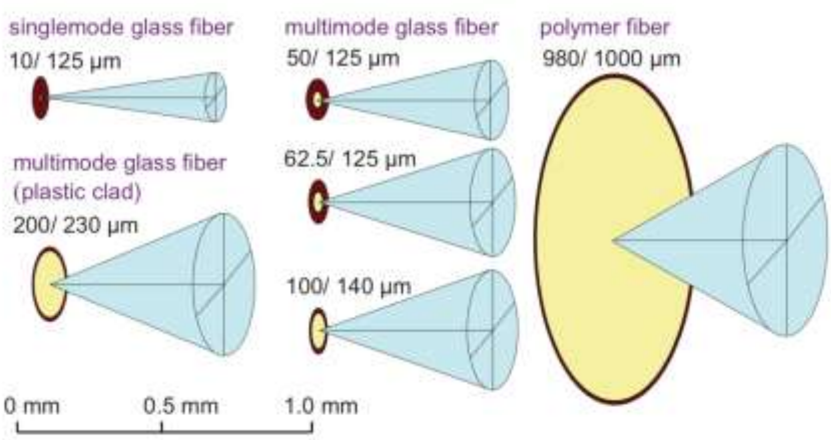


Figure 2 – Aperture angle and core diameter of glass fibers and polymer fibers

POF fibers are multimode fibers and they propagate more than one mode (they can propagate over 100 modes). The number of propagated modes depends on the core size, the numerical aperture (NA) and the optical wavelength. As the core size and NA increase, the number of modes increases. Typical values of fiber core size and NA are 50 to 100 µm and 0.20 to 0.29 respectively. Having a **large NA and core size have several advantages**, light is launched into a multimode fiber with more ease, fiber connections are easier and core-to-core alignment becomes less critical. Another advantage of multimode fibers is that they permit the use of light-emitting diodes (LEDs) when single mode fibers must use laser diodes. LEDs are cheaper, less complex, and last longer.

The numerical aperture is related to refractive index of core (n_1), cladding (n_2), and outside medium (n_0) as $NA = \frac{\sqrt{{n_1}^2 - {n_2}^2}}{n_0}$

2.1.1.3 *Single Mode Fiber (SMF)*

In fiber-optic communication, a single-mode fiber is an optical fiber designed to carry light only directly down the fiber – the single transverse mode. Modes are the possible solutions of the *Helmholtz equation for waves*, which is obtained by combining *Maxwell's equations* and the boundary conditions. These modes define the way the wave travels through space. Waves can have the same mode but have different frequencies. This is the case in single-mode fibers, where we can have waves with different frequencies, but of the same mode, which means that they are distributed in space in the same way, and that gives us a single ray of light. Although the ray travels parallel to the length of the fiber, it is often called **transverse mode** since its electromagnetic vibrations occur perpendicular to the length of the fiber.

Single mode fibers are better at retaining the fidelity of each light pulse over longer distances than multi-mode fibers. For these reasons, single-mode fibers can have higher bandwidth than multi-mode fibers. Equipment for single mode fiber is more expensive than equipment for multi-mode optical fiber, but the single mode fiber itself is usually cheaper in bulk.

2.1.1.4 ***Multi Mode Fiber (MMF)***

Multimode fiber optic cable has a large diametral core that allows multiple mode of light to propagate. Because of this, the number of light reflections created as the light passes through the core increases, creating the ability for more data to pass through at a given time. Because of the high dispersion and attenuation rate with this type of fiber, the quality of the signal is reduced over long distances. This application is typically used for short distance, data and audio/video applications in LANs. There are two kind of multi mode fiber:

- **Step-Index Multimode Fiber:** Due to its large core, some of the light rays that make up the digital pulse may travel a direct route, whereas others zigzag as they bounce off the cladding. These alternate paths cause the different groups of light rays, referred to as models, to arrive separately at the receiving point. The pulse, and aggregate of different modes, begins to spread out, losing its well-defined shape. The need to leave spacing between pulses to prevent overlapping limits the amount of information can be sent. This type of fiber is best suited for transmission over short distances.
- **Graded-Index Multimode Fiber**: Contains a core in which the refractive index diminishes gradually from the center axis out toward the cladding. The higher refractive index at the center makes the light rays moving down the axis advance more slowly than those near the cladding. Due to the graded index, light in the core curves helically rather than zigzag off the cladding, reducing its travel distance. The shortened path and the higher speed allow light at the periphery to arrive at a receiver at about the same time as the slow but straight rays in the core axis. The result: digital pulse suffers less dispersion. This type of fiber is best suited for local-area networks.

Figure 3shows a comparative of the ray propagation profile in the mentioned fibers above:

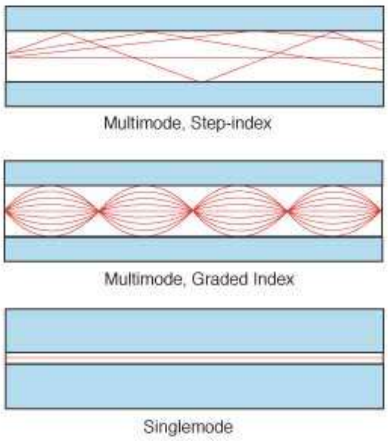


Figure 3 - Single and Multi mode fibers ray propagation

2.1.1.5 ***Attenuation***

Poly methyl methacrylate (PMMA) has been used for the core material of POF so far because it has been recognized as one of highly transparent polymers with commodity. Great efforts lowering the attenuation of the POF have been devoted in 1980’s by investigating the kind of polymer material and by improving the purification process of the materials. Historical development in the attenuation of the POF is summarized in Figure 4

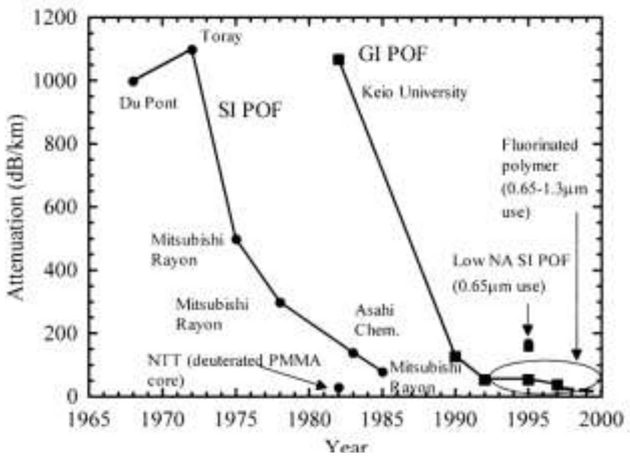


Figure 4 - Development in the attenuation of POF

The attenuation of the **first POF** developed by Du Pont was around 1000 dB/km. This was mainly due to the immature purification process of the materials. From 1970 to 1980, remarkable decrease was achieved by improving the purification and fabrication process. In 1982, it was clarified that the theoretical attenuation limit of the PMMA base of POF was approximately 110 dB/km [1]. Furthermore, it was clarified that substituting the hydrogen atoms in POF for other heavier atoms such as deuterium or fluorine enabled to lower the attenuation of POF particularly at near infrared region. All these POFs were**Step-Index (SI)** type.

The first **GI POF** proposed from Keio University in 1982 [2] was basically composed of PMMA having such a high attenuation as 1000 dB/km. In last decades, improvements of the fabrication process enabled the dramatic decrease of the attenuation, and the PMMA base of GI-POF with an attenuation of 110 dB/km at 0.65-µm wavelength was successfully obtained by interfacial-gel polymerization in 1992 [3]. Investigation of new polymer materials has been simultaneously performed to decrease the attenuation of the GI POF. In 1990's, perpetuated PMMA base and partially fluorinated GI POFs with an attenuation of 60 dB/km at 650-nm wavelength were successfully developed at Keio University. It is noted that the attenuation decrease of the GI POF follows that of SI POF behind approximately 10 years. Finally, the attenuation of 40 dB/km even at 1.3-µm wavelength was achieved in by perfluorinated (PF) polymer base GI POF.

With the growing interests in GI-POF, there have been **proposed several fabrication methods** that basically consist of polymer blending of copolymerization of more than two kinds of monomer to form the refractive index profile. However, the large attenuation problem is still there and has not been dissolved. This attenuation level is due to the inherent scattering loss of the GI POF that is strongly dependent on the correlation length and where the polymer-dopant system would significantly minimize the scattering loss in the GI POF [4]. Even if the Scattering Loss can be reducing with a dopant system, the minimum attenuation composed of PMMA is around 100 dB/km because of inherent absorption loss due to carbon-hydrogen stretching vibration. One option to reduce the absorption losses would be the use of **perfluorinated polymer** base that is able to eliminate some peaks in the spectrum. The minimum attenuation in this case is 40 dB/km around 1.0-µm. It was confirmed that the PF polymer base GI POF could achieve the attenuation of less than 1 dB/km. The theoretical attenuation spectrum of the PF polymer base GI POF is shown in and PMMA POF are shown in Figure 5 and Figure 6 respectively.

Depending on the material of the POF fiber it will present different transmission windows (minimum levels of attenuation). In case of poly(methylmethacryclate) the spectrum shows minimums at 530, 570 and 650 nm, all in the visible range Figure 5. Loss spectrum for a perfluorinated fiber (b) is broader (650 to 1300 nm) and the loss is less than 50 dB/km across this range.

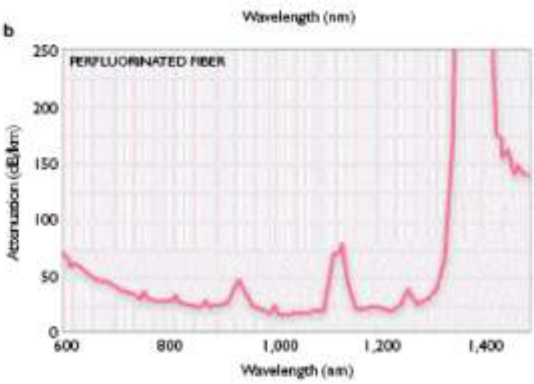


Figure 5 - Perfluorinated fiber attenuation

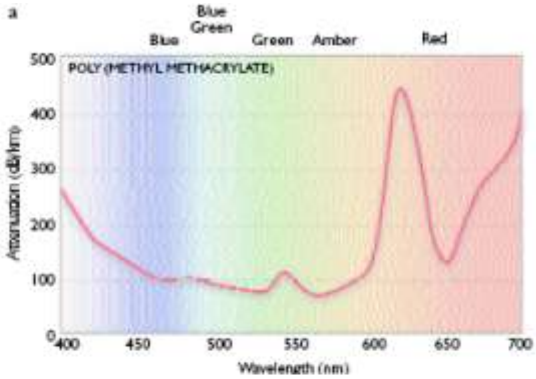


Figure 6 - Poly(methylmethacryclate) attenuation

2.1.1.6 *Dispersion and bandwidth properties in POF*

Dispersion refers initially to all processes that result in a difference in the transit times of various light components. One mode is thereby always a propagation condition of the light that is uniquely defined by the wavelength, polarization, and propagation speed.

Differential delays between various light components lead to a reduction in the modulation amplitude of higher frequencies. This makes the fiber a low-pass filter.

A short light pulse is briefly broadened when it travels the length of a fiber Figure 7and in turn reduces the transmission bandwidth.

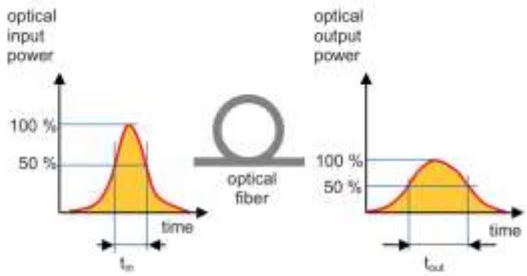


Figure 7 - Pulse broadening by passing an optical fiber

If Gaussian-shaped pulses are assumed, the result of the pulse broadening, ΔT is the square root of the difference of the squares of the input and output pulse width (FWHM full width at half maximum):

$$\Delta T = \sqrt{t_{out}^{2} - t_{in}^{2}} \quad (5)$$

The consequence of this broadening is that the time gap between the bits becomes smaller, that the pulses finally overlap and that the receiver can no longer differentiate between the two. The transmission bandwidth is limited as the light waveguide functions as a low-pass filter. The product of bandwidth and length characterizes the transmission capacity of a fiber.

Pulse broadening is caused by **mode dispersion and chromatic dispersion**. For multimode fibers it is necessary to consider the factors of material, modes and profile dispersion (in graded index fibers). Waveguide dispersion additionally occurs in single mode fibers, whereas profile dispersion and mode dispersion do not.

All the kinds of dispersion appearing in the optical fibers are summarized inFigure 8. The mechanisms dependent on the propagation paths are marked in yellow, whereas the wavelength-dependent processes are marked in green.

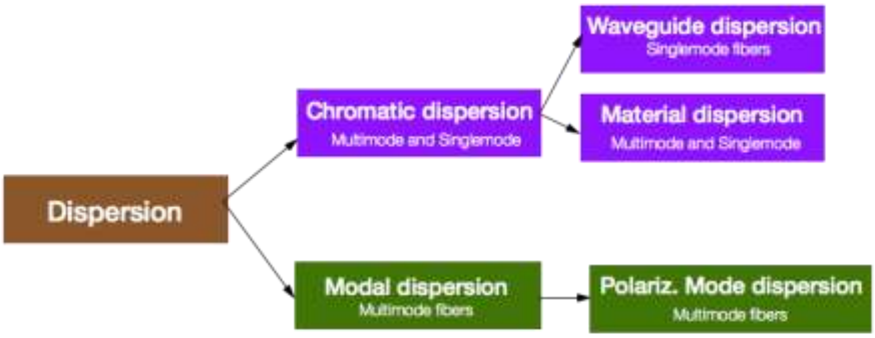


Figure 8 - Dispersion mechanisms in optical fibers

Chromatic dispersion

Chromatic dispersion is caused by delay differences among the group velocities of the different wavelengths composing the source spectrum. The consequence of the chromatic dispersion is a broadening of the transmitted pulses.The chromatic dispersion is essentially due to two contributions: material dispersion and waveguide dispersion.

Waveguide dispersion is caused by the fact that light waves penetrate into the fiber cladding to various depths, depending on the wavelength of the light wave. Thus, the different speeds of the core and cladding parts result in pulse broadening. Since only a small portion of the light wave in higher modes of larger diameter fibers spread into the cladding, this effect is only considered for single mode fiber. Waveguide dispersion is expressed by equation (6) where Δ is the index relative difference, λ the center wavelength, V the normalized frequency, b the propagation constant, n_{2g} the refractive index and ω the frequency:

$$D_{wg} \equiv -\frac{2\pi\Delta}{\lambda^2}\left(\frac{{n_{2g}}^2}{n_2\omega}\frac{Vd^2(Vb)}{dV^2}+\frac{dn_{2g}}{d\omega}\frac{d(Vb)}{dV}\right) \quad (6)$$

The **material dispersion** occurs because the refractive index changes with the optical frequency.It can be calculated with the expression (7):

$$D_{mat} \equiv \frac{1}{c}\frac{dn_{2g}(\lambda)}{d\lambda} \approx \frac{1}{c}\frac{dn_{1g}(\lambda)}{d\lambda} \quad (7)$$

Where c is the light speed in vacuum and $n_{1g}(\lambda)$ and $n_{2g}(\lambda)$ is the value of the core and cladding index respectively dependent of the wavelength.

Figure 9 shows the influence of material dispersion on pulse broadening, using polymer fibers as an example. Corresponding to the material dispersion, the longer wavelengths (red) propagate with a greater velocity than the shorter ones (blue).

The chromatic dispersion of PMMA-POF is over 300 ps/nm·km at 650 nm wavelength that is over 20 times larger than of silica fibers at 1,550 nm wavelength. For POF it is also usual to use LED with a typical spectral width of 20 nm to 40 nm and not lasers that have just a few tenths of a nanometer of spectral width.

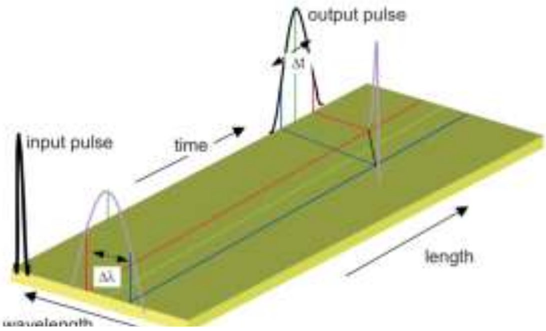


Figure 9 - Temporal broadening as a result of material dispersion

Mode dispersion

Since the light paths have different lengths, the pulses that have started simultaneously arrive at different times at the fiber's output, a fact that leads to pulse broadening. The propagation times of the two different propagation paths are determined purely geometrically for:

$$\Delta T_{mod} = \frac{L_1}{2 \cdot c \cdot n_{cladding}} \cdot AN^2 \approx \frac{L_1 \cdot n_{core}}{c} \Delta \qquad (8)$$

It depends directly on the numerical aperture with which the light is launched. The assumption is that the far field, i.e. the angular distribution of the light in the fiber, will remain constant over the entire length of the sample (no modal coupling or conversion). For a PMMA standard fiber with an AN = 0.5, a differential time delay of $\Delta t \approx 25\, ns$ for 100 m is produced. The transit time is proportional to the square of the NA. From the above-mentioned expression $B \approx 0.25/\Delta t_{mod}$ a value of 15 MHz results for the bandwidth.

Real SI-POF provides considerably higher bandwidths. The main reason for this is the presence of mode-dependent attenuation in conjunction with mode mixing. The differential delay increases proportionally to a particular length L_c (coupling length); for longer lengths, the increase is sub-linear (Figure 10). The following holds true:

$$\Delta t \propto L \quad for\ L < Lc \qquad (9)$$
$$\Delta t \propto L^{\kappa} \quad for\ L > Lc$$

Whereby the exponent κ must be determined for each fiber. It is typically between 0.5 and 0.7. The coupling length L_c ranges between 30 m and 40 m for standard SI-POF.

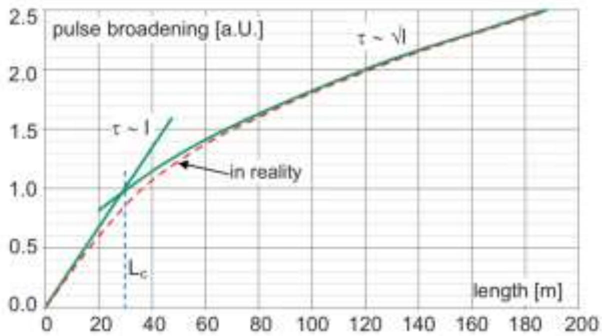


Figure 10 - Schematically representation of the pulse broadening reflecting mode coupling effects

The impulse response of a 50 m long standard POF can be seen in Figure 11. The half-value width of the impulse amounts to about 50 ns, i.e. only about 30% of the expected value. Furthermore, it is noticeable that the rear pulse edge drops more slowly. It is in the range that the higher modes lie which are attenuated very greatly by the mode-dependent losses. The dropping off of the rising edge can be explained by the effect of modal mixing.

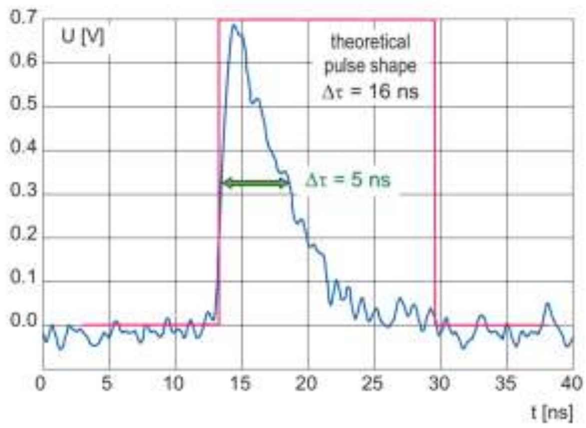


Figure 11 - Real pulse shape for 50 m POF

Calculating the bandwidth of **graded-index** fibers is clearly more complex. Profile dispersion occurs in graded-index profile fibers. It is the remainder of the mode dispersion that can no longer be compensated for and it depends on the relative refractive index difference Δ, which in turn is wavelength-dependent. An optimization of the profile exponent can be accomplished for a certain wavelength for which $d\Delta/d\lambda$. A **profile exponent of** $\boldsymbol{g \approx 2}$(10)causes a temporal broadening of:

$$\Delta T_{prof} = \frac{L_1 n_{core}}{c} \cdot \frac{\Delta^2}{8} \qquad (10)$$

In other words, a factor of $\Delta/2$- reduced broadening of the pulse as compared with the step index POF; for a typical graded-index POF this means a reduction of approximately 2 orders of magnitude. Mode dispersion or profile dispersion can only be avoided by using single-mode fibers. Due to the combination with the chromatic dispersion, certain polymer fibers have some advantages as opposed to silica glass fibers.

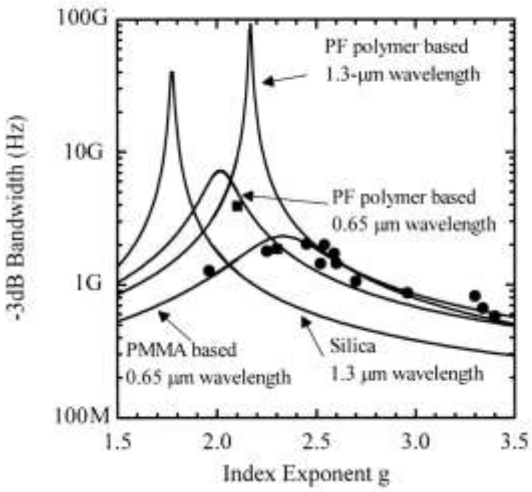


Figure 12 - Relation between the refractive index profile and bandwidth of 100 m GI POF.

2.1.2 Index profiles and types of fibers

Plastic optical fiber for data transmission until recently were limited with step index fibers to bandwidths around 38-Mhz-100m (Mitsubishi Eska). Recent results show a three fold increasing bandwidth to 105 MHz-100m. Increases in bandwidth are also possible with the use of dual step index (DSI), multi-step index(MSI) profiles, multi-core (MC), or combinations of these.

2.1.2.1 *Step Index fibers*

Like in silica, the first POF fiber had a step index profile (SI-POF). This means that a simple optical cladding surrounds a homogenous core. For this reason a protective material is always included in the cable. Figure 13schematically represents the refractive index curve. The refractive index step determines the numerical aperture (NA) and thus the acceptance angle.

For fibers with a large NA, the effect of a change in angle for a certain amount of bending is not so significant so that the bending losses diminish. Likewise, when coupling fibers to each other the loss due to angle errors is less significant when there is a large value of numerical aperture. A disadvantage of fibers with a large NA is the greater difference in time delay between the different light paths, and this in turn leads to a greater level of mode dispersion. This limits the bandwidth. The bandwidth of such fibers is approximately **40 MHz for a 100 m** long link. For many years this was a completely satisfactory solution for most applications.

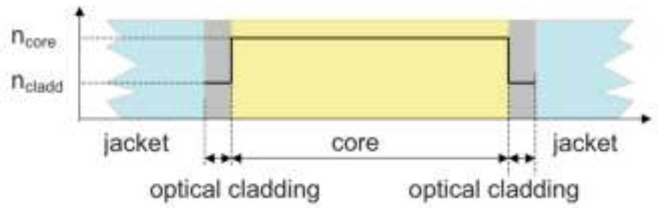


Figure 13 – Step index fiber.

The Step Index Fiber with Reduced NA (low-NA)

The majority of the initially produced SI-POF had an NA of 0.5 however it was necessary to decrease it in order to achieve data rates of 155 Mbit/s to replace copper cables in some applications over a distance of 50 m. In the mid nineties all three important manufactures developed the so-called low-NA POF. The bandwidth increased to approximately 100 MHz · 100 m because the NA was reduced to approximately 0.50.The first low-NA POF was presented in 1995 by Mitsubishi Rayon. The **big problem** of this fiber is that although it had better bandwidth it had a worse bending sensivity.

Double-Step Index Optical Fiber (DSI)

The double-step index POF features two claddings around the core, each with a decreasing refractive index, Figure 14. In the case of straight installed links, light guiding is achieved essentially through the total reflection at the interface surface between the core and the inner cladding. This index difference results in an NA of around 0.30, similar to the value of the original low-NA POF,.

When the fibers are bent, part of the light will no longer be guided by this inner interface. However, it is possible to reflect back part of the decoupled light in the direction of the core at the second interface between the inner and the outer cladding. At further bends, this light can again be redirected so that it enters the acceptance range of the inner cladding. The inner cladding has a significantly higher attenuation than the core. Light propagating over long distances within the inner cladding will be attenuated so strongly that it will no longer contribute to pulse propagation. Over shorter links the light can propagate through the inner cladding without resulting in too large a dispersion.

The first generation of DSI-POF primarily served the purpose of increasing the bandwidth of 1 mm fibers from 40 Mhz · 100 m to 100 MHz · 100 m with an unchanged minimum bending of 25 mm. The respective **applications are to be found in LANs and home networks**.

2.1.2.2 Multi-Core Step Index Optical Fiber (MC)

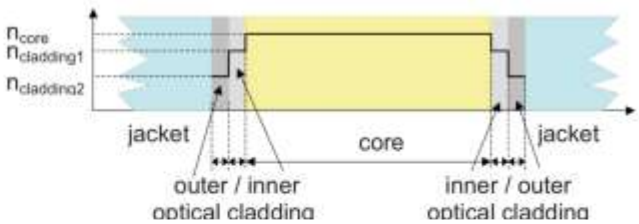


Figure 14 - Double-Step Index optical fiber

2.1.2.2 *Multi-Core Step Index Optical Fiber (MC)*

The requirements of high bandwidth and low sensivity to bending are difficult to accomplish together within one and the same fiber having a diameter of 1 mm. As a compromise, Asahi developed a multi-core fiber (MC-POF) where many cores are put together in production such a way that together they fill a round cross-section of 1 mm diameter. Figure 15shows the refractive index profile of a MC-POF, shown as a cross-section through the diameter of the fiber. The index step corresponds to these of a standard POF.

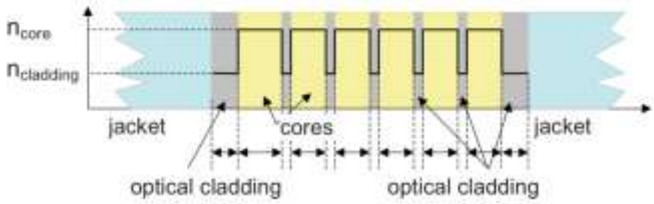


Figure 15 - Multi-Core step index optical fiber

The Double Step Index Multi-Core Fiber (DSI-MC)

An increase in bandwidth was achieved by reducing the index difference in multi-core fiber too. Due to the smaller core diameters it was still possible to avoid an increase in bending sensivity. The principle is the same as in the double-step index POF with an individual core. In this case a bundle with single cladding is completely surrounded by a second cladding material (Figure 16)

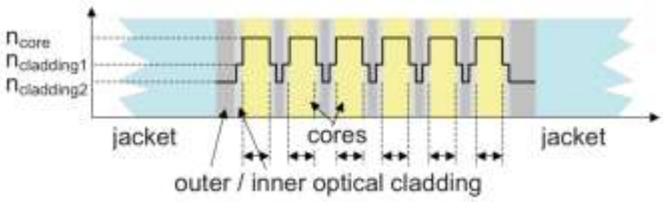


Figure 16 - Double Step Index Multi-Core fiber

2.1.2.3 *Graded Index Optical Fiber (GI)*

In graded index profiles (GI) higher bandwidth is possible. In these profiles, the refractive index continually decreases starting from the fiber axis and moving outwards to the cladding. Of particular interest are profiles that follow a power law where the parameter g is characterized as the profile exponent.

$$n = n_{fiber\ axis} \cdot \left[1 - \Delta\left(\frac{distance\ to\ fiber\ axis}{core\ radius}\right)^{g}\right] \qquad (11)$$

Due to the continually changing refractive index, the light rays in a GI fiber do not propagate in a straight line but are constantly refracted towards the fiber axis. Light rays that are launched at the center of the fiber and do not exceed a certain angle are completely prevented from leaving the core area without any reflections occurring at the interface surface. The optimum index coefficient ‘g’ has been object of analysis of some investigation groups that showed that this value is 2. Due to the smaller chromatic dispersion of fluorinated polymer compared with silica, the bandwidth of GI-POF theoretically achievable is significantly higher than that of multi-mode GI silica glass fibers. In particular, this bandwidth can be realized over a significantly greater range of wavelengths. **This makes the PF-GI-POF interesting for wavelength multiplex systems**. However, in this case the index profile must be maintained very accurately, a requirement for which no technical solution has as yet been provided.

Another factor involved in the bandwidth of GI-POF is the high level of mode-dependent attenuation compared to silica glass fibers. In this case modes with a large propagation angle are suppressed resulting in a greater bandwidth. Mode coupling is less significant for GI fibers than it is for SI fibers since the reflections at the core-cladding interface do not occur.

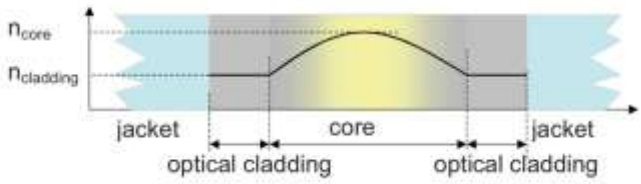


Figure 17 - Graded Index profile fiber

2.1.2.4 *Multi Step Index Fibers (MSI)*

Following the many technological problems experienced in the production of graded index fibers having an optimum index profile that remains stable for the duration of its service life, and attempt was made to approach the desire characteristics with the multi-step index profile (MSI-POF). In this case the core is formed by many layers that approach the required parabolic curve in a series of steps. A diagram of the structure is shown inFigure 18. Although in this kind of fibers the light rays are not continually curved given a sufficient number of steps, the difference to the ideal GI profile is relatively small so that large bandwidths can nevertheless be achieved. MSI-POFs were presented in 1999 by a Russian institute and since then, other companies are producing such fibers, which are often called GI fibers.

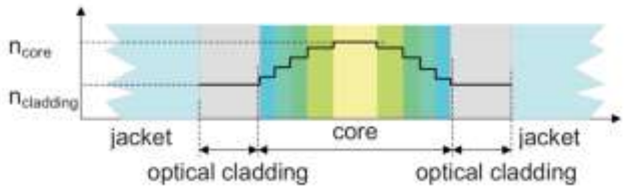


Figure 18 - Multi Step Index fibers profile

2.1.2.5 *Semi-Graded Index Profile Fibers (Semi-GI)*

A relatively new version of index profiles are fibers which have a gradient with a slightly varying index above the core cross section, but do have an optical cladding with a great index step as shown in Figure 19.

This variety of fibers has enormous advantages. The light that propagates within the gradient is only subject to very little mode dispersion. If a ray of light has a greater propagation angle, e.g. after being bent, then it continues to be led to the core-cladding interface layer through total reflection. However, these rays do have very much higher mode dispersion. Figure 19 shows how light spreads theoretically and what consequences this effect has for the pulse response.

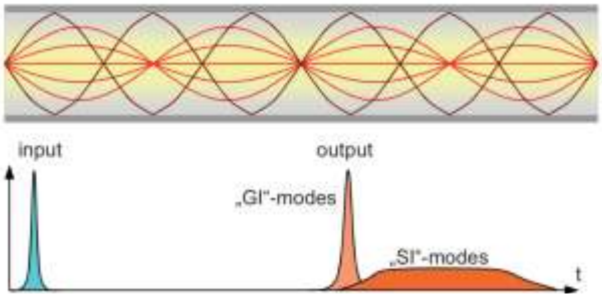


Figure 19 - Light propagation in semi-graded-index profile fibers theoretically

In principle, two different groups of modes can be seen in the picture. The paths designated as GI modes do not touch the cladding and only show a very slight difference in propagation times. The shares designated as SI modes are completely reflected at the core-cladding interface layer. These light paths are also bent in the core, but the light path, now very much longer, can no loger be compensated for in the outer areas by the lower refractive index. With very high data rates **the second mode group is drawn out so widely that it is presented solely as a kind of DC offset in the eye diagram**. At the POF-AC a data rate of 1 Gbit/s was transmitted over 500 m of a GI PCS fiber with a PRBS signal. Data rates up to 3 Gbit/s could be attained with a small surface APD receiver.

2.1.2.6 *An Overview of Index Profiles*

Figure 20 through Figure 21again show all index profiles described in an overview. Due to the wide range of possibilities offered in polymer chemistry further developments are certainly to be expected. For example, multi-core graded fibers, fibers with special cladding for a reduction of the losses at the core/cladding interface or to increase the bandwidth or even multi-core fibers with different individual cores are all conceivable. In the following figures POF variants are shown with typical parameters.

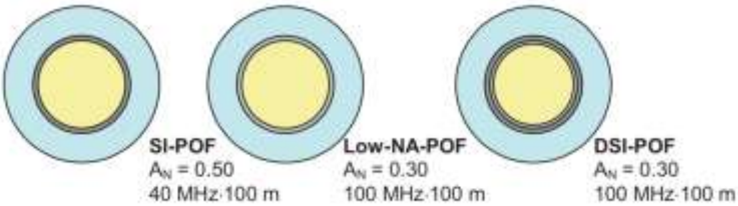


Figure 20 - POF with single core and step index core

Single-core fibers with diameters between 125 $\mu m$and 3 mm are available from different manufactures at a reasonable price and in robust quality. Most of the polymer optical fibers used in practical applications are of these types.

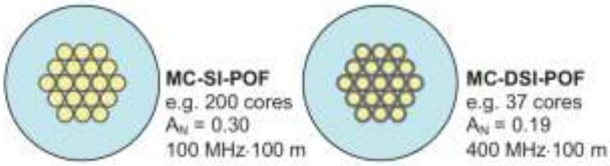


Figure 21 - POF with multiple cores and step index profile

MC fibers are available from various manufacturers. They are deployed in applications ranging from high data rates transmission systems through to optical image guides. Because of the short lengths produced, **the prices are still significantly above expectations**. However, further developments in this field can be expected in the future.

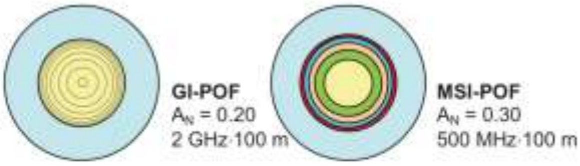


Figure 22 - Polymer fibers with graded index and multi step index profile

Graded index as well as multi-step index profile POF are commercially available today. Laboratory experiments and series of practical installations in Japan and Europe show the **great potential in regard to the bit rates** possible. Asahi Glass introduced them into the market around 2001. Lucent Technologies, later called OFS and trading number of the name of Chromis Fiberoptics as of 2004, also announced the possibility of producing large amounts of GI POF in case of demand. In Europe, fibers by Nexans are manufactured in Lyon. All three fibers will consist of the fluorinated polymer material CYTOP®. The core diameter of the Lucina™ Fiber by Asahi Glass is 120 μm with an AN = 0.28. A protective cladding made from PMMA and measuring 500 $\mu m$is placed around an area of fluorinated polymer outside the core profile. The duplex cable has external dimensions of approximately 3 by 5 mm. The lowest attenuation achieved to date is approx. 15 dB/km for a wavelength of 1,300 nm. The specified value is < 50 dB/km for 700 nm – 1,300 nm.

There has also been significant progress in the manufacture of GI or MSI-POF respectively on a PMMA basis.

2.1.3 Multichannel transmission

Present communication systems over POF use a single channel for data transmission. Commercial systems with SI-POF can deliver a bandwidth of 100 Mbit/s over 50-100m. However, the standard SI-POF has the lowest bandwidth among all POFS, small bandwidth limits the maximum data rate that can be transmitted through the fiber.

One possibility to open up this bottleneck is to implement WDM approach taking advantage of parallel over serial transmission in some applications. Besides these key-components, essential to the success of WDM over POF, an important aspect is establishing and unique set of WDM **transmission channels** in VIS for the realization of standardized commercial WDM devices and systems.

ITU-T Recs. G694.1 and G.694.2 provide grids in the IR part of the spectrum to support dense WDM and coarse WDM applications however a new spectral grid has to be defined in the visible part of the spectrum where POF works. It can be done in two ways, extending existing grids from IR into visible spectral range, or establishing independent wavelength and frequency values.

2.1.3.1 *Extension of DWDM grid into VIS*

This DWDM extension results in 313 channels between 428.3 THz (700 nm) and 749.5 THz (400 nm) for channel spacing of 100 GHz. In wavelength domain channel spacing reduces from 0.163 nm for channels in 700 nm region, to 0.053 for channels in 400 nm region. For channel spacing of (100/n) GHz, where n=2.4, or 8, the number of channels in the same spectral region equals n·3212+1.

Since demands for WDM systems are far more modest in visible than in IR spectral range, it can be stated that DWDM concept cannot be applied for WDM systems over SI-POF.

2.1.3.2 *Extension of CWDM grid into VIS*

Extending CWDM wavelength grid into VIS results in 15 channels between 400 nm and 700 nm. Having channels in high attenuation regions cannot be avoided. Channels in low attenuation regios are those at 471 nm (Channel 4), 511 nm (Channel 6), 571 (Channel 9), and 651 nm (Channel 13). These wavelengths have been highlighted in Table 1. Having a channel at 651 nm is important since most of the commercial SI-POF systems work in red window.

Ch. No.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
λ [nm]	411	431	451	471	491	511	531	551
f [THz]	729	696	665	637	611	587	565	544
L [dB/km]	158	120	100	85	84	72	75	99
Ch. No.	**9**	**10**	**11**	**12**	**13**	**14**	**15**	
λ [nm]	571	591	611	631	651	671	691	
f [THz]	525	507	491	475	461	447	434	
L [dB/km]	63	89	259	349	126	261	313	

Table 1 - Extension of CWDM grid into VIS

Good channel allocation, high channel density and availability of LEDs make extension of CWDM grid a strong candidate for a grid in VIS.

2.1.3.3 *Independent grids*

Independent grid is any wavelength or frequency grid defined in VIS. Because of the obvious CWDM nature of VIS WDM systems over SI-POF, it is convenient to have a wavelength grid with equidistant channel spacing. One approach to establish and optimize such grid is presented here. The idea is to establish grids with channel spacing from 10 nm to 50 nm in increments of 1 nm. The position of each grid on the wavelength axis should be optimized. The grid with the best performances is determined with the criteria in [12]. This grid specifies channel spacing of 20 nm and consists on 15 channels between 410 nm and 690 nm. Wavelengths in this grid differ 1 nm from the CWDM grid and the overall attenuation is lower than the CWDM grid one.

Ch. No.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
λ [nm]	410	430	450	470	490	510	530	550
f [THz]	731	697	666	638	612	588	566	545
L [dB/km]	162	121	101	86	85	72	74	102
Ch. No.	**9**	**10**	**11**	**12**	**13**	**14**	**15**	
λ [nm]	570	590	610	630	650	670	690	
f [THz]	526	508	491	476	461	447	434	
L [dB/km]	62	87	240	367	125	259	306	

2.1.4 Standardization of POF

SI POF is standardized by the *International Electrotechnical Commission (IEC)* as the A4 category of fibers. In completion, this category contains four types (families A4a-A4d) of SI POF with diameters from 490µm to 980µm to different applications: networks; multimedia sources; sensor systems. Other point that standard defines too is the dimensional requirements, as well as minimum mechanical and transmission properties. Regarding the environment requirements, nothing is specified in *IEC POF* standards.

OFS and Nexans have proposed to modify the A4 family of standards to include perfluorinated GI POF,Table 2. According to this proposal, four new fiber families (A4e-A4h) are added to the A4 category. These families will include core diameters of 500 µm, 200 µm, 120 µm, and 62.5 µm, and are intended to consider a wide variety of applications from consumer electronics to multi-Gb/s data communication.

The *Standardization Division of the VDE* in Germany established a POF working group DKE 412.7.1, responsible for the international standardisation of Gbit/s POF transmission systems with active and passive elements [5]. This group has been working in a **new commercial standard that would help the POF home/office networking market to develop**. This standard and the silicon development took special care to become flexible, robust, efficient and affordable and well suited for the high volume consumer market.

	A4e	**A4f**	**A4g**	**A4h**
Principal applications	Consumer electronics	Industrial, mobile	SOHO LAN	High speed, multi-Gb/s
Outer diameter (µm)	750 ± 45	490 ± 10	490 ± 10	250 ± 5
Core diameter (µm)	500 ± 30	200 ± 10	120 ± 10	62.5 ± 5
Attenuation at 650 nm (dB/km)	<180 dB/km	<100 dB/km	<100 dB/km	n/a
Attenuation at 850/1300 nm (dB/km)	n/a	<40 dB/km	<33 dB/km	<33 dB/km
Minimum modal bandwidth at 650 nm (MHz-km)	20	80	80	n/a
Minimum modal bandwidth at 850/1300 nm (MHz-km)	n/a	150-400	188-500	188-500

Table 2 - Nexans proposal with 4 new types of perfluorinated GI-POF

2.2 Components

2.2.1 Light sources

There are several types of light sources that can work in POFs: resonant cavity emitting diodes (RC-LEDs); laser diodes; vertical-cavity surface-emitting laser (VCSELs) diodes *(*Table 3*)*.

LEDs, including surface-light emitting diodes, can be modulated at speeds of up to 250 Mb/s and laser diodes up to 4 Gb/s. VCELs at 650 nm are still in development but new resonant cavity and near-resonant cavity sources can be modulated t speeds of up to 600 Mb/s and 1.2 Gb/s.

PF fibers, operating at wavelengths from 650 to 1300 nm, work with the light sources developed fro 650 nm POFs and the 850 and 1300 nm laser diodes used with glass optical fibers, which can transmit to 10 Gb/s. due to the large diameter of POFs (in comparison with GOF) their connectors are cheaper, less complex and are less likely to suffer damage than connector in glass optical fibers. The reduced damage risks result from POF connectors undergoing less lateral offset and angular misalignment, and being exposed to less dirt than glass connectors. Because POF connectors have lower tolerances, makers can mold them from inexpensive plastics instead of requiring precision-machined stainless steel or ceramics like glass fibers.

Finally, due to the ease of coupling light form the light source it’s possible to embed the source and drive electronics into the connector housing.

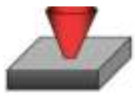
	LED	RCLED	Edge-emitting LD	VCSEL
				
Typical wavelength	650 nm	650 nm	1310 – 1550 nm	850 nm
Efficiency	1 to 10 %	5 to 20 %	10 to 50 %	10 to 30 %
Emitting area	300x300 μm^2	20x2 μm^2	3x300 μm^2	10x10 μm^2
Farfield angel (vertical/horizontal)	± 60º	± 30º / ± 10º	± 50º / ± 20º	± 10º
Threshold current	n/a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

Table 3 - Comparative of different light sources in POF

2.2.1.1 *Connectors*

Connectors are important in transmission systems to couple light between different fibers. These connectors should not only allow the connection and disconnection but has **good loss performances and protects the fiber from damage**.

In case of glass optical fiber, most of optical connectors are based on a ceramic ferrule, made of metal, ceramic or plastic. Moreover the fiber is bonded with epoxy inside the ferrule (ST, SC, FC or LC types). Some systems with crimped fiber or mechanicals splice inside the connector also exist. The fiber is usually polished to get better insertion and return loss. Due to the small fiber cores (8µm for single mode, 50µm or 62.5µm for multimode), the tolerance on the ferrule dimensions is a critical factor to have a good connector.

If we compare it with glass optical fiber, in this case tolerance and alignment here is less critic because of the larger core diameter of .1 to 1 mm. This makes it possible to have low cost components and easy to assemble connector. A lot of components have been developed and are currently used being the most popular the TOSLINK FCO5 (simplex) and FOC7 (duplex) both developed by *Toshiba* and adopted by the Japanese Institute of Standards (JIS). HP has developed a simple "snap on" connector called the *Veraslink*. SMA connectors have also been adopted for POF. All of these connectors use a simple cleaving tool (razor blade) or Hot-Plate to produce a high quality finish.

Two recently developed connectors worthy of note in POF development: a new **Small Multimedia Interface (SMI)** developed by Molex and a **"Do it Yourself" connector** developed for PF GI-POF by Nexans.

- **Small Multimedia Interface (SMI) Connector:** Developed for 1394b[2] consumer applications but finding its use in other applications as well. This duplex connector system can operate at 250 Mbps for up to 50 m today and 500 Mbps in the future. It has a small footprint of 11 mm wide and 24 mm in height making it suitable for consumer electronics.
- **"Do it Yourself" Connector for PF-GI-POF**: With its new plastic fiber of perfluorinated, *Nexans* designed a connector compatible targeting a very low cost and easy "do it yourself" type installation. This new connector is based on a new-patented system of fixing the fiber into the connector without the need for polishing. Moreover *Nexas* wanted to develop a connector that didn't require any especial crimping tool such as this one. Finally, to avoid the need for polishing (something long and delicate) a low cost cutting tool has been developed. This tool allows anyone to assemble and terminate the connector without specific training. The installation time of this kind of connectors is less than 2 minutes and gives a measured loss of less than 0.5 dB. The company is currently moving the design to all standard connectors such as ST, LC and MTRJ

2.2.2 Couplers

Couplers have an important role in a multichannel transmission because this device will couple different signals on the same optical fiber. For POF transmission systems there's a complete line of products and different fabrication techniques coming from some studies around POF. The following diagrams show different principle possibilities for manufacturing

X-Couplers couplers have one input and several outputs. Figure 23 shows an example of face coupler in which both output fibers are coupled with a butt-joint and directly to the input fiber. The main advantage of this coupler is its simple structure and the fact that here is no large mode dependency between output fibers. The minimal excess loss of a **Y-coupler** (Figure 24) is 3 dB and additional losses can be caused by a coupled interface not fully utilized. Mathematically there are at least 1.08 of these loses that are acceptable and can be minimized by suitable index matching.

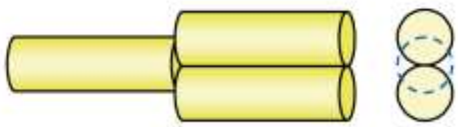


Figure 23 - Principle of the face coupler

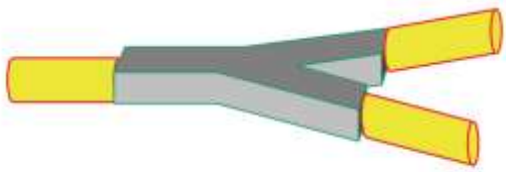


Figure 24 - Principle of the Y-coupler with waveguide element

Polished coupler are made with two fibers with polished surfaces glued in such way that there are not protruding areas. This kind of coupling produces additional losses created by sudden changes in the guided angle range as shown inFigure 24. This can be minimized with a sufficient flat polished angles. If the coupler has several ports, polishing surfaces can be complex and the alternative is using a **cylindrical-mixing element** with 7, 19, 31 etc. output fibers, the excess loss is not that large,Figure 25.

[2]1934b: Is Firewire 800 and is designed to run at 800 Mbits per second on a fully dúplex basis and its backward compatible with 1394ª

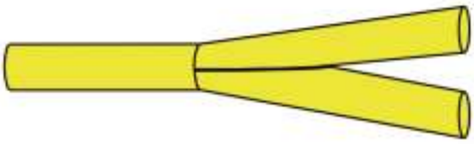


Figure 25 – Principle of the polished coupler

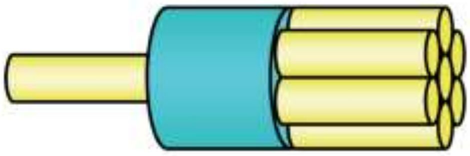


Figure 26 – Principle of the coupler with mixing cylinder

This multiple coupled structure can be improved with a curved element instead of a straight mixing cylinder, having functions as a mode mixer. Better results can be attained at a bend of 180º with a radius of several 10 mm. Figure 27shows this coupler where the mixing element is a hollow funnel with a wall thickness corresponding to the fiber thickness.

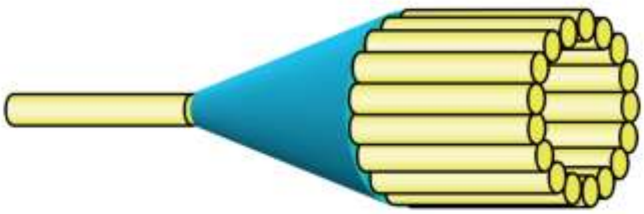


Figure 27 - Principle of the coupler with mixing elements in a conical form

2.2.3 Receivers

Receivers are, of course, extremely important components for optical transmission systems. Other than the sensitivity**, the speed** of these components is important for the transmission performance. The smaller the light wavelength, the less the photo current per watt of optical power emerges just because each photon processes more energy. Although this might seem at first a paradox, it's not because LEDs in shorter wavelengths produce higher power levels with less energy than long-wavelength diode.

In data sheets for photodiodes there is information about the **responsivity** parameter but seldom data about the quantum energy. This parameter describes the photo current per light power in A/W. In Figure 28 we can see an example of a data sheet responsivity graph.

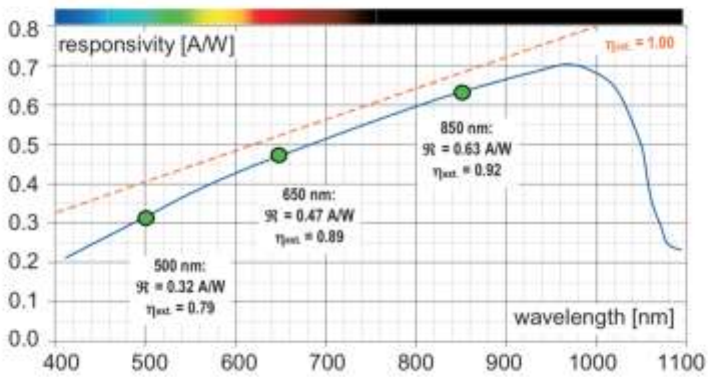


Figure 28 - Responsivity of a Si-pin photodiode

There is another parameter given in addition to the responsivity of the photodiode, it's the **absorption length**, which becomes larger at longer wavelengths. If it exceeds the thickness of the absorbing layer, then the power efficiency drops because the light passes right through the photodiode. Assuming we have a maximum thickness of the absorbing layer of 10 μm, then we can use well silicon in the range between 400 nm and 1000 nm.

The three most important versions of photodiode structures are:

- **The pin-photodiode**: It consists of an intrinsically doped interface layer between the p and n zones. The absorption primarily takes place in this area.
- **The avalanche photodiode (APD):** It has a highly doped layer in which the electrons produced are multiplied and accelerated by a strong local electric field.
- **Metal-Semiconductor-Metal photodiode (MSM):** There is no p-n junction. Finger-like electrodes are applied to an absorbing semiconductor surface. The bias voltage applied pulls of the ensuing charge carriers.

Although the APD generates a higher amplification, it introduces extra noise to the receiver that the PIN doesn't. On average, APD receivers are about 10 dB more sensitive than a PIN-PD [25]. The advantage of PIN is that they require typically 5V to 15 V of bias voltage while APD requires levels of 100 V and a more precise temperature and power controls. Furthermore, APD are considerably more expensive. All commercial POF systems work with pin-photodiodes. MSM structure has a smaller capacity than a PIN diode with the same size causing a greater transimpedance valuewhich improves the sensitivity. Although MSM PDs are not employed commercially for POF systems, it will be used in a few years.

Table 4 shows a qualitative comparison of most important characteristics of these three types of photodiodes. The PIN photodiode is the one which represents a good compromise in all its parameters.

	MSM	PIN	APD
Capacity	+ + +	+ +	+
SNR	-	+ +	+ + +
Reverse voltage	-	+ +	- - -
Responsivity	+ +	+ +	+ + +
Price	-	+ +	+

Table 4 - Comparative between different photodiode structures

Overview of Receivers

Many institutions use commercial receivers or at least amplifiers. Low-noise transimpedance amplifiers are available for almost every bit rate range. The greatest disadvantage is that these commercial components have been designed for a capacity of only a few pF. If you use photodiodes with greater capacity, the bandwidth and sensitivity drop dramatically.

An overview of the sensitivities attained so far with different bit rates as well as for different fiber diameters and various wavelengths is illustrated in Figure 29where sensitivity values are referred to a BER of 10^{-9} (q=6)

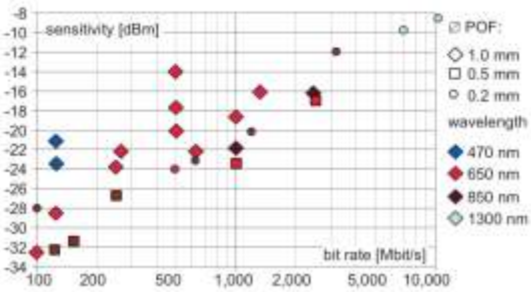


Figure 29 – Parameters of POF receivers up to now

In the graph we can clearly see how a ten-fold increase in the bit rate costs 15 dB of sensitivity because of the greater noise bandwidth as well as by the necessary reduction in the receiver resistance. Data rates above 3 Gbit/s have only been attained so far with relative thin fibers.

2.2.4 Input and output optical lenses

2.2.4.1 *Coupling Losses from the Transmitter into the POF*

The first loss we encounter is located at the coupling interface between the transmitter and he fiber. First of all, the transmitter has a certain emitting area and divergence. Since it is not usual to install the fiber directly onto the transmitter but to leave a certain protective distance, it is not possible for all of the light to fall onto the front face of the fiber. Secondly, the fiber is limited in acceptance angle. Any light falling onto the front face of the fiber at a greater angle will not be guided and radiated. Furthermore, anything less than an ideal surface as well as the refractive index difference between air and the fiber will cause the light to be partially reflected so that it is lost (Figure 30).

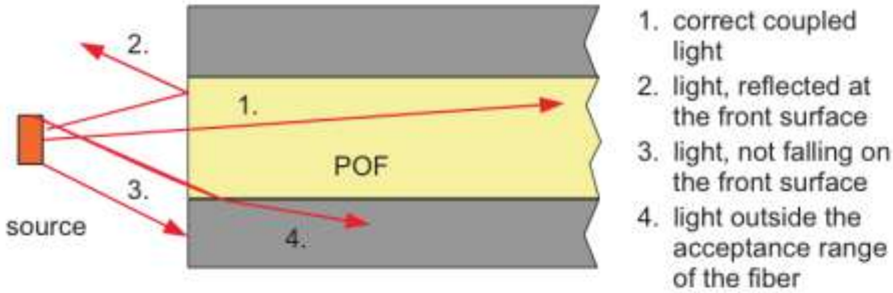


Figure 30 - Causes for losses when coupling to the POF

The most critical of all source parameters is the angle of emission or, more precisely, the far field, i.e. the emitted power in relation to the angle with the optical axis. A standard NA POF has an acceptance angle of approximately ±28º. For a DSI-POF this value is reduced to ±17º. For DSI-MC-POF or GI-POF it is only ±11º. However, the LED used for cost reasons in POF systems emit at a much wider angle. To a certain degree it is possible to reduce the emission angle of a LED by means of lenses. There are a number of LEDs available which have different emission angles. These are achieved through different designs of the LED housing, which also has the function of acting as the lens. According to the laws of optics, the product of image size and numerical aperture cannot be reduced. This means that a reduction in the angle will result in an increase in the image of the LED chip on the front face of the fiber. Typical LED chips are 200 µm to 300 µm in size. Thanks to a POF diameter of 1 mm there is some room here for maneuvering, as is schematically illustrated in Figure 30 and Figure 31.

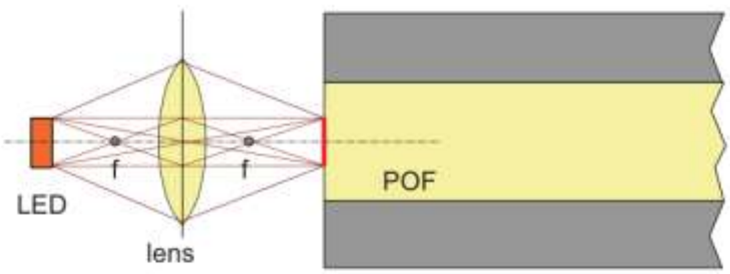


Figure 31 - Imaging of LED chip on the POF with a 1:1 magnification

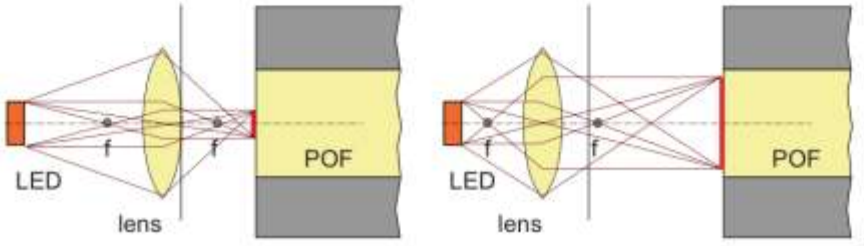


Figure 32 - Imaging of the LED chip on to the POF with a reduction (left) and enlargement (right) of the chip image on the POF

One can see that in the case of the reduction of the LED image, the angle range of the rays increases. Conversely, in the case of a magnification, the angle range becomes smaller. The illustration also shows a second effect too. Typical LED emit at such a large angle that normal lenses can hardly capture them. That means that the aperture of the lens determines how much light can be launched. For example, the authors used plano-convex lenses for this purpose with a focal length of 13 mm at 21.4 mm effective diameter. By arranging two lenses behind each other it was possible to place the LED approximately at the focal point so that the useable lens NA was approximately 0.8. However, a much more efficient coupling of the LED can be achieved if the chip is equipped with an appropriate micro-lens fitted by the manufacturer, as shown inFigure 33.

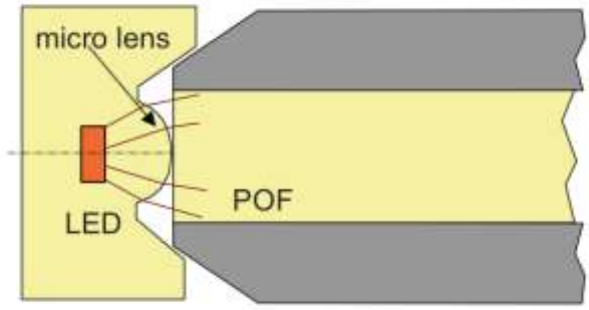


Figure 33 - Projection of the LED chip on to the POF via a micro-lens

With direct butt coupling of a LED to the POF, the typical losses are in the range of 10 dB to 12 dB. When the imaging is optimized, it is possible to reduce these losses to within a range of 4 dB to 5 dB. Any improved values can only be achieved where specially optimized components are used. Such components are, for example, VCSEL or special LED.

2.2.4.2 *Coupling Losses between POF and Receiver*

Coupling a photodiode to a POF appears relatively simple at first. In contrast to LED, the far field of a POF is relatively well known factor, being, for example, within the range of $\pm 30º$ for a standard NA POF. This means that one simply needs to place a sufficiently large LED relatively close to the end of the POF in order to capture practically all the light that is coupled out. One main problem, however, is the fact that in the case of photodiodes the area directly determines the diode capacity C_{PD}. It is important here that this capacity, together with the input resistance R of the amplifier, **forms a low-pass filter**, the critical frequency of which is formed by the product of $C_{PD} \cdot R$. R determines what voltage can be generated by a given photo current $I_{ph} \sim P_{opt}$. The electrical power is proportional to V^2 which also means that is proportional to R^2. However, since the noise power is only proportional to R, the signal-to-noise ratio increases in direct proportion to R. This means that a **larger diode area will limit either the bandwidth or the sensitivity**, depending on the choice of R. In practice, it is the diode's capacity that primarily presents the limiting parameter, at least for 1 mm POF systems. One will therefore endeavour to use as small photodiode as possible to which the POF is coupled via a micro-lens.

Commonly available receivers operate with diodes of approx. 0.7 mm diameter. For the reduced diode capacity, losses in the range of 2 dB are accepted for coupling via a lens.

2.3 Optical filters: Fiber Bragg Gratings

Optical filters have to fulfil numerous tasks in transmission systems and sensor applications. They can serve the purpose of suppressing interfering light or reducing near crosstalk in WDM systems. Fundamentally, filters fall into two categories (Table 5), the interference filters (optical grating and dielectric multi-layer structures) and interferometers where a certain wavelength range can pass through while the rest is reflected. By means of correspondingly complex structures, you can achieve almost any desired spectral curve.

Suitable additions to dye filters absorb undesired light and the spectral curves depend on the available dyes. These filters normally have worse parameters, but are many times over simpler and more reasonably priced. They are well suited for supressing interfering light and have one great advantage in that they work independently of the angle of incidence.

Filter type	Interference Filter	Dye Filter
Principle	Reflection Transmission	Absorption Transmission
Smallest spectral width	< 1nm possible	Approx. 10 nm
Construction	Many transparent layers Refractive grating Transmitting grating Mach-Zehnder interferometer	Substrate layer with dye particles
Angle dependent	Yes	No
Polarization dependent	Partially	No

Table 5 - Comparative between two main filter types in POF

A fiber Bragg grating (FBG) is a kind of distributed Bragg reflector constructed in a short segment of optical fiber that reflects particular wavelengths of light and transmits all others. This is achieved creating a periodic variation of the refractive index in the fiber core, which generates a wavelength specific dielectric mirror. FBG can therefore be used as inline optical fiber to block certain wavelengths, or as a wavelength-specific reflector.

FBGs are produced by using a UV laser to modify the refractive index of the core of the optical fiber to form the interference pattern. This interference pattern will allow most wavelengths of light to travel freely down the optical fiber whilst strongly reflecting.

The most **common technique** to manufacture FBG is the side writing technique. In this technique the fiber is irradiated transversally from the side with UV light and a phase mask or an interference pattern of two beams is used to create the intensity fringes,Figure 34.

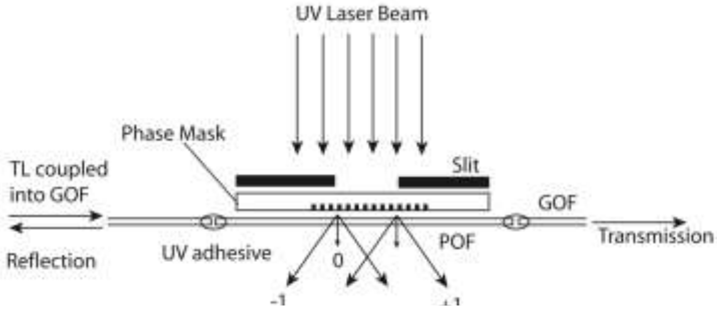


Figure 34 - Ultraviolet side writing setup

The comparison of the transmission and reflection spectra of a glass fiber FBG is illustrated in Figure 35where the reflection spectrum has been normalized with respect to the reflectivity of the transmission spectrum. This is necessary as coupling losses and the 3 dB losses from the 50/50 coupler attenuate the reflection peak in the reflection arm.

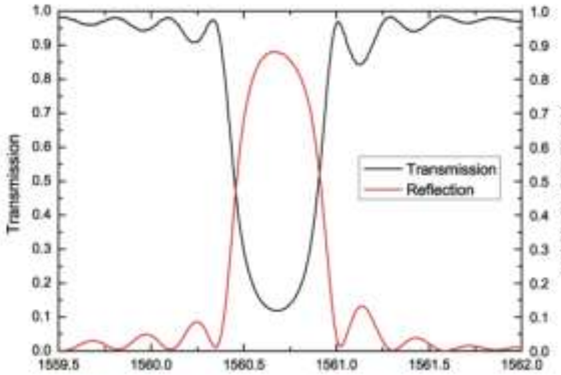


Figure 35 - transmission and reflection spectrums of a FBG

Fiber Bragg gratings are versatile wavelength filters for **multiplexing and demultiplexing** wavelength division multiplexing (WDM) signals. They also can **compensate for chromatic dispersion** that can degrade the quality of the WDM signal in an optical fiber.

Because the selected wavelength reflects from the grating, it must work in conjunction with a circulator or other isolated component. A circulator, for instance, is a three-port device designed so that light entering the first port emerges from the second port, and light entering the second port emerges from the third. An optical add/drop multiplexer is an example of a fiber Bragg grating used to multiplex and demultiplex a WDM signal (Figure 36). A signal composed of many wavelengths enters Port 1, of the first circulator, emerges from Port 2 and enters the grating, where the selected wavelength, λ_2, is reflected and all others are transmitted. The reflected light enters Port 2 and emerges from Port 3 in a process that demultiplexes it from all other wavelengths. The "add" signal at λ_2, enters Port 1 of the second circulator and emerges from Port 2. It enters the grating, reflects from it and joins the other wavelengths transmitted through the grating. It has been multiplexed into the WDM signal.

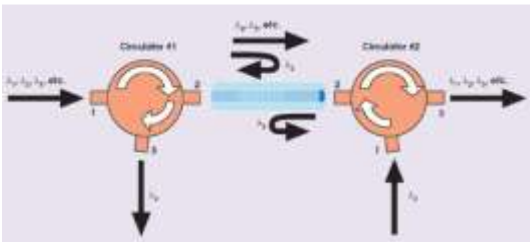


Figure 36 - Add-Drop scheme with FBG and circulators

Due to the wavelength dispersion of the fiber the signal is degraded as it travels because it cause pulses to widen as they propagate down the fiber, eventually making it difficult to distinguish a 1 from a 0 in a signal. In the extreme case, the pulses level out to a flat, continuous signal.

Pulses widen because they are not perfectly monochromatic. Each pulse has a bandwidth that, according to the Fourier theorem, is inversely proportional to its temporal width. As the pulse travels down the fiber, the short-wavelength components get ahead of the long-wavelength components, causing the entire pulse to widen.

For chromatic dispersion compensation applications, the grating in the fiber is not linearly sinusoidal as it is in a multiplexing or demultiplexing device. Rather, it is chirped, with spacing varying over the length of the grating, Figure 37.

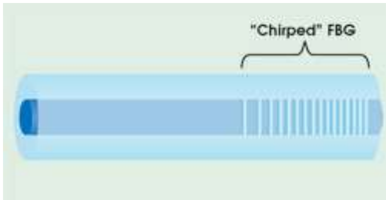


Figure 37 - Chirped FBG to compensate fiber dispersion

In the last years, **research aimed at writing refractive index structures in polymer optical fibers**. In this process different routes were taken such as ablation induced structures or surface refractive index modification accompanied with ablation. First FBGs were produced by Peng [15] and Xiong [16] using a lower initiator and chain transfer agent concentrations which would suggest that the monomer content is higher than normal [17]. Index changes of up to 10^{-3} were achieved without apparent material damage.

JianMing [18] MMA-EMA-BzMA core doped fiber with trans-4-stilbenemethanol. The fiber was irradiated with 325 nm laser light using a phase mask setup. In this case a maximum index change of $-9x10^{-3}$ was achieved. Xingshen [19] did birefringent gratings in azobenzene doped PMMA fibers with a 532 nm laser light.

Photosensivity was also investigated in CYTOP [20] with CW laser at wavelengths of 457, 488 and 514 nm achieving a diffraction efficiency of up to 1.6% and a corresponding index modulation of $3 \times 10^{-4.}$ These were only investigations of the photosensivity, POFBG in CYTOP fibers were not presented.

Scully et al. [21] showed that grating structures can be written into a pure PMMA using a femtosecond laser at 800 nm and Baum et al. [22] investigated refractive index structures in PMMA induced by frequency doubled femtosecond laser irradiation at 387 nm. The photoinduced material change was reported to lead to monomer and dimmer creation, which could lead to an unzipping process.

2.4 Multiplex technologies over POF

The best value at the time was the transmission of 2 x 2.5 Gbit/s over 458 m (University of Eindhoven). This value has endured to today as a system capacity. Nevertheless, this does not mean that the development of POF systems would not have made further progress. A large part of the current developments does not refer to the improvement in the parameters of PF GI POF, but lies more in the area of reasonably priced PMMA fibers. Consequently, it was possible in the laboratory to increase the data rates for 1 mm POF to 2.3 Gbit/s. With a 1 mm PMMA GI-POF 2 Gbit/s over 100 m are possible and with green LEDs distances of several 100 m of PMMA POF can be possible.

At the SOFM 2006 in boulder the transmission of data rates of 10 Gbit/s up to 40 Gbit/s over short lengths (30 m) of PF-GI-POF with a 50 µm core diameter was presented for the first time. These results are of primary interest for parallel data connections.

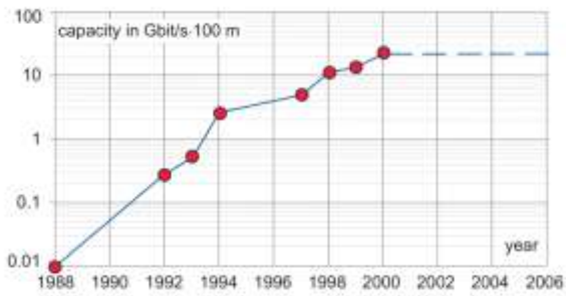


Figure 38 - Development of POF systems capacity

The following list shows **the present highest capacity** of different polymer and glass fibers (estimations).

- Up to 2,500 Mbit/s over short lengths PMMA-POF
- Up to 40,000 Mbit/s over PF-GI-POF (30 m)
- 500 m transmission distance for low data rates with PMMA SI-POF
- 550 m transmission distance for 2.5 Gbit/s with PF-GI-POF
- 1000 m transmission distance for 1.25 Gbit/s with PF-GI-POF
- 100 Mbit/s · km · bit capacity for SI- and DSI-POF
- 50 Mbit/s bit capacity on 1 mm MC-GOF
- 50 Mbit/s bit capacity on 200 µm Semi-GI-PCS
- 100 Mbit/s · km bit capacity for MSI- and GI-POF
- 500 Mbit/s · km bit capacity for PMMA GI-POF
- 2.280 Mbit/s · km bit capacity for PF-GI-POF

It has always been difficult to assess the future development of PF-GI-POF, but the successes above all at Chromis Fiberoptics are a cause for optimism. Their use in home networks could be of increasing interest especially for PMMA GI-POF. Further improvements in system capacities can be expected with **the development of new multiplex technologies**.

Different multiplex systems relevant for POF are compared in Table 6 with typical values according to current publications.

	SDM	**WDM**	**MGDM**	**SCM**
Number of fibers	N	1	1	1
Possible bit rate (for a fiber bandwidth of B)	$\approx 2 \cdot B \cdot N$	$\approx 2 \cdot B \cdot N$	$\approx 6..8 \cdot B$	$\approx 4..8 \cdot B$
Required number of wavelengths	1	N	1	1
Available transmitters for PMMA-POF	650 nm LD	650 nm LD all λ LED	650 nm LD	650 nm LD
Available transmitters for PF-POF and SiO2 fibers	850 nm – 1300 nm LD	850 nm – 1300 nm LD	850 nm 1300 nm LD	850 nm – 1300 nm LD
Required special components	Ribbons LP/PD arrays	Mux / Demux	Small TX Mode sel. RX	Linear LD Low noise RX

Advantages	Use of available components	Simple setup Optical filters	Only one wavelength required	Only 1 TX/RX required Avail. Components
Disadvantages	Thicker cables	Large MUX for PMMA-POF	Unknown influence of the mode coupling	Non stable frequency response

Table 6 - Overview of multiplex methods for POF

The table does not show any clear favourite. In the medium-term the wavelength multiplex may emerge as the clear winner for PF-GI fibers. Various **exceptional features** speak for it:

- Particularly wide band with low attenuation and dispersion (600 nm to 1300 nm)
- Relatively small multiplexer/demultiplexer
- Large number of available laser diodes at different wavelengths.

For PMMA fibers the number of possible channels are relatively limited with MGDM and WDM. Furthermore, the large core diameter and the large NA lead to relatively voluminous optical components. Multi carrier procedures are already widely developed in radio and DSL technologies and can be adapted quite easily for POF in order to better utilize the limited capacity. However, the development of better GI POF, faster transmitters and adaptative equalizers offer for the present even much more potential for very simple solutions.

Above all **the development of SDM systems** is of interest for many applications with POF. The extremely simple and reasonably priced cables, un complicated end face treatment and adjustment as well as the availability of very cheap active components will make multiple parallel systems extremely attractive especially over short distances. Here PMMA SI-POF can transport straight away many Gbit/s at distances up to a few meters and thus surpass copper conductors. In addition, the power requirements go down and available VCSEL in the near infrared range can be used.

Sections below will be focused on the **use of various optical frequencies in a single network**. Generally speaking, we are talking about different carrier frequencies. However, they are so great, just like the distance between them, that they cannot be processed by electrical components. For example, processing, combining, separating or filtering the various wavelengths is done exclusively by optical components. In single-mode glass fiber technology, a number of components have been developed over the last few years such as arrayed wave guides (AWG), Fiber-Bragg gratins and wide band tunable lasers. **They have made WDM the key technology for optical communications**. Soon many hundred optical channels will be transferred over glass fibers that will be forwarded transparently over hundreds of kilometres in optical nodes. Wavelength division multiplexing also plays an increasing role for polymer optical fibers.

Chapter 3. Methodology and work planning

3.1 Project management and tools used

To develop this TFG I used different computers tools and online platforms to make it easier, including communication with the project mentor. I used following tools to become more productive during the project development:

- **Cloud resources sync**: I used in this case Google Drive to have everything synchronized between devices (resources, memory, and all stuff related with the project). I could even edit the documents online.
- **Tasks management**: After distributing the project in tasks and these tasks in little subtasks I needed a tool/platform to manage them giving priority, status, and comments. I used an online tool, Redbooth, helpful to manage your project tasks, conversations, notes… Teamgantt has been another online tool to manage tasks in this case specially to generate a Gantt chart of the project schedule.
- **Communication**: Communication flow with the mentor was through email in most of cases. Only when I needed something more specific I met with her in her office.

3.2 Distribution in tasks

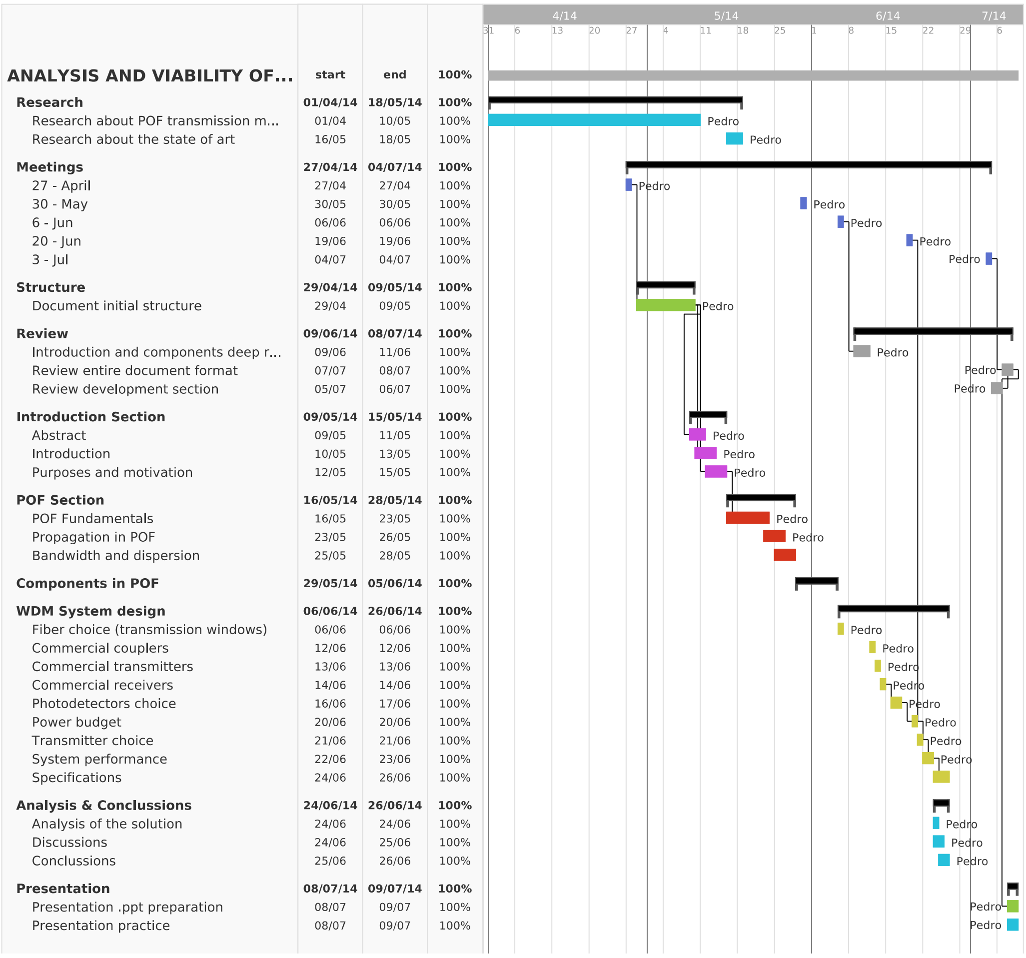
- **Documentation research, organization and structuration:** I read some resources related with the project, I knew about optical transmission but in GOF and moving to POF required some updates like transmission windows, components developed in these windows, … Project's mentor sent me all these resources and technical documents. I read, structured, and extracted some ideas from them. Although this has been a process carried out during all the project development, it has an especial role in the first steps to understand the environment around the project topic.
    - *Started from Jan-21014 and kept during the entire project.*
- **Project structure review:** After the previous step, I met with mentor in order to organize the project structure, specially the project development section. I move all the structure to the style document provided by the school. The structure has been reviewed in different meetings once the memory was getting shape.
    - *Last week of Apr-2014 and short reviews during the project development*
- **Introduction and motivation:** I worked in both sections of the project to present the project and start having and idea what's the project is about. Once finished I could start focusing in the most technical part giving more details about the implementation and the system design. The most important here is understand changes introduced in comparison with glass fibers because it'll affect to the system design.
    - *First week of May-2014*
- **System development and evaluation***:* Understood POF, its bottleneck and different commercial existing solutions in this section, using available devices we focused on development of the system, making a choice of the most suitable components and

arguing why them. With the chosen devices we characterized the system in terms of length and offered data rates keeping in mind current home solutions.

  - **May-*2014 and June-2014***

- ***Specification, analysis and discussion:*** As an example of the WDM over POF, a WDM scheme is presented here with its specifications and some comments around the obtained results.
  - ***15th-30th of June 2014***
- **Presentation creation:** Having finished and reviewed the memory, the last step has ben creating the presentation document, plan and try the presentation before the mentor and closest university friends to fix mistakes.
  - **1st - 8th of July 2014**

3.3 Gantt chart



Chapter 4. Deployment of a WDM system over POF

4.1 Topology

The main components of a WDM system, besides the fiber, are the MUX/DEMUX devices. The first one will enable to couple different wavelengths in the same POF fiber. Each of these wavelengths will be in the grid we have to choose to according to the POF transmission windows. On the other hand, the DEMUX device will enable to pull a specific wavelength filtering the rest.

Before start choosing the components that are going to be part of our system it's important to know about a common **WDM structure, their components and how are they connected**. Power and time balances will determine the maximum length and maximum data rates our designed system will be able to offer. Figure 39 shows a basic multiplexing schema with all the components numbered. Our design will be inspired in this scheme presented in 1999 by Prof. Khoe from Eindhoven University where a transmission for a 2.5 Gbit/s WDM system over PF-GI-POF was proposed. In this proposal the 3 lasers were emitting in 645 nm, 840 nm and 1,300 nm and the three channels were transmitted over a distance of 200 m simultaneously.

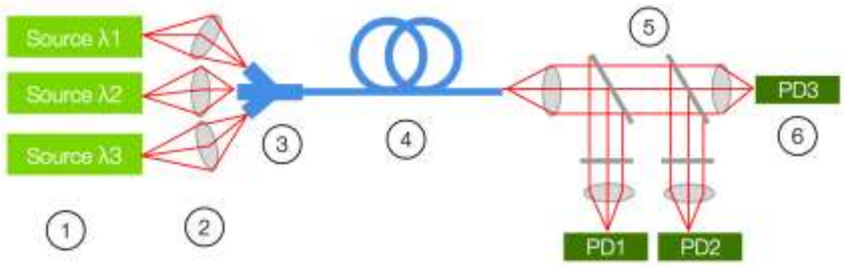


Figure 39 - WDM POF scheme multiplexing three wavelengths

In the figure above we have three light sources (1) working at different wavelengths. The wavelengths will depend on the available transmission windows on the fiber (4). Each source is characterized by the spectral width ($\Delta\lambda$) and output power (P_o) among other parameters we'll describe with more detail below. From these sources the light will be attenuated along the different components it will pass through (coupling lens (2), coupler (3), fiber (4) and demux device (5)). The power level at point (6) where the signal is detected must be larger than the sensitivity of photodetector device. This is the power balance that will be a key aspect in the link length. Comparing it with a GOF link we have here extra focus lens in transmission and reception to couple the light with/from the fiber. These focus lenses will introduce power losses that we have to take into account in the power balance:

$$S < P_{tx} - L_{len\, s_{TX}} - L_{mux} - L \cdot \alpha_{fiber} - L_{demux} - L_{len\, s_{RX}} - L_{connectors} - SM \quad (12)$$

$$L < \frac{P_{tx} - L_{len\, s_{TX}} - L_{mux} - S - L_{demux} - L_{len\, s_{RX}} - L_{connectors} - SM}{\alpha_{fiber}} \quad (13)$$

Where P_{tx} is the transmitter output power, $L_{len\, s_{TX}}$ and $L_{len\, s_{RX}}$ are the losses at input and output lens, L_{mux} and L_{demux} are losses in mux/demux devices, α_{fiber} the fiber losses, L the link distance, $L_{connectors}$ the connectors losses and SM, the security margin

Long distances will be related with low losses of components (13). We can read these values directly from the datasheet of commercial products, for example for POF fiber, coupler, light source and PD but in case of lens just for being something experimental nowadays the values we use have to be theoretical. With de development of POF solutions and the proliferation of standards around components we'll have more lens commercial packages.

The time balance will be another critical point for our system. It is directly related with the data rate, through the following expressions:

$$T_r^{\ 2} = T_{TX}^{\ 2} + T_f^{\ 2} + T_{RX}^{\ 2} \quad (14)$$

Where T_r is the **rise time of the whole system** and can be expressed using the rise time of the source, the receiver and the fiber. Thanks to the relation ofT_r with the rate of the digital modulation the criteria of the system (assuming the behaviour of a RC filter) is:

$$T_r \leq \begin{cases} \frac{0.35}{B}; RZ \\ \frac{0.7}{B}; NRZ \end{cases} \quad (15)$$

Respect to the **time in the source and the receiver** it can be expressed in relation to the bandwidth Δf in (16) while the previously explained dispersion parameters appear in the rise time of the fiber (17), where T_{int}, T_{GVD}, T_{POL} are the intermodal, chromatic and polarization dispersion[3] respectively.

$$T_{TX,RX} = \frac{0.35}{\Delta f} \quad (16)$$

$$T_f^{\ 2}(z) = T_{int}^{\ 2}(z) + T_{GVD}^{\ 2}(z) + T_{POL}^{\ 2}(z) \quad (17)$$

Once chosen the light source and the fiber dispersion values can be calculated. The chromatic dispersion is typically given in $\frac{ps}{km \cdot nm}$, thus known the link distance and the spectral width in nm of the optical source we can get the rise time. On the other hand, the **modal dispersion** depends on the type of fiber (step index or grade index) and the link distance it can be calculated as in equation (8) and (10).

[3]Polarization mode dispersion (PMD): Is a form of modal dispersion where two different polarizations of light in a waveguide, which normaly travel at the same speed, travel at different speeds due to random imperfections and asymmetries, causing random spreading of optical pulses.

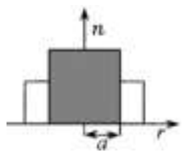
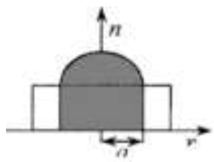
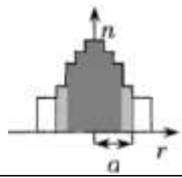
4.2 Commercial components

4.2.1 Fiber type and material

First of all, we have to analyze existing fiber types and materials to choose which one is better to use in a wavelength division multiplex transmission. It's important to remark the requirements for our transmission before making a choice:

- **Cheap**: Thinking in a house environment, it has to be accessible to the user. We shouldn't choose a great performance fiber but too expensive. Home user wouldn't install it.
- **Flat and low attenuation levels**: Grid deployment there will be better with a flatter profile in the fiber.
- **Transmission windows**: It's important that there were components working on supported transmission windows (couplers, transceivers, receivers). It has no sense choosing a fiber if nowadays there are not components supporting these windows.

The type of fiber that best suites our requirements is the Graded Index profile fiber. This kind of fiber is suitable for short and medium haul communications and it has low intermodal dispersion levels. Moreover it offers the higher product B·L in comparison to SI and M-SI profiles.

Index profile			
Fiber type	Single mode / Multi mode	Multimode	Multimode
Bandwidth · Distance	3 MHz · Km	600 MHz · Km	30 MHz · Km

The development of POFs so far has been focused on getting better losses levels with different kind of polymers. The most recent studied one, PF has shown not only these better losses of around 16 dB /km but transmission windows between 850 and 1,300 nm which allows the use of emitters and receivers used in glass fibers. The best results have been achieved with a **material called CYTOP®** (cyclic transparent optical polymer), developed at Asahi Glass in Japan. This material no longer contains hydrogen. It was possible to reduce the attenuation of fibers step by step to less than 10 dB/km at the wavelength of 1,300 nm and it seems that in the coming years the attenuation will be less than 1 dB/km [25]. A comparative between current POF core materials is shown in Table 7.

Material	Attenuation (dB/km)	Bandwidth (GHz*km)	Application	Core/ cladding refractive indexes	NA	Core diameter (μm)
PMMA	55 (538 nm)	0.003	LANs, industrial communications and sensing	1.492/1.417	0.47	250 - 1000
PS	330 (570 nm)	0.0015	High T industrial short haul communications and sensing	1.592/1.416	0.73	500 - 1000
PC	600 (670 nm)	0.0015	High T communications	1.582/ 1.305	0.78	500 - 1000

			and sensing			
CYTOP	16 (1310 nm)	0.59	LAN	1.353 / 1.34		125 - 500

Table 7 - POFs materials and their specifications

Values below 20 dB/km allow transmission ranges of up to 1,000 m. this covers not only the field of application for copper data cables but also for glass multimode fibers. Likewise, deployment in access networks would become possible.

The best values so far are shown in Figure 40 whereby the company Chromis Fiberoptics has used a continuous production process for the first time.

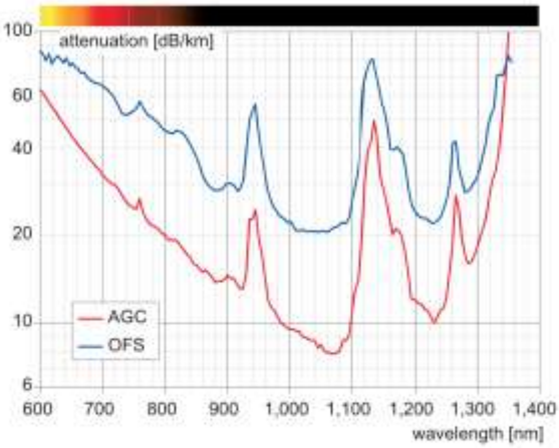


Figure 40 - Current attenuation values for PF-GF-POF

Table 8shows a comparative between different kinds of PF-GI with their specifications, including the price. Between all of them, GigaPOF120LD shows the better quality/price relationship. It has a low N/A value that is something better in order to couple the light into the fiber and have reduced intermodal dispersion. Moreover this fiber can be bought per meter, something interesting for a house installation where you'll probably not need more than 50 meters (Other commercial solutions are offered in spools of 500 m and 1000 m)

Fiber	Price (per meter)	Core/Cladding Diameter (μ)	Jacket	Trans. Losses	Min. Bend Radius	N/A
GigaPOF50SR-CB-SMP	0.47 €	50 / 490	PVC (Aqua)	5 dB/km (850 nm)	7 mm	0.19
GigaPOF62SR-CB-SMP	0.85 €	62.5 / 490	PVC (Blue)	5 dB/km (850 nm)	7 mm	0.19
GigaPOF62LD-CB-SMP	0.98 €	62.5 / 750	PVC (Blue)	5 dB/km (850 nm)	7 mm	0.185
GigaPOF120SR-CB-SMP	1.43 €	120 / 490	PVC (Purple)	5 dB/km (850 nm)	10 mm	0.185
GigaPOF120LD-CB-SMP	0.85 €	120 / 750	PVC (Purple)	5 dB/km (850 nm)	10 mm	0.185

Table 8 - Comparative between PF-GI products of FiberOptics

Its main product is the fiber GigaPOF-120LD. Until now, the simplicity of plastic optical fiber came with a heavy price: low performance and restriction to visible wavelengths. The Chromis GigaPOF line overcomes that trade-off with low attenuation, IR-transparent polymer materials, a graded refractive index, and exacting geometric tolerances. According to the company it supports Gigagit and 10-Gigabit Ethernet, HDMI, USB 3.0 and other multi-gigabit applications at distances up to 100 meters without compensation. Moreover the fiber can be factory-terminated in seconds with an automated tool from the same company and can be clamped or glued directly into optical subassemblies without a ferrule. The product datasheet is in Annexes section

4.2.2 Transmission windows of GigaPOF-120LD

Regarding the fiber attenuation profile in Figure 41the fiber offers three attenuation windows. The first one between the red spectrum at 650 nm and 950 nm where the attenuation has a peak. The attenuation level in this transmission window is around 25 dB/km. The second one is between 1000 nm and 1100 nm (there is another attenuation peak in 1130 nm approximately) with and attenuation level of around 20 dB/km. The last attenuation window is between 1160 nm and 1300 nm with a short peak at 1290 nm. The level here is around 25 dB/km too.

With the previous transmission windows we have to choose then the components can work there, receivers and transceivers as well as couplers and demux devices.

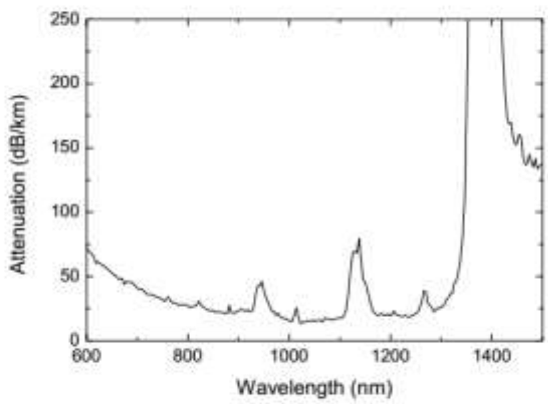


Figure 41 -Attenuation profile of GigaPOF 120LD Fiber

4.2.3 OpticalSource

The main advantage of having chosen PF-GI as our system fiber is that we can user the same type of sources that we use in glass optical fibers, lasers, because both use the same spectral range between 850 nm and 1300 nm.

Practically all commercially available POF transmitters today use LED or SLED. System experiments with high data rates from about 1 Gbit/s are exclusively carried out with laser diodes because commercially available LEDs are not fast enough.

VCSEL as well as RC-LED and NRC-LED show excellent characteristics that suggest deployment in connection with POF. Table 9lists available commercial sources

We have extracted in Table 9 best commercial coherent light sources that best fit with the chosen fiber GigaPOF 120LD. As we can see there, there aren't lasers around the wavelength of 1100 nm. The reason is that lasers working there are too expensive and consequently not suitable for a house link.

Product	T_r (ns)	λ (nm)	Power (mW)	FWHM (nm)	Datasheet	Price (€)
650 nm						
SFH757	15	650	0.2	20	Link	8

AFBR-1624Z	5	650	0.6	25	Link	13
850 nm						
OPF692	5	850	0.035	45	Link	14
OPF692-2	4.5	850	0.08	50	Link	15
VSEL-850	0.05	845	1.85	0.85	Link	29
980 nm						
VSEL-980	0.06	980	1.85	0.8	Link	25
1310 nm						
ML725B11F	0.1	1310	10	n.a.	Link	249
ML925B45F	0.3	1310	10	1.0	Link	85

Table 9 - Commercial light sources for POF fibers, including their specifications and price

4.2.4 Photodetector

Photodetector devices in POF similarly to light sources are not developed enough and the solutions shown in Table 10 are solutions thought for Silica fibers. This means the coupling between the photodetector and the fiber will be a problem to overcome using external lens to focus the light because of the high numerical aperture of the GOF fibers. In their datasheets we'll found a curve of responsivity where, depending on the wavelength where the photodetector is working we'll have different values of responsivity, needed to calculate the sensitivity of the device. It can be calculated following the equation(18).

$$S = \frac{q}{\Re} \left(eq\Delta f F(\bar{M}) + \frac{\sigma^T}{\bar{M}}\right. \qquad (18)$$

Where q is the BER parameter, $\Re$ the responsivity, e the electron charge, Δf the receiver width , $F(\bar{M})$ the noise factor in case of being an APD detector, otherwise its value is 1, σ^T the thermal noise, and $\bar{M}$ the gain factor in case of being APD ($\bar{M} = 1$ for PIN detectors). The thermal noise can be calculated as(19):

$$\sigma^T = \frac{4\, K_B\, T}{R} \Delta f \qquad (19)$$

Where K_B is the Boltzmann constant, T the system temperature, R the receiver resistance value, and Δf the receiver bandwidth.

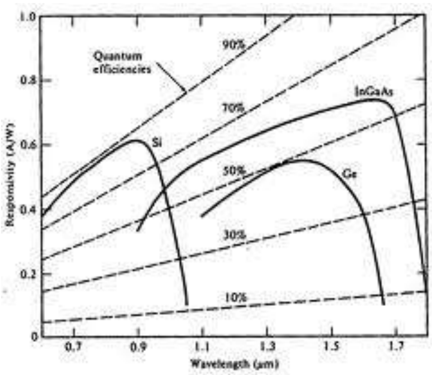


Figure 42 -Responsivity curves depending on the receiver material

The photodetector choice will depend on the transmission window and its bandwidth to fit in the there because although it is not a restrictive point in lasers in case of LEDs their bandwidth is wider and it doesn't allow to have a dense multiplex. The transmission window where the photodetectors work is given by their responsivity curve (Figure 42) where we can observe that the Si receivers work until 900 nm and up to that value the responsivity fades away. In the case of InGaAs it works from 900 nm to approximately 1700 nm where it has the same behaviour the Si one has. The remaining material, Ge, works approximately between 1100 nm to 1500 nm with lower reponsivity values that the previous ones.

Product	Spectral range (nm)	Peak (nm)	NEP (λ_p)W/√Hz	BW (MHz)	Key feature	DS	Price (€)
	Si Transimpedence Amplified Photodetectors						
FDS010	200-1100	830	1.2e-13	350	UV Grade Fused Silica Window to Provide Sensivity Down to 200 nm	Link	42
FDS10X10	340-1100	960	1.5e-14	2.33	Largest Active Area and Housed in a Ceramic Package	Link	100
FDS100	350-1100	900	1.2e-14	17.5	Largest Sensor in a TO-5 Can	Link	13
FDS025	400-1100	850	9.29e-15	2300	High Speed and Low Capacitance in a TO-46 Can with a Ball Lens	Link	30
FDS02	400-1100	850	9.29e-15	2300	High Speed and Low Capacitance in a Direct Fiber-Coupled FC/PC Package	Link	73
FDS1010	400-1100	980	2.07e-13	7.7	Large Active Area and is Mounted on a insulating Ceramic Substrate	Link	48
	InGaAs Transimpedence Amplified Photodetectors						
FDGA05	800-1800	1550	0.8e-14	140	High Speed, High Responsivity, and Low Capacitance	Link	130
FGA10	800-1800	900	2.5e-14	70	High Speed and Large Active Area	Link	158
FGA21	800-1800	1550	3.0e-14	5.3	Largest Active Area of the Series	Link	212
FGA01	800-1700	1500	4.5e-15	1.166	High Speed and Low Capacitance in a TO-46 Can with a Ball Lens	Link	55
FGA01FC	800-1700	1500	4.5e-15	1.166	High Speed and Low Capacitance in a Direct	Link	140

					Fiber-Coupled FC/PC Package		
FGA20	1200-2600	2300	2.0e-12	15.2	Long Wavelength Range	Link	254

Table 10 - Commercial photodiodes available between 200 and 2600 nm

In the table above it has been selected the most suitable photo detector for our system taking into account the price and the offered Bandwidth. For 650 and 980 nm transmission we shall use the receiver FDS025 while for the rest the rest transmission windows over the wavelength 800 nm the receiver will be FGA01. Both devices have a reasonable price and a high bandwidth that make them perfect for high-speed transmissions. Figure 45and Figure 46shows the responsivity curves of both devices. The sensibility needed for the power balance can be obtained from these curves. For wavelengths 650, 850, 980 and 1310 nm the responsivity values are 0.37, 0.4, 0.55 and 0.85 A/W respectively.

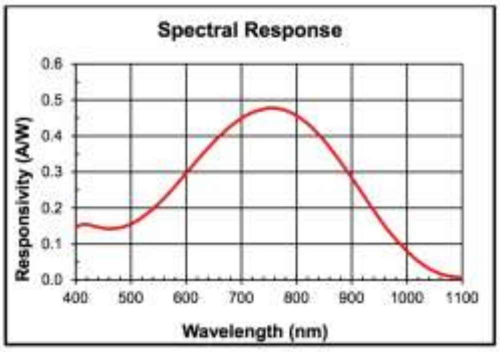


Figure 43–Responsivity curve of FDS025

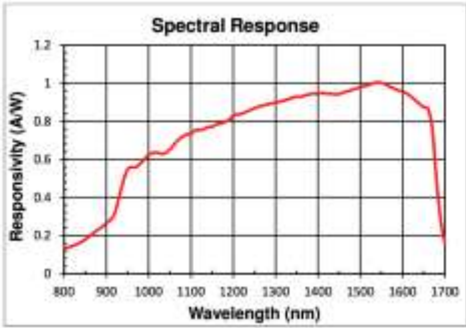


Figure 44–Responsivity curve of FGA01

4.2.5 Filter

There are not yet any special filters for POF or other thick fibers due to the very small range of applications. Users have to rely for the most part on products which are used for general measurement techniques. However, since PMMA POFs are used in the visible spectral range there are numerous utilizable products from optical applications such as photography.

For our deployment we are going to base the losses in experimental measurements (not from commercial devices) especially from a WDM system developed by Eindhoven University of 2.5 Gbit/s in wavelengths 645 nm, 840 nm and 1,310 nm shown in Figure 45. There the demultiplexer excess losses **were around 2 dB** approximately.

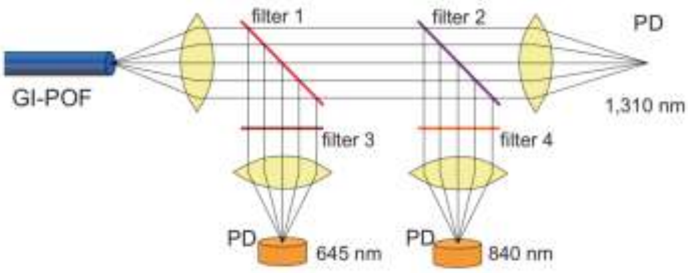


Figure 45 - 3 Wavelenth WDM demultiplexer according to [24]

4.2.6 Coupler

The need for POF couplers is relatively small since there are not yet any large-scale applications. Up to now couplers **have been used in the field of measurement techniques** and for special sensors. POF couplers for bidirectional transmission on one fiber could find wide-ranging applications in the future.Since POF couplers are relatively simple to produce, a number of manufacturers have attempted to enter the field over the years but none of them have been able to become well established. At least you can get these components today, but only if you order a certain minimum amount which is the made to order.Commercial available solutions are listed in Table 11.

Product	Coupling rate	Insertion loss	Excess Loss	Data sheet	Price (€)
IF 543 (1x3)	33:33:33	Port A – Port B 8.2 dB Port A – Port C 8.2 dB	Port A 2.2 dB	Link	50
IF 562 (1x2)	50:50	Port A – Port C 5.6 dB Port A – Port D 3.7 dB	Port A 1.6 dB	Link	43
If 540 (2x2)	50:50	Port A – Port C 5.6 dB Port A – Port D 3.7 dB	Port A 1.6 dB	Link	43
IF 544 (4X4)	25:25:25:25	n.a	n.a.	Link	90

Table 11 - Commercial couplers

4.3 System design: Optical budget and selection of components

Having listed available components to have an idea of specifications of these components we're going to characterize our system. The first step is going to be to make a choice of components in the available transmission windows of the PF-GI fiber. With these components we'll have a list of specifications like losses, frequency response, rise time useful for the time and power balance. After that, we'll evaluate the length limits depending on the transmission windows because the most restrictive one will limit our system length. This will be the link length we'll use to calculate then the data rate available with the chosen light sources working on these transmission windows. Although we'll calculate it using the most limiting distance from the power balance we'll give some comparatives of data-rate distance because in a house we are going to work with short distances where it might be compromised in order to increase the performance of the system.

Typical house links distances have a length shorter than 80-90 m. We are going to make the power budget supposing known the distance and then chosen the receiver, calculate the required power emission and with it the transmitter. To choose the receiver we have to keep in mind the commercial devices listed above, where the values required are listed below. There the transmission windows have been taken into account to the components losses. The sensibility of the receiver hasbeen calculated using the equation (20) where q=6 (BER = 10^{-9}), e is the electron charge, and NEP, Δf and $\Re$ are taken from the chosen receiver:

$$S = \frac{q}{\Re}\left(eq\Delta f + NEP \cdot \Re\right) \qquad (20)$$

With the previously selected receiversthe related sensitivity values are listed in Table 12.

	FDS025	FDS025	FGA01	FGA01
Wavelength (nm)	650	850	980	1310
Responsivity (A/W)	0.37	0.55	0.7	0.95
Bandwidth (MHz)	2300	2300	1166	1166

NEP (W/√Hz)	9.29e-12	9.29e-12	1.5e-12	1.5e-12
Sensitivity (q=6) (dBm)	- 25.67	- 25.69	- 25.11	- 25.12

Table 12 - Sensivity of commercial receivers

Between existing commercial mux devices, only **IF 544** is able to multiplex 4 signals so at first we would use that with excess losses of 2dB.

	650 nm	**850 nm**	**980 nm**	**1310 nm**
Sensibility (dBm)	- 25.67	- 25.69	- 25.11	- 25.12
L_{LENS_TX} (dB)	4	4	5	5
L_{MUX} (dB)	2.2	2.2	2.2	2.2
L (m)	70	70	70	70
α_{fiber} (dB/km)	45	25	25	30
L_{DEMUX} (dB)	2	2	2	2
L_{LENS_RX} (dB)	2	2	2	2
$L_{CONNECTORS}$ (dB)	1.2	1.2	1.5	1.5
$N_{CONNECTORS}$	6	6	6	6
SM (dB)	3	3	3	3
P_{out} (dBm)	**- 2.12**	**- 3.54**	**- 2.96**	**- 2.62**
P_{out} (mW)	**0.613**	**0.442**	**0.505**	**0.547**

Table 13 - Power budget for the available transmission wavelengths

Listed light commercial sources in Table 9 offer an output power over the values we got from the power budget so at first all of them would be valid for our link. Thinking in other important points to take into account it’s the price wider bandwidth and narrow spectral FWM for 650 nm the most suitable device is the AFBR-1624Z with an output power of 0.6 mW and spectral width (FWHM) of 25 nm. For 850 nm the most suitable one is the laser VSEL-850. Thanks to having a laser there, the data rates will be higher and lower dispersion distortions (narrow FWHM).For 980 nm we could put there another VSEL laser device with similar performance than the one in 850 nm. Finally, in 1310 nm, although we have two devices, only one of them is characterized in time consequently bandwidth terms so we’ll use that device. All datasheets of selected light sources are attached in the last section like annexes.

As the output power level of these sources is higher that the minimum required one we might think about recalculate the power budget in order to for example get larger distances but as we have the time balance as another critical factor, larger distances will suppose more penalization in the time domain. Distances taken of 100 m for a house are valid, and just only in case of having acceptable data rates once done the time evaluation we could think in increasing the link length.

4.4 Performance

With all devices characterized the next step is evaluate them in the time domain. The way to do that is **calculate the rise time of all the system** taking into account the rise time of the fiber, the transmitter and receiver devices.

Times of transmitter and receiver devices depend on their respective bandwidths and taking into account that they are an RC circuit, they can be calculated as(15). The rise time in the fiber depends on its dispersion and can be calculated disregarding the chromatic dispersion due its low value and taking into account only the intermodal dispersion where n1 is the core refractive index, z is the distance, q a parameter related with the graded index of the fiber, Δ the relative index difference and c the light speed in vacuum. For the chosen fiber, GigaPOF 120-LD the values of n_1 and n_2 are respectively 1.52 and 1.49.

In Table 14 time of different components have been calculated and the total data rate in our system wavelengths. We have considered an NRZ transmission that supposes $T_r \leq \frac{0.7}{B}$ and consequently the maximum throughput calculated:

Wavelength	**T_{TX}(ns)**	**B_{RX}(MHz)**	**T_{RX}(ns)**	**T_{FO}(ns)**	**B_{max}**
650 nm	5	2300	0.152	0.0241	≈ 140 Mbps
850 nm	0.05	2300	0.152	0.0241	$\approx 4.3\ Gbps$
980 nm	0.06	1166	0.3	0.0241	$\approx 2.2\ Gbps$
1310 nm	0.3	1166	0.3	0.0241	$\approx 1.16\ Gbps$

Table 14 - Time balance in 650 nm, 850nm and 1310 nm

The previous steps starting from the sensibility have sense for digital transmission but what happens if the signal is analogical? In that sense it would be interested to have characterized too the CNR value on the receiver side. This can be calculated with expression (21) where $\Re$ and S are known and σ_s, σ_d, and σ_J are the shot, dark, and Johnson noises.

$$CNR = \frac{(\Re \cdot S)^2}{{\sigma_s}^2 + {\sigma_d}^2 + {\sigma_J}^2} \tag{21}$$

$$CNR = \frac{(\Re \cdot S)^2}{2e(\Re \cdot S)\Delta f + 2eI_d\Delta f + \frac{4K_B T\Delta f}{R}} \tag{22}$$

For each of the wavelength the CNR in dB is calculated in Table 15:

Wavelength	**S (dBm)**	**$\Re$ (A/W)**	**${\sigma_s}^2$ (A)**	**I_d (pA)**	**${\sigma_d}^2$ (A)**	**${\sigma_J}^2$ (A)**	**CNR**
650 nm	-25.67	0.37	7.38e-16	35	2.576e-20	3.7851e-14	**14.16**
850 nm	- 25.69	0.55	1.092e-15	35	2.576e-20	3.7851e-14	**17.52**
980 nm	- 25.11	0.7	8.053e-16	50	1.306e-20	1.9189e-14	**23.61**
1310 nm	- 25.12	0.95	1.091-15	50	1.306e-20	1.9189e-14	**26.24**

Table 15 - CNR for operative wavelengths

Chapter 5. Analysis and discussion

Thinking in house scenario, transmissions there would have a bi-directional character. Although bi-directional systems can be designed just with a unique wavelength, it might introduce noise in other receivers and extra NEXT suppression would be required then. With a proper organization of wavelegths in a wavelength division multiplex transmission and the proper filter devices we could solve this problem leaving giving each one a unique direction in the link. One solution would be the presented in Figure 5 where **two wavelenghts are used for both directions**.

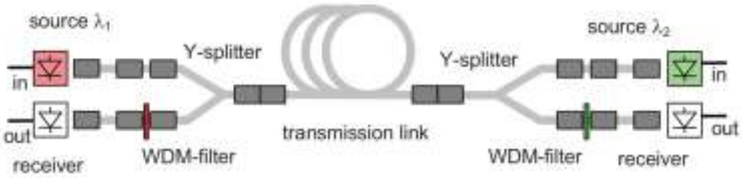


Figure 46 - Bi-directional transmission with wavelength multiplex

With 4wavelengths like the ones we have in our system we could use the two with the highest data rate in the download link, the half-rate one as the upload link for the previous one and the remaining lambda for a unidirectional download service like for example could be television. The throughput in the down link would be the sum of both down throughput and both the transmitter and receiver devices would have a serie-parallel convertor. The distribution of these wavelengths with their respective throughputs and spectral location is shown in Figure 47 where the throughput of the main download link would be around 7.5 Gbps, the respective upload link around 1.1 Gbps and the other wavelength at 650 for a unidirectional download service of 140 Mbps.

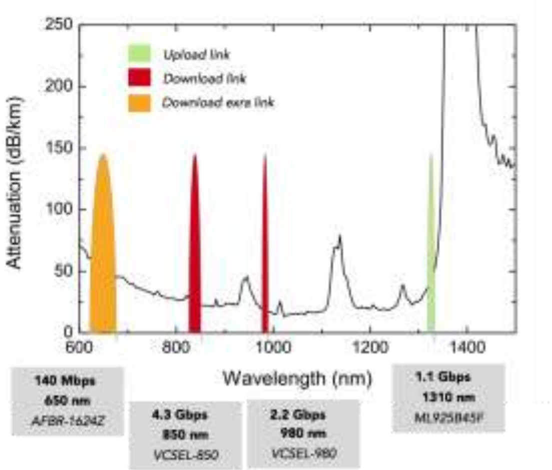


Figure 47 - WDM signals distribution

In a real scenario an optical router device would give access to some others distrusted around the house. Having 2 sources and 1 receiver and filters for each connector it's something unthinkable especially for the precise temperature control systems it would require and the increase of price it would suppose. With a proper combination of multiplex technologies like for example it's done in wireless this problem could be solved allowing the reuse of the transmission medium and devices. For example:

- **Wavelength Division Multiplex:** Currently it's something unviable due to the spectral width of light sources in these transmission windows that only allows us to have just 3-4 wavelengths that we are using to increase the data rate. Probably we'll have in the future narrow light sources in these transmission windows that will enable us, as we do in glass fibers, to have more wavelength and use them for multiple access. The main advantage of this solution is that wouldn't affect to the data rate because the wavelength wouldn't have to be shared.
- **Time Division Multiplex:** In this case time division is a solution that could be implemented. It would require sharing not only a wavelength between multiplex devices but also the data rate of that wavelength. Moreover an extra control signal would be required in order to specify how is going to be shared the spectrum and when should transmit each device.

Comparing the presented WDM solution with other solutions **like a single transmission in POF** we have shown that the offered data-rates are significantly better moving from transmissions around Mbps to almost dozens of Gbps. Today's apartments are mostly equipped with three different cable-based networks: the telephone network, the connection to the broadband coaxial cable network or an antenna system and the 230 V electrical power supply. Each of these networks is adapted for its own specific, albeit very different purpose. Figure 48shows a typical network structure in an apartment. As can be seen, only the electrical power supply effectively connects all rooms. The telephone and broadband networks do in fact provide a connection to the access networks, but no the possibility of networking different terminal devices within an apartment.

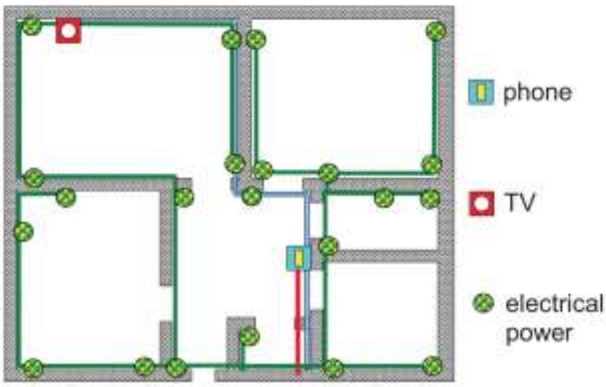


Figure 48 - Typical apartment cabling

The list of possible devices requiring networking could be expanded at will. Surveillance and control systems for heat, windows and doors have increasingly gained in importance. The tenant is thus confronted with the problem of establishing data connections between devices with the lowest possible expenditure of time and money. Two possibilities for completely overcoming such a situation without installing cables is to use Power-Line technology or to set up a radio system. Both options are technically advanced and thoroughly affordable. However, the possible bit rates and attainable quality are subject to definite limitations. Cable-based systems are preferable when transmitting high-quality moving pictures in real time or with a broadband connection of computers, for example, when working at home. Different copper cables as well as optic fibers can be considered.Figure 49 shows a configuration example of router devices multiplexing different services to distribute them optically to different points around the house

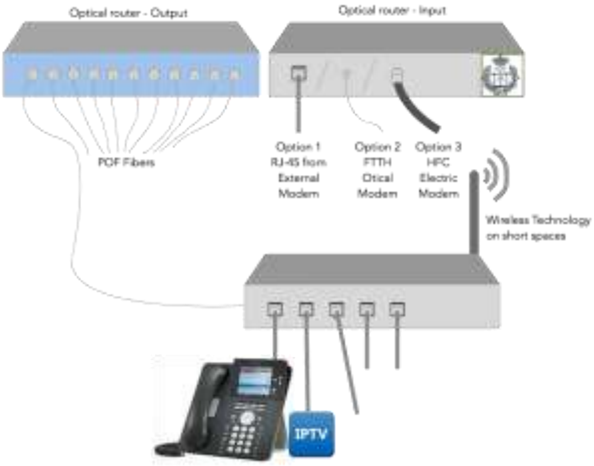


Figure 49 – Example of optical devices in a house installation multiplexing different services

The scheme shown has a broadband connection, initially maybe some VDSL lines, later a 2.5 Gbit/s glass fiber connection. A POF-based star network distributes the data into the apartments per duplex fiber. There is another switch in every apartment and from here the data would be converted to the electrical domain offering RJ-45 connectors or a wireless access point. Moreover extra optical output could be added in order to connect another optical router to this one expanding the network inside the apartment. The entire system can be set up with Fast Ethernet with components available on market today. Since they only have to cover one room each, they can operate with low transmission power and at high frequencies that would reduce the disturbances in neighboring rooms. A handover via the central building node is possible so that full mobility is given. **With this setup the bottleneck introduced by the attenuation of wireless transmissions or the copper cables would be displaced to access points closer to the final user.**

Table 16 summarizes some possible technologies for use in private surroundings.

Technology	Capacity	Advantages/Disadvantages
Radio technologies		
UMTS	2 Mbit/s over 70 m 300 Kbit/s over 100 m 14 Mbit/s (HSDPA)	No local networking
Bluetooth	1 Mbit/s over 10 m 50 Mbit/s (802.15.3)	Extremely simple networking, limited capacity
Wireless ATM	25 Mbit/s over 30 m	Support a wide area of services, still relatively expensive
Wireless LAN	54 Mbit/s over 30 m IEEE 802.11g	Widely used Shared medium
UWV / 802.11n	1 Gbit/s over 10 m	Under development
Copper cable		
PNA	Some Mbit/s	Requires existing phone line, EMI sensitive
Coaxial cable	Some 100 Mbit/s	Requires existing coaxial cables, relatively

		complex converters
Data cable (twisted pair)	1 Gbit/s over 100 m	Large cables (approx. 7-8 mm): highest developed LAN technology
PLC	Up to approx. 45 Mbit/s (Home-Plug AV)	Easy to install, critical EMI sensitivity, and radio emission, shared medium
Optical cable		
Glass SM fiber	Nearly unlimited	Extremely expensive installation
Glass MM fiber	2.5 Gbit/s	Only limited effort for installation
PMMA POF	100..1000 Mbit/s over 100 m	Still a new technology Extremely easy installation
PF-GI POF	2.5 Gbit/s over 550 m	

Table 16 - Technologies for home networks

As can be seen in Table 16, the PF-GI POF lies in the mid-range of performance characteristics for the various transmission media. As regards the simplicity of installation, radio systems and PLC, of course, cannot be surpassed. Among the cable-based systems, POF is distinguished as having the easiest cable setup and the most reasonably priced connection technology. A size comparison of different cables is illustrated in Figure 50, clearly demonstrating that POF can be integrated very well into existing cable duct systems.

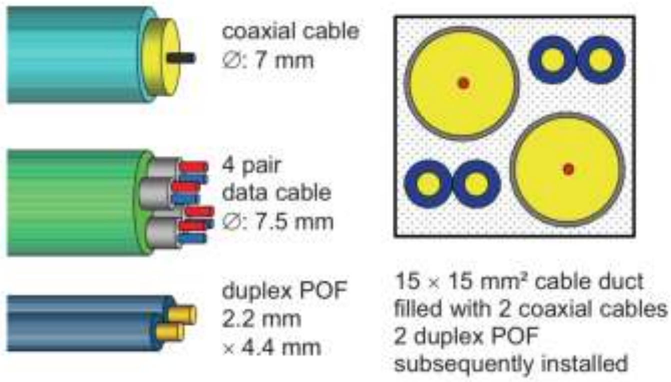


Figure 50 - Size comparison of different cables

Besides the question of transmission media, the point of greatest interest is **the interface to the consumer**. A system can only gain general acceptance when terminal devices are equipped with appropriate connectors, the services desired can be supported with sufficient quality and the components for setting up the network are available at reasonable prices. Table 5lists some of interesting interfaces.

Interface	Bit Rates	Advantages/Disadvantages
ATM Forum	25 Mbit/s, 155 Mbit/ 622 Mbit/s, 2.5 Gbit/s	Supports high-quality services and is already employed in long-distance networks, up until now too expensive for home use
Ethernet	10 Mbit/s, 100 Mbit/s, 1,000 Mbit/s	Used above all for IP applications, wide-spread and good value, dominant in LAN field difficult with video transmission
USB	12 Mbit/s (new 480 Mbit/s)	Wide-spread standard for PCs Very simple operation

		Requires running PC Up until now data rates too low
IEEE 1394	100 Mbit/s, 200 Mbit/s 400 Mbit/s, 800 Mbit/s Up to 3.2 Gbit/s planned	Universal system for all applications (including video) Multi master network with extremely easy operation.

Table 17 - Transmission available standards

POF systems have already been created for all 4 interfaces mentioned. The ATM forum has already specified the use of PMMA POF for 155 Mbit/s. Of particular interest is the inclusion of POF in the IEEE 1394 specification (up until now 100 Mbit/s and 200 Mbit/s over 50 m; 400 Mbit/s over 100 m is in preparation). In contrast to Ethernet, this interface could gain acceptance not only with computers, but also in diverse multimedia devices such as game consoles, cameras and video cameras, televisions and DVD players and with computer peripherals. The IEEE 1394 standard is intentionally not fixed to a medium, **but provides the user with the option of selecting his own cable**. Therein lies great application potential especially for POF as illustrated in the overview above.

Practically all cable lengths – measured between the access point the houses and the terminal devices are under 100 m, typical lengths being 30 m to 40 m. It can also be seen here that POF fits in well with the requirements not only for apartments, but also in the buildings.

In the field of in-house wireless, essentially IEEE 802.11 Wireless LAN and the polymer fiber are competitors too. Wireless technology has a developmental head start of a few years and the advantage of enormous political weight. The reason for this widespread belief that wireless technologies can soon meet any capacity requirements at all is the rapid development of the maximum attainable data rates of the different wireless systems. Table 18 shows some of these development steps.

Standard	Year	Capacity
IEEE 802.11	1997	2 Mbit/s (in the 2.4 GHz ISM Band)
IEEE 802.11b	1999	11 Mbit/s (in the 2.4 GHz ISM band)
IEEE 802.11g	2002	54 Mbit/s (in the 2.4 GHz band)
IEEE 802.11n	2005	Up to 320 Mbit/s (2.4 GHz ISM band, MIMO-Technology)
IEEE 802.16	2006	134 Mbit/s (11..60 GHz, line of sight)
IEEE 802.15.3	2004	200 Mbit/s / 4 m (Bluetooth WPAN, 2.4 GHz ISM Band)
UWB	???	Up to 1,000 Mbit/s (3.1 .. 10.6 GHz)
WigWam	???	Up to 1,080 Mbit/s (5 GHz ISM band, MIMO technology)

Table 18 - Wireless standards up to now

In less than a decade the capacity of wireless technologies for the networks of buildings has increased almost a thousand-fold. Two facts are taken into account with this simple comparison. The increase in capacity has for the most part resulted from a better utilization of the available frequency ranges. For example, the license-free ISM band for 2,400 MHz to 2,483 MHz is divided into 13 overlapping channels. Only three of these channels can be used at the same time. With a bi-directional bit rate of 54 Mbit/s two of these channels are needed. The 108 Mbit/s modems available in the meantime cannot work at all bi-directionally with a full bit rate. In the second license-free band from 5,150 MHz to 5,350 MHz there is somewhat capacity available, but the attenuation from walls and other disturbances increases greatly. If several devices complete simultaneously for the available frequencies, possibly also including those of the neighbors, then the attainable bit rates quickly drop.

The second part of the capacity increase results from high quality modulation procedures (up to QAM 256). The latter require better noise ratios and can there-force still only be realized for the most part over short distances.

Figure 51 from [23] shows the relationship between reach (without walls) and the attainable bit rate for the wireless systems in different generations. Although the capacities differentiate greatly, there is still a clear relationship between capacity and reach. One has to keep in mind that the capacity will drop strongly once again when several walls have to be penetrated, especially with higher frequencies. Reinforced concrete walls and ceilings are almost impenetrable.

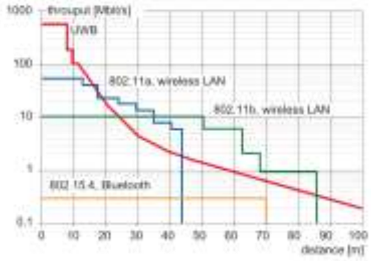


Figure 51 - Reach of radio networks

Of course, there have also been "real" improvements in capacity with wireless systems. The multiple input-multiple output (MIMO) technique is particularly effective, although each device has to have several antennas.

Dramatic increases in capacity by orders of magnitude are only possible in wireless technology when the frequency band is expanded to several GHz – with other services being switched off, or when the transmission power is increased immensely which under certain circumstances can be unhealthy.As we have shown in the previous analysis, **data rates of 6 Gbps can be transmitted using WDM over POF** without big problems. In this case all cables form a point-to-point connection. They thus guarantee the capacity independently of what the other devices are doing at the moment. However, in order to be able to profit from the mobility of wireless networks with broadband applications, e.g. a HDTV device, POF and wireless can be combined.

Chapter 6. Specifications

In a house link between the optical input router and another optical device in any place around the house the total cost is reflected in the budget in Table 19where we have included the previously selected components with their current prices. We have included their datasheets as annexes in the last project section.

Component	Price/Unit (€/u)	Units	Total (€)
Source device			
AFBR-16247	13	1	13
VCSEL-850	29	1	29
VCSEL-980	25	1	25
ML925B45F	85	1	85
Coupler	50	1	50
Optical link			
Optical fiber	0.85 €/m	60 m	51
GigaPOF Connectors	4	6	24
Receiver device			
FGA01	55	2	110
FDS025	30	2	60
Demux	Approx. 50 € (Lab.)	1	50
Installation work			
Workforce	0 €/h (self installation)	1	0
Research work[4]			
Workforce	20 €/h	50	1000
		Total	497 / 1497

Table 19 - House link WDM POF budget

[4]Although the research work has been included in the budget, the research costs related to the WDM deployment and improvement of existing components will appear reflected inside the products costs, or as an inversion for the company that started fabricating these WDM POF kits.

In both source and receiver device we haven't included the electronic layer that it would have that would process the electric signal and redirect it to the respective output for example through Ethernet connectors or converting it into a Wireless signal to be transmitted. In case of the transmitter device it would include the modulator device too.Although the total budget price seems expensive we have to think that these prices are for **individual devices**, in case of in a future having standards for WDM in POF and companies developing devices like mentioned above the price for them would be cheaper and these optical units I mention would be cheaper too.

Furthermore, the installation costs is 0 because the idea of the solution would be **selling it as kits "easy-to-install" for users**. The package would have both device, a master and a slave one and he/she should only prepare the link, cutting the fiber, putting the connectors in both sides, an ensure the optical link doesn't have short curve radius that might affect to the signal transmission. Moreover, although the kit would have only a slave device these could be bought separately and the price would be around 300 € taking into account that in that case only the upload LED and laser at 650 nm and 1310 nm would be required.

Chapter 7. Conclusions and future guidelines

After having analyzed the deployment of WDM multiplex technology over POF we have seen that although it offers higher performance than existing technologies it's still an expensive solution to be used as the unique transmission technology at home. The main reason of that price is that POF is still in development and not only WDM but also other mux/demux techniques in glass fibers has to be moved to POF too. Moreover companies seems still against to start developing and improving POF solutions because there are no enough a clear solution or technology that users might adopt and it causes that the current solutions prices are high. Moreover, while there's a big range of commercial POF fibers, lasers and LEDs to chooses and couple to these fibers, commercial demux devices are still laboratory testing devices. If we compare them with Glass, where AWG allows to demux all wavelengths using a unique device, in GOF current analyzed solutions are based in the combination of different FBG filters using lenses increasing the related losses and a worse performance.

Another aspect to take into account in this field is that most of home devices **are ready to work with electrical signals** coming from copper cables like for example RJ45 in the computer side or RG6 for TV signals. Nowadays, most component and equipment suppliers are unsure what specifications for physical layer of POF-based home networking (i.e., transmitters, receivers, connectors, etc.) will prevail in the marketplace, so some may be reluctant to invest in developing or launching POF-oriented home networking products. On the other hand, other suppliers are developing and launching products prior to any formal standardization of the physical layer. Obviously, the sooner standards for POF media and transmission/modulation/encoding schemes are set, the sooner POF-based home networking market will take off. Websites like www.homefibre.com are offering easy-to install kits of POF with everything an user would need to get his/her house ready for optical communications, and incredibly it's a success.

We have designed here one solution that might contribute with this process, and from the analytical and professional side we have shown the big problem of low data rates with a simple wavelength can be overcome. **Future investigation lines** could be focused on measure and characterize the system from a more realistic scenario. **Non-Linear phenomena** exists here too and although we haven't analyzed them exhaustively and we have included them as a power penalization in the power budget with real measures we could check how these phenomena appear in POF and how it affects to our low-dense WDM grid. Phenomena like **four wave mixing (FWM) or Kerr effect** that have an important role in a high performance systems in GOF. Another investigation branch might be the electronic side of that system and how would be that "optical router" which every user would have in his/her house, paying attention in conversion between different physical layers, and modulation schemes.

Although POF started as a great solution for automobile and industrial communications as we have seen along the project its features in comparison with other solutions have made that a lot of research groups have arisen since then with a similar purpose I have with this project, characterize and make it possible to bring POF to the home layer. The Japanese POF Consortium, HSPN and PAVNET, The French POF Club or the Polymer Optical Fiber Application Center are some of groups around the world working on different applications and standardization around POF. In Europe the most important one is *"The POF-ALL Project"* for *"Paving the Optical Future with Affordable, Lightning-fast Links",*www.ist-pof-all.org . It has been promoted since the beginning of 2006 and is geared directly toward the development of POF systems. A major and ultimate purpose of POF-ALL is to design and manufacture an "optical modem" up to **100 times faster than traditional DSL modems**, which would allow the download of a DVD-quality movie inless than 3 minutes. Another advantage would be the symmetrical communication speed for download and upload, allowing applications such as peer-to-peer transfer of homemade movies, high-quality videoconferencing and video on demand. Performances of fast Ethernet over POF will ease delivery of triple play at home: the cabling infrastructure will likely consist of a hybrid *"power+POF"* electrical sockets. POF shall be used to create the *"information backbone",* granting tap-proof and maintenance-free installation combined with zero electromagnetic pollution. The topology could either be that of a ring, a star or a mesh network, to accommodate varying standards and needs.

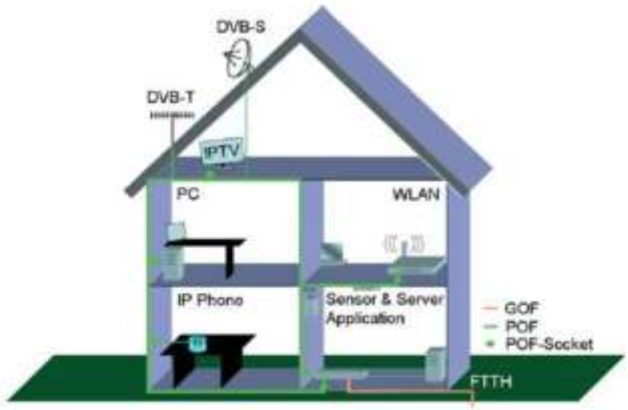


Figure 52 - POF home integration idea from POF-ALL

Will POF be the **future technology** we'll see in every European household in five to ten years? Maybe. It will depend on industry backing and on the success of joint co-operations between major European companies and universities, such as the POF-ALL projects.

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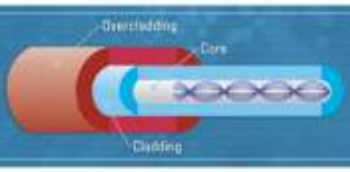
Chapter 9. Annexes

In this last chapter it has been attached datasheets of all chosen devices in the designed system.

9.1 GigaPOF 120LD



GigaPOF®-120LD
Gigabit perfluorinated optical fiber

GigaPOF-120LD is a revolutionary POF offering high performance and unmatched simplicity in a single package. With instant termination, relaxed optical alignment tolerances, and excellent IR and visible transparency, no other multi-gigabit medium is as easy to use.

Graded-index perfluorinated POF: combining the best of the glass fiber and plastic fiber worlds

Until now, the simplicity of plastic optical fiber came with a heavy price: low performance and a restriction to visible wavelengths. The Chromis GigaPOF® line overcomes that trade-off with low attenuation, IR-transparent polymer materials, a graded refractive index, and exacting geometric tolerances. GigaPOF-120LD easily supports Gigabit and 10-Gigabit Ethernet, HDMI, USB 3.0 and other multi-gigabit applications at distances up to 100 meters without dispersion compensation.

A versatile performer

GigaPOF-120LD meets the need for a multi-gigabit fiber that can be used with large alignment tolerances. The 120-μm core and strong mode coupling of this fiber allow an input offset tolerance of more than 30 microns, but it still couples well to most high-speed detectors.

Like the rest of our GigaPOF® line of optical fibers, GigaPOF-120LD can be factory-terminated in seconds with our automated tool, and can be clamped or glued directly into optical sub-assemblies without a ferrule. For field-installable applications, very simple crimp-on connectors and inexpensive tools, make it the easiest-to-install high-speed medium in the world.

Unequaled speed and flexibility

GigaPOF-120LD not only has a qualitatively higher bandwidth than other large-core optical media, but it can be used over a wavelength range from 780-1310 nm. No other gigabit optical medium offers this combination of simplicity and versatility.

Product Specifications	
Transmission Characteristics	
Attenuation at 850 nm (dB/km)	≤ 50
Attenuation at 1300 nm (dB/km)	≤ 50
Bandwidth at 850 nm (MHz.km)	≥ 500
Numerical aperture	0.185 ± 0.015
Macro-bend loss (dB for 10 turns on a 25-mm radius quarter circle)	≤ 0.60
Zero dispersion wavelength (nm)	1200–1650
Dispersion slope (ps/nm^2.km)	≤ 0.06
Physical Characteristics	
Core diameter (μm)	120 ± 10
Over-cladding diameter (μm)	750 ± 5
Core to over-cladding concentricity (μm)	≤ 5
Maximum tensile load (N)	15.0
Long-term bend radius (mm)	10.0
Environmental Performance	
Temperature induced attenuation at 850 nm from −20 °C to +70 °C (dB/km)	≤ 5
Temperature induced attenuation at 850 nm from +75 °C 85 % RH 30 day cycle (dB/km)	≤ 10

9.2 Plastic Fiber coupler

Plastic Plastic Fiber Couplers (Splitters)

7/13

Description

Fiber couplers, or splitters, are special fiber optic devices with one or more input fibers for distributing optical signals into two or more output fibers. The optical light is passively split into multiple output signals (fibers), each containing light with properties identical to the original except for reduced amplitude. Because the splitter is a passive device it is immune to EMI, consumes no electrical power and does not add noise to system design. The splitter's passive design is bi-directional and operationally independent of wavelength, constrained only by the physical properties of the PMMA fiber core.

Fiber couplers have input and output configurations defined as M×N. M is the number of input ports and is one or greater. N is the number of output ports and is always equal to or greater than M. When there are multiple inputs, output signals are always a combination of the input signals – a coupler can also be considered a combiner.

Fiber optic couplers or splitters are available in a wide range of styles and sizes to split or combine light with minimal loss. All couplers are manufactured using a very simple proprietary process that produces reliable, low-cost devices. They are physically rugged and insensitive to operating temperatures. Couplers can be fabricated in custom fiber lengths and/or with terminations of any type.

Applications

- ➤ Feedback Control Circuits
- ➤ Ethernet and Automotive LANs
- ➤ Medical Instruments
- ➤ Automotive Electronics
- ➤ Optical Sensors
- ➤ Wavelength Multiplexing
- ➤ Audio Systems
- ➤ Electronic Games

Features

- ◆ Light, Compact Design
- ◆ Standard Jacketed 1000 µm Core Plastic Fiber Cable
- ◆ High Isolation
- ◆ Light-Tight Stainless Steel Housing
- ◆ Low Loss
- ◆ Excellent Temperature Stability
- ◆ RoHS Compliant

Maximum Ratings

(T_A =25°C)

Operating Temperature Range (T_{OP})........................-40° to 85°C

Storage Temperature Range (T_{STG}).......................-55°to 85°C

Fiber Bending Radius............25 mm

Fiber Tensile Strength.................5 kg

Fiber Characteristics (T_A =25°C)

Material: Fiber couplers are manufactured with Mitsubishi GH4001 1000 µm core jacketed step-index optical fiber. See website for detailed fiber specifications.

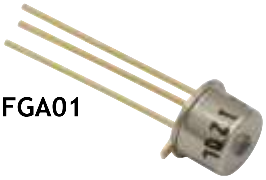
Parameter	Symbol	Min.	Typ.	Max.	Unit
Fiber Attenuation (650 nm light)	–	–	.14	.16	dB/m
Fiber N/A	–	–	.51	–	–
Core Refractive Index	–	–	1.492	–	–
Cladding Refractive Index	–	–	1.402	–	–

9.3 InGaAs High Speed Photodiode – FGA01

THORLABS

InGaAs High Speed Photodiode with Ball Lens

FGA01



Description

The Thorlabs FGA01 photodiode is ideal for measuring both pulsed and CW fiber light sources, by converting the optical power to an electrical current. The FGA01 InGaAs Photodiode is a three pin device with a TO-46 package size. This specific photodiode has a ball shape lens, which is a great optical component for improving signal coupling between fibers. The photodiode anode produces a current, which is a function of the incident light power and the wavelength. The responsivity $\Re$ (λ) can be read from the plot on the following page to estimate the amount of photocurrent to expect. This can be converted to a voltage by placing a load resistor (R_L) from the photodiode anode to the circuit ground. The output voltage is derived as:

$$V_o = P \times \Re \times R_L$$

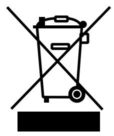
The bandwidth, f_{BW}, and the rise time response, t_R, are determined from the diode capacitance, C_J, and the load resistance, R_L, as shown below. The diode capacitance can be lowered by placing a bias voltage from the photodiode cathode to the circuit ground.

$$f_{BW} = \frac{1}{(2\pi)R_L C_J},\ t_R = \frac{0.35}{f_{BW}}$$

Specifications

Specification	Symbol	Value
Wavelength Range	λ	800 - 1700 nm
Peak Wavelength	λ_P	1550 nm
Responsivity	$\Re(\lambda)$	1.003 A/W
Rise/Fall Time[1] (R_L=50 Ω, 5 V)	t_r/t_f	0.30 ns / 0.30 ns
NEP, Typical (1550 nm, 20 V)	W/√Hz	4.50 x 10^{-15}
Dark Current (5 V)	I_d	0.05 nA (Typ.) 2.00 nA (Max)
Bias Voltage (Reverse)		20 V (Max)
Reverse Current		2 mA (Max)
Capacitance (5 V)	C_j	2.0 pF (Typ.)
Optical Power Damage Threshold		18 mW

[1]Rise and Fall times are measured between 10% to 90% of the step height in accordance with Manufacture specification sheet.



Physical Specifications	
Active Area Diameter	Ø0.12 mm
Coupling Lens	Ø0.06" Ball Lens
Package	TO-46
Sensor Material	InGaAs
Storage Temperature	-55 to 125 °C
Operating Temperature	-40 to 75 °C

Specifications Subject to Change without Notice

December 5, 2013
TTN019860-S01, Rev C

9.4 Si High Speed Photodiode with Ball Lens – FDS025

THORLABS

Si High Speed Photodiode with Ball Lens

FDS025

Description

The Thorlabs FDS025 photodiode is ideal for measuring both pulsed and CW fiber light sources, by converting the optical power to an electrical current. The FDS025 Si Photodiode is a three pin device with a TO-46 package size. This specific photodiode has a ball shape lens, which is a great optical component for improving signal coupling between fibers. The photodiode anode produces a current, which is a function of the incident light power and the wavelength. The responsivity $\Re(\lambda)$ can be read from the plot on the following page to estimate the amount of photocurrent to expect. This can be converted to a voltage by placing a load resistor (R_L) from the photodiode anode to the circuit ground. The output voltage is derived as:

$$V_o = P \times \Re \times R_L$$

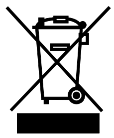
The bandwidth, f_{BW}, and the rise time response, t_R, are determined from the diode capacitance, C_J, and the load resistance, R_L, as shown below. The diode capacitance can be lowered by placing a bias voltage from the photodiode cathode to the circuit ground.

$$f_{BW} = \frac{1}{(2\pi)R_L C_J},\ t_R = \frac{0.35}{f_{BW}}$$

Specifications

Specification	Symbol	Value
Wavelength Range	λ	400 - 1100 nm
Peak Wavelength	λ_P	750 nm
Responsivity	$\Re(\lambda)$	0.48 A/W
Rise/Fall Time (R_L=50 Ω, 5 V)	t_r/t_f	47 ps / 246 ps
NEP, Typical (850 nm, 20 V)	W/√Hz	9.29×10^{-15}
Dark Current (5 V)	I_d	35 pA (Typ.) 500 pA (Max)
Bias Voltage (Reverse)		20 V (Max)
Reverse Current		5 mA (Max)
Capacitance (5 V)	C_j	0.94 pF (Typ.)
Optical Power Damage Threshold		18 mW

[1]Rise and Fall times are measured between 20% to 80% of the step height in accordance with Manufacture specification sheet.



Physical Specifications	
Active Area Diameter	Ø0.25 mm
Coupling Lens	Ø0.06" Ball Lens
Package	TO-46
Sensor Material	Si
Storage Temperature	-55 to 125 °C
Operating Temperature	-40 to 75 °C

Specifications Subject to Change without Notice

November 11, 2013
TTN019843-S01, Rev B

9.5 AFBR-1624Z Transmitter

AFBR-1624Z/1629Z Transmitter

The AFBR-1624Z/1629Z transmitter incorporates a 650 nm LED and integrated driver IC in a light gray, nonconductive plastic Versatile Link housing. Its input data is compatible with TTL logic level. This transmitter can operate from DC to 50 MBd with any kind of data pattern using 1 mm plastic optical fiber (POF). Within the specified ranges AFBR-1624Z and AFBR-1629Z devices will support a BER < 10E-9.

Transmitter Electrical Characteristics

(T_A = -40 °C to +85 °C, V_{CCT} = 3.3 V ± 5% or 5 V ± 5%)

Parameter	Symbol	Min	Typical	Max	Unit	Notes
Supply Current (Optical Power ON)	I_{CCT}		21	31	mA	1
Input Voltage – Low	V_{IL}	-0.3		0.8	V	2
Input Voltage – High	V_{IH}	2.0		Vcc+0.3	V	2
Data Input Capacitance	C_{IN}			7	pF	
Data Input Resistance	R_{IN}	2			kΩ	
Propagation Delay	t_{TD}			30	ns	

Transmitter Optical Characteristics

(T_A = -40 °C to +85 °C, V_{CCT} = 3.3 V ± 5% or 5 V ± 5%)

Parameter	Symbol	Min	Typical	Max	Unit	Notes
Output Optical Power (peak), 1 mm POF	P_N	-5.5	-2	+2	dBm	3
Output Optical Power (peak), PCS (200 µm)	P_N	-16.5	-13	-9	dBm	3
Output Optical Power (Average), OFF	P_S			-50	dBm	
Extinction Ratio	ER	10			dB	
Peak Wavelength	λ_c	630		685	nm	
Rise Time (20%–80%)	t_{RT}			5	ns	
Fall Time (20%–80%)	t_{FT}			5	ns	
Pulse Width Distortion	PWD	-3		+3	ns	4, 5
Pulse Width Distortion of first pulse	PWD	-5		+3	ns	5, 6

Notes:
1. For any type of data between DC and 50 Mbd. Typical value 21 mA for PRBS-7 pattern at 25° C at 5 V and 50 Mbaud.
2. Standard TTL compatible input.
3. Measured with polished connector end face: after 1 meter 1 mm POF, NA = 0.5, or 200 µm PCS, NA = 0.37.
4. Pulse width is measured at 50% threshold using a rising edge trigger tested with PRBS-7 pattern
5. Electrical input pulse width is determined at 1.5 V and dU/dt between 1 V and 2 V shall not be less than 1 V/ns.
6. The first pulse is shorter as the LED is completely discharged. This helps to mitigate the increase of pulse width of the first pulse of the Receiver

6

9.6 VCSEL-850 Transmitter

THORLABS INC

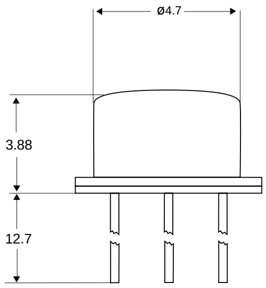
435 Route 206 • P. O. Box 366
Newton, NJ 07860-0366

www.thorlabs.com

SALES (973) 579-7227
FAX (973) 300-3600

VCSEL-850

850nm VCSEL Laser Diode in TO-46 Package



1. Feature

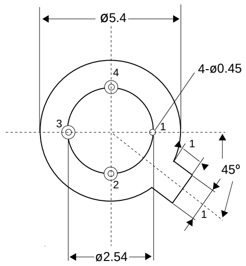
a. Oxidation process
b. Flat window
c. Monitor Photodiode
d. High speed 2.5Gbps

2. Application:

a. High-speed data communications and telecommunications applications
b. Gigabit Ethernet
c. Fiber Channel
d. ATM transceiver modules and system

3. Optical and Electrical Characteristics

Parameter	Symbol	Min.	TYP.	Max.	Unit	Test Condition
Peak Wavelength	l_p	830	845	860	nm	I_f = 8mA@RT
Spectral Width (RMS)	Dl	-	-	0.85	nm	I_f = 8mA@RT
Beam Divergence	Q	-	25	30	Deg	Full width at $1/e^2$; I_f = 8mA@RT
Forward Voltage	V_f	1.7	1.9	2.2	V	I_f = 8mA@RT
Threshold Current	I_{th}	-	2.2	3	mA	-
Slope Efficiency	dP/dI	0.12	0.32	0.4	W/A	I_f = 8mA@RT
Optical Ouptut Power	P_{out}	-	1.85	-	mW	I_f = 8mA@RT
Dynamic Resistance	dV/dI	20	40	65	W	I_f = 8mA@RT
Rise / Fall Time	t_r / t_f	-	50	100	ps	20%-80%
Jitter p-p	t_j	-	35	-	ps	-
ë$_p$ Temperature Coefficient	de$_p$/dT	-	0.06	-	nmºC	T_A=0~70ºC, I_f= 8mA
Operating Temperature Range	T_{op}	-5	25	80	ºC	-
Monitor Current	I_m	100	-	-	mA	I_f = 8mA@RT



(mm)
Bottom View

1. Case
2. VCSEL Anode
3. VCSEL Cathode/Photodiode Anode
4. Photodiode Cathode

2. Maximum Ratings

Parameter	min.	Max.	Unit	Condition
Storage Temperature	-40	100	ºC	-
Operating Temperature	0	85	ºC	-
Continuous Forward Current	-	10	mA	-
Continuous Reverse Voltage	-	5	V	@10mA

3. Monitoring PIN Specs

Parameter	Symbol	Min.	TYP.	Max.	Unit	Test Condition
Dark Current	I_r	-	0.2	1	nA	V_r = 10V
Shunt Resistance	P_p	100	200	-	GW	-
Breakdown Voltage	V_{br}	-	50	-	V	-
Junction Capacitance	C_p	-	40	-	pF	@V_r = 10V, 10KHz

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5/14/04

9.7 VSEL-980 Transmitter

THORLABS INC

435 Route 206 • P. O. Box 366
Newton, NJ 07860-0366

www.thorlabs.com

SALES (973) 579-7227
FAX (973) 300-3600

VCSEL-980

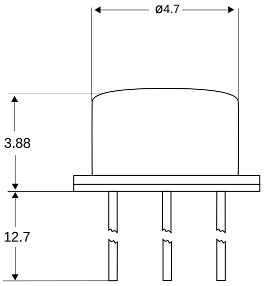
980nm VCSEL Laser Diode in TO-46 Package

1. Feature

a. Oxidation process
b. Flat window
c. Monitor Photodiode
d. High speed 2.5Gbps

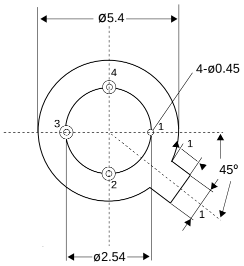
2. Application:

a. High-speed data communications and telecommunications applications
b. Gigabit Ethernet
c. Fiber Channel
d. ATM transceiver modules and system



3. Optical and Electrical Characteristics

Parameter	Symbol	Min.	TYP.	Max.	Unit	Test Condition
Peak Wavelength	l_p	970	980	990	nm	I_f = 8mA@RT
Spectral Width (RMS)	Dl	-	-	0.85	nm	I_f = 8mA@RT
Beam Divergence	Q	-	25	30	Deg	Full width at $1/e^2$; I_f = 8mA@RT
Forward Voltage	V_f	1.7	1.9	2.2	V	I_f = 8mA@RT
Threshold Current	I_{th}	-	2.2	3	mA	-
Slope Efficiency	dP/dI	0.12	0.32	0.4	W/A	I_f = 8mA@RT
Optical Ouptut Power	P_{out}	-	1.85	-	mW	I_f = 8mA@RT
Dynamic Resistance	dV/dI	20	40	65	W	I_f = 8mA@RT
Rise / Fall Time	t_r / t_f	-	50	100	ps	20%-80%
Jitter p-p	t_j	-	35	-	ps	-
$ë_p$ Temperature Coefficient	de_p/dT	-	0.06	-	nm/ºC	T_A=0~70ºC, I_f= 8mA
Operating Temperature Range	T_{op}	-5	25	80	ºC	-
Monitor Current	I_m	100	-	-	mA	I_f = 8mA@RT



(mm)
Bottom View

1. Case
2. VCSEL Anode
3. VCSEL Cathode/Photodiode Anode
4. Photodiode Cathode

2. Maximum Ratings

Parameter	min.	Max.	Unit	Condition
Storage Temperature	-40	100	ºC	-
Operating Temperature	0	85	ºC	-
Continuous Forward Current	-	10	mA	-
Continuous Reverse Voltage	-	5	V	@10mA

3. Monitoring PIN Specs

Parameter	Symbol	Min.	TYP.	Max.	Unit	Test Condition
Dark Current	I_r	-	0.2	1	nA	V_r = 10V
Shunt Resistance	P_p	100	200	-	GW	-
Breakdown Voltage	V_{br}	-	50	-	V	-
Junction Capacitance	C_p	-	40	-	pF	@V_r = 10V, 10KHz

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11923-S01 Rev A
5/18/04

9.8 ML7XX8 Series Transmitter

ML7XX8 SERIES

Notice: Some parametric limits are subject to change.

InGaAsP – MQW – FP LASER DIODES

TYPE NAME

ML720J8S, ML720K8S
ML725B8F, ML725C8F, ML725J8F

DESCRIPTION

ML7XX8 series are InGaAsP laser diodes which provide a stable, single transverse mode oscillation with emission wavelength of 1310nm and standard continuous light output of 5mW.

ML7XX8 are hermetically sealed devices having the photo diode for optical output monitoring. This is suitable for such applications as the light sources for optical communication systems.

FEATURES

- 1310nm typical emission wavelength, FP-LDs
- Low threshold current, low operating current
- Wide temperature range operation (-40 to 85ºC)
- ϕ5.6mm TO-CA N package
  Flat window cap : ML720J8S, ML725B8F
  Ball lens cap : ML720K8S, ML725C8F
  Aspherical lens cap : ML725J8F

APPLICATION

- Optical communication system

ABSOLUTE MAXIMUM RATINGS

Symbol	Parameter	Conditions	Ratings	Unit
Po	Light output power	CW	**10[7]**	**mW**
VRL	Laser reverse voltage	**-**	**2**	**V**
VRD	PD reverse voltage	**-**	**20**	**V**
IFD	PD forward current	**-**	**2**	**mA**
Tc	Operation temperature	**-**	**-40 to +85**	**ºC**
Tstg	Storage temperature	**-**	**-40 to +125**	**ºC**

ELECTRICAL/OPTICAL CHARACTERISTICS(Tc=25ºC)

Symbol	Parameter	Test Conditions	Min.	Typ.	Max.	Unit
Ith	Threshold current	CW	**3**	**5**	**15**	**mA**
Iop	Operation current	CW, Po=5mW	**10**	**20**	**35**	**mA**
Vop	Operating voltage	CW, Po=5mW	**---**	**1.1**	**1.5**	**V**
η	Slope efficiency	CW, Po=5mW	**0.3[0.2]**	**0.5[0.35]**	**0.7[0.5]**	**mW/mA**
λc	Center wavelength	CW, Po=5mW	**1290**	**1310**	**1330**	**nm**
$\Delta\lambda$	Spectral Width	CW, Po=5mW,RMS(-20dB)	**---**	**1.0**	**2.0**	**nm**
θ//	Beam divergence angle(parallel)	CW, Po=5mW	**---**	**25[11]**	**---**	**deg.**
$\theta\perp$	Beam divergence angle (perpendicular)	CW, Po=5mW	**---**	**30[11]**	**---**	**deg.**
tr,tf	Rise and Fall time (20%-80%)	Ib=Ith,Po=5mW,10-90%	**---**	**0.3**	**0.7**	**nsec**
Im	Monitor Current (PD)	CW, Po=5mW, VRD=1V,	**0.1**	**0.5**	**0.9**	**mA**
Id	Dark Current (PD)	VRD=10V	**---**	**---**	**0.1**	**μA**
Ct	Capacitance (PD)	VRD=10V, f=1MHz	**---**	**10**	**20**	**pF**
Pf <2>	Fiber coupled power	CW, PL=5mW,SI10/125	**[0.4/1.5]**	**[0.8/2.0]**	**[---]**	**mW**
Df <2>	Fiber coupled distance	CW, PL=5mW,SI10/125 <3>	**[5.0/6.0]**	**[5.8/7.5]**	**[6.2/9.0]**	**mm**

Note : <1> [ ] applied to the lens cap type.
Note : <2> Pf, Df are applied to the [ball lens type/aspherical lens type].
Note : <3> Df is a distance between reference plane of the base to the fiber.

9.9 GigaPOF Standard Connector

Chromis Fiberoptics

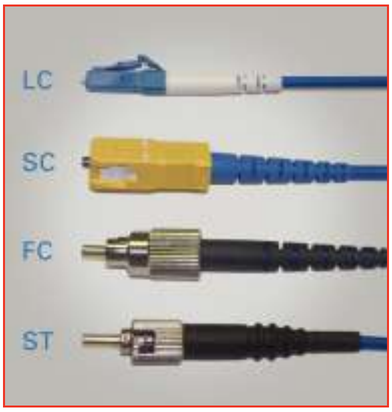
GigaPOF® Standard Connectors

LC, SC, FC, ST— Glue on

GigaPOF® standard glue-on connectors are available in LC, SC, FC, and ST form factors for factory-assembly or your own prototype building. They are completely compatible with the industry-standard LC, SC, FC, and ST footprints, respectively. The GigaPOF® standard connectors quickly and easily attach to GigaPOF® premises cables using all familiar standard termination tools.

All familiar optical connectors

The interfacial dimensions of GigaPOF® standard glue-on connectors comply with the industry standards of optical connectors, except for the fiber ferrule inner diameter. The ferrule holes are sized to fit with our SR-series of 490 micron fibers or LD-series of 750 micron fibers. See the ferrule specifications below.



Convenient portable installation toolkits

Complete Installation toolkits (part numbers GigaPOF-TL-KIT-LC and GigaPOF-TL-KIT-SC) are available for quick and easy attachment of the standard connectors to GigaPOF® premises cables, our 2.9-mm simplex and duplex cables.

Manual or automatic termination

GigaPOF® connectors can be hand-polished in under a minute. For larger installations or for factory-assembly environments, our automatic termination tool (GigaPOF-TL-MM) gives you a perfect end-face every time in about 10 seconds.

Ferrule Specifications

	LC (for SR series fiber)	SC (for SR series fiber)	FC (for LD series fiber)	FC (for SR series fiber)	ST (for LD series fiber)	ST (for SR series fiber)
Style	Simplex, Duplex	Simplex, Duplex	Simplex	Simplex	Simplex	Simplex
Ferrule Inner Diameter (µm)	495 + 2/-0	494+2/-1	750+20/-5	490+10/-4	750+20/-5	490+10/-4
Concentricity (µm)	5	7	20	15	20	15
Material	Stainless alloy	LCP (Gray)	Stainless alloy	Stainless alloy	Stainless alloy	Stainless alloy

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SP-CN-03 (01)